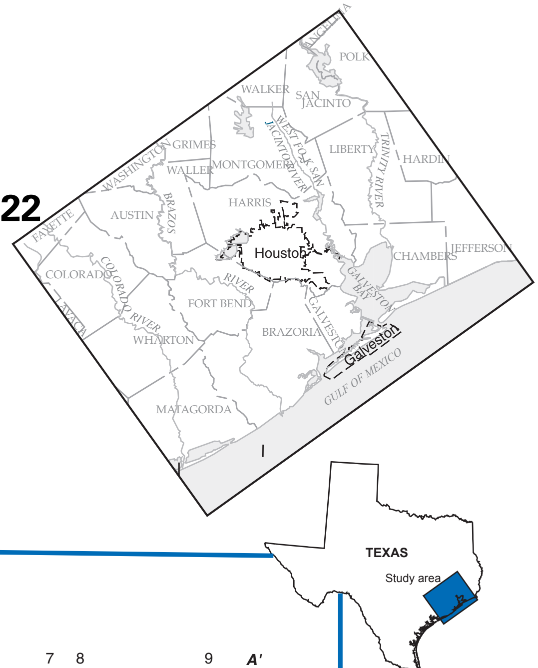
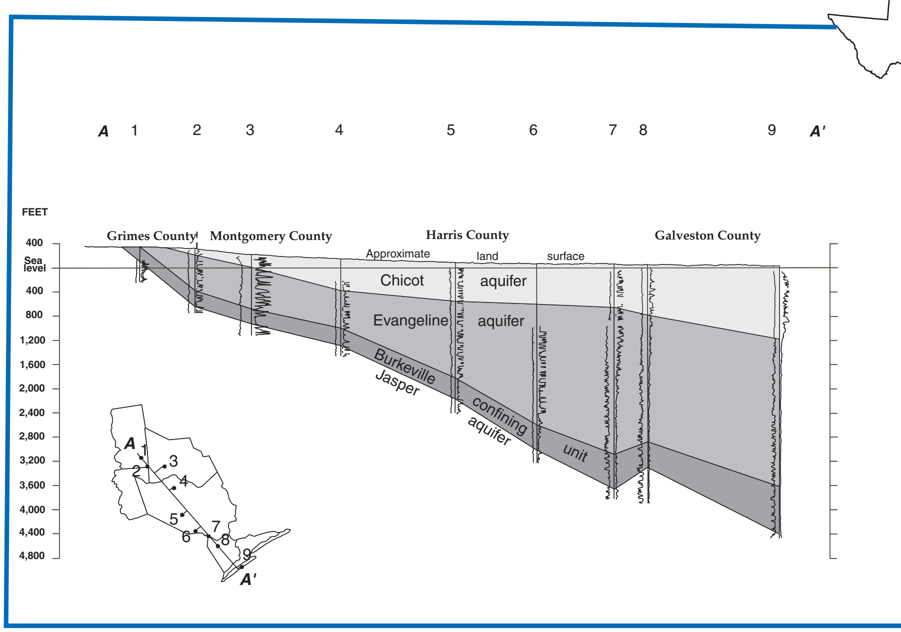
In cooperation with the City of Houston

Hydrogeology and Simulation of Ground-Water Flow and Land-Surface Subsidence in the Chicot and Evangeline Aquifers, Houston Area, Texas

Water-Resources Investigations Report 02–4022





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By Mark C. Kasmarek and Eric W. Strom

U.S. GEOLOGICAL SURVEY
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VERTICAL DATUM AND ABBREVIATED UNITS

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated units:

ft, foot	in/yr, inch per year
ft/d, foot per day	mg/L, milligram per liter
ft^2/d, foot squared per day	Mgal/d, million gallons per day
ft^3/s, cubic foot per second	mi, mile
gal/min, gallon per minute	mi^2, square mile
in., inch	°F, degree Fahrenheit

Note: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness. In this report, the mathematically reduced form, foot squared per day, is used for convenience.

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Abstract

In November 1997, the U.S. Geological Survey, in cooperation with the City of Houston Utilities Planning Section and the City of Houston Department of Public Works & Engineering, began an investigation of the Chicot and Evangeline aquifers in the greater Houston area in Texas to better understand the hydrology, flow, and associated land-surface subsidence. The principal part of the investigation was a numerical finite-difference model (MODFLOW) developed to simulate ground-water flow and land-surface subsidence in an 18,100-square-mile area encompassing greater Houston.

The focus of the study was Harris and Galveston Counties, but other counties were included to achieve the appropriate boundary conditions. The model was vertically discretized into three 103-row by 109-column layers resulting in a total of 33,681 grid cells. Layer 1 represents the water table using a specified head, layer 2 represents the Chicot aquifer, and layer 3 represents the Evangeline aquifer.

Simulations were made under transient conditions for 31 ground-water-withdrawal (stress) periods spanning 1891–1996. The years 1977 and 1996 were chosen as potentiometric-surface calibration periods for the model. Simulated and measured potentiometric surfaces of the Chicot and Evangeline aquifers for 1977 match closely. Water-level measurements indicate that by 1977, large ground-water withdrawals in east-central and southeastern areas of Harris County had caused the potentiometric surfaces to decline as much as 250 feet below sea level in the Chicot aquifer and as much as 350 feet below sea level in the Evangeline aquifer. Simulated and measured potentiometric surfaces of the Chicot and Evangeline aquifers for 1996 also match closely. The large potentiometric-surface decline in 1977 in the southeastern Houston area showed significant recovery by 1996. The 1996 centers of potentiometric-surface decline are located much farther northwest. Potentiometric-surface declines of more than 200 feet below sea level in the Chicot aquifer and more than 350 feet below sea level in the Evangeline aquifer were measured in observation wells and simulated in the flow model.

Simulation of land-surface subsidence and water released from storage in the clay layers was accomplished using the Interbed-Storage Package of the MODFLOW model. Land-surface subsidence was calibrated by comparing simulated long-term (1891–1995) and short-term (1978–95) land-surface subsidence with published maps of land-surface subsidence for about the same period until acceptable matches were achieved.

Simulated 1996 Chicot aquifer flow rates indicate that a net flow of 562.5 cubic feet per second enters the Chicot aquifer in the outcrop area, and a net flow of 459.5 cubic feet per second passes through the Chicot aquifer into the Evangeline aquifer. The remaining 103.0 cubic feet per second of flow is withdrawn as pumpage, with a shortfall of about 84.9 cubic feet per second supplied to the wells from storage in sands and clays. Water simulated from storage in clays in the Chicot aquifer is about 19 percent of the total water withdrawn from the aquifer.

Simulated 1996 Evangeline aquifer flow rates indicate that a net flow of 14.8 cubic feet per second enters the Evangeline aquifer in the outcrop area, and a net flow of 459.5 cubic feet per

second passes through the Chicot aquifer into the Evangeline aquifer for a total inflow of 474.3 cubic feet per second. A greater amount, 528.6 cubic feet per second, is withdrawn by wells; the shortfall of about 54.8 cubic feet per second is supplied from storage in sands and clays. Water simulated from storage in clays in the Evangeline aquifer is about 10 percent of the total water withdrawn from the aquifer.

INTRODUCTION

Ground water from the Chicot aquifer of Holocene and Pleistocene age and the underlying Evangeline aquifer of Pliocene and Miocene age is an important resource to Harris County and adjacent counties in Texas. The water withdrawn from these aquifers supplies most of the water used for industrial, municipal, agricultural, and commercial purposes. The greater Houston metropolitan area is the 10th largest metropolitan area in the United States (U.S. Census Bureau, 2000). The Houston area covers about 2,500 mi^2 and had an estimated population of 2.95 million people in 1995; the area is projected to use 1,232 Mgal/d by 2030 (Turner Collie and Braden, Inc., 1996). As the population of the area increases, the need for management practices that lead to sustainable use of this ground-water resource will be critically important.

Historically, the Houston metropolitan area has relied almost entirely on ground water for its water supply. The area has an abundant source of potable ground water, but the large quantities of ground water withdrawn have resulted in potentiometric-surface declines in the Chicot and Evangeline aquifers, land-surface subsidence, and to a lesser extent, saline-water intrusion. These consequences of ground-water withdrawals led to the creation of the Harris-Galveston Coastal Subsidence District (HGCSD) in 1975. For its three jurisdictional areas, the HGCSD has a ground-water management plan (Harris-Galveston Coastal Subsidence District, 1999), which mandates that ground water account for no more than 10 percent of total water use in the southeastern area; no more than 20 percent in the central area; and ultimately (by 2030), no more than 20 percent in the northwestern area.

The majority of water use, where conversion to an alternate source has occurred, is from surface water. One means of minimizing associated costs and possible economic effects is to optimize the use of the area's ground-water resource. A numerical ground-water-flow model provides an effective tool for water managers to use as an aid in making ground-water-resource management decisions.

In November 1997, the U.S. Geological Survey (USGS), in cooperation with the City of Houston Utilities Planning Section and the City of Houston Department of Public Works & Engineering, began an investigation of the Chicot and Evangeline aquifers in the greater Houston area to better understand the hydrology, flow, and associated land-surface subsidence. As part of the investigation, a numerical model was developed to simulate ground-water flow and land-surface subsidence in the greater Houston area.

Purpose and Scope

The purpose of this report is to update the description of the hydrogeology and document model simulations of ground-water flow and land-surface subsidence in the Chicot and Evangeline aquifers in the greater Houston area. The modeled study area encompasses all of Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, and Waller Counties and parts of Angelina, Austin, Colorado, Fayette, Grimes, Hardin, Jefferson, Lavaca, Matagorda, Montgomery, Polk, San Jacinto, Walker, Washington, and Wharton Counties (fig. 1). The model simulates the aquifers from 1891 through 1996, but discussions are limited to predevelopment, 1977, and 1996 simulated conditions. This report is intended to aid public, municipal, Federal, State, and local water-supply and water-management agencies in planning ground-water use.

Previous Studies

The following discussions of the first three previous models were modified from Carr and others (1985). Four USGS and two private consulting engineering ground-water-modeling studies have been made in the study area. The first ground-water model (Wood and Gabrysch, 1965) covered about 5,000 mi^2 in Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller Counties and was an electric-analog model that used resistors and capacitors to simulate transmissivities and storativities, respectively. The aquifer system was conceptually represented as basically two layers defined as the “Heavily Pumped Layer” and the “Alta Loma Sand.” One resistor-capacitor network was used for each layer, and each network was constructed over a base map of

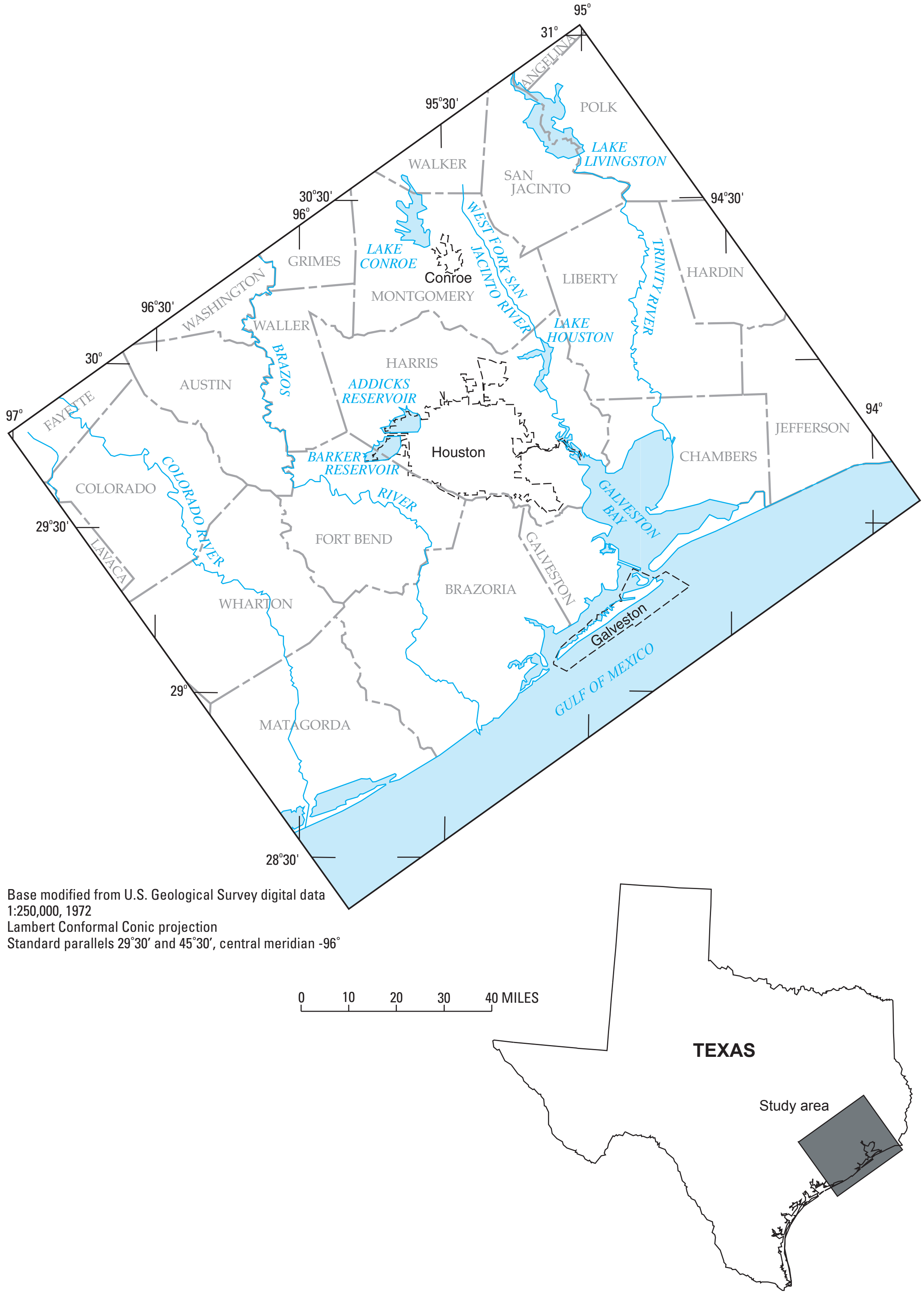


Figure 1. Location of the Houston area, Texas.

the area at a scale of 1 in. equals 1 mi. The model used five ground-water-withdrawal (stress) periods to approximate pumpage from 1890 through 1960 (1890–1930, 1931–40, 1941–47, 1948–53, and 1954–60) and was useful in predicting potentiometric-surface declines under different conditions of ground-water withdrawal. Transient simulations yielded reasonable results, but the model was limited by its inability to simultaneously stress both layers and its inability to simulate the results of ground-water withdrawal in the western part of the study area, which was caused by insufficient historical ground-water-withdrawal data. Evaluation of model simulations indicated that a more thorough hydrogeologic understanding of the aquifer system was needed, and the transmissivity of the aquifers and vertical leakage between the aquifers needed further analysis. However, this initial model proved to be valuable because its use facilitated a clearer understanding of the aquifer system.

The second model (Jorgensen, 1975) was an electronically updated electric-analog model that used updated and additional hydrologic data from 1890 to 1970. The conceptual model divided the aquifer system into the Chicot and Evangeline aquifers, and the model made allowances for the vertical movement of water between the two aquifers. The model also accounted for water contributed to the system from storage in clay layers as withdrawals caused the clay layers to be depressurized and to compact. The model used six stress periods to approximate pumpage from 1890 through 1970 (1890–1930, 1931–46, 1947–53, 1954–60, 1961–64, and 1965–70) and covered an expanded study area of about 9,100 mi^2. Expanding the study area enabled the lateral boundaries to be farther from areas of large ground-water withdrawal. The modeled area consisted of all of Fort Bend, Harris, and Waller Counties and parts of Brazoria, Chambers, Galveston, Liberty, and Montgomery Counties. The two main model limitations were its inability to simulate saline-water encroachment and land-surface subsidence, which are caused by the progressive increase in ground-water withdrawal throughout the model area.

The third model (Meyer and Carr, 1979) was the first finite-difference digital-computer model of the aquifer system. The conceptual model covered 27,000 mi^2 and consisted of five layers, each with 63 rows and 67 columns. The model grid was variably spaced with the smallest cells representing a 1- by 1-mi area; cell size increased toward the lateral boundaries of the model. Layer 1 (lowermost) was equivalent to the total thickness of the sand beds in the Evangeline aquifer. Layer 2 was equivalent to the clay thickness between the centerline of the Chicot aquifer and the centerline of the Evangeline aquifer. Layer 3 was mainly equivalent to the Alta Loma Sand where present; otherwise it was equivalent to the total sand thickness of the Chicot aquifer. Layer 4 was equivalent to the clay thickness between land surface and the centerline of the Chicot aquifer. Layer 5 represented an upper boundary simulating recharge from precipitation and return flow from irrigation and other sources.

Compared to the first and second models, the expanded study area of the third model provided more distance to the lateral model boundaries from the areas of large ground-water withdrawal. Ground-water withdrawals were compiled for seven historical periods from 1890 through 1975 (1890–1930, 1931–45, 1946–53, 1954–60, 1961–70, 1971–73, and 1974–75). The model was useful in predicting potentiometric-surface declines under different ground-water-withdrawal scenarios and included methods to increase or decrease the values of storage in clays for heads equivalent to preconsolidation stress, which allowed simulation of land-surface subsidence. Initial preconsolidated stress approximates the maximum effective stress to which deposits within the study area have been subjected before ground-water development; that stress was estimated from model calibration to be 70 ft of head. Additionally, this model and the two previously mentioned models were designed to simulate well-field ground-water withdrawals for periods of 1 year or longer.

The fourth model (Carr and others, 1985) was actually four separate finite-difference digital-computer models that geographically overlapped each other to simulate the entire study area as four subregions: Eastern, Houston, Central, and Southern. These subregions extended from Louisiana along the Texas Gulf Coast almost to Mexico. The model was conceptually equivalent to the Meyer and Carr (1979) model. The separate models were tested where possible for declines in the potentiometric surfaces of the aquifers from 1890 through 1975 for the Houston subregion and from 1900 through 1970 for all other subregions. Transient simulations were able to satisfactorily match measured potentiometric-surface declines and land-surface subsidence. Significant findings of this study were that a large part of the updip section of the Chicot aquifer is under water-table conditions, vertical leakage from land surface to the Chicot aquifer is an important part of the hydrologic system, and transmissivities from model calibration were about 70 to 80 percent of those obtained solely from aquifer tests. Additionally, an initial preconsolidation stress as indicated by model calibration was 70 ft.

The fifth ground-water model was a three-dimensional, finite-difference digital ground-water model developed by Espey, Huston and Associates Inc. (1982) for the HGCSD. This model, also known as GWMOD, used the Trescott (1975) computer code subsequently modified by Meyer and Carr (1979). The model encompassed 27,000 mi^2, which included all of Galveston and Harris Counties and parts of Brazoria, Chambers, Fort Bend, Hardin, Jefferson, Liberty, Matagorda, Montgomery, Waller, and Wharton Counties. The vertical configuration of the aquifers was based on several previous modeling studies of the hydrogeology in the area by the USGS using both analog and digital models (Wood and Gabrysch, 1965; Jorgensen, 1975; and Meyer and Carr, 1979). The model used a uniformly spaced grid of 30 rows and 39 columns with a cell size of 7.2 mi^2 and could simulate water released from storage in sands and clays as water levels declined. Model calibration was accomplished using 1960–80 ground-water-withdrawal data collected by several agencies and primarily involved modifying transmissivity and vertical hydraulic conductance between the aquifers. Model calibration was tested by comparing the simulated potentiometric surfaces to measured hydrograph data compiled and maintained by the USGS. Three main ground-water-withdrawal scenarios were selected to simulate water-level declines through 2020. One scenario simulated water levels that would occur if ground-water withdrawals required to meet future water demand were supplemented by existing and projected surface-water supplies. Another scenario simulated water levels that would occur if ground-water withdrawals were constrained to 1980 levels. Still another scenario simulated water levels that would occur if all post-1980 water demand was supplied by ground water.

Modeling of land-surface subsidence was associated with, but not part of, the ground-water model (Espey, Huston and Associates Inc., 1982). The subsidence modeling involved a modified version of the COMPAC code developed by Helm (1975; 1976a, b; 1978) known also as the PRESS (Predictions Relating Effective Stress to Subsidence) model. This program solves the Terzaghi equations of consolidation on the basis of constant, one-dimensional total stress and transient changes of pore pressures at specific sites in the aquifers. Simulated water-level declines from the model of Espey, Huston and Associates Inc. (1982) were used as input data for PRESS models at 21 different geographic locations. Input data included stratigraphic data obtained from electric logs and micro-logs of water wells, consolidation characteristics and preconsolidation stresses of clays obtained from scientific literature, and historical land-surface-subsidence data from land-survey leveling and releveling in the area. These data and USGS extensometer data were used during model calibration for spatial and temporal evaluation and comparison. Hydrographs from adjacent water wells were used to derive the model input loading function, and drillers' logs and USGS interpretations of depths of the aquifer tops and bottoms were used to distribute the change in effective stress as a function of depth. Calibration of the PRESS models and land-surface-subsidence simulations were done for the same time periods and water-level-decline data as those of the ground-water model.

The sixth ground-water model, developed by LBG-Guyton Associates (1997), converted the HGCSD 1982 GWMOD code to a format that could be used with the USGS MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) code. The model contained 5,850 cells—five layers of 30 rows by 39 columns with cells 2.5 minutes on a side (2.50 by 2.87 mi). The model area encompassed 8,400 mi^2, which included all of Fort Bend, Galveston, and Harris Counties and parts of Brazoria, Chambers, Grimes, Hardin, Liberty, Matagorda, Montgomery, Waller, and Wharton Counties. The arrangement of the aquifers in the vertical direction was from bottom to top. The original GWMOD model had the ability to simulate water released from storage in sands and clays as water levels declined. To verify that the conversion from GWMOD to MODFLOW was successful, simulated potentiometric surfaces from MODFLOW transient simulations using ground-water-withdrawal data from 1960 through 1987 were compared to potentiometric surfaces for 1979, 1987, and 1994. This comparison showed nearly identical potentiometric surfaces. Transient model calibration was based on potentiometric surfaces for 1980, 1988, and 1995 published by the USGS. The simulated 1995 potentiometric surface in the Chicot aquifer was lower than the published potentiometric surface, but the simulated 1995 potentiometric surface in the Evangeline aquifer was higher than the published surface. It was concluded that a better correlation between the simulated and the measured potentiometric surfaces could have been achieved by moving the northern model boundary about 17 mi north.

Associated with but not part of the LBG-Guyton Associates (1997) ground-water model was Fugro-McClelland (Southwest) Inc. (1997) modeling of land-surface subsidence. Similar to Espey, Huston and Associates Inc. (1982), Fugro-McClelland (Southwest) Inc. used the PRESS model to simulate land-surface subsidence. The simulated water-level declines from the LBG-Guyton Associates (1997) ground-water model were used as input data for PRESS models at 22 sites. The modeling included recalibrating 20 of the 21 Espey, Huston and Associates Inc. PRESS models and calibrating two additional PRESS models. Recalibration of the 20 PRESS models was necessary because the models had not been tested since their original 1982 calibrations, which were based on measured land-surface subsidence through 1978 and potentiometric-surface data through 1980. The 22 PRESS models were used to estimate land-surface subsidence from 1995 to 2030 for a ground-water-withdrawal scenario provided by the HGCSD. This scenario was based on water-level declines if all post-1995 water demand was provided by ground water.

Physiographic Setting

The study area is a gently sloping coastal plain, and the land-surface altitude of the study area ranges from about 300 ft above sea level near the northwestern boundary to sea level at the Gulf Coast. The vegetation in the northwestern area generally is composed of hardwood and pine forests, but as land-surface altitude decreases toward the coast the vegetation becomes increasingly dominated by grasses and shrubs.

The major rivers in the study area are the Brazos, Colorado, San Jacinto, and Trinity Rivers (fig. 1). Numerous constructed lakes and reservoirs are present in the study area but generally influence the water table only on a local scale. The Gulf of Mexico and Galveston Bay have a large effect on the downdip ground-water system and climate of the area.

Winter in the study area is generally of short duration and mild with very few days of freezing temperatures. Relative humidity is moderate, and prevailing winds are from the northwest. During the winter months, moisture-laden Pacific and Canadian air masses produce regionally extensive bands of moderate rainfall. In contrast, summer is generally of long duration and hot. The relative humidity is high, and the prevailing winds are from the southwest. During the summer months atmospheric convective cells can produce low to high rates of localized rainfall, and infrequently, moisture-laden tropical air masses produce moderate to extremely high rates of rainfall. The average annual rainfall over the study area is about 48 in., and the average annual temperature is 68.9 °F (Liscum and others, 1997).

Acknowledgments

The authors acknowledge the City of Houston, Harris-Galveston Coastal Subsidence District, Texas Water Development Board (TWDB), and the numerous water-well owners in the study area for their help in supplying needed data. Additionally, the authors thank and acknowledge Eve L. Kuniansky (USGS) for her modeling expertise, Robert K. Gabrysch (consulting engineer to HGCSD) for his advice and insight on land-surface subsidence and hydrology in the Houston area, and Jeffery W. East (USGS) for his hydrologic insight and computer-programming expertise.

HYDROGEOLOGY OF THE CHICOT AND EVANGELINE AQUIFERS

The general direction of flow within the aquifer system is from the northwest to the southeast. Precipitation entering through the outcrop areas flows downward and laterally through the aquifers toward the coast. Near the coastline and at depth, the more dense saline water is present in the sediments and forms an effective boundary to continued downdip flow. The presence of saline water causes the less dense freshwater to be redirected upward as diffuse leakage, which is eventually discharged in coastal areas and Galveston Bay. Slight hydraulic connection between land surface and the Chicot aquifer and between the Chicot aquifer and the Evangeline aquifer allows water to flow into and between the different units of the aquifer system. The system has been characterized as “leaky” (Gabrysch and Coplin, 1990).

Hydrogeologic Units and Geologic Setting

The Chicot aquifer, the Evangeline aquifer, the underlying Burkeville confining unit, and the Jasper aquifer are the uppermost hydrogeologic units of the vast Gulf Coast aquifer system in the study area (fig. 2), as described in Williamson and others (1990). The correlation of hydrogeologic units with time- and

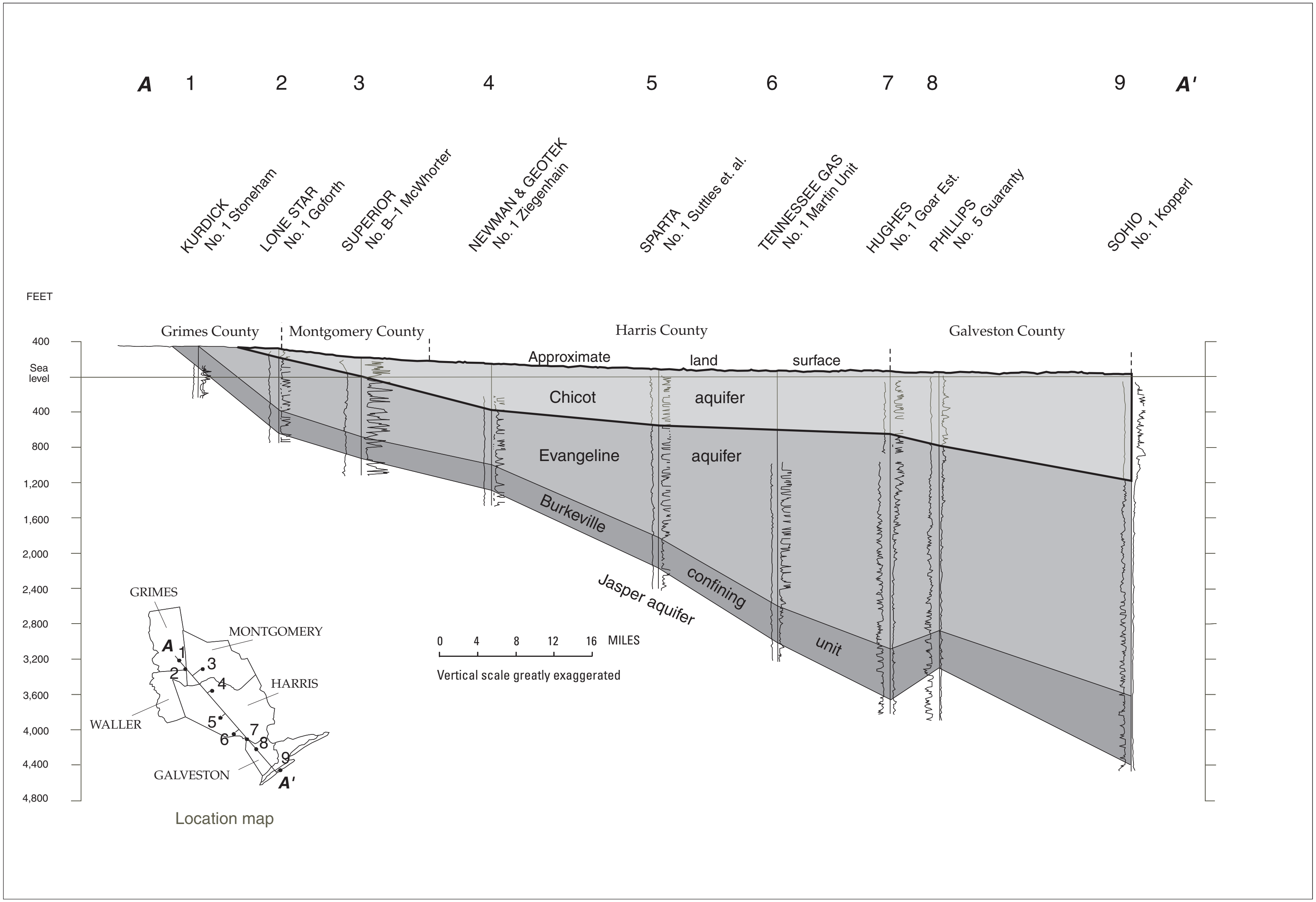


Figure 2. Generalized hydrogeologic section showing the northwest-to-southeast dip of the hydrogeologic units of interest in the Houston area, Texas (modified from Carr and others, 1985).

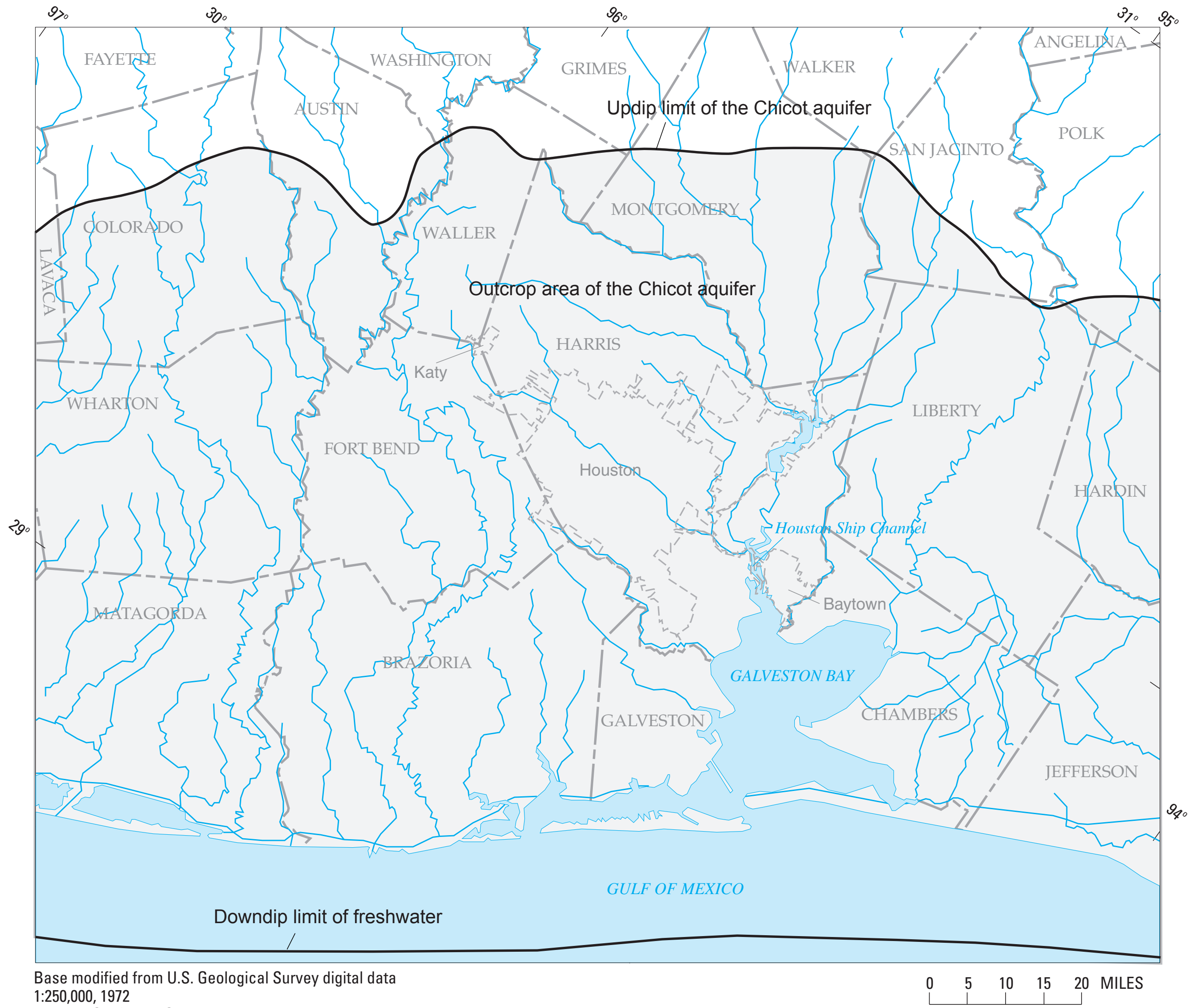
<table>
<tr><th colspan="5">Geologic units</th><th>Hydrogeologic units</th></tr>
<tr><th>Erathem</th><th>System</th><th>Series</th><th>Group</th><th>Formation</th><th>Aquifers and confining units</th></tr>
<tr><td rowspan="9">Cenozoic</td><td rowspan="5">Quaternary</td><td>Holocene</td><td>Houston</td><td>Alluvium</td><td rowspan="5">Chicot aquifer</td></tr>
<tr><td rowspan="4">Pleistocene</td><td rowspan="4">Houston</td><td>Beaumont Clay</td></tr>
<tr><td>Montgomery Formation</td></tr>
<tr><td>Bentley Formation</td></tr>
<tr><td>Willis Sand</td></tr>
<tr><td rowspan="4">Tertiary</td><td>Pliocene</td><td>Citronelle</td><td>Goliad Sand</td><td rowspan="2">Evangeline aquifer</td></tr>
<tr><td rowspan="3">Miocene</td><td rowspan="3">Fleming</td><td rowspan="3">Fleming Formation</td></tr>
<tr><td>Burkeville confining unit</td></tr>
<tr><td>Jasper aquifer</td></tr>
</table>

Figure 3. Correlation of geologic and hydrogeologic units of the Gulf Coast aquifer system in the Houston area, Texas (modified from Sellards and others, 1932; Baker, 1979; and Meyer and Carr, 1979).

rock-stratigraphic (geologic) units of the Gulf Coast aquifer system is shown in figure 3.

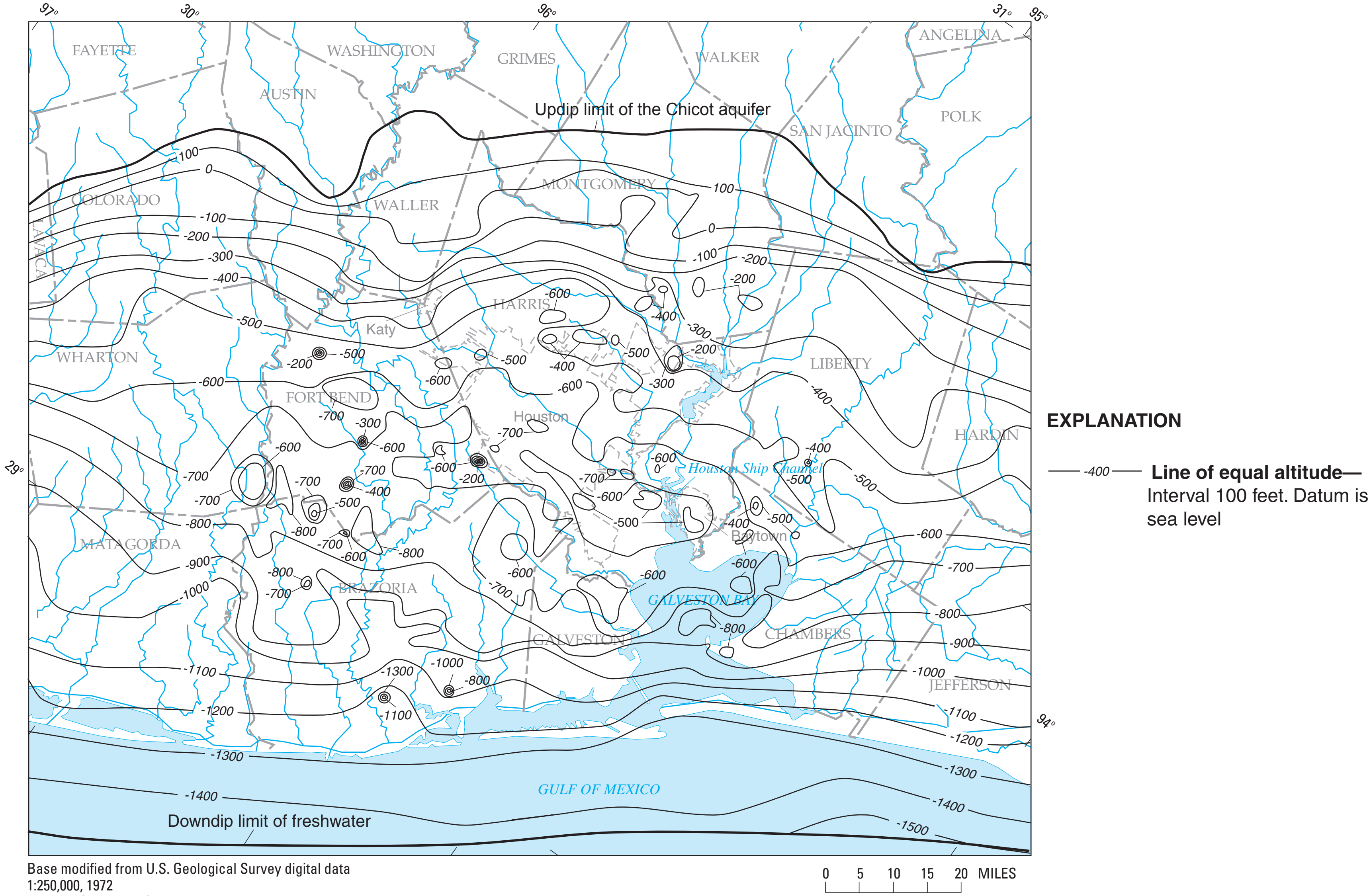
The lateral extent of the Gulf Coast aquifer system extends from the western panhandle of Florida and southwestern Alabama through Mississippi, Louisiana, and along the Texas Gulf Coast into Mexico. In the study area, the northwestern (updip) limit of the Chicot aquifer is an undulating surface approximately parallel to the coastline extending as far northwest as Austin, Colorado, Montgomery, Polk, San Jacinto, and Waller Counties (fig. 4). To the southeast, the freshwater part of the aquifer extends a considerable distance beneath the Gulf of Mexico (fig. 4). The altitude of the base of the Chicot aquifer in the Houston area (fig. 5) ranges from more than 1,500 ft below sea level southeastward of the coastline to more than 100 ft above sea level near the updip limit of the outcrop area and varies locally because of numerous salt domes.

In the study area, the northwestern (updip) limit of the Evangeline aquifer is an undulating surface approximately parallel to the coastline extending as far northwest as Austin, Fayette, Grimes, Montgomery, Polk, San Jacinto, Walker, and Washington Counties (fig. 6). The freshwater part of the aquifer extends to the southeast through the subcrop area approximately to the coastline. The altitude of the base of the Evangeline aquifer in the Houston area (fig. 7) ranges from more than 5,000 ft below sea level southeastward of the coastline to more than 200 ft above sea level near the updip limit of the outcrop area and varies locally because of numerous salt domes. In general, where the aquifers crop out, they do so parallel to the coastline and thicken



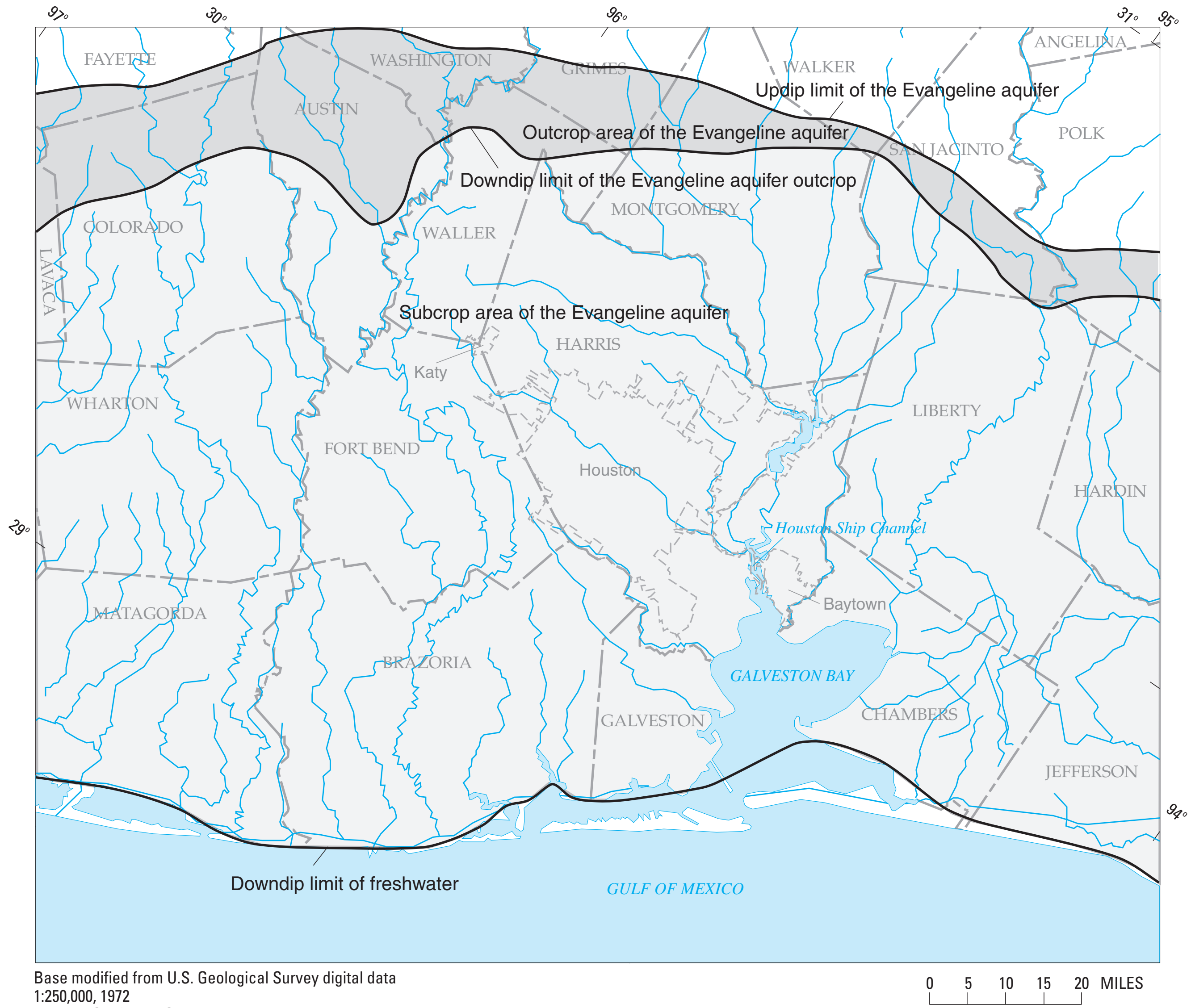
Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

Figure 4. Approximate areal extent of the Chicot aquifer in the Houston area, Texas (modified from Carr and others, 1985).



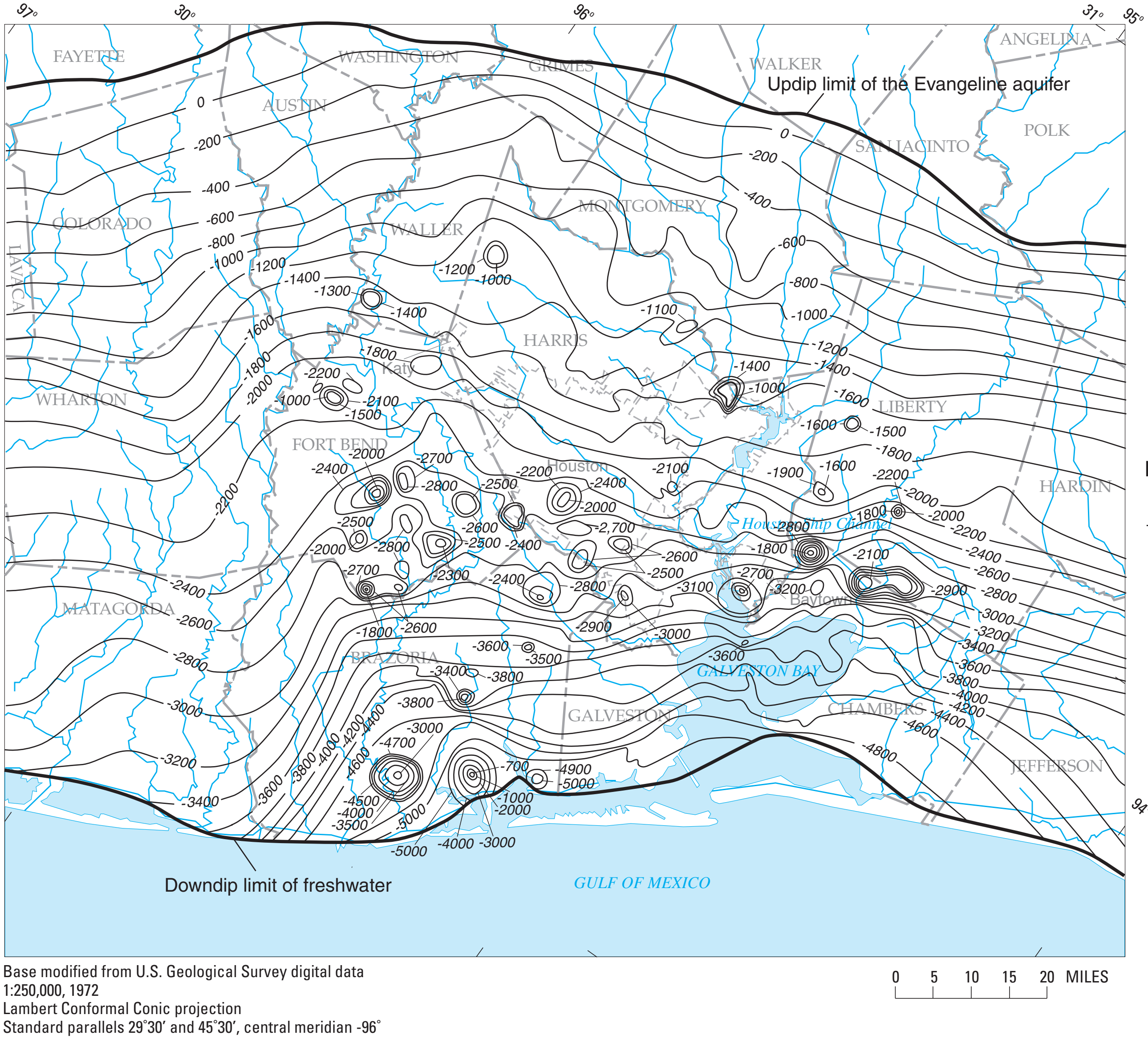
Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

Figure 5. Altitude of the base of the Chicot aquifer in the Houston area, Texas (modified from Jorgensen, 1975; Meyer and Carr, 1979).



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

Figure 6. Approximate areal extent of the Evangeline aquifer in the Houston area, Texas (modified from Carr and others, 1985).



EXPLANATION

-1800 **Line of equal altitude—** Interval variable, in feet. Datum is sea level

Figure 7. Altitude of the base of the Evangeline aquifer in the Houston area, Texas (modified from Jorgensen, 1975; Meyer and Carr, 1979).

downdip to the southeast with the older units having a greater dip angle. Both aquifers have shallow water-table conditions in their updip areas and become confined downdip.

The Burkeville confining unit lies stratigraphically below the Evangeline aquifer. This unit is considered a no-flow basal unit in the Houston area that restricts the upward movement of more dense saline water from depth.

The paleo-depositional environment was a fluvial deltaic or shallow-marine environment that produced interlayered, discontinuous sequences of sand, silt, clay, and gravel. Changes in land-surface altitudes related to naturally occurring land-surface subsidence of the depositional basin and sea-level transgressions and regressions created cyclical sedimentation facies. During periods when the sea level declined, fluvial deltaic processes deposited continental sediments; but as the sea level rose, the deposited continental sediments were reworked, and marine sediments were deposited. Because of this complex depositional process, the facies alternate cyclically from predominantly continental sediments that compose the aquifers to predominantly marine sediments that compose the clay layers and confining unit. Therefore, the aquifer system has a high degree of heterogeneity in both lateral and vertical extent (Sellards and others, 1932).

Growth faults are common throughout the unconsolidated sediments of the study area, and traces of some of these faults have been mapped and named in Harris County. On the basis of the study of well logs and seismic line data, these faults have been delineated to depths of 3,000 to 12,000 ft below land surface. The presence of most of these faults is associated with the natural geologic processes of the depositional environment. The scale of fault movement is insufficient to completely offset entire hydrologic units, but over geologic time, the movement does offset individual layers that compose these units. Widely distributed and ongoing faulting processes increase the complexity of the hydraulic characteristics of the aquifers in areas adjacent to the faults. A thorough discussion of faulting in the Houston metropolitan area is presented in Verbeek and others (1979).

Numerous salt domes have been mapped in the study area (Jorgensen, 1975) and are shown in figures 5 and 7 as small areas of concentric contours. The salt originated from the Jurassic-age Louann Salt and has risen from the underlying strata. In some areas, the salt domes penetrated both aquifers. The upward intrusive movement of the salt domes decreases the thickness of the adjacent aquifer sediments in radial extent and alters the normal hydraulic characteristics of and flowpaths in the adjacent aquifer sediments. These widely distributed salt domes increase the complexity of the hydraulic characteristics of the aquifers in adjacent areas.

Aquifer Properties

Carr and others (1985) estimated transmissivity and storativity of the Chicot and Evangeline aquifers. Transmissivity of the Chicot aquifer ranges from about 3,000 to about 50,000 ft^2/d, and storativity ranges from about 0.0004 to 0.1. Transmissivity of the Evangeline aquifer ranges from about 3,000 to about 15,000 ft^2/d, and storativity ranges from about 0.0005 to 0.1. For both aquifers, the larger storativities are in the updip outcrop areas where the aquifers are under water-table conditions; the smaller storativities are in areas where the aquifers are under confined conditions.

Recharge and Discharge

The primary mechanism of recharge to the Chicot aquifer flow system is infiltration of precipitation into the northern updip outcrop area of the Chicot aquifer where the Beaumont Clay is predominantly sand or is nonexistent. Most of the recharge to the flow system occurs in this northern updip area (Gabrysch, 1977). In this updip area and southward to the coast, water-table and perched water-table conditions exist in the shallow sediments. The water table in these shallow sediments has remained relatively stable over time (fig. 8). However, beneath much of the greater Houston area and southern areas of the Chicot aquifer, the deeper layers of the aquifer that are predominantly used for ground-water withdrawals act as a confined system, with exchange of flow to and from the shallow sediments impeded by a thick sequence of numerous interbedded sand and clay layers. The pressure head of the confined system has been gradually reduced over time by ground-water withdrawals, which has resulted in induced recharge from the shallow sediments caused by increasing hydraulic gradients. Therefore, the shallow sediments act as a source or sink layer relative to the confined system. Toward the coast, where the Beaumont Clay is predominantly clay (fig. 9), recharge to and discharge from the confined flow system is further impeded by the thickness of the clay. Similarly, the primary mechanism of recharge to the Evangeline aquifer flow system is infiltration of precipitation into

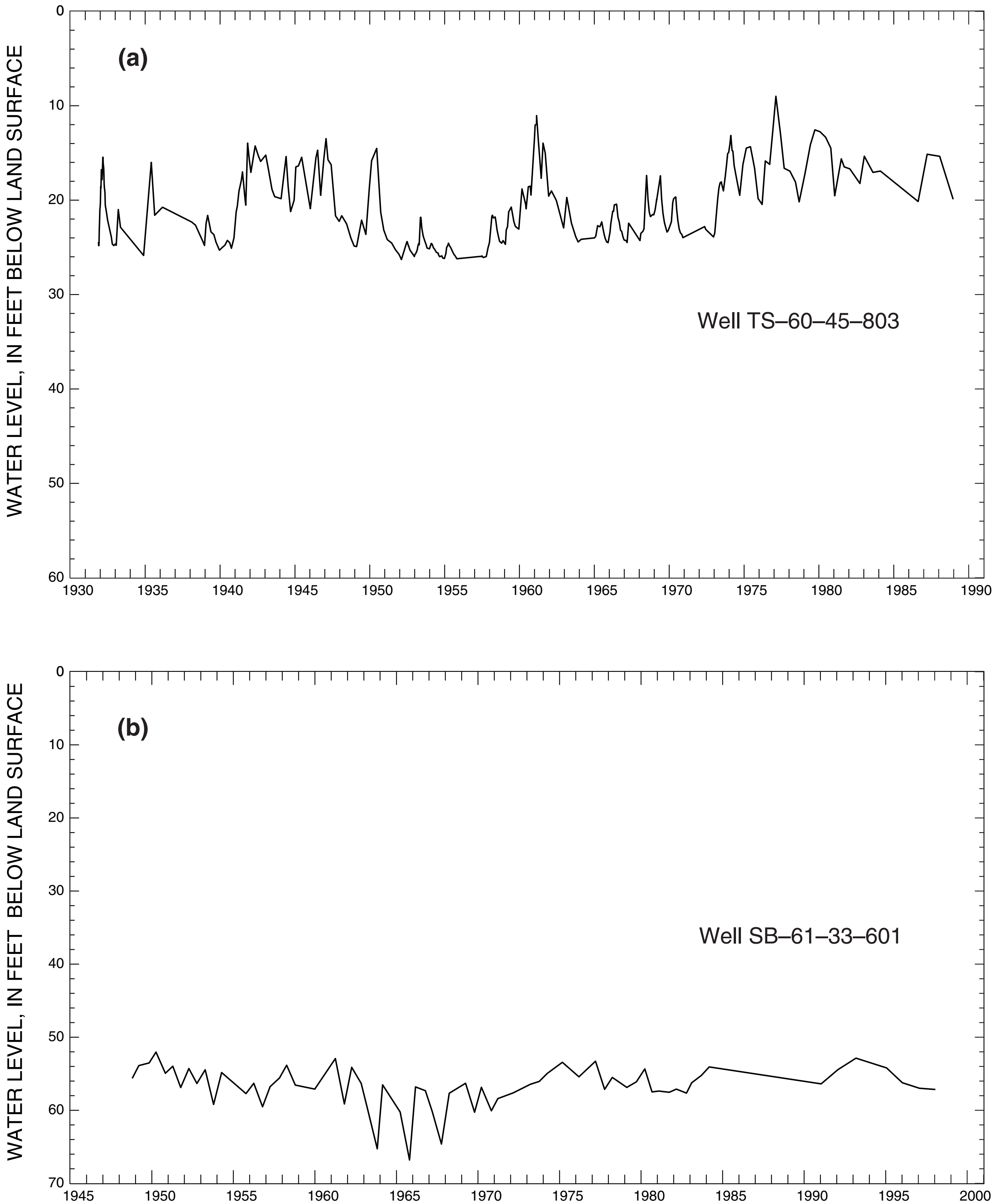
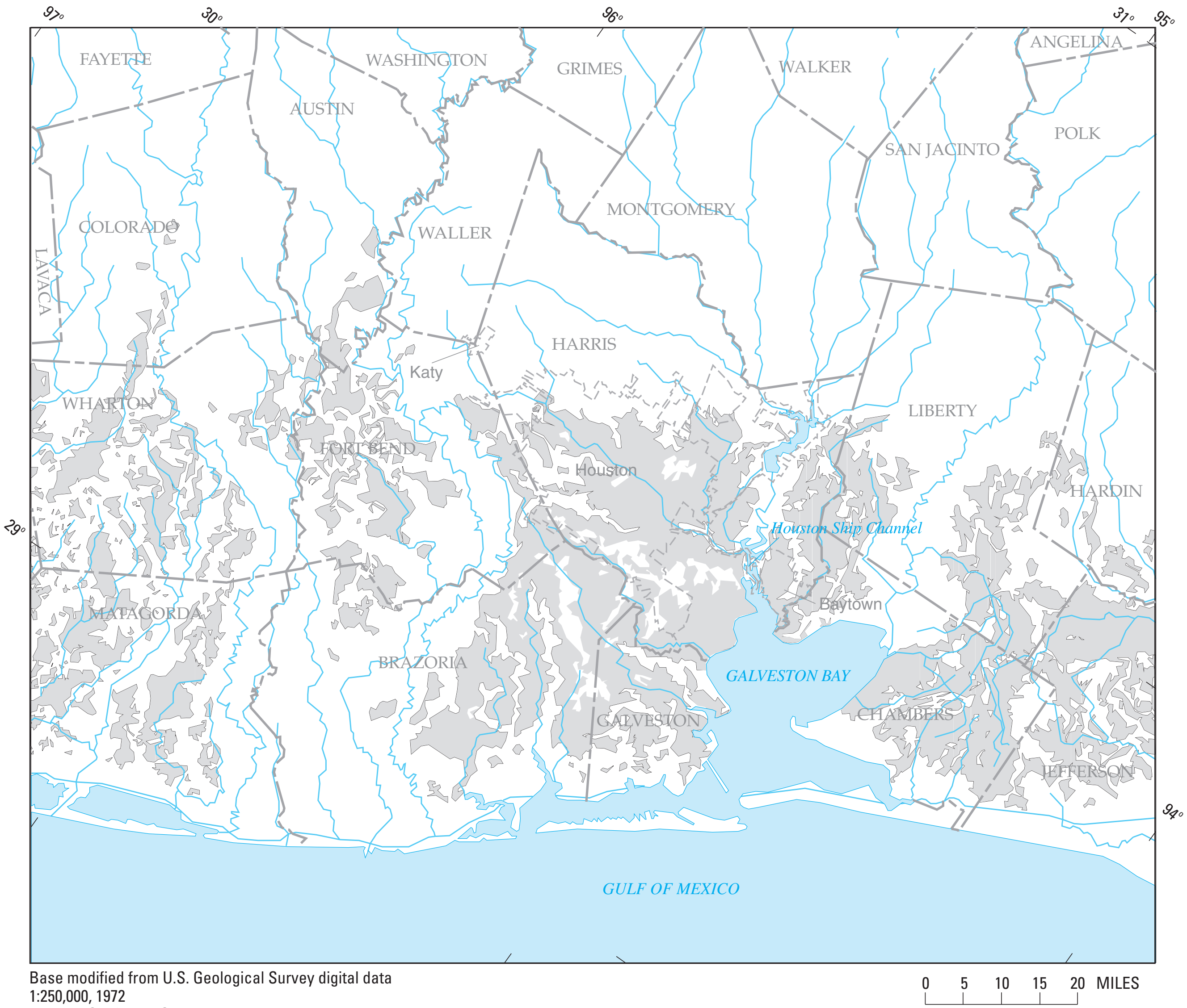


Figure 8. Hydrographs showing water levels in wells screened in the outcrops of the (a) Chicot aquifer in Montgomery County and (b) Evangeline aquifer in Liberty County, Houston area, Texas.



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

Figure 9. Outcrop of areas that are predominantly clay in the Beaumont Clay, Houston area, Texas (modified from Barnes, 1992).

the Evangeline aquifer outcrop area, and southward of this outcrop area the aquifer acts as a confined system.

Estimated precipitation recharge rates in the outcrops of the Chicot and Evangeline aquifers (Noble and others, 1996) were examined. This study used the "interface" method with tritium as an environmental tracer. "Interface" refers to the deepest point below the water table that tritium at postnuclear-testing concentrations has traveled. The estimated recharge rate was 6 in/yr, which reasonably agrees with recharge estimates of Ryder and Ardis (1991) and R.K. Gabrysch and Fred Liscum (U.S. Geological Survey [retired], oral commun., 1999). This estimated recharge rate is total recharge to the saturated zone, rather than net recharge to the deeper, more regional flow system, because much of the total recharge discharges along local and intermediate flowpaths to streams and rivers.

Naturally occurring discharge from the aquifer system occurs in several ways. In localized flow systems, seeps and springs in areas of low topographic relief discharge into the many streams and rivers. Evapotranspiration is another mechanism of discharge of local- and intermediate-scale ground-water flow. In the deeper, more regional flow system, the discharge of water from the aquifer system occurs along the coast as diffuse upward leakage into the numerous bays and estuaries and adjacent offshore areas.

Ground-Water Development

Rates of recharge to and discharge from the Chicot and Evangeline aquifers are affected by ground-water withdrawal from the aquifers. The term "predevelopment" used in this report indicates aquifer conditions before 1891 or before the aquifer was stressed by appreciable ground-water withdrawal. Consistent with the model of Carr and others (1985), the term "post development" used in this report indicates aquifer conditions after 1891 or after the start of appreciable ground-water withdrawal.

Ground-water withdrawal from wells altered the predevelopment potentiometric-surface gradients and changed the naturally occurring flowpaths in the aquifer system. Continued ground-water withdrawal through time has caused the potentiometric surface to decline in both aquifers (Coplin and Santos, 2000). As the potentiometric surface declined throughout the area, the numerous clay layers within the aquifers were depressured and compacted, resulting in land-surface subsidence. The volume of water released from the compacting clay layers, or water released from storage in clay layers, is important when analyzing the aquifer's response to ground-water withdrawal.

The principal areas of ground-water withdrawal in the study area are in Harris and Galveston Counties, the former including the city of Houston. The following discussion primarily focuses on these areas. Much of the early ground-water-use information is modified from Lang and Winslow (1950) and Wood and Gabrysch (1965).

Houston was founded in 1836 and initially used surface-water sources to meet water-supply demands. In 1878, the Houston Water Works, an independent company, was established to manage water-supply needs. In 1886, the first well was drilled to a depth of 140 ft below land surface and was reported as free flowing at more than 1,000 gal/min. By 1905, as the population and water demand increased, 65 wells were in production, ranging from 115 to 1,130 ft deep. In 1906, the City of Houston purchased Houston Water Works, which had the capacity to supply as much as 19 Mgal/d of water, of which only 11 Mgal/d were actually used. By 1935, ground-water withdrawal averaged 24.5 Mgal/d, and by 1941, ground-water withdrawal had gradually increased to 27.2 Mgal/d. From 1941 to 1950, ground-water use more than doubled the amount recorded in 1941 as ground-water withdrawal by independent water supply and improvement districts increased by 100 percent. The start of rice irrigation in the 1890s near Katy (fig. 4); the opening of the Houston Ship Channel (fig. 4) in 1915, which increased industrial and commercial water-supply demand; and industrial growth near Baytown (fig. 4) in the 1920s contributed to the increase in ground-water development exclusive of public-supply demands. Ground-water withdrawal continued to increase until 1954 when water released from the newly constructed Lake Houston (fig. 1) began to augment ground-water supplies. The additional surface-water supply resulted in reduced ground-water withdrawal from 1954 to 1960. In the early 1960s, ground-water withdrawal increased at a rate comparable to pre-1954 rates until the mid-1970s.

In 1976, the total ground-water withdrawal for the entire study area was in excess of 450 Mgal/d but gradually decreased to 390 Mgal/d in 1981. Starting in 1982, ground-water withdrawal gradually increased, and in 1990, the largest total recorded ground-water withdrawal in the study area was in excess of 493 Mgal/d. However, by 1996, ground-water withdrawal had declined to about 463 Mgal/d, or about 30 Mgal/d less than in 1990, about 73 Mgal/d more than in 1981, and about 13 Mgal/d more than in 1976 (fig. 10).

In 1975, because of increasing ground-water withdrawal and subsequent land-surface subsidence in Harris and Galveston Counties, the HGCSD was created by State of Texas legislation to halt land-surface subsidence leading to flooding by regulating ground-water withdrawal. In late 1976, ground-water withdrawal began to decrease in eastern Harris County because of the availability of water from Lake Livingston (fig. 1). This surface-water supply was used by the many steel and petrochemical industries in the area to augment ground-water withdrawal. The policies of the newly created HGCSD resulted in decreased ground-water withdrawal in the Baytown and southeastern Harris County areas. Additionally, because of concerns about declining water levels in Fort Bend County, which is adjacent to Harris County, the Fort Bend Subsidence District was created in 1989 by similar State of Texas legislation.

Potentiometric Surfaces and Land-Surface Subsidence

In the updip area of the Chicot aquifer and the outcrop area of the Evangeline aquifer (figs. 4, 6), water-table conditions generally exist. The water table generally is a subdued replica of the topography (Williams and Williamson, 1989) and ranges from about 10 to 30 ft below land surface on the basis of seismic refraction work by Noble and others (1996). Hydrographs indicate that the water table remains fairly stable where not directly influenced by a nearby pumping well. This is attributed to the relatively high annual precipitation and infiltration that normally occur in the Houston area.

The potentiometric surfaces of the aquifers are measured annually by the USGS in Harris, Galveston, Fort Bend, and surrounding counties, and these data from about 480 wells were used to construct the 1996 water-level-altitude maps of the Chicot and Evangeline aquifers (Kasmarek and others, 1996). The water-level-altitude map of the Chicot aquifer, January 1996, shows a range in water-level altitudes from 150 ft above sea level in northwestern Harris County and southeastern Waller County to 200 ft below sea level in southwestern Harris County (fig. 11). The water-level-altitude map of the Evangeline aquifer, January 1996, shows a range in water-level altitudes from 100 ft above sea level in northwestern Harris County and southeastern Waller County to 350 ft below sea level in west-central Harris County (fig. 12).

Ground-water development in the study area has caused declines of the potentiometric surfaces of the aquifers and subsequent land-surface subsidence. In the 1890s, before the beginning of appreciable ground-water withdrawal, potentiometric surfaces were much higher than land surface within the confined part of the aquifers. Production of water from a single well screened in the Chicot or Evangeline aquifer would locally decrease the hydraulic pressure in the aquifer causing the water level in the well to decline. To meet the increasing water demand, more wells were drilled, which caused further potentiometric-surface declines.

Potentiometric-surface declines in these confined aquifers causes a decrease in hydraulic pressure that creates a load on the skeletal matrix of the aquifer. Because the sand layers are more transmissive than the clay layers, the depressuring of the sand layers is relatively rapid, causing only slight skeletal matrix consolidation of the sand layers. However, the depressurizing and subsequent dewatering of the clay layers requires more time compared to that in the sand layers and is dependent on the thickness and hydraulic characteristics of the clay layers as well as the vertical stress of the sediment overburden. The delayed drainage of the clay layers continues to occur until the excess (transient) pore pressure in the clay layers equals the pore pressure of the adjacent sand layers. Until pressure equilibrium is attained, dewatering of the clay layers continues to apply a load to the skeletal matrix of the clay layers. This loading process is similar to what occurs in the sand layers; but additionally, the individual clay grains change their orientation, aligning themselves perpendicular to the applied vertical load. Therefore, the dewatering caused by the depressurization of the clay layers combined with the individual clay-grain realignment reduces the porosity and ground-water-storage capacity of the clay layers, which in turn allows them to compact.

Because of the weight of the overburden and the inelastic compaction characteristics of the clay layers, about 90 percent of the compaction is permanent. Thus, when potentiometric surfaces rise and repressure compacted clay layers, there is little, if any, rebound of the land surface (Gabrysch and Bonnet, 1975). Although the compaction of one clay layer generally will not cause a noticeable decrease in land-surface altitude, if numerous stacked clay-layer sequences (which are

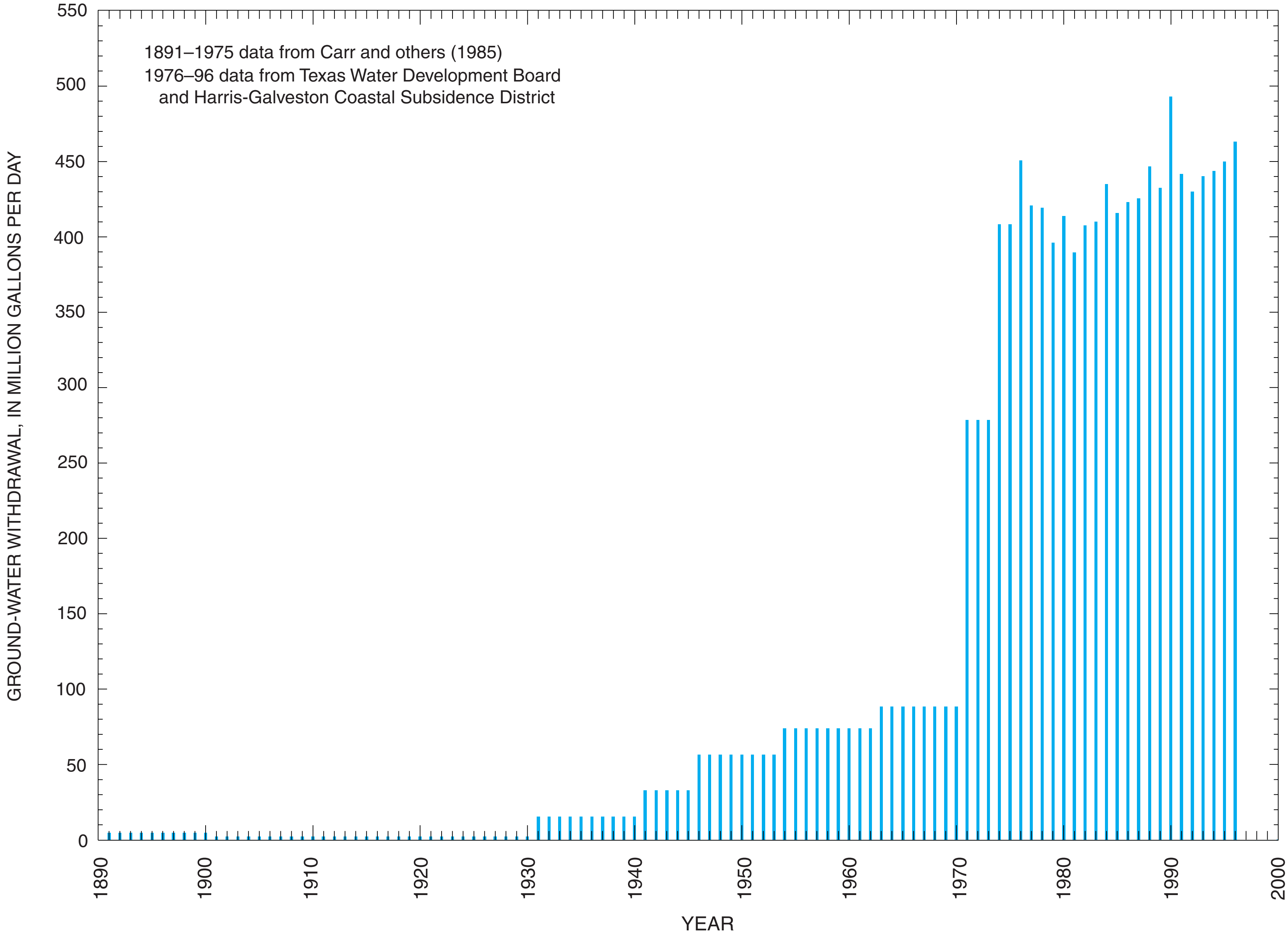
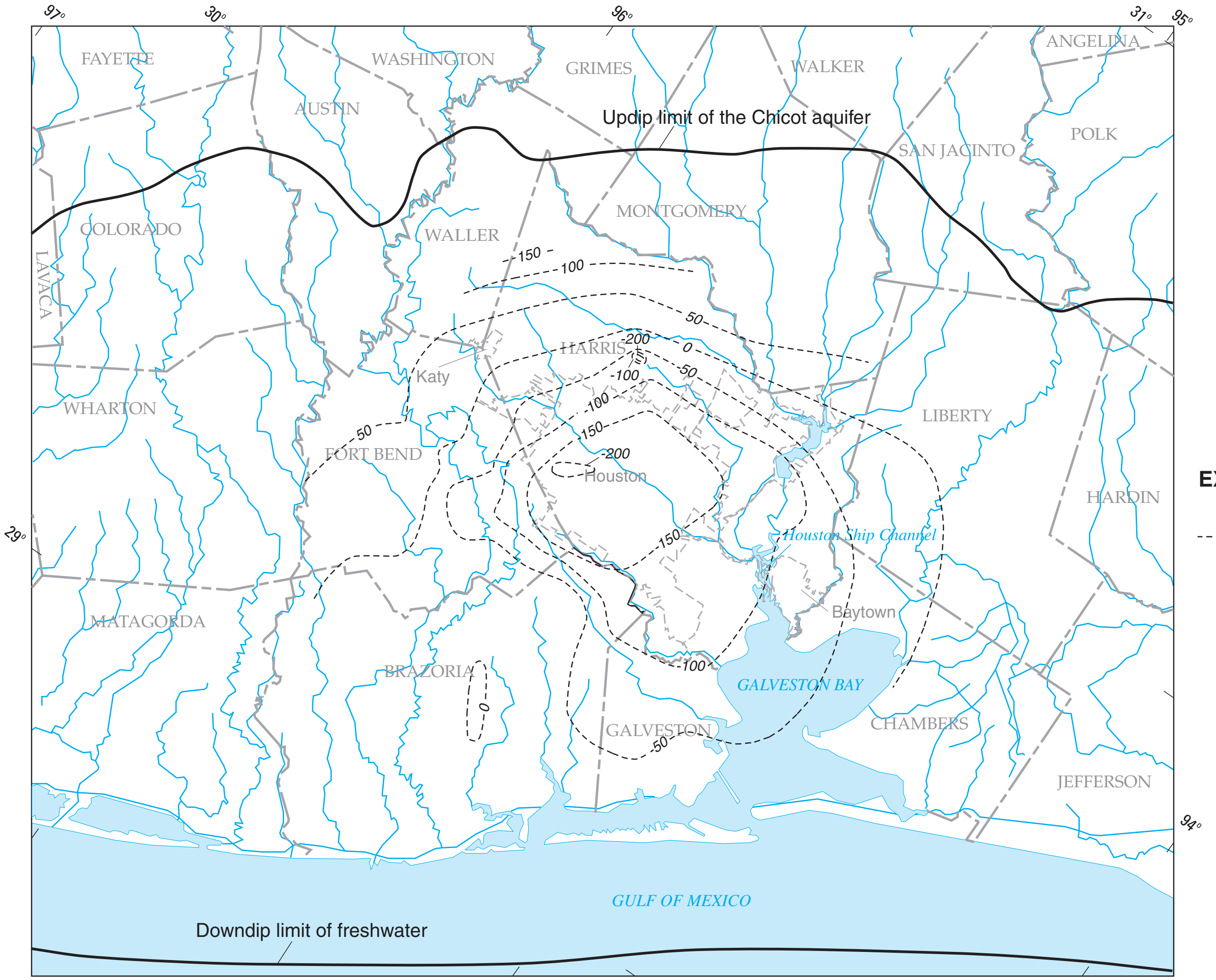


Figure 10. Total ground-water withdrawal in the Houston area, Texas, 1891–1996.



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

0 5 10 15 20 MILES

EXPLANATION

- - - - 50 - - - - **Line of equal altitude of potentiometric surface**—Intervals 50 and 100 feet. Datum is sea level

Figure 11. Measured potentiometric surface of the Chicot aquifer, Houston area, Texas, January 1996 (modified from Kasmarek and others, 1996).

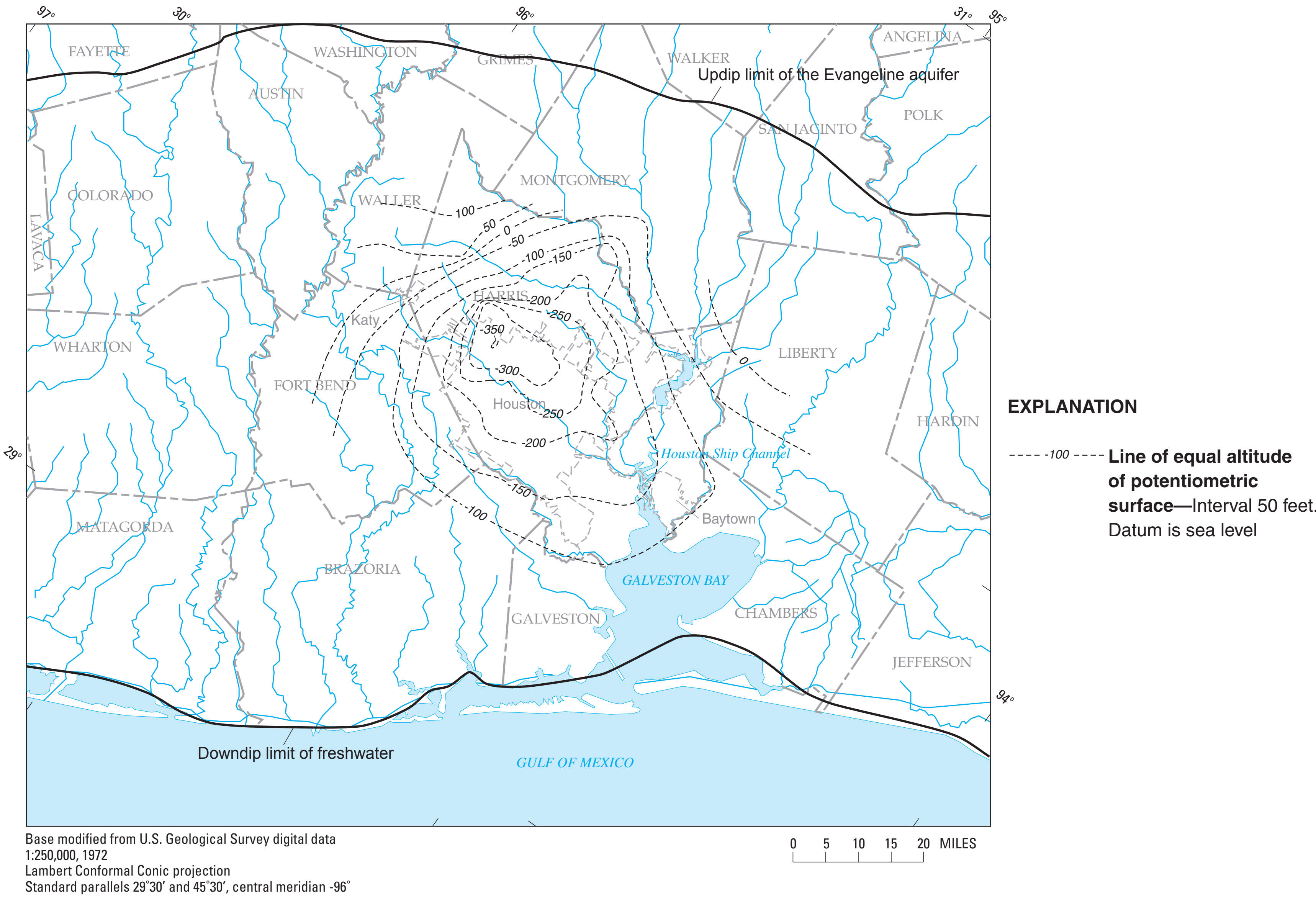


Figure 12. Measured potentiometric surface of the Evangeline aquifer, Houston area, Texas, January 1996 (modified from Kasmarek and others, 1996).

characteristic of the aquifer system) depressure and compact, then significant decreases in land-surface altitude can and do occur (Gabrysch and Bonnet, 1975).

SIMULATION OF GROUND-WATER FLOW AND LAND-SURFACE SUBSIDENCE IN THE CHICOT AND EVANGELINE AQUIFERS

A numerical model of ground-water flow and land-surface subsidence was developed to simulate potentiometric surfaces from 1891 to 1996 in the Chicot and Evangeline aquifers and land-surface subsidence resulting from potentiometric-surface declines in the aquifers in Harris, Galveston, and surrounding counties. Included in this section is a description of the model, simulations of predevelopment and post-development (transient) flow conditions, and model limitations.

Numerical Model

Anisotropic and heterogeneous three-dimensional flow of ground water, assumed to have constant density, can be described by the partial differential equation

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t}, \qquad (1)$$

where

K_{xx}, K_{yy}, and K_{zz} = hydraulic conductivity along the x, y, and z coordinate axes [Lt^{-1}], which are assumed parallel to the major axes of hydraulic conductivity;

S_s = specific storage [L^{-1}];

W = source or sink term [t^{-1}];

h = hydraulic head [L]; and

t = time [t].

The finite-difference computer code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) numerically approximates this equation and was used to simulate the Chicot and Evangeline aquifer system. The Interbed-Storage Package (Leake and Prudic, 1991) was used to simulate clay compaction and storage. Published data and data from field investigations were collected and reviewed prior to model input and calibration. Data analysis included defining the hydrogeologic framework and translating that framework into a conceptual model of the aquifer system suitable for simulation. The aquifers were simulated as separate layers and discretized into two-dimensional finite-difference grids. Applying the field data to the grid required matching aquifer confining-unit properties to the scale of the model. After establishing the grid, the hydraulic characteristics were assigned to the model cells.

Grid Design

The finite-difference grid used in the numerical model (fig. 13) covers 18,100 mi^2 and encompasses all of Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, and Waller Counties and parts of Angelina, Austin, Colorado, Fayette, Grimes, Hardin, Jefferson, Lavaca, Matagorda, Montgomery, Polk, San Jacinto, Walker, Washington, and Wharton Counties (fig. 1). The focus of the study is Harris and Galveston Counties, but the study area was extended well beyond Harris and Galveston Counties so that the high rates of ground-water withdrawal that occur in Harris and Galveston Counties would have a minimal effect on potentiometric surfaces at the model boundaries. The model grid was oriented parallel to the Texas Gulf Coast to better coincide with the ground-water divides, boundaries, and predevelopment flowpaths. The system was assumed horizontally isotropic; that is, a lateral anisotropy ratio of 1 was used in the simulations. Each grid layer consists of 103 rows and 109 columns. The model was vertically discretized into three layers resulting in a total of 33,681 grid cells. Layer 1 represents the water table using a specified head, layer 2 represents the Chicot aquifer, and layer 3 represents the Evangeline aquifer. The grid cells are variably spaced. Each of the smallest cells (in the primary area of interest) equals about 0.90 mi^2, and each of the largest cells (along parts of the outer model boundaries) equals about 4.54 mi^2.

Boundaries and Stresses

Model boundaries determine the locations and quantities of simulated flow into and out of the model; therefore, the selection of appropriate boundaries for the model is a major concern in any modeling effort. The selection of model boundaries for the aquifers in this model was based on a conceptual interpretation of the flow system developed using information reported by Meyer and Carr (1979), Carr and others (1985), Williamson and others (1990), and data supplied by the TWDB.

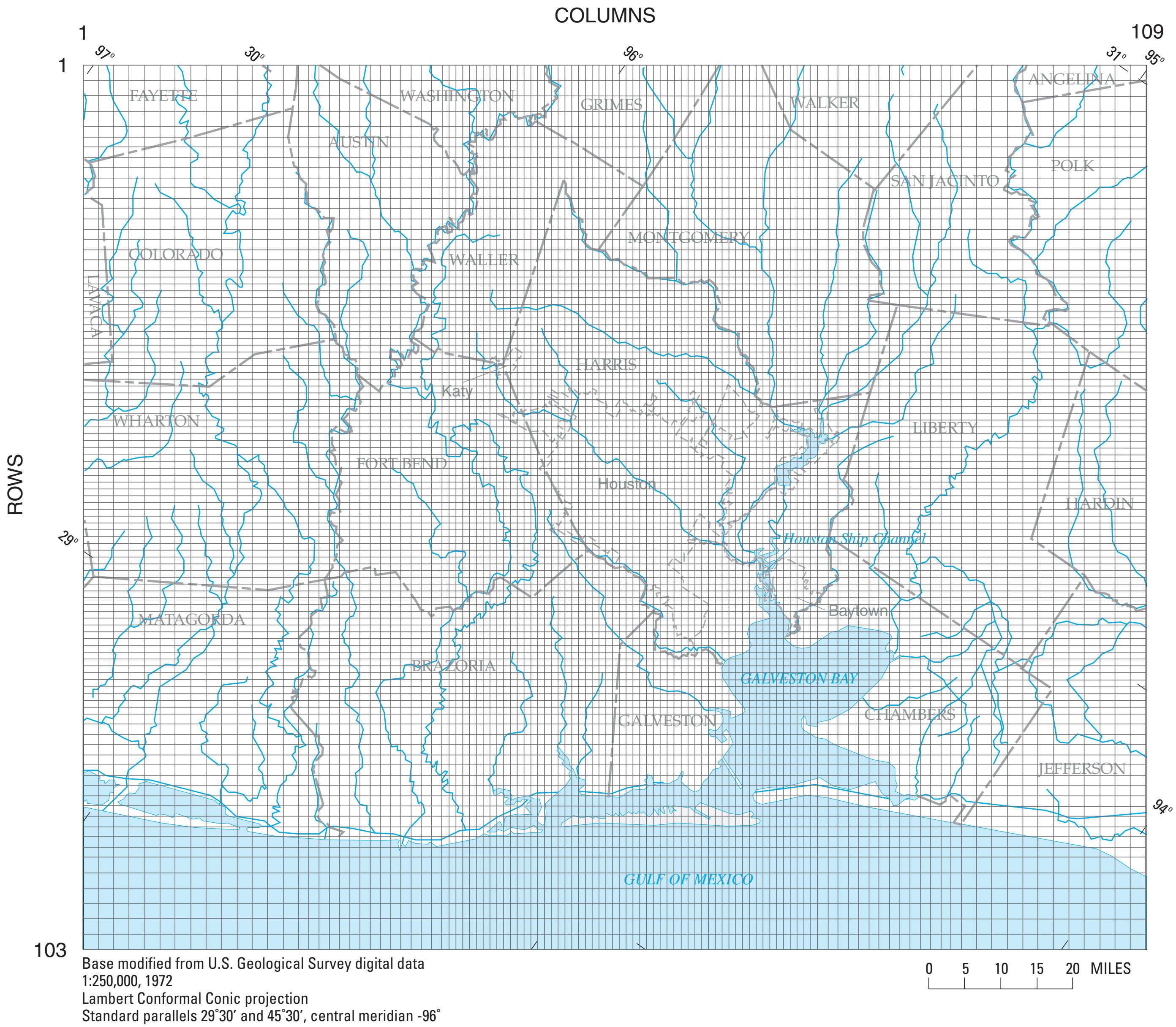


Figure 13. Finite-difference grid used in the numerical model of the Chicot and Evangeline aquifers, Houston area, Texas.

The altitude of the base of the Chicot aquifer (layer 2) is a composite from two sources of data: Jorgensen (1975), the smaller of the two sources in areal extent, has more specific detailed data in Harris and Galveston Counties; Carr and others (1985), the larger of the two sources in areal extent, has more generalized data in the adjacent counties. This composite base of the aquifer was created by digitizing these two separate but similar aquifer bases and selectively combining them. The composite map allowed the more detailed, data-enhanced aquifer base of Jorgensen (1975) to be applied to the inner, finer-grid model area, and the more generalized aquifer base in Carr and others (1985) to be applied to the outer, coarser-grid model area.

The altitude of the base of the Evangeline aquifer (layer 3) was created using the same technique. Two different but similar Evangeline aquifer bases in Jorgensen (1975) and Carr and others (1985), respectively, were composited into a single base.

The northern updip limits of both aquifers are the northern extent of the outcrop sediments of each aquifer (figs. 4, 6) and are simulated as no-flow boundaries. An average of about 48 in/yr of precipitation falls on the aquifer outcrops in the study area. Only a small fraction of this amount enters the ground-water-flow system as recharge, but the amount is sufficient to maintain approximately constant potentiometric surfaces in the aquifer outcrops. Hydrographs during documented historical droughts show that water levels in the outcrops of the Chicot and Evangeline aquifers have not varied appreciably over the long term (fig. 8).

Some of the water that enters the ground-water system travels only a short distance before being discharged locally. The local-scale flow is not accounted for in the model when using grid cells of at least 0.90 mi^2. As a result, the model simulates the regional-scale flow system, and to some unknown degree, the intermediate-scale flow system. Constant specified heads representing the water table were simulated in the outcrops of the Chicot and Evangeline aquifers. A vertical hydraulic conductance term representing interbedded clays in the aquifers and the vertical head differences control the amount of recharge to the aquifer from layer 1.

An approximation of the water table was mapped using the technique described in Williams and Williamson (1989). This technique used multiple linear regressions of potentiometric-surface measurements with land-surface-altitude data to estimate depth to water below land surface for coastal aquifers. The depth-to-water data were subsequently subtracted from digital altitude models to map the water table.

The downdip limit of freshwater (freshwater/saline-water interface) (defined for the purposes of this study as a concentration of 10,000 mg/L of dissolved solids) is represented by no-flow downdip lateral boundaries for both aquifers (figs. 4, 6). Its location in each aquifer was estimated from geophysical log data and (for the Evangeline aquifer) from the coastward extent of freshwater withdrawals. A no-flow boundary at a specified location implies a stable downdip freshwater/saline-water interface. The region where dissolved solids concentrations are between 1,000 and 10,000 mg/L is relatively small, which indicates little mixing, and flow is parallel to the freshwater/saline-water interface rather than across the freshwater/saline-water interface. As freshwater flows downdip toward the denser saline water, flow is redirected upward toward the surface as diffuse upward leakage. However, the low vertical hydraulic conductivity of the Beaumont Clay, where present, restricts upward flow to the surface. The movement of the freshwater/saline-water interface is controlled not only by pressure gradients, but also by density-related gravity effects when the layers are not horizontal, which in some circumstances could be significant (Davies, 1987). A freshwater/saline-water interface has been assumed to be a no-flow boundary in Coastal Plain aquifers by Bush and Johnston (1988), Mallory (1993), Arthur (1994), Barker and Pernik (1994), Strom and Mallory (1995), and Strom (1998), as well as other investigators. Further discussions on the use of a no-flow downdip boundary for Coastal Plain aquifers can be found in Barker and Pernik (1994).

The northeastern and southwestern lateral boundaries for the Chicot and Evangeline aquifers were selected to be approximately parallel to assumed flowpaths and at large distances from the potentiometric-surface declines caused by ground-water withdrawal in the Houston area. The southwestern lateral boundary was placed a few miles west of the western Colorado River Basin divide, and the eastern lateral boundary was placed a few miles east of the eastern Trinity River Basin divide. Corresponding ground-water divides, particularly in the more updip areas, are contained within the model area adjacent to the lateral extent of the grid. In the absence of large ground-water withdrawals or changing hydraulic gradients near these boundaries, little flow across the boundaries should occur. The lateral boundaries thus were modeled as no-flow.

The model boundary at the base of the Evangeline aquifer is the underlying Burkeville confining unit. This lower boundary is simulated as no-flow.

Simulations were made under transient conditions for 31 withdrawal (stress) periods that began on January 1, 1891, and ended on December 31, 1996 (table 1). Water-use data and stress periods for 1891–1975 are the same as those used by Carr and others (1985). For model simulations for 1976–96, the model uses water-use data compiled from HGCSD for Harris and Galveston Counties and data compiled by the TWDB and the USGS for the other counties. The withdrawal for each stress period is shown in figure 10. Ground-water withdrawals range from about 2.15 Mgal/d during 1901–30 to more than 493 Mgal/d in 1990.

Table 1. Stress periods used in the model of the Chicot and Evangeline aquifers, Houston area, Texas

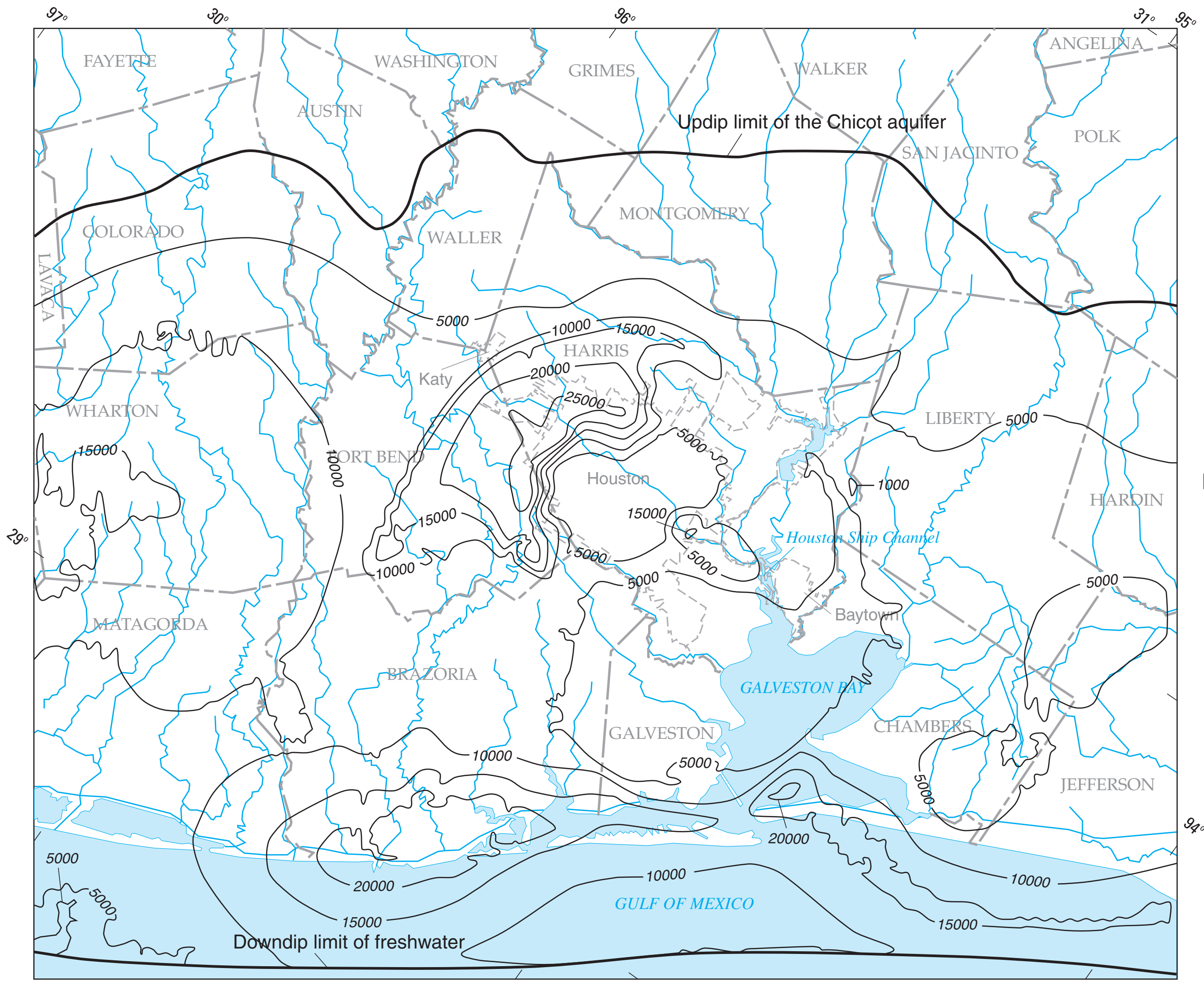
Stress period	Length of time (years)	Time interval
1	10	1891–1900
2	30	1901–30
3	10	1931–40
4	5	1941–45
5	8	1946–53
6	7	1954–60
7	2	1961–62
8	8	1963–70
9	3	1971–73
10	2	1974–75
11	1	1976
12	1	1977
13	1	1978
14	1	1979
15	1	1980
16	1	1981
17	1	1982
18	1	1983
19	1	1984
20	1	1985
21	1	1986
22	1	1987
23	1	1988
24	1	1989
25	1	1990
26	1	1991
27	1	1992
28	1	1993
29	1	1994
30	1	1995
31	1	1996

Model Calibration

Using the results of previous models, the initial model calibration strategy was to modify the best-known hydraulic properties as little as possible and vary the least-known hydraulic properties to achieve the best overall agreement between simulated and measured aquifer potentiometric surfaces and land-surface subsidence. Model calibration was based on transient conditions because few potentiometric-surface data representing predevelopment conditions of the aquifers are available. The calibration values of hydraulic properties determined during transient simulations subsequently were used to simulate potentiometric surfaces for predevelopment conditions. Predevelopment ground-water-flow conditions were simulated in a steady-state model, which assumes no ground-water withdrawal or change in aquifer storage and uses the hydraulic properties of the aquifers estimated from calibration of the transient model. The resulting heads were then iteratively used as starting heads for the transient runs until calibration was complete.

Transmissivity

Transmissivity data for the Chicot and Evangeline aquifers were taken from Carr and others (1985) and were used to construct the initial transmissivity data grids. Maps of the calibrated values of transmissivity used in the model simulations for both aquifers are shown in figures 14 and 15. Chicot aquifer transmissivity ranged from less than 5,000 ft^2/d in the updip areas to more than 25,000 ft^2/d in central Harris County. Evangeline aquifer transmissivity ranged from less than 5,000 ft^2/d to more than 25,000 ft^2/d in approximately the same areas. Transmissivity data were modified to account for the differences between aquifer bases presented by Jorgensen (1975) and Carr and others (1985). Cumulative clay thicknesses of each aquifer (Gabrysch, 1982) were digitized and subtracted from the aquifer thickness data to construct the total cumulative sand thickness maps (figs. 16, 17). The surfaces of the tops of the Chicot and Evangeline aquifers and their respective thicknesses were determined by using the aquifer bases (figs. 5, 7) and digital altitude models of land surface.



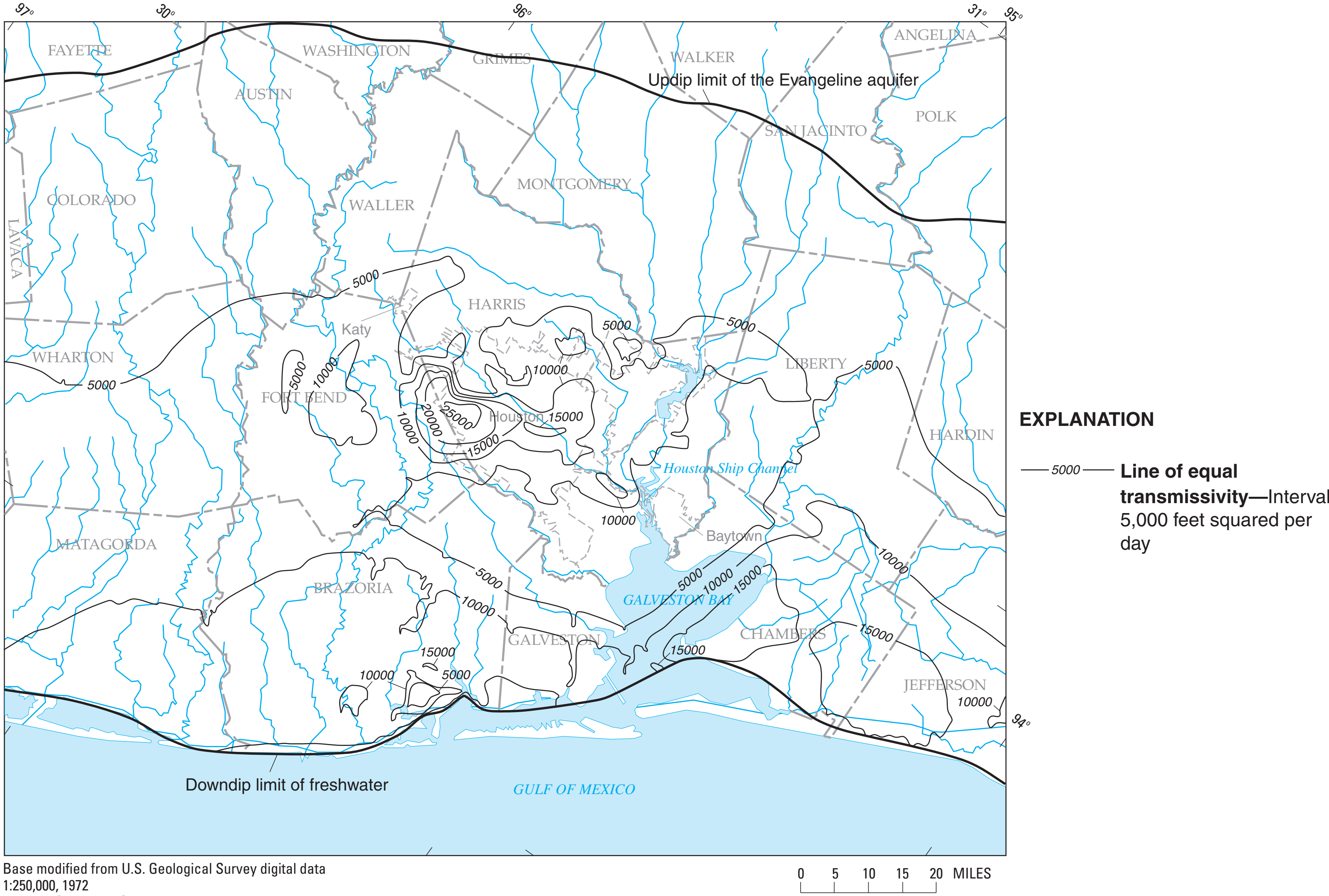
Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

0 5 10 15 20 MILES

EXPLANATION

5000 **Line of equal transmissivity—**Interval variable, in feet squared per day

Figure 14. Modeled transmissivity of the Chicot aquifer, Houston area, Texas.



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
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Figure 15. Modeled transmissivity of the Evangeline aquifer, Houston area, Texas.

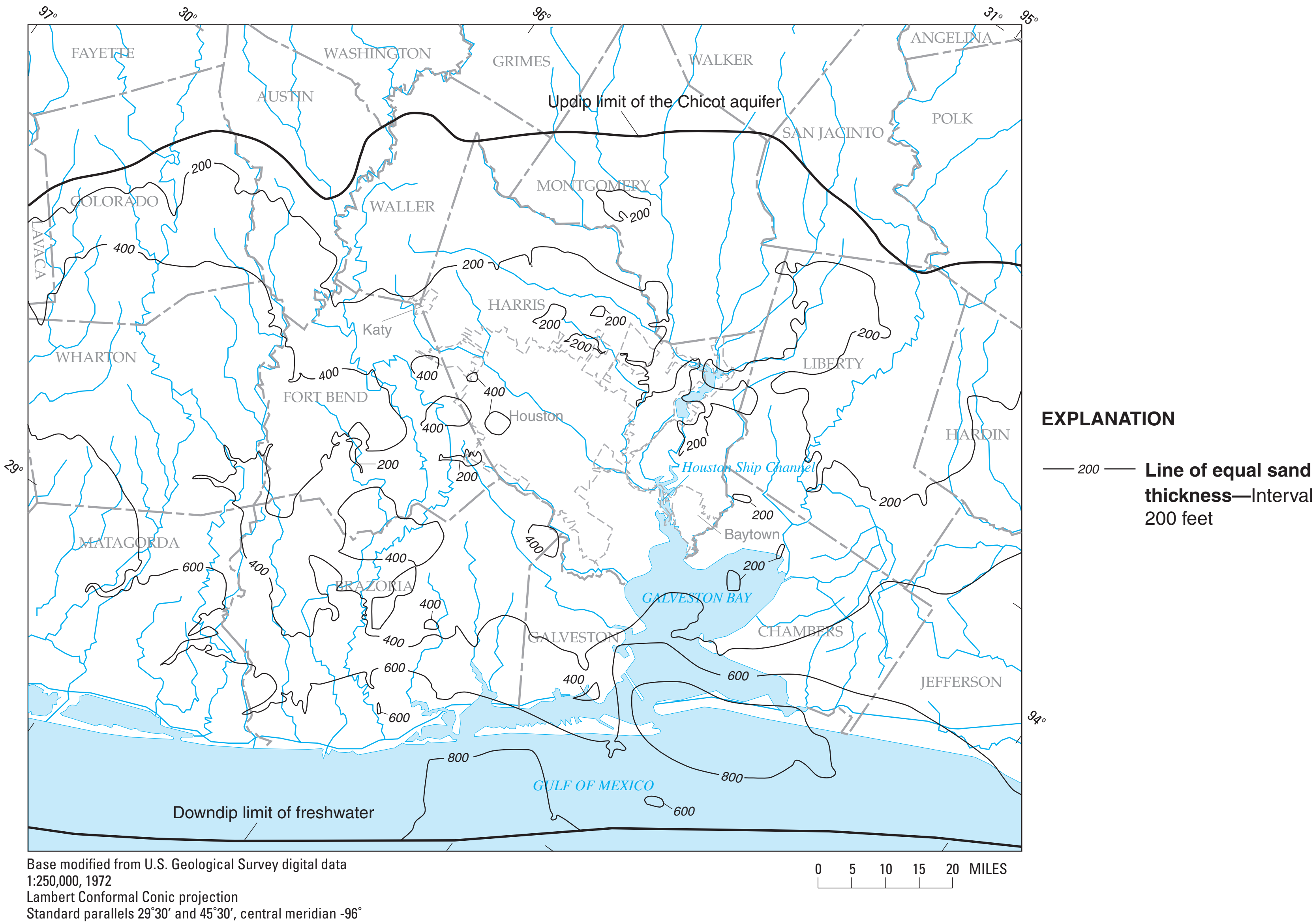
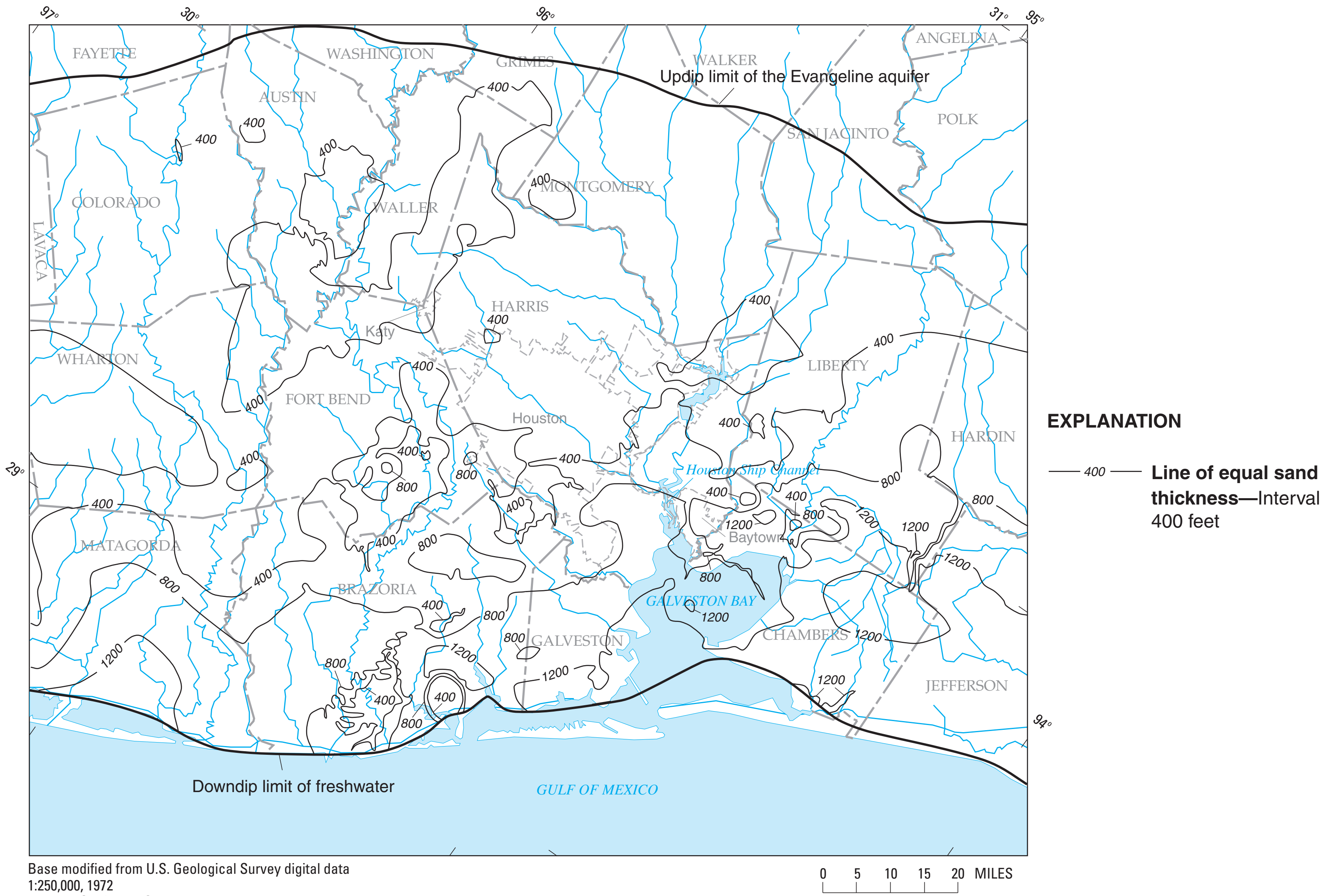


Figure 16. Total cumulative sand thickness of the Chicot aquifer, Houston area, Texas.



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

Figure 17. Total cumulative sand thickness of the Evangeline aquifer, Houston area, Texas.

Vertical Hydraulic Conductance

Numerous clay layers impede vertical flow within and between the water table, Chicot aquifer, and Evangeline aquifer. Vertical flow between layers is simulated by MODFLOW using a vertical hydraulic conductance term and the computed differences in the hydraulic head between the layers. Vertical hydraulic conductance is computed internally by MODFLOW by multiplying the cell area times the cell leakance. The cell leakance is the vertical hydraulic conductivity of the impeding material divided by the thickness of the impeding material. An increase in the input leakance corresponds to an increase in the transmissive properties of clay or other sediments that impede vertical flow.

Leakance is one of several aquifer-system properties that were varied to calibrate the model. The initial leakance values used in the model for the Chicot aquifer were computed by dividing a constant vertical hydraulic conductivity of 0.001 ft/d by the cumulative clay-layer thicknesses from land surface to the centerline of the Chicot aquifer (fig. 18). The cumulative clay-layer thickness data between the centerlines of the aquifers were based on maps from Carr and others (1985). The initial leakance values for the Chicot aquifer were reduced several orders of magnitude where the Beaumont Clay was predominantly clay (fig. 9) to represent the clay's inherent low vertical hydraulic conductivity as discussed in Heath (1983).

Similarly, initial leakance values used in the model for the Evangeline aquifer were computed by dividing a constant vertical hydraulic conductivity of 0.001 ft/d by the cumulative clay-layer thicknesses from the centerline of the Chicot aquifer to the centerline of the Evangeline aquifer (fig. 19). The cumulative clay-layer thickness data between the centerlines of the aquifers were based on maps from Carr and others (1985). The final leakance distributions in the aquifers for the calibrated model are shown in figures 20 and 21.

Potentiometric Surfaces

The years 1977 and 1996 were chosen as potentiometric-surface calibration periods for the model. The year 1977 was chosen because, during the mid-1970s, the potentiometric surfaces in both aquifers had declined to record low levels in Harris and Galveston Counties. In addition, the first water-level-altitude maps of both aquifers were published for 1977 by the USGS (Gabrysch, 1979). The year 1996 was chosen because 1996 was the most recent year that water-level data from wells were available, the most recent land-surface altitudes were determined in late 1995, changes in potentiometric surfaces correlate with land-surface subsidence during the 1977–95 period, and the magnitude and distribution of ground-water withdrawal were very different from those in 1977. Water-level data from wells and land-surface data for 1996 indicated a broad range of stresses, both spatially and temporally, which are important during model calibration.

Model calibration strategy included three main elements. Comparison of the published water-level-altitude maps (Gabrysch, 1979; Kasmarek and others, 1996) with the corresponding simulated potentiometric surfaces provided one means of model calibration. Second, long-term hydrographs at selected observation wells screened in the Chicot and Evangeline aquifers were compared to simulated hydrographs (figs. 22, 23). The simulated and measured hydrographs reflect the generally declining potentiometric surfaces through the mid-1970s, which were followed by subsequent rises in potentiometric surfaces in southeastern Harris County attributed to changes in ground-water withdrawal. The simulated hydrographs indicate that the model is able to simulate changes in the potentiometric surfaces caused by changes in stresses through time. Third, a combined total of 690 water-level measurements (213 for 1977 and 477 for 1996) from wells in both aquifers (fig. 24) were compared with their corresponding simulated values, and the root-mean-square (RMS) error between the two was computed. The RMS error is the square root of the sum of the square of the differences between measured and simulated water levels divided by the total number of water-level measurements. The errors were weighted on the basis of the number of calibration points in each aquifer. The weighting process consisted of dividing the number of water-level measurements in an aquifer by the total number of water-level measurements and multiplying the value by the RMS error. The weighted errors for each aquifer were then summed to determine the total error for the system. The strategy used was to minimize the RMS error during the model calibration process. The total number of water-level measurements used to calibrate each aquifer, the calibration year, and the RMS error of the simulated water levels in the Chicot and Evangeline aquifers for 1977 and 1996 are listed in table 2.

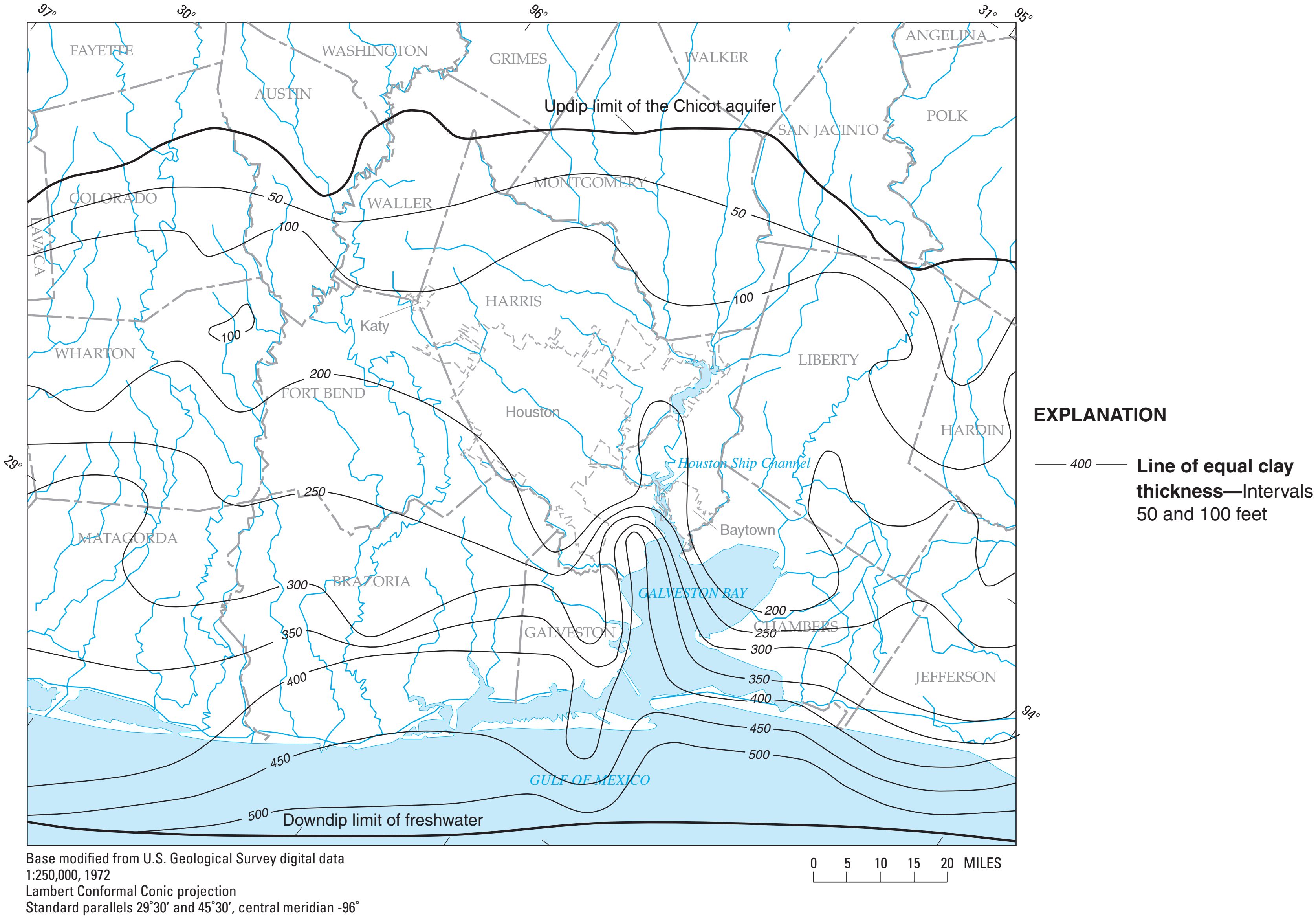


Figure 18. Cumulative clay thickness from land surface to the centerline of the Chicot aquifer, Houston area, Texas (modified from Carr and others, 1985).

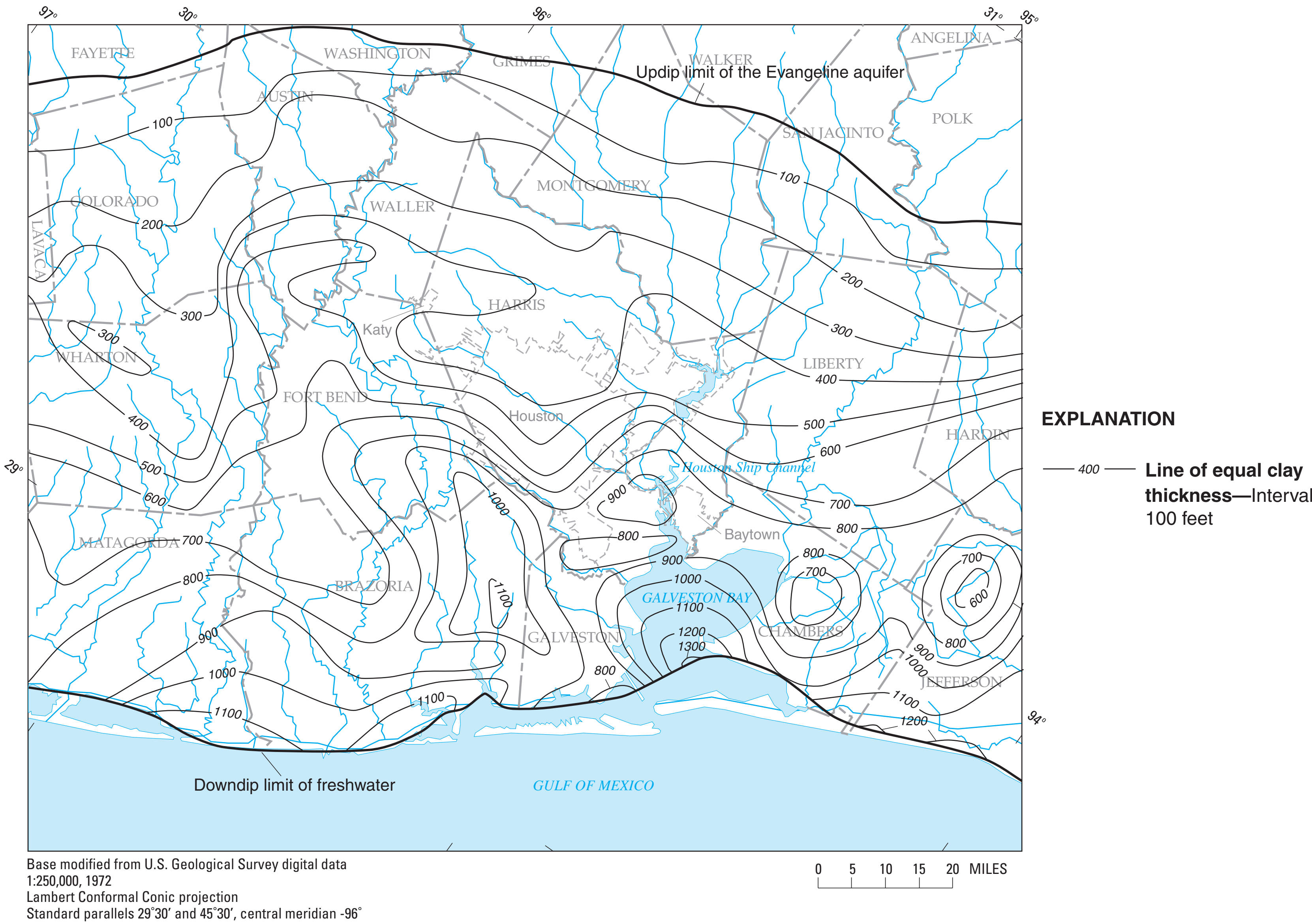
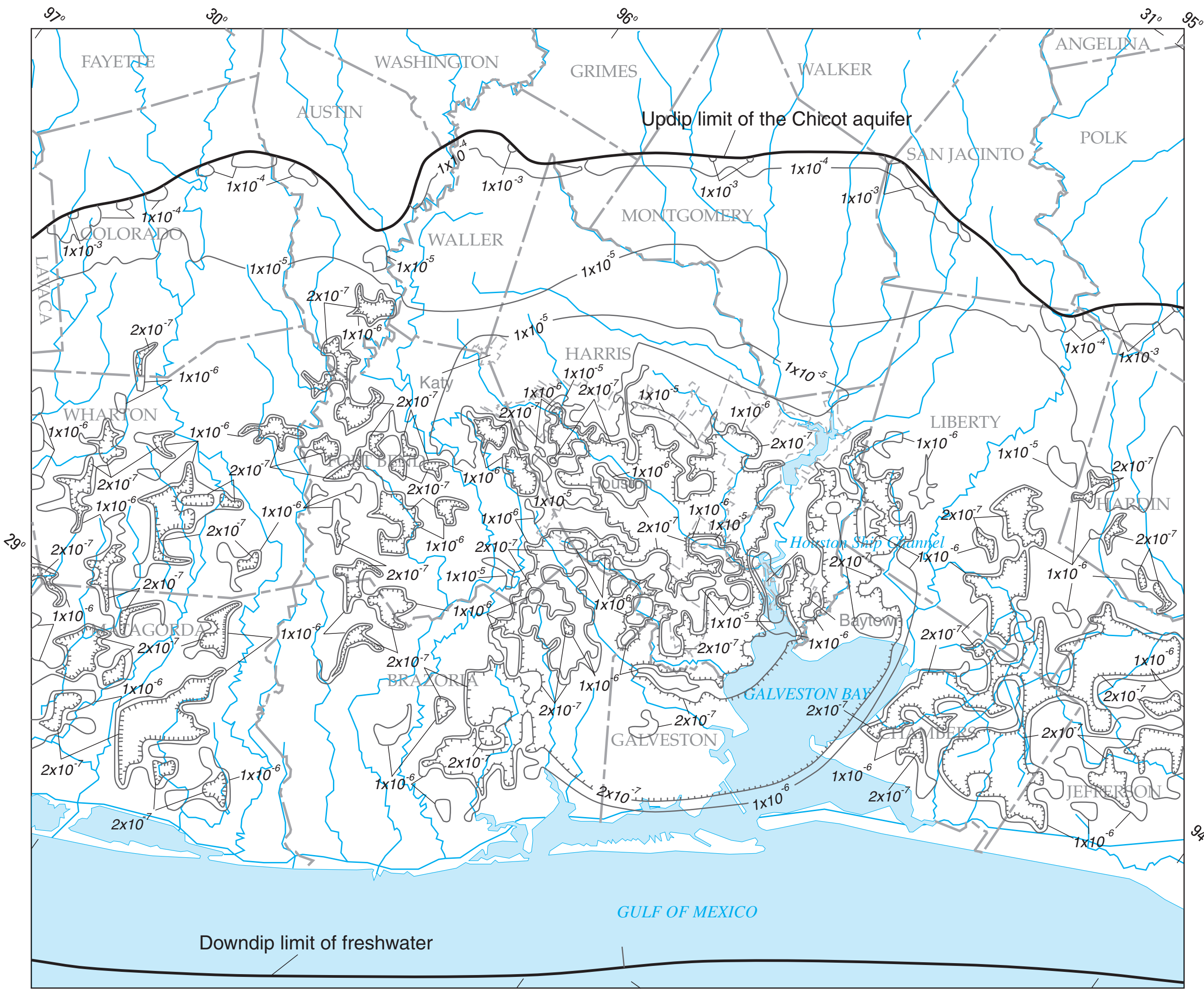


Figure 19. Cumulative clay thickness from the centerline of the Chicot aquifer to the centerline of the Evangeline aquifer, Houston area, Texas (modified from Carr and others, 1985).



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

0 5 10 15 20 MILES

EXPLANATION

—— $1x10^{-5}$ —— **Line of equal leakance**—Hachures indicate decrease in leakance. Interval variable, in foot per day per foot

Figure 20. Simulated leakance of the Chicot aquifer, Houston area, Texas.

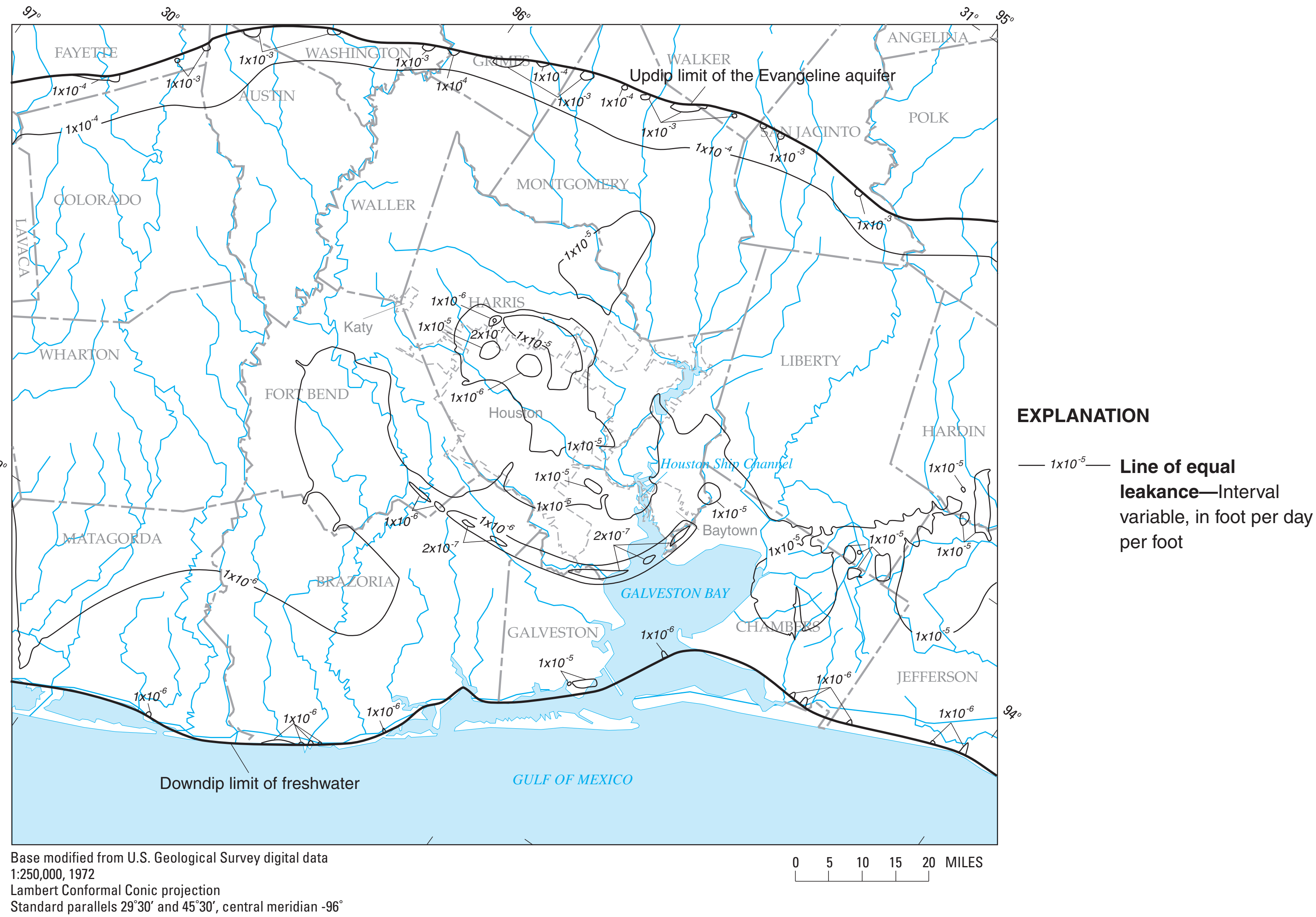


Figure 21. Simulated leakance of the Evangeline aquifer, Houston area, Texas.

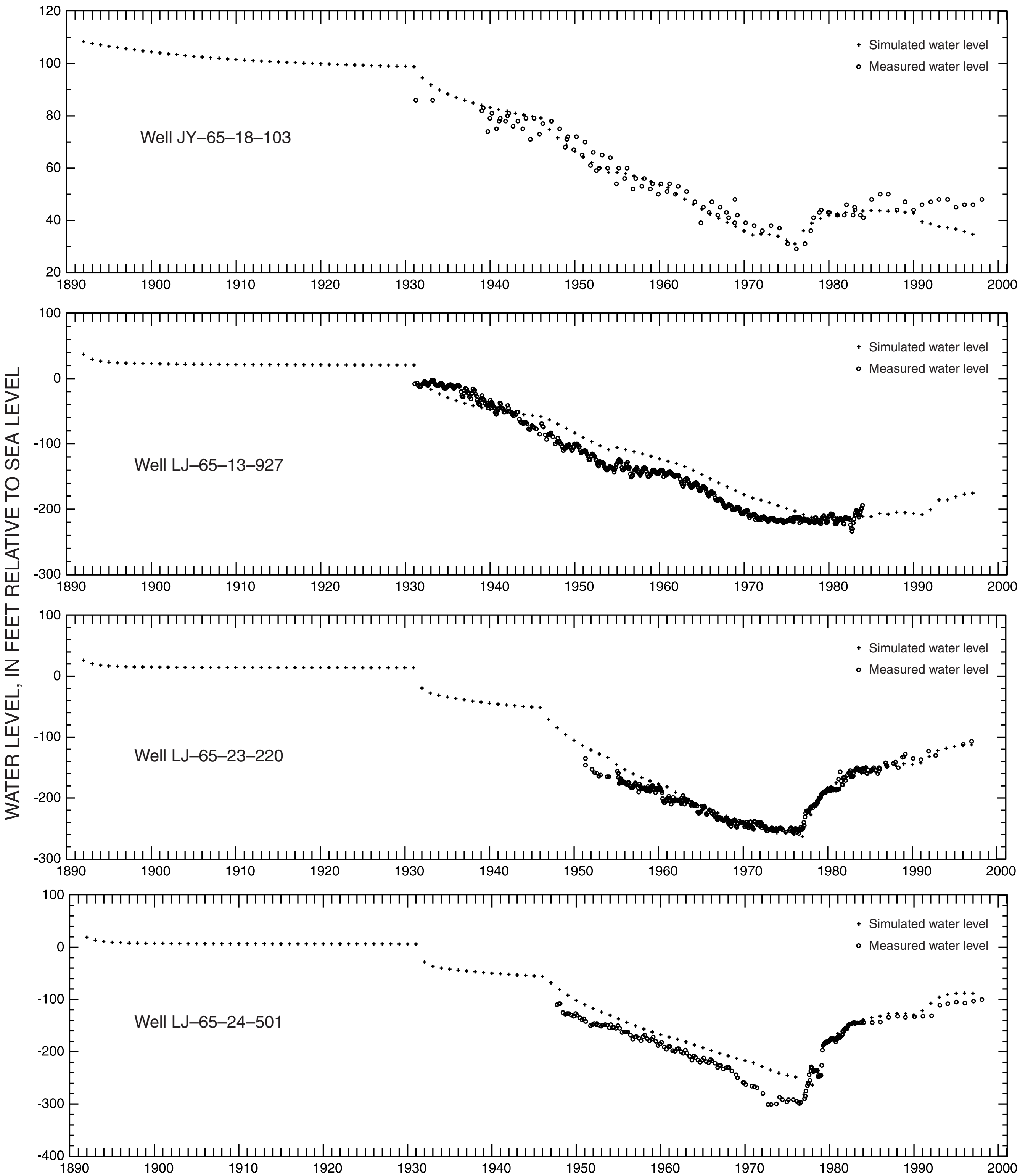


Figure 22. Hydrographs showing simulated and measured water levels in selected observation wells screened in the Chicot aquifer in Fort Bend and Harris Counties, Houston area, Texas.

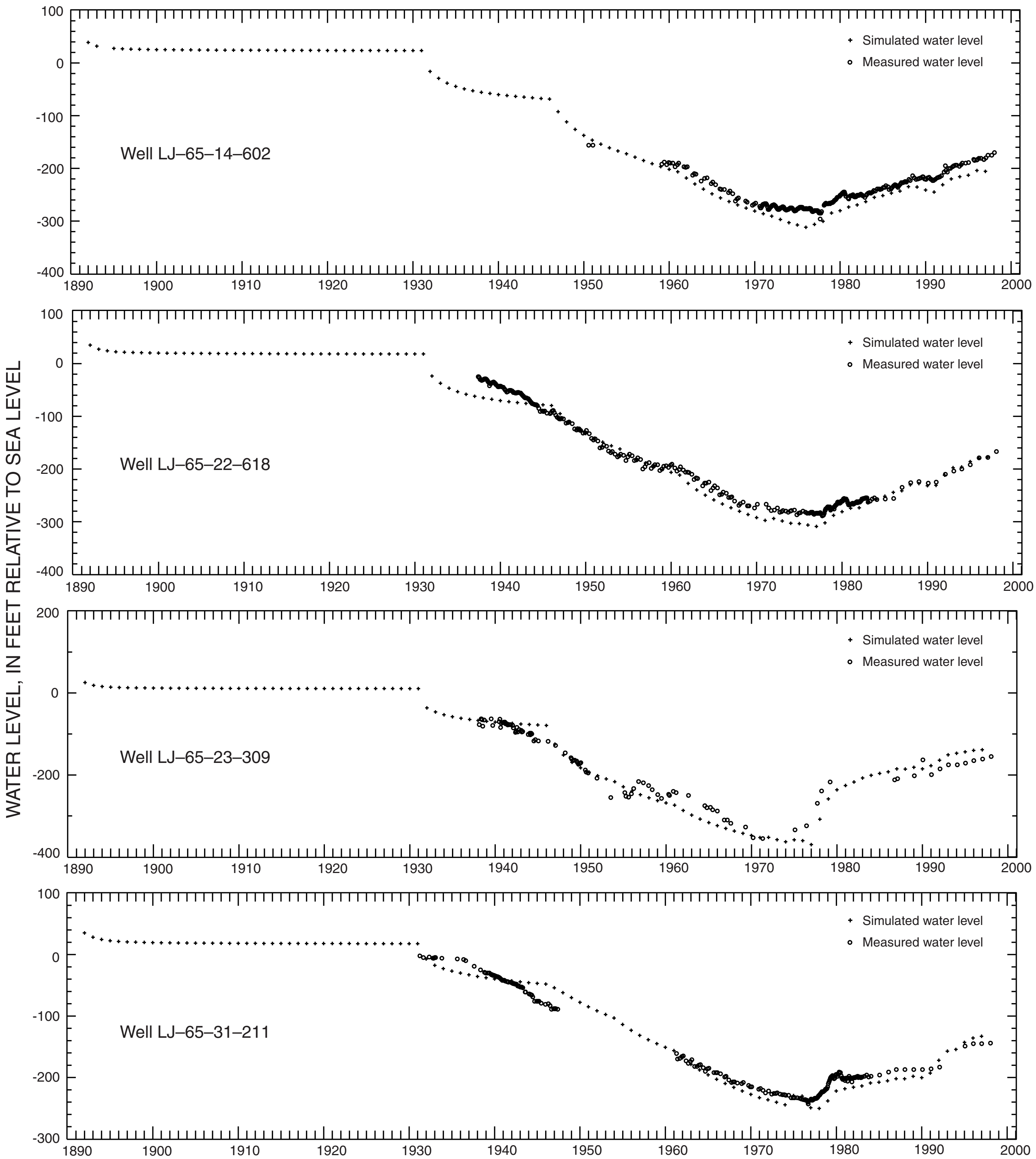
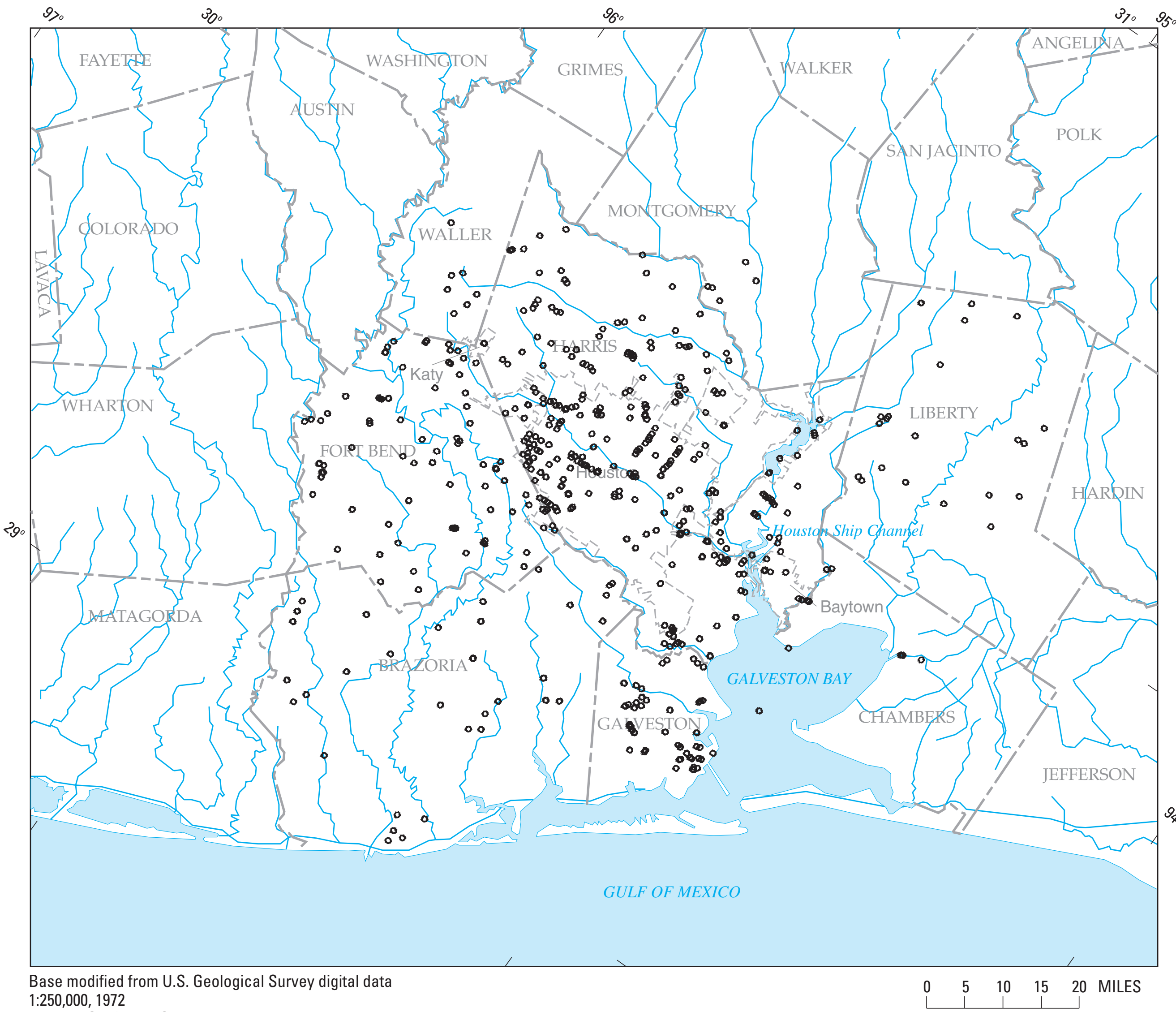


Figure 23. Hydrographs showing simulated and measured water levels in selected observation wells screened in the Evangeline aquifer in Harris County, Houston area, Texas.



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

EXPLANATION

∘ Well used for contour control and determination of root-mean-square errors

Note: Symbol can represent more than one well

Figure 24. Data points (wells) used to construct the 1977 and 1996 water-level-altitude maps of the Chicot and Evangeline aquifers, Houston area, Texas, and to determine respective root-mean-square errors (modified from Gabrysch, 1979; Kasmarek and others, 1996).

Table 2. Root-mean-square errors of simulated water levels in the Chicot and Evangeline aquifers, Houston area, Texas, 1977 and 1996

Aquifer	Number of water-level measurements	Weighted[1] root-mean-square error of simulated water levels (feet)
1977		
Chicot	101	46.4
Evangeline	112	39.2
1996		
Chicot	227	26.1
Evangeline	250	34.2

[1] See text, p. 29.

1977 Ground-Water-Flow Conditions

Simulated and measured potentiometric surfaces in the Chicot and Evangeline aquifers for 1977 (figs. 25, 26) match closely. Water-level measurements indicate that by 1977, large ground-water withdrawals in east-central and southeastern areas of Harris County had caused potentiometric-surface declines of as much as 250 ft below sea level in the Chicot aquifer and as much as 350 ft below sea level in the Evangeline aquifer. These areas of large potentiometric-surface declines are caused by coalescing cones of depression at the major well fields combined with ground-water withdrawal from the numerous other wells throughout the area.

1996 Ground-Water-Flow Conditions

Simulated and measured potentiometric surfaces in the Chicot and Evangeline aquifers for 1996 (figs. 27, 28) also match closely. The large potentiometric-surface decline in 1977 in the southeastern Houston area (Gabrysch, 1979) showed significant recovery by 1996. New centers of potentiometric-surface decline are much farther northwest. Potentiometric-surface declines of more than 200 ft below sea level in the Chicot aquifer and more than 350 ft below sea level in the Evangeline aquifer were measured in observation wells and simulated in the flow model.

Simulated 1996 Chicot aquifer flow rates (fig. 29) indicate that a net flow of 562.5 ft^3/s enters the Chicot aquifer in the outcrop area, and a net flow of 459.5 ft^3/s passes through the Chicot aquifer into the Evangeline aquifer. The remaining 103.0 ft^3/s of flow is withdrawn as pumpage, with a shortfall of about 84.9 ft^3/s supplied to the wells from storage in the sands and clays. Water simulated from storage in clays in the Chicot aquifer is about 19 percent of the total water withdrawn from the aquifer.

Simulated 1996 Evangeline aquifer flow rates (fig. 29) indicate that a net flow of 14.8 ft^3/s enters the Evangeline aquifer in the outcrop area, and a net flow of 459.5 ft^3/s passes through the Chicot aquifer into the Evangeline aquifer for a total inflow of 474.3 ft^3/s. A greater amount, 528.6 ft^3/s, is withdrawn by wells; the shortfall of about 54.8 ft^3/s is supplied from storage in the sands and clays. Water simulated from storage in clays in the Evangeline aquifer is about 10 percent of the total water withdrawn from the aquifer.

An important percentage of the total water budget shown in figure 29 is derived from the dewatering of the numerous clay layers of the aquifers. As early as 1959, Winslow and Wood (1959, p. 1,034) determined that about one-fifth of the water pumped from wells in the Katy-Houston-Pasadena-Baytown area during 1954–59 was derived from compaction of clays. Wood and Gabrysch (1965, p. 16) recognized that water was derived from compaction in construction of the first analog model of the ground-water-flow system but estimated only 1 percent of the water was derived from compaction of clays. Later, Jorgensen (1975, p. 49) showed that water derived from compaction ranged from 17 to 22 percent for different periods. In the 1996 water budget of the model of this report, amounts of water withdrawn from the Chicot and Evangeline aquifers that were derived from compaction of clays were 19 and 10 percent, respectively.

Predevelopment Ground-Water-Flow Conditions

The simulated predevelopment potentiometric surfaces in the Chicot and Evangeline aquifers (figs. 30, 31) indicate that prior to ground-water development, flow generally was toward the coast. In updip areas of the aquifers, the influence of topography and major rivers can be seen, and along the coast, the influence of Galveston Bay can be seen.

Simulated predevelopment flow rates for the Chicot and Evangeline aquifers (fig. 32) are appreciably different from flow rates in the aquifers under stressed or post-development conditions. A specified-head boundary in the water table, together with the relatively small (0.90-mi^2) grid-cell size, allows simulation of much of the intermediate-scale flow that, under

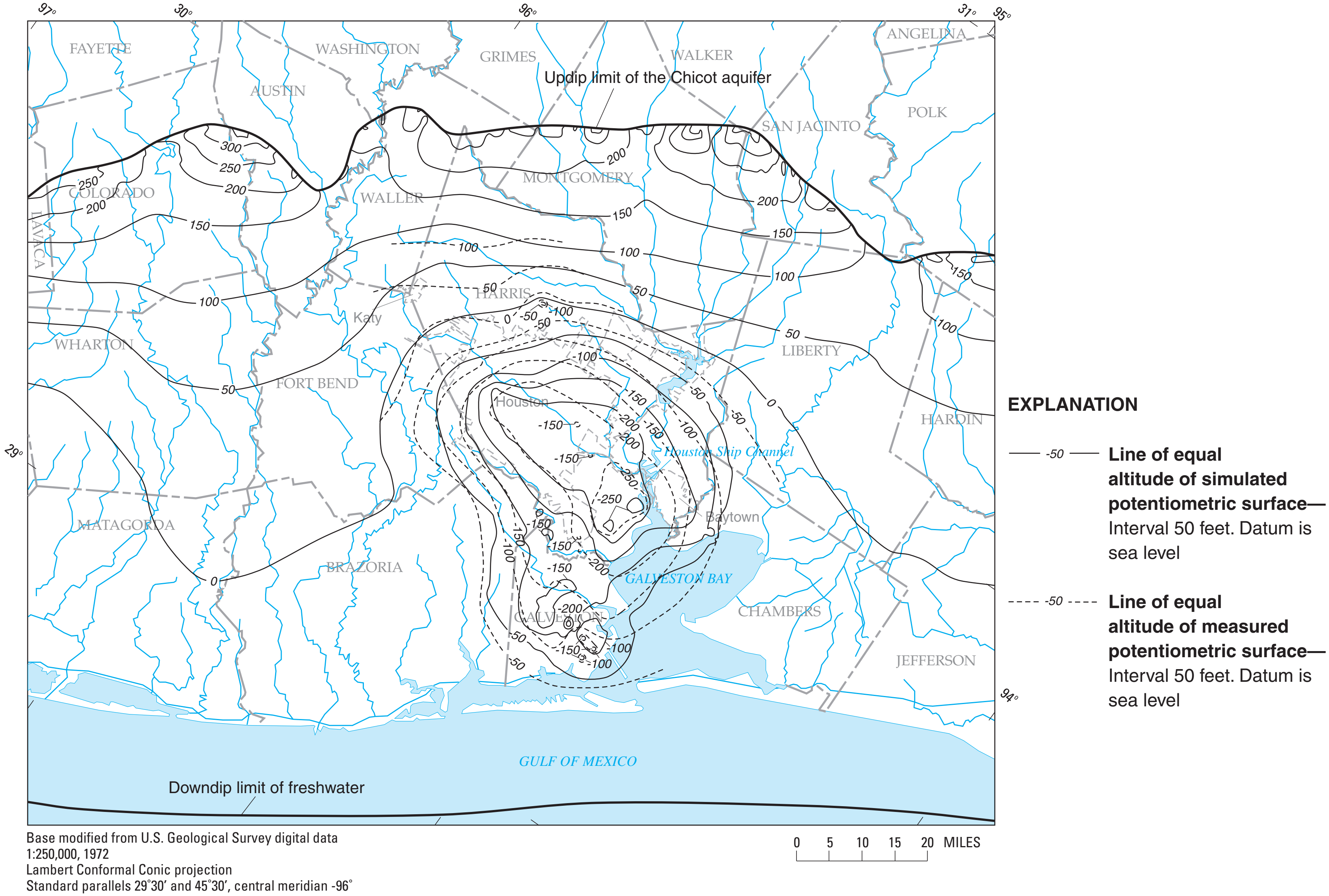


Figure 25. Simulated and measured potentiometric surfaces in the Chicot aquifer, Houston area, Texas, 1977 (measured water levels modified from Gabrysch, 1979).

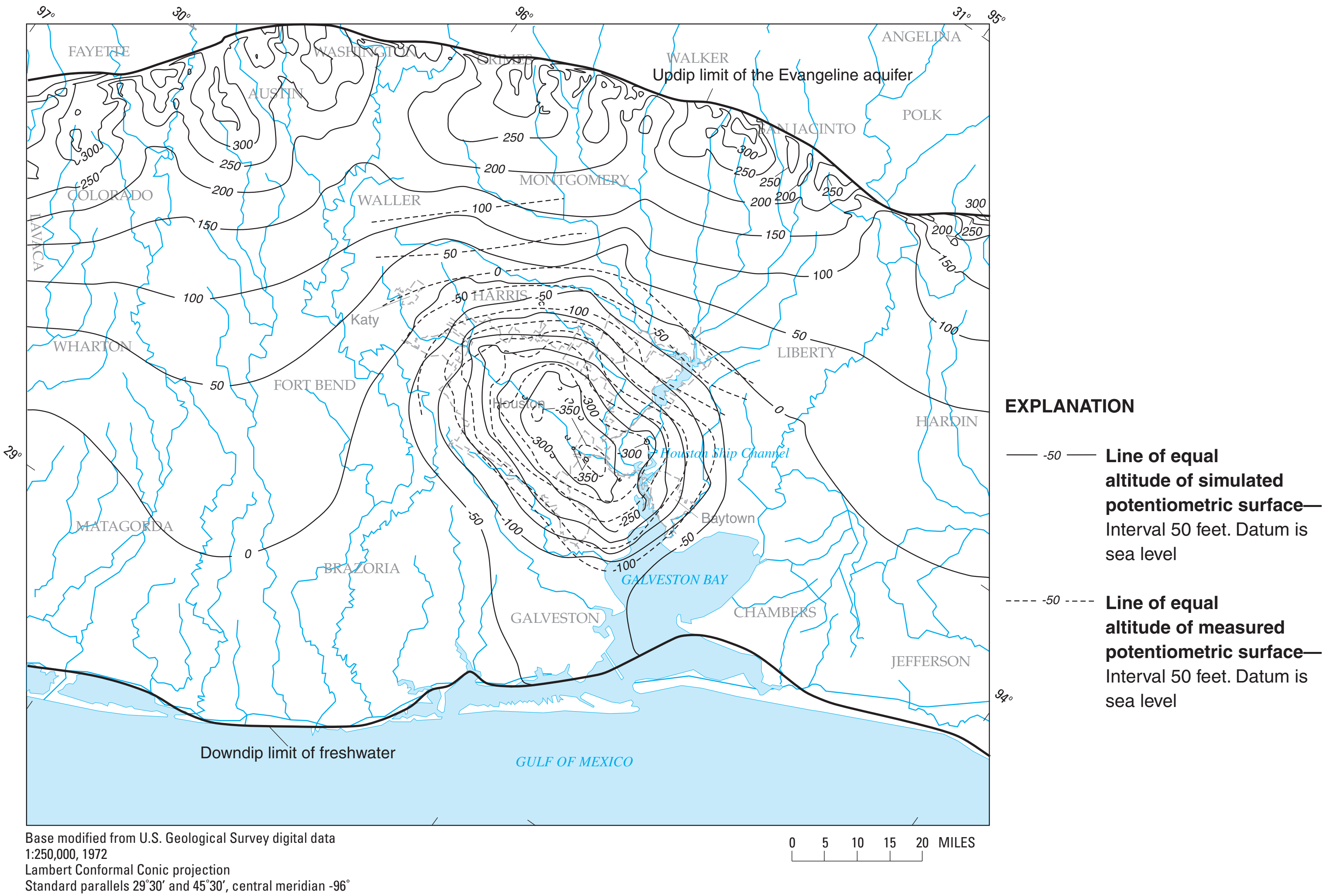


Figure 26. Simulated and measured potentiometric surfaces in the Evangeline aquifer, Houston area, Texas, 1977 (measured water levels modified from Gabrysch, 1979).

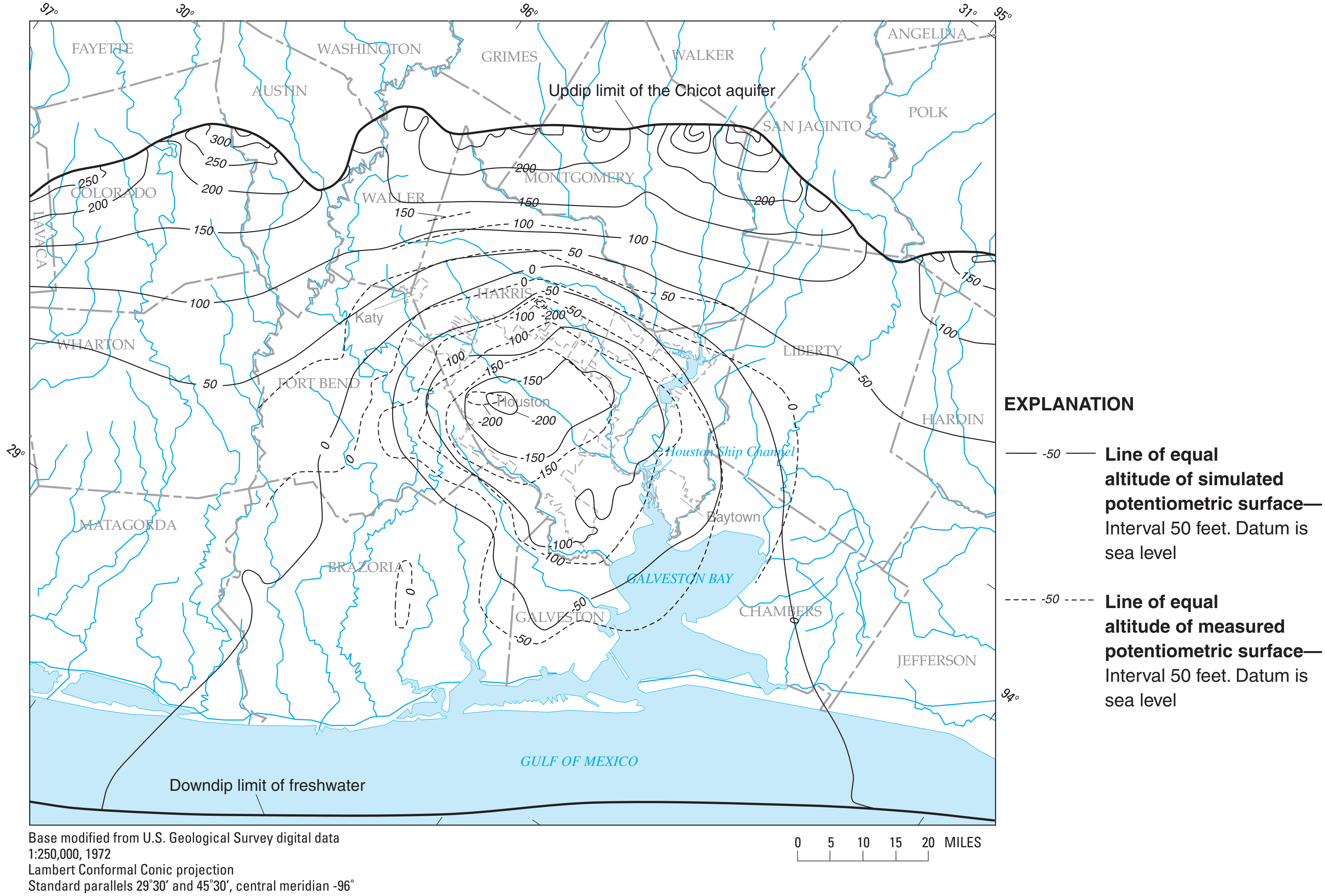


Figure 27. Simulated and measured potentiometric surfaces in the Chicot aquifer, Houston area, Texas, 1996 (measured water levels modified from Kasmarek and others, 1996).

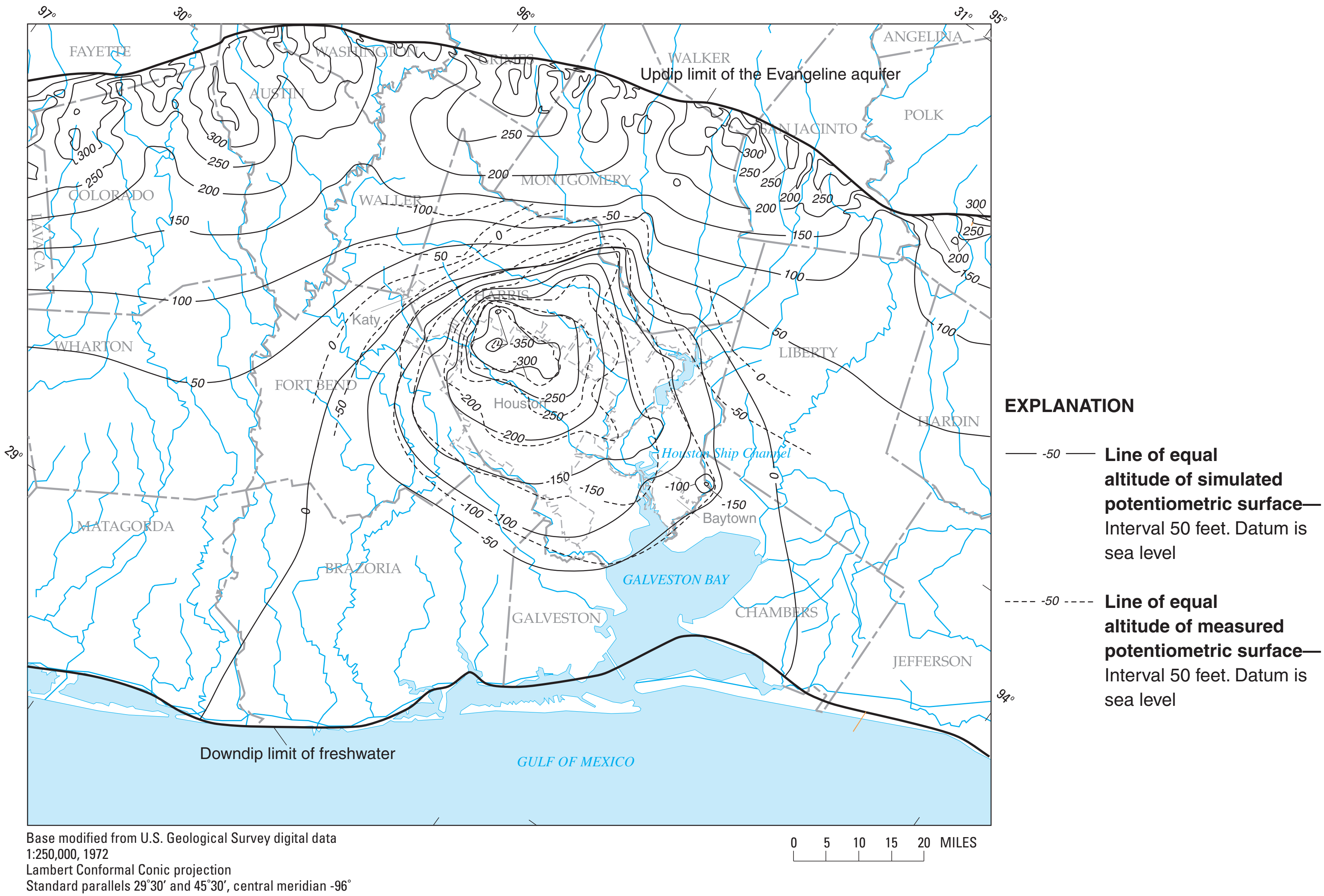


Figure 28. Simulated and measured potentiometric surfaces in the Evangeline aquifer, Houston area, Texas, 1996 (measured water levels modified from Kasmarek and others, 1996).

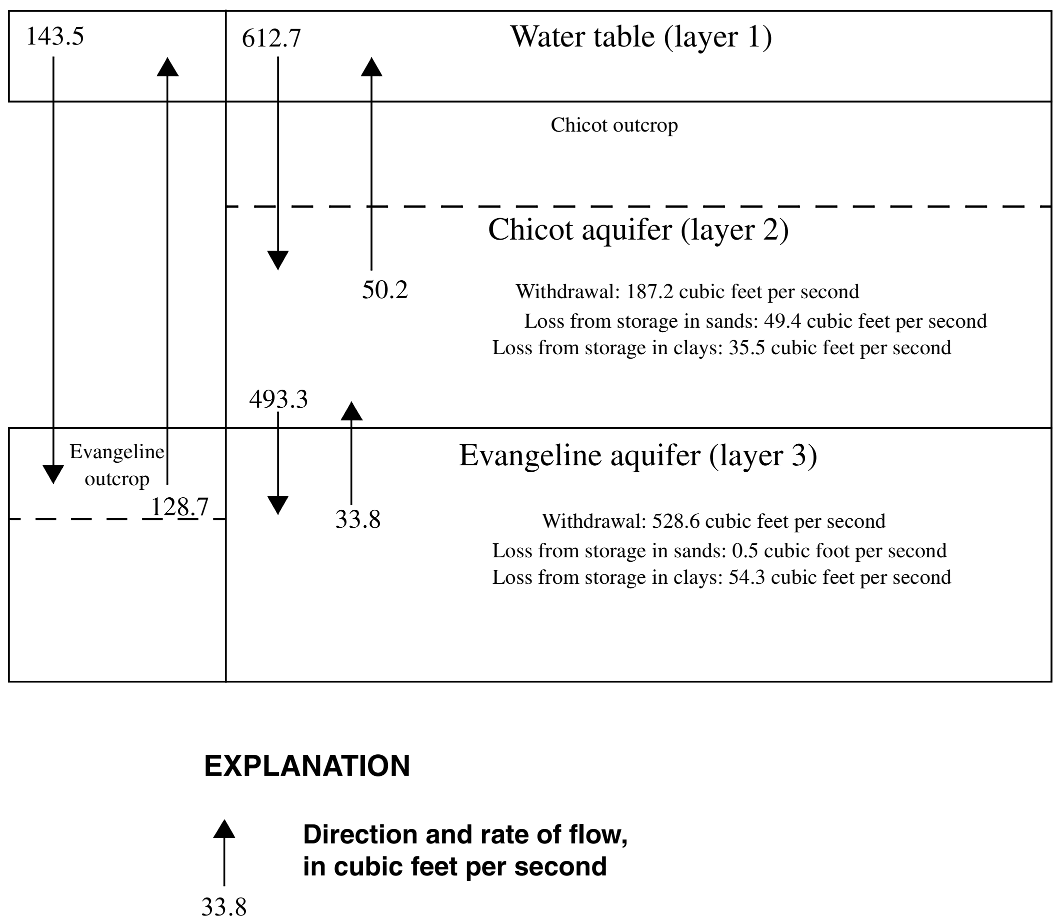


Figure 29. Simulated 1996 flow rates for the Chicot and Evangeline aquifers, Houston area, Texas.

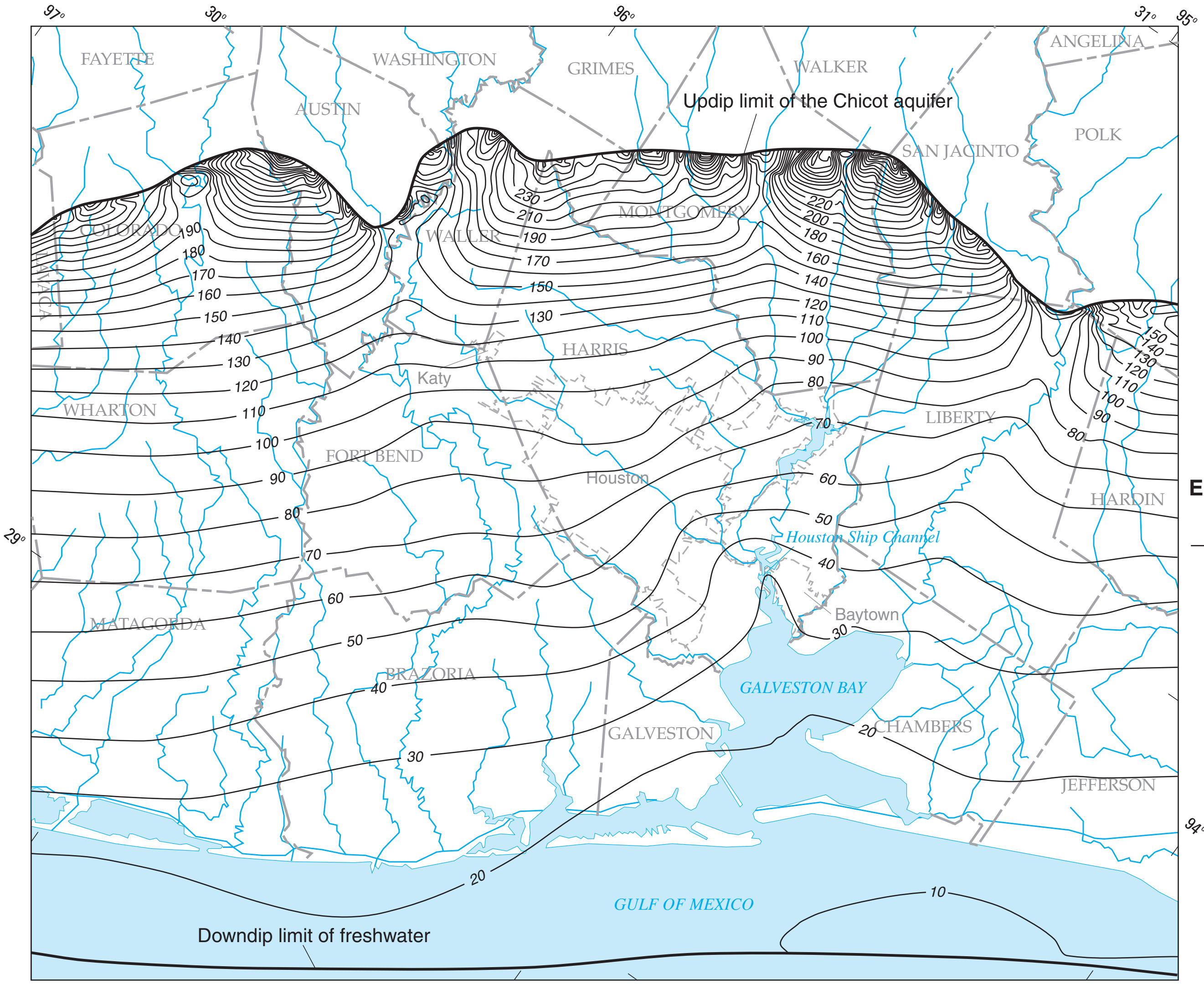
predevelopment conditions, never enters the deeper regional system. As gradients in the aquifers increase as a result of increased ground-water withdrawal (fig. 29), more recharge is induced by converting some of the former intermediate flowpaths into regional flowpaths. Additionally, when the aquifers are unable to transmit sufficient water from the outcrops to areas with high rates of ground-water withdrawal, water is released from storage in sands and clays to meet the demand until a new equilibrium is established.

Storage in Sands

On the basis of aquifer-test analyses and calibration of a numerical model, Carr and others (1985) derived the storativity of the sands in the Chicot and Evangeline aquifers. Storativity of sand ranged from 0.1 to 0.0004, with storativities at the larger end of the range representing water-table conditions in the outcrop areas and those at the smaller end of the range representing confined conditions. The storativities of sand used in this model are from Carr and others (1985) and were not modified during the model calibration process.

Land-Surface Subsidence and Storage in Clays

Simulation of land-surface subsidence and water released from storage in the clay layers was accomplished using the Interbed-Storage Package developed by Leake and Prudic (1991) for use with MODFLOW. The water table has remained fairly stable in the Houston area, while the confined pressure head in the Chicot and Evangeline aquifers has declined. The assumption was made in this analysis that, although the lowering of potentiometric surfaces in the aquifers resulted in increased effective stress, the geostatic stress in the Chicot and Evangeline aquifers has remained constant. Previous investigations (Riley, 1969; Helm, 1975) indicate that for sediments in confined aquifers where the geostatic pressure remains constant, compaction (or

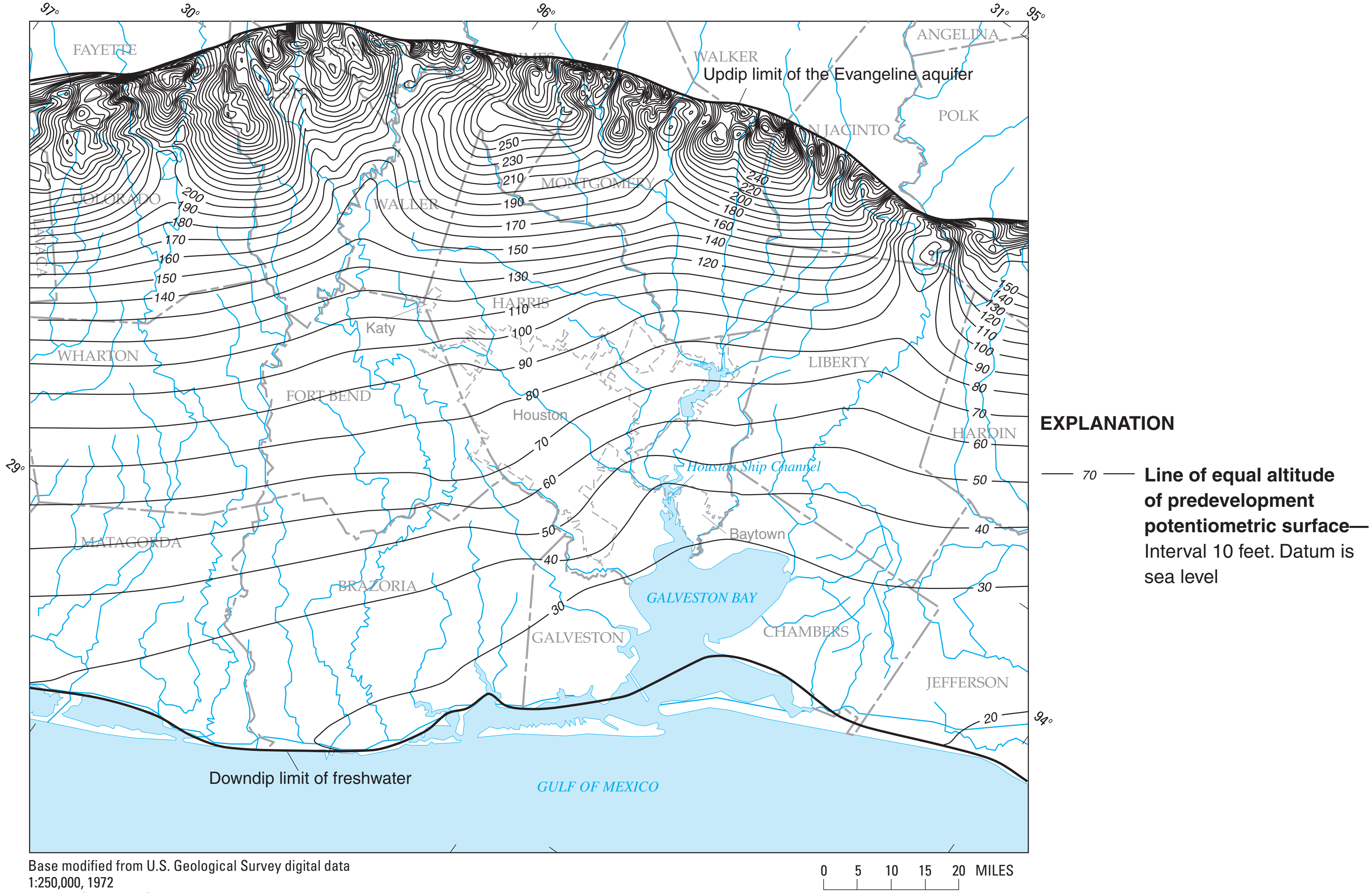


Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

EXPLANATION

— 70 — **Line of equal altitude of predevelopment potentiometric surface—** Interval 10 feet. Datum is sea level

Figure 30. Simulated predevelopment potentiometric surface in the Chicot aquifer, Houston area, Texas.



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

Figure 31. Simulated predevelopment potentiometric surface in the Evangeline aquifer, Houston area, Texas.

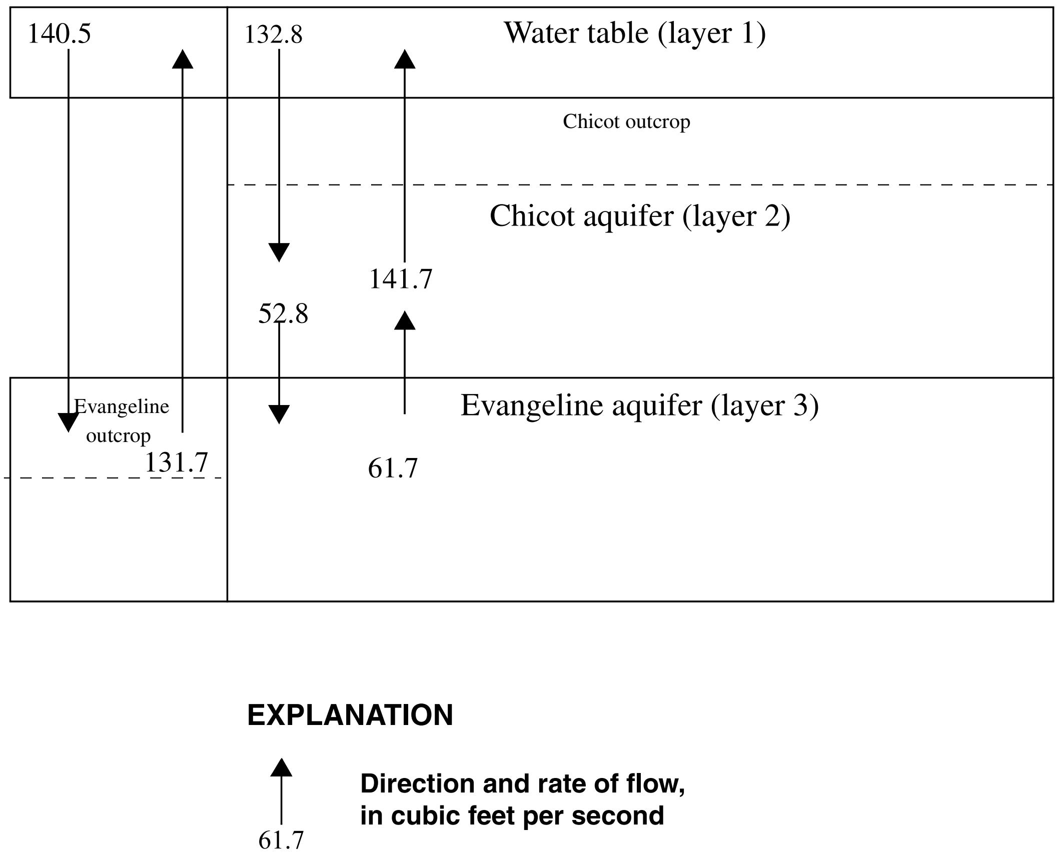


Figure 32. Simulated predevelopment flow rates for the Chicot and Evangeline aquifers, Houston area, Texas.

expansion) of the interbedded clay is proportional to the change in hydraulic head, or (modified from Leake and Prudic [1991])

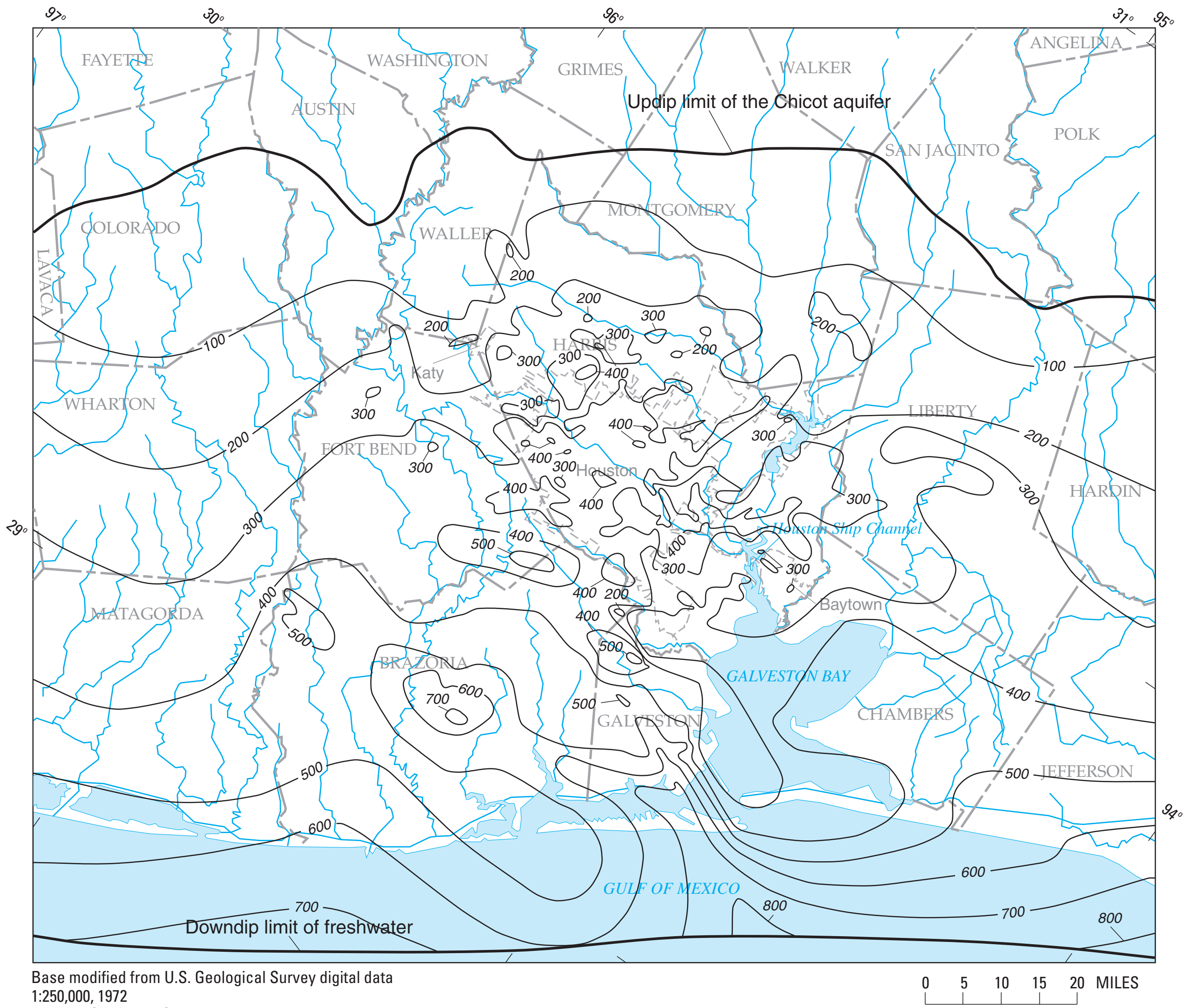
$$\Delta b = -\Delta h \cdot S_s \cdot b_o , \qquad (2)$$

where

Δb = amount of compaction or expansion [L];
Δh = change in hydraulic head [L];
S_s = skeletal component of either elastic or inelastic specific storage [L^{-1}]; and
b_o = thickness of the interbed [L].

For changes in hydraulic head that remain above a given preconsolidation head, an elastic response is calculated. For changes in hydraulic head that are below a given preconsolidation head, an inelastic response is calculated and the resultant head becomes the new preconsolidation head. Inelastic storativities generally are several orders of magnitude larger than elastic storativities.

An initial preconsolidation head of 70 ft below the water table was used in the model as was used by Meyer and Carr (1979) and Carr and others (1985). Elastic and inelastic skeletal specific storativities are properties for which calibration values were obtained by interactive model calibration with potentiometric surfaces of the aquifers. The required total cumulative clay interbed thicknesses of each aquifer (figs. 33, 34) were modified from Gabrysch (1982). The clay interbed thicknesses were multiplied by areally distributed configurations of elastic and inelastic skeletal specific storage values during model calibration until an acceptable match between historically measured land-surface subsidence and potentiometric surfaces of the aquifers was achieved. The mean values of simulated inelastic skeletal specific storage for the Chicot and Evangeline aquifers were 7.34×10^{-5} ft^{-1} and 1.42×10^{-5} ft^{-1}, respectively. For comparison, the mean values of simulated inelastic skeletal specific storage determined by Meyer and Carr (1979) for the Chicot and Evangeline aquifers were 8.7×10^{-5} ft^{-1} and 1.5×10^{-5} ft^{-1}, respectively. The specific storage values for the clays in the Evangeline aquifer are smaller than those for the Chicot



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

EXPLANATION

—— 400 —— **Line of equal clay thickness—**
Interval 100 feet

Figure 33. Total cumulative clay thickness of the Chicot aquifer, Houston area, Texas (modified from Gabrysch, 1982).

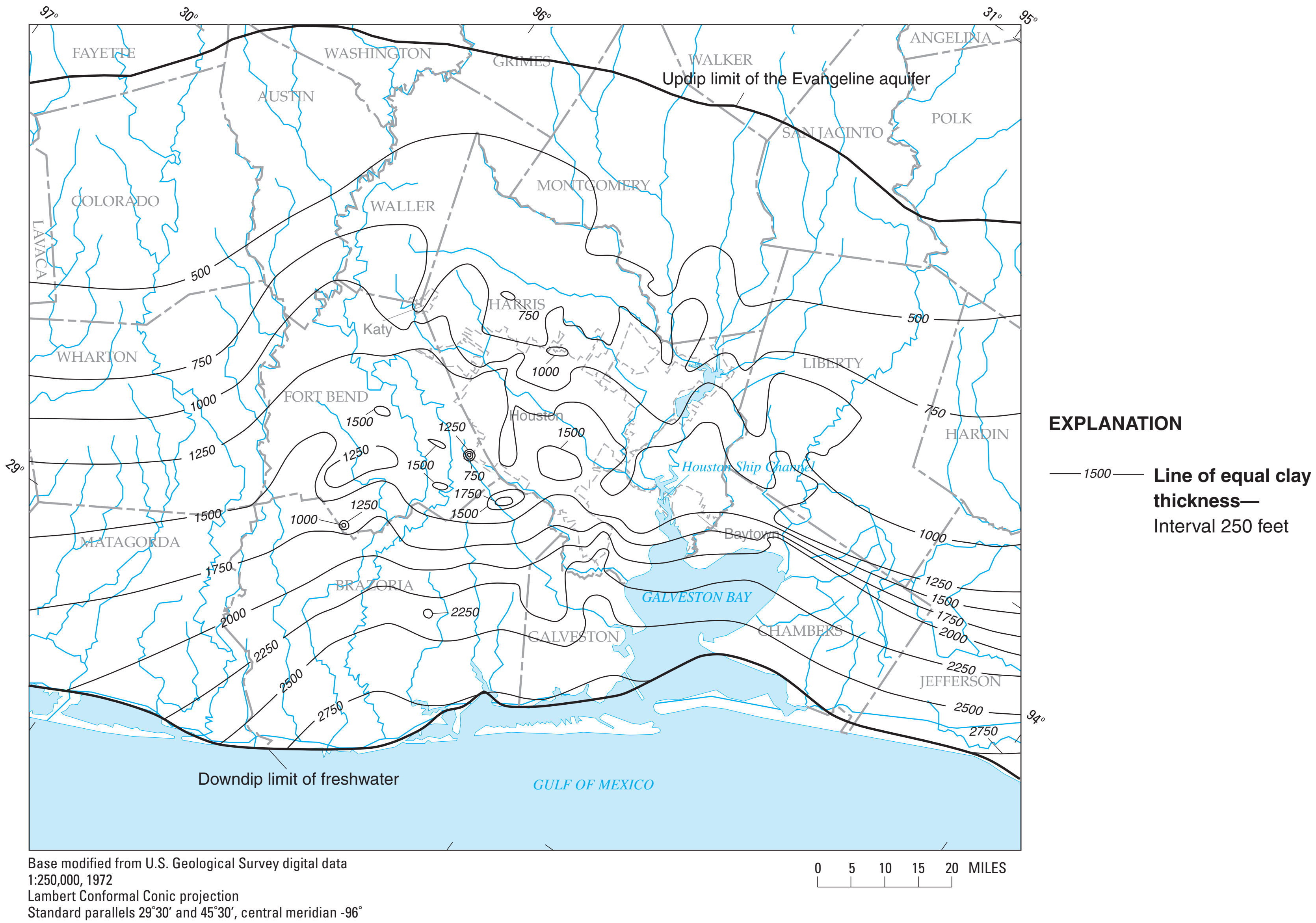


Figure 34. Total cumulative clay thickness of the Evangeline aquifer, Houston area, Texas (modified from Gabrysch, 1982).

aquifer because the clays in the Evangeline aquifer are older sediments, buried more deeply, and relatively more consolidated. The model of this report incorporated measurements of potentiometric surfaces and land-surface subsidence obtained throughout Harris, Galveston, and surrounding counties since Meyer and Carr (1979) completed their investigation.

The final calibration values of inelastic clay storativity (inelastic skeletal specific storage multiplied by cumulative interbed thickness—dimensionless) for the Chicot and Evangeline aquifers are shown in figures 35 and 36, respectively. Elastic clay storativity typically is about two orders of magnitude less than inelastic clay storativity (S.A. Leake, U.S. Geological Survey, oral commun., 1999). Elastic clay storativities in the Chicot and Evangeline aquifers were computed by multiplying inelastic storativities by 1.067×10^{-2} and 1.0×10^{-2}, respectively.

Land-surface subsidence values were obtained in the calibration process by comparing simulated long-term (1891–1995) and short-term (1978–95) land-surface subsidence with published maps of subsidence for about the same periods until acceptable matches were achieved. In the equation controlling land-surface subsidence used in the model, changes in the potentiometric surface, as well as clay storativities, determine land-surface subsidence. As a result, all of the other aquifer properties that affect the potentiometric surfaces also will affect land-surface subsidence.

Measured land-surface subsidence during 1906–95 (fig. 37) indicates that the greatest amount occurred in the southeastern Houston area near the northern end of Galveston Bay. The land surface subsided as much as 9 to 10 ft in this area. A larger geographic area encompassing the maximum land-surface-subsidence areas and much of the immediate Houston area has subsided at least 6 ft. The configurations of measured land-surface subsidence for 1906–95 (fig. 37) and simulated land-surface subsidence for 1891–1995 (fig. 38) are quite similar. Model simulations reflect more spatial detail in land-surface subsidence because the resolution of the model grid is considerably finer than the spacing of the benchmarks where subsidence is measured.

Changes in ground-water withdrawal after the mid-1970s (discussed previously) are reflected in changes in the potentiometric surfaces of the aquifers and in measured and simulated land-surface subsidence during 1978–95 (figs. 39, 40), which is the period of the most recent map of measured land-surface subsidence. The area of greatest land-surface subsidence has shifted to the northwestern Houston area, in response to concentrated ground-water withdrawal in that area. Model simulations indicate the same general shape and magnitude in land-surface subsidence as the measured land-surface subsidence for this period.

Sensitivity Analysis

The sensitivity of the model to a given input parameter can be tested by varying only the parameter of interest over a range of values, monitoring the response of the model, and determining the RMS error of the simulated water levels from the calibrated model compared to the measured water levels. Increasing and decreasing the values by a multiplier tested the sensitivity of the model to changes in transmissivity, ground-water withdrawal, vertical hydraulic conductance, sand storativity, and inelastic clay storativity. The results of this analysis (figs. 41, 42) indicate that the model is more sensitive to decreases than increases in transmissivity from the calibration value; but the model is more sensitive to increases than decreases in ground-water withdrawal, vertical hydraulic conductance, sand storativity, and inelastic clay storativity from the calibration value. The sensitivity analysis was run using measured and simulated 1996 potentiometric-surface data. Less water was derived from storage in 1996 than in the years before 1977 because HGCSD ground-water-withdrawal regulations were in effect throughout Harris and Galveston Counties in 1996. Therefore the model is less sensitive to decreases in storativity during 1996 than during the pre-1977 period.

Model Limitations

The accuracy of ground-water models is limited by assumptions made in the formulation of the governing flow equations and by assumptions made to construct a model. Models also are limited by cell size, number of layers, boundary conditions, discretization of time, accuracy and availability of hydraulic properties, accuracy of calibration, historical data for matching, and parameter sensitivity. Models also are limited by the availability of data and by the interpolations and extrapolations that are inherent in using data in a model. A model might be calibrated, but the calibration parameter values are not unique in yielding a particular distribution of hydraulic head and (or) land-surface subsidence.

The model developed in this study is suitable for analyzing regional ground-water flow and land-surface

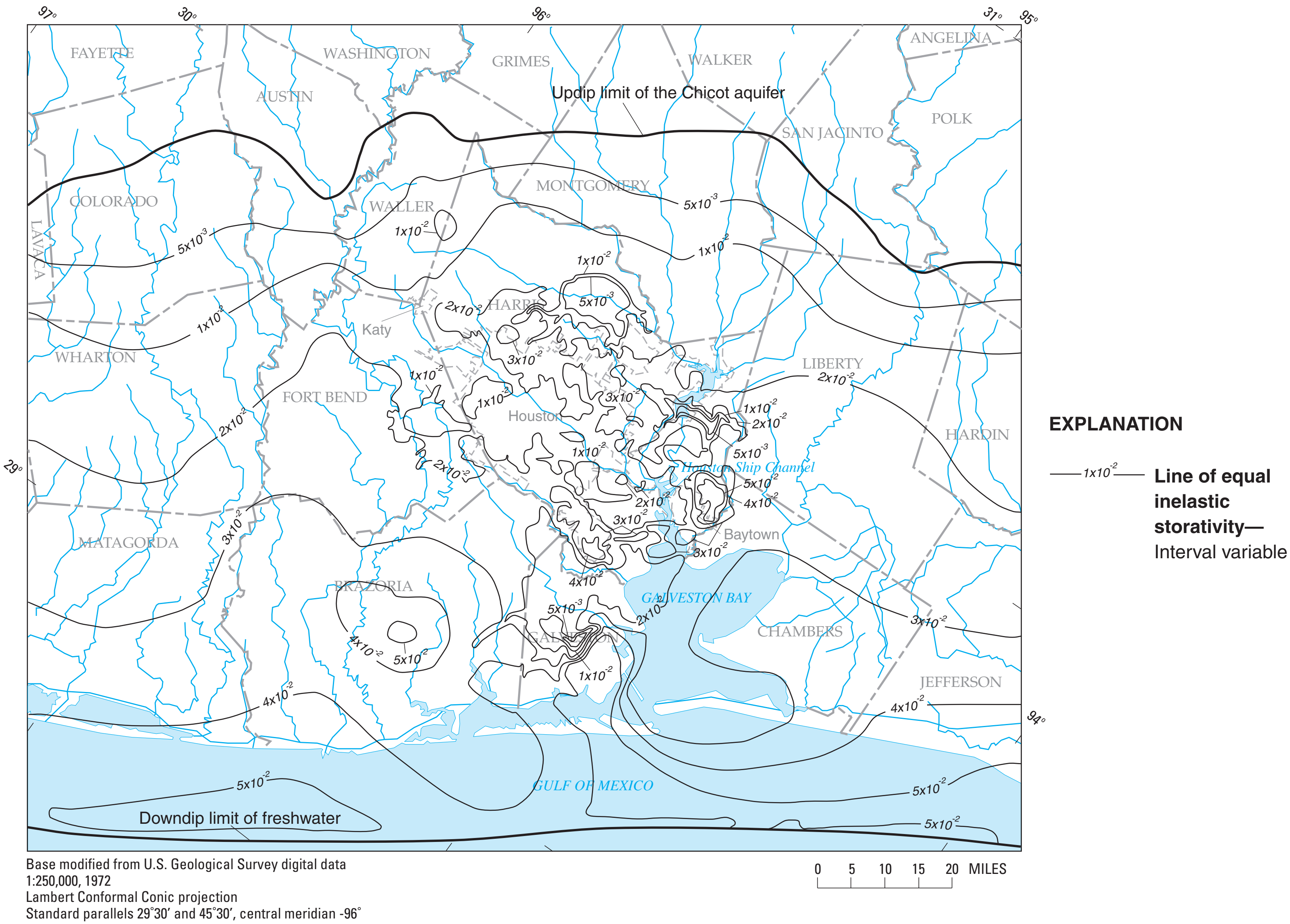


Figure 35. Inelastic storativity of the Chicot aquifer, Houston area, Texas.

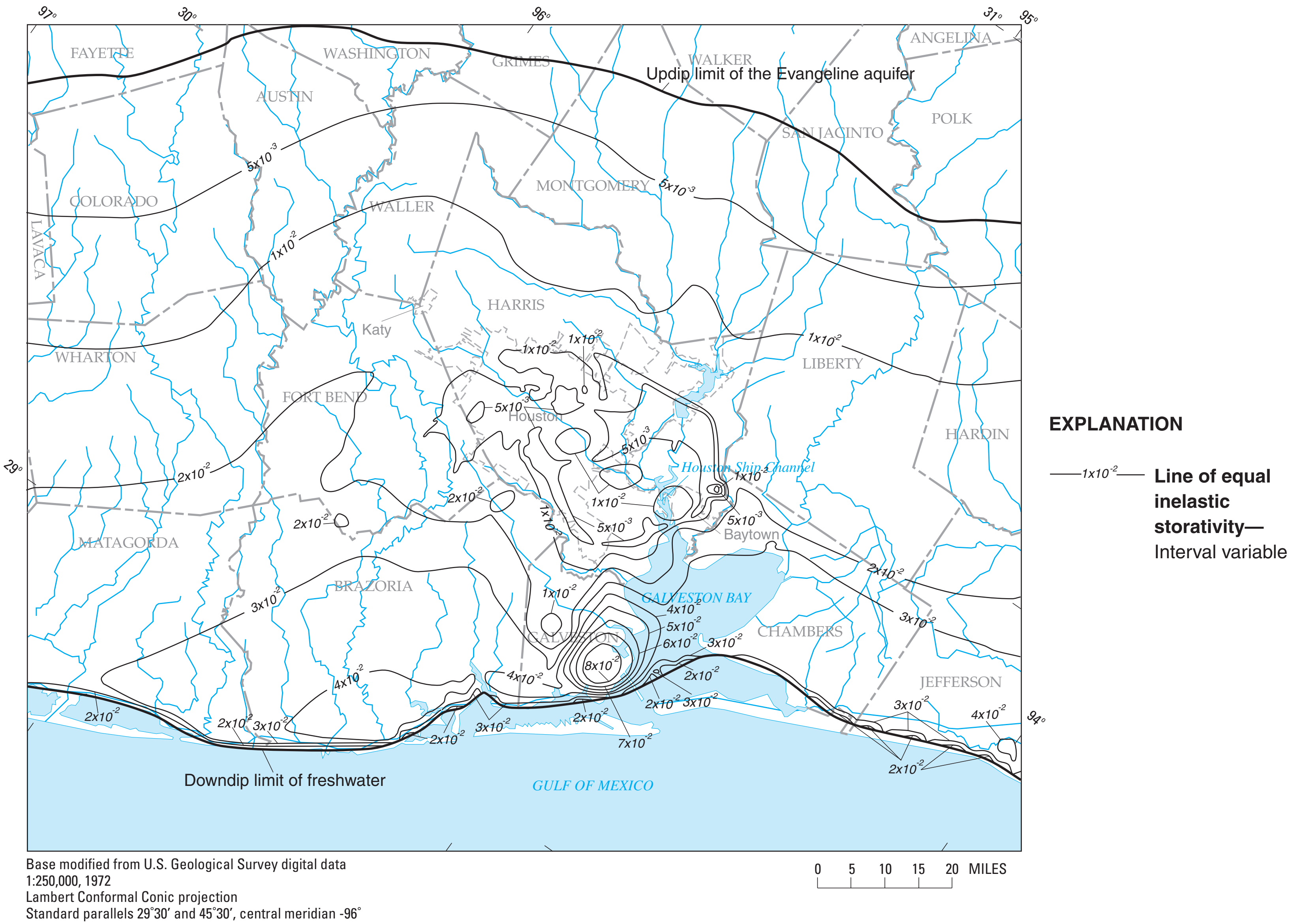
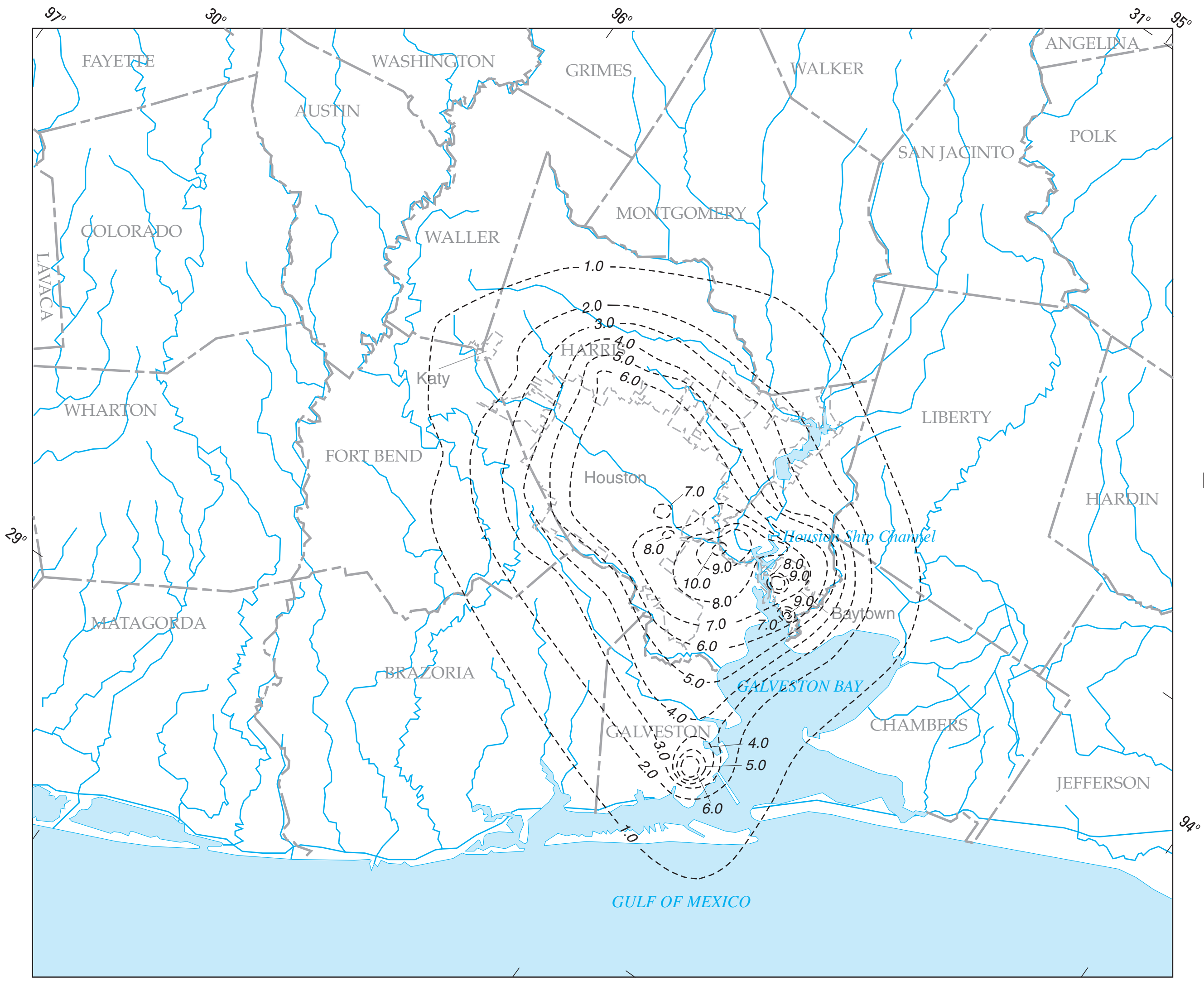


Figure 36. Inelastic storativity of the Evangeline aquifer, Houston area, Texas.



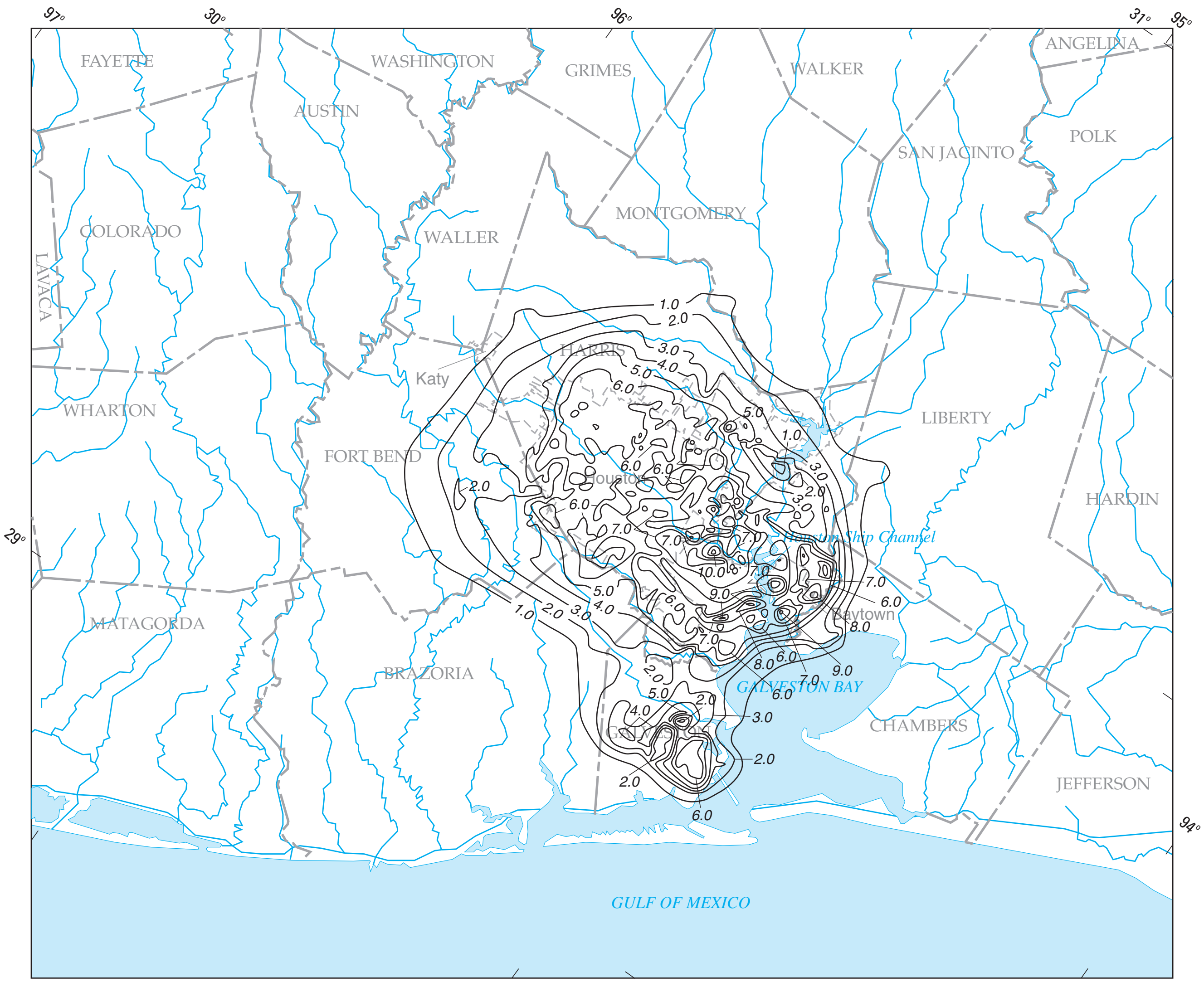
Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

0 5 10 15 20 MILES

EXPLANATION

---- 7.0 ---- **Line of equal land-surface subsidence—** Interval 1.0 foot

Figure 37. Measured land-surface subsidence, Houston area, Texas, 1906–95 (modified from Harris-Galveston Coastal Subsidence District, 1998).



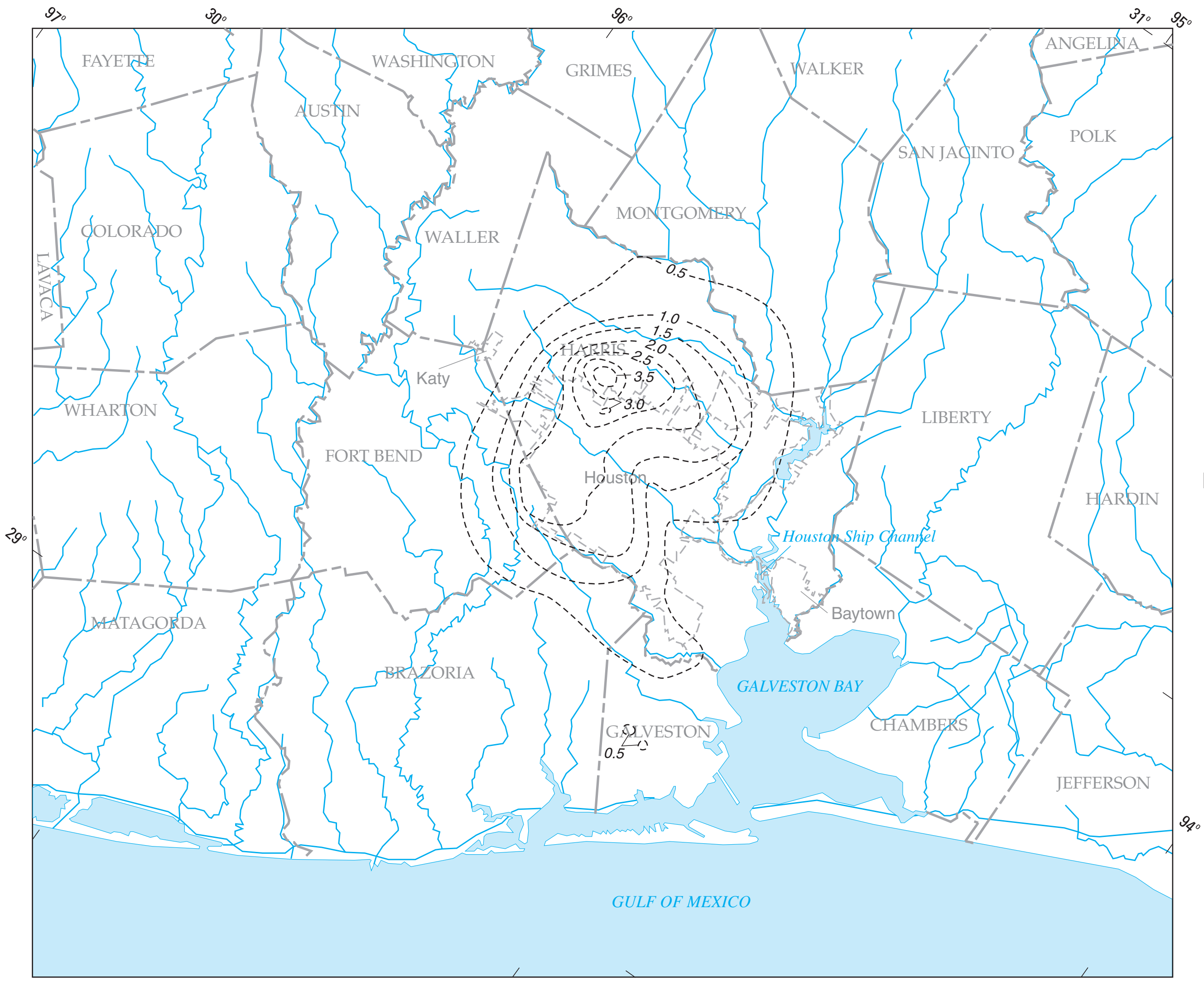
Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

0 5 10 15 20 MILES

EXPLANATION

0.5 — **Line of equal land-surface subsidence—** Interval 1.0 foot

Figure 38. Simulated land-surface subsidence, Houston area, Texas, 1891–1995.

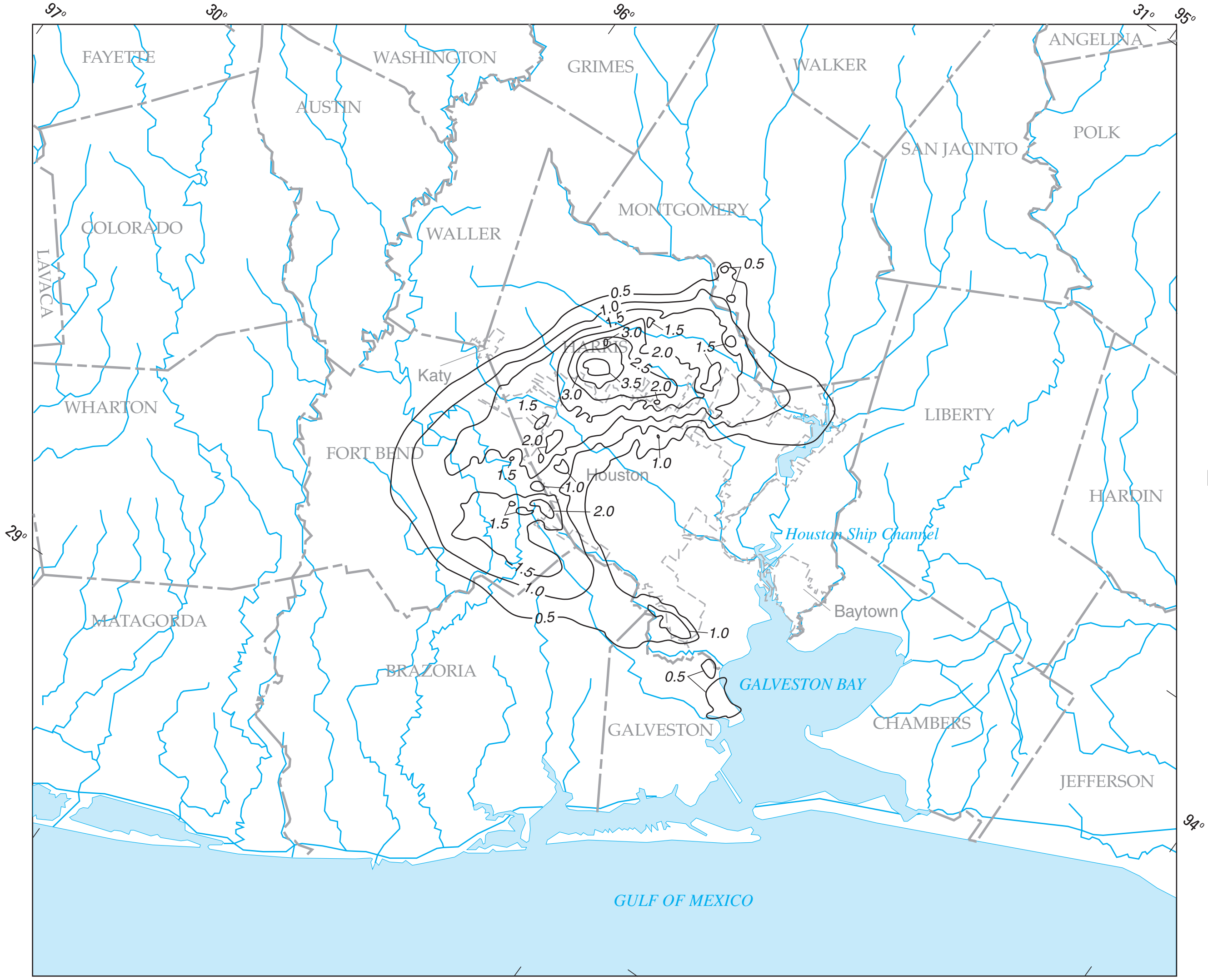


Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

EXPLANATION

---- 0.5 ---- **Line of equal land-surface subsidence—**
Interval 0.5 foot

Figure 39. Measured land-surface subsidence, Houston area, Texas, 1978–95 (modified from Harris-Galveston Coastal Subsidence District, 1998).



Base modified from U.S. Geological Survey digital data
1:250,000, 1972
Lambert Conformal Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°

0 5 10 15 20 MILES

EXPLANATION

—— 1.5 —— **Line of equal land-surface subsidence—** Interval 0.5 foot

Figure 40. Simulated land-surface subsidence, Houston area, Texas, 1978–95.

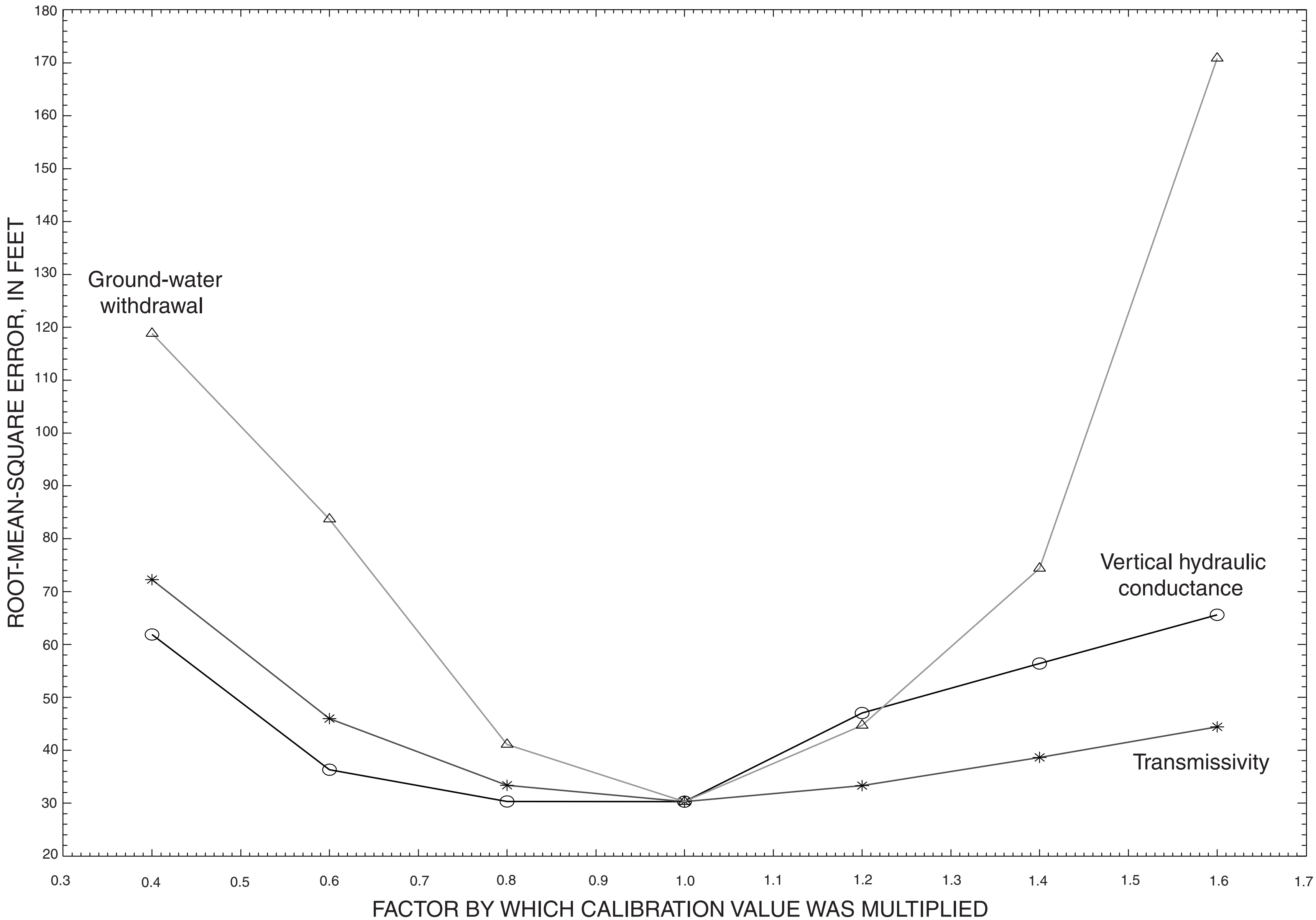


Figure 41. Sensitivity of the model of the Chicot and Evangeline aquifers, Houston area, Texas, to changes in aquifer properties and ground-water withdrawal.

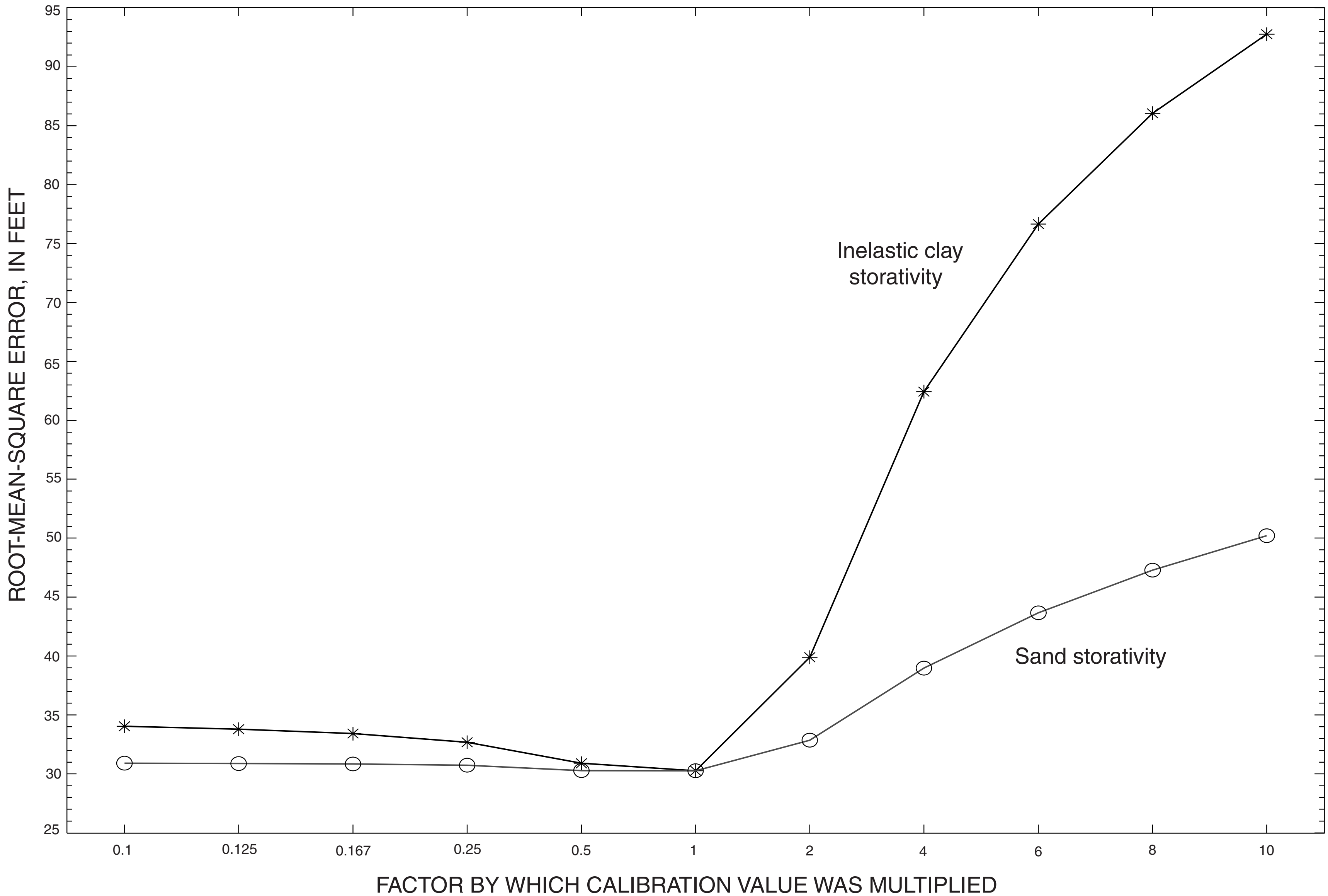


Figure 42. Sensitivity of the model of the Chicot and Evangeline aquifers, Houston area, Texas, to changes in clay and sand storage properties.

subsidence for the area within the city limits of Houston and southward to the Gulf of Mexico. In the northern part of the model area, the Chicot and Evangeline aquifers could be in hydraulic connection with the underlying Jasper aquifer. Any simulations of large ground-water withdrawal in this area will not reflect the potential contribution of water from the Jasper aquifer. The model is not designed for analysis of wells with large rates of ground-water withdrawal located adjacent to the lateral boundaries. These boundaries are located away from the main area of interest (Houston) and large pumping centers to minimize any boundary effects. Although the lateral boundaries are located at estimated ground-water-flow divides, large stresses nearby can change the locations of the flow divides. The subsequent change in fluxes and their effect on potentiometric surfaces probably would not be simulated accurately by the model.

Site-specific analysis is limited by horizontal and vertical discretization of the model and the availability of site-specific data. The model calculates a single potentiometric-surface value or land-surface-subsidence value for an entire cell area, which might or might not be a good approximation of potentiometric surface or land-surface subsidence for any individual well located in that cell. In addition, the transmissivity and other aquifer hydraulic properties are assumed uniform throughout each grid cell.

The assumption of a freshwater/saline-water interface as a fixed boundary in the downdip areas of the aquifers might not be valid if large-capacity wells or well fields are located nearby. The model is not designed to estimate movement of the freshwater/saline-water interface or to evaluate any change in salinity.

Numerous historical head and ground-water-withdrawal data for the Chicot and Evangeline aquifers are available, as well as historical land-surface-subsidence data for comparing simulated and measured data. However, the model results for predevelopment conditions illustrate only general trends and approximate potentiometric surfaces because few measured predevelopment heads are available for comparison to simulated predevelopment heads.

The best available ground-water-withdrawal data, which were supplied by the TWDB, HGCSD, and USGS, were used in the simulations. However, it is impossible to ascertain the exact historical ground-water withdrawals from the aquifers or the accuracy of reported ground-water withdrawals. If large inaccuracies in the modeled ground-water-withdrawal data exist, the calibration parameters would less likely reflect the actual field parameters.

Ground-water-withdrawal data were available for the model through 1996. For the model to be used as a tool to estimate potentiometric surfaces in the future, the ground-water-withdrawal data must be updated as new data become available. Changes in the distribution of ground-water withdrawal (such as new large-capacity wells or the cessation of pumping in existing large-capacity wells or well fields) must be taken into account in any future projection scenarios.

The Interbed-Storage Package is used with the assumption that geostatic pressure remains constant. The change in geostatic pressure caused by fluctuations in unconfined water levels is assumed negligible compared to the geostatic pressure of the entire saturated thickness. Large withdrawals of ground water that drain the system would result in overestimated effective stress using this method. The assumptions are made that model time steps are sufficiently long to allow all excess pore pressure in the numerous clay layers to dissipate and that inelastic compaction is proportional to change in effective stress. Users of the model are referred to Leake and Prudic (1991) for a discussion of the time constant before discretizing model time.

Additionally, a horizontal component of clay deformation occurs in the immediate vicinity of pumping wells (Poland and Davis, 1969). This deformation could be expansion (with an increase in porosity) in some locations and compression (with a decrease in porosity) in other locations. The cell size of the model precludes simulation of the effects of such local-scale deformation. However, the effects of such deformation might not be an issue; attempts by the USGS over several years to electronically measure distance changes along a 28-mi transect that crossed areas of subsidence yielded no measurable changes (R.K. Gabrysch, U.S. Geological Survey [retired], written commun., 2001).

As new hydraulic data become available, the possibility exists that some of the hydraulic properties (such as transmissivity or leakance) used in the model will need to be changed, in which case the model must be recalibrated. The addition of the Jasper aquifer to the model, changes in historical ground-water-withdrawal data, additional aquifer tests, or any other data that are appreciably different from the data used to calibrate the model could change the model calibration. Models are constructed using the best available information at the time, but their solutions are not unique. Models are imperfect and simplistic representations of a very complex natural system; however, if used with caution and judgment, models can be very valuable tools.

SUMMARY

In November 1997, the U.S. Geological Survey, in cooperation with the City of Houston Utilities Planning Section and the City of Houston Department of Public Works & Engineering began an investigation of the Chicot and Evangeline aquifers in the greater Houston area to better understand the hydrology, flow, and associated land-surface subsidence. The principal part of the investigation was a numerical finite-difference model developed to simulate ground-water flow and land-surface subsidence in an 18,100-mi^2 area encompassing greater Houston.

The Chicot aquifer and the Evangeline aquifer are the uppermost hydrogeologic units (youngest) of the Gulf Coast aquifer system and dip from the northwest to the southeast. Both aquifers are under water-table conditions in their updip sections (outcrop areas) and become confined downdip.

The finite-difference grid used in the numerical model encompasses all of Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, and Waller Counties and parts of Angelina, Austin, Colorado, Fayette, Grimes, Hardin, Jefferson, Lavaca, Matagorda, Montgomery, Polk, San Jacinto, Walker, Washington, and Wharton Counties. The focus of the study was Harris and Galveston Counties, but the other counties were included to achieve the appropriate boundary conditions. The model grid was oriented parallel to the Texas Gulf Coast to better coincide with the ground-water divides, boundaries, and predevelopment flowpaths. Each grid layer consists of 103 rows and 109 columns. The model was vertically discretized into three layers resulting in a total of 33,681 grid cells. Layer 1 represents the water table using a specified head, layer 2 represents the Chicot aquifer, and layer 3 represents the Evangeline aquifer.

Simulations were made under transient conditions for 31 ground-water-withdrawal (stress) periods that began on January 1, 1891, and ended on December 31, 1996. For the period 1891–1975, water-use data and ground-water-withdrawal periods from previous reports involving models of the Chicot and Evangeline aquifers in the Houston area were used. For the period 1976–96, water-use data compiled from HGCSD for Harris and Galveston Counties and data compiled by the TWDB and the USGS for all other counties were used.

The finite-difference computer code MODFLOW was used to simulate the Chicot and Evangeline aquifers. Published data and data from previous field investigations were collected and reviewed prior to developing model input data. Data analysis included defining the hydrogeologic framework and translating that framework into a conceptual model of the aquifer system suitable for simulation.

On the basis of the results of previous models, the initial model calibration strategy was to modify the best-known hydraulic properties as little as possible and to vary the least-known hydraulic properties to achieve the best overall agreement between simulated and measured aquifer potentiometric surfaces and land-surface subsidence. Model calibration was based on transient conditions because few potentiometric-surface data representing the predevelopment period for the aquifers are available. The calibration values of hydraulic properties determined during transient simulations subsequently were used for simulating potentiometric surfaces for predevelopment conditions.

The years 1977 and 1996 were chosen as potentiometric-surface calibration periods for the model. The year 1977 was chosen because, during the mid-1970s, the potentiometric surfaces in both aquifers had declined to record low levels in Harris and Galveston Counties. In addition, the first water-level-altitude maps of both aquifers were published for 1977. The year 1996 was chosen because 1996 was the most recent year that water-level data from wells were available, the most recent land-surface altitudes were determined in late 1995, changes in potentiometric surfaces correlate with land-surface subsidence during the 1977–95 period, and the magnitude and distribution of ground-water withdrawal were very different from those in 1977. Water-level data from wells and land-surface data for 1996 indicate a broad range of stresses, both spatially and temporally, which are important during model calibration.

Simulated and measured potentiometric surfaces of the Chicot and Evangeline aquifers for 1977 match closely. Water-level measurements indicate that by 1977, large ground-water withdrawals in east-central and southeastern areas of Harris County had caused potentiometric-surface declines of as much as 250 ft below sea level in the Chicot aquifer and as much as 350 ft below sea level in the Evangeline aquifer. These areas of large potentiometric-surface declines are

caused by coalescing cones of depression at the major well fields combined with ground-water withdrawal from the numerous other wells throughout the area.

Simulated and measured potentiometric surfaces of the Chicot and Evangeline aquifers for 1996 also match closely. The large potentiometric-surface decline in 1977 in the southeastern Houston area showed significant recovery by 1996. New centers of potentiometric-surface decline are much farther northwest. Potentiometric-surface declines of more than 200 ft below sea level in the Chicot aquifer and more than 350 ft below sea level in the Evangeline aquifer were measured in observation wells and simulated in the flow model.

Simulated 1996 Chicot aquifer flow rates indicate that a net flow of 562.5 ft^3/s enters the Chicot aquifer in the outcrop area, and a net flow of 459.5 ft^3/s passes through the Chicot aquifer into the Evangeline aquifer. The remaining 103.0 ft^3/s of flow is withdrawn as well pumpage, with a shortfall of about 84.9 ft^3/s supplied to the wells from storage in sands and clays. Water simulated from storage in clays in the Chicot aquifer is about 19 percent of the total water withdrawn from the aquifer.

Simulated 1996 Evangeline aquifer flow rates indicate that a net flow of 14.8 ft^3/s enters the Evangeline aquifer in the outcrop area, and a net flow of 459.5 ft^3/s passes through the Chicot aquifer into the Evangeline aquifer for a total inflow of 474.3 ft^3/s. A greater amount, 528.6 ft^3/s, is withdrawn by wells; the shortfall of about 54.8 ft^3/s is supplied from storage in sands and clays. Water simulated from storage in clays in the Evangeline aquifer is about 10 percent of the total water withdrawn from the aquifer.

Simulation of land-surface subsidence and water released from storage in the clay layers was accomplished using the Interbed-Storage Package of the MODFLOW model. The elastic and inelastic skeletal specific storativities are properties for which calibration values were obtained by interactive model calibration with potentiometric surfaces of the aquifers. The mean values of simulated inelastic skeletal specific storage for the Chicot and Evangeline aquifers were 7.34×10^{-5} ft^{-1} and 1.42×10^{-5} ft^{-1}, respectively. Calibration land-surface subsidence values were obtained in the calibration process by comparing simulated long-term (1891–1995) and short-term (1978–95) land-surface subsidence with published maps of land-surface subsidence for about the same periods until acceptable matches were achieved.

A sensitivity analysis was performed on model parameters of transmissivity, ground-water withdrawal, vertical hydraulic conductance, sand storativity, and inelastic clay storativity. The results of this analysis indicate that the model is more sensitive to decreases than increases in transmissivity from the calibration value; but the model is more sensitive to increases than decreases in ground-water withdrawal, vertical hydraulic conductance, sand storativity, and inelastic clay storativity from the calibration value.

The accuracy of ground-water models is limited by assumptions made in the formulation of the governing flow equations and by assumptions made to construct a model. Models also are limited by cell size, number of layers, boundary conditions, discretization of time, accuracy and availability of hydraulic properties, accuracy of calibration, historical data for matching, and parameter sensitivity. Models also are limited by the availability of data and by the interpolations and extrapolations that are inherent in using these data in a model. A model might be calibrated, but the calibration parameter values are not unique in yielding a particular distribution of hydraulic head and (or) land-surface subsidence.

As new hydraulic data become available, the possibility exists that some of the hydraulic properties (such as transmissivity or leakance) used in the model will need to be changed, in which case the model must be recalibrated. The addition of the Jasper aquifer to the model, changes in historical ground-water-withdrawal data, additional aquifer tests, or any other data that are appreciably different from the data used to calibrate the model could change the model's calibration. Models are constructed using the best available information at the time, but their solutions are not unique. Models are imperfect and simplistic representations of a very complex natural system; however, if used with caution and judgment, models can be very valuable tools.

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