Southeast Texas Groundwater Conservation District

P.O. Box 1407 • 271 East Lamar, Jasper, TX 75951
Phone: (409) 383-1577 / Fax: (409) 383-0799
E-mail: Jmartin@setgcd.org

Non- Exempt Well Permit Application Form

This permit application form must be completed and submitted, along with additional information requirements as outlined in the District Rules. The permit application must be accompanied by applicable fees. *A permit must be obtained prior drilling any new non-exempt well*.

Intended Well Usage

- ☐ Less than 100,000 gallons per day or 36,500,000 gallons annually **with no** intent to transfer out of District
- ☐ Greater than 36,500,000 gallons annually **with no** intent to transfer out of District
- ☒ Any amount **with** intent to transfer out of District

Well Owner Information

Name of Well Owner: Daniel Ayres Telephone: 409-384-0832
Mailing Address: 811 County Road 2076
City: Newton State: Texas Zip: 75966

- ☐ Well owner will be operating the well
- ☐ Person other than well owner will be operating the well. If so, provide:

Name of Operator: TBD (Any Operator will Hold a Water Operator License from TCEQ)
Mailing Address: ______ Telephone: ______
City: ______ State: ______ Zip: ______

Land Owner Information

If applicant is other than landowner, please complete the following information and provide documentation establishing the applicable authority to construct and operate a well for the proposed use.
Name of Property Owner: ______ Telephone: ______
Mailing Address: ______
City: ______ State: ______ Zip: ______

Well Driller Information

Name of Company: TBD
Mailing Address: ______ Telephone: ______
City: ______ State: ______ Zip: ______
Contact Name: ______ Contact E-mail: ______
Name of Licensed Driller: ______ License #: ______

Well Specifications

☒ New Well ☐ Modification of existing well Permit – Permit Number: ______
☐ Replacement Well (*If so, indicate status of old well*): ______
Casing Size: 12 inch Pump Size: 7.5hp Estimated Depth of Well: 400
Gallons Per Minute: 400 gpm Anticipated or estimated annual amount of water usage: 516.5 ac ft/ yr

Well Location

Physical 911 address: 1063 County Road 2076
City: Newton State: Texas Zip: 75966
GPS Coordinates (**required**): Latitude: N: N 30° 56.639' Longitude: W: W. 93° 35.42'

Additional information must be completed and attached to this document. Please refer to the District's Rule and the Permit Application Checklist for a complete list of all required data.

I, the undersigned applicant, hereby agree and certify that:

a. The applicant will comply with the District's Rules and all Groundwater use permits and plans promulgated pursuant to the District's Rules;

b. The applicant will comply with the District's Management Plan;

c. The applicant will comply with all District and State well plugging and capping guidelines in effect at the time of well closure; and,

d. By signing this form, the well owner understands that this allows the Southeast Texas Groundwater Conservation District to enter the property to inspect the well.

I hereby certify that I have furnished the above information and to the best of my knowledge and belief, all data herein contained are true and correct.

____ ____________________

Well Owner Signature or Authorized Representative | Date

____

Print Name

____

Position/Title

Application For a Permit

To Produce Groundwater from

Newton County, Texas

Submitted To:

Southeast Texas Groundwater Conservation District
C/o Mr. John Martin
Post Office Box 477
Kirbyville, Texas 75956

Submitted By:

Daniel Ayres
811 County Road 2076
Newton, Texas, 75966

Telephone: 409-383-0521
Mobile: 409-384-0832

September 18, 2015
Rev. October 5, 2015

Application For a Permit To Drill, Produce and Transfer Groundwater

1. Rule 5.4(a) and Rule 14.4 (a) The name and mailing address of the applicant and the owner of the land on which the well is or will be located;

Daniel Ayres
811 County Road 2076
Newton, TX, 75966

Telephone: 409-383-0521
Mobile: 409-384-0832

A location map of the property, the warranty deed for the property and a plat map of the property are shown in Exhibit 1

Rule 5.4(c) and Rule 14.4(e) A map showing the location of all existing wells within one half (1/2) mile radius of the proposed well or the existing well to be modified if requested by the District.

The map requested along with a spread sheet showing the information about the wells within the radius is attached in Exhibit 2.

Exhibit 2 is a print out of the TWBD WIID system, in a one-mile radius from the proposed well showing the location of other wells in the vicinity

Rule 14.4(b) If the applicant is other than the owner of the property, documentation establishing the applicable authority to construct and operate a well for the proposed use;

Not applicable

Rule 5.4(d) and Rule 14.4(c) The location of each well and the estimated rate at which water will be withdrawn;

The Address of the tract of land for the proposed well is 1063 County Road 2076. The property is about 75 acres. The location of the proposed well within the tract is N 30° 56.639' W. -93° 35.42', as identified by a GARMIN GPS72 hand–held GPS unit. There are 4 existing wells owned by the same owner on the property given in Table 1 and on a map in Exhibit 1. Exhibit 3 contains a detailed listing and map obtained from the

County Appraisal District and includes the location of the proposed well, a map of the subject property, and the physical and mailing addresses of persons owning property within one half (1/2) mile radius of the proposed well.

Table 1. Location of wells on property owned by Daniel Ayres.

	Latitude	Longitude
Camp Site:	N. 30° 56.541’	W. 93° 35.333’
Church Site:	N. 30° 56.718’	W. 93° 35.530’
Home Site:	N. 30° 56.634'	W. 93° 35.639’
Pond Site:	N. 30° 56.744’	W. 93° 35.528’

Three of these free flowing wells will be capped and taken out of production to increase water available for the new well

Rule 5.4(i) and Rule 5.4(f) and Rule 14.4(d) A statement of the nature and purpose of the proposed use, the amount of water to be used for each purpose, the place of use, and the purposes of use in the proposed receiving area for which water is intended;

The application is for a new well, to be drilled into the Jasper Aquifer, which is the source of the groundwater for the springs on the property. The springs and the well obtain their water from the same reservoir. The groundwater will be produced to a secured ground storage tank facility. The groundwater will be sold in bulk at the site and transported to a bottling facility or facilities of any other purchaser. The well may serve as an emergency supply for rural domestic water users or municipalities. The spring water will be used for consumptive purposes, i.e. it will be sold as bottled spring water in a widespread variety of locals. The well is located on the outcrop area of the Jasper formation in Jasper and Newton Counties where Wesselman (1967) calculates the recharge is 526 mgd. We estimate that the groundwater can be produced at the rate of approximately 400 gallons per minute for 24 hours per day and 7 days per week. Based on this estimate, the daily and weekly usages are expected to average about 576,000 gal/day or 4,032,000 gal/wk. The Jasper Aquifer is regionally extensive and we do not expect the water availability or the pumping rate to vary from season to season. Regional groundwater-level decline at the end of 45 years of pumping is calculated by the Houston Area Groundwater Model (HAGM) to be an additional 0.6 feet. (See Hydrogeological Report in Appendix 6 for the full analysis using the Houston Area Groundwater model), and perhaps 1.2 feet with the new model under preparation by the State of Texas. It is not possible to estimate the amount of water that will be consumed in any one locale.

Rule 5.4(d) and Rule 14.4(f) A map from the county appraisal District indicating the location of the proposed well or the existing well to be modified, the subject property, and the physical addresses and mailing addresses of any person owning property within a one-half (1/2) mile radius of the well or wells for which the application is filed;

The names and addresses of the property owners within one-half (1/2) mile of the location of our proposed well are included herein as Exhibit 3. It is our understanding that each of the houses belonging to these property owners may have its own water well, although no wells for these properties are registered in the TWDB well record data base. The Hydrogeology Report indicates that over the next 50 years the maximum drawdown in the potentiometric surface is only about 24.82 feet at the well itself. This is less than the potentiometric surface of +111 ft agl at the well. There is a significant difference between 06.ft of drawdown reported in the model and the 24.82 feet of drawdown calculated in the Hydrology report. This is caused by the used of a storage coefficient of 0.15 instead of 0.0003 that was used in the model.

Three of these free flowing wells owned by Ayres will be capped and taken out of production to increase water available for the new well

Rule 5.4(e) and Rule 14.4(g) Notice of any application to the Texas Commission on Environmental Quality to obtain or modify a certificate of Convenience and Necessity to provide water or wastewater service with water obtained pursuant to the requested permit;

Not Applicable.

Rule 5.4(g) and Rule 14.4(h) A declaration that the applicant will comply with the District's Rules and all Groundwater use permits and plans promulgated pursuant to the District's Rules;

I, Daniel Ayres, will comply with the all District Rules as verified by my notarized signature below.

Rule 5.4(h) and Rule 14.4(i) Water conservation plan;

The applicant will implement a water conservation plan with the express purpose of avoiding "waste" of the groundwater/spring water resource. Specific examples of the "waste" that will be avoided through high quality workmanship during the well construction phase and in the subsequent ongoing operational phase are as follows:

- “ withdrawal of groundwater from a groundwater reservoir at a rate and in an amount that causes or threatens to cause intrusion into the reservoir of water unsuitable for agricultural, gardening, domestic , or stock raising purposes”:
- the flowing or producing of wells from a groundwater reservoir if the water produced is not used for a beneficial purpose;
- escape or thieving of groundwater from a groundwater reservoir to any other reservoir or geologic strata whether or not containing groundwater :

- pollution or harmful alteration of groundwater in a groundwater reservoir by saltwater or by other deleterious matter from another stratum or from the surface of the ground;
- willfully or negligently causing, suffering, or allowing groundwater to escape into any river, creek, natural watercourse, depression, lake reservoir, drain, sewer, street, highway, road, or road ditch, or onto any land other that that of the owner of the well unless such discharge is authorized by permit, rule, or order issued by the commission under Chapter 26, Texas Water Code; groundwater released on well startup or well development in order to improve water quality shall not constitute waste as defined above.

Rule 5.4((j) and Rule 14.4 (j) A water well closure plan: A declaration that the applicant will comply with well plugging guidelines and report closure to the Board.

I, Daniel Ayres, Applicant and Owner declare that I will comply with all District well plugging and capping guidelines and report closures to the Commission.

Rule 14.4(k) A hydrogeological report addressing the area of influence, draw down, recovery time, and other pertinent information required by the District shall be required for the following:

See Exhibit 4

Rule 14.4(k)(i) Requests to drill a well(s) or well field with a daily maximum capacity of more than 250,000 gallons; and

The estimated rate at which water will be withdrawn from the well is approximately 400 gallons per minute 80% of the time.

Well construction plan.

- Well depth: ~400 ft ±

- Well casing: 12-in steel surface casing set and cemented in 16-in bore hole to 50 ft then 12-in ID steel casing to TD with centralizers. Casing will stand 2 ft above 6-ft x 6-ft x 6-in non-shrink concrete pad.[1]
- Screen: 304 Stainless Steel, 10- to 30-slot Johnson-Type Well screen depending on electric geophysical down-the-hole logs including short and long normal resistivity, single point resistivity, caliper, acoustic velocity, temperature, and neutron and gamma ray logs, and grain-size analysis. The screens will be spotted across the Jasper aquifer according to analysis of all data.
- Well Adapter: Baker artesian-well pitless adapter.
- Annular Space Seal: sand filter pack across screened section, Enviroplug or Class A, non-shrink, pozzolanic concrete, from top of screened interval to surface
- Well pad: 6-ft x 6-ft x 6-in Class A, non-shrink, pozzolanic concrete with embedded wire screen.
- A typical well head is shown in the photograph below.

Typical well head with the concrete well pad covered by gravel.

[1] Edward E. Johnson, Inc. Ground Water and Wells, 1980, p. 186-187.

- Transportation is provided from a bulk water filling station similar to photograph below.

Concrete block wall at loading facility. Wooden structure contains pipes and valves.

Concrete-block wall. Photograph shows semi-circular wall in front of loading facility

Close up of concrete-block wall showing portals behind which is 3-inch fire hose. Small square brass door leads to control valves.

Rule 14.4(k)(ii) requests to modify to increase production or production capacity of a Public Water Supply, Municipal, Commercial, Industrial, Agricultural or Irrigation well with an outside casing diameter greater than 6 5/8 inches.

The well will be equipped with 12-inch ID steel casing with Johnson Type helically wound stainless-steel (304) well screen. The well will be test for an aquifer performance test and the pumping rate will be equal to or greater than the rate necessary for its ultimate planned use and the hydrogeologic report must address the impacts of that use. The report will include hydrogeologic information addressing and specifically related to the proposed water pumpage rate and pumping water levels at the proposed water well site intended for the proposed well or for the proposed transporting of water outside the District. Applicants may not rely solely on reports previously filed with or prepared by the District.

Rule 14.4(l) A declaration that the applicant will comply with the District's management plan:

I, Daniel Ayres, Applicant and Owner declare that I will comply with the District Management Plan.

Rule 14.4(m) Drought contingency plan.

This is not a municipal water supply project that depends on a continuous supply of water; but rather a bulk-water-sale facility to commercial bottlers with on-site storage. In the event of a drought, bulk sales can be discontinued. Additionally, the project could provide emergency water supplies to schools, municipalities, hospitals, rural water supply systems and others.

Were it necessary to curtail production, the water shortage contingency plan will consist of the following: Cessation or Reduction of pumping if the elevation of the static potentiometric surface in the Jasper Aquifer drops 37 feet of drawdown.

Flowing artesian well on the Ayres property flowing into a pond

Shut-in pressure of 48 psi of artesian well on the Ayres Property, Newton County, Texas. On March 30, 2015

Rule 14.4(n) Data showing the availability of water in the District and in the proposed receiving area during the period for which water supply is requested.

As a matter of policy, Section 36.208 of the Texas Water Code requires groundwater conservation districts within each groundwater management area (GAM) to adopt future target conditions. GAM Task 13-037 goals set a future drawdown target of 21 ft. Table 3 that shows drawdowns at various distances from the proposed well at the end of 50 years as 27.37 feet. This is for a well that produces 100 percent of the time at 400 gpm. Further recharge from the Sabine river will ultimately reduce groundwater withdrawal to about 115.68 gpm and drawdown may be as low as about 3 feet at the pumping well but for well bore efficiency.

As described above, all the groundwater will be used for consumptive purposes, i.e. will be sold as groundwater in a wide area. It is not possible to estimate the amount which will be consumed in any one locale.

The source of the water is the Jasper Aquifer, which is the lower-most aquifer of the Gulf Coast Aquifer system. The long-term availability of water from this proposed well was evaluated using the MODFLOW model created by the USGS and published in Hydrology and Simulated Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas 1891-2009. [2]

The Houston Area Groundwater Model (HAGM) was run and then modified as follows.

1) Ran the base model as is to establish base conditions.
2) The proposed well is located in Row 67, Column 234 of the model.

[2] Kasmarek, (*supra*)

3) At the end of the base model Stress Period 1(1891) Layer 4 the head is 191.1 ft-asl[3]

4) At the end of the base model Stress Period 78(2009) Layer 4 the head is 186.4 ft-asl/

5) Extended the model by adding 6 more Stress Periods, (2015, 2020, 2030, 2040, 2050, and 2060).

6) To do this:
    a. In the "*.wel" file, duplicated Stress Period 78 for each of the new time steps

    b. In the "*.ghb" file, duplicated Stress Period 78 for each of the new time steps

    c. In the "*.dis" file, added the following to the code for the 6 new time steps:

```
365.250000  6  1.000000  TR
365.250000  5  1.000000  TR
365.250000  10  1.000000  TR
365.250000  10  1.000000  TR
365.250000  10  1.000000  TR
365.250000  10  1.000000  TR
```

    d. In the"* .oc" file, added output controls save the data for the 6 new Stress Period, and changed the output from binary to ascii.

7) At the end of the extended model Stress Period 84(2060) Layer 4 the head is 186.3 ft-asl

8) To add a pumping rate of 400 gpm in Layer 4 Row 67 Column 234. Used the extended model as above and added a pumping rate of 400gpm or 77,000 cfd to Layer 4 Row 67 Column 234 for each of the 6 new Stress Periods.

9) The end of the extended model with withdrawals for Ayres Well is Stress Period 84(2060) Layer 4 the head is 185.7 ft-asl

Table 2: Head in future resulting in pumping 400 gpm in Row 67, Column 234.

Stress Period	Year	Head	Drawdown in well since 2009
1	1891	191.1	

[3] asl = above sea level

78	2009	186.4	
84	2060	186.3	0.1[4]
84	2060	185.7	0.6[5]

There is ample water in the system to accommodate a pumping rate of 400 gpm, 24 hours a day, 365.25 days per year for the next 45 years with *de minimis* drawdown.

The Extended Model and the Extended Model with additional pumping are in Appendix 6 of the Hydrogeology report attached hereto in Exhibit 4. It contains 2 DVDs with the model and the data.

The Groundwater Management Plant for the Gulf Coast Aquifers says there are 402,646 acre-feet per year than can be sustainably writhdrawn from the 4 Gulf Coast Aquifers as a whole. Total capacity of the well under this Application is 646, however, given that the proposed well may only pump 80 percent of the time, the total groundwater withdrawal will probably be 516.5 acre feet per year. This is only 1 percent total available sustainable pumping.

Rule 14.4(o) Alternative sources of supply that might be utilized by the applicant, and the feasibility and the practicability of utilizing such supplies.

Because of the unique nature of groundwater with a low total dissolved solids (TDS) content, and the necessity to show the source of the water is groundwater, no other source is sought. Alternative water for bottling can easily be located as the Jasper Aquifer is widely extant in Newton and Jasper Counties. Further, the water is not being used for life-critical uses such as schools, municipalities or rural water associations. If it were, emergency supplemental supplies are available. During Hurricane Rita, WaterBank contacted the Saucier Rural Water System. Further, WaterBank also

[4] Year 2060 of the extended model with no additional pumping
[5] Year 2060 of the extended model with additional pumping in Row 67 Column 234

contacted the Galveston municipal supply system and arranged to fill tanker trucks at the central supply facilities.

Rule 14.4(p) The projected effect of the proposed transfer on aquifer conditions, depletion, subsidence, or existing permit holders or other Groundwater users within the District;

It is our opinion that the projected effect of the proposed transfer on aquifer conditions, depletion, subsidence, or existing permit holders or other groundwater users within the District will be *de minimis*, and, as stated above, if the drawdown of the potentiometeric surface in the borehole exceeds 27.37 feet of pumping may be reduced to maintain this drawdown.

Rule 14.4(q) The indirect costs and economic and social impacts associated with the proposed transfer of water from the District;

We do not anticipate any indirect costs to be incurred as a result of this project. There may be some slight reduction in surrounding spring flow discharge into the Little Cow Creek. We do anticipate positive economic and social impacts, specifically, the following:

- employment opportunities for area residents; and,
- economic multiplier effect of perhaps "8" with leakage;[6] and,
- availability of high quality bulk-water supply to area residents; and,

[6] The definition of economic multiplier is the number of times that a dollar or earned wages circulates within the local economy. That is, it is earned and the spent for dry cleaning. The3w dry cleaner then pays it to an employee who spends it for a rubber duck. The seller of the rubber duck spends it on food where the seller of the food pays it in salaries and so on. However, when the dollar is spent for gasoline at a Shell station some of it is sent to a refinery located elsewhere and it is removed from the local economy which is called leakage.

- We do not anticipate any social impacts. The facility will be constructed so that it is unobtrusive.

Rule 14.4(r) Proposed plan of applicant to mitigate adverse hydrogeologic, social or economic impacts of the proposed transfer of water from the District. 14.4(r)

The only known adverse hydrogeologic impact would be a drought that is beyond the control of the project owner and, the implementation of the drought contingency plan is intended to mitigate this impact. If extended drought occurs and if the static potentiometric surface drops below 37 feet of drawdown in the well, production will cease. This facility is not anticipated to serve any client that requires the water as a matter of life or death. No adverse economic or social impacts are anticipated, but rather only positive impacts. During hurricane seasons, The State of Texas and FEMA have found it necessary to go beyond the boundaries of the state to find bottled water. WaterBank knows this to be the case as it was one of the major suppliers during Hurricane Rita. The provision of a stable water supply to Texas bottling companies will ensure water from Texas for Texans.

In the unlikely event that operation of the proposed well adversely affects a neighbors well by lowering the potentiometric surface or water level, the Applicant may offer to replace the lost water supply by a plan of replacement as we find in New Mexico Statutes NMSA 72-12A-7.

Rule 14.4(s) How the proposed transfer is addressed in the approved regional water plan and a certified District management plan. 14.4(s)

This is not addressed at this time and will be re-assessed when the well is brought into production due to the fact that the production volumes are only theoretical and the end location and use of water is unknown

Rule 14.4(t) The time schedule for construction and/or operation of the well.

Dates of construction are hard to predict based on the indeterminate length of time to design the well and acquire the drilling permit and other economic factors. In a perfect world, construction of the proposed well could be completed and tested by about January 1, 2016; but, this is out of the hands of the project owner as the well approval could take an unforeseen amount of time to obtain the permit and the driller cannot schedule the drilling and construction of the well until the permit is approved and we anticipate that the continuous operation of the well will begin prior to the end of calendar year 2016 . It is planned that the actual construction is in the near term and the actual dates of construction should not be viewed as a limiting factor. TCEQ requires a minimum of 90-days to approve the submitted plans. The actual time frame may extend well beyond the 90-day period.

At present, Applicant has identified a number of potential purchasers of the water and has had discussions with many of them. Certainly the availability of a bulk water source provides security to municipalities and rural water systems for back-up water the need for which cannot be known; but, which back up plans are part of the planning which water systems must consider as a public necessity.

Rule 14.4(u) Construction and operation plans for the proposed facility, including, but not limited to:

See Rule 5.4(d) and Rule 14.4(c) above. Photographs of similar facilities are given above. The Plan also includes security provisions such as fencing and alarms system.

A technical description of the facility to be used for storage, loading and transportation of the water and detailed plans of the surface facilities, including storage and loading facilities are to be determined according with sound construction and engineering standards. These plans and drawings have not been prepared but will be prepared by an engineering firm with experience in these matters. The photography shows similar facilities from around the country.

The bulk water loading terminal is near Reading, Pennsylvania.. It consists of a stainless steel water storage tank behind a block wall. Pipes run from the storage tank to the wall that contains insets of fire-hose rolls that connect to stainless steel, 6,000 gallons dedicated tanker trucks. The facility is sited on a semi-circular loop road behind a copse of trees and native vegetation off of a main road and cannot be seen from the main road through the copse of trees.

The well plans will be prepared by a Texas engineer for submittal to the Southeast Texas Groundwater Conservation District 14. We recommend at this point a 10,000 gallon storage tank. Because the potentiometric surface associated with the Jasper Aquifer stands about 111 ft above the land surface, we anticipate that a pump similar to a 7.5 HP Grundfoss 385S-750-1, 480 volt 3Φ single stage pump with a 4" discharge line should be suitable. The pump is 7.5-in in diameter and weighs 151 lbs. The pump is capable of producing 450 gpm against 50-ft of head.

Hydraulic efficiency is achieved in placing a 7.5-in diameter pump and motor in a 12-in diameter casing. This leaves about 4.5-in clearance in the casing around the pump that allows for low friction loss as the water flows in the well to the pump bowls. High efficiency minimizes energy necessary to produce the water.

With the pump producing at 400 gpm, It will take 25 minutes to fill the storage tank. The average load of water for a tanker truck is 6,000 gallons or 50,000 pounds. If the well produces directly into the tankers at 400 gpm it will require only 15 minutes to fill the truck. This is an acceptable period for loading a tanker. If water is drawn directly from the storage tank shorter loading periods can be achieved. Detailed specifications can always change depending on engineering considerations.

Of course, the well will be constructed according to TCEQ and District requirements and requirements of the Federal Drinking Water-well-construction standards

Rule 14.4(u)(i) A technical description of the proposed well(s) and production facility, including depth of the well, the casing diameter, type and setting, the perforated interval, and the size of pump;

See discussion under **Rule 5.4(d) and Rule 14.4(c)** above.

Rule 14.4(u)(ii) a technical description of the facilities to be used for transportation of water.

See information under **Rule 5.4(d) and Rule 14.4(c) above.**

Rule 14.4(v) If the water is to be used by someone other than the applicant, a signed contract between the applicant and the user or users; and

Accordingly, a signed contract is not appropriate at this time. Production from the approved and proposed well will be sold to a marketer or end user for bottling.

Marketing inquiries are in progress. A typical contract is attached as Appendix 5

Rule 14.4(w) Additional information or documentation that may be requested by the District.

I, Daniel Ayres, affirm that the foregoing statements are true and correct to the best of my knowledge and belief.

____

Daniel Ayres

ACKNOWLEDGEMENT

STATE OF TEXAS)
) ss.
COUNTY OF NEWTON)

Before me, ________________________, on this day personally appeared Daniel Ayres, known to me or proved to me by government issued photo-identification to be the person whose name is subscribed to the foregoing instrument and acknowledged to me that he executed the same for the purposes and consideration therein expressed, and he is of majority and executed this application of his own free will and volition.

Given under my hand and seal of office this the __________ day of September, 2015.

(SEAL)

____

Notary Public - Signature

My Commission Expires: ____________

Exhibit 1

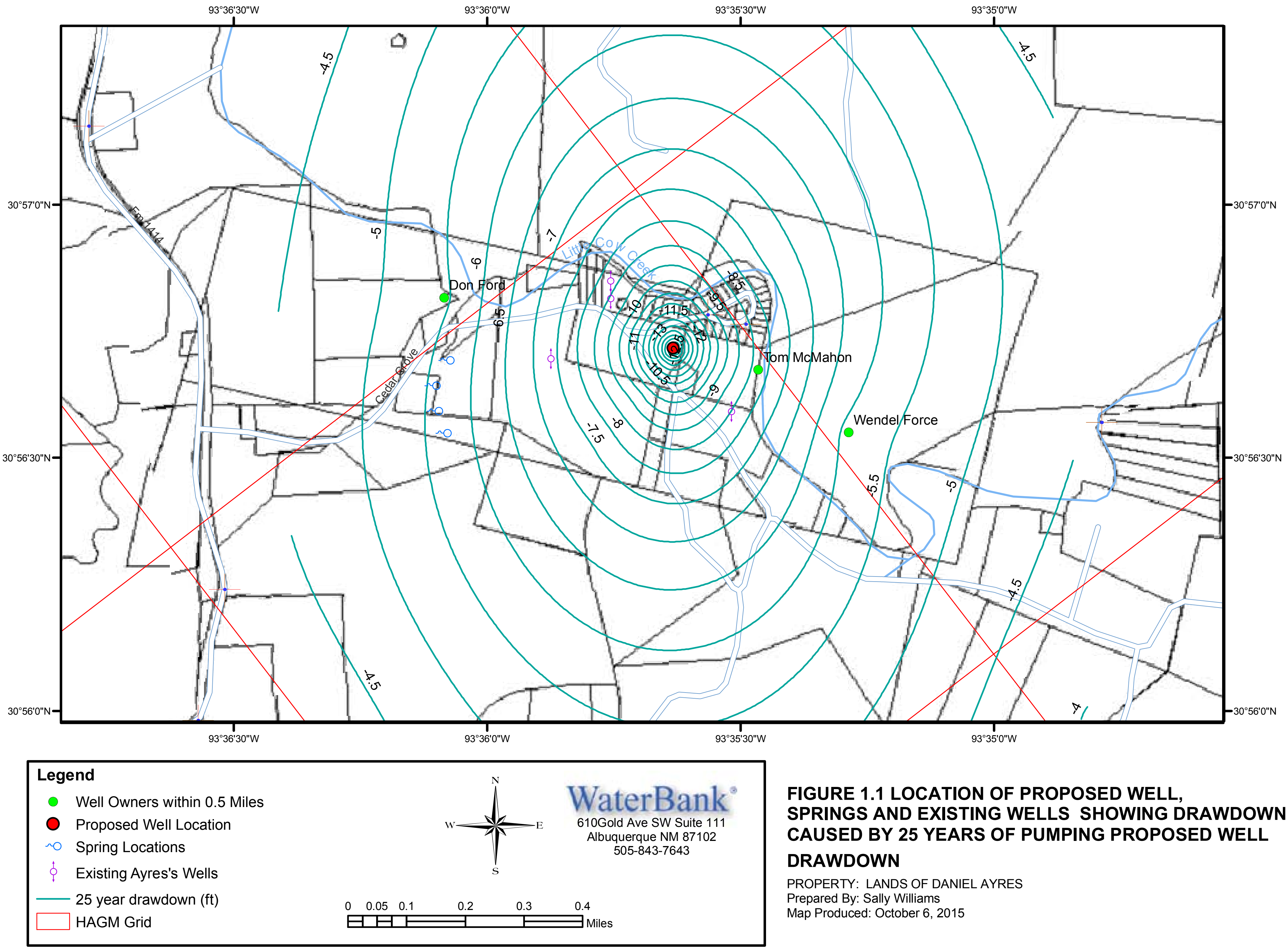


FIGURE 1.1 LOCATION OF PROPOSED WELL, SPRINGS AND EXISTING WELLS SHOWING DRAWDOWN CAUSED BY 25 YEARS OF PUMPING PROPOSED WELL

DRAWDOWN

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 6, 2015

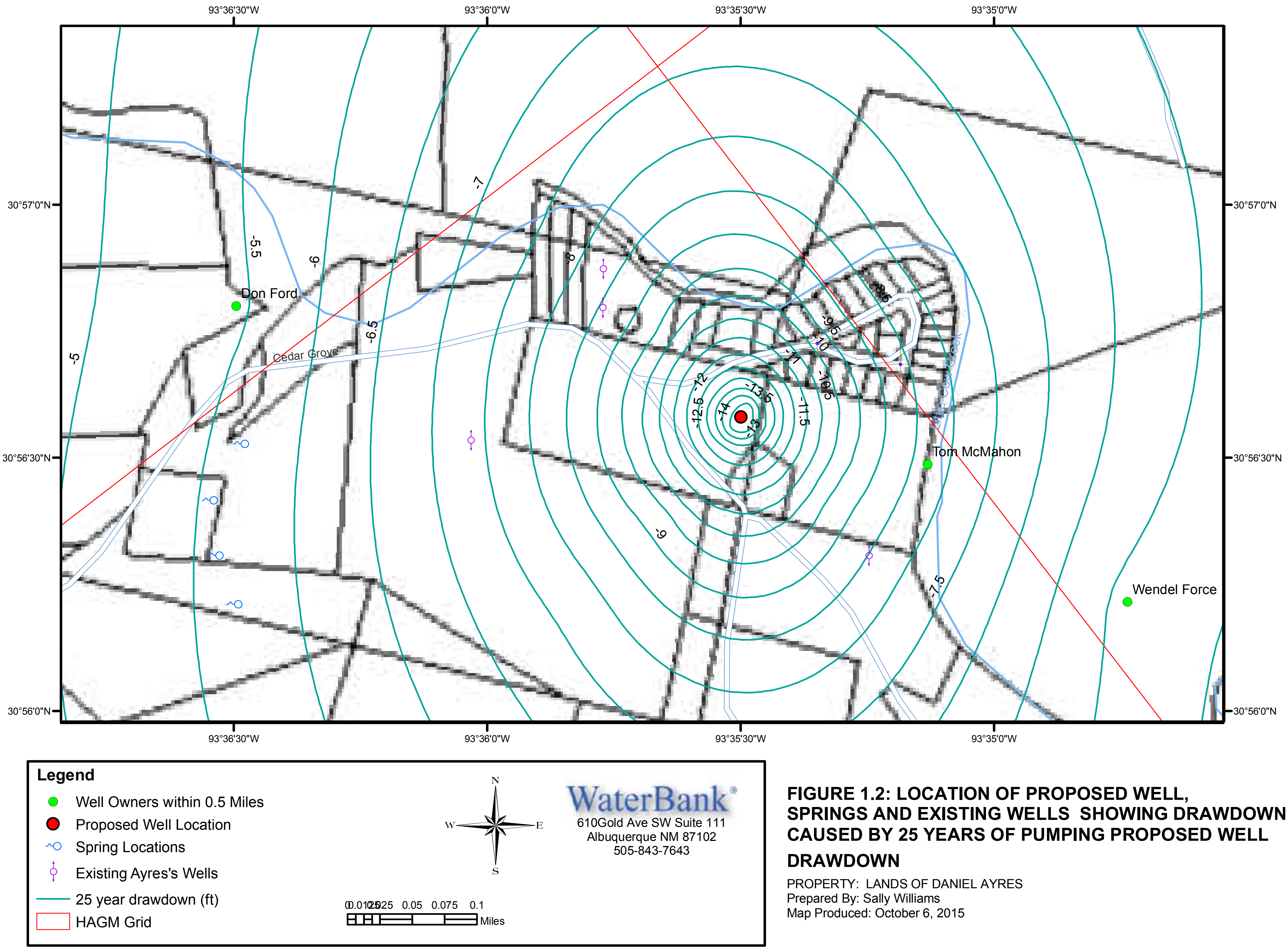


FIGURE 1.2: LOCATION OF PROPOSED WELL, SPRINGS AND EXISTING WELLS SHOWING DRAWDOWN CAUSED BY 25 YEARS OF PUMPING PROPOSED WELL DRAWDOWN

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 6, 2015

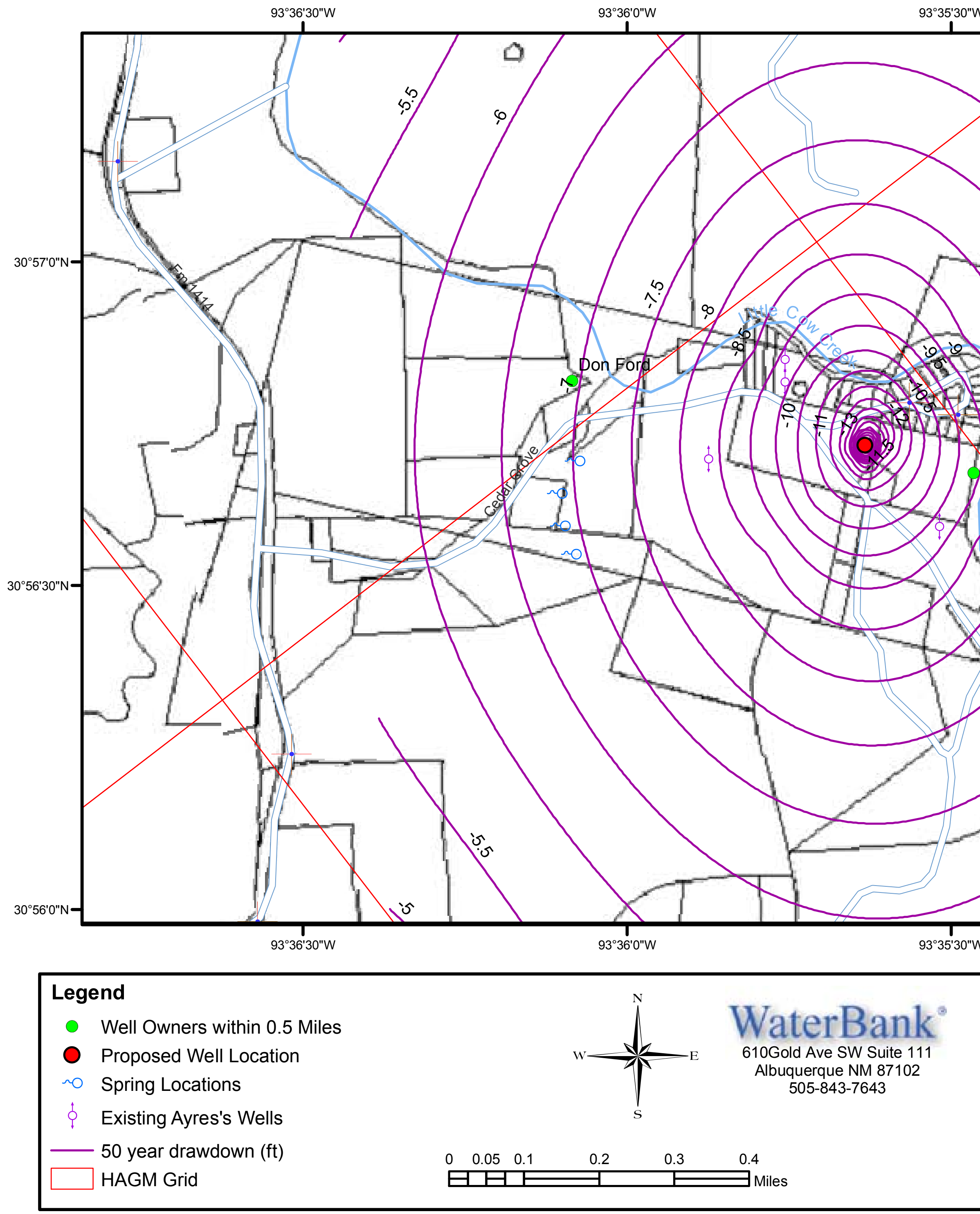


FIGURE 1.3 LOCATION OF PROPOSED WELL, SPRINGS AND EXISTING WELLS SHOWING DRAWDOWN CAUSED BY 50 YEARS OF PUMPING PROPOSED WELL DRAWDOWN

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 6, 2015

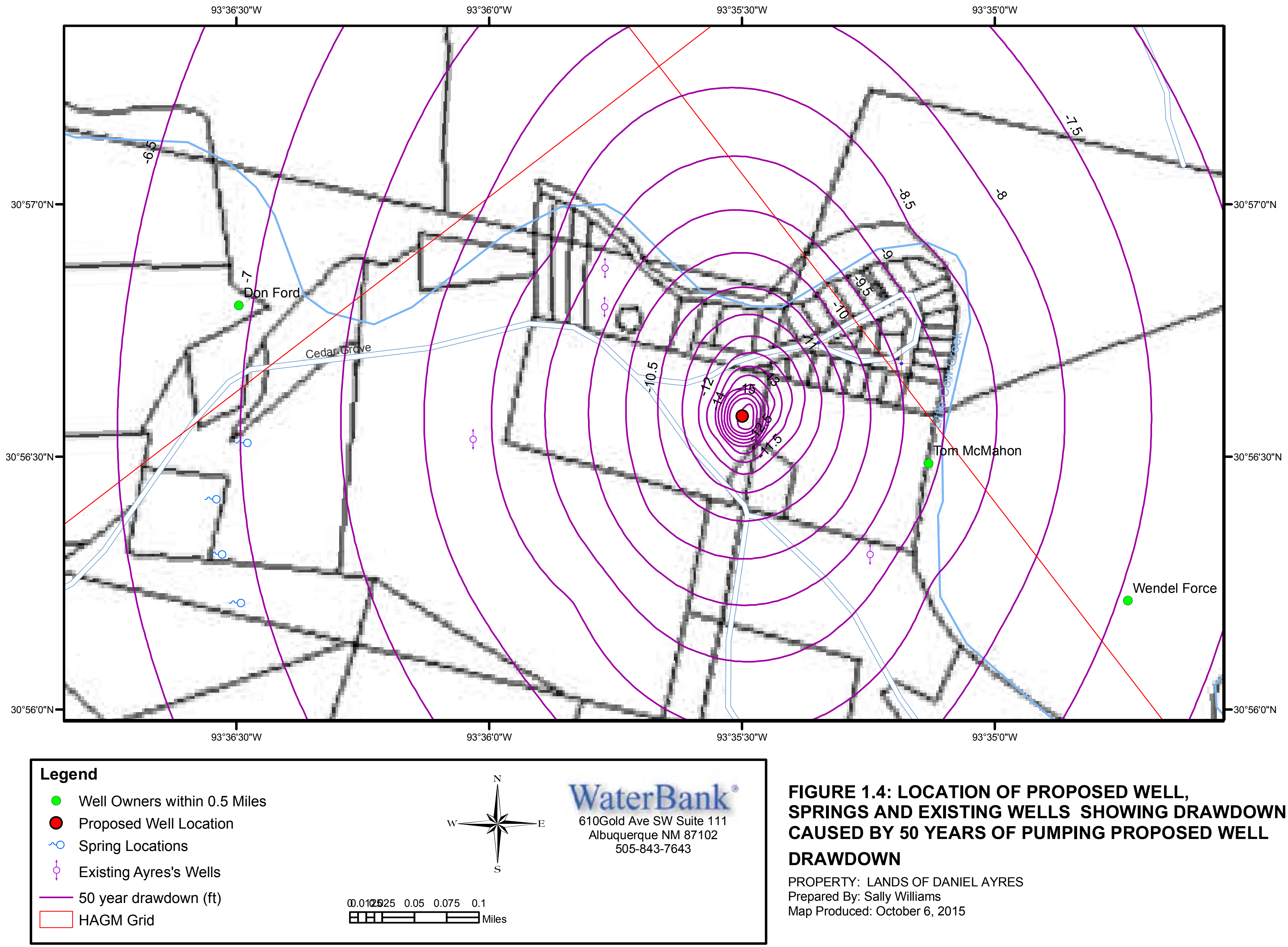
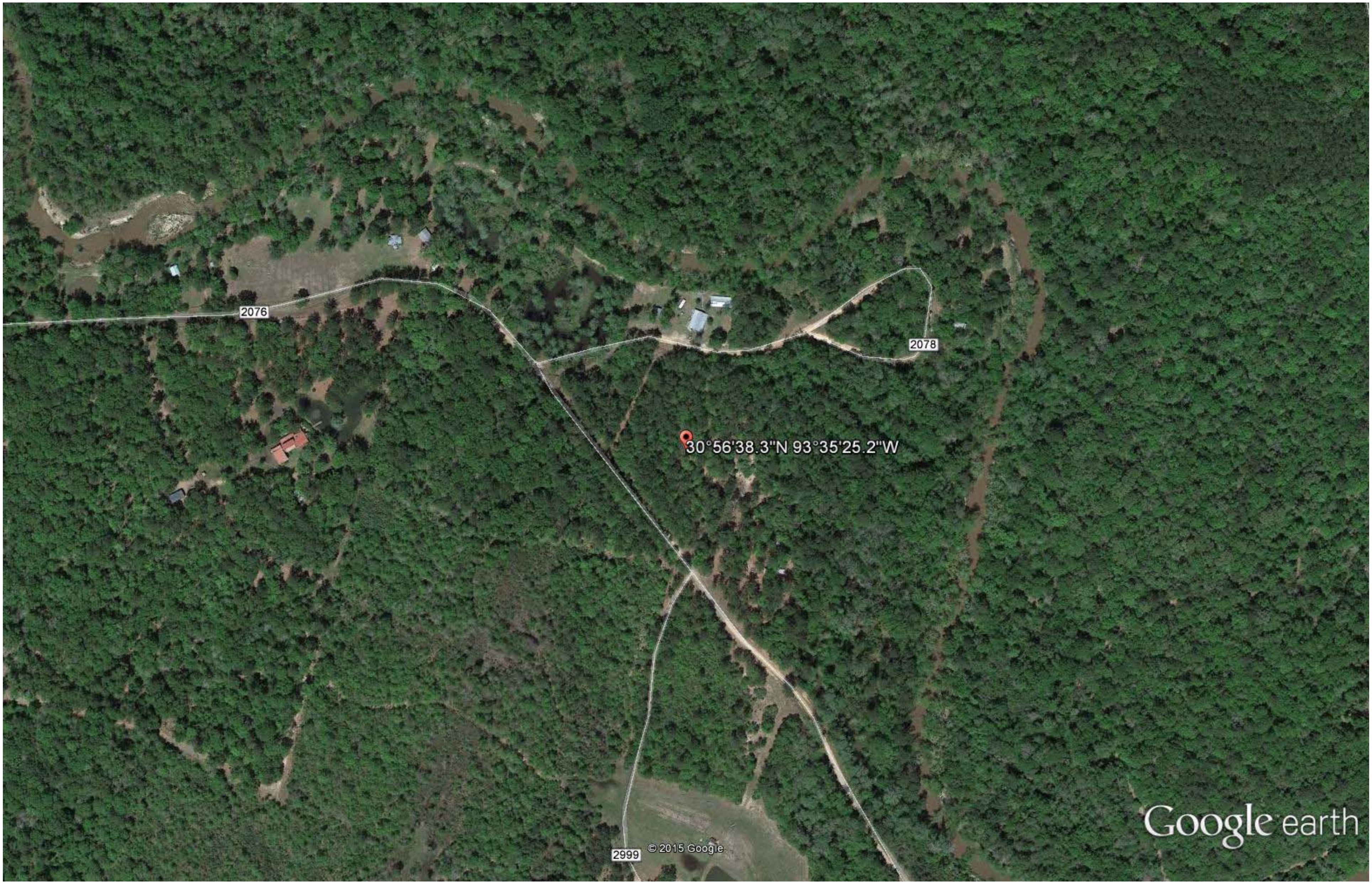


FIGURE 1.4: LOCATION OF PROPOSED WELL, SPRINGS AND EXISTING WELLS SHOWING DRAWDOWN CAUSED BY 50 YEARS OF PUMPING PROPOSED WELL DRAWDOWN

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 6, 2015



Google earth

feet 2000
meters 700

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NOTICE OF CONFIDENTIALITY RIGHTS: IF YOU ARE A NATURAL PERSON, YOU MAY REMOVE OR STRIKE ANY OF THE FOLLOWING INFORMATION FROM THIS INSTRUMENT BEFORE IT IS FILED FOR RECORD IN THE PUBLIC RECORDS: YOUR SOCIAL SECURITY NUMBER OR YOUR DRIVER'S LICENSE NUMBER.

131395

General Warranty Deed

Date: March 18, 2005

Grantor: Yola Clark,

Grantee: Daniel Ayres

Grantee's Mailing Address:

Daniel Ayres
Rt. 1, Box 812
Newton, TX 75966
Newton County

Consideration:

TEN AND NO/100 DOLLARS ($10.00) and other good and valuable consideration.

Property (including any improvements):

BEING 16.844 acres of land, more or less, and being a part of the HENRY STEPHENSON SURVEY, ABSTRACT 369, Newton County, Texas, and being the same land described in Exhibit "A" attached hereto and to which reference is made for a more particular description in metes and bounds

Reservations from Conveyance:

None

Exceptions to Conveyance and Warranty:

Liens described as part of the Consideration and any other liens described in this deed as being either assumed or subject to which title is taken; validly existing easements, rights-of-way, and prescriptive rights, whether of record or not; all presently recorded and validly existing instruments, other than conveyances of the surface fee estate, that affect the Property; and taxes for 2005, which Grantee assumes and agrees to pay, and subsequent assessments for that and prior years due to change in land usage, ownership, or both, the payment of which Grantee assumes.

Grantor, for the Consideration and subject to the Reservations from Conveyance and the Exceptions to Conveyance and Warranty, grants, sells, and conveys to Grantee the Property, together with all and singular the rights and appurtenances thereto in any way belonging, to have and to hold it to Grantee and Grantee's heirs, successors, and assigns forever. Grantor binds Grantor and Grantor's heirs and successors to warrant and forever defend all and singular the Property to Grantee and Grantee's heirs, successors, and assigns against every person whomsoever lawfully claiming or to claim the same or any part thereof, except as to the Reservations from Conveyance and the Exceptions to Conveyance and Warranty.

When the context requires, singular nouns and pronouns include the plural.

Yola M. Clark
Yola Clark

STATE OF TEXAS)

COUNTY OF NEWTON)

This instrument was acknowledged before me on 3/26/05
____________________, 2005, by Yola Clark.

Hal Michael Perdue
Notary Public, State of Texas

HAL MICHAEL PERDUE
NOTARY PUBLIC STATE OF TEXAS
COMMISSION EXPIRES:
AUGUST 19, 2007

PREPARED IN THE OFFICE OF:

Edward J Tracy
P. O. Box ET
Newton, Texas 75966
Phone: 409-379-4800
Fax: 409-379-4802

BARROW SURVEYING

Texas Registered Professional Land Surveyors

Henry Stephenson Survey, Abstract No. 369
Newton County, Texas

Legal Description
16.844 Acre Tract

BEING a 16.844 acre tract of land as situated in the Henry Stephenson Survey, Abstract No. 369 of Newton County, Texas and being all of a called 3.66 acre tract and out of and a part of a called 22.145 acre tract, said 22.145 acre tract having been conveyed from THE VETERANS LAND BOARD OF TEXAS to WILLIAM JAMES CLARK by Deed recorded in Volume 311, Page 380 of the Deed Records of Newton County, and said 3.66 acre tract being that same certain tract as described in a Release of Lien from COUNTY NATIONAL BANK to WILLIAM J. CLARK and filed for record in Volume 39, Page 698 of the Deed of Trust Records of Newton County, Texas. Said 16.844 acre tract being more particularly described by metes and bounds as follows:

BEGINNING at a 1/4" iron pipe found for the Northwest corner of said 3.66 acre tract and being located on the South line of the Clark 22.145 acre tract, from which a 2" iron pipe found on the West bank of Little Cow Creek bears South 73°52'32" East a distance of 329.30 feet;

THENCE North 73°52'32" West, with the South line of the 22.145 acre tract, at 254.92 feet pass a 5/8" iron rod set in the East edge of Cedar Grove Road, **IN ALL a total distance of 314.93 feet** to a 5/8" iron rod found for the most Westerly Southwest corner of this tract and the most Easterly Southeast corner of a 61.622 acre tract as during September 2001;

THENCE along the West edge of Cedar Grove Road with it's meanders as follows:

1. North 34°41'53" West a distance of 359.87 feet to a point for corner;
2. North 38 ° 32 ' 12 " West a distance of 247.77 feet to a point for corner;
3. North 40 ° 39 ' 06 " West a distance of 253.16 feet to a point for corner;
4. North 48 ° 09 ' 56 " West a distance of 88.58 feet to a point for corner;
5. North 54 ° 09 ' 35 " West a distance of 56.62 feet to a point for corner;
6. North 63 ° 50 ' 02 " West a distance of 47.62 feet to a point for corner;
7. North 71 ° 56 ' 25 " West a distance of 7.78 feet to a 2" round concrete monument found for the Northwest corner of this tract and the Southeast corner of the Cedar Grove Methodist Church 2.66 acre tract as recorded in Volume "V", Page 67 of the Deed Records of Newton County, same being an angle corner of the 61.622 acre tract and located on the North line of the Clark 22.145 acre tract;

THENCE South 73°36'00" East a distance of 131.17 feet with a South line of the 61.622 acre tract and the North line of the Clark 22.145 acre tract, to a 3/4" iron pipe found for an angle corner of the 61.622 acre tract and of this tract;

THENCE South 40°59'00" East a distance of 253.16 feet to a 5/8" iron rod found for an angle corner of the 61.622 acre tract and of this tract;

THENCE South 74°16'00" East a distance of 150.96 feet to a 3/4" iron pipe found for an angle corner of the 61.622 acre tract and of this tract;

THENCE North 47°45'15" East a distance of 161.27 feet to a 5/8" iron rod found for an angle corner of the 61.622 acre tract and of this tract, same being located on the North line of the 22.145 acre tract;

THENCE South 73°53'53" East a distance of 29.00 feet to a 3/4" iron pipe found for a Southeast corner of the 61.622 acre tract;

Exhibit "A"

P.O. Drawer 68 • Newton, Texas 75966 • (409) 379-2265 • Fax (409) 379-2860

THENCE South 74°02'20" East a distance of 931.82 feet, with the North line of the Clark 22.145 acre tract to a point for corner on the West bank of Little Cow Creek for the Northeast corner of this tract, from which a 2" iron pipe found for reference bears North 74°02'20" West a distance of 19.78 feet;

THENCE along the West Bank of Little Cow Creek with it's meanders as follows:

1. South 16°29'31" West a distance of 4.32 feet to a point for corner;
2. South 08°05'32" West a distance of 154.46 feet to a point for corner;
3. South 09°52'10" West a distance of 74.34 feet to a point for corner;
4. South 04°06'19" West a distance of 75.73 feet to a point for corner;
5. South 15°22'37" West a distance of 77.51 feet to a point for corner;
6. South 20°57'57" West a distance of 62.55 feet to a point for corner;
7. South 23°39'23" West a distance of 134.46 feet to a point for corner;
8. South 23°39'23" West a distance of 53.12 feet to a point for corner;
9. South 09°00'57" West a distance of 145.25 feet to a point for corner;
10. South 04°59'38" West a distance of 126.33 feet to a point for corner;
11. South 11°29'03" East a distance of 108.94 feet to a point for corner;
12. South 22°15'21" East a distance of 138.00 feet to a 5/8" iron rod set for Southeast corner of this tract and said 3.66 acre tract;

South 72°45'00" West a distance of 148.13 feet, with the South line of the 3.66 acre tract, to a 5/8" iron rod set for the Southwest corner of this tract in the East edge of Cedar Grove Road;

THENCE with the following calls along the West boundary of the 3.66 acre tract and generally with the East edge of Cedar Grove Road as follows:

1. North 26°00'00" West a distance of 266.67 feet to a point for corner;
2. North 28°00'00" West a distance of 293.89 feet to a 5/8" iron rod set for an angle corner of the 3.66 acre tract and of this tract;

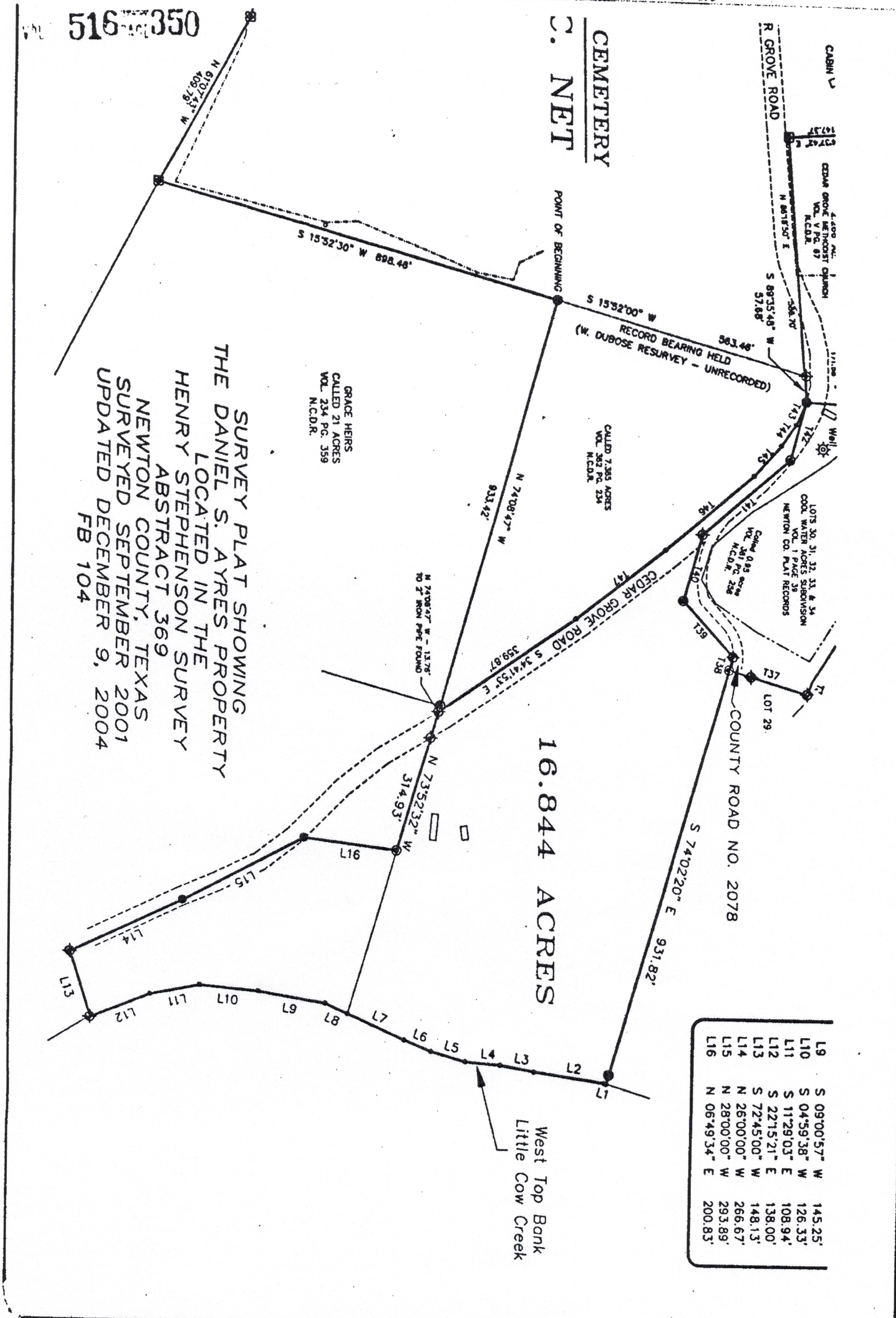
THENCE North 06°49'34" East a distance of 200.83 feet, with a West line of the 3.66 acre tract, to the **PLACE OF BEGINNING** 16.844 acres of land.

NOTE: The bearings recited herein are based and/or rotated to the a South line of a 61.622 acre tract as surveyed September of 2001.

D. Bric Barrow

D. Bric Barrow
Registered Professional Land Surveyor No. 5365
Surveyed January 17, 2005

STATE OF TEXAS
REGISTERED
D. BRIC BARROW
5365
PROFESSIONAL
LAND SURVEYOR



Filed for record 29TH of MARCH, A.D., 20 05 at 12:44 P.M.

THE STATE OF TEXAS
COUNTY OF NEWTON } 131395

I hereby certify that this instrument was filed for record as listed above and duly recorded in the OFFICIAL PUBLIC Records of Newton County, Texas, in the Volume and Page as stamped hereon by me.

Mary Cobb

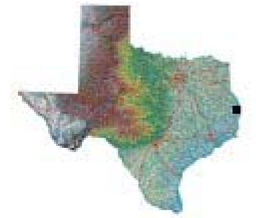
Mary Cobb, County Clerk, Newton County, Texas

By: ____________________, Deputy

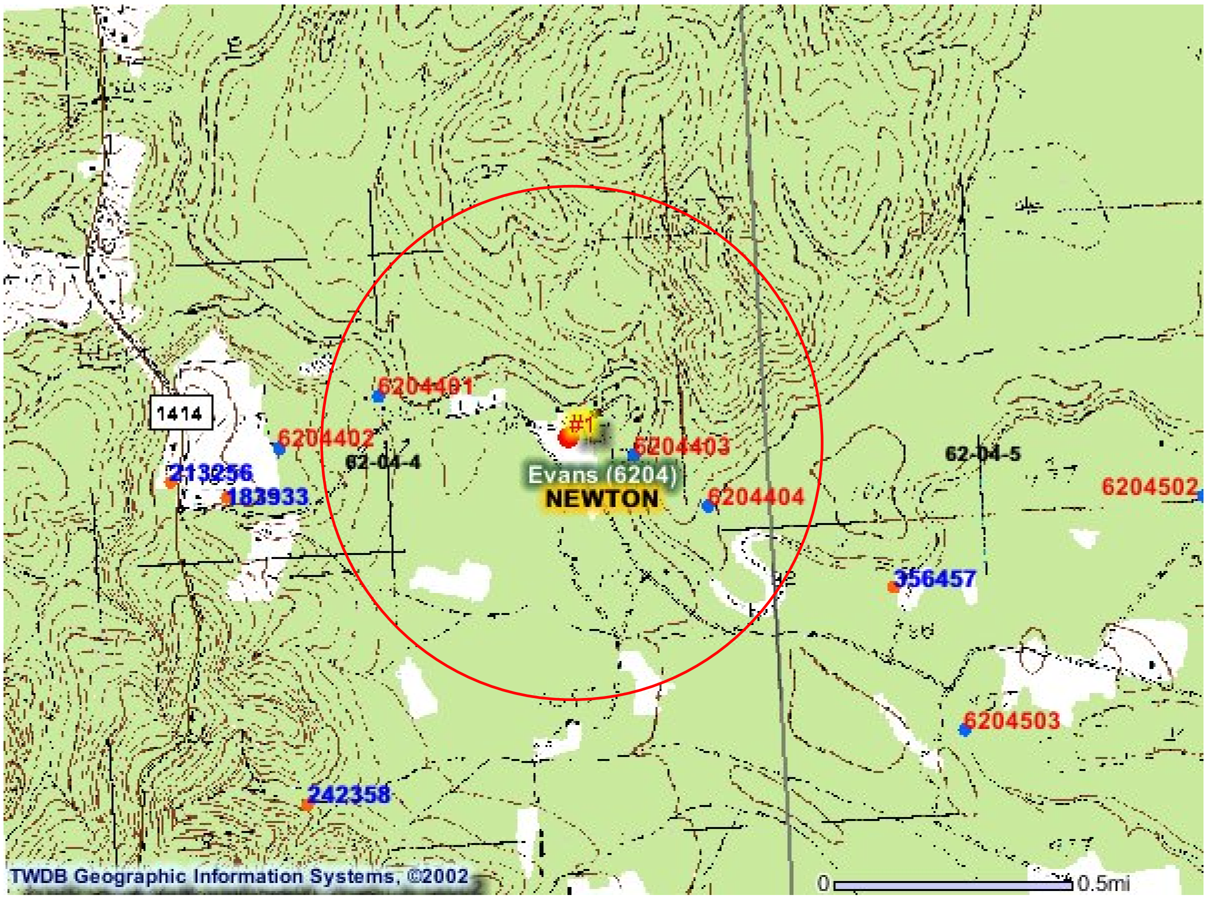
Exhibit 2

Texas Water Development Board

Water Information Integration & Dissemination System



Water Well Locations



Legend

- TWDB Groundwater Data
- Submitted Driller's Reports
- State Hwy
- FM & RM Roads
- Other State Roads
- Interstate Hwy
- US Hwy
- 7.5' USGS Grid
- 2.5' State Grid
- Counties

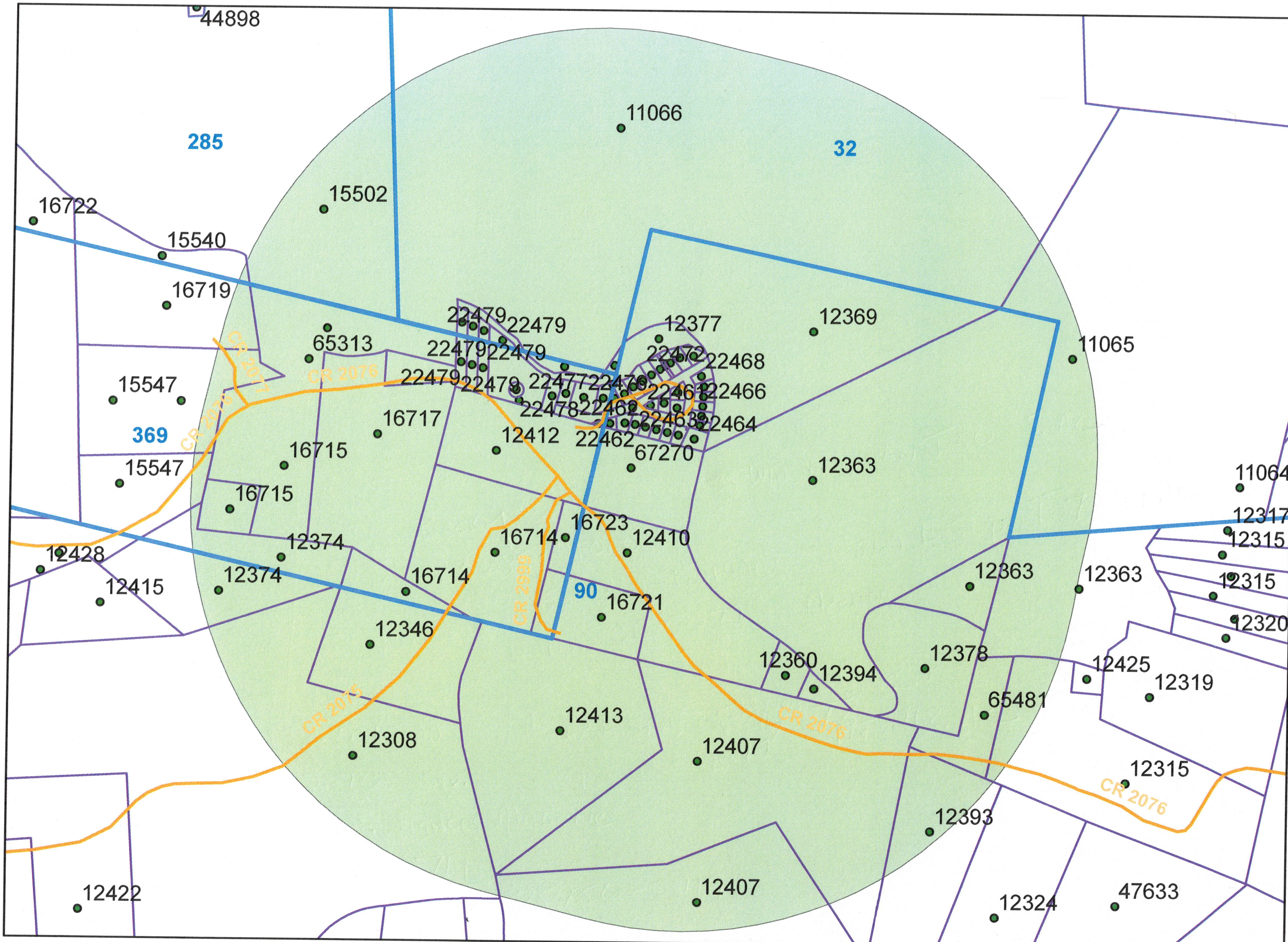
#1 is Proposed location of Ayres's Wells

1/2 mile radius

1	261344410	6204401	Don Ford	H	106	120	M	N	122JSPR	305644	933549	351
2	261344412	6204403	Tom McMahon	H	110	100	N	N	122JSPR	305636	933517	351
3	261344413	6204404	Wendel Force	H	105	200	N	N	122JSPR	305630	933508	351

1	W	0	0	0.4
2	W	0	0	0.35
3	W	0	0	0.16

Exhibit 3

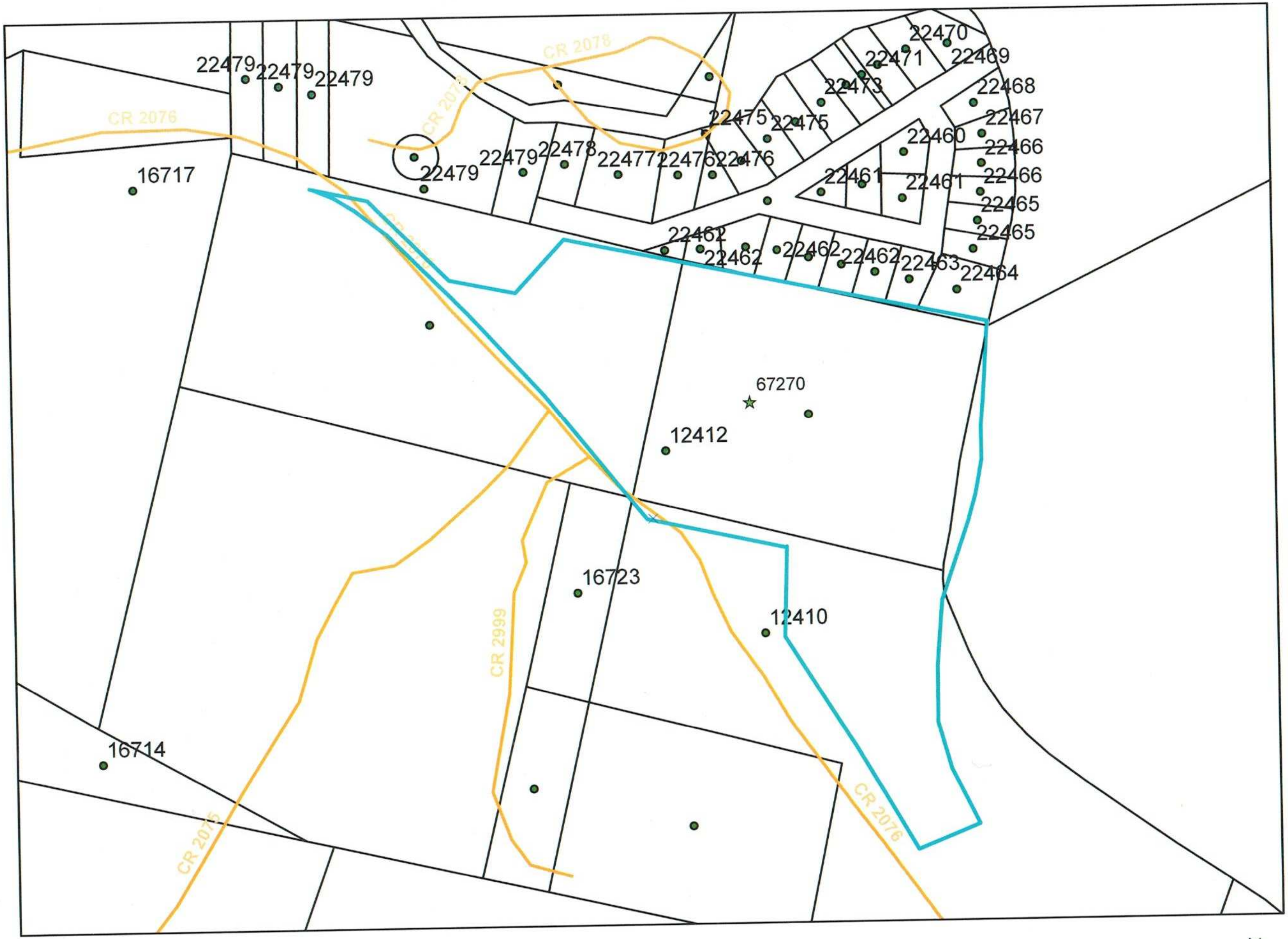


NEWTON CENTRAL APPRAISAL DISRICT

FOR REFERENCE ONLY. NOT A LEGAL DOCUMENT.
THERE IS NO WARRANTY OF ANY KIND
EXPRESSED OR IMPLIED, AND SPECIFICALLY THERE IS
NO WARRANT OF MERCHANTABILITY OR OF FITNESS.

0 0.1 0.2 0.4 Miles

N



NEWTON CENTRAL APPRAISAL DISRICT

FOR REFERENCE ONLY. NOT A LEGAL DOCUMENT.
THERE IS NO WARRANTY OF ANY KIND
EXPRESSED OR IMPLIED, AND SPECIFICALLY THERE IS
NO WARRANT OF MERCHANTABILITY OR OF FITNESS.

Parcel_ID	Geo_ID	Owner_Name	Owner_ID	Property_Address
22460	002400-000200	PLATT MICHAEL KELLY	8264	CR 2078 BURKEVILLE, TX 75932
22461	002400-000400	AYERS DANIEL STEPHEN	4821	CR 2078 BURKEVILLE, TX 75932
22462	002400-000600	TODD GADELLE MCMAHON	14328	CR 2078 BURKEVILLE, TX 75932
22463	002400-000700	AYERS DANIEL STEPHEN	4821	CR 2078 BURKEVILLE, TX 75932
22464	002400-000800	AYERS DANIEL STEPHEN	4821	CR 2078 BURKEVILLE, TX 75932
22465	002400-001000	STEVENS LUCILLE % JOEY CLIFT	8268	CR 2078 BURKEVILLE, TX 75932
22466	002400-001200	CLIFT JOEY % REDDICK STEVENS	2084	143 CR 2078 NEWTON, TX 75966
22467	002400-001400	PLATT L C JR	1142	CR 2078 BURKEVILLE, TX 75932
22468	002400-001600	PLATT L C JR	1142	CR 2078 BURKEVILLE, TX 75932
22469	002400-001800	AYRES DAVID & ANGELINE	4685	CR 2078 BURKEVILLE, TX 75932
22470	002400-002000	PRATER CHARLES L	8272	CR 2078 BURKEVILLE, TX 75932
22471	002400-002200	TODD CONLEY L JR	8277	CR 2078 BURKEVILLE, TX 75932
22472	002400-002400	TODD CONLEY L JR	8277	CR 2078 BURKEVILLE, TX 75932
22473	002400-002600	MILLER R H JR	8275	CR 2078 BURKEVILLE, TX 75932
22474	002400-002800	MILLER R H JR	8276	CR 2078 BURKEVILLE, TX 75932
22475	002400-003000	TODD CONLEY L JR	8277	CR 2078 BURKEVILLE, TX 75932
22476	002400-003200	TODD GADELLE MCMAHON	14328	CR 2078 BURKEVILLE, TX 75932
22477	002400-003400	TODD CONLEY L JR	8277	119 CR 2078 NEWTON, TX 75966
22478	002400-003600	TODD CONLEY L JR	8277	CR 2078 BURKEVILLE, TX 75932
22479	002400-003800	AYERS DANIEL STEPHEN	4821	CR 2078 BURKEVILLE, TX 75932
65313	000369-000810	CORMIER MARK & DIANA	36332	
12308	000090-000400	ADAMS BARBARA B	1844	CR 2075 BURKEVILLE, TX 75932
12360	000090-008800	HITT PAUL EDWARD JR	31660	1375 CR 2076 NEWTON, TX 75966
12363	000090-009400	MALONE NORMA FRANCES	30693	CR 2076 BURKEVILLE, TX 75932
12369	000090-010400	LTP OPPORTUNITY FUND I % LOUISIANA TIMBER PARTNERS	31490	CR 2078 BURKEVILLE, TX 75932
12374	000090-011600	WINGATE JOHNNIE % JOSEPH WINGATE	1896	CR 2076 BURKEVILLE, TX 75932
12377	000090-012800	AYERS DANIEL STEPHEN	4821	CR 2078 BURKEVILLE, TX 75932
12378	000090-013000	HICKS MARGIE	1900	CR 2076 BURKEVILLE, TX 75932
12394	000090-016600	SPENCE KEITH	27572	1043 CR 2076 NEWTON, TX 75966
12410	000090-019600	SIMMONS S E ESTATE % MELBA SIMMONS HAYNES	1926	CR 2076 BURKEVILLE, TX 75932
12412	000090-020000	HOWELL BLAKE A C/O KEITH SPENCE	1928	1043 CR 2076 NEWTON, TX 75966
12413	000090-020200	POINDEXTER MAXINE & DERWIN	31636	CR 2076 BURKEVILLE, TX 75932
16714	000369-000600	GRACE OCIE B % DELORES G BENNETT	1876	
16715	000369-000800	AYERS DANIEL STEPHEN	4821	811 CR 2076 BURKEVILLE, TX 75932

Parcel_ID	Mail_Address	Mail_City	Mail_State	Mail_Zip
22460	5390 ROSE LANE	BEAUMONT	TX	77708-2912
22461	811 COUNTY ROAD 2076	NEWTON	TX	75966
22462	PO BOX 865	NEWTON	TX	75966
22463	811 COUNTY ROAD 2076	NEWTON	TX	75966
22464	811 COUNTY ROAD 2076	NEWTON	TX	75966
22465	143 COUNTY ROAD 2078	NEWTON	TX	75966
22466	107 BRECKENRIDGE LOOP	LAFAYETTE	LA	70506
22467	P O BOX 926	NEWTON	TX	75966-0926
22468	P O BOX 926	NEWTON	TX	75966-0926
22469	8355 EVANGELINE LANE	BEAUMONT	TX	77706
22470	5210 LINDA LANE	BEAUMONT	TX	77708
22471	PO BOX 865	NEWTON	TX	75966
22472	PO BOX 865	NEWTON	TX	75966
22473	P O BOX 267	LUFKIN	TX	75901-0267
22474	P O BOX 267	LUFKIN	TX	75901-0267
22475	PO BOX 865	NEWTON	TX	75966
22476	PO BOX 865	NEWTON	TX	75966
22477	PO BOX 865	NEWTON	TX	75966
22478	PO BOX 865	NEWTON	TX	75966
22479	811 COUNTY ROAD 2076	NEWTON	TX	75966
65313	4820 ARTHUR LANE	BEAUMONT	TX	77706
12308	6012 RIVERVIEW WAY	HOUSTON	TX	77057
12360	1375 COUNTY ROAD 2076	NEWTON	TX	75966
12363	P O BOX 719	KIRBYVILLE	TX	75956-0719
12369	333 TEXAS STEET SUITE 2300	SHREVEPORT	LA	71101
12374	9130 GROSS ST	BEAUMONT	TX	77707-1240
12377	811 COUNTY ROAD 2076	NEWTON	TX	75966
12378	7764 US HIGHWAY 190 E	NEWTON	TX	75966
12394	1043 COUNTY ROAD 2076	NEWTON	TX	75966
12410	15926 DANTE DR	HOUSTON	TX	77053-3510
12412	1043 COUNTY ROAD 2076	NEWTON	TX	75966
12413	923 CHAY DRIVE	LAKE CHARLES	LA	70611
16714	3000 MURWORTH DR #1213	HOUSTON	TX	77025-4412
16715	811 COUNTY ROAD 2076	NEWTON	TX	75966

Parcel_ID	Legal_Description
22460	COOLWATER ACRES, LOT 1
22461	COOLWATER ACRES, LOT 2 3 4
22462	COOLWATER ACRES, LOT 5 6 7 8 9 10
22463	COOLWATER ACRES, LOT 11
22464	COOLWATER ACRES, LOT 12
22465	COOLWATER ACRES, LOT 13 14
22466	COOLWATER ACRES, LOT 15 16, MH SERIAL # 2823931, TITLE # 00656852, LABEL # TEX0019172
22467	COOLWATER ACRES, LOT 17
22468	COOLWATER ACRES, LOT 18
22469	COOLWATER ACRES, LOT 19
22470	COOLWATER ACRES, LOT 20
22471	COOLWATER ACRES, LOT 21, AB 90, 369
22472	COOLWATER ACRES, LOT 22
22473	COOLWATER ACRES, LOT 23
22474	COOLWATER ACRES, LOT 24
22475	COOLWATER ACRES, LOT 25 26, AB 90
22476	COOLWATER ACRES, LOT 27
22477	COOLWATER ACRES, LOT 28
22478	COOLWATER ACRES, LOT 29
22479	COOLWATER ACRES, LOT 30-34
65313	A369 HENRY STEPHENSON, TRACT 4-1, ACRES 3.319
12308	A90 JOHN DRODDY, TRACT 2, ACRES 123.860
12360	A90 J DRODDY, TR 44, 8.868 AC MH SER # 21952798619A, TITLE # 00780742, LAB # TEN0287942, PID 1937
12363	A90 JOHN DRODDY, TRACT 47, ACRES 89.880
12369	A90 John Droddy, TRACT 52, ACRES 24
12374	A90 JOHN DRODDY, TRACT 58, ACRES 15.000
12377	A90 JOHN DRODDY, TRACT 64, ACRES 5.460, CONLEY TODD
12378	A90 JOHN DRODDY, TRACT 65, ACRES 11.000, MCMAHON TOMB
12394	A90 JOHN DRODDY, TRACT 83, ACRES 1.000, SUPP 5213
12410	A90 JOHN DRODDY, TRACT 98, ACRES 12.340
12412	A90 JOHN DRODDY, TRACT 100, ACRES 1.000, JAMES M SMITH
12413	A90 JOHN DRODDY, TRACT 101, ACRES 40.160
16714	A369 HENRY STEPHENSON, TRACT 3, ACRES 21.000
16715	A369 HENRY STEPHENSON, TRACT 4, ACRES 18.183

Parcel_ID	pct_ownership	exemptions	state_cd	jurisdictions	abs_subdv_cd	mapsco	map_id	agent_c
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22476	100		C1	CAD, F43, G01, R01, S22	S2400			
22477	100	HS, OV65	A1	CAD, F43, G01, R01, S22	S2400			
22478	100		C1	CAD, F43, G01, R01, S22	S2400			
22479	100		C1	CAD, F43, G01, R01, S22	S2400			
65313	100		D7	CAD, F43, G01, R01, S22	A369			
12308	100		D2	CAD, F43, G01, R01, S22	A90		30	
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12378	100		D2	CAD, F43, G01, R01, S22	A90		30	
12394	100		A1	CAD, F43, G01, R01, S22	A90			
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12413	100		D2	CAD, F43, G01, R01, S22	A90		30	
16714	100		D2	CAD, F43, G01, R01, S22	A369		30	
16715	100		D2	CAD, F43, G01, R01, S22	A369			

Parcel_ID	Neighborhood_c	Neighborhood_na	Hyperlink
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22462			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22462
22463			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22463
22464			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22464
22465			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22465
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22470			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22470
22471	N22CG	CEDAR GROVE	https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22471
22472			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22472
22473			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22473
22474			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22474
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22477	N22CG	CEDAR GROVE	https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22477
22478			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22478
22479			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=22479
65313	N22CG	CEDAR GROVE	https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=65313
12308			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12308
12360			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12360
12363			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12363
12369			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12369
12374	N22BV	BURKEVILLE	https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12374
12377			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12377
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12394	N22CG	CEDAR GROVE	https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12394
12410			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12410
12412	N22CG	CEDAR GROVE	https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12412
12413			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=12413
16714			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=16714
16715	N22CG	CEDAR GROVE	https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=16715

16719	000369-001400	HUDSON REBECCA SUZANNE	27046	168 CR 2077 NEWTON, TX 75966
16723	000369-002000	SIMMONS S E ESTATE % MELBA SIMMONS HAYNES	1926	
11066	000032-001400	LTP OPPORTUNITY FUND I % LOUISIANA TIMBER PARTNERS	31490	CR 2083 BURKEVILLE, TX 75932
15502	000285-004200	SMITH REID H & BETTY	14475	
15540	000285-010000	HUDSON REBECCA SUZANNE	27046	
15547	000285-011500	MAIER KATHY L ETAL	36213	9319 FM 1414 NEWTON, TX 75966
67270	000369-001100	AYERS DANIEL STEPHEN	4821	

16719	168 COUNTY ROAD 2077	NEWTON	TX	75966
16723	15926 DANTE DR	HOUSTON	TX	77053-3510
11066	333 TEXAS STEET SUITE 2300	SHREVEPORT	LA	71101
15502	P O BOX 310	BURKEVILLE	TX	75932-0310
15540	168 COUNTY ROAD 2077	NEWTON	TX	75966
15547	2825 S TEXAS STATE HIGHWAY 87	NEWTON	TX	75966
67270	811 COUNTY ROAD 2076	NEWTON	TX	75966

16719	A369 HENRY STEPHENSON, TRACT 7, ACRES 19
16723	A369 HENRY STEPHENSON, TRACT 10, ACRES 1.000
11066	A32 THOMAS BYERLY, TRACT 7, ACRES 590.810 (SIA #125)
15502	A285 WILLIAM McMAHAN, TRACT 21, ACRES 246.500
15540	A285 WM MCMAHAN, TRACT 50, ACRES 3.000, THIS THREE ACRES & VALUE IS IN 369-1400 FOR HS PURPOSES
15547	A285 WM MCMAHAN, TRACT 57-1, ACRES 17.000
67270	ABS A369 HENRY STEPHENSON,TRACT 5-1,16.39 ACRES

16719	100	HS, OV65	E1	CAD, F43, G01, R01, S22	A369				
16723	100		C1	CAD, F43, G01, R01, S22	A369				
11066	100		D2	CAD, F43, G01, R01, S22	A32			30	
15502	100		D2	CAD, F43, G01, R01, S22	A285			30	
15540	100		D7	CAD, F43, G01, R01, S22	A285				
15547	100		D2	CAD, F43, G01, R01, S22	A285			30	
67270	100		D2	CAD, F43, G01, R01, S22	A369				

16719	N22CG	CEDAR GROVE	https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=16719
16723			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=16723
11066			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=11066
15502			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=15502
15540			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=15540
15547			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=15547
67270			https://propaccess.trueautomation.com/clientdb/Property.aspx?prop_id=67270

Parcel ID	Owner Name	Mail Address	Geo ID	Property Address
12411	Simmons W G Estate	c/o Pamela Robertson 6460 Iron Horse Blvd #9E North Richland Hills, TX 75932	000090-019800	CR 2076 Burkeville, TX 75932
65481	Byrd Marylon	1717 N. 6th St. Orange, TX. 77630	000090-001610	CR 2075 Burkeville, TX 75932
12407	Mark Simmons Estate	c/o Clara L Walker 5215 Madden Ln. Houston, TX. 77048	000090-019000	CR 2076 Burkeville, TX 75932
12393	Whatley James Eugene	2299 Alvin St. Orange, TX. 77632	000090-016400	CR 2076 Burkeville, TX 75932
12315	Marble Johnny & Tammy	1368 Robinson Rd. Silsbee, TX. 77656	000090-001600	Pvt 6036 Burkeville, TX 75932
15547	Maier Kathy L	2825 S. TX State HWY 87 Newton, TX. 75932	000285-011500	9319 FM 144 Newton, TX. 75966
16719	udson Rebecca Suzanne		000369-001400	

		168 CR 2077 Newton, TX. 75932		168 CR 2077 Newton, TX. 75966
11065	Malone Norma Frances	P.O. Box 719 Kirbyville, TX. 75956-0719	000032-001200	CR 2076 Burkeville, TX 75932

Exhibit 4

HYDROGEOLOGY REPORT IN SUPPORT OF THE DANIEL AYRES APPLICATION FOR 646 ACRE FEET PER YEAR OF GROUNDWATER IN NEWTON COUNTY, TEXAS

Submitted To:

Daniel Ayres
811 County Road 2076
Newton, Texas, 75966

Submitted By:

WESTWATER RESOURCES
Dr. William M. Turner
Texas PG # 12098
610 Gold Avenue, SW, Suite 111
Albuquerque, NM 87102
Tel: 505-843-7643

September 18, 2015
Revised October 22, 2015

Geoscientist Seal

The contents of this report (including figures and tables)
document the work of the following licensed Texas Geoscientist.

William M. Turner, Ph.D., P.G. No. 12098
The report is work of Dr. William M. Turner and employees under his direct supervision. The seal appearing on this document was authorized

October 21, 2015 by:

William M. Turner

EXECUTIVE SUMMARY

Large quantities of fresh water are present in the aquifers of Jasper and Newton Counties, Depth from the land surface to the base of fresh water—varies from possibly zero in a small area of northwestern Jasper County to more than 3,000 feet in the central parts of both counties. The water contains less than 1,000 ppm (parts per million) of dissolved solids. About 45 percent of the sediments to these depths are sands that will yield fresh water to wells. Precipitation in the recharge area is estimated at about 54 inches per year by Wesselman 1967[1] . But according to the National Weather Service the 1981 to 2010 average precipitation is 56.51 inches per year Wesselman also estimates that an average of at least 500 mgd (million gallons per day) or 560,494 acre feet per year of precipitation infiltrates the outcrops of the all aquifers within Jasper and Newton Counties That water flows to streams, or is transmitted downdip into the artesian parts of the aquifers. It is estimated that at least this much water is available for development in Jasper and Newton Counties on a sustained yield basis by the proper construction and placement of well fields. "GAM Run 11-019 on January 23, 2012 estimates recharge is 92,886 acre feet per year across the gulf coast aquifer. [2]

Daniel Ayres plans to develop a water source in Newton County, Texas on land which he owns. The well will be drilled and constructed in the Jasper Aquifer to a depth of about 400ft. The location of the well is shown in Figure 1 in Appendix 1. Figure 1 also shows calculated 50-year drawdown in the area.

This report examined 50 year water availability and the ability of the proposed new well to produce.

The new well will be in the Jasper Aquifer which is the lowest and oldest of the Gulf Coast Aquifers. The Jasper Aquifer daylights in Jasper and Newton Counties and it is in this area that recharge takes place to the aquifer. The thickness of the Jasper in the vicinity of the proposed well is about 650 ft. If the aquifer is a confined aquifer, the storage coefficient may be as low as 0.000383.

[1] Wesselman, J.B., 1967, Ground-Water Resources of Jasper and Newton Counties, Texas, Texas Water Development Board, Report 59.
[2] http://www.twdb.texas.gov/groundwater/docs/GAMruns/GR11-019.pdf

If it is an unconfined aquifer or changes to an unconfined aquifer if the pumping water level in the aquifer drops below the bottom of a confining bed the storativity will rise to about 0.15.

The proposed well is two and one-half miles west of the Sabine River that with time will provide water to the proposed well. Further, in such situations we have considered the effect of an image well on the drawdown within the Jasper Aquifer in its recharge zone. Further, we have considered the effect of stream depletion and its effect on actual groundwater depletion at the end of 50 years of continuous pumping of 400 gallons per minute. The stream depletion effects at the end of 50 years will diminish storage depletion in the aquifer. At the end of 50 years of continuous pumping the well will be drawing only about 116 gpm of water from storage within the Jasper Aquifer and drawdown will be about 7.18 feet. Using analytical methods and assuming a storativity of 0.15 and pumping the proposed well at a constant rate of 400 gallons per minute for 50 years, the maximum drawdown to the potentiometric surface at the new well will be between about 24.82 feet and 8.52 feet as the actual groundwater depletion rate diminishes as recharge from the Sabine River increases with time. The amount of groundwater withdrawn is small compared to the volume of water in storage and the Desired Future Condition for GAM-14. The amount of drawdown is close to projected future drawdown target levels on the high side and significantly lower than the target levels after stream depletion and image well effects develop.

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LIST OF APPENDICES

1.0 INTRODUCTION

Mr. Daniel Ayres, a resident of Newton, Texas, and the owner of a manufacturing plant in Jasper, Texas, plans to file an Application for a permit to appropriate up to 646 acre feet per annum of groundwater to be drawn from a proposed new well or wells on his property, in Newton County, Texas. Figure 1 in Appendix 1 shows the location of the proposed well and existing wells within one-half mile. He intends to produce 400 gallons per minute from the proposed well and to sell bulk spring water from the new well on his property to one or more water bottling companies in Texas, Louisiana, and Arkansas. The water will be sold also for emergency water supplies and ordinary consumer supplies. During Hurricane Rita, WaterBank imported bottled water into Texas, from New Mexico, Oklahoma, Alabama, and Arkansas. There was little water actually bottled then in Texas and there is a need for additional water bottled in Texas not only for emergency water supplies but for the consumer market. Further, emergency supplies of bulk water may serve upwards of 740 mutual domestic and rural water utilities in the event of pump outages and other emergencies; but, not all at the same time. Most of these are in East Texas. We would plan to cooperate and coordinate with the Texas Rural Water Users Association.

Mr. Ayres owns about 75 acres of land in a very sparsely populated part of Newton County, Texas. His contact information is:

Daniel Ayres
811 County Road 2076
Newton, Texas, 75966

Telephone: 409-383-0521 x 204
Email: d.ayres@msvmobile.com

His ownership is demonstrated by warranty deeds and real estate property tax bills in Appendix 2 hereto. Pursuant to *Edwards Aquifer Authority v. Day*, 274 S.W.3d 742, Mr. Ayres owns the water in the Jasper Formation beneath his property in fee simple. That is, he owns both the naked legal title to the water in place and the equitable title to the water.

The project contemplates the drilling and construction of the proposed well situated at N 30° 56.639” Latitude, W. -93° 35.42” Longitude as determined by a GARMIN GPS72 hand–held GPS unit. The well will be spudded, drilled and constructed into the Jasper Formation within its recharge zone. The aquifer from which it is proposed to pump water is identified on Figure 1. The geologic formations and hydrologic units are composed of varying proportions of gravel, sand, silt, marl and clay

The most comprehensive hydrogeological reports on the hydrogeology of southeast Texas are Wesselman (1967)[3], Baker (1986)[4], and Kasmarek (2013)[5]. These reports will be referred to so frequently in the present report and they are included in Appendices 3,4 and 5 respectively to this report. The Wesselman report appears to be the most comprehensive pre-computer age report with the most raw data.

Precipitation in the vicinity of the Ayres property is about 60 inches per year. Wesselman gives the precipitation in Newton County as 54 inches per year as the sum of the mean monthly precipitation for the period of 1910 through 1960. The southeast Texas Coastal Plain is the area of greatest precipitation in the State, and for this reason, the potentiometric surface of the aquifers are near the land surface or above.

Wesselman (1967)[6] estimates under present conditions (1966), that an average of at least 500 mgd (million gallons per day) of fresh water infiltrates the outcrops of the aquifers within Jasper and Newton Counties.. This recharge is discharged as spring flow to streams, or is transmitted downdip into the artesian parts of the aquifers. It is estimated that at least this much water is available for development in Jasper and Newton Counties on a sustained yield basis by the proper construction and placement of well fields. The Ayres project calls for only 576,000 gallons per day or 210,384,000 gallons per years. This is 0.0012 percent of total daily recharge

[3] Wesselman, J.B., 1967, Groundw3ater resources of Jasper and Newton Counties, Texas: Texas Water Development Board Report 59, 177 p.
[4] Baker, T.E., Hydrology of The Jasper Aquifer In The Southeast Texas Coastal Plain, Texas Water Development Board, Pub. 295, p. 2.
[5] Kasmarek, M.C., 2013, Hydrogeology and Simulation of Groundwater Flow and Land Surface Subsidence in Northern Part of the Gulf Coast Aquifer System, Texas, 1891-2009, U.S. Geol. Survey, Scientific Investigation Report 2012-5154, version. 1.1, November 2013.
Kasmarek, M.C., Hydrogeology and Simulation ofr Groundwater Flow and Land Surface Subsidence in Northern Part of the Gulf Coast Aquifer System, Texas, 1891-2009, U.S. Geol. Survey, Scientific Investigation Report 2012-5154, version. 1.1, December, 2013
[6] Wesselman (op. cit, p. 1)

determined by Wesselman. The Jasper Aquifer recharge is estimated by Wesselman at 868 times the proposed pumping rate. Some believe the recharge rate is much less than that estimated by Wesselman.

The present report deals more with local conditions and the impact of producing water from the Jasper aquifer.

2.0 HAGM COMPUTER MODEL

The Houston Area Ground Water Model (HAGM) uses the MODFLOW-2000 Code. Kasmarek's recent publications[7] deal with the HAGM model and the results of model studies. It is the groundwater-flow model described in the Kasmarek report (*supra*). It comprises four layers, one for each of the major hydrogeologic units of the aquifer system except the Catahoula confining system because it is the assumed, no-flow base, of the multi-layer groundwater-flow system. The HAGM is composed of 137 rows and 245 columns of 1-square-mile grid cells with lateral no-flow boundaries at the extent of each hydrogeologic unit to the northwest, at groundwater divides associated with large rivers to the southwest and northeast, and at the downdip limit of freshwater to the southeast. In the vicinity of the Ayres proposed new well (Model cell, R67, C234) the Sabine River is about two and one-half miles to the east and Northeast and acts as a recharge boundary as it flows directly across the exposed outcrop of the Jasper aquifer. However, the HAGM in the area is a general head boundary and does not recharge the modeled area when effects of pumping reach it. In fact, those cells that contain the Sabine River were removed from the model.[8] This is unrealistic because the river must be treated as a head dependant boundary or a constant flux boundary. The Jasper Aquifer is Layer 4 of the HAGM. Further the model makes no allowance for anisotropy. The model was calibrated within the specified criteria by using trial-and-error adjustment of selected model-input data in a series of transient simulations until the model output (potentiometric surfaces, land-surface subsidence, and selected water-budget components) acceptably reproduced field measured (or

[7] Kasmarek, M.C., 2013, Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in he3 Northern Part of the Gulf Coastal Aquifer System, Texas, 1891-2009. U.S. Geological Survey, Scientific Investigation Report 2012-5154, v. 1.1, December 2013,

[8] Personal communication between William Turner and Cindy Ridgeway September 18, 2015, Chief, Groundwater Availability Monitoring Section, Texas Water Development Board.

estimated) aquifer responses including water level and subsidence. The HAGM-simulated subsidence generally compared well to 26 Predictions Relating Effective Stress to Subsidence (PRESS) models in Harris, Galveston, and Fort Bend Counties. Simulated HAGM results indicate that as much as 10 feet (ft) of subsidence has occurred in southeastern Harris County where groundwater withdrawal is significant and has been going on for more than 100 years. Measured subsidence and model results indicate that a larger geographic area encompassing this area of maximum subsidence and much of central to southeastern Harris County has subsided at least 6 ft. For the western part of the study area, the HAGM simulated as much as 3 ft of subsidence in Wharton, Jackson, and Matagorda Counties. For the eastern part of the study area, the HAGM simulated as much as 3 ft of subsidence at the boundary of Hardin and Jasper Counties. In the southeastern part of the study area in Orange County, the HAGM simulated as much as 3 ft of subsidence. Measured subsidence for these areas in the western and eastern parts of the HAGM which would include Newton County has not been reported and would suggest that there is no major dewatering of the aquifers within this area. In fact artesian, flow of wells was observed on the Ayres property several miles north of Newton, Texas. Figure 4 is a photograph of one of these wells that discharges into a pond on the Ayres Property.

In preparation of the Application for a proposed well, the HAGM was used to project long-term drawdown caused by the new pumping stress at the end of 45 years (2015-2060) of continuously pumping the new well at 400 gpm. Future average decline of the potentiometric head was calculated to be about 0.6 feet at the end of the 45 year pumping period.

The Houston Area Groundwater Model (HAGM) was run and then modified as follows.

1) Ran the base model as is to establish base conditions.
2) The proposed well is located in Row 67, Column 234 of the model.
3) At the end of the base model Stress Period 1(1891) Layer 4 the head is 191.1 ft-asl[9][10]
4) At the end of the base model Stress Period 78(2009) Layer 4 the head is 186.4 ft-asl/

[9] asl = above sea level

[10] If t = 0 in 1891 and original potentiometric head was 191.1 ft asl and if present shut in head is 111 ft asl, 80 feet of drawdown has already taken place.

5) Extended the model by adding 6 more Stress Periods, (2015, 2020, 2030, 2040, 2050, and 2060).

6) To do this:
   a. In the “*.wel” file, duplicated Stress Period 78 for each of the new time steps

   b. In the “*.ghb” file, duplicated Stress Period 78 for each of the new time steps

   c. In the “*.dis” file, added the following to the code for the 6 new time steps:
      365.250000 6 1.000000 TR
      365.250000 5 1.000000 TR
      365.250000 10 1.000000 TR
      365.250000 10 1.000000 TR
      365.250000 10 1.000000 TR
      365.250000 10 1.000000 TR

   d. In the”* .oc” file, added output controls save the data for the 6 new Stress Period, and changed the output from binary to ascii.

7) At the end of the extended model Stress Period 84(2060) Layer 4 the head is 186.3 ft-asl

8) To add a pumping rate of 400 gpm in Layer 4 Row 67 Column 234. Used the extended model as above and added a pumping rate of 400gpm or 77,000 cfd to Layer 4 Row 67 Column 234 for each of the 6 new Stress Periods.

9) The end of the extended model with withdrawals for Ayres Well is Stress Period 84(2060) Layer 4 the head is 185.7 ft-asl

Table 1: Approximate head in future resulting in pumping 400 gpm in Row 67, Column 234 beginning 2016

Stress Period	Year	Head	Drawdown at well location since 1891 (ft)	Drawdown at well location Since 2009 (ft)
1	1891	191.1		
78	2009	186.4	4.7	
84	2060	186.3	4.8	0.1[11]
84	2060	185.7	5.4	0.6[12]

[11] Year 2060 of the extended model with no additional pumping
[12] Year 2060 of the extended model with additional pumping in Row 67 Column 234

The modified MODFLOW files both with and without the additional pumping are found on 2 DVD in Appendix 6.

According to the HAGM the proposed pumping rate generates only a very small increase in drawdown decline over the next 45 years. .

3.0 WATER USAGE

Mr. Ayres has retained the services of Westwater Resources dba WaterBank® conduct marketing studies and to identify prospective users of bulk water users for use by one or more bottled water companies as well as fire fighting, and swimming pools in the area and emergency uses. The Application seeks a pumping rate of 400 gallons per minute but the well will be operated cyclically so that the aquifer has the opportunity to recover from pumping periods.

4.0 HYDROGEOLOGY

A detailed description of the geology of the Texas Gulf coast area is contained within Kasmarek (*supra*, pp 4-13). The geologic map of the Jasper – Newton area is reproduced from Kasmarek (*supra*, p. 11). The geologic map is contained as Figure 2 in Appendix 1.

The well will be drilled in the Jasper Aquifer which underlies all other aquifers of the Coastal Aquifer System. It is confined above by the Burkeville Formation and below by the Catahoula Sandstone. The Burkeville Formation restricts flow between the Evangeline Formation above the Burkeville Formation and the underlying Jasper Formation. As the cone of depressin of the proposed well reaches the contact with the overlying Burkeville, The storage coefficient within the Jasper will change from a specific yield value of about 0.15 to a confined specific storage value on the order of 0.00001. The Jasper Formation is of Miocene age. The proposed well site is situated near the top of the Jasper aquifer within Newton County.

The Burkeville confining system was named by Wesselman (1967) for outcrops near the town of Burkeville in Newton County, Texas. It separates the Jasper and Evangeline aquifers and retards but does not completely block the interchange of water between the two aquifers.

The Burkeville confining system is a rock-stratigraphic unit predominantly consisting of silt and clay. Upper and lower boundaries of the unit do not strictly correspond to geologic time boundaries, although in some places the unit appears to possess approximately isochronous boundaries.

The configuration of the top and bottom of the Burkeville Formation is irregular. Boundaries are not restricted to a single stratigraphic unit, but are included within the Fleming Formation and Oakville Sandstone in some places. This is shown in section D-D' (Figure 3). The thickness of the Burkeville confining system ranges from about 100 to 1,000 feet. In general, the greatest variations occur in the relatively deep subsurface within the zone of moderately saline water to brine. A typical thickness of the Burkeville is about 300 feet. The Burkeville confining system is predominantly composed of fine-grained materials, such as silt and clay, as shown in numerous geophysical logs. In most places, these fine-grained sediments are interbedded with sand lenses, which contain fresh to slightly saline water. Some of these sand lenses yield water to small-capacity wells. Because of its relatively large percentage of silt and clay when compared to the underlying Jasper aquifer and overlying Evangeline aquifer, the Burkeville is a semi-confining unit. The effectiveness of the unit as a confining layer is further borne out by the fact that hydro-static pressures in the Jasper and Evangeline are notably different immediately above and below the Burkeville where detailed testing by well drillers has been done.[13]

The Burkeville has a greater percentages of silt and clay than the sub- and super-adjacent aquifers. However, the Evangeline and the Jasper Formation are in hydraulic continuity across the Burkeville aquitard and the overlying Evangeline aquifer will become a source of recharge to the Jasper aquifer. The strength of recharge depends on the vertical component of hydraulic conductivity across the Burkeville and the hydraulic gradient. Therefore, if the potentiometric head in the Jasper is less than the potentiometric head in the Evangeline, water will move across the Burkeville into the Jasper Formation.

4.1 Jasper Aquifer

The Lagarto Clay and Oakville Sandstone have not been differentiated on the surface in southeast Texas. In the report area, the Lagarto and Oakville comprise a thick sequence of calcareous clay and silt interbedded with sand. In the upper part of the sequence there is a clay unit, 200 to 300 feet thick that contains minor amounts of sand. This clay unit is equivalent in

[13] Baker 1986, Supra, p. 10.

part to the Castor Creek Member (Fisk, 1940) of the Fleming Formation (Kennedy, 1892) in Vernon Parish (Rogers and Calandro, 1965). (See Table 3.) The Jasper aquifer, as named in this report, includes all the sediments between the upper clay bed of the Catahoula Sandstone and the clay unit mentioned above. The aquifer consists of about 50 percent sand and is equivalent to the Carnahan Bayou, Dough Hills, and Williamson Creek Members (Fisk, 1940) of the Fleming Formation (Kennedy, 1892) in Vernon Parish (Rogers and Calandro, 1965) . (See Table 3.) The aquifer is named for the town of Jasper. It is the principal aquifer in the report area in terms of storage, availability, quality of water, and potential for development. The approximate altitudes of the base of the Jasper aquifer and the base of fresh water, and the approximate downdip limits of fresh water and slightly saline water are shown on Figure 2. The Jasper aquifer contains fresh water to depths of more than 3,000 feet below sea level in the area east of Kirbyville. In most of the northern half of the report area, all the sands in the aquifer contain fresh water; but, in the southern half, sands containing fresh water overlie and inter tongue with those containing slightly saline water (Figures 28, 29, 30, and 31). The approximate thickness of sands containing fresh water in the Jasper aquifer is shown in Figure 3. In the northern parts of Jasper and Newton Counties, the sand thickness progressively increases southward to more than 900 feet in the area between Kirbyville and Bon Wier; southward from this area, the sand thickness progressively decreases to zero.

The Jasper aquifer furnishes the water supplies for the towns of Jasper, Newton, Kirbyville, and Burkeville and for the community of Harrisburg. It supplies the water needs for all rural users in about a third of the report area. Burkeville Aquiclude

The full thickness of the Jasper Aquifer was estimated by Wesselman. At its outcrop , it appears at the land surface where it is recharged by precipitation and infiltration of the Sabine River water about 5 miles to the east. The Sabine River is the state boundary between Texas and Louisiana in this area. The Jasper Aquifer continues to trend to the east and passes into Louisiana.

The Jasper Aquifer dips south toward the Mississippi River Embayment at about 0.54 degrees or about 50 feet per lateral mile. It is composed of weakly cemented sandstone interbedded with shaley units.

5.0 HYDRAULIC PROPERTIES

The form of an aquifer can inform us as to the hydraulic properties of the aquifer. In the present case Wesselman (s*upra*., Figure 6) shows that the sand thickness of the fresh-water-bearing Jasper Sand has a uniformly increasing thickness from north to south. This suggests a rather uniform depositional process during Jasper Age. If so, then we may surmise that the hydraulic properties are somewhat uniform. The base of the Evangeline aquifer overlying the Jasper and Burkeville aquitard is a subcrop that also shows a uniformly increasing thickness to the top of the Burkeville that also connotes a relatively gentle depositional environment that suggests uniform hydraulic properties to the aquifer. Kasmarek (*supra*., Figure 2) is a northwest to southeast cross section through the geologic formations. It shows them thickening gradually from northwest to southeast and dipping about 0.5 degrees toward the Gulf Coast. This is typical of geologic strata throughout the Mississippi embayment.

5.1 Hydraulic Conductivity (Permeability)

Hydraulic conductivity or permeability is a measure of the ability of a fluid to move through the interconnected void spaces in the aquifer. Hydraulic conductivity is a function of both the soil and rock medium and the fluid. To separate the effects of the soil rock medium from those of the fluid, the hydraulic conductivity (k) is defined as:

$$K = k\rho g/\mu$$

Where ”μ” is the dynamic viscosity of the fluid and “ρ” is the fluid density. Hydraulic conductivity is a function of the medium only. Wesselman (*supra,* p. 1) estimates the average permeability of the Jasper aquifer as 545 gpd/ft^2 (72.86 ft/d). Wesselman (*supra*, Table 4) provides seven values of hydraulic conductivity determined from aquifer performance tests. Their geometric mean is 519 gpd/ft^2 . We will use a hydraulic conductivity value of 545 gpd/ft^2 (72.86 ft/d) as given by Wesselman. The saturated thickness of the Jasper aquifer is 650 feet thick in the vicinity of the proposed well according to Wesselman (*supra*, Figure 6). This is not inconsistent with the high value reported by Kasmarek.

5.2 Transmissivity

Transmissivity is the product of hydraulic conductivity and aquifer thickness. Because the proposed new well will only encounter and draw groundwater from the Jasper aquifer our inquiry into the hydraulic properties relates only to the Jasper aquifer. Kasmarek (*supra*, p. 10) lists the transmissivity of the Jasper aquifer as 1,070 to 14,000 ft^2/d. or 8,000 gpd/ft to 104,720 gpd/ft and so it seems that Kasmarek obtained the values from Wesselman. Baker (1986) estimated the transmissivity of the Jasper aquifer from simulations for an area coincident with most of the Jasper aquifer in the HAGM area at from about 2,500 to 35,000 gpd/ft . The transmissivity of the aquifer increases from west to the east and beyond the Sabine River. Baker (*supra*, p. 39)

Wesselman is the only study that actually published transmissivity and hydraulic conductivity values derived from aquifer performance tests in Jasper County. The transmissivity from 11 aquifer performance tests range in value from 8,000 to 105,000 gpd/ft of aquifer width in the direction of groundwater flow. Their geometric mean is 38, 939 gpd/ft which we shall use in this report.

The higher the transmissivity the farther the cone of depression around a well will spread. The transmissivity is on the order of about 5,205.7 ft^2/d (38,929 gpd/ft).

5.3 Storativity

Kasmarek cites Wesselman (1967) as estimating storativities of 0.000383 to 0.00119. Strom and others reported storativities for the Jasper aquifer as large as 0.2. The very low storativity values are typical for confined aquifers and certainly apply to the Jasper aquifer to the south of the proposed well site where it is confined by the Burkeville aquitard. The location of the proposed well is within the unconfined part of the aquifer within its surface recharge area where storativities from 0.05 to 0.2 are typical. We think that storativities in Miocene unconfined aquifers are probably closer to 0.15 and we will use this value for analog determinations of drawdown in this report. Conservative results for drawdown calculations are obtained by using a storativity of 0.15. If the storativity is as low as .000383 the drawdown near the well will be much less and the extent of the cone of depression will be much wider. Therefore it seems that the HAGM is operating under much smaller storativity values.

At present there are four wells drilled on Mr. Ayres property. Their location is shown on Figure 1. Their locations were determined by a hand-held GPS device. All are artesian wells and flow at the surface . Table 2 lists their geographic locations. Well 1 appears to have a shut in pressure of 48 pounds per square inch (psi) equivalent to a column of water about 111 ft above the land surface. Figure 5 shows the shut-in pressure on one of the wells. The wells have been flowing for years. Westwater has recommended that these wells be fitted with control valves and the free-flow be terminated to conserve water and reservoir pressure.

Table 2. Location of wells on property owned by Daniel Ayres.

	Latitude	Longitude
Camp Site:	N. 30° 56.541’	W. 93° 35.333’
Church Site:	N. 30° 56.718’	W. 93° 35.530’
Home Site:	N. 30° 56.634'	W. 93° 35.639’
Pond Site:	N. 30° 56.744’	W. 93° 35.528’

6.0 DRAWDOWN

The above sections of the report discusses the hydrogeology of the area and drawdowns at 45 years based on the HAGM. The HAGM and other regional groundwater models do not deal well with small scale local matters and for that reason analytical methods are generally relied on. Using the analytical methods, this section of the report deals with 25 and 50-year calculations.

It is assumed that no well will be located closer than 500 feet to any existing residence in the area . Locations of the nearest wells of other ownership were obtained from the WIID provided by the Texas Water Development Board. The nearest well is the McMahon well that is about 790 feet from the proposed well. The long-term decline will be the algebraic sum of head drawdown and/or build up caused by the pumping well and an image wells where the image well (a recharge or injection well for a recharge boundary) is located on the far side of the recharge boundary at twice the distance of the real well from the recharge boundary. Because the recharge boundary is nearby, we have simply computed the drawdown as equivalent to the sum of the negative drawdown caused by the proposed well plus the positive recharge of caused by an image wells located at twice the distance from the proposed well to the recharge boundary times the drawdown calculated using the Theis (1937) relationship. This makes the drawdown very conservative leading to greater drawdown and we can ignore the image well for the moment.

Theis assumed that water is instantaneously released from an aquifer when the pump is turned on. He also assumed that the well has an infinitesimally small diameter and there is no well-bore storage. Further, he assumed that the aquifer is homogeneous and isotropic and is aerially extensive. Finally, he assumed that the well is 100 % efficient. In our case, the well will have a considerable amount of water stored in the well bore but there will be no well bore dewatering effects because the potentiometric surface, which is a pressure effect, is well above land surface. to zero gage pressure or the land surface. On the Ayres property the potentiometric surface is about 111 ft above land surface. We may consider that water is not instantly released from the aquifer to the interior of the well bore when the pump is turned on but in the long term the release of water from the aquifer will approach a semi-steady state. Further, the aquifer is well bedded and it is dipping to the south. The aquifer is therefore, highly anisotropic. This means that the effects of pumping will spread along the strike of the aquifer and drawdown will be retarded along the dip of the aquifer. The HAGM does not account for anisotropy. We can say that the well is for all intents and purposes of large areal extent. However, the aquifer is bounded by barrier boundaries and a recharge boundary. These boundaries will not make much difference for a short term pump test.

Steady state conditions for a well-aquifer system means that point in time after the pump is turned on when the rate of decline in the water level inside the casing is the same as the rate of decline of the water level or potentiometric surface in the aquifer. For this reason, it is the recovery data after the pump is turned off that is the most reliable for analysis. We do not have any aquifer-performance -test data from wells in the Jasper Aquifer. However, the transmissivity and storage coefficient values that were used in the Houston Area Groundwater Aquifer Model (HAGM) were determined by the U.S. Geological Survey and the Texas Water Board and are deemed for initial purposes trustworthy for further analytical computations.. We believe the conditions for the use of the Theis relationship can be accounted for in analytical methods and the digital computer models. Using the Theis relationship drawdown at the pumping well and at nearby and even more distant locations can be determined and graphical representations of the drawdown can be prepared for future times.

The Theis relationship is

$$s = \frac{114.6\, QW_u}{T}$$

where

s = drawdown, feet
W_u = Theis Well Function of argument "u", dimensionless
Q = discharge rate, gpm
T = undamaged aquifer transmissivity, gpd/ft

$$u = \frac{1.87\, r^2 S}{Tt}$$

where

u = argument of Well Function, dimensionless
r = distance from center of well to point of observation, feet
S = storage coefficient, dimensionless
t = time since discharge began, days
T = aquifer transmissivity, gpd/ft

The Well Function can be evaluated by a series expansion or it can be approximated from published tables. We have determined "W_u" from a series expansion. To determine drawdown caused by the pumping well, where it is assumed all water comes from storage in the aquifer rather than recharge, the common practice is to take "r" as 1.

Using the transmissivity of 38,939 gpd/ft and storativity of 0.15 given above the drawdown within the Jasper aquifer after 25 and 50 years of pumping continuously at 400 gpm are given in Tables 3 and 4 respectively for different distances. If the storage coefficient is the lowest reported by Wesselman of 0.000383, the calculated drawdown at the end of 25 and 50 years of continuous pumping are given in Tables 5 and 6.

Table 3: Drawdown calculated using the Theis relationship after 25 years.

Distance (ft)	u (dim)	Wu (dim)	Drawdown (-ft)	Image Well (+ft)	Total Drawdown
1	7.85E-10	20.39	24.00	0.60	23.40
100	7.85E-06	11.18	13.16	0.60	12.56
300	7.06E05	8.91	10.57	0.6	9.97
500	9.81E-05	7.96	9.37	0.60	8.77
790	4.90E-04	7.05	8.29	0.60	7.71
1000	7.85E-04	6.57	7.74	0.60	7.14
5000	1.96E-02	3.37	3.97	0.60	3.37
10000	7.85E-02	2.04	2.41	0.60	1.81

t = 25 yrs, S = 0.15, Q = 400 gpm, T = 38,939 gpd/ft

Table 4: Drawdown calculated using the Theis relationship after 50 years.

Distance (ft)	u (dim)	Wu (dim)	Drawdown (ft)	Image Well (-ft)	Total Drawdown
1	3.92E-10	21.08	24.82	1.15	27.37
100	3.92E-06	11.87	13.98	1.15	12.83
300	3.53E-5	9.67	11.39	1.15	10.24
500	9.81E-05	8.65	10.19	1.15	9.04
790	2.45E-04	7.74	9.11	1.15	7.96
1000	3.92E-04	7.27	8.55	1.15	7.40
5000	9.81E-03	4.06	4.78	1.15	3.63
10000	3.92E-2	2.70	3.18	1.15	2.03

t = 50 yrs, S = 0.15, Q = 400 gpm, T = 38,939 gpd/ft

Table 5: Drawdown calculated using the Theis relationship after 25 years.

Distance (ft)	u (dim)	Wu (dim)	Drawdown (-ft)	Image Well (+ft)	Total Drawdown
1	2.00E-12	26.36	31.04	7.06	23.98
100	2.00E-08	17.15	20.19	7.06	13.13
300	1.80E-07	14.95	17.60	7.06	10.54
500	5.01-07	13.93	16.40	7.06	9.34
790	1.25E-06	13.03	15.32	7.06	8.26
1000	2.00E-06	12.54	14.77	7.06	7.71
5000	5.01E-05	9.32	10.98	7.06	3.92
10000	2.00E-04	7.94	9.35	7.06	2.29

t = 25 yrs = 9,131.25 days, S = 0.000383, Q = 400 gpm, T = 38,939 gpd/ft

Table 6: Drawdown calculated using the Theis relationship after 50 years.

Distance (ft)	u (dim)	Wu (dim)	Drawdown (ft)	Image Well (-ft)	Total Drawdown
1	1.00E-12	27.05	31.85	7.88	23.97
100	1.00E-08	17.84	21.00	7.88	13.12
300	9.02E-08	15.64	18.42	7.88	10.54
500	2.50E-07	14.62	17.21	7.88	9.33
790	6.25E-07	13.71	16.14	7.88	8.26
1000	1.00E-06	13.24	15.58	7.88	7.70
5000	2.50E-5	10.02	11.79	7.88	3.91
10000	1.00E-04	8.63	10.16	7.88	2.28

t = 50 yrs = 18,262.5 days, S = 0.000383, Q = 400 gpm, T = 38,939 gpd/ft

When compared with the saturated thickness of 650 ft and the potentiometric surface today at an elevation above land surface of 111 ft, the drawdown is insignificant. Figures 1-1, 1-2, 1-3 and 1-4 shows the drawdown with distance from the proposed well at 25 and 50 years after initiation of pumping. Figures 10 and 11 show the least squares best fit curves for drawdown versus distance for 25 and 50 years after commencement of pumping. Calculations of drawdown from the least squares best fit straight lines may not fit the exact data given in the two tables above but the error is vanishingly small. Figures 6 through 9 were achieved by creating a table of drawdown at various distances from the proposed well and creating a data table that also included the geographic coordinates of each of the three nearby wells and the drawdown in Tables 3 and 4 above. The data was kriged[14] and contoured using the Surfer software package.[15] Surfer exported a shape file that was imported into ArcView (ver. 9.3.1)[16] and overlain on the base map of the area. The equation that describes the drawdown at the end of 25 years at any distance from the pumping well is generally,

$$s = -5.41 * \log(r) + 23.38$$

where

s = drawdown, ft
r = distance from pumping well, ft

At the end of 50 years of continuous pumping the drawdown is calculated as:

$$s = -5.38 * \log(r) + 24.82$$

The maximum lowering to the potentiometric surface at the end of 25 years will be 23.40 ft at the pumping well. If the potentiometric surface is 111 feet above the land surface now[17], at the end of 25 years the potentiometric surface will still be 87.60 ft above the land surface. Consequently, the well will still flow under artesian conditions and no impairment to a domestic well will occur. At the end of 50 years, the maximum drawdown will be 27.37 ft and the potentiometric head will be 87.63 ft above ground level or an additional 0.03 feet or a *de minimis*

[14] Kriging is the generic name for a family of techniques which are used for mapping of surfaces from limited sample data and the estimation of values at *unsampled* locations. First developed almost 60 years ago by Georges Matheron and named in honor of Daniel Krige, these methods are now widely used in the minerals industry and groundwater investigations and have disseminated out into many other fields where 'spatial' data is studied. http://www.kriging.com/whatiskriging.html
[15] Surfer, Golden Software, ver. 11.6.1159 , Golden Colorado.
[16] ArcView, ver. 9.3.1, ESRI, : 380 New York Street, Redlands, CA 92373-8100
[17] Above land surface (als)

amount. That is, the potentiometric surface will be above ground and no drawdown within the wells themselves will occur.

After 100 years the total drawdown at the McMahon well ate a distance of 790 ft will be about 8.11 feet. The water column after the end of years will be about 102.89 ft above the land surface depending on the elevation of the land surface.

The annual rate of ground-water decline in the vicinity of the nearest well can be calculated over a 100-year period. The results of these calculations are shown in Figure6. Drawdown will be greatest in the first year of pumping. At the end of the first year, the total effect on the nearest well at 500 ft will be about 5.6 ft. Using

7.0 IMAGE WELL CONSIDERATIONS

The proposed well will be situated about 2.5 miles west of the Sabine River. In this event, as the cone of depression extends radially away from the pumping well, it will eventually encounter the Sabine River as a recharge zone and the rate of decrease in the water table will diminish. This is treated mathematically by assuming that there is an injection well at a location that is located equal to this distance east of the Sabine River.[18] The production well pumping rate "Q" is treated as "-Q" and the injection well is treated at "+Q". If the proposed well drawdown is treated mathematically as a negative, the injection well rise in the potentiometric surface is treated mathematically as positive. The effect of the recharging image well on the pumping well will be determined by using a distance of 26,400 feet. In this report we consider only one injection image well. However, in the limit, the first image well will require another discharging image well west of the Sabine River a distance of 52,800 feet from the first image well. This goes on and on with injection or recharging image wells and pumping wells. Of course the effect of each pumping and recharging well on groundwater levels in the actual proposed producing well becomes smaller and smaller.

[18] Davis, S.N., and DeWeist, R.J.M., 1966. Hydrogeology, John Wiley & Sons, Inc., pp. 461, p. 223-224.

Because the drawdown caused by pumping the proposed well does involve aquifer recharge from the Sabine River it cannot be ignored and use of the image well theory becomes quite tedious and time consuming. Using image well theory and one image well drawdown at and in the vicinity of the proposed well are given in Tables 3 through 6 above.

8.0 GLOVER-BALMER CONSIDERATION

Determination of the actual amount of water that is induced to recharge the groundwater system at any time "t" after initiation of pumping as a practical matter Glover – Balmer (1954)[19] gave an exclusive closed form solution to Theis' equation and the step response function derived by glover and Balmer for dimensionless stream depletion or, in other words, the induced recharge caused by pumping is

$$q = Q^{*}\mathrm{erfc}\{x/\sqrt{4Tt/S}\}$$

where

q = stream depletion rate, ft^3/d
Q-q = groundwater depletion rate, ft^3/d
Q = pumping rate, 7.7E04 ft^3/d
x = distance from Sabine River = 2.5 miles = 13,200 ft
T = Aquifer transmissivity = 38,939 gpd/ft =5,205.7 ft^2/d
S = 0.15, dimensionless
t = period of pumping of well, days
erfc = the complementary error function = 1 –erf, dimensionless

The amount of water actually drawn from the groundwater system can be calculated. This groundwater extraction rate them becomes the actual stress on the groundwater system at time "t".

When the induced infiltration occurs the proposed well will see the Sabine River as a recharge boundary and the actual drawdown will be reduced at the pumping well to only 8.93 ft of drawdown. This is well within the Desired Future Conditions of drawdown of 21 feet set out

[19] Glover, R.E., and Balmer, G.G., 1954, River depletion resulting from pumping a well near a river: Transactions, American Geophysical Union, v. 35, no. 3, p. 468-470.

in the GAM Task 13-037 goals. It is immutable that the Sabine River will represent a recharge boundary to the Jasper Aquifer.

Pumping wells that are situated in stream-connected aquifers will induce infiltration from the stream. The amount of induced infiltration depends on the:

1. Composition of the aquifer,
2. Structural disposition of the aquifer,
3. Anisotropy of the aquifer,
4. The distance from the stream,
5. Orientation of the well to the stream as it may meander,
6. Period of pumping, and,
7. Hydraulic diffusivity of the aquifer.
8. Linearity of the stream boundary,
9. Completely penetrating stream.

The Theis Equation has been universally applied since 1935 when C.V. Theis published it. Because the Glover and Balmer equation is derived from the Theis Equation it too is universally applicable as the literature demonstrates. For example, the State of Oklahoma utilizes the Glover – Balmer Method and calls it the Oklahoma Stream Depletion Model (OSDM)[20] The method is used also in Kansas, Colorado, Nebraska, New Mexico, Texas, Connecticut, India.[21] The "Interaction of Aquifer and River Canal Network near a Well Field" has just been published by Ghosh, et al. for the Ganga River and canal network at Haidwar, India.[22] A Google search yields many papers on the method.

However, it should only be considered to give a good estimate subject to verification by other methods. In our case, the proposed well will be drilled in the unconfined, recharge area of the Jasper aquifer about two and one/half miles west of the Sabine River. It can be shown

[20] http://biosystems.okstate.edu/Home/gareyf/OSDF.htm
[21] Ghosh, N.C., Mishra, G.C., Sandhu, SS., Grischek, T., and Singh, V.V., 2015. Interaction of Aquifer and River-Canal Network near Well Field. Groundwater, v. 53, no. 5, pp. 794-805.
[22] Ghosh, N.C., Mishra, G.C., Sandhu, C.S.S., Grisce3ck, and Singh, V.V., 2015, Interaction of Aquifer and River-Canal Network near Well Field, Groundwater, v. 53, n. 5, pp. 794-805.

through the simple application of the Glover – Balmer Equation[23] that the amount of depletion can be estimated.

The method requires that the well be completely penetrating and that the aquifer be homogeneous and isotropic and areally extensive. It requires that the stream be linearly disposed from the well. In the present case, the aquifer dips to the south and is demonstrably very anisotropic. Further the river meanders past the well site and it is not a strictly linear recharge boundary. Because of these divergences from the assumptions inherent in the development of the method the stream depletion is considered an estimate. In the present case, at the end of 50 years, 115.68 gpm of the total 400 gpm will be supplied by groundwater storage. Drawdown within the aquifer will be about 7.18 ft at the proposed well.

In most cases rivers have an organic substrate that can retard infiltration. In the Albuquerque Basin, the Glover-Balmer method is widely used to determine the depletion effects of wells on the Rio Grande. However, recent detailed local computer model studies by the U.S. Geological Survey have shown that because of river bed effects, the actual stream depletion is only about 30 percent of the amount calculated.

Hantush (1965)[24] and Hunt (1999)[25]. considered the streambed lined with semipervious material for the first time and developed an analytical model for a partially penetrating stream to determine rate of stream depletion as a function of the SDF (stream depletion factor) and time following on the work of Glover and Balmer (1954). The solution given by Hantush modified by Hunt for partially penetrating stream with streambed conductance is

$$Q_s = Q_p\left[erfc\left(\sqrt{\frac{Sx^2}{4Tt}}\right) - \exp\left(\frac{t\lambda^2}{4ST} + \frac{\lambda x}{2T}\right) * erfc\left(\sqrt{\frac{t\lambda^2}{4ST}} + \sqrt{\frac{Sx^2}{4Tt}}\right)\right]$$

[23] Glover, R.E., and Balmer, G.G., 1954, River depletion resulting from pumping a well near a river: Transactions, American Geophysical Union, v. 35, no. 3, p. 468-470.
[24] Hantush, M., 1965, Wells near streams with semipervious beds. Journal of Geophysical Research , v. 70, n. 12: 2829-2838.
[25] Hunt, B., 1999. Unsteady stream depletion from groundwater pumping. Ground Water, v. 37, n. 1: pp 98-102.

where all terms are as defined above and

q_s = stream depletion, ft^3/d

Q_p = pumping rate, ft^3/d

λ = riverbed conductance parameter, ft/d

x = normal distance from surface water boundary, ft

This relationship is easily programmed into an Excel spreadsheet using serial expansions given in Tuma[26]. The term "exp" represents "e^x" where "e" is Euler's Number taken to be about 2.718281828 and λ is the streambed conductance parameter, (l/t)

In our calculation, at the end of 50 years of continuous pumping at the rate of 400 gpm, the depletion rate on the Sabine River will be about 284.3 gpm using a stream conductivity factor of 1.00 or about 459 acre feet per year. That is, theoretically under ideal conditions 71 percent of the water pumped from the proposed well will be induced recharge coming from the Sabine River rather than storage within the Jasper Aquifer. Aquifer depletion in 50 years will be about 115.7 gpm or only 186.8 acre feet per year. However, if the depletion is only 30 percent because of non-ideal conditions, stream depletion in 50 years will be about 37.2 af/yr .and aquifer depletion in the 50thyear of continuous pumping will be about 615.5 af/y. Therefore, aquifer storage withdrawals increase with time. The point of the calculation is to show that still, under a worst case scenario, with poor stream bed conductance some of the water will be from induced recharge..

[26] Tuma, J.J., 1970. Engineering Mathematics Handbook, McGraw Hill Book Company, p 154.

9.0 MAXIMUM DRAWDOWN

As a check on the drawdowns calculated in Tables 2 and 3, we can calculate for any desired pumping rate, pumping period, and distance from the pumped well, and the particular aquifer transmissivity the greatest possible drawdown.[27] It is determined by the Theis Equation (1935)[28] and further by the treatment of Robinson and Skibitzke (1962)[29]

The maximum drawdown occurs when:

$e^{-u} = W(u)$

where

e = base of the Naperian logarithm

and all other terms are as defined above. This occurs when $u = 0.43862$ and $W(u) = 0.647$

Consequently:

$s_{max} = (0.647)Q/4\pi T$

and

$T = 2.3r^2S/4t$

or,

$s_{max} = 0.8238{*}Qt/ r^2S$

Where all units are dimensionally consistent and

$Q = ft^3/d$
$T = ft^2/d$
$r = ft$
$t = days$

[28] Theis, C.V., 1935. The relation between the lowering of the petiometric surface and the rate and duration of discharge of a well using ground water storage. Transactions, American Geophysical Union, Washington, D.C., pp.518-424.
[29] Robinson, G.E. and Skibitzke, H.E., 1962. A formula for calculating transmissibility causing maximum possible drawdown due to pumping. U.S. Geological Survey Water Supply Paper 1536-F. U.S. Superintendant of Documents, Washington, D.C..

S = dimensionless

Table 7: Maximum drawdown calculated using the Robinson Skibitzke method and drawdown calculated using the Theis relationship after 50 years

Distance (ft)	T (ft^2/d)	T_{calc} (gpd/ft)	s_{max} (ft)	Theis Drawdown (ft)
1				24.82
100				13.98
300		3.18	9327	11.39
500		8.83	3357	10.18
790		22.05	1345	9.10
1000		35.33	839	8.55
4696	38,939	779.03	38.07	4.92
5000	38,939	883.16	33.58	4.77
10000	38,939	3,532.62	8.39	3.18
33200	38,939	38,938	0.76	0.76

t = 50 yrs, S = 0.15, Q = 400 gpm = 7.7E-04 ft^3/d

If the drawdown in the proposed well and at radial distances away from it is given by

$$s = 857.2\ Q\ W(u)/T$$

and the maximum drawdown is given by

$$s_{max} = 0.646Q/4\pi T$$

where

Q = pumping rate, ft^3/d

T = transmissivity, ft^2/d

r = radial distance, ft

the radial distance at which the drawdown caused by pumping is actually equal to the maximum drawdown and the distance at which for any pumping rate, transmissivity, storage coefficient, and point in time the limit to the cone of depression is reached. The radial distance will be based on

r = 4Tt/(2.3S)^2

where W(u) must be known. Hence

857.2 Q W(u)/T = 0.646Q/4πT

and

W(u) = 0.646/(4π857.20

W(u) = 5.997E-05

At this low value of W(u) determination of "u" cannot be reliably calculated using the Excel spreadsheet calculational method. It is determined from Driscoll (1986)[30]

u = ~7.59

The distance then from the proposed pumping well where drawdown is equivalent to the maximum drawdown is

r = (uTt/1.87S)^0.5

where "u" is the argument of the Theis Well Function and "T" is in gpd/ft, "t" is 50 years in days and S = 0.15.

r = ((7.59* 38939gpd/ft*18,262.5 d)/(1.87*0.15))^0.5

r = 138,716 ft = 26 miles

[30] Driscoll, Fletcher, 1986, Groundwater and Wells, Appendix 9.E., p. 921-922 derived from Kazman R.G., and Evans, M.M., U.S. Geological Survey and U.S. Geological Survey, (1942),Water Supply Paper 887.

Figure 15 is a plot of drawdown versus distance and maximum drawdown at 50 years for the unconfined aquifer case. The calculated drawdown is above the maximum drawdown curve indicating that the actual drawdown is well above the maximum drawdown but as time and distance from the proposed well increase, the drawdown curve becomes asymptotic to the maximum drawdown curve such that the calculated drawdown curve coincides with the maximum drawdown curve.

10.0 DRAWDOWN RECOVERY

Drawdown recovery is the time it takes for drawdown to recover to or near to its pre-pumping stage. The general rule of thumb is that the recovery period is at least two times the pumping period. Therefore, in an aquifer performance test of 48 hours, the period for which data is measured during the recovery period is 96 hours. If the proposed well operates 30 years and is shut in, the recovery period is about 60 years. One of our affiliated companies, Genesis Resources, operates dry gas wells in Okmulgee County, Oklahoma. It is single phase flow just as water is single phase flow. The gas wells began producing about 1983. They were shut in about 2010. The ratio of the time since production began to the time since production ended is therefore, the quotient of 27/10 = 2.7. In the limit this ratio will equal “1” at $t = \infty$ full recovery will have taken place. So, if the well is shut in for 54 years, or twice the production period, the quotient will be 81/54 or 1.5 which for all intents and purposes is near full recovery.

11.0 OWNERSHIP AND LOCATION OF EXISTING WELLS

Table 4 is the ownership and location of all existing wells within at least one mile of the proposed new well. The prior version of this report and some of its figures used locations given by the Texas WIID database. We believe that some of these locations are incorrect and are having more accurate locations determined by a surveyor.

12.0 MONITORING

Artesian wells in the vicinity of the proposed well will be shut in and equipped with a high accuracy pressure gage that will be read at least monthly.

13.0 RECHARGE

Recharge to the Jasper – Newton County area is important because the recharge must exceed the amount of water withdrawn from the proposed well and other wells in the area to avoid a groundwater mining condition. We begin with precipitation and calculate the recharge using several hydrometeorolgical methods.

Table 6 below gives the average monthly precipitation and average annual precipitation in East Texas from the National Weather Service

Table 6. Average monthly precipitation at nearby East Texas.[31]

Month	Precipitation (in)	Month	Precipitation (in)
Jan	4.74	July	3.77
February	4.72	August	4.11
March	4.57	September	4.58
April	3.77	October	4.77
May	4.78	November	5.36
June	5.76	December	5.58

Total average precipitation is 4.71 inches per month and 56.51 inches per year. We will use annual precipitation of 56.51 inches per year. Monthly precipitation information indicates that the amount of monthly precipitation is fairly uniform throughout the year. The lack of wide variation indicates a uniform supply of water, which will recharge the Jasper Aquifer in its outcrop area.

[31] http://www.ncdc.noaa.gov/cdo-web/quickdata

The net depletion of incident precipitation caused by interception of the forest canopy in the area varies from 7 to 15 percent.[32] Silvicultural practices have only short-term and minor effects on precipitation interception. If annual interception depletion is 15 percent, the precipitation reaching the forest floor will be about 48.03 inches.

Shuttleworth (1993) states[33] the net interception loss caused by vegetative cover is typically 10 to 30 percent of rainfall. Therefore, if 30 percent of total precipitation is intercepted the runoff (surface + groundwater) will be 39.56 in.

Forest floor conditions can allow infiltration rates from 1.58 to 2.36 inches per hour.[34] The condition of the forest floor is not an impediment to recharge

Further, the total precipitation less the interception storage will equal the runoff ratio or the ratio of runoff to precipitation. Figure 27 from Sellers[35] shows that for this area of East Texas with 56.51 inches of annual precipitation the runoff ratio $\Delta f/r$ is about 0.28 in^{-1}. Sellers states that

$$\Delta f / r = ar$$

$$or$$

$$\Delta f = ar^2$$

The coefficient "a" takes into account the annual variation in precipitation and spatial differences in the amount of energy available for evaporation.

Using this relationship if "a" is 0.005 and "r" is 56.51 inches, the runoff will be 15.97 inches over the area or 28 percent of precipitation which agrees with that determined from Figure 27 in Sellers.

Outflow (sheet flow + groundwater flow) = Precipitation – interception storage

Outflow = (56.51 – (56.51*0.28) = 40.69 in

[32] Lull, W.H., 1964, Ecological and Silvicultural Aspects, *in* Handbook of Applied Hydrology, Ven Te Chow, *ed.* McGraw-Hill Book Company (p.6-11)
[33] Shuttleworth, W.J., 1993, in Handbook of Hydrology, ed. by Maidment, D.R., 1993, McGraw Hill, Inc. , p. 4.44
[34] *Id.* at p 6-14
[35] Sellers, W.D., 1972 Physical Climatology, University of Chicago Press, Chicago, Illinois, p. 89

Depth of runoff = $0.005 \text{ in}^{-1} * 56.51^2 \text{ in}^2 = 15.97$ in

The amount of groundwater recharge is estimated using the Maxey-Eakin method[36].

The method is given by the equations:

ME = aP

where

a = Percentage of Recharge, dim

P = Precipitation, in

Some workers have denigrated the method as being unreliable. However, Avon and Durbin[37] have conducted a rigorous statistical analysis of the reliability of the method and find that the method is within ± 10%. of actual recharge at a 95% confidence level. The method was developed in Nevada which has a different Climatological and geomorphological setting than East Texas. It is based on precipitation in what are called Hardeman Zones.[38] The main geomorphologic difference is that there is very little ground cover in Nevada. In the Western U.S., rainfall commonly falls directly on the exposed soil surface. To adapt the method to East Texas, we believe that we should diminish the precipitation to that which actually reaches the land surface or 72 percent of actual rainfall or 40.69 inches. The difference is lost to evaporation of the remainder. Table 4 of the Avon report indicates that if total precipitation exceeds 20 inches the coefficient "a" is 20.3 percent.

Therefore, for the present case, if adjusted precipitation reaching the ground is 40.69 inches, the amount reaching the aquifer will be 8.26 inches over the 800 square miles of the Jasper Formation outcrop in Jasper and Newton Counties. This agrees well with the amount of

[36] Maxey, G.B., and Eakin, T.E., Ground Water in White River Valley, Department of Conservation and Natural Resources Water Resources Bulletin No. 8, 59 pp.

[37] Avon, L., and Durbin, T.J., 1994, Evaluation of the Maxey, Eakin Method for estimating recharge to ground-water basins in Nevada, American Water Resources Bulleting, AWWA, v. 30, n. 1, February 1994.

[38] Hardeman, G., 1936, Nevada Precipitation and Acreages of Land by Rainfall Zones. University of Nevada

[38] Avon Experimental Station, Reno., Nevada.

recharge calculated by Scanlon *et al*.[39] using the Chloride Bromide ratio method. The recharge rate from Scanlon is given as between 6 and 16 inches of recharge.. Using 8.26 inches of recharge produces about 352,243 acre feet per year or about 965 acre feet per day or 314,389,480 gallons per day in Jasper and Newton Counties. This assumes that the Jasper occupies 800 square miles of outcrop in Jasper and Newton Counties. If it is less, the Jasper recharge will be less.

We may conclude that the total amount of groundwater recharge within Newton and Jasper Counties is extremely large.

14.0 WATER AVAILABILITY

The State of Texas has goals set for Recoverable Storage for Aquifers in Groundwater Management in Area 14.which includes Newton and Jasper County, attached hereto in Appendix 8. Table 9 [40] in the GAM Task 13-037 Report recognizes total storage of 260 million acre feet in storage within Jasper and Newton Counties. The report also estimates 195,000,000 acre feet is 75 percent is recoverable. A total of 32,282 acre feet will be withdrawn in the next 50 years of continuous operation or 0.016 percent of the total amount in recoverable storage.

Under the same GAM Task 13-037 Future Conditions of aquifer drawdown were set. Within Jasper County a target drawdown of 21 feet was determined. In Newton County the forecast desireable drawdown is 18 feet. The HAGM forecasts an incremental drawdown of from 0.6 to 1.2 feet. Using the ordinary Theis calculations indicate a spot drawdown of about 27.37 feet at the end of 50 years at the well tapering off rapidly away from the well to only several feet at a distance of 10,000 feet which is well within the desireable future drawdown.

[39] Scanlon, P.A., Reedy, B.R., Strasberg, G., Huang, Y., and Senay, G., Oct. 31, 2011, Bureau of Economic Geology Jackson School of Geosciences, University of Texas at Austin. Figure 18, p.55.
[40] Wade, S., Thorkildsen, D., and Anaya, R., 2014, Texas Water Development Board, Groundwater Resources Division, June 9,2014.

15.0 CAVEAT

The report is based on a continuous production rate of 400 gpm day and night. In the real world no pumps operate 100 percent of the time. As storage tanks fill the pumps shut off. As maintenance is carried out, pumps shut off. If the company is a startup it is unlikely that production will occur to plant capacity immediately and for some time thereafter. We estimate that in the present case, the proposed well may only operate 80 percent of the time.

16.0 CONCLUSIONS

We conclude from this report that:

1. The proposed well pumping 400 gpm will, in the long term, produce up to 284.33 gpm from the Sabine River as induced recharge.
2. The long term depletion of storage in the Jasper Aquifer will be a maximum about 115.68 gpm.
3. The long term drawdown at the proposed well at the end of 50 years will be about 27.37 ft with image well considerations if the aquifer is unconfined and 23.97 ft if the aquifer is confined.
4. Error in GPS location of the wells is not known and we estimate the distance at 790 feet.
5. At this distance the long term drawdown at the end of 50 years in the McMahon Well will be about 7.96 ft with image well effects. The length of the water column is about 511 ft and drawdown will be about 4.6 percent of the total water column.
6. The proposed well is capable of producing at least 400 gpm for substantially more than 50-years with very little drawdown in comparison with the height of the water column from the bottom of the well to the top of the potentiometric surface at the proposed well.
7. There is ample groundwater in storage to meet the proposed demand.
8. The recharge to the Jasper Aquifer is estimated by Wesselman at 500 million gallons per day is 868 times the demand under the Ayres Application.
9. Under rules of the Groundwater Management Plan and Declared Future Conditions set out in Exhibits A and B of the October 12, 2011 Minutes of the Texas Water Board the proposed project is feasible..

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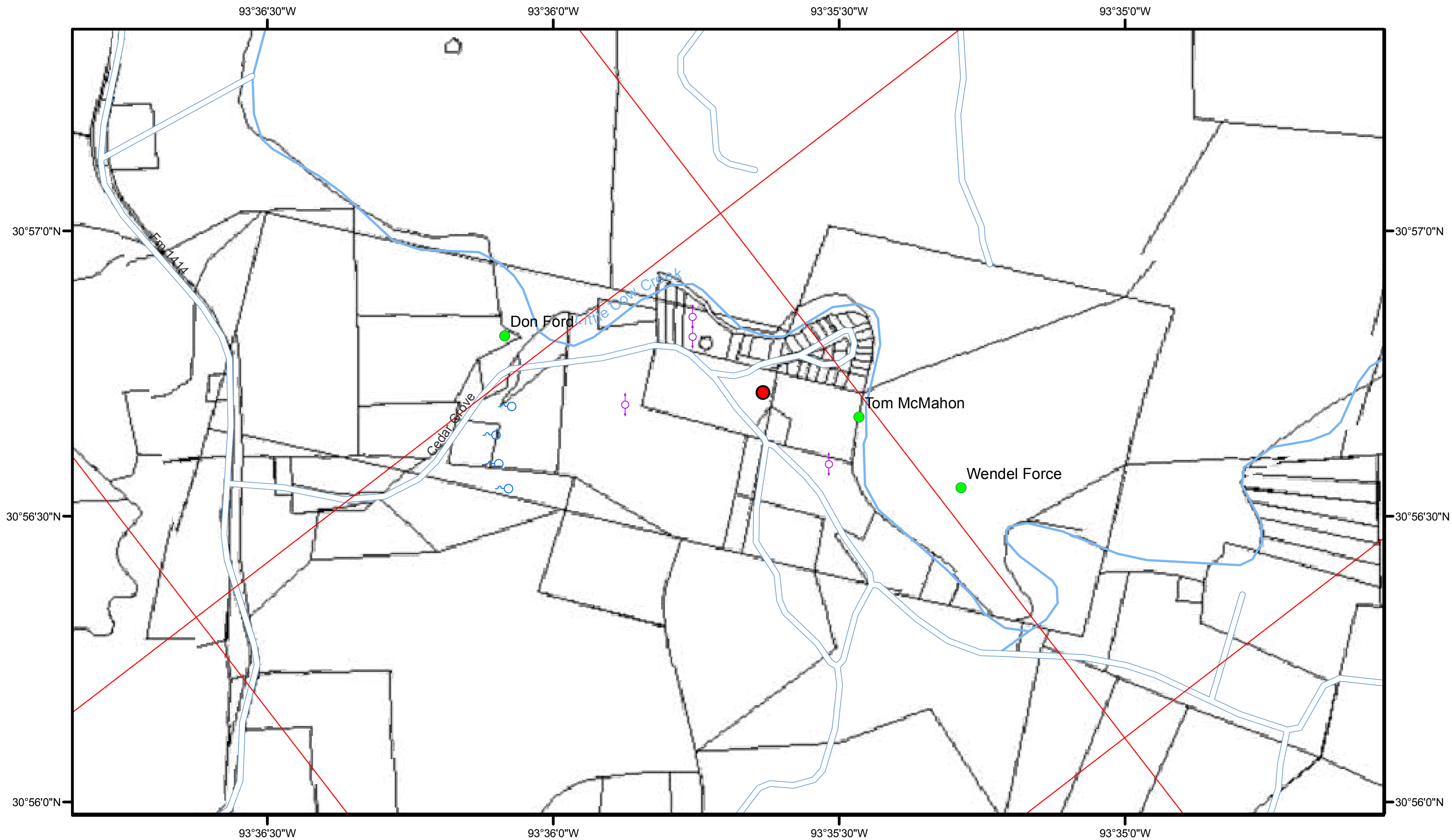
APPENDIX 1

FIGURES



Legend

- Well Owners within 0.5 Miles
- Proposed Well Location
- Spring Locations
- Existing Ayres's Wells
- HAGM Grid

N
W E
S

0 0.05 0.1 0.2 0.3 0.4 Miles

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FIGURE 1: LOCATION OF PROPOSED WELL, SPRINGS AND EXISTING WELLS

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 22, 2015

Figure 2a. Flowing artesian well on the Ayres property flowing into a pond

Figure 2b. Shut-in pressure of 48 psi of artesian well on the Ayres Property, Newton County, Texas. On March 30, 2015

Figure 3

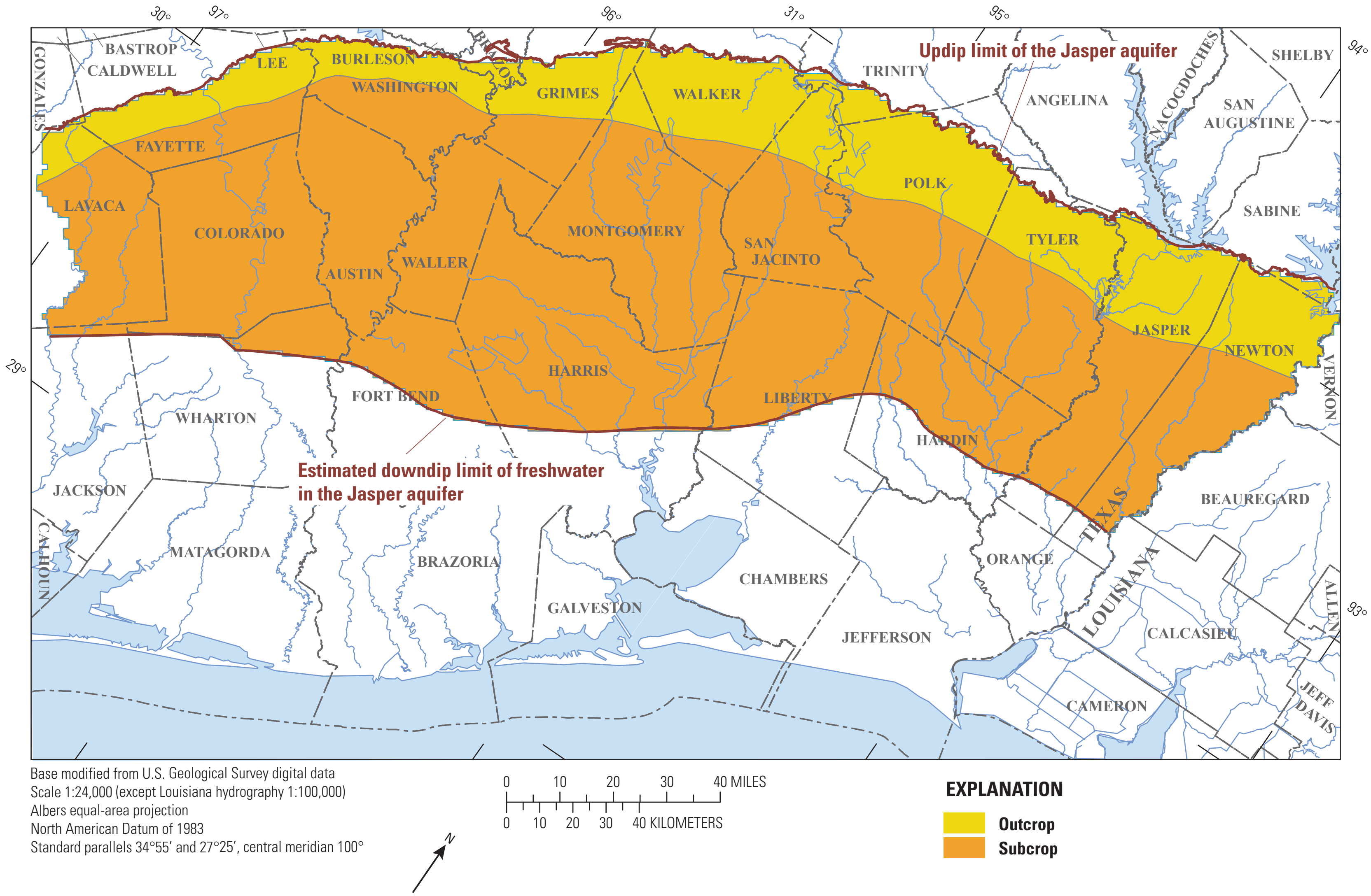


Figure 7. Extent, outcrop area, and subcrop area of the Jasper aquifer in the Houston Area Groundwater Model study area.

Figure 4

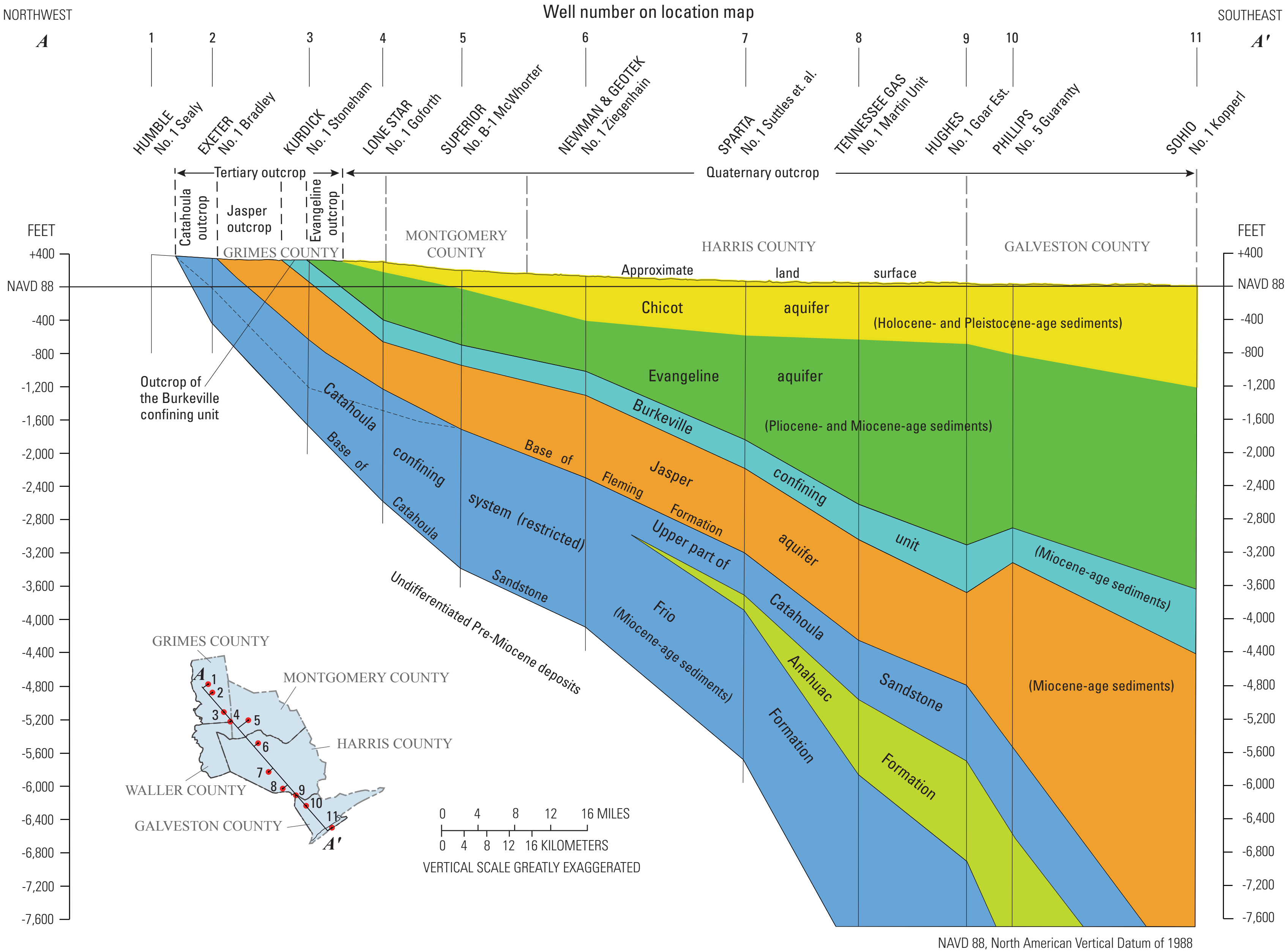
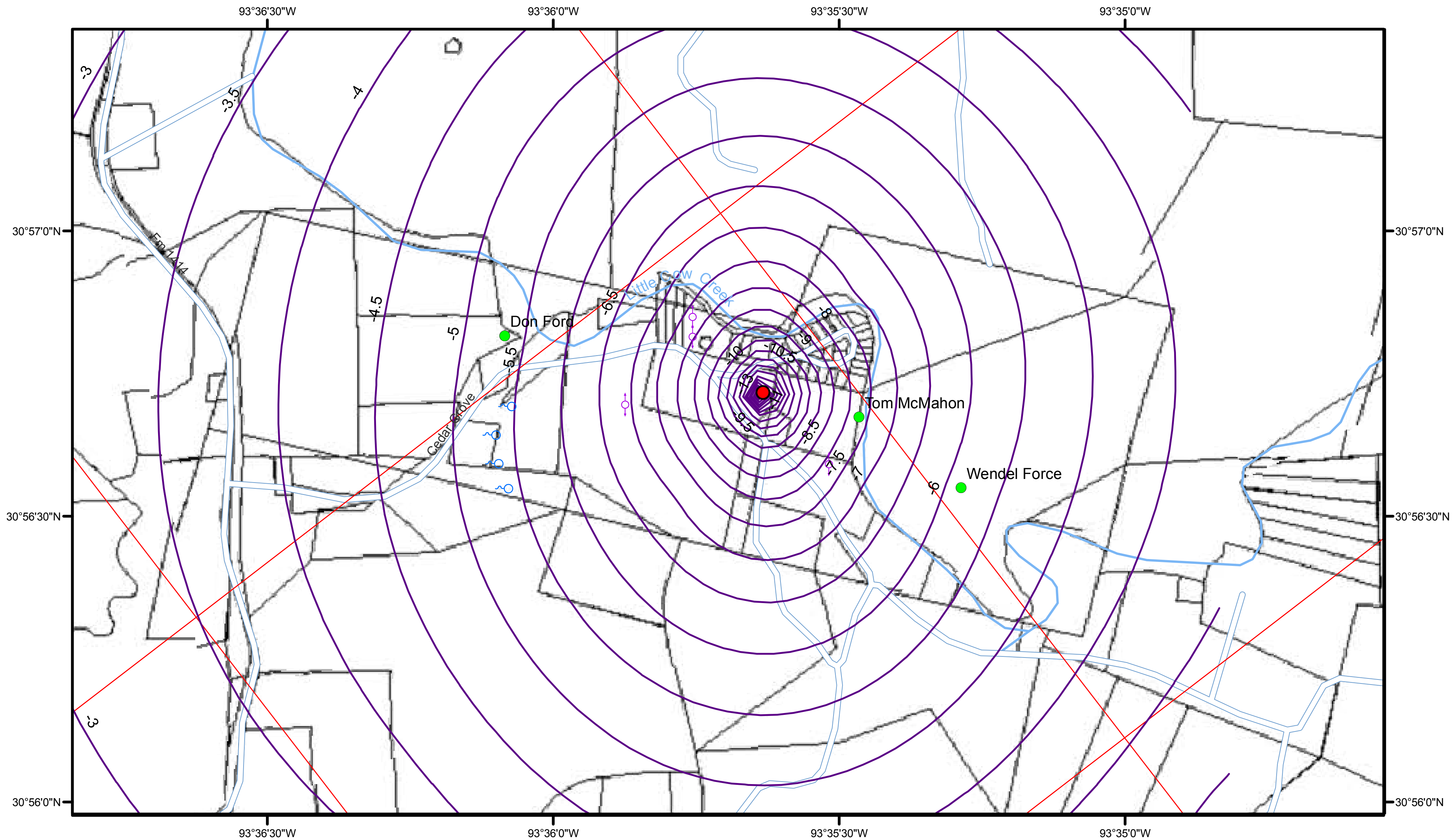


Figure 2. Hydrogeologic section of the Gulf Coast aquifer system in Harris County and adjacent counties, Texas.



Legend

- Well Owners within 0.5 Miles
- Proposed Well Location
- Spring Locations
- Existing Ayres's Wells
- drawdown 25 s0.15
- HAGM Grid

N W E S

0 0.05 0.1 0.2 0.3 0.4 Miles

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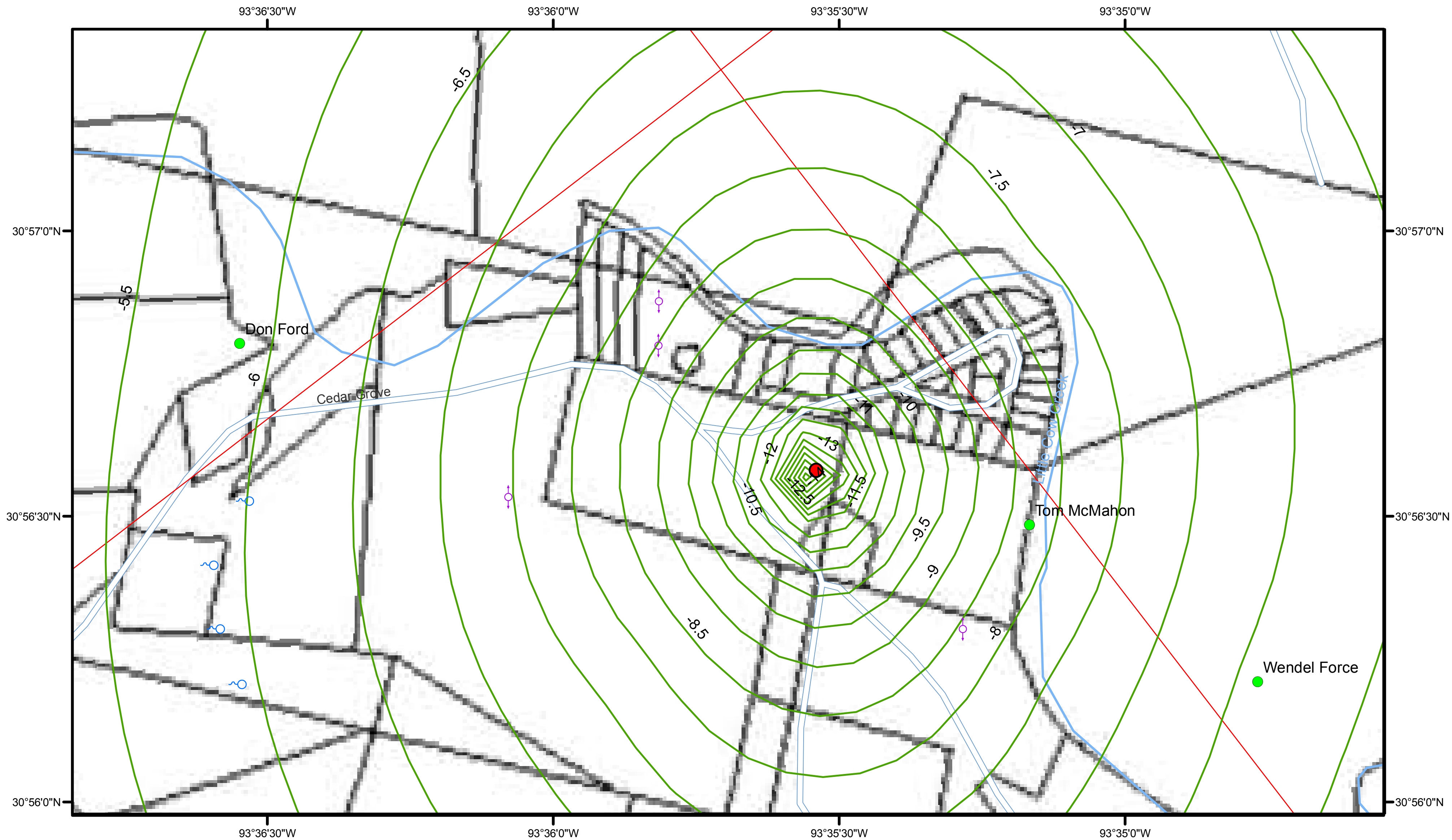
FIGURE 5: MAXIMUM DRAWDOWN AFTER 25 YEARS FROM PROPOSED WELL,

S=0.15 t=25 years

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 22, 2015



Legend

- Well Owners within 0.5 Miles
- Proposed Well Location
- Spring Locations
- Existing Ayres's Wells
- drawdown 25 s0.000383
- HAGM Grid

N W E S

0 0.025 0.05 0.1 0.15 0.2 Miles

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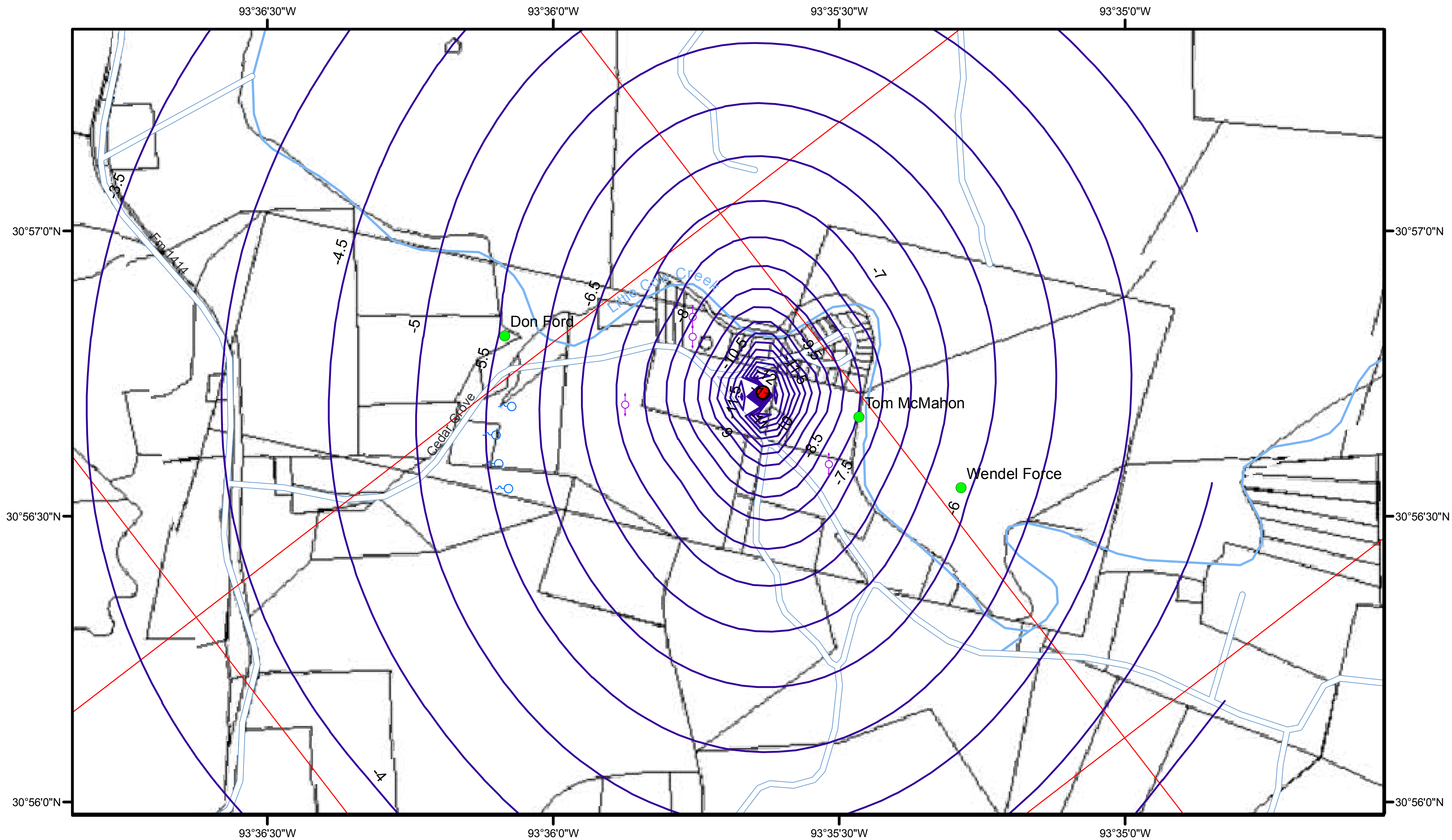
FIGURE 6: MAXIMUM DRAWDOWN AFTER 25 YEARS FROM PROPOSED WELL,

S=0.15 t=25 YEARS

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 22, 2015



Legend

- Well Owners within 0.5 Miles
- Proposed Well Location
- Spring Locations
- Existing Ayres's Wells
- drawdown 50 s0.15
- HAGM Grid

N
W E
S

0 0.05 0.1 0.2 0.3 0.4 Miles

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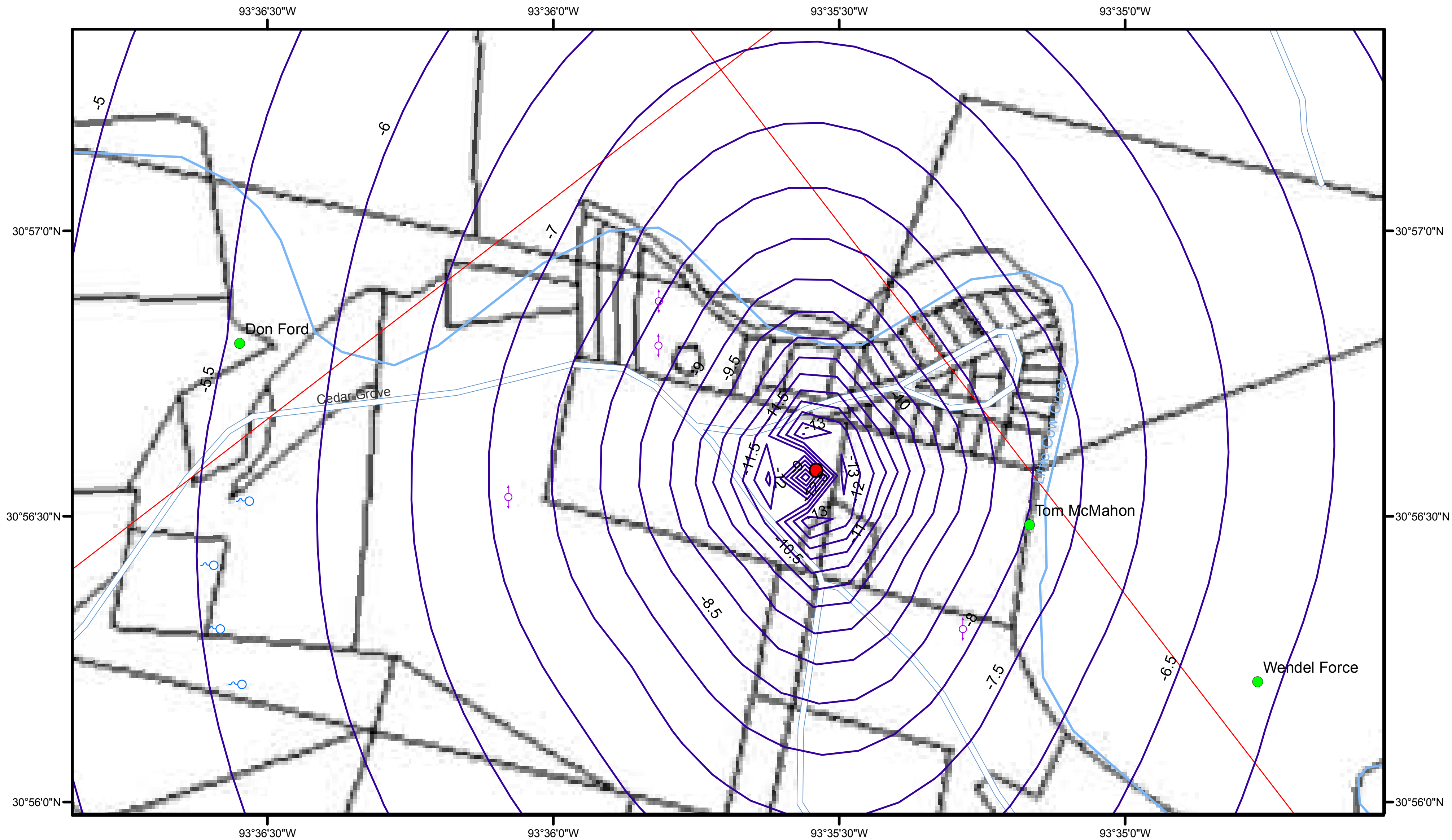
FIGURE 7: MAXIMUM DRAWDOWN AFTER 50 YEARS FROM PROPOSED WELL,

S=0.15 t=50 YEARS

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 22, 2015



Legend

- Well Owners within 0.5 Miles
- Proposed Well Location
- Spring Locations
- Existing Ayres's Wells
- drawdown 50 s0.15
- HAGM Grid

0 0.025 0.05 0.1 0.15 0.2 Miles

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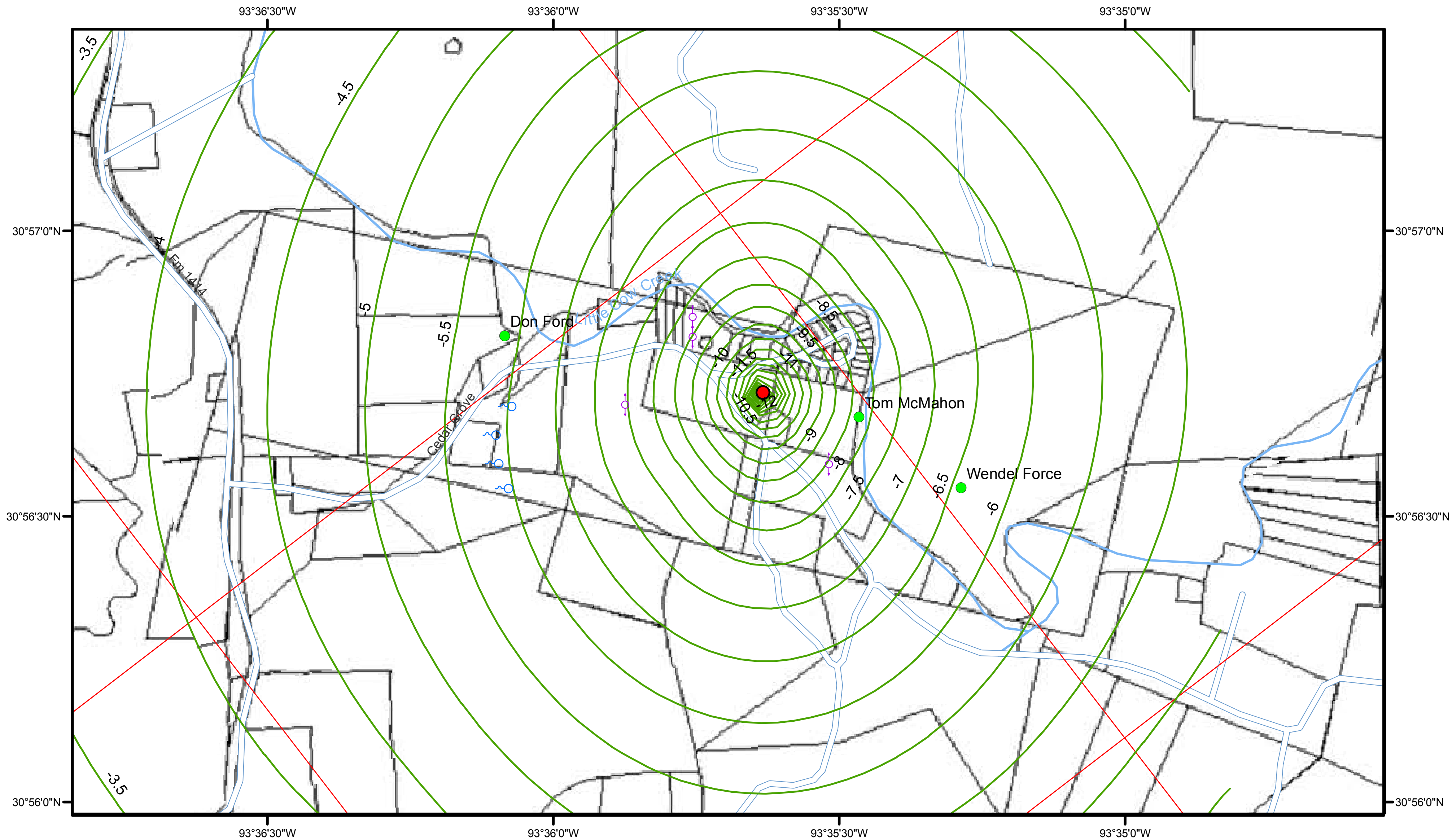
FIGURE 8: MAXIMUM DRAWDOWN AFTER 50 YEARS FROM PROPOSED WELL,

S=0.15 t=50 YEARS

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 22, 2015



Legend

- Well Owners within 0.5 Miles
- Proposed Well Location
- Spring Locations
- Existing Ayres's Wells
- drawdown 25 s0.000383
- HAGM Grid

0 0.05 0.1 0.2 0.3 0.4 Miles

N S W E

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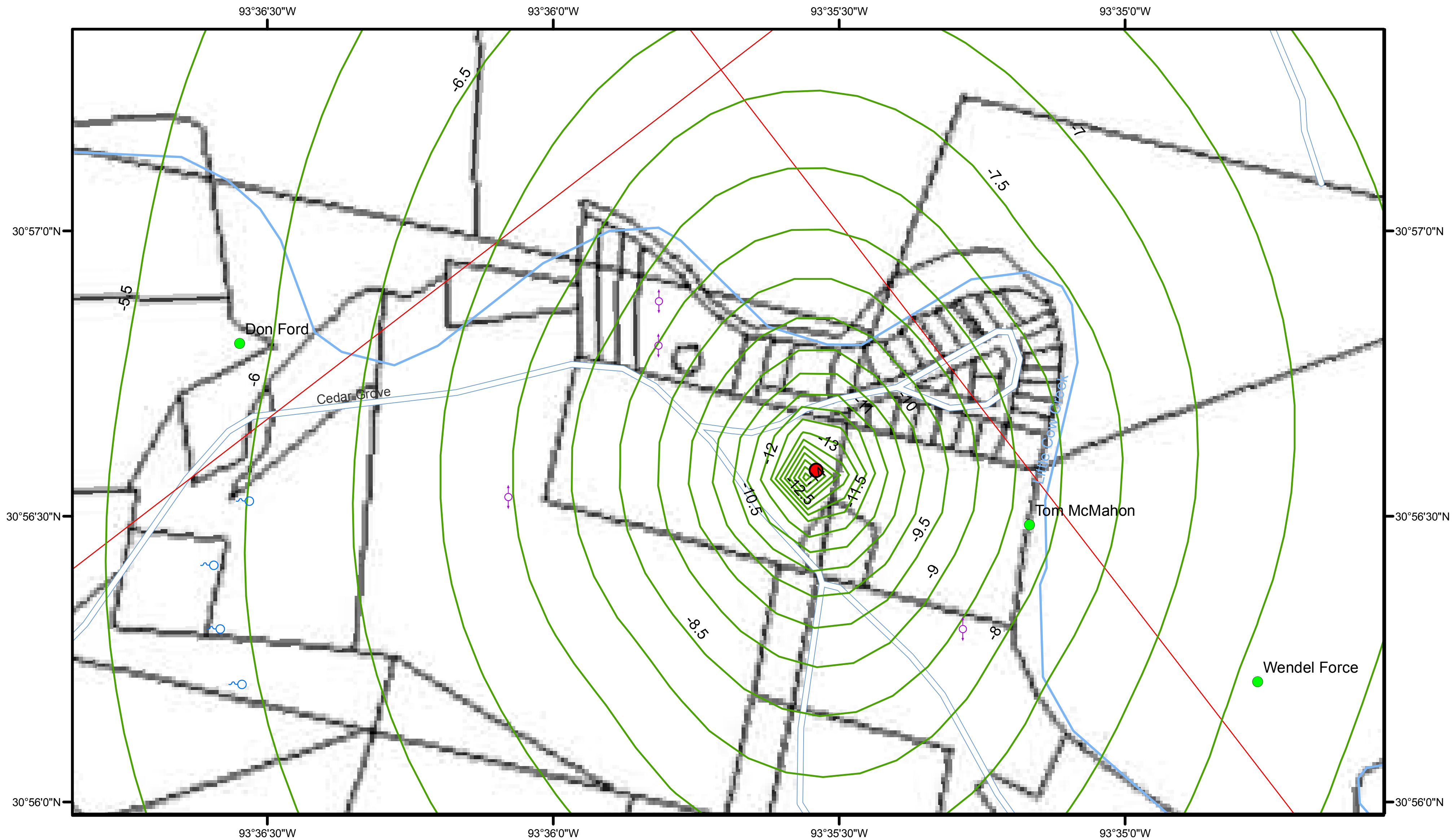
FIGURE 9: MAXIMUM DRAWDOWN AFTER 25 YEARS FROM PROPOSED WELL,

S=0.000383 t=25 YEARS

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 22, 2015



Legend

- Well Owners within 0.5 Miles
- Proposed Well Location
- Spring Locations
- Existing Ayres's Wells
- drawdown 25 s0.000383
- HAGM Grid

N W E S

0 0.025 0.05 0.1 0.15 0.2 Miles

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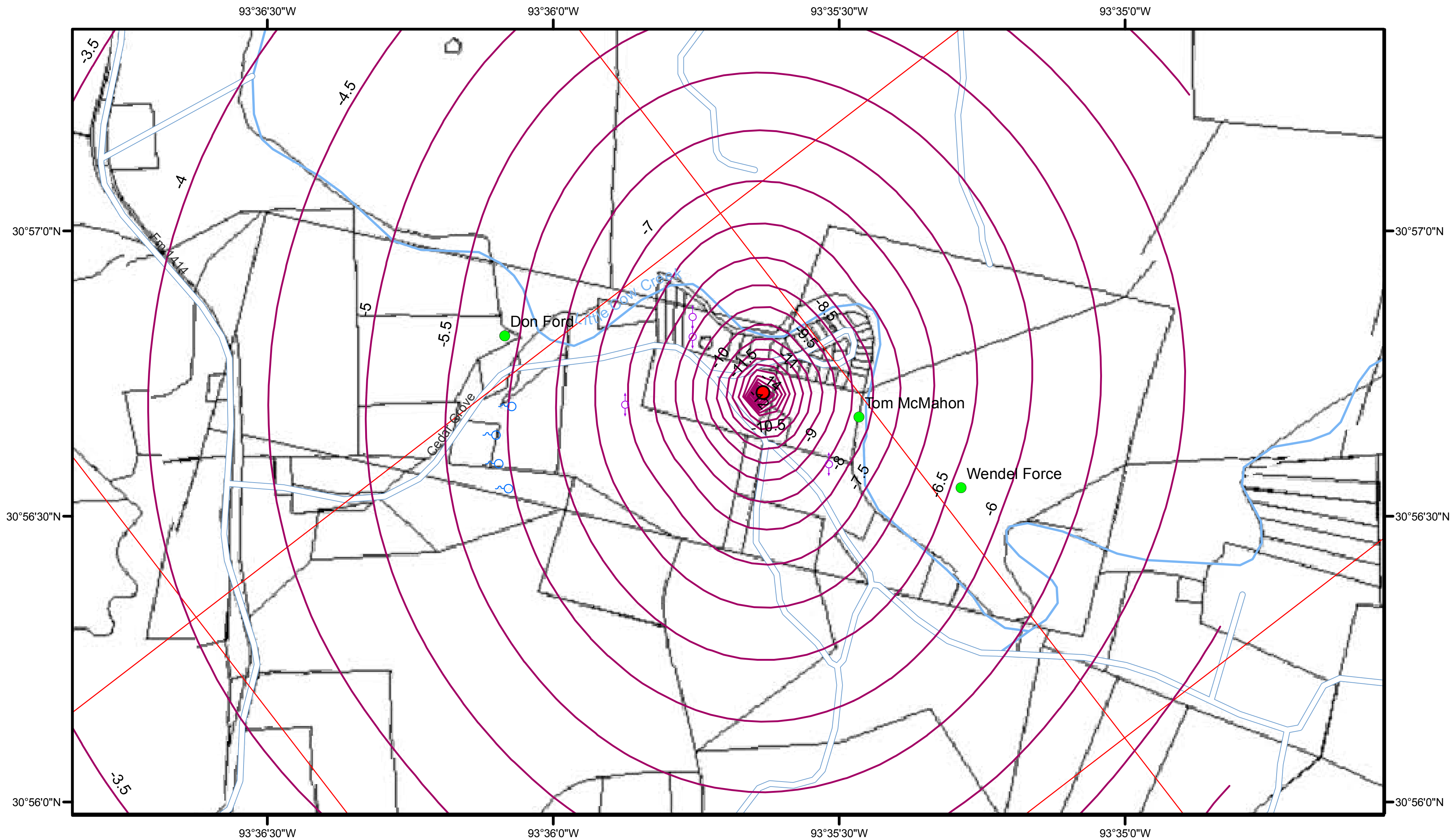
FIGURE 10: MAXIMUM DRAWDOWN AFTER 25 YEARS FROM PROPOSED WELL,

S=0.000383 t=25 YEARS

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 22, 2015



Legend

- Well Owners within 0.5 Miles
- Proposed Well Location
- Spring Locations
- Existing Ayres's Wells
- drawdown 50 s0.000383
- HAGM Grid

0 0.05 0.1 0.2 0.3 0.4 Miles

N W E S

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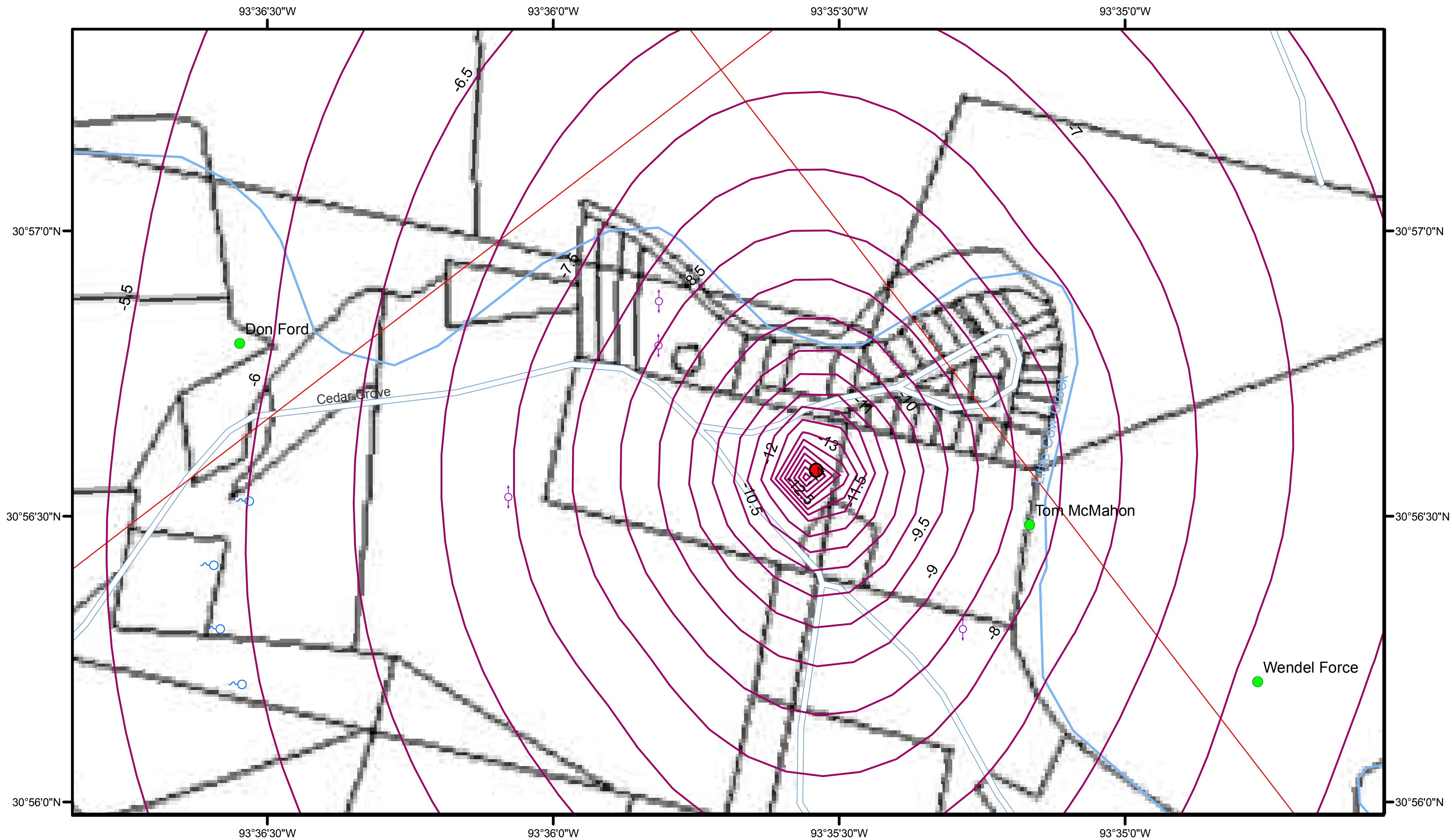
FIGURE 11: MAXIMUM DRAWDOWN AFTER 50 YEARS FROM PROPOSED WELL,

S=0.000383 t=50 YEARS

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 22, 2015



Legend

- Well Owners within 0.5 Miles
- Proposed Well Location
- Spring Locations
- Existing Ayres's Wells
- drawdown 50 s0.000383
- HAGM Grid

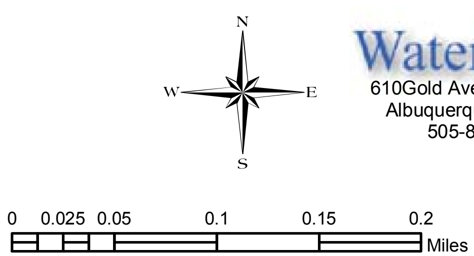


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FIGURE 12: MAXIMUM DRAWDOWN AFTER 50 YEARS FROM PROPOSED WELL,

S=0.000383 t=50 YEARS

PROPERTY: LANDS OF DANIEL AYRES
Prepared By: Sally Williams
Map Produced: October 22, 2015

FIGURE 13

PLOT OF TOTAL DRAWDOWN V. DISTANCE FROM PROPOSED WELL AT THE END OF 25 YEARS

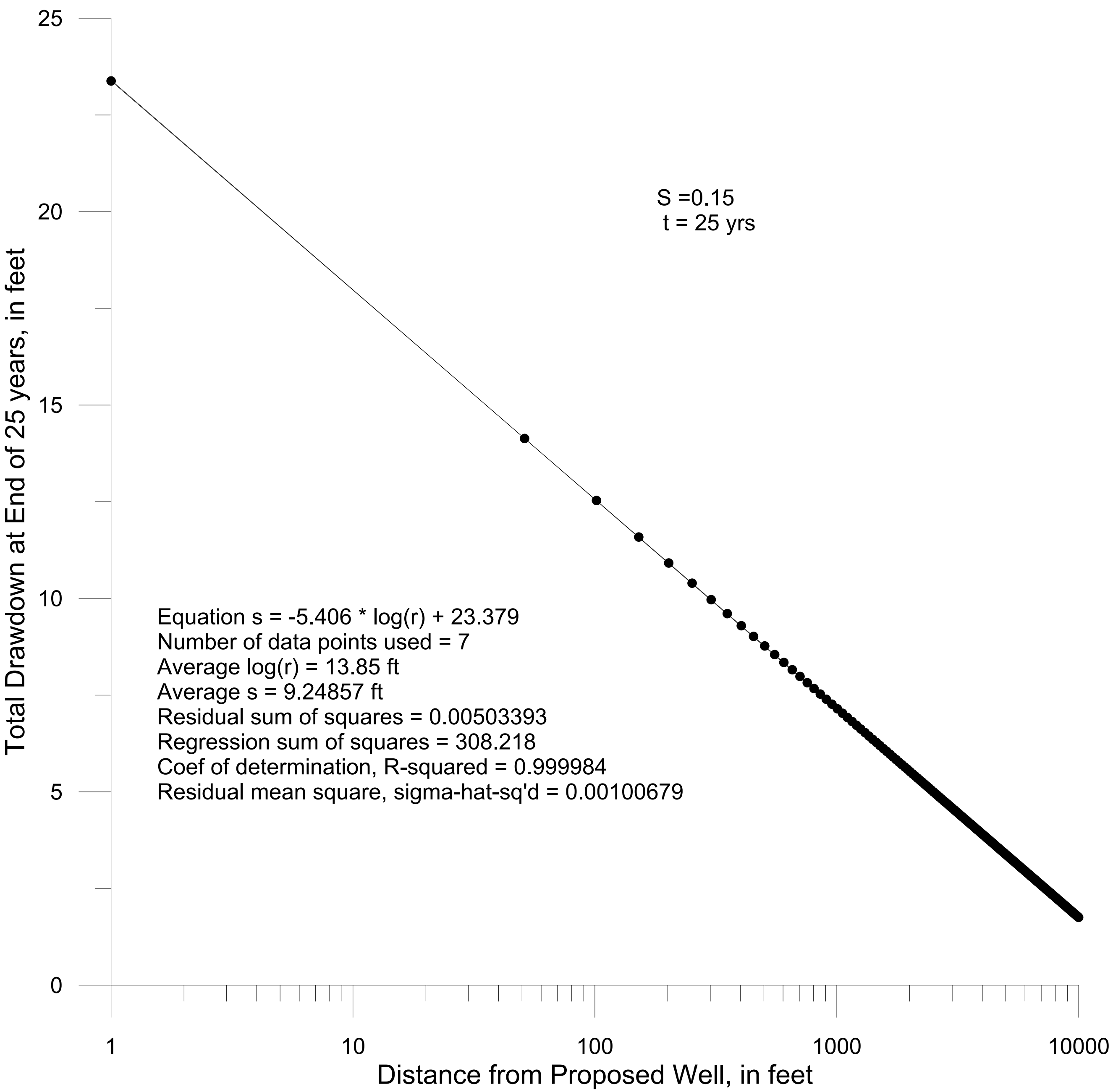

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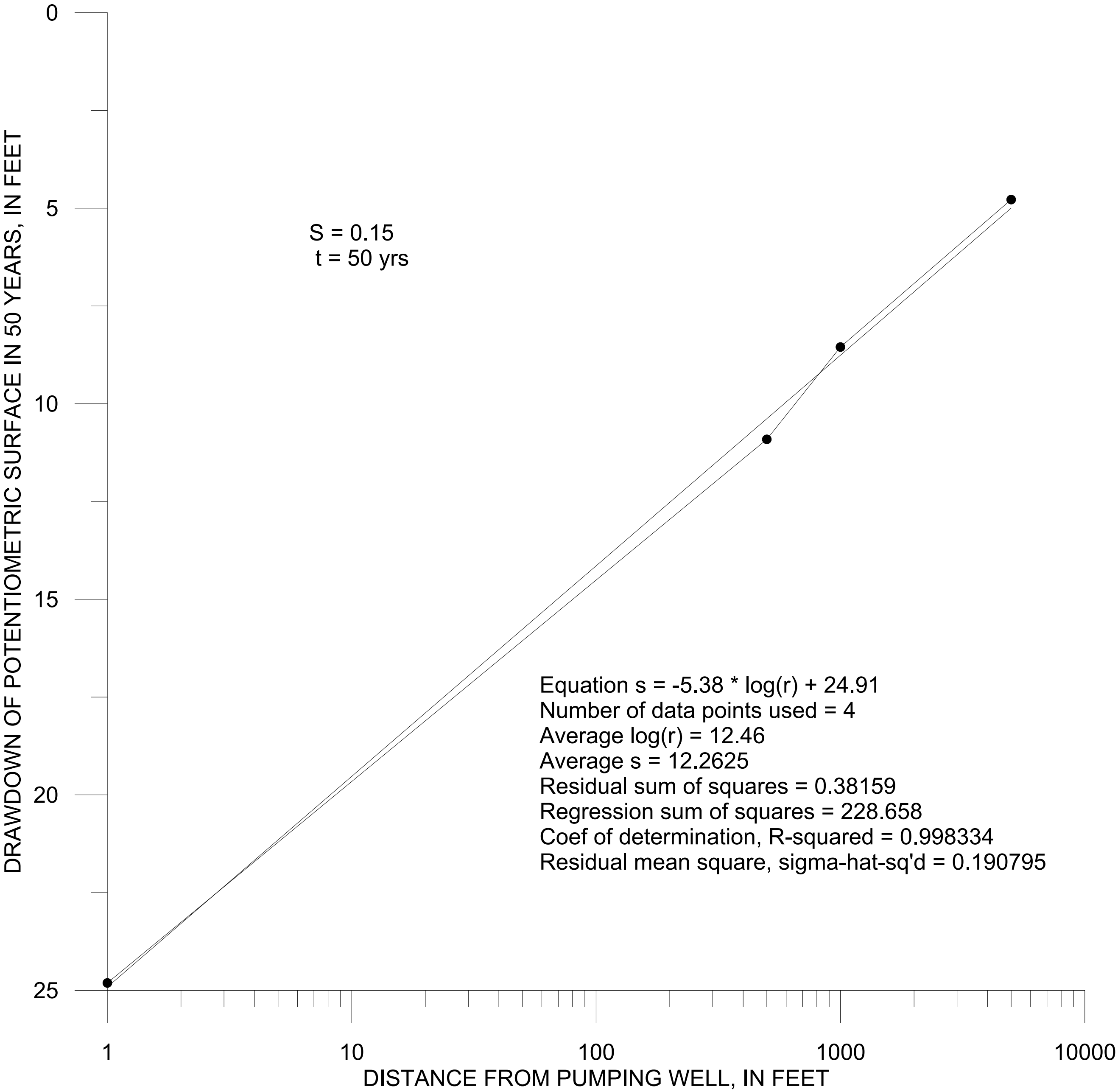
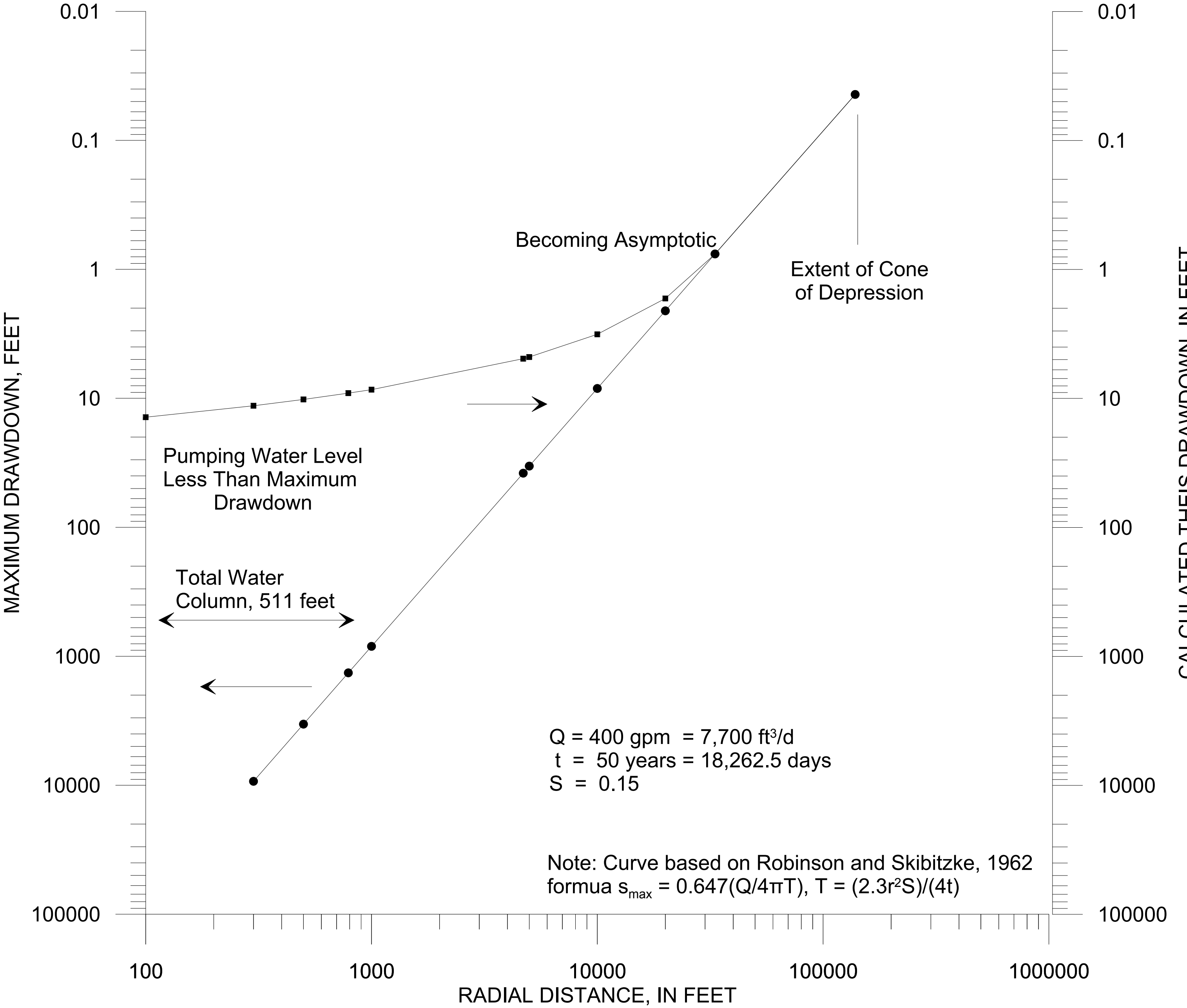
FIGURE 14. DISTANCE-DRAWDOWN CURVE FROM PRODUCTION WELL AFTER 50 YEARS



WATERBANK

FIGURE 15. PLOT OF MAXIMUM DRAWDOWN VERSUS RADIAL DISTANCE FROM PUMPED WELL AND THEIS DRAWDOWN CURVE



APPENDIX 2

WARRANTY DEED

VOL 516 PAGE 346

NOTICE OF CONFIDENTIALITY RIGHTS: IF YOU ARE A NATURAL PERSON, YOU MAY REMOVE OR STRIKE ANY OF THE FOLLOWING INFORMATION FROM THIS INSTRUMENT BEFORE IT IS FILED FOR RECORD IN THE PUBLIC RECORDS: YOUR SOCIAL SECURITY NUMBER OR YOUR DRIVER'S LICENSE NUMBER.

131395

General Warranty Deed

Date: March 18, 2005

Grantor: Yola Clark,

Grantee: Daniel Ayres

Grantee's Mailing Address:

Daniel Ayres
Rt. 1, Box 812
Newton, TX 75966
Newton County

Consideration:

TEN AND NO/100 DOLLARS ($10.00) and other good and valuable consideration.

Property (including any improvements):

BEING 16.844 acres of land, more or less, and being a part of the HENRY STEPHENSON SURVEY, ABSTRACT 369, Newton County, Texas, and being the same land described in Exhibit "A" attached hereto and to which reference is made for a more particular description in metes and bounds

Reservations from Conveyance:

None

Exceptions to Conveyance and Warranty:

Liens described as part of the Consideration and any other liens described in this deed as being either assumed or subject to which title is taken; validly existing easements, rights-of-way, and prescriptive rights, whether of record or not; all presently recorded and validly existing instruments, other than conveyances of the surface fee estate, that affect the Property; and taxes for 2005, which Grantee assumes and agrees to pay, and subsequent assessments for that and prior years due to change in land usage, ownership, or both, the payment of which Grantee assumes.

Grantor, for the Consideration and subject to the Reservations from Conveyance and the Exceptions to Conveyance and Warranty, grants, sells, and conveys to Grantee the Property, together with all and singular the rights and appurtenances thereto in any way belonging, to have and to hold it to Grantee and Grantee's heirs, successors, and assigns forever. Grantor binds Grantor and Grantor's heirs and successors to warrant and forever defend all and singular the Property to Grantee and Grantee's heirs, successors, and assigns against every person whomsoever lawfully claiming or to claim the same or any part thereof, except as to the Reservations from Conveyance and the Exceptions to Conveyance and Warranty.

When the context requires, singular nouns and pronouns include the plural.

Yola M. Clark
Yola Clark

STATE OF TEXAS)

COUNTY OF NEWTON)

This instrument was acknowledged before me on 3/26/05 ____________________, 2005, by Yola Clark.

Hal Michael Perdue
Notary Public, State of Texas

HAL MICHAEL PERDUE
NOTARY PUBLIC STATE OF TEXAS
COMMISSION EXPIRES:
AUGUST 19, 2007

PREPARED IN THE OFFICE OF:

Edward J Tracy
P. O. Box ET
Newton, Texas 75966
Phone: 409-379-4800
Fax: 409-379-4802

VOL 516 PAGE 348

Barrow Surveying

Texas Registered Professional Land Surveyors

Henry Stephenson Survey, Abstract No. 369
Newton County, Texas

Legal Description
16.844 Acre Tract

BEING a 16.844 acre tract of land as situated in the Henry Stephenson Survey, Abstract No. 369 of Newton County, Texas and being all of a called 3.66 acre tract and out of and a part of a called 22.145 acre tract, said 22.145 acre tract having been conveyed from THE VETERANS LAND BOARD OF TEXAS to WILLIAM JAMES CLARK by Deed recorded in Volume 311, Page 380 of the Deed Records of Newton County, and said 3.66 acre tract being that same certain tract as described in a Release of Lien from COUNTY NATIONAL BANK to WILLIAM J. CLARK and filed for record in Volume 39, Page 698 of the Deed of Trust Records of Newton County, Texas. Said 16.844 acre tract being more particularly described by metes and bounds as follows:

BEGINNING at a 1/4" iron pipe found for the Northwest corner of said 3.66 acre tract and being located on the South line of the Clark 22.145 acre tract, from which a 2" iron pipe found on the West bank of Little Cow Creek bears South 73°52'32" East a distance of 329.30 feet;

THENCE North 73°52'32" West, with the South line of the 22.145 acre tract, at 254.92 feet pass a 5/8" iron rod set in the East edge of Cedar Grove Road, **IN ALL a total distance of 314.93 feet** to a 5/8" iron rod found for the most Westerly Southwest corner of this tract and the most Easterly Southeast corner of a 61.622 acre tract as during September 2001;

THENCE along the West edge of Cedar Grove Road with it's meanders as follows:

1. North 34°41'53" West a distance of 359.87 feet to a point for corner;
2. North 38 ° 32 ' 12 " West a distance of 247.77 feet to a point for corner;
3. North 40 ° 39 ' 06 " West a distance of 253.16 feet to a point for corner;
4. North 48 ° 09 ' 56 " West a distance of 88.58 feet to a point for corner;
5. North 54 ° 09 ' 35 " West a distance of 56.62 feet to a point for corner;
6. North 63 ° 50 ' 02 " West a distance of 47.62 feet to a point for corner;
7. North 71 ° 56 ' 25 " West a distance of 7.78 feet to a 2" round concrete monument found for the Northwest corner of this tract and the Southeast corner of the Cedar Grove Methodist Church 2.66 acre tract as recorded in Volume "V", Page 67 of the Deed Records of Newton County, same being an angle corner of the 61.622 acre tract and located on the North line of the Clark 22.145 acre tract;

THENCE South 73°36'00" East a distance of 131.17 feet with a South line of the 61.622 acre tract and the North line of the Clark 22.145 acre tract, to a 3/4" iron pipe found for an angle corner of the 61.622 acre tract and of this tract;

THENCE South 40°59'00" East a distance of 253.16 feet to a 5/8" iron rod found for an angle corner of the 61.622 acre tract and of this tract;

THENCE South 74°16'00" East a distance of 150.96 feet to a 3/4" iron pipe found for an angle corner of the 61.622 acre tract and of this tract;

THENCE North 47°45'15" East a distance of 161.27 feet to a 5/8" iron rod found for an angle corner of the 61.622 acre tract and of this tract, same being located on the North line of the 22.145 acre tract;

THENCE South 73°53'53" East a distance of 29.00 feet to a 3/4" iron pipe found for a Southeast corner of the 61.622 acre tract;

Exhibit "A"

P.O. Drawer 68 • Newton, Texas 75966 • (409) 379-2265 • Fax (409) 379-2860

VOL 516 PAGE 349

THENCE South 74°02'20" East a distance of 931.82 feet, with the North line of the Clark 22.145 acre tract to a point for corner on the West bank of Little Cow Creek for the Northeast corner of this tract, from which a 2" iron pipe found for reference bears North 74°02'20" West a distance of 19.78 feet;

THENCE along the West Bank of Little Cow Creek with it's meanders as follows:

1. South 16°29'31" West a distance of 4.32 feet to a point for corner;
2. South 08°05'32" West a distance of 154.46 feet to a point for corner;
3. South 09°52'10" West a distance of 74.34 feet to a point for corner;
4. South 04°06'19" West a distance of 75.73 feet to a point for corner;
5. South 15°22'37" West a distance of 77.51 feet to a point for corner;
6. South 20°57'57" West a distance of 62.55 feet to a point for corner;
7. South 23°39'23" West a distance of 134.46 feet to a point for corner;
8. South 23°39'23" West a distance of 53.12 feet to a point for corner;
9. South 09°00'57" West a distance of 145.25 feet to a point for corner;
10. South 04°59'38" West a distance of 126.33 feet to a point for corner;
11. South 11°29'03" East a distance of 108.94 feet to a point for corner;
12. South 22°15'21" East a distance of 138.00 feet to a 5/8" iron rod set for Southeast corner of this tract and said 3.66 acre tract;

South 72°45'00" West a distance of 148.13 feet, with the South line of the 3.66 acre tract, to a 5/8" iron rod set for the Southwest corner of this tract in the East edge of Cedar Grove Road;

THENCE with the following calls along the West boundary of the 3.66 acre tract and generally with the East edge of Cedar Grove Road as follows:

1. North 26°00'00" West a distance of 266.67 feet to a point for corner;
2. North 28°00'00" West a distance of 293.89 feet to a 5/8" iron rod set for an angle corner of the 3.66 acre tract and of this tract;

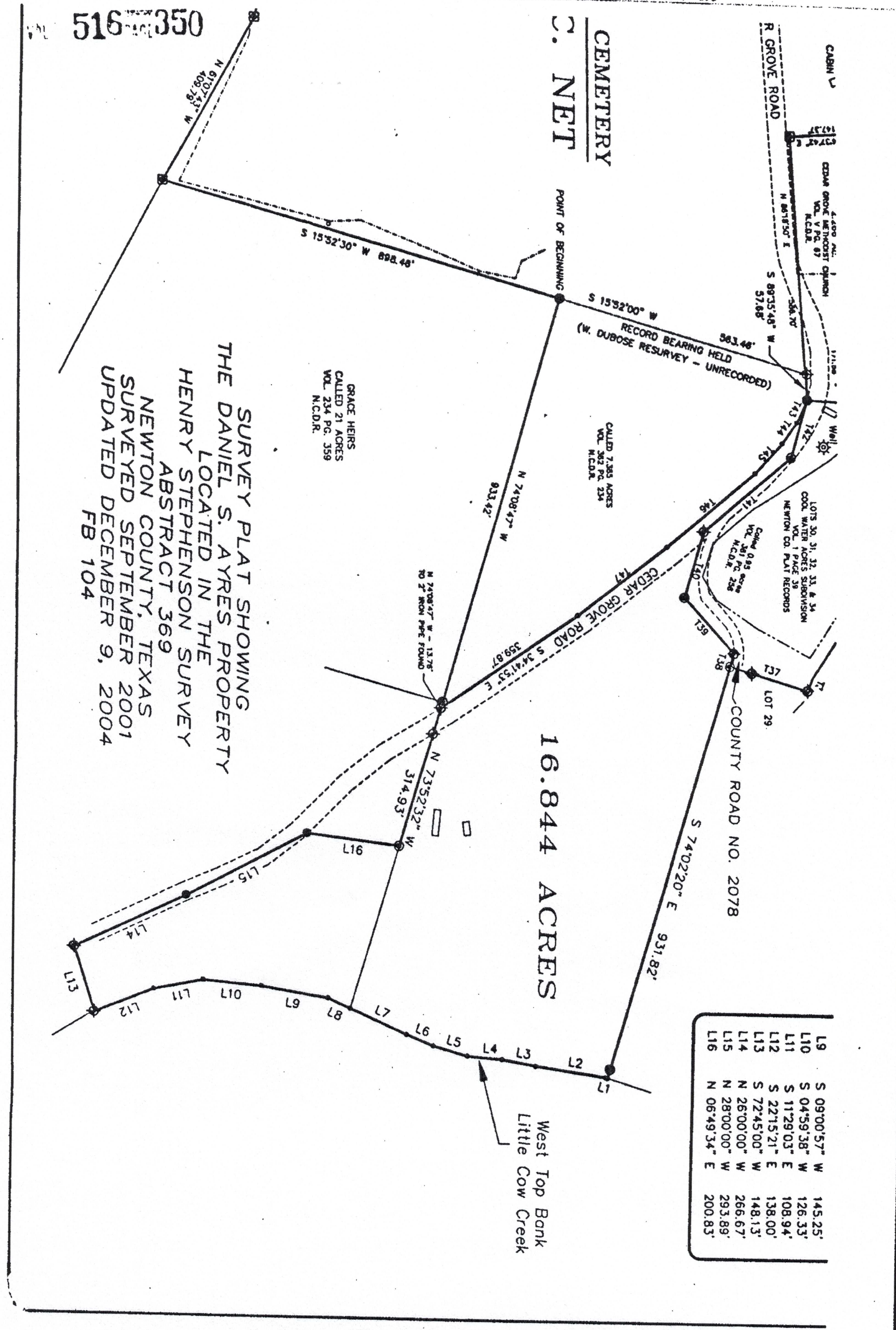
THENCE North 06°49'34" East a distance of 200.83 feet, with a West line of the 3.66 acre tract, to the **PLACE OF BEGINNING** 16.844 acres of land.

NOTE: The bearings recited herein are based and/or rotated to the a South line of a 61.622 acre tract as surveyed September of 2001.

D. Bric Barrow

D. Bric Barrow
Registered Professional Land Surveyor No. 5365
Surveyed January 17, 2005

STATE OF TEXAS
REGISTERED
D. BRIC BARROW
5365
PROFESSIONAL
LAND SURVEYOR



Filed for record 29TH of MARCH, A.D., 20 05 at 12:44 P.M.

THE STATE OF TEXAS
COUNTY OF NEWTON } 131395

I hereby certify that this instrument was filed for record as listed above and duly recorded in the OFFICIAL PUBLIC Records of Newton County, Texas, in the Volume and Page as stamped hereon by me.

Mary Cobb

Mary Cobb, County Clerk, Newton County, Texas

By:______________________, Deputy

APPENDIX 3

Wesselman, J.B., 1967, Groundwater Resources of Jasper and Newton County, Texas, Texas Water Development Board, Report 59, September 1967.

TEXAS
WATER
DEVELOPMENT
BOARD

REPORT 59

GROUND-WATER RESOURCES OF JASPER AND NEWTON COUNTIES, TEXAS

SEPTEMBER 1967

TEXAS WATER DEVELOPMENT BOARD

REPORT 59

GROUND-WATER RESOURCES OF JASPER AND NEWTON COUNTIES, TEXAS

By

J. B. Wesselman
United States Geological Survey

Prepared by the U.S. Geological Survey
in cooperation with the
Texas Water Development Board
Sabine River Authority of Texas
and
Jasper and Newton Counties

September 1967

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GROUND-WATER RESOURCES OF JASPER AND NEWTON COUNTIES, TEXAS

ABSTRACT

Large quantities of fresh water are present in the aquifers of Jasper and Newton Counties. Depth from the land surface to the base of fresh water--water containing less than 1,000 ppm (parts per million) of dissolved solids--varies from possibly zero in a small area of northwestern Jasper County to more than 3,000 feet in the central parts of both counties, and is about 1,000 feet along the southern boundary of the report area. About 45 percent of the sediments to these depths are sands that will yield fresh water to wells.

Under present conditions (1966), it is estimated that an average of at least 500 mgd (million gallons per day) of fresh water infiltrates the outcrops of the aquifers. This recharge is discharged as spring flow to streams, or is transmitted downdip into the artesian parts of the aquifers. It is estimated that at least this much water is available for development in Jasper and Newton Counties on a sustained yield basis by the proper construction and placement of well fields.

Use of the ground water in the report area was about 52 mgd in 1965. Approximately 40 mgd was produced by one well field in the southwestern part of Jasper County. Over 400 mgd remains undeveloped.

The geologic and hydrologic units that yield fresh or slightly saline water (water containing 1,000 to 3,000 ppm of dissolved solids) to wells in Jasper and Newton Counties are: the Yegua Formation; the Jackson Group; the Catahoula Sandstone; and the Jasper, Evangeline, and Chicot aquifers. The Jasper and Evangeline aquifers are separated by the Burkeville aquiclude. The Jasper, Evangeline, and Chicot aquifers crop out in the report area.

The average coefficients of permeability range from 260 to 1,322 gpd (gallons per day) per square foot. The average for the Jasper aquifer is 545 gpd; the Evangeline, 260 gpd; and the Chicot, 1,322 gpd. The difference in permeability is one of the criteria used to differentiate the Evangeline and Chicot aquifers.

Water levels in all the aquifers have been lowered to some extent. The greatest decline, about 200 feet, has been in the Evangeline aquifer in the southwestern part of Jasper County. This decline has caused a local subsidence of the land surface of from 1 to 2 feet.

The chemical quality of most of the ground water in the report area is excellent. Many users of the water have had "iron" problems, but workable

remedies are being applied. Contamination is and has been a minor problem. Large quantities of slightly to very saline water exist downdip from the fresh water. Waters of this type move updip when the pressure head of the fresh-water-bearing part of the aquifers is reduced. The rate and magnitude of this movement could be observed by the construction of observation wells near and in the interface between the fresh and slightly saline water.

The program of ground-water observation needs to be expanded in the report area. The expanded program should include an annual inventory of new wells and pumpage, pumping tests of new wells, collection of quality of water and water-level data, and collection of new subsurface data as it becomes available. Also needed is an expanded net of bench marks and a periodic releveling program to measure the subsidence of the land surface. Much of the hydrologic data probably will be analyzed by the use of an analog model. A preliminary analog model of southeast Texas and southwest Louisiana is being constructed. Data from the recommended program will be needed to refine this model.

GROUND-WATER RESOURCES OF JASPER AND NEWTON COUNTIES, TEXAS

INTRODUCTION

Location and Extent of Area

Jasper and Newton Counties, located along the eastern border of Texas near the Gulf of Mexico (Figure 1), are almost equal to each other in size. Their combined area is 1,879 square miles, and their length is approximately twice their combined width. The western edge of Newton County adjoins the eastern edge of Jasper County. Newton County is bordered on the east by Calcasieu, Beauregard, Vernon, and Sabine Parishes of Louisiana. Jasper County is bordered on the west by Hardin and Tyler Counties, and on the north by Angelina and San Augustine Counties. Both Jasper and Newton Counties are bordered on the north by Sabine County and on the south by Orange County.

Purpose and Scope of Investigation

The investigation of the ground-water resources of Jasper and Newton Counties, begun in September 1963, was a cooperative project of the two counties, the Sabine River Authority of Texas, the Texas Water Development Board, and the U.S. Geological Survey. The purpose of the project was to determine the occurrence, availability, dependability, quality, and quantity of ground-water resources in both counties. Particular emphasis was placed on evaluating sources of water for public supply, industry, and irrigation.

Furthermore, the scope of the project necessitated including in the final report an analytical discussion of the area geology and hydrology as related to the ground water, plus tables of basic data and figures to illustrate conditions shown by these data. The following subjects were to be discussed or recommendations made: the construction and operating characteristics of existing wells in the county, the contamination of ground water, the subsidence of the land surface as a consequence of ground-water removal, and the establishment of a continuing program for collecting water-level and water-quality data.

Methods of Investigation

The 570 wells inventoried in this investigation included those for industrial, public supply, and irrigation use, as well as a representative number for livestock and domestic use (Table 5). Locations of wells inventoried during this and previous investigations are shown on Figure 27.

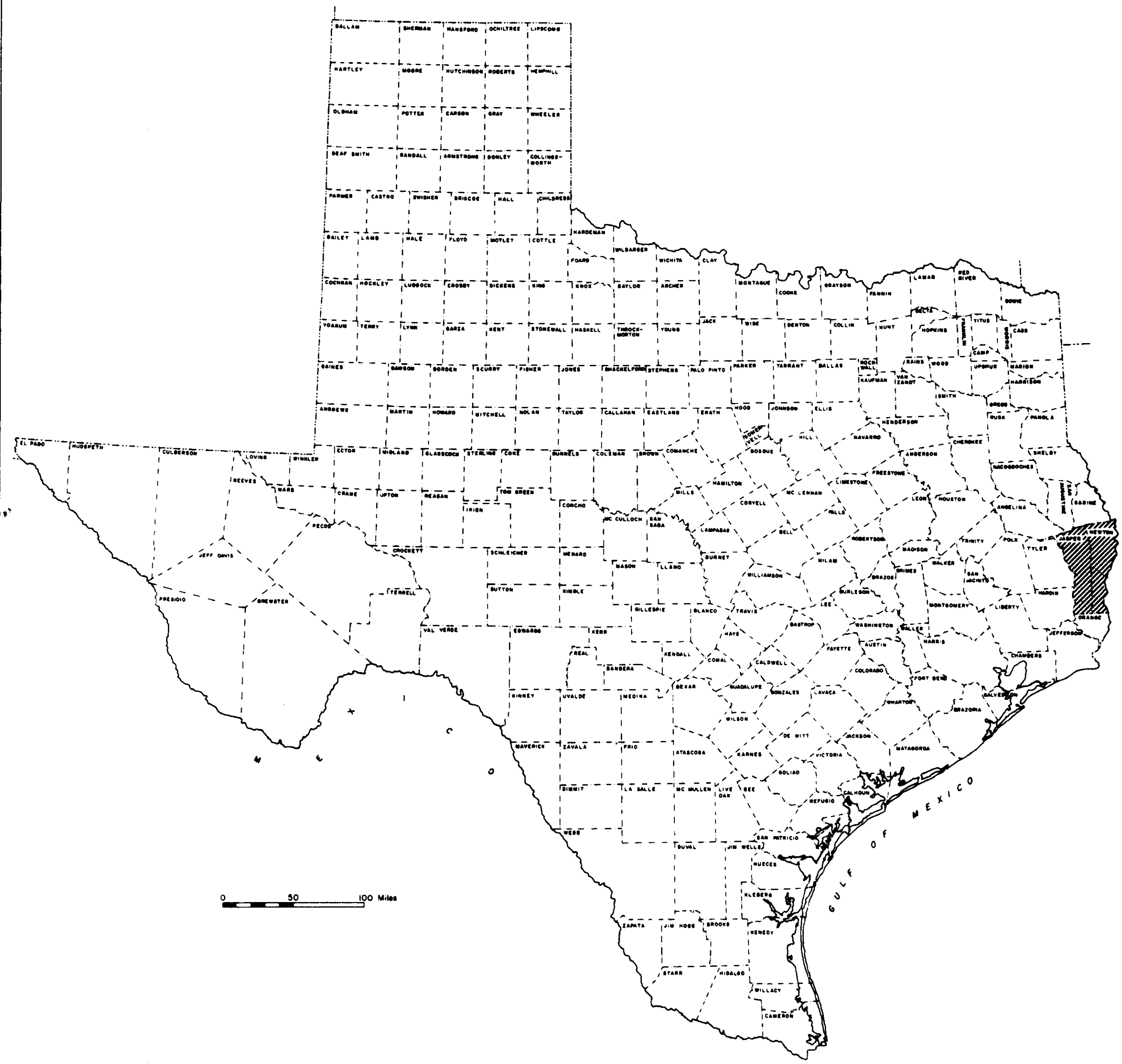

Figure 1

Location of Jasper and Newton Counties

U. S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

Drillers' logs of 52 wells are presented in Table 6. Electric logs of 178 oil tests and 2 stratigraphic test holes were used in the correlation and evaluation of the subsurface characteristics of the water-bearing sands. The electric logs, together with the drillers' logs of selected water wells, were used in determining the total thickness of sand containing fresh water.

Samples of water were collected from wells to determine the chemical quality of the water. The results of analyses are presented in Table 7. Pumping tests were made to determine the hydraulic characteristics of the fresh-water-bearing sands, and results of the tests are presented in Table 4. Measurements of water levels in wells made during this and previous investigations were used to determine the effect of pumpage on water levels.

Municipal, industrial, and irrigation pumpage was inventoried. Part of the inventory was based on data from the U.S. Department of Agriculture and the Texas Water Development Board. Surface elevations were obtained from the topographic maps of the U.S. Geological Survey.

Previous Investigations

In his study of the coastal plain of Texas, Taylor (1907) included wells in Jasper and Newton Counties. Deussen (1914), in a reconnaissance investigation of the southeastern part of the Texas Coastal Plain, discussed the geology and ground water of Jasper and Newton Counties and included a list of wells and springs with drillers' logs of wells.

Cromack's report (1942) included inventories of 161 wells in Jasper County and 121 wells in Newton County, 215 chemical analyses of water samples, and drillers' logs of 29 wells. Most of his well data are included in this report. The well numbers used by Cromack and the corresponding numbers used in this report are listed in Table 1.

A report by Wood, Gabrysch, and Marvin (1963) discussed the ground-water supplies available from the principal water-bearing formations in the Gulf Coast region of Texas, including Jasper and Newton Counties. Parts of these counties were likewise included in similar reconnaissance reports (Baker and others, 1963a, and 1963b) on the Sabine and Neches River basins.

Measurements of water levels in wells have been made in Jasper and Newton Counties since 1949 as part of the observation-well program in Texas. Records of these measurements are maintained by the Texas Water Development Board. Records of water levels in selected wells in Jasper and Newton Counties have been published by the U.S. Geological Survey in reports on the water levels and artesian pressures in the United States (Hackett, 1962, p. 165-166).

Economic Development

In 1960 (U.S. Census Bureau data), the population of Jasper County was 22,100 and the population of Jasper, the county seat, was 4,889. Other population and commercial centers in the county are Kirbyville, Buna, and Evadale. Bessmay and Call are former lumber centers. In 1960, Newton County had a population of 10,372 and Newton, the county seat, had a population of 1,233. Other population centers in the county include the towns of Burkeville, Wiergate, Bon Wier, and Deweyville.

Table 1.--Well numbers used in this report and corresponding numbers used in the report by G. H. Cromack (1942)

Old number	New number	Old number	New number	Old number	New number	Old number	New number
Jasper County							
1	PR-37-61-801	31	PR-36-57-801	61	PR-61-16-102	91	PR-62-17-903
2	PR-37-61-901	32	PR-36-57-903	62	PR-61-15-601	92	PR-62-17-905
3	PR-37-62-703	33	PR-62-01-103	63	PR-61-16-201	93	PR-62-17-907
4	PR-37-62-702	34	Not used	64	PR-61-16-501	94	PR-62-17-902
5	PR-37-63-703	35	PR-62-01-201	65	PR-61-16-602	95	PR-62-17-901
6	PR-61-07-102	36	PR-62-01-302	66	PR-61-16-301	96	PR-62-17-509
7	PR-61-07-202	37	PR-62-01-602	67	PR-62-09-103	97	PR-62-17-403
8	PR-61-07-306	38	PR-62-01-603	68	PR-62-09-104	98	PR-61-24-607
9	PR-37-63-801	39	PR-62-01-905	69	PR-62-01-704	99	PR-61-24-905
10	PR-37-63-802	40	PR-62-01-906	70	PR-62-09-501	100	PR-61-32-301
11	PR-37-63-501	41	PR-62-01-501	71	PR-62-10-401	101	PR-62-17-706
12	PR-37-63-601	42	PR-62-01-408	72	PR-62-09-602	102	PR-62-17-802
13	PR-37-64-701	43	PR-62-01-502	73	PR-62-09-901	103	PR-62-25-307
14	PR-61-08-105	44	PR-62-01-409	74	PR-62-09-802	104	PR-62-25-303
15	PR-61-08-106	45	PR-61-08-902	75	PR-62-09-702	105	PR-62-25-604
16	PR-61-08-101	46	PR-61-16-305	76	PR-61-16-904	106	PR-62-25-302
17	PR-61-08-202	47	PR-61-08-803	77	PR-61-24-202	107	PR-62-25-504
18	PR-61-08-301	48	PR-61-08-505	78	PR-61-24-203	108	PR-62-25-505
19	PR-61-08-504	49	PR-61-08-506	79	PR-61-24-503	109	PR-62-25-102
20	PR-61-08-601	50	PR-61-08-503	80	PR-61-24-605	110	PR-61-32-302
21	PR-62-01-407	51	PR-61-08-502	81	PR-62-17-402	111	PR-62-25-404
22	PR-36-57-701	52	PR-61-08-401	82	PR-62-17-101	112	PR-61-32-601
23	PR-36-57-402	53	PR-61-07-601	83	PR-61-24-301	113	PR-61-32-907
24	PR-37-64-301	54	PR-61-07-610	84	PR-61-24-303	114	PR-61-40-304
25	PR-37-56-902	55	PR-61-07-603	85	PR-62-17-206	115	PR-62-33-106
26	PR-36-49-802	56	PR-61-07-611	86	PR-62-17-207	116	PR-62-25-802
27	PR-36-57-103	57	PR-61-07-604	87	PR-62-17-507	117	PR-62-33-210
28	PR-36-57-202	58	PR-61-08-703	88	PR-62-17-201	118	PR-62-33-203
29	PR-36-57-203	59	PR-61-07-904	89	PR-62-17-302	119	PR-62-33-202
30	PR-36-57-501	60	PR-61-16-107	90	PR-62-17-508	120	PR-62-33-201

(Continued on next page)

Table 1.--Well numbers used in this report and corresponding numbers used in the report by G. H. Cromack (1942)--Continued

Old number	New number	Old number	New number	Old number	New number	Old number	New number
121	PR-62-33-406	132	PR-62-33-803	142	PR-61-48-704	152	PR-62-41-904
122	PR-61-40-603	133	PR-62-33-802	143	PR-61-48-401	153	PR-62-09-703
123	PR-61-40-502	134	PR-62-41-203	144	PR-61-48-501	154	PR-62-01-802
124	PR-61-40-503	135	PR-62-41-201	145	PR-61-48-801	155	PR-61-08-903
125	PR-61-40-804	136	PR-61-48-215	146	PR-61-48-903	156	PR-61-16-202
126	PR-61-40-902	137	PR-61-48-214	147	PR-62-41-402	157	PR-61-07-801
127	PR-62-33-701	138	PR-61-48-216	148	PR-62-41-401	158	PR-61-07-103
128	PR-62-33-407	139	PR-61-48-217	149	PR-62-41-702	159	PR-37-61-903
129	PR-62-33-408	140	PR-61-48-503	150	PR-62-41-803	160	PR-37-61-904
130	PR-62-33-501	141	PR-61-48-405	151	PR-62-41-902	161	PR-37-63-602
131	PR-62-33-804						

Newton County

Old number	New number	Old number	New number	Old number	New number	Old number	New number
1	TZ-36-50-702	20	TZ-62-02-101	39	TZ-62-02-501	58	TZ-62-11-401
2	TZ-36-50-801	21	TZ-62-02-202	40	TZ-62-02-402	59	TZ-62-11-202
3	TZ-36-50-901	22	TZ-62-02-301	41	TZ-62-02-401	60	TZ-62-11-604
4	TZ-36-51-701	23	TZ-36-59-701	42	TZ-62-02-803	61	TZ-62-11-605
5	TZ-36-58-401	24	Not used	43	TZ-62-02-703	62	TZ-62-12-401
6	TZ-36-58-102	25	Not used	44	TZ-62-03-702	63	TZ-62-11-904
7	TZ-36-58-301	26	TZ-36-59-803	45	TZ-62-11-201	64	TZ-62-11-501
8	TZ-36-58-302	27	TZ-36-59-901	46	TZ-62-11-102	65	TZ-62-11-402
9	TZ-36-59-101	28	TZ-62-03-203	47	TZ-62-11-103	66	TZ-62-10-504
10	TZ-36-52-401	29	TZ-62-03-304	48	Not used	67	TZ-62-10-402
11	TZ-36-52-802	30	TZ-62-03-305	49	TZ-62-10-311	68	TZ-62-10-803
12	TZ-36-52-503	31	TZ-62-04-103	50	TZ-62-10-310	69	TZ-62-10-701
13	TZ-36-60-208	32	TZ-62-04-503	51	TZ-62-10-201	70	TZ-62-18-101
14	TZ-36-60-603	33	TZ-62-03-601	52	TZ-62-10-101	71	TZ-62-18-201
15	TZ-36-60-702	34	TZ-62-04-701	53	TZ-62-10-102	72	TZ-62-18-202
16	TZ-36-60-404	35	TZ-62-03-902	54	TZ-62-10-502	73	TZ-62-18-304
17	TZ-36-59-601	36	TZ-62-03-501	55	TZ-62-10-503	74	TZ-62-19-401
18	TZ-36-59-503	37	TZ-62-03-401	56	TZ-62-10-601	75	TZ-62-19-102
19	TZ-36-57-904	38	TZ-62-02-601	57	TZ-62-10-602	76	TZ-62-19-202

(Continued on next page)

Table 1.--Well numbers used in this report and corresponding numbers used in the report by G. H. Cromack (1942)--Continued

Old number	New number	Old number	New number	Old number	New number	Old number	New number
77	TZ-62-11-802	89 90	TZ-62-18-804	100	TZ-62-25-305	111	TZ-62-34-805
78	TZ-62-19-307	90	TZ-62-18-807	101	TZ-62-26-104	112	TZ-62-42-101
79	TZ-62-19-308	91	TZ-62-18-901	102	TZ-62-26-404	113	TZ-62-42-503
80	TZ-62-19-301	92	TZ-62-19-402	103	TZ-62-26-506	114	TZ-62-43-405
81	TZ-62-19-605	93	TZ-62-19-701	104	TZ-62-26-614	115	TZ-62-43-404
82	TZ-62-18-601	94	TZ-62-27-103	105	TZ-62-26-903	116	TZ-62-42-905
83	TZ-62-18-505	95	TZ-62-26-301	106	TZ-62-42-601	117	TZ-62-42-906
84	TZ-62-18-403	96	TZ-62-26-204	107	TZ-62-33-602	118	TZ-62-42-907
85	TZ-62-18-404	97	TZ-62-26-103	108	TZ-62-34-501	119	Not used
86	TZ-62-18-704	98	TZ-62-25-306	109	TZ-62-34-602	120	Not used
87	TZ-62-18-705	99	TZ-62-25-304	110	TZ-62-34-801	121	TZ-62-18-102
88	TZ-62-18-805						

Jasper County is 85 percent forested and Newton County is 95 percent forested. The economy of both counties is based primarily on forest products. The large paper mill at Evadale is the only major industry located in the area.

Oil has also been important to the economy during the last three decades. Production of oil amounted to 3,267,338 barrels (1928-60) in Jasper County, and to 11,786,110 barrels (1937-60) in Newton County.

The raising of beef and chickens is an important source of income. Some rice is irrigated in the southern part of the counties, and small amounts of feed grains and vegetables are grown. Minnows and catfish are raised commercially in a few places.

Recreation is becoming an important industry because of the development of lakes in the area on the Angelina, Sabine, and Neches Rivers. Many of the workers from the fast-growing petrochemical center known as the Golden Triangle of Orange and Jefferson Counties are buying land in Jasper and Newton Counties. This added stimulation of the economy will complement the growth that will occur as new industries are attracted to Jasper and Newton Counties by the large water supply and the undeveloped land.

Physiography and Drainage

Jasper and Newton Counties are a part of the physiographic province of the West Gulf Coastal Plain. The land surface ranges in elevation above mean sea level from less than 10 feet (where the Neches and Sabine Rivers flow south out of the counties) to more than 600 feet (in northwest Newton County). Lowlands border the rivers and range in width from 0 to about 6 miles except where they occupy a strip about 10 miles wide at the southern end of both counties. In the northern parts of Jasper and Newton Counties, the rivers breach a northward-facing escarpment known as the Kisatchie Wold (Veatch, 1906).

The upland areas can be divided into several land surfaces which have been used in mapping the geology of the area. Three upland surfaces are distinct and have been mapped by Bernard (1950), and by Bernard and LeBlanc (1965), as the Montgomery, Bentley, and Willianna Formations of Pleistocene age. The lowest of the upland surfaces is in the vicinity of Buna and Kirbyville where it is mostly clay and comparatively treeless.

Jasper and Newton Counties are drained by the Sabine and Neches Rivers. The rivers empty south of the two counties into Sabine Lake, a salt-water body, extending inland from the Gulf of Mexico.

Climate

The climate in Jasper and Newton Counties is warm and humid as indicated by the records of temperature, precipitation, and evaporation in the report area and adjacent counties (Figures 2, 3, and 4). The precipitation is fairly well distributed throughout the year. The average annual temperature at Beaumont is about 70°F. Temperatures below freezing occur on the average of 12 days per year, and temperatures above 100°F are unusual. Approximate dates of the first and last killing frosts are December 2 and March 2, respectively; hence the growing season is about 275 days. Because of their higher altitudes,

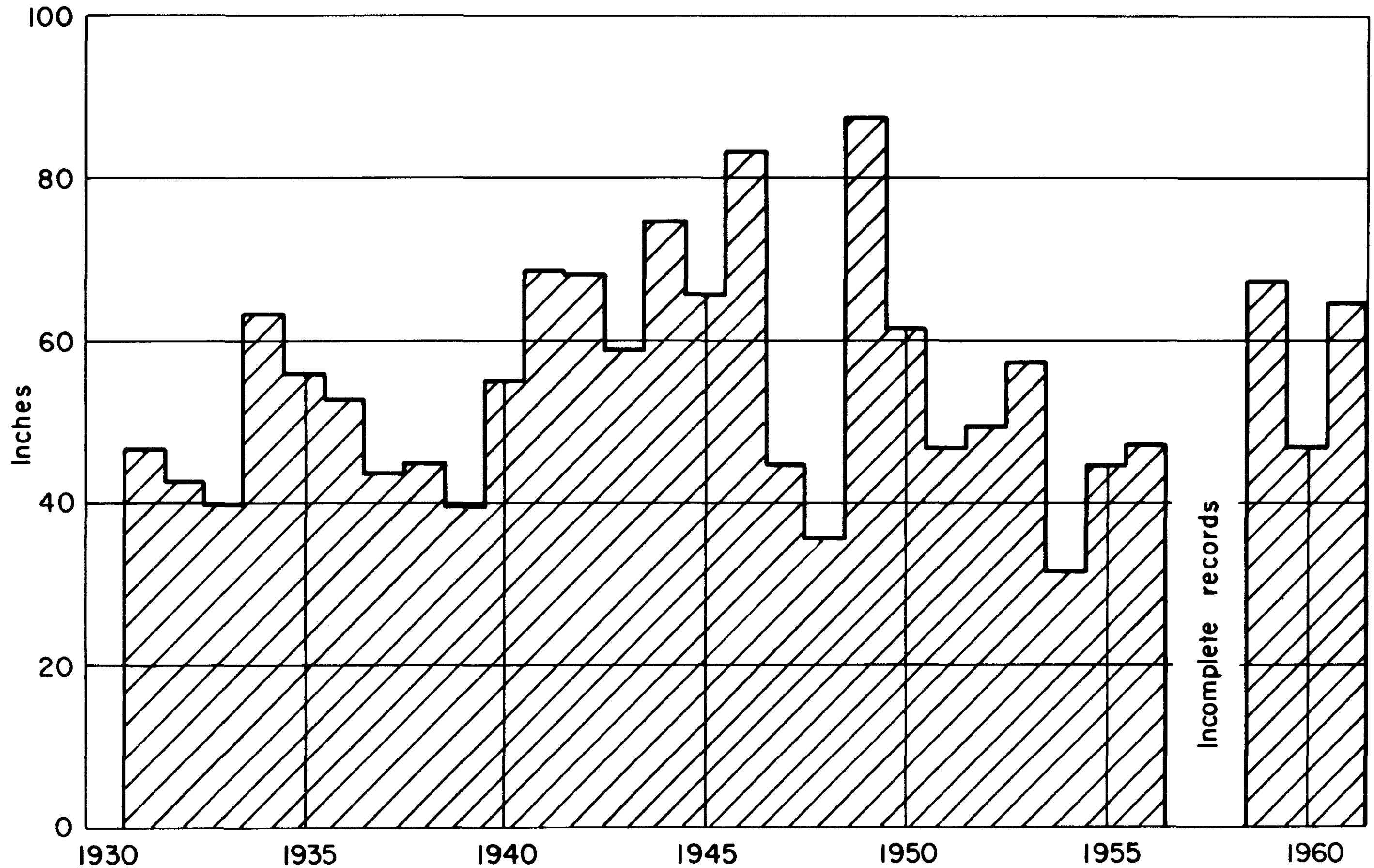

Figure 2

Annual Precipitation at Beaumont, Jefferson County

(From records of U.S. Weather Bureau)

U. S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

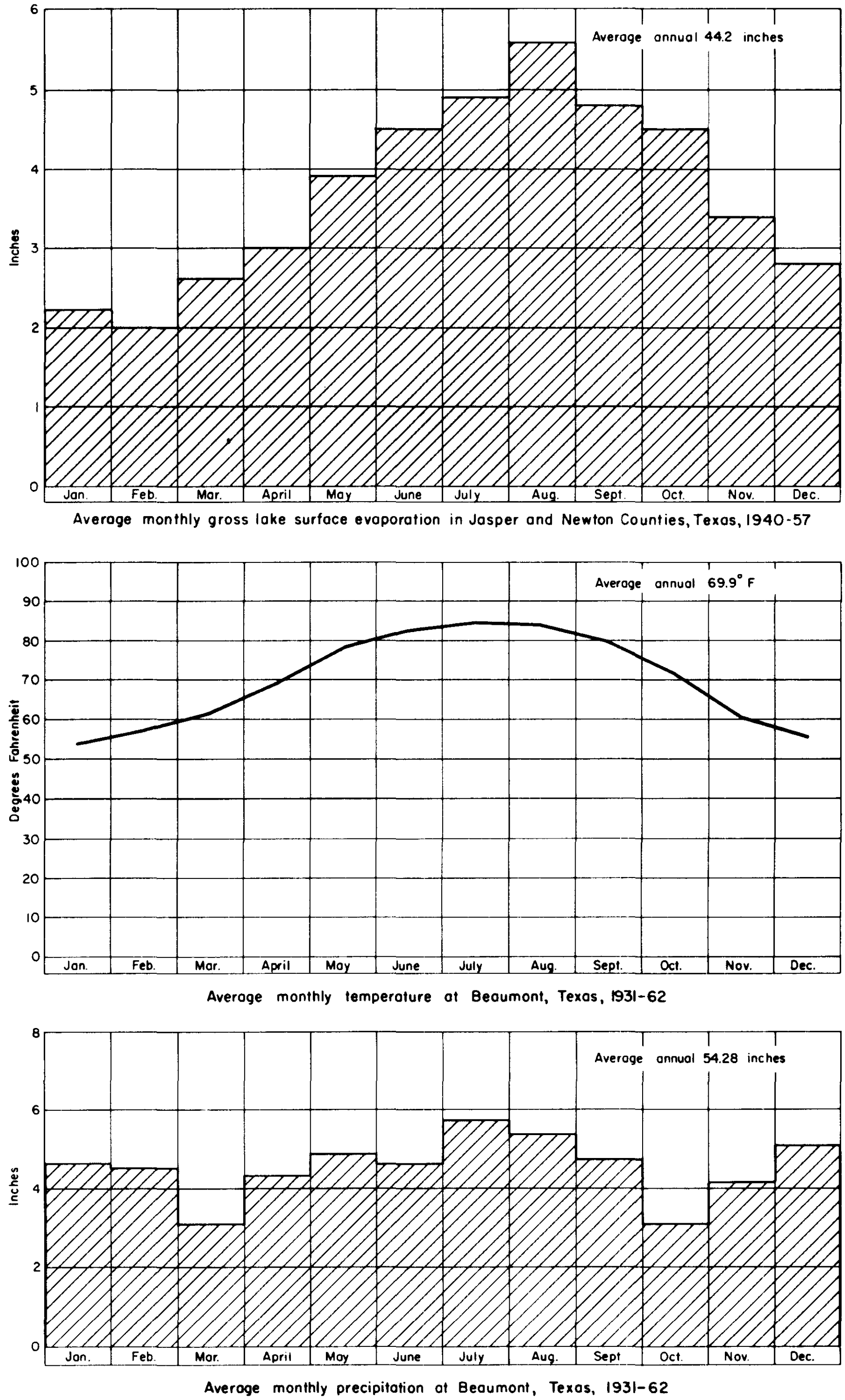

Figure 3

Average Monthly Precipitation and Temperature at Beaumont, and Average Monthly Gross Lake Surface Evaporation in Jasper and Newton Counties

(From records of U.S. Weather Bureau, and Lowry, 1960)

U. S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

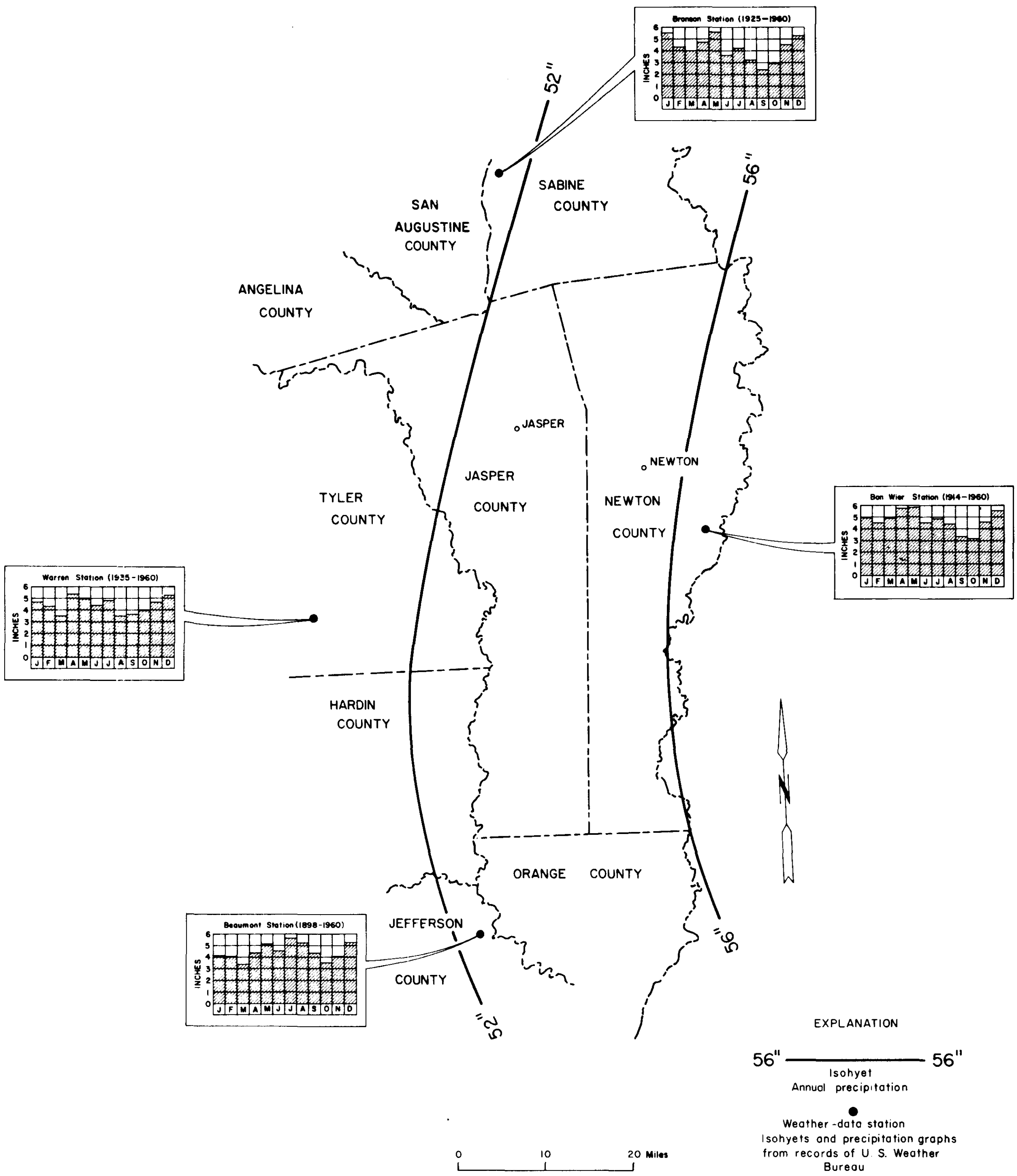

Figure 4

Average Annual Precipitation 1931-60, and Average Monthly Precipitation for Period of Record at Selected Stations in Jasper and Newton Counties and Adjacent Areas

U. S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

the northern parts of the counties have earlier frosts, more freezing days, a shorter growing season, and a greater daily and seasonal variation in temperature.

The average annual net lake surface evaporation rate in the report area was about 3 inches from 1940 to 1957 and about 10 inches from 1950 to 1956 (Lowry, 1960, pls. 2 and 3). These evaporation rates were derived by subtracting the effective rainfall from the gross lake surface evaporation.

Well-Numbering System

The well-numbering system in this report is the one adopted by the Texas Water Development Board for statewide use and is based on latitude and longitude.

Under this system, each 1-degree quadrangle in the State is given a number consisting of two digits. These are the first two digits in the well number which are indicated on Figure 27 by the large double-lined numbers: 36, 37, 61, and 62. The 1-degree quadrangles are divided into 7-1/2 minute quadrangles, which are given two-digit numbers from 01 to 64. These are the third and fourth digits of the well number which are shown in the northwestern corner of each 7-1/2 minute quadrangle on Figure 27. Each 7-1/2 minute quadrangle is subdivided into 2-1/2 minute quadrangles and given a single digit number from 1 to 9. This is the fifth digit of the well number. The wells within a 2-1/2 minute quadrangle are given two-digit numbers as they are inventoried, beginning with 01. These are the last two digits of the number used to identify each well. The last three digits are given at the well location on Figure 27. A two-letter prefix is used to identify the county. Prefixes for Jasper, Newton, and adjacent counties are as follows:

County	Prefix	County	Prefix
Jasper	PR	Hardin	LH
Newton	TZ	San Augustine	WT
Orange	UJ	Sabine	WS
Tyler	YJ		

Acknowledgements

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Well drillers generously supplied drillers' logs, electrical logs, and well-completion data. All landowners contacted granted access to their lands, wells, and records.

GEOLOGY AS RELATED TO THE OCCURRENCE OF GROUND WATER

General Stratigraphy and Structure

Geologic units discussed in this report are, in order of decreasing age: the Yegua Formation and Jackson Group of Eocene age, rocks of Oligocene age equivalent to the Vicksburg Formation in Louisiana, the Catahoula Sandstone of Miocene(?) age, the Oakville Sandstone of Miocene age, the Lagarto Clay of Miocene(?) age, the Goliad Sand of Pliocene age, the Willis Sand of Pliocene(?) age, the Lissie Formation and Beaumont Clay of Pleistocene age, and the alluvium of Recent age. The physical characteristics and water-bearing properties of the geologic units are summarized in Table 2. The geologic and hydrologic units in this report are correlated with the units in related reports (Table 3). The geology and locations of wells are included in a map of the report area (Figure 27). On this map the geology is shown in two subdivisions (from Bernard, 1950): formations of Tertiary age--which include the Catahoula Sandstone, the Lagarto Clay and Oakville Sandstone, and the Goliad Sand; and formations of Quaternary age--which include the Willis Sand, the Lissie Formation, the Beaumont Clay, and the alluvium. Figures 28, 29, 30, and 31 are sections showing geologic and hydrologic units. The regional strike of the beds is generally east-northeast and parallel to the coastline of the Gulf of Mexico. The beds dip toward the Gulf of Mexico, and most of them thicken in the downdip direction (Figure 28). Consequently, the formations form a homocline, with the older beds dipping at steeper angles than younger beds. The Yegua Formation and the Jackson Group crop out north of Jasper and Newton Counties; the younger formations crop out in the report area. The Tertiary formations are overlain by gently dipping beds of Pleistocene and Recent age in all of the southern and central parts of the report area and in much of the northern part (Figure 27).

Sand, gravel, silt, clay, shale, and marl comprise most of the sediments in the report area, but locally they contain minor amounts of limestone, lignite, and volcanic ash. They were deposited by rivers as valley deposits or as coalescing deltas or lagoonal deposits on or near a migrating shoreline, or as marine deposits near or offshore from the coast. Petrified wood is common in some of the sand deposits, and marine fossils are common in some clay and marl units. In general, coarser materials are found updip; but downdip the material tends to become finer and grade into clays or marls. Some clay beds, such as those in the Lagarto Clay and the Catahoula Sandstone, are of marine origin. The beds of sand and clay are lenticular and are difficult, if not impossible, to trace. However, entire zones of alternating clay and sand can often be traced over extended areas.

Faults are common in both counties. Oil fields have been developed along faults at several localities in both counties. Traces of faults can be observed at the surface, particularly in the outcrop areas of Tertiary rocks. Downdip from the Tertiary outcrops, surface traces tend to be obscured by the overlying Pleistocene deposits. Bernard (1950, p. 134-136), however, reports a prominent set of strike faults, averaging N. 80° E. on the Pleistocene surface in the report area. Most of the faults are normal and downthrown to the south. No hydrologic effect from a specific fault or system of faults was recognized in the report area. However, faulting probably causes some of the anomalous changes in the altitude of the base of fresh water shown on Figures 5, 7, and 9.

Table 2.--Physical characteristics and water-bearing properties of the geologic units

System	Series	Geologic unit	Composition	Water-bearing properties and distribution of supply
Quaternary	Recent	Alluvium	Gravel, sand, silt, and clay.	CHICOT AQUIFER. Capable of yielding large[2] quantities of fresh water[3] to wells in most of the southern part of the report area.
	Pleistocene	Beaumont Clay	Gravel and clay.	
		Lissie Formation	Gravel, sand, silt, and clay.	
Tertiary(?)	Pliocene(?)	Willis Sand	Gravel and sand.	
Tertiary	Pliocene	Goliad Sand	Sand, silt, and clay. Sand comprises 35-50 percent of the formation.	EVANGELINE AQUIFER. Capable of yielding large quantities of fresh water to wells in the southern part of the report area.
	Miocene(?) and Miocene	Lagarto Clay and Oakville Sandstone	Upper clay, 200-300 ft thick; contains minor amounts of sand.	BURKEVILLE AQUICLUDE.
			Calcareous clay and silt interbedded with sand. Maximum thickness of individual sand beds is 200 ft. Locally sand beds grade into conglomerate.	JASPER AQUIFER. Capable of yielding large quantities of fresh water to wells in the central and much of the northern part of the report area.
	Miocene(?)	Catahoula Sandstone	Sand in lower part, sand and shale in the middle, and clay in the upper part.	Capable of yielding small to large[2] quantities of fresh to slightly saline[3] water to wells in the northern part of the report area.
	Oligocene	[1]	Clay, with a few thin beds of sand.	Capable of yielding small quantities of fresh to slightly saline water to wells in the northern part of the report area.
	Eocene	Jackson Group		Capable of yielding small quantities of fresh to slightly saline water in the northwestern part of Jasper County.
		Yegua Formation	Sand, silt, and clay.	Capable of yielding small quantities of slightly to moderately saline water[3] to wells near the northern boundary of the report area.

[1] Rocks of Oligocene age equivalent to the Vicksburg Formation in Louisiana.
[2] Yield of wells: small, less than 100 gpm (gallons per minute); large, more than 1,000 gpm.
[3] Quality of water as ppm (parts per million) of dissolved solids: fresh, less than 1,000 ppm; slightly saline, 1,000-3,000 ppm; moderately saline, 3,000-10,000 ppm. (From table in section on quality of ground water.)

Table 3.--Stratigraphic and hydrologic units used in this report and in recent reports of adjacent areas

		Harder (1960)		Rogers and Calandro (1965)		Baker and others (1963a & b)		Baker (1964)		Wesselman (1965)		This report			
System 1/	Series 1/	Formation	Hydrologic unit	Group or Formation	Hydrologic unit	Group or Formation	Hydrologic unit	Formation	Hydrologic unit	Formation	Hydrologic unit	Group or Formation	Hydrologic unit	Series	System
Quaternary	Recent	Alluvium		Alluvium	Alluvium	Alluvium		Flood Plain and Terrace Deposits		Alluvium	Upper aquifer	Alluvium		Recent	Quaternary
	Pleistocene	Prairie formation Montgomery formation	Chicot aquifer	Stream terrace and upland deposits	Stream terrace and upland deposits	Beaumont Clay	GULF COAST AQUIFER	Beaumont Clay	GULF COAST AQUIFER	Beaumont Clay		Beaumont Clay	Chicot aquifer	Pleistocene	
		Bentley formation				Lissie Formation		Lissie Formation		Lissie Formation	Middle aquifer	Lissie Formation			
		Williana formation				Willis Sand		Willis Sand		Willis Sand	Lower aquifer	Willis Sand		Pliocene(?)	Tertiary(?)
Tertiary	Pliocene	Foley formation	Evangeline aquifer	Fleming Formation of Kennedy (1892) ?	Blounts Creek Member ?	Goliad Sand		Goliad Sand		Goliad Sand		Goliad Sand	Evangeline aquifer	Pliocene	
	?	?	? ?		Castor Creek Member	Lagarto Clay		Lagarto Clay				Lagarto Clay	Burkeville aquiclude	Miocene(?)	
	Miocene	Fleming formation of Fisk (1940)			Williamson Creek Member	Oakville Sandstone		Oakville Sandstone				Oakville Sandstone	Jasper aquifer	Miocene	Tertiary
					Dough Hills Member										
					Carnahan Bayou Member										
					Lena Member	Catahoula Sandstone						Catahoula Sandstone	Catahoula Sandstone	Miocene(?)	
		Catahoula formation		Catahoula Formation	Catahoula Formation										
	Oligocene			Vicksburg Group	Sandel Formation of Anderson (1960)							2/	2/	Oligocene	
	Eocene			Jackson Group	Jackson Group	Jackson Group	Jackson Group					Jackson Group	Jackson Group	Eocene	
				Cockfield Formation	Cockfield Formation	Yegua Formation	Yegua Formation					Yegua Formation	Yegua Formation		

1/ Applicable to Harder (1960) and Rogers and Calandro (1965)
2/ Rocks of Oligocene age equivalent to the Vicksburg Formation in Louisiana.

Deep salt intrusions are probably associated with some of the oil-bearing structures. Logs do not indicate the penetration of salt by oil tests in the report area, and such intrusions are believed to be too deep to have a direct effect on the fresh ground water in Jasper and Newton Counties. Emplacements of salt at shallow depth do affect the ground water in neighboring counties and parishes.

Major Hydrologic Units

An aquifer is a geologic formation, group of formations, or part of a formation that is water-bearing. An aquiclude is an impermeable or relatively impermeable rock that may contain water but is incapable of transmitting an appreciable quantity. The correlations of the stratigraphic and hydrologic units are shown in Tables 2 and 3. The major hydrologic units are the Jasper aquifer, Burkeville aquiclude, Evangeline aquifer, and Chicot aquifer. The Yegua Formation, Jackson Group, and Catahoula Sandstone contain aquifers of minor importance in the report area.

Jasper Aquifer

The Lagarto Clay and Oakville Sandstone have not been differentiated on the surface in southeast Texas. In the report area, the Lagarto and Oakville comprise a thick sequence of calcareous clay and silt interbedded with sand. In the upper part of the sequence there is a clay unit, 200 to 300 feet thick, that contains minor amounts of sand. This clay unit is equivalent in part to the Castor Creek Member (Fisk, 1940) of the Fleming Formation (Kennedy, 1892) in Vernon Parish (Rogers and Calandro, 1965). (See Table 3.)

The Jasper aquifer, as named in this report, includes all the sediments between the upper clay bed of the Catahoula Sandstone and the clay unit mentioned above. The aquifer consists of about 50 percent sand and is equivalent to the Carnahan Bayou, Dough Hills, and Williamson Creek Members (Fisk, 1940) of the Fleming Formation (Kennedy, 1892) in Vernon Parish (Rogers and Calandro, 1965). (See Table 3.)

The aquifer is named for the town of Jasper. It is the principal aquifer in the report area in terms of storage, availability, quality of water, and potential for development. The approximate altitudes of the base of the Jasper aquifer and the base of fresh water, and the approximate downdip limits of fresh water and slightly saline water are shown on Figure 5. The Jasper aquifer contains fresh water to depths of more than 3,000 feet below sea level in the area east of Kirbyville. In most of the northern half of the report area, all the sands in the aquifer contain fresh water; but in the southern half, sands containing fresh water overlie and intertongue with those containing slightly saline water (Figures 28, 29, 30, and 31).

The approximate thickness of sands containing fresh water in the Jasper aquifer is shown in Figure 6. In the northern parts of Jasper and Newton Counties, the sand thickness progressively increases southward to more than 900 feet in the area between Kirbyville and Bon Wier; southward from this area, the sand thickness progressively decreases to zero in the southern part of the report area.

The Jasper aquifer furnishes the water supplies for the towns of Jasper, Newton, Kirbyville, and Burkeville and for the community of Harrisburg. It supplies the water needs for all rural users in about a third of the report area.

Burkeville Aquiclude

The Jasper and Evangeline aquifers are separated by the Burkeville aquiclude, a clay bed that is usually 200 to 300 feet thick (Figures 28, 30, and 31). This clay bed, which contains minor amounts of sand in places, crops out in the vicinity of Burkeville and is named the Burkeville aquiclude in this report. As previously discussed, the clay is in the upper part of the undivided Lagarto and Oakville Formations and is equivalent in part to the Castor Creek Member (Fisk, 1940) of the Fleming Formation of Kennedy (1892), as mapped by Rogers and Calandro (1965) in Vernon Parish (Table 3). The Burkeville aquiclude also is equivalent to "Zone 2," which directly underlies the "heavily pumped layer" in the Houston district (Wood and Gabrysch, 1965, Figure 4).

Evangeline Aquifer

The Evangeline aquifer in the report area includes all the sediments between the Burkeville aquiclude and the Chicot aquifer. It comprises the Goliad Sand and sands at the top of the Lagarto and Oakville Formations, and is equivalent to the "heavily pumped layer" in the Houston district (Wood and Gabrysch, 1965). In Louisiana, the Evangeline aquifer is equivalent to the Blounts Creek Member (Fisk, 1940) of the Fleming Formation of Kennedy (1892) in Vernon Parish (Rogers and Calandro, 1965), and the Foley Formation in Calcasieu Parish (Harder, 1960). (See Table 3.)

The approximate altitudes of the base of the Evangeline aquifer and the base of fresh water in the aquifer are shown on Figure 7. The aquifer contains fresh water to depths of more than 1,500 feet below sea level in an area near the southern boundaries of Jasper and Newton Counties. North of the line designated as "Downdip limit of aquifer containing only fresh water" on Figure 7, all the sands in the aquifer contain fresh water (Figures 28, 29, and 30); south of this line, the sands contain fresh, slightly saline, and more highly saline water (Figures 28 and 31). The downdip limit of fresh water in the aquifer is in Orange County. The estimated thickness of fresh-water sands in the Evangeline aquifer (Figure 8) is more than 500 feet in the southern parts of Jasper and Newton Counties.

In 1965, the Evangeline aquifer supplied more than 80 percent of the ground water used in Jasper and Newton Counties.

Chicot Aquifer

The Chicot aquifer comprises the Willis Sand, the Lissie Formation, the Beaumont Clay, and the Recent alluvium. The basis for the separation of the Evangeline aquifer from the overlying Chicot is their differences in lithology and permeability. No continuous clay separation exists between the two aquifers. The Chicot is equivalent to: the Williana, Bentley, Montgomery, and Prairie Formations in Calcasieu Parish (Harder, 1960), Louisiana; to the "Upper" and "Middle" aquifer units in Orange County (Wesselman, 1965), Texas; and, at least in part, to the Alta Loma Sand of Rose (1943, p. 3) in the Houston district, Texas.

The approximate altitude of the base of the Chicot aquifer is shown on Figure 9. As previously mentioned, the Recent alluvium, Beaumont Clay and Lissie Formation of Pleistocene age, and the Willis Sand of Pliocene(?) age comprise the rocks designated as the Quaternary System on Figure 27. The water-bearing beds in these formations comprise also the Chicot aquifer, the updip limit of which is shown by the line designated as the "Updip limit of Chicot aquifer" on Figure 9. South of this line the Chicot aquifer is a continuous hydraulic unit. North of the line only remnants of the formations that comprise the Chicot are present. The remnants overlie the Jasper and Evangeline aquifers and most of the water in them passes as recharge to the underlying aquifers.

The Chicot aquifer contains only fresh water in Jasper and Newton Counties. The approximate thickness of the sands in the Chicot aquifer is shown on Figure 10. These sands are more than 400 feet thick in the southern part of Newton County.

Sands of the Chicot are generally more permeable than those of the Evangeline and Jasper aquifers. In much of the report area, the electric logs show a thick, high-resistivity sand at the base of the Chicot.

The Chicot aquifer supplies water for rice irrigation and domestic use to rural dwellings in the southern parts of Jasper and Newton Counties and to the town of Buna.

Minor Hydrologic Units

Yegua Formation

The Yegua Formation is not a source of fresh water in Jasper and Newton Counties. However, it contains small quantities of slightly to moderately saline water in the extreme northern parts of either county. Deussen (1914) reported slightly saline water from a well (PR-36-49-802) in northeast Jasper County. Five sands were screened between depths of 1,037 and 1,320 feet--the uppermost of these sands is probably in the Jackson Group, but the basal sand is in the Yegua Formation.

Jackson Group

Available electric logs and well data indicate that the Jackson Group contains fresh or slightly saline water in one locality in the report area. In the northwestern part of Jasper County a flowing well (PR-37-61-901), 986 feet deep, produces fresh water with traces of oil and gas. Logs of nearby oil tests indicate that individual fresh-water-bearing sands as much as 20 feet thick occur at depths from 710 to 935 feet below land surface. The maximum sand thickness shown on one log is 40 feet. In places in northwestern Jasper County, the sandy beds in the Jackson Group are the only dependable source of fresh ground water. However, the presence or absence of these sands and the quality of the water in them can be detected only by test drilling.

Catahoula Sandstone

The sands of the Catahoula Sandstone compose a separate hydrologic unit. The approximate altitude of the base of the Catahoula Sandstone in Jasper and Newton Counties and the approximate downdip limits of fresh and slightly saline water are shown on Figure 11.

The Catahoula Sandstone is overlain by younger fresh-water sands in much of Jasper and Newton Counties. Few data are available concerning the geologic or hydrologic properties of the Catahoula. However, electric logs of oil tests in Jasper and Newton Counties indicate that 700 feet is the maximum thickness for the Catahoula in the area where it contains fresh or slightly saline water (Figure 11). According to these logs, the thickness of individual sand beds is as much as 60 feet, and a total of approximately 230 feet of sand is the maximum observed on any one log (TZ-36-59-501).

In most of the area in Jasper County where the Catahoula contains fresh water, sands containing slightly and moderately saline water are interbedded with those containing fresh water. In places in the extreme northwestern extension of Jasper County, fresh water is not available in the Catahoula Sandstone.

GROUND-WATER HYDROLOGY

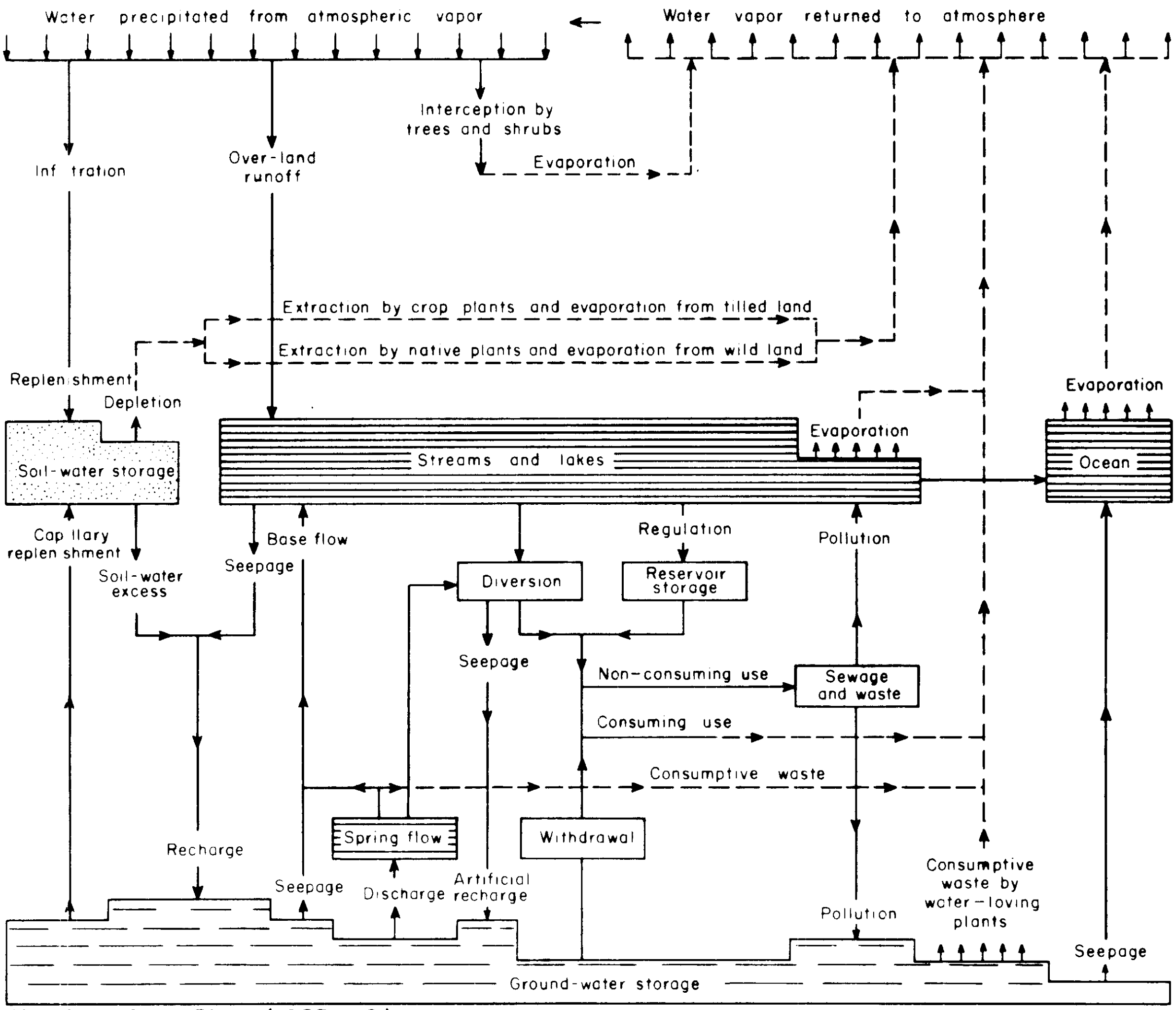
Ground water is an integral part of the hydrologic cycle as shown in Figure 12 (Piper, 1953, p. 9). In this diagram, the complex course of water is traced from precipitation to surface and ground water and to its eventual return to water vapor in the atmosphere. For a comprehensive discussion of hydrologic principles, the reader is referred to: Meinzer (1923a and 1923b), Meinzer and others (1942), Todd (1959), Tolman (1937), and Wisler and Brater (1959); for non-technical discussions, to Leopold and Langbein (1960), and Baldwin and McGuinness (1963).

The following discussion concerns the general principles of ground-water hydrology as applied in Jasper and Newton Counties.

Source and Occurrence of Ground Water

The principal source of fresh ground water is precipitation on the outcrops of the aquifers. Much of this precipitation runs off as streamflow. Part of it is evaporated at the land surface, transpired by plants, or retained by capillary forces in the soil; the remainder moves downward by gravity through the zone of aeration to the zone of saturation. In this zone, the rocks are saturated with water; that is, water fills all of the pore spaces between rock particles (such as sand grains).

Water-bearing rock units, or aquifers, are of two types--water table, or unconfined aquifers, and artesian, or confined aquifers. Unconfined water occurs where the upper surface of the zone of saturation is under atmospheric pressure only and the water is free to rise or fall in response to the changes in the volume of water in storage. The upper surface of the zone of saturation is the water table, and a well penetrating an aquifer under water-table conditions becomes filled with water to the level of the water table. Water-table conditions occur in the outcrop areas of the aquifers.



Modified from Piper (1953, p.9)

Figure 12

Hydrologic Cycle

U. S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

Confined water occurs where an aquifer is overlain by rock of lower permeability, such as clay, that confines the water under a pressure greater than atmospheric. Such artesian conditions occur downdip from the outcrop of the aquifer. A well penetrating sands under artesian pressure becomes filled with water to a level above the base of the confining layer of rock; and, if the pressure head is large enough to cause the water in the well to rise to an altitude greater than that of the land surface, the well will flow. Flowing wells are most common at the lower altitudes, especially in the valleys of the larger streams. The level or surface to which water will rise in artesian wells is called the piezometric surface.

Recharge, Movement, and Discharge of Ground Water

The main source of the recharge to the aquifers in Jasper and Newton Counties is the direct infiltration of rainfall. Small amounts of artificial recharge such as infiltration of irrigation water, industrial waste water, or sewage, occurs in local areas in Jasper and Newton Counties.

Sand and gravel cap most of the hills in the upland areas north of Kirbyville and overlie alternating beds of sand and shale. Precipitation infiltrates the caps of sand and gravel and perched ground water is usually present in the larger hills. Some of the water recharges underlying sands, but most of it is discharged as spring flow especially where the shale beds crop out in the valleys of the deeply entrenched streams.

Some of the recharge moves downdip in a southerly direction from the outcrop areas to the artesian parts of the aquifers, usually at rates of less than a foot per day under natural conditions.

In addition to recharge from outcrop areas, many artesian aquifers are supplied by the movement of water from adjacent aquifers. Under natural conditions, water moves slowly upward through the relatively impermeable confining beds into other aquifers or to the land surface. The rate of movement depends on the thickness and vertical permeability of the confining beds and the head differential of the aquifer. However, heavy withdrawals from a deep aquifer can cause a downward movement of water from an overlying aquifer. In southwestern Jasper County where there are heavy withdrawals from the Evangeline aquifer, most of the water is supplied by downward movement from the overlying Chicot aquifer.

The natural discharge of ground water in the report area consists mostly of the spring flow and evapotranspiration losses in the outcrop areas. Ground water is discharged artificially by pumping or flowing wells.

Hydraulic Characteristics of the Aquifers

"The worth of an aquifer as a fully developed source of water depends largely on two inherent characteristics: its ability to store and its ability to transmit water" (Ferris and others, 1962, p. 70). Measurements of these characteristics are the coefficients of storage and transmissibility.

The coefficient of storage of an aquifer is the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. In the water-table aquifer, the coefficient of storage is nearly equal to the specific yield, which is the amount of water a saturated formation will yield by draining under the force of gravity. The storage coefficients of water-table aquifers range from about 0.05 to about 0.30; whereas, those of artesian aquifers range from about 0.00001 to 0.001. Where artesian conditions prevail, the coefficient of storage is a measure of the elasticity of the aquifer.

The coefficient of storage is important in any calculation of the quantity of water that could be obtained from an aquifer; but the availability of the water, especially in an artesian aquifer, depends primarily on the ability of the aquifer to transmit water. The coefficient of permeability is a measure of that ability and is defined as the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a unit hydraulic gradient (1 foot per foot) at a temperature of 60°F. In field practice the adjustment of 60°F is commonly disregarded, and the permeability is then understood to be a field coefficient at the prevailing water temperature. The coefficient of transmissibility is the product of the field coefficient of permeability and the saturated thickness of the aquifer.

The specific capacity of a well is its yield per unit drawdown and is directly related to transmissibility. The measured specific capacity may differ from the computed theoretical specific capacity of a well because of one or more reasons. Improper well construction and development, screen losses, unfavorable local geologic conditions, screening only part of the available aquifer--all are factors which will decrease the measured specific capacity. On the other hand, in some wells the effective diameter may be increased by proper development. As a result, the measured specific capacity can be larger than the theoretical. Wood and others (1963, p. 40) reported that "...the measured specific capacities of most wells in the region [Gulf Coast] are smaller than the theoretical, indicating that many of the sands in the gravel-packed zone are poorly connected to the interior of the screen so that 'screen losses' are considerable during pumping."

The coefficients of storage and transmissibility of the aquifers were determined by aquifer tests made in wells in Jasper, Newton, Orange, and Hardin Counties. The test data were analyzed by the Theis non-equilibrium method as modified by Cooper and Jacob (1946, p. 526-534), or by the Theis recovery method (Wenzel, 1942, p. 95-97). The results of the tests and specific capacities of the wells are shown in Table 4. Because none of the wells are completed in a full section of an aquifer, and some in only a small part of an aquifer, the figures in the table are less than the aquifer's total capability.

The coefficients of transmissibility and storage may be used to predict future drawdowns in water levels caused by pumping. The theoretical relation between drawdown and distance from the center of pumping for different coefficients of transmissibility is shown in Figure 13. The calculations of drawdown are based on a withdrawal of 1 mgd (million gallons per day) for 1 year from an aquifer having coefficients of transmissibility and storage as shown. For example, if the coefficients of transmissibility and storage are 50,000 gpd (gallons per day) per foot and 0.001, respectively, the drawdown or decline in the water level would be 12 feet at a distance of 1 mile from a well or group of wells discharging 1 mgd for 1 year. If the coefficients of transmissibility and storage are 5,000 gpd per foot and 0.0001, respectively, the same pumping rate for the same time would cause 84 feet of decline at the same distance.

Table 4.--Summary of aquifer tests in Jasper, Newton, Orange, and Hardin Counties, Texas

Well	Date	Coefficient of transmissibility (gpd per ft)	Coefficient of permeability (gpd per ft^2)	Coefficient of storage	Specific capacity (gpm per ft of drawdown)	Remarks
			Jasper Aquifer			
PR-61-07-302	Mar. 26, 1964	12,300	304	--	--	Recovery test. 26 ft screen, 40 ft sand.
303	do	11,100	277	1.19×10^{-3}	--	Interference test. Assumed 40 ft sand for coefficient of permeability.
62-01-401	Dec. 20, 1955	86,400	655	--	16	Recovery test. Specific capacity from 24 hour test. 132 ft screen.
402	do	59,000	760	3.82×10^{-4}	8	Interference test. Specific capacity reported by driller. 78 ft screen.
403	Dec. 21, 1955	65,500	602	5.9×10^{-4}	5	Interference test. 92 ft screen. Specific capacity reported by driller.
404	Dec. 20, 1955	58,300	730	--	10	Recovery test. 80 ft screen. Specific capacity reported by driller.
406	Dec. 17&22, 1964	89,800	550	--	39.4	Average of two drawdown and recovery tests. 163 ft screen. 2 hour specific capacity at 1,500 gallons per minute was 34.9 gpm ft.
17-901	Mar. 4, 1965	81,500	--	--	2	Recovery test.
25-601	July 8, 1964	8,000	--	--	.4	Recovery test. 61 ft screen. Has some screen opposite fine-grained sand in the Burkeville aquiclude. Did not use in computing averages.
TZ-62-10-309	Feb. 24, 1964	105,000	--	--	10	100 minute recovery test. Specific capacity from 20 hour test. 100 ft screen. Indicated T from first 20 minutes of recovery = 51,333.
26-203	Mar. 9, 1965	19,100	478	--	1.5	Recovery test. 40 ft slotted pipe.
			Evangeline Aquifer			
LH-61-47-201	Dec. 1952	18,000	156	--	15.6	
202	Dec. 6&7, 1952	16,000	131	--	12.8	
208	Jun. 6, 1962	38,000	304	--	17.5	
55-203	Feb. 16&19, 1962	63,000	181	--	45.5	
204	May 5, 1958	65,000	188	--	37.7	
PR-61-48-202	Feb. 23, 1954	50,000	213	--	44.2	Recovery test.
203	Feb. 22, 1954	83,000	332	8.9×10^{-4}	27.2	Interference test.
204	do	111,000	300	6.3×10^{-4}	46.4	Do.
205	do	90,000	290	8.3×10^{-4}	37.3	Do.
207	Nov. 16, 1953	42,000	257	1.5×10^{-3}	18.2	Recovery test.
208	Feb. 22, 1954	94,000	362	1.3×10^{-3}	38.2	Interference test.
301	do	111,000	411	7.9×10^{-4}	35.4	Do.
TZ-64-19-802	Oct. 13, 1964	28,500	--	--	--	Recovery test. Not used to compute averages.
			Chicot aquifer			
PR-62-33-401	Feb. 29, 1965	136,000	1,240	--	11	Recovery test. 24 hour specific capacity.
41-801	Apr. 15, 1964	92,500	1,130	--	--	Recovery test.
TZ-62-42-701	do	302,000	910	--	--	Do.
UT-62-50-201	June 3, 1964	510,000	1,700	--	--	Do.
49-601	May 30, 1960	490,000	1,630	--	--	Do.

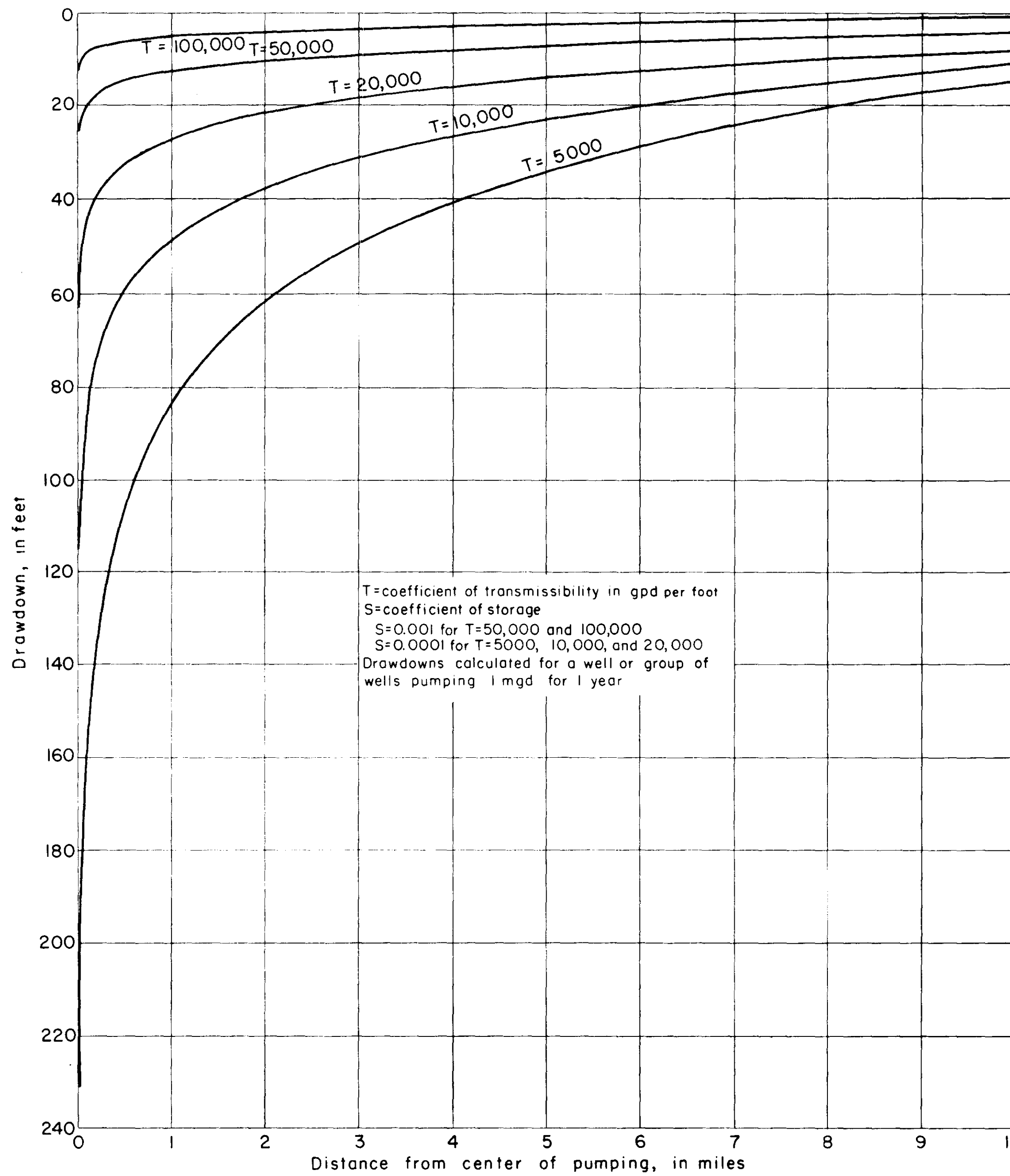


Figure 13

Relation of Drawdown to Transmissibility and Distance

U. S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

In Figure 14 is shown the relation of drawdown to distance and time as a result of pumping from an aquifer, with characteristics similar to those of the Evangeline aquifer, where artesian conditions prevail and where infinite areal extent is assumed. Also shown is the fact that the rate of drawdown decreases with time. For example, if the drawdown at 100 feet from a well is 11 feet after 1 mgd has been pumped for 1 year, the drawdown would be about 15 feet after 1 mgd has been pumped for 100 years. The total drawdown at any one place within the cone of depression or the influence of several wells would be the sum of the influences of the several wells. The equilibrium curve illustrates the time-drawdown relation when a line source of recharge is 25 miles from the point of discharge.

Figure 15 shows the relation of drawdown to distance and time as a result of pumping from a water-table aquifer with characteristics similar to those of the Jasper and Evangeline aquifers, and with infinite areal extent being assumed. The drawdown is less than that in an artesian aquifer because of the larger coefficient of storage.

In Figure 16 is shown the relation of drawdown to distance and time due to pumping in an artesian aquifer having hydraulic properties similar to those of the Jasper and Chicot aquifers.

Overlapping of cones of depression or interference between wells may cause a decrease in yield of the wells, or an increase in pumping costs, or both. Moreover, when the pumping level declines below the top of the screen in a well, the saturated thickness of the aquifer decreases; the result is a decrease in the yield and efficiency of the well.

Major Aquifers

Jasper Aquifer

The coefficients of transmissibility from aquifer tests on 11 wells that tap the Jasper aquifer in Jasper and Newton Counties (Table 4) ranged from 8,000 gpd per foot at well PR-62-25-601 to 105,000 gpd per foot at well TZ-62-10-309. Coefficients of storage determined from three tests ranged from 0.00038 to 0.0012. The coefficients of permeability determined from the tests ranged from 277 to 760 gpd per square foot and averaged 545 gpd per square foot. Rogers and Calandro (1965) have reported a range in coefficients of permeability from 300 to 850 gpd per square foot for the three stratigraphic units in Vernon Parish which correspond to the Jasper aquifer.

Figure 6 shows the thickness of the sands containing fresh water in the Jasper aquifer. In the northern part of the report area where the sands are 550 feet thick, the transmissibility of the entire thickness of the aquifer probably would be about 300,000 gpd per foot (550 feet times 545 gpd per square foot, the average coefficient of permeability). With one exception (well TZ-62-26-203), the aquifer tests upon which permeability is based are located updip from the 500-foot contour in the northern part of Jasper County. The coefficient of permeability will probably be less downdip. This may be indicated by the 478 gpd per square foot at well TZ-62-26-203.

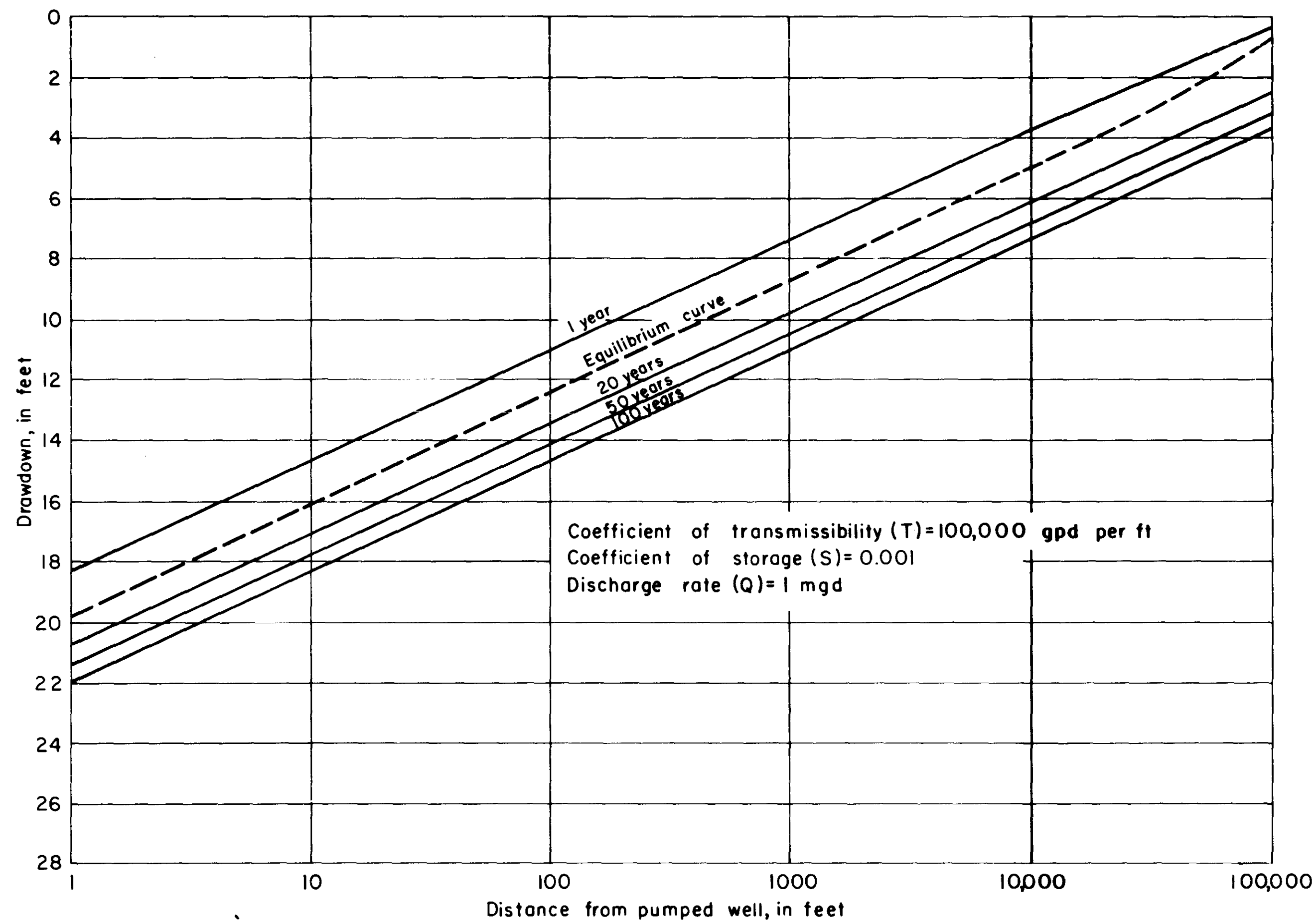


Figure 14

Relation of Drawdown to Distance and Time as a Result of Pumping from the Evangeline Aquifer Under Artesian Conditions

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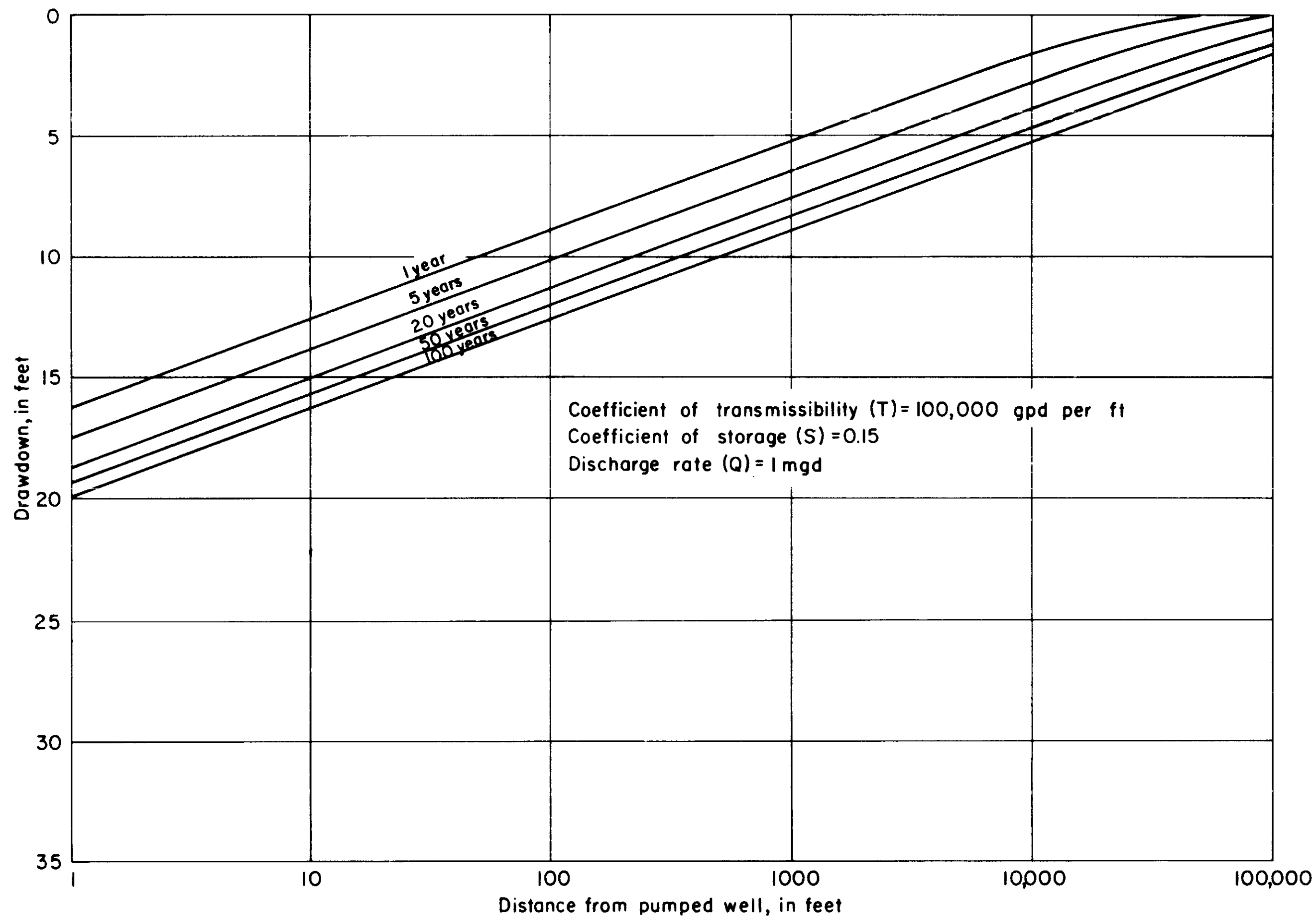


Figure 15

Relation of Drawdown to Distance and Time as a Result of Pumping from the Jasper and Evangeline Aquifers Under Water-Table Conditions

U. S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

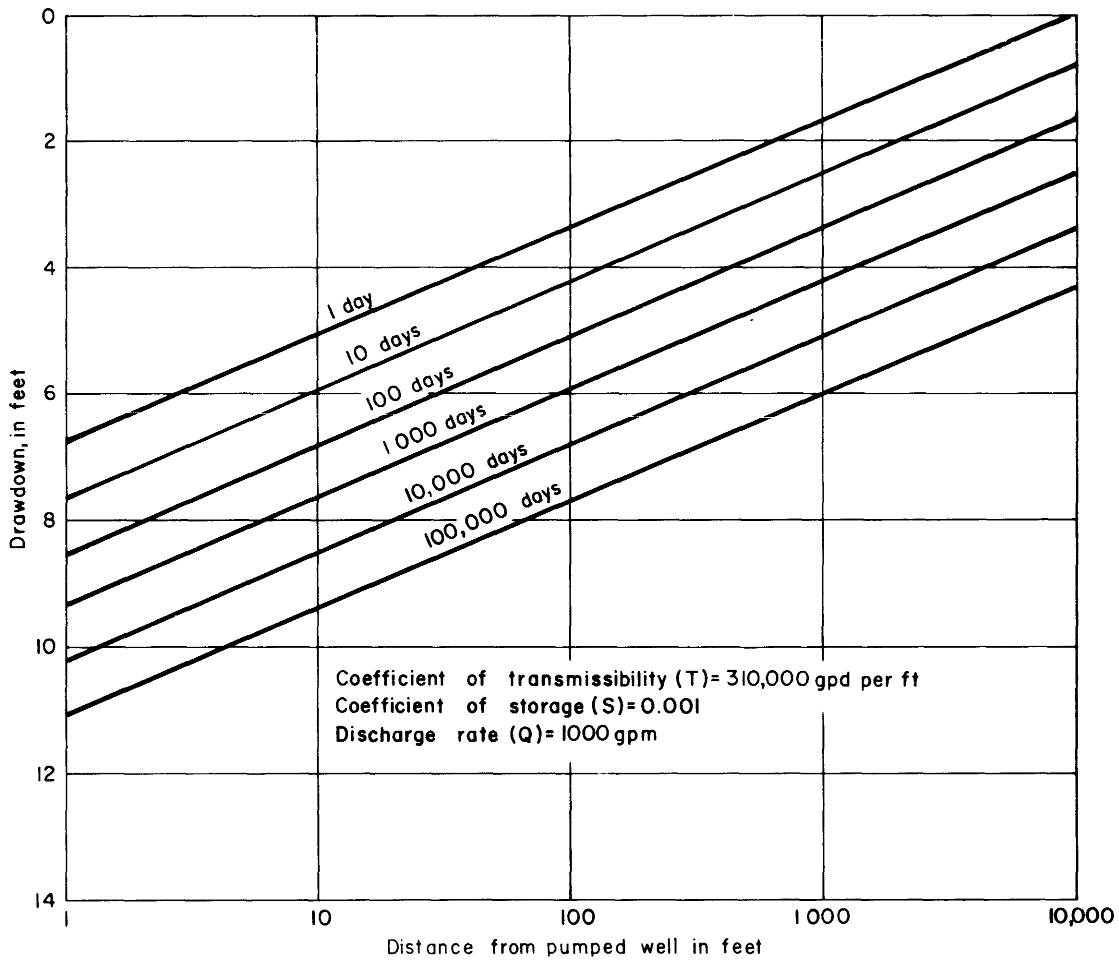


Figure 16

Relation of Drawdown to Distance and Time as a Result of Pumping from the Jasper and Chicot Aquifers Under Artesian Conditions

U.S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

The largest specific capacity observed in a well in the Jasper aquifer was 39.4 gpm (gallons per minute) per foot in well PR-62-01-406 (163 feet of screen).

Evangeline Aquifer

The coefficients of transmissibility determined from aquifer tests of 13 wells that tap the Evangeline aquifer in Jasper, Newton, and Hardin Counties ranged from 16,000 gpd per foot at well LH-61-47-202 to 111,000 gpd per foot at wells PR-61-48-204 and PR-61-48-301 (Table 4). The average values of the coefficients of transmissibility and storage were approximately 62,000 gpd per foot and 0.001, respectively. The average coefficient of permeability was 260 gpd per square foot.

The maximum thickness of sands containing fresh water in the Evangeline aquifer is more than 500 feet in the southern parts of Jasper and Newton Counties (Figure 8). The product of the average coefficient of permeability (260 in Table 4) and the maximum sand thickness (500 feet) indicates that a coefficient of transmissibility of approximately 130,000 gpd per foot is possible in a large area in the southern parts of Jasper and Newton Counties. In southeastern Jasper County, where a coefficient of permeability of 411 gpd per square foot has been measured in well PR-61-48-301 and where the sand thickness is as great as 555 feet (well PR-61-48-701), a transmissibility of as much as 200,000 gpd per foot may be possible.

The above figures compare favorably with those reported by Wood and Gabrysch (1965) for the "heavily pumped layer" in the Houston district. They have reported that the coefficients of transmissibility ranged from 75,000 to 150,000 gpd per foot and that the coefficients of storage ranged from about 0.0001 to 0.002.

Values for the specific capacity of 12 wells in the Evangeline aquifer ranged from 12.8 to 46.4 gpm per foot (Table 4). Because the wells in the area are not screened through the entire thickness of the water-bearing sands, the specific capacities of the wells listed are less than the maximum that could be developed.

Chicot Aquifer

The coefficients of transmissibility determined from tests of five wells that tap the Chicot aquifer in Jasper, Newton, and Orange Counties ranged from 92,500 gpd per foot at well PR-62-41-801 to 510,000 gpd per foot at well UJ-62-50-201 (Table 4). The coefficients of permeability ranged from 910 to 1,700 gpd per square foot and averaged 1,322 gpd per square foot. The average of 1,322 gpd per square foot compares favorably with the average of 1,400 gpd per square foot reported from 20 aquifer tests in the "Middle" aquifer in Orange County (Wesselman, 1965, p. 22).

On the basis of sand thickness of 225 feet and an average permeability of 1,400 gpd per square foot, the composite transmissibility of the "Middle" aquifer in Orange County (approximately equivalent to the Chicot aquifer) was computed to be about 310,000 gpd per foot (Wesselman, 1965, p. 22). The transmissibility of the Chicot aquifer is even higher in southeastern Newton County where the sand thickness is more than 400 feet (Figure 10). These determinations compare reasonably well with the composite transmissibility of the "500-" and "700-" foot sands (380,000 gpd per foot) as determined in Calcasieu Parish, Louisiana (Harder, 1960, p. 32-35).

The coefficients of storage determined in Orange County ranged from 0.00047 to 0.063 and averaged 0.0067 (Wesselman, 1965, table 2). The coefficients of storage are probably larger in Jasper and Newton Counties than in Orange County.

The measured specific capacities of eight wells in the Chicot ("Middle") aquifer in Orange County (Wesselman, 1965, table 2) and one well in Jasper County ranged from 6.6 to 29.6 gpm per foot of drawdown. Specific capacities as large as 66.2 gpm per foot of drawdown, have been reported (well TZ-62-34-201).

Minor Aquifers

Yegua Formation and Jackson Group

No aquifer tests of the Yegua Formation or the Jackson Group have been performed and little information is available on their hydraulic characteristics.

Catahoula Sandstone

No large wells have been completed in the Catahoula Sandstone; consequently, aquifer tests are not available for this aquifer in Jasper or Newton Counties. However, Rogers and Calandro (1965, p. 19) have reported on one pumping test and commented on yields in neighboring Vernon Parish:

> "A pumping test made at well V-398 (T. 4 N., R. 8 W.) in the Catahoula Formation indicated a coefficient of transmissibility of 19,000 gpd per foot and a coefficient of permeability of 320 gpd per square foot. Variation in sand size in the Catahoula is similar to younger sands for which permeabilities between 150 and 600 gpd per square foot have been determined. Therefore, the range of permeability values for the Catahoula is probably as great as the range for the younger deposits.
>
> "Nearly all the wells that have been installed in the Catahoula Formation in Vernon and nearby parishes yield less than 50 gpm. However, in 1962 well V-398 pumped 450 gpm for 8 hours and 250 gpm for 24 hours. At 250 gpm the well had a specific capacity of 8.3 gpm per foot of drawdown, from a sand having a permeability of 320 gpd per square foot."

Their results and evaluation probably are valid for the Catahoula in adjacent Newton County. The percentage of sand in the Catahoula is less and the sand is finer in Jasper County; consequently, the values of hydraulic characteristics are probably less.

Use of Ground Water

The first records of use of the ground water in Jasper and Newton Counties were included in the report on the underground waters of the Southeastern Coastal Plain by Deussen (1914). This report included records of wells from all aquifers except the Jackson Group. The records showed flowing wells in the Catahoula Sandstone and in the Jasper, Evangeline, and Chicot aquifers. Totals of the yields reported indicated a discharge of about 1 mgd from flowing wells.

The estimated use of ground water in Jasper and Newton Counties in 1965 was about 52 mgd (or about 58,300 acre-feet for the year), of which more than 40 mgd was produced by the well field that supplies the paper mill at Evadale in the southwestern part of Jasper County. This well field is supplied from the middle part of the Evangeline aquifer. Previous to the development of the well field at Evadale, the maximum use of ground water from all aquifers in the report area was less than 10 mgd.

Production of water for the paper mill at Evadale began in 1955 when the well field produced 17.8 mgd, a rate maintained in 1956 and 1957. From 1957 to 1962, as the rate of production increased, the average was about 21 mgd. Withdrawals had increased to more than 45 mgd late in 1964 and early in 1965. The average production for May, June, and July, 1965, was about 43 mgd. The reduction from the 45 mgd rate was achieved by instituting recovery methods which made possible the reuse of some of the plant's effluent. At present, work is proceeding on more new facilities which will recover even more of the water. Daily use of water is then expected to level off at or below 40 mgd. Industrial use of water, other than that at Evadale, is estimated to have been about 0.5 mgd in 1965.

In 1965, domestic use of ground water in rural areas was about 2.5 mgd. Municipal use, as reported to the Texas Water Development Board, was about 1.5 mgd.

A total of 90 wells with a combined flow of almost 4 mgd were observed in Jasper and Newton Counties in the course of the well inventory (Table 5). However, not all existing flowing wells were visited. Other flowing wells, such as the seismic test hole PR-61-16-402 which produces 480 gpm, may exist in the heavily timbered river bottoms of northern Jasper and Newton Counties. The following tabulation lists the observed discharge of flowing wells in the report area in 1965.

County		Jackson Group	Catahoula Sandstone	Jasper aquifer	Evangeline aquifer	Total
Jasper	Wells:	1	5	38	1	45
	Mgd:	.01	.18	2.28	.01	2.39
Newton	Wells:	None	None	30	15	45
	Mgd:	None	None	.90	43	1.3

Use of ground water for rice irrigation in southern Jasper and Newton Counties, which began in 1940 when an average of about 1 mgd was pumped, increased to a maximum of about 2 mgd for the 1949-54 period. Crop controls in 1955 resulted in a decrease in use to about 1 mgd, and present usage is about 1 mgd. This water is pumped from the Chicot aquifer.

Water Levels

Water-level data are presented by hydrographs and maps of the piezometric surfaces. Figures 17 and 18 are graphic presentations of water levels in wells in the Jasper, Evangeline, and Chicot aquifers. These hydrographs were prepared from records of water-level measurements made in previous investigations and as part of the observation-well program of the U.S. Geological Survey and the Texas Water Development Board. Figures 19, 20, and 21 are maps of the approximate piezometric surface in the Jasper aquifer (1964-65), and in the Evangeline and Chicot aquifers (1964).

Water-level differences aid in separating the Jasper, Evangeline, and Chicot aquifers. Comparison of the piezometric surfaces (Figures 19 and 20) shows an especially pronounced difference between the water levels of the Jasper and the Evangeline aquifers.

In 1947, at Evadale, a test hole was drilled that penetrated all three aquifers. The procedure of testing included recording the water levels of selected individual sands in each aquifer. The electric log of this test hole, the names of the hydrologic units, and the positions of the screens, packer, cement plug, and the water levels of individual sands measured in 1947 are shown on Figure 22. After the tests were made, the test hole was completed as a dual-observation well--the sands of the Evangeline aquifer between the cement plug and the packer supplying one unit (herein referred to as PR-61-48-209-B), and the sands of the Evangeline above the packer plus the sands of the Chicot supplying the other (well PR-61-48-209-A). Records of water-level measurements made in the two units are shown in Figure 18.

Jasper Aquifer

The short periods of record shown on the hydrographs of Figure 17 are not sufficient for a detailed analysis of the water levels in the Jasper aquifer. The maximum decline shown in the hydrograph of well PR-36-57-801 was about 10 feet. Water levels rose 1 foot in 1 well, PR-62-01-402, at Jasper over a period of 10 years. The two wells are in different sands in the Jasper aquifer near the outcrop. Water levels in another well (PR-62-01-401) at Jasper show a decline of about 4 feet over 11 years. Some decline would be expected in the Jasper area because of pumpage. In the outcrop of the Jasper aquifer, considerable seasonal fluctuation is reported; but, because no data are available, timing and range of this fluctuation have not been determined.

Most of the data for the construction of Figure 19, the piezometric map of the Jasper aquifer (1964-65), were from flowing wells that tapped only the upper part of the aquifer; wells in the lower part probably had a higher head than that shown by the map. Pressure declines are indicated at three localities on Figure 19: the closed contour at and near Kirbyville from pumpage in the area, the indentation of the contours east of Dam B Reservoir from the concentration of flowing wells near the reservoir, and the indentation of the contours east and southeast of Burkeville from the concentration of flowing wells along Little Cow Creek near its junction with the Sabine River.

Evangeline Aquifer

The ground-water resources of Jasper and Newton Counties were relatively undeveloped in 1955. Since 1955, the withdrawals from the industrial well field at Evadale and from the city of Beaumont's well field in southeastern Hardin County (Baker, 1964, p. 43) have created a cone of depression in the Evangeline aquifer. This cone of depression is centered in southwestern Jasper County (Figure 20) and extends across much of the southern part of the report area.

As previously discussed, water-level measurements of selected individual sands were made during the drilling of test well PR-61-48-209 (at Evadale). The water level of the lowest fresh-water sand in the Evangeline aquifer was 27.7 feet above the land surface in 1947 (Figure 22). Prior to 1947, the water level of the aquifer at this location probably had declined about 10 feet. This sand also is the lowest sand in the lower unit of the observation well PR-61-48-209-B. In August 1965 the water level of this unit was 160 feet below the land surface (Figure 18), which was a decline of about 200 feet from its original level--the largest decline known to have taken place in Jasper and Newton Counties. Ten miles from the well field, the total decline has been less than one-half of this amount. At Kirbyville, the total decline in the Evangeline aquifer probably has been about 15 feet.

Identifying a possible decline of water levels in the outcrop would be difficult, as the decline would fall into the range of seasonal variations of water levels.

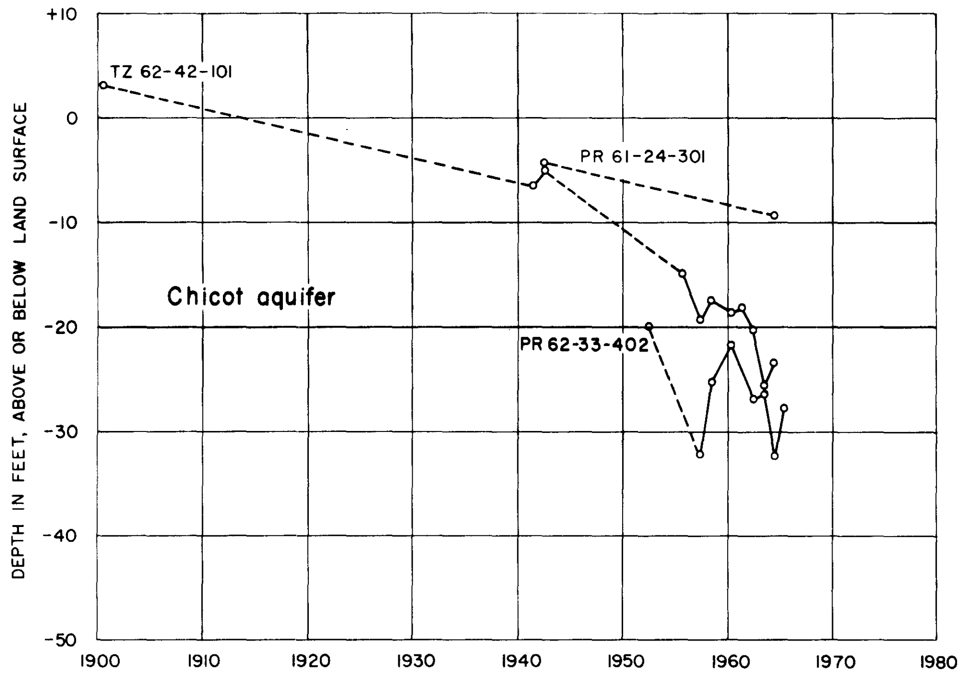
Flowing wells from this aquifer are located across the Neches River in the Spurger area of Tyler County and along the Sabine River in both Newton County and Beauregard Parish. The area of flowing wells in Newton County extends from the vicinity of Salem to about 6 miles north of Bon Wier. Pressure declines of these wells probably have been fairly small as no well owner has reported a reduction of flow since the wells were constructed. In general, flowing wells in the Sabine River bottom are completed in the basal sands of the Evangeline aquifer.

Chicot Aquifer

Most of the water-level decline in the Chicot aquifer in the report area has been caused by pumping in Orange County and in southwestern Louisiana. A decline of about 35 feet in the northeastern corner of Orange county (and the southeastern corner of Newton County) between 1941 and 1962-63 is shown by Wesselman (1964, figs. 9 and 10). The original head at this location was about 10 feet higher than in 1941, making a total decline of about 45 feet by 1962-63.

The hydrograph (Figure 17) of well TZ-62-42-101, the first to be drilled for irrigation in Jasper and Newton Counties, shows a decline in head of about 10 feet between 1942 and 1956, and about 15 feet between 1942 and 1963. The estimated decline from 1900 to 1942 was 8 feet.

The approximate boundary of the artesian part of the Chicot aquifer is shown on Figure 21 by a line that begins near the northeastern corner of Hardin County, passes north of Kirbyville and out of Newton County in the



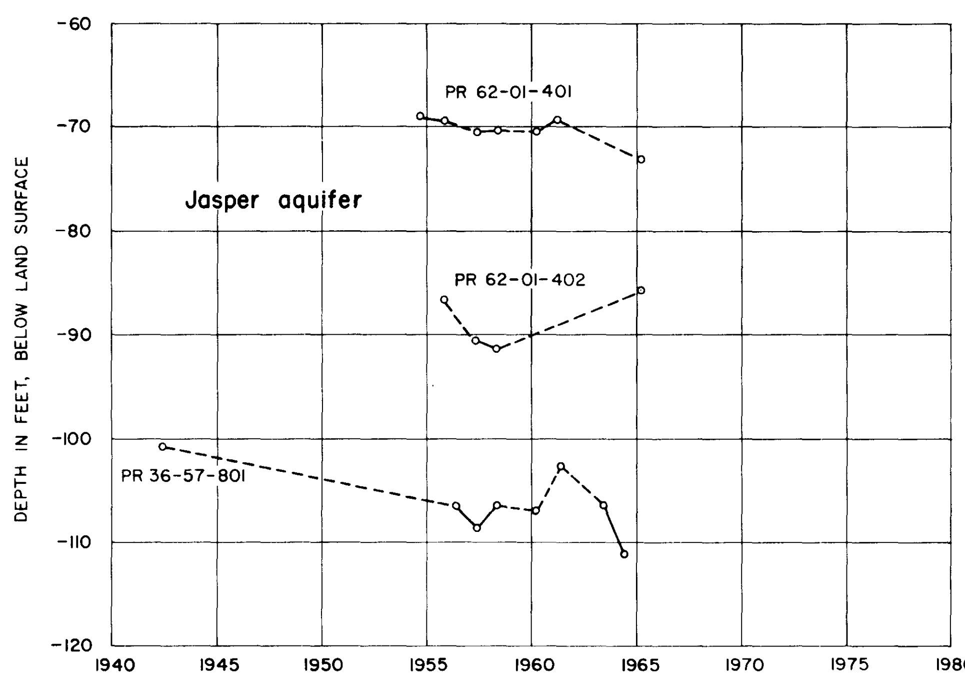


Figure 17

Water Levels in Wells Tapping the Jasper and Chicot Aquifers

U.S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

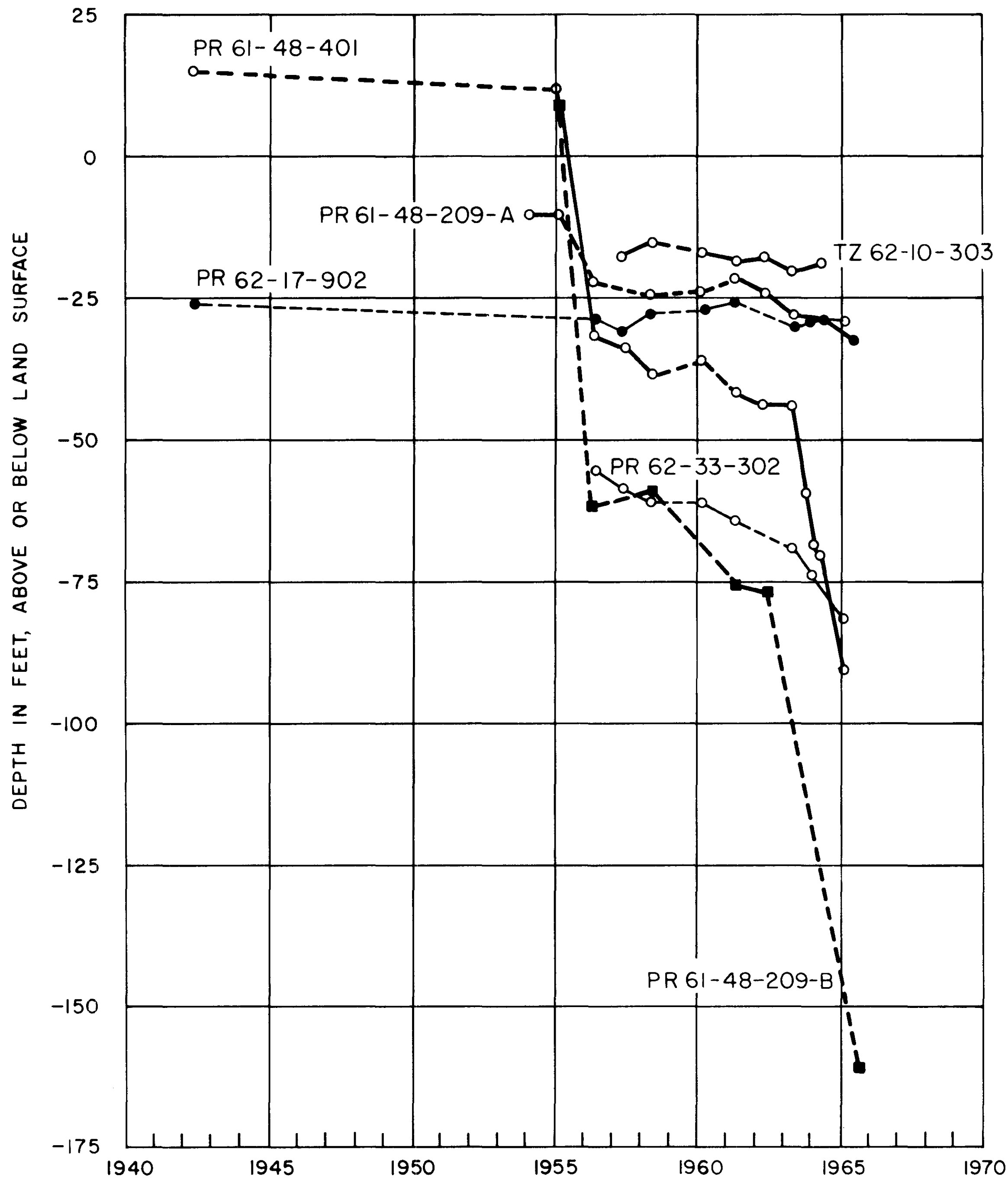


Figure 18

Water Levels in Wells Tapping the Evangeline Aquifer

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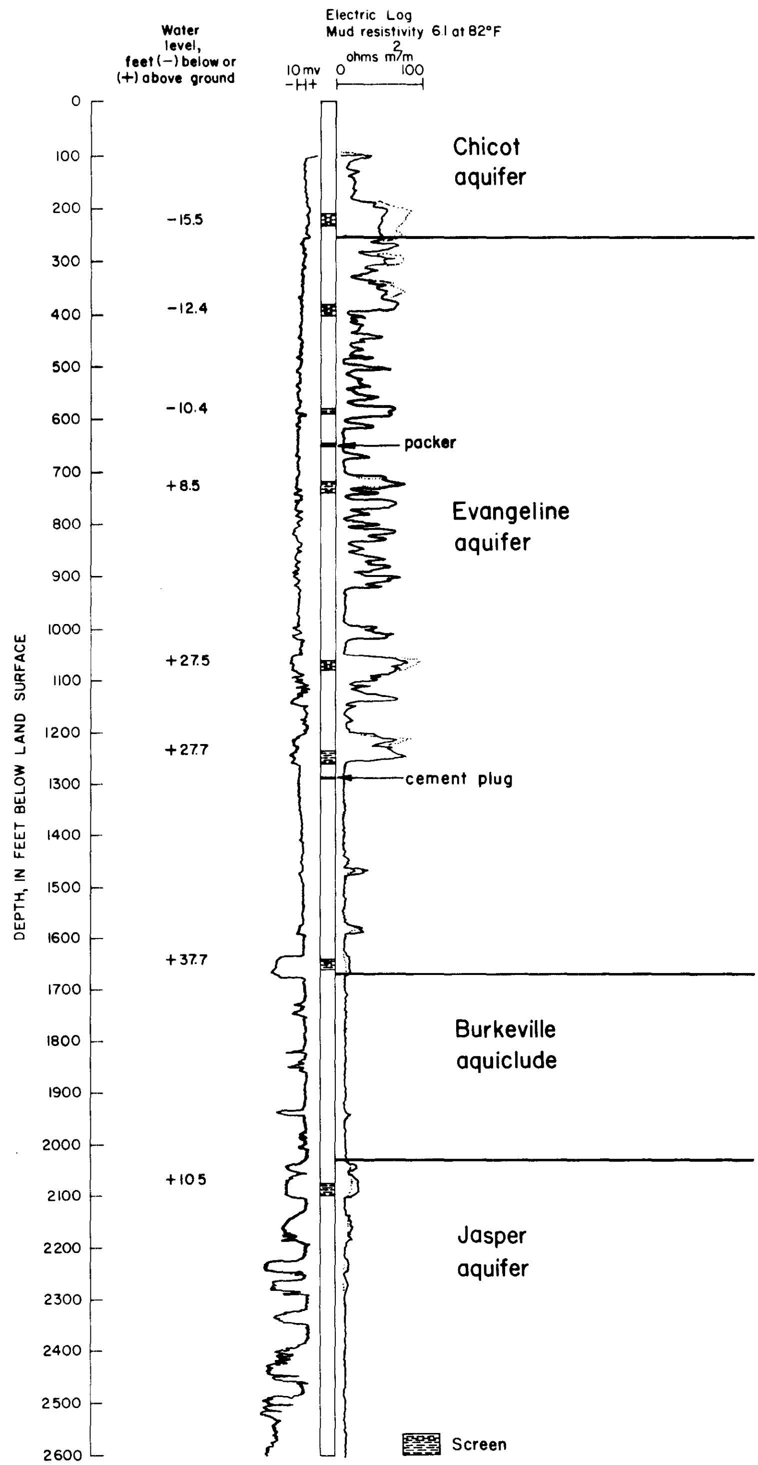

Figure 22

Electric Log of Observation Well PR-61-48-209 at Evadale Showing Hydrologic Units, Screens, Packer, Cement Plug, and Water Levels of Individual Sands Measured in 1947

U. S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

vicinity of Salem and Big Cow Creek. Because the Chicot is the most permeable aquifer in the report area, wells in the artesian part of the Chicot have the least variations of water level.

Water levels have declined little, if any, in the outcrop of the Chicot aquifer.

Relation of Water-Level Declines to Land Subsidence

The pressure in an artesian aquifer helps support the framework of the aquifer. When the artesian pressure is lowered, water is released from storage in the aquifer and the beds are compacted, most of the compaction taking place in the fine-grained sediments. The amount of total compaction and resulting subsidence depends on the thickness of the fine-grained sediments and the amount of decline in artesian head.

According to Winslow and Wood (1959, p. 1030) the removal of ground water and the consequent lowering of artesian pressure has resulted in a subsidence of the land surface in almost the entire upper Gulf Coast region of Texas, including Orange County to the south of Jasper and Newton Counties. Winslow and Wood (1959, fig. 3, p. 1032) show that the land surface subsided more than 0.25 foot in parts of Orange County during the 1918-54 period. Their work was based on the releveling of previously established level lines by the U.S. Coast and Geodetic Survey. Their map shows some subsidence over an area encompassing more than half of Orange County. Because of a lack of data, the extent of subsidence since 1954 cannot be determined. However, the land surface probably has continued to subside, especially in localized areas where large declines in artesian pressure have occurred.

The well field at the paper mill at Evadale in south Jasper County was developed since 1954 and a network of bench marks was established in and around the plant in order to measure differential subsidence. The leveling from January 1955 to July 1963 was referenced to a point 1 mile south of the plant site and about 2 miles southwest of the original well field. A new well field was developed in 1962 between the original reference point and the plant site. A new reference point, selected and established in the last series of measurements in July 1963, is 3 miles east of the plant, and will be used to supplement the old reference point in future determinations of land-surface elevation. The maximum differential subsidence from 1955 to 1963 was 0.228 foot at a bench mark about 500 feet from well PR-61-48-205. At the time of the latest subsidence measurements (1963), the estimated water-level difference between the original reference point and the point of maximum subsidence was approximately 25 feet. On the assumption that the original water level was the same at both points and that subsidence was directly related to the difference in decline in water levels, the ratio of subsidence to water-level decline would be 0.228 foot for 25 feet, or 0.912 foot for 100 feet. On the basis of the estimated declines of water levels of 140 feet at the point of maximum subsidence and 115 feet at the original reference point and the subsidence rate of 0.912 foot per 100 feet of water-level decline, a total subsidence of 1.28 feet would be indicated at the point of maximum subsidence, and 1.05 feet of subsidence at the original reference point. Winslow and Doyel (1954, p. 419-420) reported the ratio between the subsidence of the land surface and the decline of artesian pressure head to be about 1 foot of subsidence to 100 feet of decline. The ratio was determined in the northern part of the Houston-Galveston region where the aquifers have a relatively high sand percentage comparable to that of the report area.

Some subsidence has probably taken place in the vicinity of the irrigation wells in south Jasper and Newton Counties. At the present (1965), land subsidence is not a serious problem, except locally, in Jasper and Newton Counties; however, subsidence could become serious if water levels continue to decline.

Well Construction

Generally, when a well is to be constructed for public-supply or industrial use, a test hole is drilled to the depth desired. Formation samples are collected during drilling, and upon completion of the test hole an electric log is run so that the occurrence of sands containing fresh water can be ascertained. In some such holes, tests are made to determine the quality of the water and the transmissibility of individual sands.

If favorable conditions are indicated by the data collected, the test hole is usually reamed to the top of the first sand that is to be screened; and the surface casing is then installed and cemented into place. The diameter of the surface casing ranges from 12 to 20 inches.

The section to be screened is then reamed with the largest drilling bit that can pass the surface casing. This step is followed by the use of an underreamer, a device that expands and cuts a hole larger than the diameter of the surface casing. Usually the hole is underreamed to a diameter of 30 inches. The blank pipe and screen are then installed. The bottom of the screen is closed off with a back-pressure valve which permits the use of fluid to keep the hole clean during the placing of the screen but prevents water, sand, or gravel from entering through the bottom of the string. "Gravel," which is mostly sand, is pumped into the annular space between the screen and the formation by means of a gravel tube that is withdrawn as the space is filled. The gravel reservoir--the space between the lower part of the surface casing and a blank liner connected to the screen (Figure 23)--is also filled with gravel. The construction of a typical industrial or public-supply well is shown in Figure 23. The screen is pipe, 6 to 14 inches in diameter, that has been perforated and wrapped with stainless steel wire to form a screen. Where corrosion is a problem, the pipe is also stainless steel. Generally the openings in the screen, which range from 0.016 to 0.050 inches, are larger than the sand particles in the formation but smaller than those in the gravel envelope after the development of the well. Blank pipe of the same diameter as the screen is used to separate screens.

The well is developed by surging, swabbing, pumping, backwashing, and the use of chemicals until the specific capacity and sand-water ratio are satisfactory. The well is then tested by pumping from 4 to 24 hours and samples of water for chemical and bacterial analyses are collected. One well in Newton County, constructed by this procedure, reportedly produced 3,970 gpm.

The size and type of pump installed depends upon the pumping lift and the quantity of water needed. The larger public-supply and industrial wells have high-capacity, deep-well turbine pumps powered by electricity. Irrigation wells are equipped with the same type of pumps, but are usually powered by diesel or gas motors. Pump settings in 1965 ranged from 100 to 400 feet below land surface.

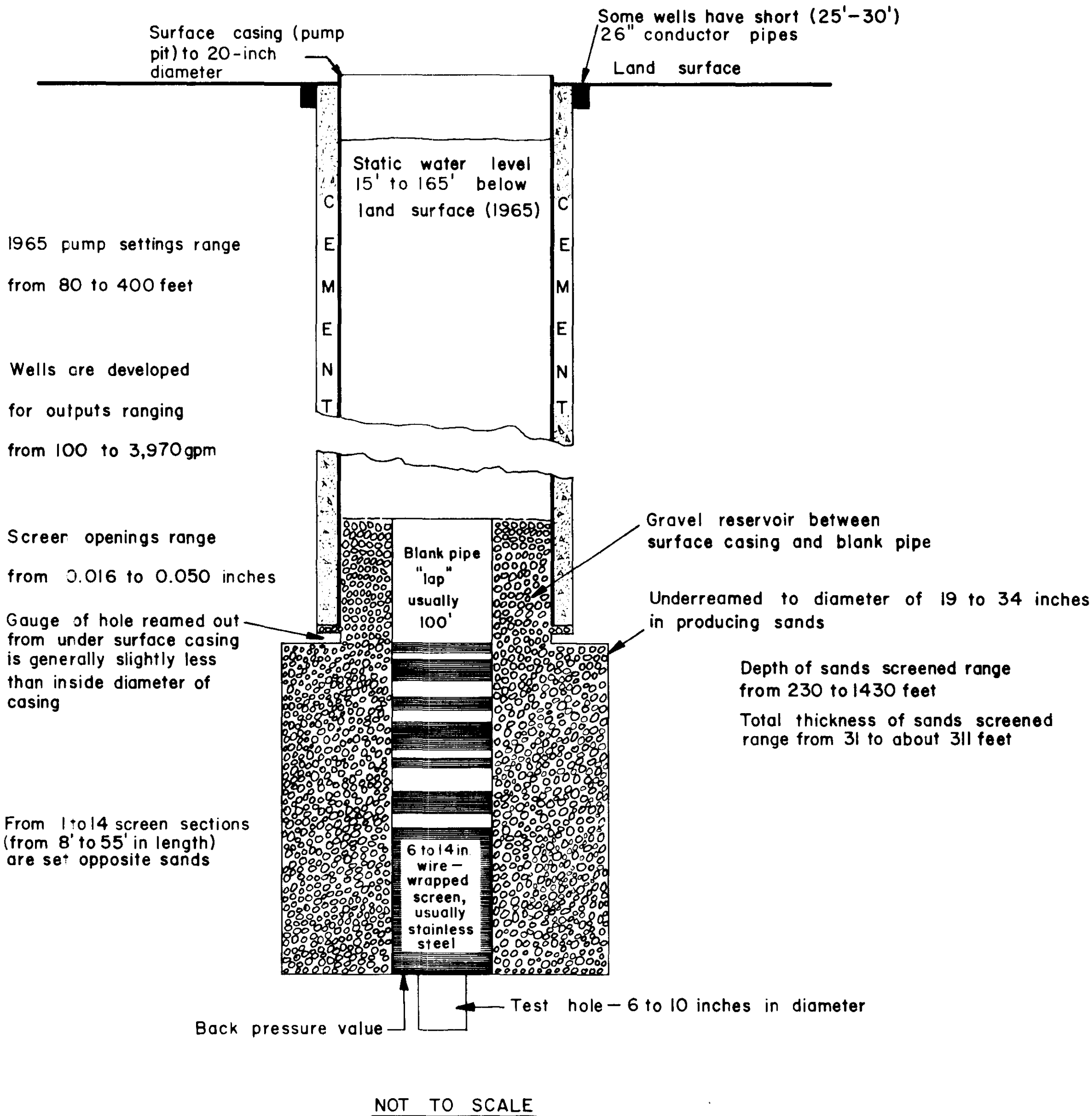

Figure 23

Construction of a Typical Large-Capacity Well

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Shallow dug wells, usually 30 to 36 inches in diameter, were common in the area prior to 1945 and some are still being constructed. However, in the report area most of the modern, small-capacity wells that furnish water for domestic use and for small industries are drilled wells that have been completed with a single screen. In this type of well, the screen is an integral part of the pipe that conducts the water out of the well. The sizes of the screen and pipe range from 1-1/4 to 4 inches. In some small-capacity wells, more than one size of screen or pipe may be used. In the construction of some small public-supply wells, 4- or 6-inch casing is placed and cemented from the surface to the top of the sand. A screen of slightly smaller size is then lowered through the pipe and set into the sand. The screen is lowered on a short section (1 to 10 feet) of blank pipe which has a lead nipple on top. The lead nipple is battered down to form a seal between the pipe and the surface pipe.

A variety of screen types is available, but stainless steel and plastic have become the most widely used because of their resistance to corrosion by acid water. Plastic is coming into widespread use as the material for conductor pipe and screens in the small and relatively shallow wells. Stainless steel screen is used in the larger wells. Most of the smaller wells are now being equipped with air lifts, instead of the traditional centrifugal and jet pumps. The rapid and recent adoption of the air lift has resulted from the general realization that this method of lift reduces most iron and corrosion problems. Submersible pumps are used in the small wells, especially where iron stain is not a problem.

CHEMICAL QUALITY OF GROUND WATER

The chemical analyses of water from selected wells in the report area are given in Table 7. The quality of water commonly determines its suitability for use. A general classification of water, according to dissolved-solids content, is as follows (Winslow and Kister, 1956, p. 5):

Description	Dissolved-solids content (parts per million)
Fresh	Less than 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	More than 35,000

The U.S. Public Health Service (1962, p. 7) has established standards for the chemical quality of water to be used on common carriers engaged in interstate commerce. These standards are commonly used in evaluating water for use as a public supply. The following are the limits of concentration for some of the constituents.

Description	Concentration (parts per million)
Chloride (Cl)	250
Fluoride (F)	(*)
Iron (Fe)	.3
Manganese (Mn)	.05
Nitrate (NO_3)	45
Sulfate (SO_4)	250
Total dissolved solids	500

*According to the Public Health Service (1962, p. 41), the optimum fluoride level for a given community depends on climatic conditions because the amount of water (and consequently the amount of fluoride) ingested is influenced primarily by air temperature. The optimum value of 0.8 ppm (parts per million) in Jasper and Newton Counties is based on the annual average of maximum daily air temperature of 79.1°F at Beaumont. Presence of fluoride in average concentrations greater than twice this value (0.8 ppm), or 1.6 ppm, would constitute grounds for rejection of the supply. No excessive concentrations of fluoride were found in Jasper and Newton Counties.

Water having concentrations of chemical constituents in excess of the recommended limits may be objectionable for various reasons. Maxcy (1950, p. 271), in relating nitrate concentrations to the occurrence of methemoglobinemia ("blue-baby" disease), recommends an upper limit of 44 ppm nitrate as NO_3 in water used for infant feeding.

In the 1942 well inventory of Jasper and Newton Counties, analyses of water from 41 shallow wells (11 to 57 feet deep) in the Catahoula Sandstone and the Jasper, Chicot, and Evangeline aquifers showed more than the recommended limit of nitrate concentration. No deep wells are known that yield water with excessive nitrate content. Shallow wells were not as prevalent in 1963 and 1964 as in previous years, and only a few shallow wells were sampled. One of these, a 34-foot-deep well, yielded water with an excessive amount of nitrate. Probably the majority, if not all, of these wells were polluted by sewage or by other organic material from surface water entering the wells.

Water having a chloride content exceeding 250 ppm may have a salty taste, and sulfate in water in excess of 250 ppm may produce a laxative effect. Both constituents are discussed further in the portions of this report section concerning aquifers.

Excessive concentrations of iron and manganese in water cause reddish-brown or dark gray precipitates that discolor clothes and stain plumbing fixtures. The recommended limit for iron is 0.3 ppm. Amounts of iron in excess of the recommended limit are common in water from all the aquifers in the report area, and iron stain and red water are, or have been, common complaints.

Iron in the water pumped from the aquifers underlying the two-county area comes from two sources: (1) iron in solution in the ground water (Chicot aquifer produces water of this type), and (2) iron derived from the corrosion of the well casing, pump, and pipes by acid (low pH) ground water. Corrosiveness of water generally increases with decreasing pH. Laboratory determinations of iron and pH of a large number of samples are given in Table 7. The pH values shown in the table probably are not representative of the actual pH of the water in the aquifer. The pH of water samples may change (generally increases) during storage in the laboratory.

As previously mentioned, the use of air lift reduces most of the iron and corrosion problems in domestic supplies. The use of plastic material for conductor pipe and screen in the small and relatively shallow wells and the use of stainless steel for screen in the larger wells also helps to control the corrosion problems. The water for domestic use is usually stored in large tanks. The iron precipitate is allowed to settle to the bottom and water is then withdrawn from the top of the tank.

Calcium and magnesium are the principal constituents responsible for hardness in water. Hardness causes an increase in the consumption of soap and induces the formation of scale in hot-water heaters and water pipes. A classification commonly used with reference to hardness is as follows: 60 ppm or less, soft; 61 to 120 ppm, moderately hard; 121 to 180 ppm, hard; and more than 180 ppm, very hard. If calcium carbonate causes more than 75 ppm hardness in water to be used in steam boilers (American Society for Testing Materials, 1959, p. 24), then the water should be treated to prevent formation of scale. In high-pressure boilers, the tolerance is much less than 75 ppm. One of the major items of concern to most industries is the development of water supplies that do not contain corrosive or scale-forming constituents which affect the efficiency of boilers or cooling systems. Suggested water-quality tolerances for a number of industries have been summarized by Hem (1959, p. 253) and Moore (1940). Hardness of the ground water is not a problem in most of Jasper and Newton Counties.

The suitability of water for irrigation depends on the chemical quality of the water and on other factors, such as soil texture and composition, types of crops, irrigation practices, and climate. The most important chemical characteristics pertinent to the evaluation of water for irrigation are: the proportion of sodium to total cations, an index of the sodium hazard; total concentration of soluble salts, an index of the salinity hazard; RSC (residual sodium carbonate); and the concentration of boron. A system of classification commonly used for judging the quality of water for irrigation was proposed by the U.S. Salinity Laboratory Staff (1954, p. 69-82). The classification is based primarily on the salinity hazard as measured by the electrical conductivity of the water and the sodium hazard as measured by the SAR (sodium-adsorption ratio). This classification was used to prepare Figure 24 which includes analyses from five of the water-bearing units. However, this classification is not directly applicable to the report area because of the high rainfall. If the use of water of questionable quality is contemplated, then the type of soil to be watered, the local conditions of drainage, and the crops to be irrigated should be given consideration.

An excessive concentration of boron renders a water unsuitable for irrigation. Scofield (1936, p. 286) indicated that boron concentrations of as much as 1 ppm are permissible for irrigating most boron-sensitive crops and that

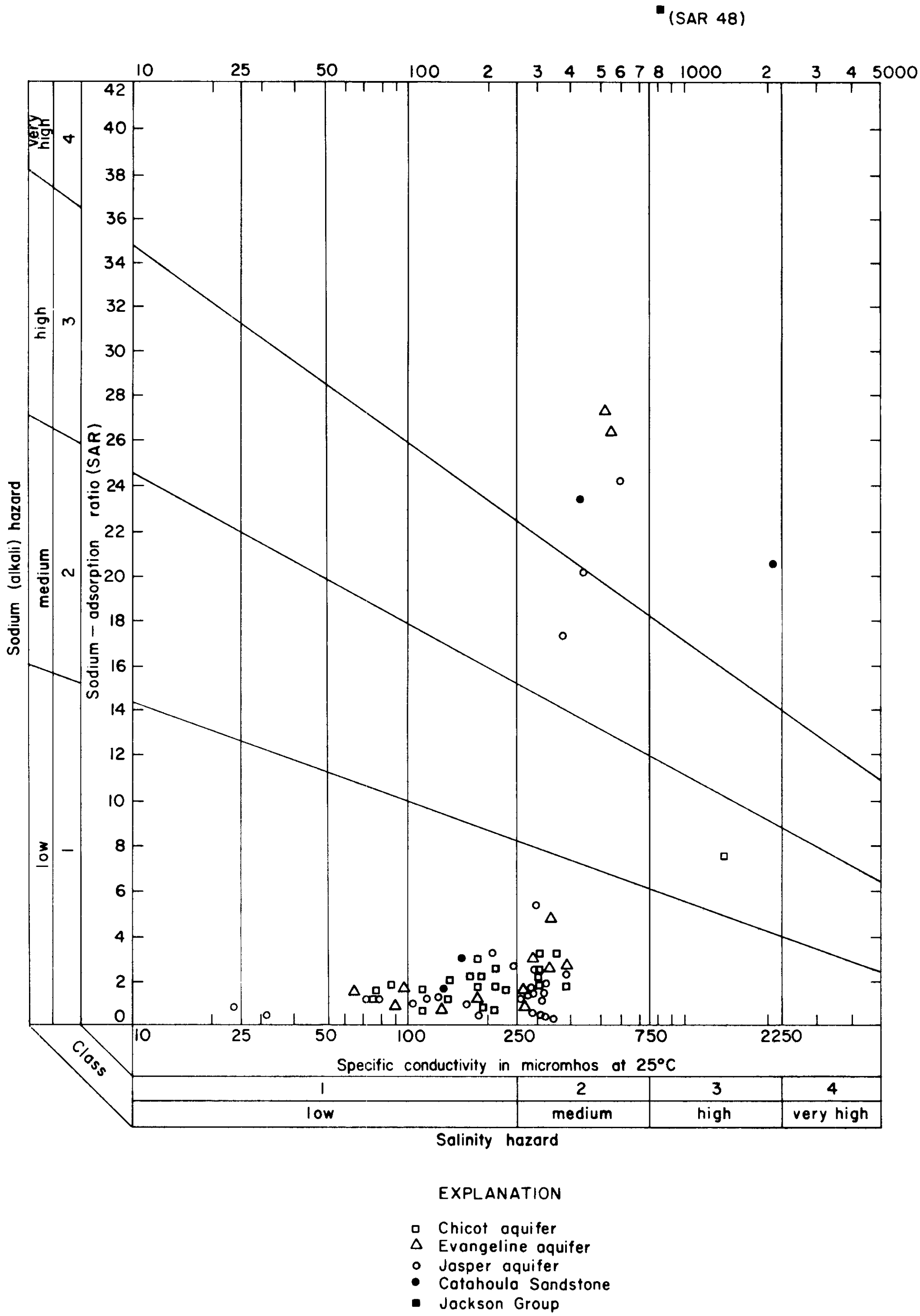

Figure 24

Classification of Irrigation Waters

(Modified from U. S. Salinity Laboratory Staff, 1954, p. 80)

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concentrations of as much as 3 ppm are permissible for the more boron-tolerant crops. The highest boron concentration shown by the analyses (Table 7) is 1.8 ppm. Most analyses show a boron concentration of less than 1 ppm.

Another factor in assessing the quality of water for irrigation is the RSC (residual sodium carbonate) of the water. Excessive RSC will cause the water to be alkaline, and the alkaline water will cause the organic material of the soil to dissolve. The soil may become a grayish black. The affected soil is referred to as "black alkali." Wilcox (1955, p. 11) states that laboratory and field studies have resulted in the conclusion that water containing more than 2.5 epm (equivalents per million) RSC is not suitable for irrigation. Water containing from 1.25 to 2.5 epm is marginal, and water containing less than 1.25 epm RSC is probably safe. Correct irrigation practices and proper use of amendments might make possible the successful use of marginal water for irrigation. The degree of leaching in Jasper and Newton Counties may raise, to some extent, the permissible limits of water quality.

The temperature of ground water is often of great importance to industries and to others planning to use the water. Ground water has a more uniform temperature than surface water. The temperatures of water samples are given in Table 5. The thermal gradient is about 1°F per 64 feet of depth for the Jasper aquifer in Jasper and Newton Counties. This is a steeper gradient than exists downdip in the Evangeline and Chicot aquifers. An even steeper gradient exists in the older beds. The temperature gradient of the flowing well in the Jackson Group north of Rockland in northwest Jasper County is about 1°F per 50 feet.

Following is a discussion of the water quality of the respective water-bearing units.

Major Aquifers

Jasper Aquifer

In northern Jasper County, the Jasper aquifer provides water for domestic, municipal, and recreational use, and for small industries. All water being used from the Jasper is fresh. In this aquifer, saline water is present only at depth and generally at a considerable distance downdip (Figures 5 and 28).

Of the water samples collected in the report area, only one contained more than 500 ppm dissolved solids. It was from a well (PR-61-16-301), 13 feet deep, which yielded water that contained 503 ppm dissolved solids and was also high in nitrate. Fifteen shallow wells in the Jasper aquifer yielded water whose nitrate content was higher than recommended. No samples showed excessive chloride, fluoride, or sulfate, by U.S. Public Health Service (1962) standards. The iron problem in water from wells in this aquifer is usually caused by the corrosion of pipes, fixtures, and casing by acid (low pH water). Silica content ranged from 10 to 78 ppm, and hardness from 1 to 408 ppm. Much of the water is soft. The well that yielded very hard water (408 ppm) was PR-61-16-301. The silica content of most of the water is high enough to require treatment for boiler usage.

Evangeline Aquifer

All water being used from the aquifer is fresh. Water from only two wells contained more than 500 ppm dissolved solids. These wells, 16 and 26 feet deep, had a dissolved-solids concentration of 513 and 681 ppm, respectively. One of these wells and five other shallow wells in the Evangeline aquifer produced water containing an excess of nitrate according to Public Health Service standards. Analyses of water from the Evangeline aquifer indicate no excessive amounts of chloride, fluoride, or sulfate.

Most of the domestic wells that produce from the Evangeline downdip were drilled to escape red (iron) water in the shallower sands (Chicot); in general, the efforts were successful. Water used for the paper mill and as small supplies for the public does not contain iron in concentrations that are considered undesirable. Silica content ranges from 17 to 46 ppm; water used by the paper mill is in the 17 to 19 ppm range. Hardness ranges from 1 to 553 ppm with most samples being in the soft (less than 60 ppm) classification. The sample containing 553 ppm hardness came from a well 16 feet deep. This sample also contained 681 ppm dissolved solids.

The downdip limit of fresh water in the Evangeline aquifer occurs in Orange County. The interface of fresh and slightly saline water is shown on cross-sections A-A' (Figure 28) and D-D' (Figure 31) and on Figure 7. The thickness of sands containing fresh water in the Evangeline aquifer is shown in Figure 8.

Chicot Aquifer

The Chicot aquifer furnishes water for irrigation, municipal, and domestic uses in the southern half of Jasper and Newton Counties. The water in the Chicot in the report area is fresh. Analyses of water from four shallow wells in the aquifer had a dissolved-solids content of more than 500 ppm. A sample of water from well PR-61-40-503, completed at 27 feet in the clay that caps the Chicot aquifer, contained more than 1,000 ppm dissolved solids. The well was sampled in 1942, and the analysis showed a dissolved-solids content of 2,210 ppm. Small amounts of slightly saline water probably occur elsewhere in the clays of the area. The other three wells whose analyses showed dissolved solids in excess of 500 ppm are 65, 23, and 69 feet deep and contain 765, 518, and 803 ppm dissolved solids, respectively. Three of the analyses showed more than 250 ppm chloride, and the fourth showed 240 ppm chloride. One well is at a pumping station in an oil field where most of the trees have died. This well may have been contaminated by oil-field brine. The practice of disposing saline oil-field water into surface pits has been discontinued at this location, and all salt water is now injected back into saline-water-bearing horizons.

No wells completed in the Chicot aquifer produced water with excessive fluoride or sulfate, but most of the samples from this aquifer showed undesirable amounts of iron. Iron staining has been common; almost everyone using water from this aquifer reports past or present red water or rust problems. Water produced through plastic pipe stains as readily in some areas as that from iron pipes. The conclusion is that much of the formation water contains an undesirable amount of dissolved iron. This problem can be controlled by the use of air lift and settling tanks.

Silica content ranges from 12 to 74 ppm and is usually high enough to require treatment before use in modern high-pressure boilers.

Hardness ranges from 1 to 885 ppm, but most of the wells yield soft water. The well which produced water with a hardness of 885 ppm had a 2,218 ppm dissolved-solids concentration.

According to the 1942 well inventory, 18 shallow wells in the Chicot aquifer yielded water that contained more than 45 ppm nitrate. Of the wells sampled in 1964 only one yielded water with an excessive concentration of nitrate.

The nearest occurrence of slightly saline water in the Chicot aquifer is in Orange County near where Jasper, Newton, and Orange Counties have a common point. The thickness of fresh-water sands in this aquifer in Jasper and Newton Counties is shown on Figure 10.

Minor Aquifers

Yegua Formation

One well (PR-37-61-903), an oil test, reportedly flowed saline water from the Yegua Formation in Jasper and Newton Counties (Table 7).

Jackson Group

One well (PR-37-61-901), in extreme northwest Jasper County, is known to produce fresh water from the Jackson Group in the report area. The flow of fresh water is accompanied by traces of crude oil and contains dissolved natural gas. It is a sodium bicarbonate water with a dissolved-solids content of 459 ppm. The temperature of the water is 84.5°F.

Catahoula Sandstone

To date, the Catahoula Sandstone has undergone very little development in Jasper and Newton Counties. Because the Catahoula will be the only source of ground water in some of the area around and near the new Sam Rayburn Reservoir, the aquifer will probably be more heavily developed in the future. In the area of the reservoir, electric logs and chemical analyses show that the quality varies between wide limits. Water in the Catahoula ranges from a fresh, soft, sodium bicarbonate type to a moderately hard, sodium chloride type. Sulfate content was low in all samples, and the pH of all samples except one was near or above 7.0. The total dissolved solids ranged from 36 to 545 ppm. According to the 1942 inventory, a high concentration of nitrate was present in two shallow wells, one in Newton County and the other in Jasper County. No iron staining was noted during the fieldwork, but the analysis of a sample of water from a test well at the Sam Rayburn Reservoir construction site showed a concentration of 3 ppm iron.

Slightly to moderately saline water occurs in some places in the outcrop. The approximate location of the downdip limit of occurrence of fresh water in the Catahoula Sandstone is shown in Figure 11.

Relation of Fresh Ground Water to Salty Ground Water

Most of the geologic formations composing the fresh-water aquifers in Jasper and Newton Counties consist of sediments that were deposited beneath the Gulf of Mexico. These sediments either contained salt water at the time of deposition, or were deposited in fresh water and later were filled with salt water at a time of higher sea level. At some time after deposition, the sea receded and the process of recharge and discharge began. Fresh water furnished to the recharge area began to force the saline water downdip to discharge areas until the pressure exerted by the fresh water equaled the pressure of the salt water. Flushing of the salt water from the sands may have been accomplished in several ways. Winslow and others (1957, p. 387-388) concluded that the discharge in Harris County, under conditions similar to those in Jasper and Newton Counties, took place through the overlying clays. Before large withdrawals by wells began, the system was probably in dynamic equilibrium (that is, the fresh water-salt water interface was nearly stationery because the pressure head of the fresh water that was moving downdip from the outcrop and discharging upward through the clays was balanced by the static head of the salt water). The cross sections (Figures 28, 29, 30, 31) show the relation of fresh water and salt water in Jasper and Newton Counties.

In the vicinity of Evadale, large ground-water withdrawals from the Evangeline have upset the equilibrium in the aquifer. As a result, the salt water is probably moving updip in response to a reversal of the hydraulic gradient (Figure 20). Updip movement of salt water can be expected at any place where large concentrated withdrawals have lowered the artesian pressure head and upset the equilibrium at the fresh water-salt water interface. The rate of movement updip is slow, depending on the hydraulic gradient and permeability of the sands.

The fresh water-salt water interface in the Catahoula Sandstone occurs in the outcrop area in western Jasper County. Data for the accurate description of the interface and interfingering are not available, but an estimate of the position of the interface is shown on Figure 11 as the downdip limit of fresh water. The interface between fresh and slightly saline water for the sands of the Jackson Group is in the extreme northern part of Jasper County. The interface in the Yegua Formation is north of Jasper and Newton Counties.

Disposal of Oil-Field Brines

The oil-field brine produced during 1961 in Jasper and Newton Counties amounted to about 5.4 million barrels, of which 83.5 percent was returned to saline-water-bearing formations by injection wells and 16.5 percent was disposed of in open-surface pits (Texas Water Commission and Texas Water Pollution Control Board, 1963, p. 249-257 and 387-402).

Some of the open pits are located in outcrops of sand. Where the pits are in clay, they are ineffective as a means of disposing brine--because they simply fill and overflow to the nearest stream or sand outcrop. Another reason for the ineffectiveness of pits in clay (except for storage) is that the annual gross lake-surface evaporation of about 44 inches is offset by an annual precipitation of about 54 inches. Evaporation is also retarded by the presence of oil scum. Most of the water placed in unlined pits constructed in sandy soil seeps into the ground, and the generally water-saturated conditions of the outcrop probably cause much of this water to be discharged into the nearest stream as spring or seepage flow. Because salt water has a higher specific gravity than fresh water, some of the former will sink and mix with naturally occurring ground water and remain in the ground water.

The dead trees and vegetation noted in the vicinity of the old pit locations in the southern and central parts of the report area probably died because of their proximity to disposal pits. In these areas, injection wells have replaced pits. More injection wells have been drilled since the 1961 inventory and the ratio of pit to injection-well disposal is improving.

In summary, the disposal of oil-field brines has not resulted in serious damage to the ground-water supplies of Jasper and Newton Counties. Deleterious local effects from bad practices were noted, but remedial action has been taken. Some contamination exists where pits are still used but the quantity of salt water is so small that the effects are local. All salt water should be disposed of in such a way that it cannot reach the streamways or ground-water reservoirs.

Protection of Water Quality in Oil-Field Drilling Operations

The Texas Railroad Commission requires that, in drilling wells, contractors use casing or cement to protect fresh-water strata from contamination. For the past decade, the Railroad Commission has received recommendations from the Texas Water Development Board and from its predecessors, the Texas Water Commission and the Texas Board of Water Engineers, concerning the depths to which the fresh water should be protected.

Where oil or gas fields are established the recommended depths are incorporated in some of the field rules. Figure 25 shows the amount of casing required by the Oil and Gas Division of the Railroad Commission of Texas and the depth of fresh to slightly saline water in these fields.

RELATION OF GROUND WATER TO STREAMFLOW

Measurements of stream discharge and related surface-water data have been made in Texas for many years. During the water year 1963-64, the following surface-water data were obtained by the U.S. Geological Survey in the report area: measurements of discharge and stage of streams at 9 stations; contents and stage of a reservoir at 1 station; measurements of discharge and stage at 5 partial-record stations; and chemical analyses and water temperatures at 1 station (U.S. Geol. Survey, 1965). The station locations are shown on Figure 27.

The discharge from springs and seeps contributes to the stream discharge in much of the report area. Hydrographs of the flow at gaging stations located in small watersheds in the report area indicate that almost all of the flow of perennial streams during the summer and early autumn is ground-water discharge. During the winter, when plant growth is at a minimum and the evaporation rate is lower, the rate of ground-water discharge is usually more than double the summer rate.

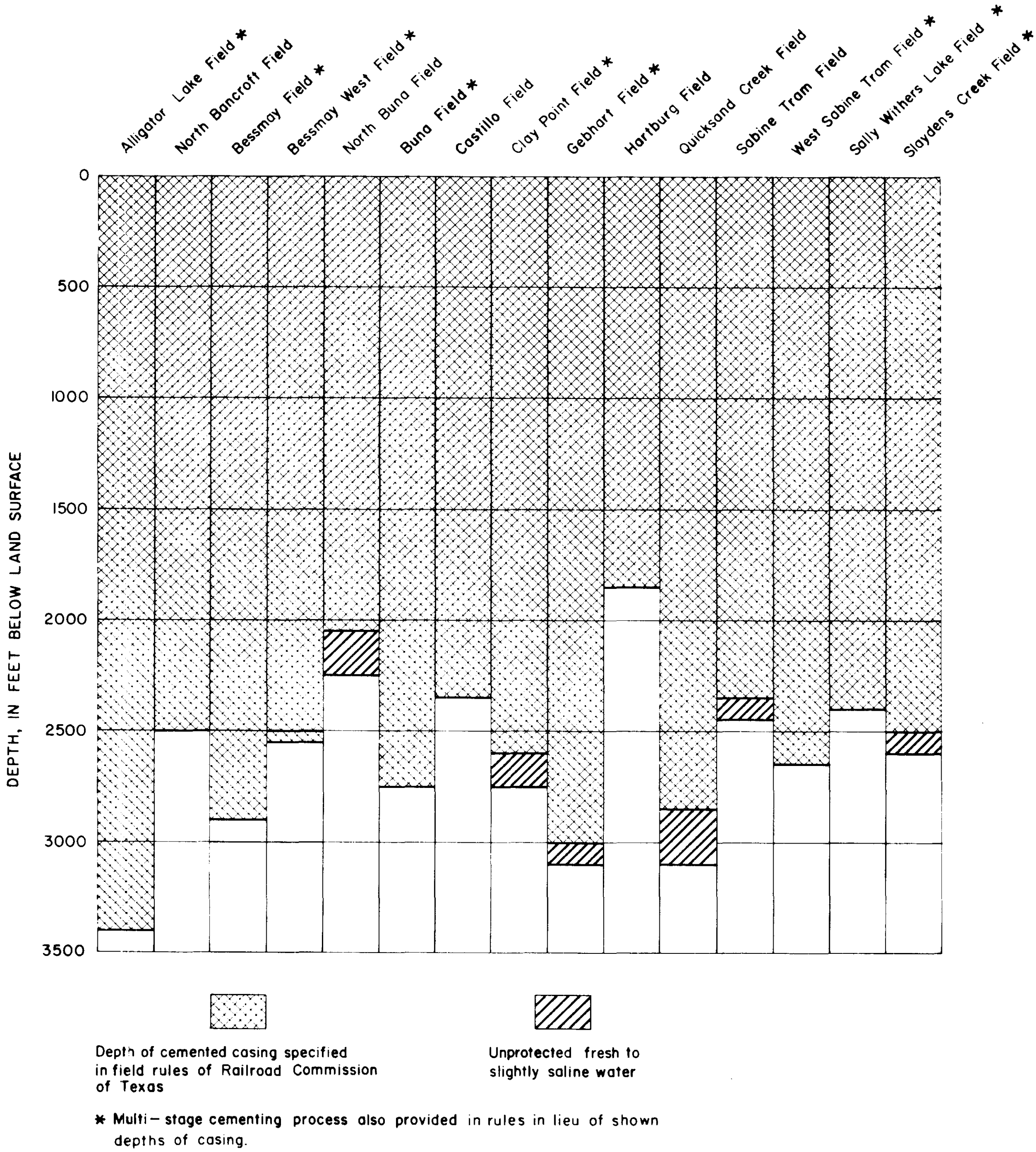

Figure 25

Comparison Between Depth to Base of Sand Containing Fresh to Slightly Saline Water and Amount of Surface Casing Required in Oil Fields

U.S. Geological Survey in cooperation with the Texas Water Development Board, Sabine River Authority of Texas and Jasper and Newton Counties

Estimates of the annual rate of ground-water discharge, or rejected recharge, in representative watersheds in the report area are in the following table:

Station number	Location of station	Drainage area (sq mi)	Estimated annual rate of ground-water discharge	
			Cubic feet per second	Acre-feet per sq mi
8-285.1	Quicksand Creek near Bon Wier, Tex.	65.1	28	315
8-295	Big Cow Creek near Newton, Tex.	128	47	266
8-296	Big Cow Creek near Belgrade, Tex.	342[1]	106	224
8-300	Cypress Creek near Buna, Tex.	69.2	.2	2
8-260 and 8-285	Sabine River basin (in Tex. and La.) between 8-260, Sabine River near Burkeville, Tex., and 8-285, Sabine River near Bon Wier, Tex.	747[2]	350	339

[1] Includes the drainage area of Big Cow Creek above station 8-295.
[2] Estimated 375 sq mi in report area.

These watersheds include about 850 sq mi, or about 45 percent of the report area. From these data the ground-water discharge to streams in Jasper and Newton Counties is about 500,000 acre-feet per year, or 446 mgd.

AVAILABILITY OF GROUND WATER

The volume of ground water available for development--without depleting to below stream level the storage level in the outcrops--is dependent upon the rate of recharge to the aquifers. If the water table in the outcrops were lowered to the level of the stream beds, the rate of recharge would be at least as much as the sum of the water being discharged as base flow (500,000 acre-feet per year, or 446 mgd), plus the amount of water being transmitted by the aquifers at the present gradient, or 70,000 acre-feet per year (62 mgd). This sum is 570,000 acre-feet per year, or 508 mgd.

To withdraw this amount of water would require properly spaced wells and controlled rates of pumping. Ideal conditions are not likely to occur, and these requirements do not take into consideration all factors that will be encountered in the development of the aquifers in the report area. However, the 570,000 acre-feet per year rate gives some conception of the magnitude of water supply that can be safely developed on a continuous basis from the aquifers in Jasper and Newton Counties.

An immense quantity of ground water is in transient storage in the two counties. The average thickness of sand saturated with fresh water is more than 700 feet. On the basis of a porosity of 30 percent, the aquifers have enough fresh water to cover the surface of both counties to a depth of 210 feet. Not all of this water is recoverable. If the three aquifers were dewatered everywhere to a depth of 400 feet below land surface, and if only one-half of the water present in the sands were to be produced, then 44 million acre-feet of water would be available from storage. This quantity is equivalent to a body of water about 35 feet deep covering the surface of Jasper and Newton Counties, and is enough water to sustain the present (1965) usage for more than 750 years. The preceding figures are all conservative and do not include the removal from storage of water in the clay parts of the aquifers and aquicludes.

Of the 570,000 acre-feet per year estimated to be available, about 70,000 acre-feet per year, or 62 mgd, is being transmitted by the three major aquifers at the present gradients (Figures 19, 20, and 21). The determination of amount of water (17,000 acre-feet per year or 15 mgd) being transmitted in the Jasper aquifer was made along a line midway between the center of the outcrop and the downdip limit of fresh water in the aquifer. This line crosses the counties 1.5 miles north of Kirbyville. The determinations for the Evangeline (11,000 acre-feet per year or 10 mgd) and Chicot (42,000 acre-feet per year or 37 mgd) aquifers were made on a line midway between the centers of their respective outcrops and the southern county line. The downdip limit of fresh water for both aquifers occurs in Orange County. The line for the Evangeline aquifer extends eastward about a mile south of Call, and the one for the Chicot aquifer passes across the counties about a mile north of Buna. The 1963 and 1964 production of water in Jasper and Newton Counties was between 40 and 50 mgd, and in Orange County was 20 mgd, an amount approximately equal to that being transmitted by the three aquifers at the present gradient.

The total thickness of sand containing fresh water is an important factor in the delineation of areas favorable for future development of ground-water resources. Figure 26 shows the total thickness of sand containing fresh water in Jasper and Newton Counties. This map is a compilation of data given in Figures 6, 8, and 10 plus data for the Catahoula Sandstone and Jackson Group. The maximum thickness of these sands is in the central part of the report area, which is also the area where the fresh-water-bearing sand in the Jasper aquifer is thickest (Figure 6). Because there has been very little development of the Jasper aquifer, this area in the central part of Jasper and Newton Counties is regarded as the most favorable for the future development of ground-water resources.

More than 400 feet of sand saturated with fresh water is available in all of Jasper and Newton Counties south of a line crossing the north edge of the city of Jasper (Figure 26). Between this line and the southern boundary of the counties, the thickness increases to as much as 1,200 feet at Kirbyville. Southward from Kirbyville, the interface between slightly saline water and fresh water rises first through the Jasper aquifer, and then through the Evangeline aquifer; thus, at the southern boundary of the report area the Chicot aquifer and only the top part of the Evangeline aquifer contain fresh water. At some locations along the southern boundary, slightly less than 400 feet of fresh-water-bearing sand may be present.

North of the line through the city of Jasper, the thickness of saturated sand gradually decreases to about 200 feet near the updip limit of the Jasper aquifer (Figure 6). In the northwestern part of Jasper County, where only the Catahoula Sandstone and older formations are present, the thickness of fresh-water-bearing sands is as small as 20 feet and could be as small as zero in some localities.

Wells capable of producing more than 1,000 gpm of fresh water can be constructed anywhere south of a line extending northeastward from the intersection of U.S. Highway 190 and the Tyler-Jasper county line to the intersection of State Highway 63 and the Texas-Louisiana state line.

CONCLUSIONS AND RECOMMENDATIONS

A large supply of fresh water is available in the aquifers of Jasper and Newton Counties. The proper development and maximum utilization of this supply will depend on the correct location and development of well fields. With good planning, all of the report area except the northwestern part of Jasper County will support large well fields.

Salt water in the downdip parts of the Jasper and Evangeline aquifers will move updip as development continues and the piezometric surface is lowered. Subsidence of the land surface will occur as a result of water-level declines in all the aquifers. Neither of these factors should impede development of the water resources but they should be considered in making plans for a type of development that provides the most fresh water with the least intrusion of salt water and that causes evenly distributed land subsidence.

In the southwestern part of Jasper County where the Evangeline aquifer has been partially developed, some subsidence has occurred, water levels have declined, and some movement of salt water probably has taken place. The movement of salt water and declines of water levels that have and will take place should be carefully evaluated before new well fields are constructed in this aquifer in the southern parts of Jasper or Newton Counties.

This report has described the basic framework of the aquifers, but continued collection of basic hydrologic data will be necessary if the problems which will accompany the development of the ground-water resources are to be understood and resolved. Hence, a continuing inventory should be made of all the new large-capacity wells, and should include the identification of the aquifers from which the water is being produced. The annual inventory of pumpage of water should be expanded and should include records of water pumped from individual wells and from the different aquifers.

The program of measuring water levels in observation wells should be expanded, and wells tapping all the aquifers should be included in the program. This information is needed to delineate the vertical hydraulic gradients between the aquifers, as well as to determine the direction and rate of lateral movement of water in the aquifers.

Periodic chemical quality resampling of water from key wells to chart the movement of salt water into the fresh-water parts of the aquifers should also be included in the continuing program. The observations should determine not only the lateral but also the vertical movement of salt water.

An expanded program for measuring subsidence is needed in Jasper and Newton Counties. Further delay in starting such a program will make difficult, if not impossible, precise determination of total subsidence. An enlarged network of bench marks should be run and leveled periodically. This program should be in conjunction with the continuing and expanding program for the collection of water-level and pumpage records, so that correlations of cause and effect can be made in the future.

As new wells are drilled in the area, aquifer tests should be made to obtain additional information on the hydraulic properties of the aquifers.

The continuing program of basic-data collection should extend into the adjoining counties because the development in those areas will affect the ground-water supplies in the report area. In addition to Jasper and Newton Counties, the area of observation should include parts of Orange, Tyler, Hardin, and Jefferson Counties. These observations would supplement similar observations being made in adjoining areas in Louisiana by the U.S. Geological Survey.

The ultimate objective of the continuing program should be to provide data for more precise quantitative evaluations of the aquifers in Jasper and Newton Counties. These evaluations are needed for more accurate predictions of the effects of future development on water levels, salt-water encroachment, and land-surface subsidence. In recent years, electrical-analog models have proved useful in the evaluation of aquifers. Such a model has been completed for the aquifers of the Houston area (Wood and Gabrysch, 1965). A preliminary model of the Chicot and Evangeline aquifers in Texas and Louisiana, including Jasper and Newton Counties, is now being constructed. The program recommended above would provide data that could be used in the model and thus aid in the proper planning and development of the ground-water resources of Jasper and Newton Counties.

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Table 6.--Drillers' logs of wells in Jasper and Newton Counties

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Jasper County

Well PR-36-49-802

Owner: Gilmer Lumber Co. Driller: Jake Giles.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Soil	4	4	Sand, blue, water	40	1,077
Clay	14	18	Gumbo and shale	10	1,087
Sand	2	20	Rock	2	1,089
Gumbo, blue, and shale	362	382	Shale, brown, and gumbo	34	1,123
Rock	2	384	Rock	2	1,125
Gumbo, blue, and shale	76	460	Shale, brown, and gumbo	57	1,182
Rock	1	461	Rock	1	1,183
Gumbo, blue, and shale	50	511	Coal, lignite	4	1,187
Rock	2	513	Shale, brown, and gumbo	6	1,193
Gumbo, blue, and shale	52	565	Sand, blue, water	30	1,223
Sand	8	573	Shale, brown, and gumbo	28	1,251
Gumbo, blue, and shale	30	603	Sand, blue, water	11	1,262
Rock	1	604	Coal, lignite	3	1,265
			Rock	3	1,268
Gumbo, blue, and shale	6	610	Sand, blue, water	17	1,285
Rock	3	613	Shale, brown, and gumbo	5	1,290
Gumbo, blue, and shale	272	885	Sand, blue, water	30	1,320
Sand, blue	40	925			
Gumbo, blue, and shale	112	1,037			

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-36-57-102

Owner: Paul A. Teegarden, Inc. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	9	9	Sand, lignite	20	182
Sand	57	66	Sand	13	195
Clay	51	117	Clay	27	222
Sand	9	126	Clay, sandy	69	291
Clay	5	131	Sand, salt and pepper	48	339
Sand	31	162	Clay	1	340

Well PR-36-57-901

Owner: Harrisburg Water Supply Corp. Driller: C. C. Innerarity.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand, surface	1	1	Shale, soft, blue	35	380
Clay, red	20	21	Shale, blue	65	445
Sand, gravel with clay	94	115	Shale, sand streaks	40	485
Sand	50	165	Clay, blue	110	595
Sand, clay streaks	40	205	Sand streaks	10	605
Clay	25	230	Clay, blue	75	680
Clay, soft	5	235	Sand	38	718
Sand	110	345			

Well PR-37-61-903

Owner: Kountze Bros., well 6. Driller: --

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red, and sand	65	65	Sand, gray, artesian flow	20	85

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well PR-37-61-903--Continued					
Rock, gray, sand	20	105	Sand, dark gray	19	784
Gumbo, blue, and shale	70	175	Marl, green	16	800
Gumbo, blue	88	263	Shale, green, hard streaks	35	835
Shale, green	12	275	Marl, green, with shell	145	980
Gumbo, blue	25	300	Marl, green, and rock	138	1,118
Shale, green	190	490	Rock and sand	2	1,120
Marl, green, and boulders	45	535	Marl, green	80	1,200
Marl, green	80	615	Shale, dark brown	8	1,208
Sand, dark blue	15	630	Marl, green	21	1,229
Sand, dark gray	25	655	Sand, gray, artesian flow of salt water	12	1,241
Shale, dark gray	17	672	Shale, green	8	1,249
Shale, green	20	692			
Shale, green, and shell	73	765			

Well PR-37-61-904

Owner: Bob Boykin, well 1. Driller: Great Lakes Oil Syndicate.

Clay	80	80	Shale and boulders	17	443
Sand, salt water	19	99	Gumbo	77	520
Shale, sandy	301	400	Sand, white, sulfur water	32	552
Sand	3	403	Shale, brown	136	688
Gumbo, blue	23	426			

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Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-37-61-904--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand, blue, sulfur water	37	725	Shale and boulders	14	1,154
Gumbo	314	1,039	Gumbo, gas	136	1,290
Shale, sandy	40	1,079	Sand	8	1,298
Gumbo	61	1,140			

Well PR-37-62-702

Owner: B. F. Boykin, well 2. Driller: Midwest Co. of Texas.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Soil, surface, and white sand	16	16	Shale	41	738
Shale	96	112	Shale, sandy, layers of sand and shells	127	865
Sand, gray	40	152	Rock	1	866
Rock	3	155	Shale, hard	62	961
Shale, blue	69	224	Shale, shells and rock	211	1,172
Sand, fine-grained, gray	45	269	Rock	3	1,175
Shale and sand	68	337	Sand, shell, and rocks	5	1,180
Shale	24	361	Shale and rock	72	1,252
Shale and sandy shale	76	437	Sand	7	1,259
Shale, blue	74	511	Sand, shale, and shells	329	1,588
Shale, sandy	17	528	Shale, hard	11	1,599
Shale, gray	83	611	Sand and shale	91	1,690
Sand and shale	85	696	Sand, shale, and lignite	22	1,712
Rock	1	697			

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Jasper County

Well PR-37-62-702--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Shale and sandy shale	14	1,726	Rock	1	1,875
Rock and shale	3	1,729	Shale, sandy	36	1,911
Sand and shale	70	1,799	Shale, sandy, and lignite	75	1,986
Rock	1	1,800	Sand	10	1,996
Shale	42	1,842			
Sand and shale	32	1,874			

Well PR-37-63-602

Owner: H. Ralph, well 1. Driller: Guffey Oil Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	20	20	Sand and gravel	40	460
Sand	25	45	Gumbo	80	540
Gravel	15	60	Shale	110	650
Sand, flowing water	20	80	Sand, gravel, and water	150	800
Soapstone	60	140	Soapstone	50	850
Sand	20	160	Sand	90	940
Rock	20	180	Gumbo	60	1,000
Gumbo	20	200	Shale, loose	150	1,150
Sand	20	220	Gumbo	350	1,500
Gumbo	20	240	Sand and gravel	50	1,550
Sand	110	350	Gumbo, gravel and boulders	165	1,715
Gumbo and gravel	50	400	Rock	5	1,720
Shale	20	420			

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Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-37-63-602--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Gumbo	40	1,760	Gravel, coarse, and shale	60	2,100
Rock	10	1,770	Rock, soft, and gravel	130	2,230
Gumbo	230	2,000	Gravel, hard, sand and water	47	2,277
Sand	40	2,040			

Well PR-37-63-801

Owner: I. S. Bean. Driller: Cleveland & East Texas Oil Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red	15	15	Limestone, water-bearing	10	192
Sand, fine, white	5	20	Rock, fine-grained	3	195
Limestone, soft, white	42	62	Shale, green	24	219
Shale, green	3	65	Sand, white	1	220
Sandstone, limestone, mixed streaks	21	86	Shale, green, blue, streaks of limestone	86	306
Shale	2	88	Sand, fine, gray	6	312
Sandstone, hard	4	92	Clay, blue	9	321
Sandstone, soft	12	104	Shale, blue	5	326
Shale, greenish	24	128	Shale and sand streaks	9	335
Sand, white	3	131	Sand, gray	10	345
Limestone	9	140	Shale, blue	3	348
Shale, green	4	144	Sand, fine, gray	12	360
Shale, green, with limestone	32	176	Sand and shale	5	365
Clay, blue, tough	6	182	Limestone, soft	15	380

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Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-37-63-801--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, blue, and shale	9	389	Limestone, sheets of sand	17	500
Sand, white, fine-grained	26	415	Sand, fine, white	24	524
Clay, blue, and shale	10	425	Sandstone, soft	5	529
Limestone	10	435	Sand and shale	462	991
Shale, blue	15	450	Rock	1	992
Limestone	12	462	Sand	1	993
Sand, fine, white	11	473	Shale, blue, soft	407	1,400
Shale, blue	10	483			

Well PR-37-63-904

Owner: Ray Prewitt. Driller: Merritt Bros.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand	5	5	Soapstone	2	28
Clay	17	22	Quicksand	8	36
Gravel	4	26			

Well PR-37-64-402

Owner: U.S. Army Corps of Engineers. Driller: Paul Hardeman, Inc.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, sandy, and sand	38	38	Shale, blue	51	211
Shale, blue, sandstone	106	144	Sand	52	263
Sand	16	160	Shale, blue	37	300

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-61-07-301

Owner: Tennessee Gas & Transmission Co. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Soil	4	4	Shale, sandy	8	201
Clay, red	10	14	Shale	8	209
Sand, gray	4	18	Rock	2	211
Sand and shale	46	64	Shale, sticky	19	230
Shale, hard	3	67	Shale, sandy	19	249
Sand, fine, shale layers	93	160	Shale, sandy	38	287
Shale	33	193			

Well PR-61-07-303

Owner: Tennessee Gas & Transmission Co. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, sandy	31	31	Shale	101	303
Shale, blue	151	182	Sand	35	338
Sand	20	202	Shale, blue	91	429

Well PR-61-07-604

Owner: Martin Dies. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, sandy	5	5	Clay, sandy	20	172
Sand and gravel	50	55	Sand, gray	52	224
Clay	31	86	Clay	88	312
Clay, sandy	44	130	Sand, gray	49	361
Clay	22	152	Clay	3	364

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-61-07-801

Owner: State of Texas well 1. Driller: -- Adams.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand, surface	5	5	Shale, packed	23	873
Clay	7	12	Gumbo	27	900
Sand, gray, water	38	50	Shale and boulders	40	940
Sand, yellow, and gravel	10	60	Gumbo	30	970
Sand, blue, water	60	120	Rock, broken	3	973
Shale	15	135	Shale, packed	27	1,000
Sand	190	325	Limestone, hard	4	1,004
Gumbo	35	360	Shale and gumbo	166	1,170
Sand, water	50	410	Rock	5	1,175
Gumbo	60	470	Gumbo	65	1,240
Sand	30	500	Sand, gray, water	60	1,300
Shale, packed	35	535	Gumbo and gypsum	198	1,498
Gumbo	143	678	Sand, water	20	1,518
Shale and boulders	22	700	Gumbo, tough	32	1,550
Gumbo	40	740	Packsand	50	1,600
Shale	60	800	Sand and shale	25	1,625
Gumbo	50	850	No record	705	2,350

Well PR-61-08-104

Owner: Bert Hinson. Driller: Crews Water Well Service.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
No record	30	30	Shale	135	175
Sand, water	10	40	Sand, water	62	237

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-61-08-502

Owner: J. W. Campbell. Driller: Frank Balcar.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
No record	208	208	Shale, blue	49	364
Clay	16	224	Clay	32	396
Shale	32	256	Shale, hard	10	406
Clay, red and yellow	16	272	Sand, white	19	425
Shale, sandy	43	315			

Well PR-61-08-903

Owner: -- Seale well 1. Driller: -- Seale.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand	60	60	Dolomitic rock, pyrites, quartz, sand, oil showing	9	767
Sand and rock	90	150	Dolomitic rock, pyrites, quartz, sand, yellow clay, oil showing	19	786
Clay, blue, and sand, at 275 ft, artesian water and gas; at 250 ft, oil showing	260	410	Quicksand, dolomitic rock, gumbo	22	808
Limerock	10	420	Gumbo, shale, gravel, dolomitic rock, quicksand, iron pyrites, oil showing	24	832
Clay, blue	100	520	Dolomitic rock, quicksand, yellow clay, lignite(?), slight oil showing	21	853
Limerock	5	525	Clay, hard, gray, calcareous concretions, limerock, pyrites	77	930
Gumbo and sand	150	675			
Limerock	6	681			
Gumbo	23	704			
Sand, oil showing	23	727			
Limerock	3	730			
Gumbo and shale	28	758			

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Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well PR-61-08-903--Continued					
Quicksand, fine, concretions, much fine pyrites, splendid oil showing ----------	11	941	Sand, fine gray, limerock concretions, some white quartz, black carbonaceous particles, considerable iron oxide -----------	21	1,116
Shale, sand, fine quartz, dolomitic rock, iron oxide, calcite --------------	79	1,020	Sand, fine gray, lime concretions, white quartz, black carbonaceous matter, magnetic iron oxide in abundance, oil showing good -----------------	12	1,128
Sand, fine white, pyrites, shale, large amount of lime -------	40	1,060	Sandrock, white quartz -	42	1,170
Sand, fine white, pyrites, shale, some limerock -------------	10	1,070	Sandrock, gas and oil showing --------------	29	1,190
Shale, pebbles, variegated chips of flint rock, limerock, and pyrites --------------	2	1,072	Sand, fine gray, carbonaceous particles, magnetic iron oxide -----	80	1,270
Sand, extremely fine, gray, shell fragments, very fine white quartz, black carbonaceous matter, some clay and limestone, oil showing very good ------------	23	1,095	Clay, bluish-gray, very fine sand, black particles, magnetic iron, quartz ---------	50	1,320
			Shale, hard, blue ------	151	1,471

Well PR-61-15-201

Owner: State of Texas Parks and Wildlife Service. Driller: Simmons Water Well Service.

Clay, brown ------------	55	55	Gumbo, clay, rock strips ---------------	275	380
Sand, gray -------------	50	105	Sand, blue -------------	62	442

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well PR-61-15-202

Owner: State of Texas Hen House Ridge. Driller: Simmons Water Well Service.

Clay	65	65	Sand	51	170
Shale, blue	54	119			

Well PR-61-15-603

Owner: U.S. Army Corp of Engineers, Sandy Creek Park. Driller: Simmons Water Well Service.

Clay	30	30	Sand and gravel	30	170
Sand, coarse	24	54	Shale	45	215
Shale, blue, and red, clay, sandy	36	90	Sand	45	260
Sand	50	140			

Well PR-61-15-901

Owner: B. O. Easely. Driller: George Bellinger.

Sand	14	14	Rock	2	141
Shale	125	139	Sand	40	181

Well PR-61-16-202

Owner: D. M. Thomas. Driller: Commodore Oil Co.

Surface	43	43	Gumbo	22	530
Sand, artesian water at 85 ft	396	439	Sand	135	665
Lime	16	455	Lime and gumbo	205	870
Sand	53	508	Sand	10	880

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well PR-61-16-202--Continued					
Lime	40	920	Lime, artesian water	22	1,347
Packsand	30	950	Sand	18	1,365
Gumbo	10	960	Gumbo and shale	60	1,425
Sand	15	975	Lime and sand	45	1,470
Packsand	25	1,000	Sand	10	1,480
Lime and gumbo	143	1,143	Sand and shale	25	1,505
Lime, hard, and sand	37	1,180	Gumbo	25	1,530
Gumbo	35	1,215	Gumbo	15	1,545
Sand	25	1,240	Sand, salt water	25	1,570
Lime and gumbo	85	1,325	No record	1,934	3,504

Well PR-61-24-201

Owner: E. C. Carruth. Driller: Crews Well Service.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand	20	20	Gumbo	43	183
Sand, water	5	25	Sand, salt and pepper, water	13	196
Clay	50	75	Gumbo, blue	19	215
Sand, water	10	85	Shale, soft	20	235
Clay	10	95	Shale, hard	25	260
Shale	45	140			

Well PR-61-32-606

Owner: R. V. Taylor. Driller: R. V. Taylor.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand, yellow	8	8	Sand, water	2	32
Quicksand	22	30	Clay	1	33

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-61-48-214

Owner: Southern Pine Co. Driller: Frank Balcar.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, yellow	30	30	Gumbo, blue	21	115
Sand	3	33	Shale, sandy	35	150
Shale, yellow, sandy	19	52	Shale, blue	55	205
Clay	38	90	Clay, dark-colored	5	210
Quicksand	4	94	Sand and gravel	16	226

Well PR-61-48-401

Owner: Champion Paper Co. Driller: L. B. Jenson.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Loam, fine, sandy	2	2	Sand, coarse, white	49	638
Clay, red	23	25	Clay, blue	18	656
Sand, white	50	75	Clay, fine, blue	30	686
Clay, yellow	21	96	Clay, hard, blue	19	705
Sand, fine, blue	33	129	Sand, coarse, white	55	760
Clay, yellow	27	156	Clay, hard, blue	9	769
Sand, white	17	173	Clay, soft, blue	25	794
Clay, yellow	52	225	Sand, white	10	804
Sand, fine, blue	27	252	Clay, hard, blue	20	824
Clay, hard, yellow	134	386	Sandstone, fragmentary	4	828
Sand, white	90	476	Clay, hard, blue	82	910
Clay, blue	81	557	Sandstone, rotten	6	916
Sand, blue	22	579	Clay, blue	7	923
Clay, hard, blue	10	589	Sand, white	22	945

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Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well PR-61-48-401--Continued					
Clay, hard, blue	67	1,012	Sand, white	34	1,096
Sand, coarse, white	19	1,031	Clay, blue	18	1,114
Gravel, fine	17	1,048	Sand, white	97	1,211
Gravel, coarse	14	1,062			

Well PR-61-48-704

Owner: City of Beaumont. Driller: Frank Balcar.

No record	70	70	Gumbo	30	540
Clay	14	84	Sand	16	556
Shale, sandy	48	132	Shale	14	570
Clay	31	163	Gumbo	50	620
Shale, blue, sandy	69	232	Shale	20	640
Packsand	28	260	Gumbo, blue	5	645
Shale	50	310	Sand	37	682
Sand, blue	17	327	Shale	53	735
Shale, sandy	78	405	Gumbo, yellow	57	792
Shale and gumbo	75	480	Sand	22	814
Sand and shale	30	510			

Well PR-61-48-801

Owner: T. H. Mabry. Driller: Wise & Fletcher.

Loam, fine, sandy	2	2	Sand, yellow	12	18
Clay, yellow	4	6	Clay, gray	9	27

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-61-48-801--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand, white	23	50	Sand, coarse, white	53	684
Clay, yellow	33	83	Clay, blue	13	697
Sand, fine, blue	34	117	Sand, fine, blue	21	718
Clay, blue	35	152	Stone, soft	38	756
Sand, white	21	173	Clay, hard, blue	12	768
Clay, blue	61	234	Sand, coarse, white	31	799
Sand, fine, blue	30	264	Clay, hard, blue	54	853
Clay, blue	31	295	Unable to tell strata	15	868
Sand, fine, blue	61	356	Clay, hard, blue	68	936
Clay, gray	70	426	Clay, fine, blue	13	949
Sand, white	94	520	Clay, hard, blue	41	990
Clay, blue	63	583	Sand, white, water-bearing	22	1,012
Sand, fine, blue	37	620	Clay, hard, blue and green	27	1,039
Clay, blue, hard	11	631			

Well PR-62-01-406

Owner: City of Jasper. Driller: Layne-Texas Co.

No record	22	22	Sand, few red clay streaks	101	181
Sand	8	30	Sand, coarse, and gravel	60	241
Clay, white	14	44	Clay	2	243
Sand	32	76	Sand	3	246
Clay, sandy	4	80			

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-62-01-406--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	14	260	Shale	5	653
Sand	18	278	Sand	10	663
Clay, white, blue	31	309	Shale and sand streaks	10	673
Sand and clay streaks	26	335	Shale	19	692
Clay, blue, and sand streaks	30	365	Sand and shale layers	11	703
Clay, sandy	28	393	Sand	43	746
Sand and shale streaks	16	409	Sand, lignite, and shale streaks	11	757
Sand	30	439	Sand	10	767
Sand, coarse, and fine gravel	43	482	Shale, few sand streaks	5	772
Shale	8	490	Shale and sandy shale streaks	26	798
Sand	5	495	Shale and sand streaks	17	815
Clay, red, white, and green	30	525	Shale, sandy	4	819
Sand and shale	28	553	Shale	21	840
Sand	25	578	Shale and sandy shale	15	855
Clay	1	579	Shale	17	872
Sand	8	587	Shale, sandy	9	881
Clay	2	589	Sand and shale streaks	14	895
Sand	3	592	Shale, sandy	47	942
Shale	1	593	Shale streaks of sand	17	959
Sand and streaks of lignite	55	648	Shale	27	986

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well PR-62-01-406--Continued					
Shale and sand streaks -	71	1,057	Sand and shale streaks --------------	20	1,254
Shale and layers of sand ----------------	20	1,077	Shale, sandy, and shale breaks ---------	35	1,289
Sand and shale layers --	23	1,100	Sand and shale streaks -	4	1,293
Shale, sandy -----------	12	1,112	Shale, sandy -----------	14	1,307
Sand, coarse -----------	8	1,120	Sand -------------------	3	1,310
Shale ------------------	5	1,125	Shale, sandy -----------	10	1,320
Sand -------------------	5	1,130	Shale ------------------	13	1,333
Shale, sandy -----------	7	1,137	Sand -------------------	6	1,339
Shale ------------------	44	1,181	Shale, sandy -----------	8	1,347
Sand, fine -------------	19	1,200	Sand -------------------	3	1,350
Shale ------------------	26	1,226	Shale ------------------	2	1,352
Shale, sandy, and sand -	8	1,234			

Well PR-62-01-409

Owner: City of Jasper. Driller: Layne-Texas Co.

Soil, sandy ------------	2	2	Sand, gravel and clay streaks --------------	68	139
Clay, sandy, red -------	16	18	Clay, sandy ------------	15	184
Clay, sandy, and gravel ---------------	11	29	Sand -------------------	21	205
Sand -------------------	7	36	Clay -------------------	15	220
Clay -------------------	7	43	Sand -------------------	31	251
Sand -------------------	28	71	Sand with clay ---------	114	365

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-62-01-409--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	8	373	Sand	14	474
Sand and gravel	18	391	Shale, hard	42	516
Sand and lignite	12	403	Sand	65	581
Sand	49	452	Rock	1	582
Gumbo	8	460			

Well PR-62-01-501

Owner: B. G. Lindsey. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Soil	3	3	Clay and sandy clay	59	256
Clay	39	42	Sand and small gravel	34	290
Sand	8	50	Sand and clay	40	330
Clay	64	114	Sand and gravel	55	385
Sand	83	197	Clay	5	390

Well PR-62-01-701

Owner: Texas Electric Co., Inc. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	32	32	Sand, white, clay layers	29	212
Sand, fine	10	42	Sand and sandy clay	40	252
Sand and gravel	79	121	Clay	12	264
Clay, sandy	31	152	Sand, coarse, and gravel	71	335
Clay, sandy, sand layers	19	171	Shale, broken	91	426
Sand	12	183			

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well PR-62-01-701--Continued					
Sand	31	457	Shale	2	734
Shale, broken	26	483	Sand	15	749
Sand	64	547	Shale	17	766
Shale	36	583	Shale and sand layers	32	798
Sand and shale breaks	83	666	Sand	31	829
Shale	5	671	Sand and shale breaks	29	858
Sand	31	702	Shale, hard, gray	91	949
Shale	5	707	Shale, hard	51	1,000
Sand	25	732			

Well PR-62-01-802

Owner: C. T. Flourney well 1. Driller: Helmerick & Payne, Inc.

Surface	60	60	Shale, gummy	47	780
Clay	90	150	Shale, sandy	25	805
Sand and gravel, water	70	220	Shale	80	885
Clay, reddish-brown and yellow	69	289	Sand	65	950
Shale, green	55	344	Shale, gummy	3	953
Sand, water	75	419	Shale, green	75	1,028
Shale, blue and green	31	450	Sand and shale streaks	52	1,080
Sand, water	10	460	Shale, sticky	5	1,085
Shale, green, yellow, and blue	260	720	Gumbo	25	1,110
Sand	13	733	Shale and streaks of sand	100	1,210

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-62-01-802--Continued

	Thickness (feet)	Depth (feet)
Sand	30	1,240
Shale	5	1,245
Rock and sand	7	1,252
Shale, green and blue gumbo	196	1,448
Sand, water	11	1,459
Shale, green, blue, sandy	121	1,580
Sand, greenish-gray, water	6	1,586
Shale, gumbo and sandy shale	84	1,670
Sand, fine-grained, gray	21	1,691
Shale, hard, sandy	34	1,725
Sand, gray, water	10	1,735
Gumbo, gray	13	1,748
Packsand	26	1,774
Sand, coarse-grained, white	27	1,801
Shale, streaks of sand and gumbo	97	1,898
Sand	14	1,912
Shale, hard	13	1,925
Sand	10	1,935
Shale, streaks of sand and gumbo	29	1,964
Sand, soft, white	10	1,974
Sand, salt and pepper	26	2,000
Sand, coarse-grained	24	2,024
Shale, sticky	9	2,033
Shale with streaks of sand and lignite	18	2,051
Sand, fine-grained and sulfur	12	2,063
Shale and sand, water	6	2,069
Sand, fine-grained, gray	18	2,087
Shale, blue, streaks of sand	19	2,106
Gumbo, hard shale, shells, lignite, and streaks of sand with salt water	132	2,238

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

Well PR-62-09-703

Owner: C. F. Smith. Driller: Layne-Bowler Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Soil	9	9	Gumbo	51	384
Clay	51	60	Clay	21	405
Sand	55	115	Sand, fine-grained	21	426
Clay	34	149	Sand, coarse-grained	20	446
Gumbo	12	161	Rock	8	454
Clay and boulders	32	193	Gumbo	11	465
Clay	42	235	Sand, fine-grained	29	494
Gumbo	15	250	Sand, coarse-grained	13	507
Gravel	27	277	Gravel	3	510
Clay, blue	3	280	Sand	3	513
Sand, white	53	333	Gumbo	10	523

Well PR-62-17-504

Owner: G. T. Ellis. Driller: G. T. Ellis.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Soil	10	10	Clay, red	108	130
Sand, fine	12	22	Sand	20	150

Well PR-62-17-903

Owner: City of Kirbyville. Driller: Frank Balcar.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red	4	4	Clay, yellow	38	84
Sand, white	24	28	Sand, gray	131	215
Shale and sand	18	46	Shale	33	248

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well PR-62-17-903--Continued					
Sand	36	284	Gumbo and shale	94	875
Shale	12	296	Rock	15	890
Shale and sand	28	324	Shale and boulders	55	945
Clay	13	337	Gumbo	62	1,007
Rock, soft	22	359	Rock	2	1,009
Gumbo	21	380	Gumbo	56	1,065
Shale and boulders	62	442	Rock	7	1,072
Gumbo and shale	43	485	Gumbo	110	1,182
Sand	20	505	Sand and boulders	32	1,214
Shale	20	525	Gumbo	26	1,240
Gumbo	28	553	Sand	8	1,248
Shale	18	571	Gumbo and shale	50	1,298
Sand, coarse, red	37	608	Sand	19	1,317
Gumbo and shale	62	670	Gumbo and shale	103	1,420
Gumbo	111	781	Gumbo	7	1,427

Well PR-62-17-909

Owner: Lewis Troy. Driller: Harvey Roff.

Clay	20	20	Clay	120	150
Sand	10	30	Sand	35	185

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well PR-62-33-203

Owner: Kirby Lumber Co. Driller: Frank Balcar.

Clay, red	18	18	Clay	24	194
Sand, yellow	3	21	Sand, brown	57	251
Clay, reddish-gray	77	98	Shale, and rock	1	252
Shale	52	150	Gravel	8	260
Shale, sandy	20	170	Sand	20	280

Well PR-62-33-401

Owner: Jasper County Water Control & Improvement District no. 1. Driller: Katy Drilling Co.

Soil, surface, and clay	12	12	Clay	35	257
Sand and clay streaks	56	68	Sand	47	304
Clay	28	96	Clay	11	315
Sand	35	131	Sand and gravel	61	376
Clay	19	150	Clay	62	438
Sand and clay streaks	30	180	Sand	8	446
Sand and gravel	42	222	Clay	52	498

Well PR-62-41-801

Owner: Mrs. Eunice Marceaux. Driller: Coastal Water Wells.

Topsoil	4	4	Clay	25	121
Clay	31	35	Shale	67	188
Sand, white	61	96	Shale, sandy	12	200

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Jasper County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well PR-62-41-801--Continued					
Shale ------------------	30	230	Sand, fine and shale ---	40	520
Sand -------------------	46	276	Sand, fine -------------	44	564
Shale, hard ------------	14	290	Sand, fine, streaks of shale ----------------	69	633
Shale, sandy -----------	10	300	Sand, fine -------------	43	676
Sand -------------------	135	435	Sand, fine, streaks of shale ----------------	54	730
Shale ------------------	29	464			
Sand, fine -------------	16	480			

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Newton County

Well TZ-36-59-803

Owner: Wier Long Leaf Lumber Co. Driller: McMasters & Pomeroy.

	Thickness (feet)	Depth (feet)
Cinders	3	3
Sand, surface	12	15
Gravel	15	30
Sand	21	51
Clay	15	66
Sand	23	89
Clay	11	100
Sand	18	118
Clay	64	182
Sand and gravel	39	221
Clay	11	232

Well TZ-62-10-310

Owner: City of Newton. Driller: McMasters & Pomeroy.

	Thickness (feet)	Depth (feet)
Sand	3	3
Clay	4	7
Sand	21	28
Clay	4	32
Sand	26	58
Shale	6	64
Sand and shale	30	94
Clay	21	115
Shale	37	152
Sand and gravel	37	189
Shale	11	200

Well TZ-62-10-901

Owner: Texas Eastern Pipeline Co. Driller: Raybord Drilling Co.

	Thickness (feet)	Depth (feet)
Clay	12	12
Sand, white	148	160
Sand, fine, red	1	161
Sandrock, hard	5	166
Shale, white	29	195
Sand	55	250
Shale, white	10	260
Sand, coarse, white, trace of lignite	40	300

Newton County

Well TZ-62-18-102, partial log

Owner: Southwestern Lumber Co. Driller: Tide Water Oil Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand, surface	360	360	Sand	10	760
Sand, hard	113	473	Shale	130	890
Sand, streaks of shale	27	500	Sand and gravel	116	1,006
Sand	15	515	Clay and shells	34	1,040
Sand and gravel	19	534	Sand and gravel	45	1,085
Sand and clay	106	640	Shale, sandy, and lime, streaks of	727	1,812
Sand	15	655	Sand and gravel	188	2,000
Sand and shale	45	700	Shale and lime	530	2,530
Shale, sticky	50	750	Total depth		5,848

Well TZ-62-18-404

Owner: Southwestern Settlement & Development Co. Driller: W. T. Arnett.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red and white joint	47	47	Gumbo	5	337
Sand, blue	152	199	Rock, blue, hard	1	338
Sulfur and shale	48	247	Shale, blue and brown	107	445
Rock and soapstone	1	248	Sand, blue	50	495
Sand, gray	29	277	Rock and soapstone	2	497
Sand and shale, oil seepage	22	299	Shale, hard, blue	38	535
Rock and soapstone	1	300	Marl, blue	3	538
Sand, water	32	332	Sand, water, artesian flow	140	678

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Newton County

Well TZ-62-18-404--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Gumbo	18	696	Shale, blue and yellow	467	1,269
Rock, hard, blue sandstone	1	697	Gumbo	43	1,312
Shale, blue, and brown, oil signs	73	770	Sand, mineral water, artesian flow	34	1,346
Marl, blue	18	788	Gumbo	6	1,352
Rock, hard, blue	2	790	Shale, blue	11	1,363
Sand, oil seepage	9	799	Gumbo, blue	19	1,382
Rock, blue, soapstone	3	802	Shale, blue and purple	113	1,495

Well TZ-62-19-301

Owner: J. M. Inman. Driller: R. T. Briscoe.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	17	17	Sand	133	1,403
Sand, gray	359	376	Shale and sand	30	1,433
Shale and gumbo	465	841	Shale, sticky	14	1,447
Sand	122	963	Shale, sandy	59	1,506
Shale and lime	307	1,270			

Well TZ-62-34-201

Owner: C. E. Ebner. Driller: Coastal Water Wells.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Soil surface	10	10	Sand, fine	30	140
Sand, fine	90	100	Shale, sandy	60	200
Shale, blue	10	110	Sand, water	132	332

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Newton County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well TZ-62-42-101

Owner: Adolph Ebner. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	25	25	Clay	10	332
Sand, good, white	57	82	Sand, shale layers	55	387
Clay	80	162	Sand, good	31	418
Sand	60	222	Shale, soft, sandy, and sand	35	453
Clay, soft	40	262	Sand	71	524
Sand and clay, sandy	60	322			

Well TZ-62-42-102

Owner: Adolph Ebner. Driller: Coastal Water Wells.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Topsoil	4	4	Sand, fine	33	244
Clay	21	25	Gumbo	53	297
Shale, sandy	13	38	Shale, sandy	31	328
Sand, coarse, good	50	88	Sand, fine, gray	38	366
Clay	32	120	Sand, fine	21	387
Shale	40	160	Sand, medium coarse to gravel	39	426
Sand, fine	46	206	Shale, gummy	3	429
Shale	5	211			

Well TZ-62-42-401

Owner: C. H. Cox. Driller: Coastal Water Wells.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand	30	30	Sand, fine	42	102
Shale	30	60	Gumbo	68	170

(Continued on next page)

Table 6.--Drillers' logs of wells in Jasper and Newton Counties--Continued

Newton County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well TZ-62-42-401--Continued					
Sand	5	175	Sand, fine	16	322
Gumbo	15	190	Gumbo	45	367
Sand	17	207	Shale, sandy	51	418
Gumbo	43	250	Sand, fine	32	450
Sand, fine	27	277	Gumbo	8	458
Sand, coarse	29	306	Sand	86	544

Well TZ-62-42-701

Owner: Bascome Funches. Driller: Coastal Water Wells.

Topsoil	3	3	Shale	310	435
Clay	37	40	Sand, fine	65	500
Sand, fine	72	112	Sand, coarse	90	590
Sand, coarse, and gravel	13	125			

Well TZ-62-42-905

Owner: Frank Nelson. Driller: George Glidden.

Dirt, white	2	2	Gumbo, blue	16	185
Clay	14	16	Sand, fine-grained, hard	8	193
Clay, sandy	8	24	Gumbo, blue	64	257
Clay, yellow	19	43	Sand, hard, packed, water	16	273
Sand, fine-grained	8	51	No record	20	293
Gumbo, blue	99	150			
Sand, coarse, water	19	169			

APPENDIX 4

Baker, E.T., Jr, 1986, Hydrology of the Jasper aquifer in the southeast Texas Coastal Plain of Texas, Texas Water Development Board, Report 295, 64 pp.

Report 295

Hydrology of the Jasper Aquifer in the Southeast Texas Coastal Plain

October 1986

Texas Water Development Board

TEXAS WATER DEVELOPMENT BOARD

REPORT 295

HYDROLOGY OF THE JASPER AQUIFER
IN THE SOUTHEAST TEXAS COASTAL PLAIN

By

E. T. Baker, Jr.
U.S. Geological Survey

This report was prepared by the U.S. Geological Survey under cooperative agreement with the Texas Water Development Board

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FOREWORD

Effective September 1, 1985, the Texas Department of Water Resources was divided to form the Texas Water Commission and the Texas Water Development Board. A number of publications prepared under the auspices of the Department are being published by the Texas Water Development Board. To minimize delays in producing these publications, references to the Department will not be altered except on their covers and title pages.

ABSTRACT

The Jasper (Miocene) aquifer is one of several important hydrologic units in the Gulf Coastal Plain. Because the Jasper aquifer underlies shallower aquifers in many areas, regional water withdrawals from the Jasper are not significant; however, it is capable of yielding 3,000 gallons per minute or more of water to wells in certain areas. The Jasper is underlain by the Catahoula confining system (restricted) and overlain by the Burkeville confining system. The Evangeline and Chicot aquifers, in turn, overlie the Burkeville and also are prolific water-yielding aquifers.

The ground-water hydrology of the Jasper aquifer in an area of about 20,000 square miles, was simulated by a two-dimensional digital model using a steady-state approach. The model represents hydrologic conditions prior to development by wells, when natural recharge equaled natural discharge. The model's grid pattern of 15 x 24 nodes varies from a dimension of 5 by 10 miles in the outcrop to 10 by 10 miles in the artesian section downdip from the outcrop.

The model was calibrated by simulating the predevelopment potentiometric surface of the Jasper aquifer. Results of the calibration showed that the simulation closely agrees with historical records of water levels in most areas Sensitivity analysis showed that the model is very sensitive to changes in recharge on the outcrop of the Jasper. The shape of the potentiometric surface is affected more by changes in transmissivity than by changes in vertical-hydraulic conductivity. The sensitivity of most of the modeled part of the aquifer to a 60-mile extension of its downdip boundary into highly saline water was about equal to a 25-percent reduction in transmissivity or a 25-percent increase in vertical-hydraulic conductivity.

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HYDROLOGY OF THE JASPER AQUIFER IN THE SOUTHEAST TEXAS COASTAL PLAIN

By

E.T. Baker, Jr.
U.S. Geological Survey

INTRODUCTION

This report has been prepared to document the construction and calibration of a digital-computer model that simulates water flow in the Jasper aquifer of Miocene age in southeast Texas, and to present an account of the improvement in our understanding of the hydrology of interconnected aquifers and confining layers. It is in this area of Texas that the Jasper has its greatest ground-water potential. For this reason, only this segment of the aquifer, which extends statewide across the coastal plain of the State, has been modeled. The ground-water flow model of the Jasper is designed to quantify certain hydraulic properties of the hydrologic system such as vertical-hydraulic conductivity and to a lesser extent, recharge and transmissivity, and to be used as a tool to aid water planners in the regional development of the Jasper aquifer and in the protection of its water supplies.

This report on the model also serves to improve our understanding of the hydrology of the interrelationship of adjoining aquifer systems and confining systems. The improvement is achieved by the development of the digital model of the hydrologic system prior to significant ground-water development.

The scope of this report directed primarily to a discussion of: (1) the geohydrology of the ground-water system including the frame work of the southeastern Coastal Plain; (2) a discussion of the hydrologic and hydraulic parameters that are built into the model; and (3) a discussion of the calibration and various sensitivity analyses of the model including a steady-state simulation prior to development of the aquifer by wells.

This report constitutes the ultimate objective of a project to evaluate the ground-water resources of the Miocene aquifer(s) in the Gulf Coastal Region of Texas. As an interim part of the project, a report (Baker, 1979) was prepared to illustrate the stratigraphic and hydrogeologic framework of the Jasper aquifer as well as other hydrogeologic units from the Sabine River to the Rio Grande (Louisiana to Mexico). This was shown by a series of 11 dip sections that are about 50 miles apart and 100 miles long and 1 strike section 500 miles long. Ground water having concentrations of less than 3,000 mg/l (milligrams per liter) of dissolved solids (fresh to slightly saline water) is shown on the sections and serves as an index to the availability of freshwater.

Description of the Study Area

The study area, which extends slightly beyond the modeled area, is about 25,000 square miles and is predominantly within the southeast Texas Coastal Plain (Figure 1). The eastern limit of the area, however, extends into western Louisiana from 20 to 50 miles. The western boundary of the area is slightly west of the Brazos River and is about 170 miles west of the Texas-Louisiana border. The northern boundary is the most inland extent of the Miocene-age formations (Catahoula Sandstone), which is about 100 miles inland from the coastline. The southern boundary of the described area approximates the coastline, although the model's southern boundary is from 30 to 50 miles inland from the Gulf of Mexico.

The land surface is mostly a smooth depositional plain in the southern two-thirds of the area and a slightly rolling dissected terrain in the northern one-third. Altitudes range from sea level to more than 600 feet in places on the outcrop of the Jasper aquifer.

Precipitation ranges from 40 to almost 60 inches, becoming progressively greater from west to east. The southeast Texas Coastal Plain is the area of greatest precipitation in the State, and for this reason, the water tables of the aquifers are near the land surface.

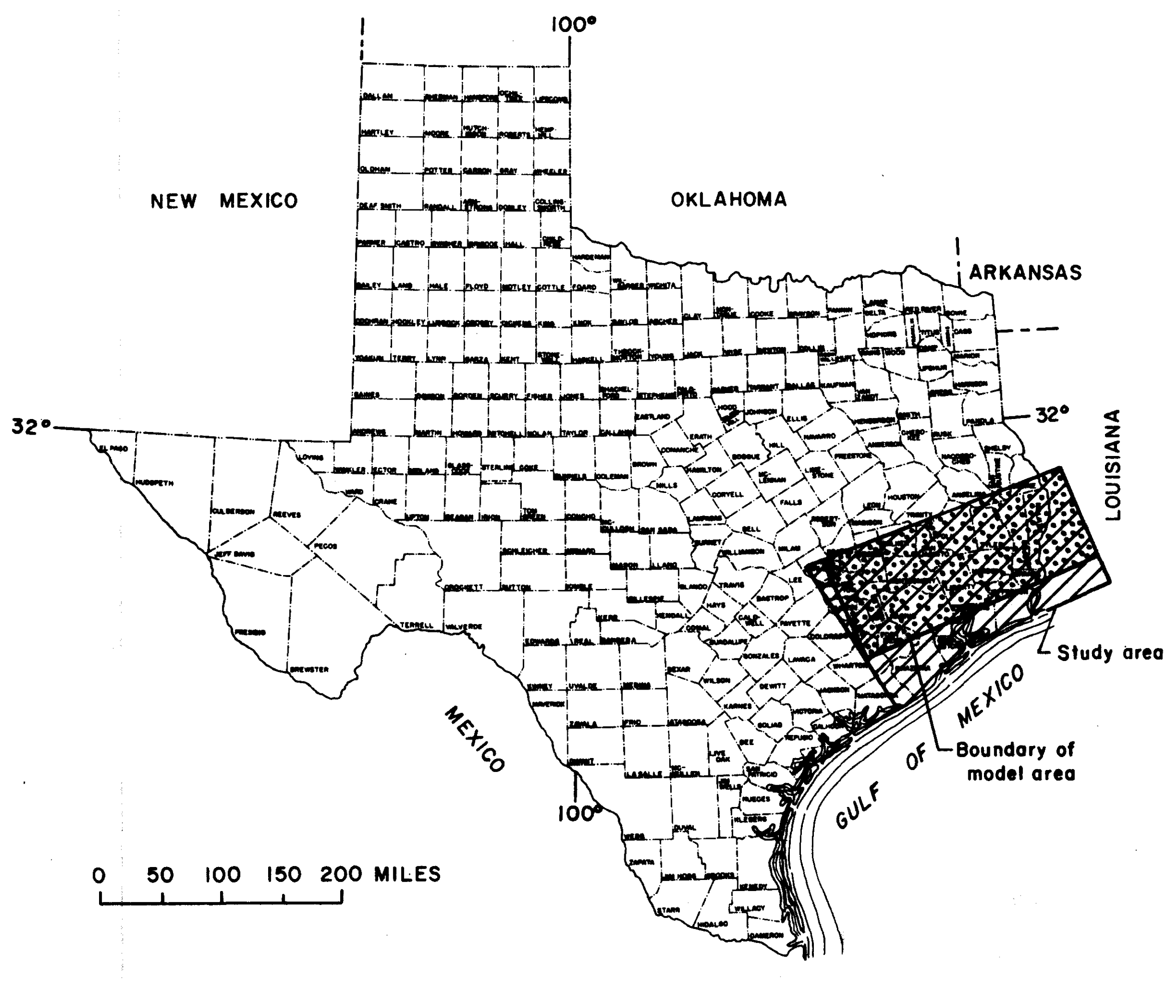

Figure 1.—Location and Extent of the Study Area

Several major streams cross the area in a southward direction and flow into the Gulf of Mexico. These include, from east to west, the Sabine, Neches, Trinity, San Jacinto, Brazos, and Colorado Rivers. About 55 percent of the average annual runoff in Texas is transported by these rivers, their base flows being sustained by large volumes of seepage from the aquifers.

The economic development of the study area varies widely. The urbanized sections in the south part of the area have a large and diversified industrial base. Houston, the Beaumont-Port Arthur-Orange complex, and Lake Charles are densely populated centers to the south with large petrochemical industries. Extensive rice irrigation also is practiced in the south. The northern sections are largely rural with only a relatively small scattering of industry and less irrigated farming. Large volumes of surface and ground water are used by industry for cooling and processing purposes and by rice and cotton growers for irrigation. The rapid growth and development of much of the area is due to the accessibility and abundance of surface and ground water. Not withstanding the fact that large volumes of water are pumped from various aquifers underlying the Coastal Plain, the Jasper aquifer remains relatively undeveloped. This is primarily because it lies beneath two prolific aquifers -the Chicot and Evangeline-that because of their shallower positions, are the more extensively pumped aquifers in the southern part of the area.

History of Hydrologic Modeling in the Texas Coastal Plain

The first attempt at modeling the ground-water system in the Texas Coastal Plain resulted in the construction of an electrical-analog model of the Chicot and Evangeline aquifers in the Houston district (Wood and Gabrysch, 1965). This model covered an area of 5,000 square miles in all or parts of Harris, Galveston, Brazoria, Fort Bend, Austin, Waller, Montgomery, Liberty, and Chambers Counties. It was used to predict water-level responses under various conditions of pumping, but had only limited success because the Chicot and Evangeline were simulated independently, and agricultural pumping in the western part of the area could not be represented. The model indicated a need for improvement in aquifer delineation and a more adequate modeling of the aquifers' transmissivities and the vertical leakage between them.

Ten years later, a second electrical-analog model was constructed incorporating additional hydrologic data and more advanced concepts of the hydrologic system (Jorgensen, 1975). This model, also of the Chicot and Evangeline aquifers, was larger than the first one and included an area of about 9,000 square miles, with the Houston district as its center. The larger area minimized the boundary effects within the Houston district, which were a problem with the first model. The effects of the withdrawals of water from well fields for a year or longer were simulated by this second electrical-analog model.

A third model, also of the Chicot and Evangeline aquifers and centering on the Houston district, was constructed several years later (Meyer and Carr, 1979). The five-layer, finite-difference model used a digital computer for simulation of three-dimensional ground-water flow in an area of 27,000 square miles. This model simulated water-level responses to pumping, changes in storage in the clay layers, and land-surface subsidence.

The most recent hydrologic modeling of ground-water flow in the Chicot and Evangeline aquifers refined much of the previous work and extended coverage of these aquifers throughout the Coastal Plain of Texas (Carr and others, 1985). This work resulted in a series of multilayered, three-dimensional models that also simulate the response of water levels to pumping, changes in storage in the clay layers, and land-surface subsidence.

Metric Conversions

For those readers interested in using the metric system, the metric equivalents of inch-pound units of measurements are given in parentheses. The inch-pound units used in this report have been converted to metric units by the following factors:

From	Multiply by	To obtain
feet	0.3048	meters (m)
feet per day (ft/d)	0.3048	meters per day (m/d)
feet per mile (ft/mi)	0.189	meters per kilometer (m/km)
feet per second (ft/s)	0.3048	meters per second (m/s)
square feet per day (ft^2/d)	0.0929	square meters per day (m^2/d)
gallons per minute (gal/min)	0.06309	liters per second (l/s)
inches	25.4	millimeters (mm)
miles	1.609	kilometers (km)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
square miles	2.590	square kilometers (km^2)

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 mean sea level. NGVD of 1929 is referred to as sea level in the text of this report.

GEOHYDROLOGIC FRAMEWORK OF THE SOUTHEAST TEXAS COASTAL PLAIN

Miocene and younger sediments that underlie the southeast Texas Coastal Plain and that form important hydrologic units are thousands of feet thick at the coastline. These clastic sediments constitute geologic formations, which collectively or in part, form important hydrologic units. The geologic formations and hydrologic units are composed of varying proportions of gravel, sand, silt, and clay. They thicken toward the Gulf of Mexico and are inclined in that direction. The younger geologic formations and hydrologic units crop out nearer the Gulf and the older ones farther inland. All of them have outcrops or subcrops that are virtually parallel to the shoreline.

In the following discussion, emphasis is placed on the geologic and hydrologic units of Miocene age. It is necessary, however, to discuss the older and younger units in order to understand their relationship, both stratigraphically and hydrologically, to the Miocene. (Stratigraphic and geologic units that are pertinent to the discussion are described in Table 1. The units were determined from several sources and may not necessarily follow the usage of the U.S. Geological Survey.) Four dip sections and one strike section are located in Figure 2 and are presented in Figures 3-7 to visualize the interrelationships and to show the presence of water having concentrations of less than about 3,000 mg/l of dissolved solids within the units.

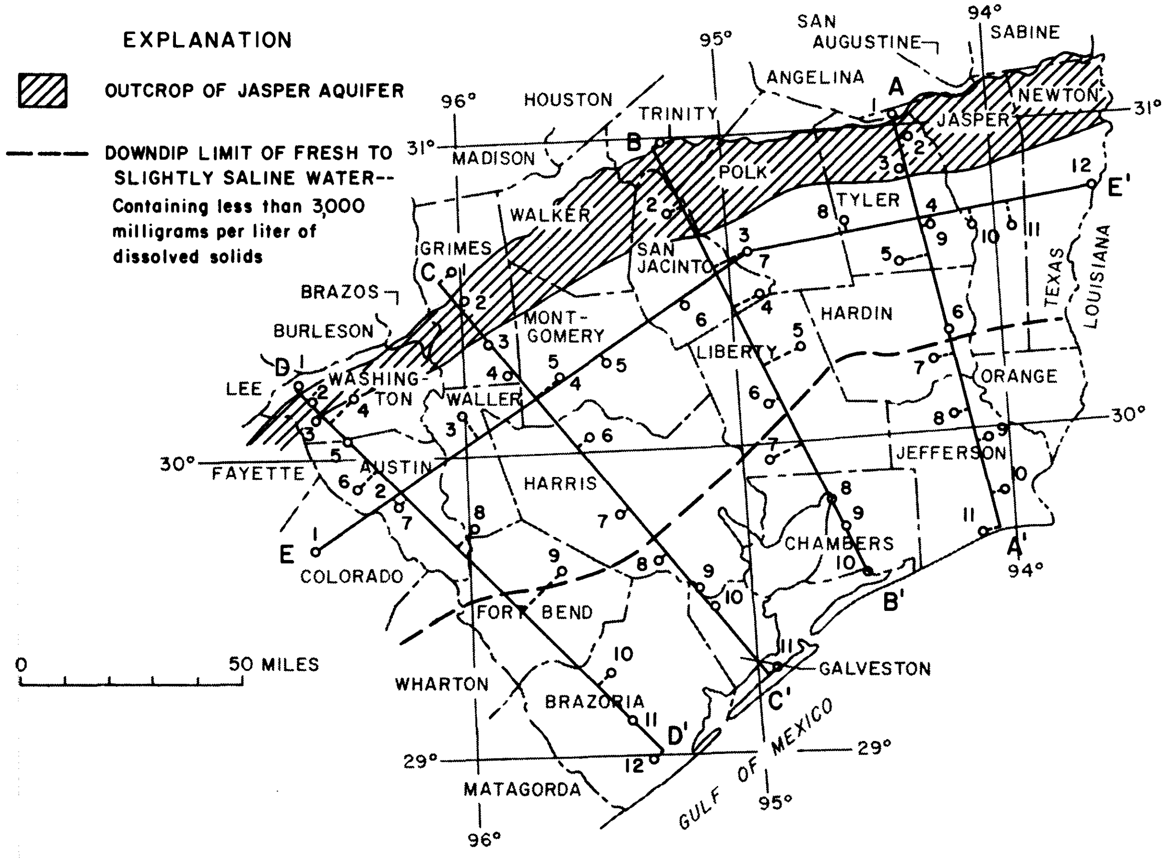

Figure 2.—Location of Stratigraphic and Hydrologic Sections

Stratigraphic Units

Pre-Miocene

Pre-Miocene rocks are composed of beds of sand, clay, carbonate rocks, and other rock types that are tens of thousands of feet thick. Within this thick section of rocks that underlie the Jasper

Table 1.--Stratigraphic and Hydrologic Framework of the Southeast Texas Coastal Plain 1/

Erathem	System	Series	Stratigraphic Units	Hydrogeologic Units	Selected Faunal Markers	Remarks
Cenozoic	Quaternary	Holocene	Alluvium	Chicot aquifer		Quaternary System undifferentiated on sections.
		Pleistocene	Beaumont Clay			
			Montgomery Formation			
			Bentley Formation			
			Willis Sand			
	Tertiary	Pliocene	Goliad Sand	Evangeline aquifer		
		Miocene	Fleming Formation	Burkeville confining system	*Potamides matsoni* *Bigenerina nodosaria var. directa* *Bigenerina humblei* *Amphistegina sp.*	
			Oakville Sandstone	Jasper aquifer		Oakville Sandstone included in Fleming Formation east of Washington County.
			Surface: Catahoula Sandstone / Subsurface: Upper part of Catahoula Sandstone			
			Subsurface: Anahuac Formation	Catahoula confining system (restricted)	*Discorbis nomada* *Discorbis gravelli* *Heterostegina sp.* *Marginulina idiomorpha*	Anahuac and "Frio" Formations may be Oligocene in age.
		?	Subsurface: "Frio" Formation		*Textularia mississippiensis*	
		Pre-Miocene rocks				

1/ Modified from Baker (1979, p. 4).

aquifer are identifiable stratigraphic units. These units are not delineated on the sections included with this report; however, a discussion of these units and their identity in the subsurface to a depth of about 8,000 feet are presented by Baker (1979).

The stratigraphic units of pre-Miocene age are hydrologically significant. Some are aquifers and others are confining layers. The hydrologic relationship of the Jasper aquifer to the underlying contiguous units is of primary importance from the standpoint of boundary effects on the digital model. Stratigraphic examination of geophysical logs indicates, however, that freshwater in the stratigraphic units of pre-Miocene age is separated from water in the Jasper by confining layers.

Miocene

The outcropping stratigraphic units that are designated as Miocene in age are, from oldest to youngest, the Catahoula Sandstone, Oakville Sandstone, and Fleming Formation. The "Frio" Formation, Anahuac Formation, and a unit, that is referred to in this report as the upper part of the Catahoula Sandstone, are assigned by the author as possible downdip equivalents of the surface Catahoula although the Anahuac and "Frio" Formations may be Oligocene in age. The data in Table 1 and the dip sections (Figures 3-6) illustrate this relationship.

The Catahoula Sandstone is a pyroclastic unit that has been independently mapped on the outcrop by various geologists with little modification. Within the report area, it is composed of interbedded and interlensing sand and clay. The dip sections show that the thickness of the Catahoula increases downdip at a large rate. It eventually includes, when the Anahuac Formation is reached at depths of about 2,800 to 3,600 feet below sea level, the "Frio" Formation, the Anahuac Formation, and the upper Catahoula unit.

The Oakville Sandstone and Fleming Formation are composed almost entirely of terrigenous clastic sediments that form sand and clay interbeds. Their boundaries are discernible contacts in some areas and arbitrary ones within zones of lithologic gradation in other areas.

Within the limits of the report area, the Oakville Sandstone on the surface is recognized and mapped as a formation only west of the Brazos River in Washington County. Here its predominantly sandy character is barely distinguished from the overlying Fleming Formation, which is only slightly less sandy. Eastward from the vicinity of the Brazos River, the Oakville grades into the base of the Fleming. The position of the base of the Oakville in the deeper parts of the subsurface has been delineated on section D-D' (Figure 6) merely as an approximation.

The Fleming Formation, which is the uppermost unit of Miocene age, is lithologically similar to the Oakville Sandstone. Where the Fleming is not separated from the Oakville and directly overlies the Catahoula Sandstone from about Grimes County to the Sabine River, the percentage of sand in the formation increases eastward. In the far eastern part of the study area, the quantity of sand in the formation greatly exceeds the quantity of clay. This can be seen in strike section E-E' (Figure 7).

Post-Miocene

The stratigraphic units of post-Miocene age consist chiefly of interbedded sand and clay and subordinate beds of silt and gravel. Collectively, they are estimated to be in excess of 2,000 feet thick at the coastline in southeast Texas. This wedge of clastic sediment rapidly thins inland from the coastline to extinction along an irregular line from 70 to 100 miles inland from the coastline.

The Goliad Sand of Pliocene age; Willis Sand, Bentley Formation, Montgomery Formation, and Beaumont Clay of Pleistocene age; and alluvium of Holocene age comprise the post-Miocene sediments. All of these units are similar in lithology, and for this reason, delineation using electrical logs has not been attempted on the stratigraphic and hydrologic sections. Notwithstanding, the difficulty in identifying these stratigraphic units individually in the subsurface, as a group they constitute significant aquifers in the southeast Texas Coastal Plain.

Hydrologic Units

The fallowing discussion will emphasize five hydrologic units-the Catahoula confining system (restricted), which underlies the Jasper aquifer; the Jasper aquifer; and the Burkeville confining system and the Evangeline and Chicot aquifers, which overlie the Jasper. The hydrology of the units underlying and overlying the Jasper is important for understanding the water flow system in the Jasper and for modeling the aquifer.

Catahoula Confining System (Restricted)

The Catahoula confining system (restricted), which was named by Baker (1979) after the Catahoula Sandstone, is treated in this report as a quasi-hydrologic unit. In most of southeast Texas, this confining system has different boundaries than the stratigraphic Catahoula. Its top (base of the Jasper aquifer) is delineated along lithologic boundaries that are time-stratigraphic in some places, but transgress time lines in other places. Its base, which coincides with the base of the stratigraphic unit, is delineated everywhere in the report area along time-stratigaphic boundaries that are independent of lithology. No attempt was made to establish a lithologic (hydrologic) base for the unit, which would have created a distinct hydrologic unit. Such an effect would have involved a thorough hydrologic evaluation of pre-Miocene formations, which was beyond the scope of this study.

In some places, the Catahoula confining system (restricted) is identical to the stratigraphic unit, but there are notable exceptions. These departures of the hydrologic boundaries from the stratigraphic boundaries are most prominent in the eastern part of the study area near the Sabine River (Figure 7) and in numerous places at the outcrop and in the shallow subsurface (Figures 3-6). In these places, the very sandy parts of the Catahoula Sandstone (stratigraphic unit) that lie immediately below the Oakville Sandstone or Fleming Formation are included in the overlying Jasper aquifer. This leaves a lower section from 0 to 2,000 feet or more in thickness that consists predominantly of clay or tuff with some interbedded sand to compose the Catahoula confining system (restricted). In most places, this delineation creates a unit that generally is deficient in sand so as to preclude its classification in these areas as an aquifer. For this reason, in most of its shallow to moderately deep subsurface extent, the Catahoula confining system (restricted) functions hydrologically as a confining layer that greatly restricts interchange of water between the overlying Jasper aquifer and the underlying aquifers.

The quantity of clay and other fine-grained clastic material in the Catahoula confining system (restricted) generally increases downdip, until the Anahuac Formation is encountered at depths of 2,800 to 3,600 feet below sea level. Below this level, the “Frio” Formation becomes characteristically sandy and contains moderately saline water to brine (3,000 to more than 35,000 mg/l of dissolved solids) that extends to depths of many thousands of feet.

Jasper Aquifer

The Jasper aquifer, which was named by Wesselman (1967) for the town of Jasper in Jasper County, Texas, until recently had not been delineated farther west than Washington, Austin, and Fort Bend Counties in southeast Texas. Recently, delineations of the Jasper, as well as other related hydrogeologic units, were made by Baker (1979) across the Coastal Plain of Texas from the Sabine River to the Rio Grande.

The configuration of the Jasper aquifer in the subsurface, as shown in the sections, is geometrically irregular because the delineation was made on the basis of the aquifer being a rock-stratigraphic unit. The hydrologic boundaries were defined from observable physical (lithologic) features rather than from inferred geologic time lines, which do not necessarily correspond to lithologic features.

The position of the base and top of the Jasper aquifer in southeast Texas transgresses stratigraphic boundaries along strike and downdip. The base of the aquifer coincides with the stratigraphic lower boundary of the Oakville Sandstone or Fleming Formation in some places. In other places, the base of the Jasper lies within the Catahoula Sandstone or coincides with the base of that unit. The top of the aquifer is within the Fleming in places and is within the Oakville in other places. The dip of the top of the Jasper is fairly uniform in rate within the zone of fresh to slightly saline water. Within this zone, which is about 50 to 75 miles in width, the dip averages about 55 ft/mi to the south-southeast (Figure 8).

The Jasper aquifer ranges in thickness, where it is not eroded, from as little as 200 feet to about 3,200 feet within the area of its delineation. The maximum thickness occurs in the region where the aquifer contains moderately saline water to brine. An average range in thickness of the aquifer within the zone of water having concentrations of less than 3,000 mg/l of dissolved solids is from about 1,000 to 1,500 feet. At the Sabine River, the Jasper attains a thicknessof 2,400 feet in well 12 in section E-E’ (Figure 7), where the aquifer is composed predominantly of sand. This predominance of sand in the Jasper in the eastern part of the study area, however, diminishes in a westward direction.

The Jasper aquifer contains water having concentrations of less than 3,000 mg/l of dissolved solids from its outcrop to about 50 to 75 miles downdip from its outcrop. This downdip limit approximately parallels the coastline passing a few miles north of Beaumont and near the center of Houston. Water having concentrations of less than 3,000 mg/l of dissolved solids occurs in the Jasper as deep as 3,000 feet below sea level in section D-D’ (Figure 6). Although pumpage from the Jasper is not significant, it is capable of yielding 3,000 gal/min or more of water to wells in certain areas.

Burkeville Confining System

The Burkeville confining system was named by Wesselman (1967) for outcrops near the town of Burkeville in Newton County, Texas. It separates the Jasper and Evangeline aquifers and retards the interchange of water between the two aquifers.

The Burkeville confining system is a rock-stratigraphic unit predominantly consisting of silt and clay. Upper and lower boundaries of the unit do not strictly correspond to geologic time boundaries, although in some places the unit appears to possess approximately isochronous boundaries. The configuration of the top and bottom of the unit is irregular. Boundaries are not restricted to a single stratigraphic unit, but are included within the Fleming Formation and Oakville Sandstone in some places. This is shown in section D-D’ (Figure 6).

The thickness of the Burkeville confining system ranges from about 100 to 1,000 feet. In general, the greatest variations occur in the relatively deep subsurface within the zone of moderately saline water to brine. A typical thickness of the Burkeville is about 300 feet.

The Burkeville confining system is predominantly composed of fine-grsined materials, such as silt and clay, as shown in numerous geophysical logs. In most places, these fine-grained sediments are interbedded with sand lenses, which contain fresh to slightly saline water. Some of these sand lenses yield water to small-capacity wells. Because of its relatively large percentage of silt and clay when compared to the underlying Jasper aquifer and overlying Evangeline aquifer, the Burkeville is a confining unit. The effectivenessof the unit as a confining layer is further borne out by the fact that hydro-static pressures in the Jasper and Evangeline are notably different immediately above and below the Burkeville where detailed testing by well drillers has been done.

Evangeline and Chicot Aquifers

The Evangeline and Chicot aquifers were named and defined by Jones (Jones, Turcan, and Skibitzke, 1954) for ground-water reservoirs in southwestern Louisiana. They also have been mapped in Texas, but until recently, had not been delineated farther west than Washington, Austin, and Fort Bend Counties in southeast Texas. Their positions in the Coastal Plain of Texas westward to the Rio Grande are now known from mapping by D. G. Jorgensen, W. R. Meyer, and W. H. Sandeen of the U.S. Geological Survey (Baker, 1979).

The Evangeline aquifer primarily has been delineated as a rock-stratigraphic unit. Although the aquifer is composed of at least Pliocene-age sediments, its lower boundary crosses time lines to include sections of sand in the Fleming Formation. Within most of the study area, the Evangeline at the surface includes about the upper one-third of the Fleming outcrop as seen in sections A-A’, B-B’, and C-C’ (Figures 3-5). In the western part of the area where the Oakville Sandstone is recognized, the Evangeline includes more than three-fourths of the Fleming outcrop as seen in section D-D’ (Figure 6). The upper boundary of the aquifer probably closely follows the top of the Pliocene-age sediments or the Goliad Sand, which is not exposed, except perhaps in a few isolated places, in the report area. This stratigraphic relationship of the top of the Evangeline is somewhat speculative.

The Chicot aquifer has been defined to exclusively include the Quaternary age sediments. Its delineation in the subsurface on this stratigraphic basis is problematical due to the difficulty in identifying the base of the Quaternary deposits on electrical logs. This subsurface delineation in southeast Texas has been based largely on the presence of a greater sand-to-clay ratio in the Chicot than in the underlying Evangeline aquifer. In some places, a prominent clay layer has been used as the boundary. Differences in hydraulic conductivity or water levels in some areas also have been used to differentiate the Chicot from the Evangeline. At the surface, the base of the Chicot on the sections has been picked at the most landward edge of the oldest, undissected coastwise terrace of Quaternary age.

The Evangeline and Chicot aquifers are typically wedge-shaped and have a large sand-to-clay ratio. Individual sand beds are characteristically tens of feet thick. Near the outcrop, the Evangeline ranges in thickness from about 400 to 600 feet but near the coastline, where the aquifer's top is about 1,200 feet deep, its thickness averages about 2,300 feet. Water having concentrations of less than 3,009 mg/l of dissolved solids is not present in the aquifer, at the coastline. The Chicot attains a thickness of about 1,200 feet at the coastline, where, in places, it still contains water having concentrations of less than 3,000 mg/l of dissolved solids in most of its full thickness (Figures 5 and 6).

Huge quantities of water are pumped from the Chicot and Evangeline aquifers for municipal supply, industrial use, and irrigation. The most extensive and concentrated development is in the Houston area, where large-capacity wells yield from 1,000 to more than 3,000 gal/min and average about 2,000 gal/min.

GROUND-WATER DEVELOPMENT

The Jasper aquifer regionally is relatively undeveloped. This primarily is because it underlies the Evangeline and Chicot aquifers, which are capable of supplying large volumes of adequate-quality water for most needs. Most of the wells that produce water from the Jasper are located on its outcrop and short distances downdip where the Burkeville confining system is exposed, or where the Chicot and Evangeline are not thick enough to provide sufficient water to large capacity wells.

Moderate to large volumes of water are pumped locally from the Jasper aquifer only in a few widely spaced localities (Figure 9). These centers of pumpage are mostly towns and industrial sites, where one or more public-supply or industrial wells are usually within the confines of the city limits or at individual industrial sites. By far, the largest withdrawal of water within the modeled area is in Beauregard Parish near De Ridder, Louisiana, where industrial usage exceeded 20 Mgal/d during 1979. This site is about 10 miles east of the Sabine River. Elsewhere (Figure 9), municipal or industrial pumpage at any one site is many orders of magnitude smaller than the pumpage near De Ridder and ranges from 0.10 to 4.0 Mgal/d.

As a result of the relatively limited development in the Jasper aquifer in southeast Texas, water levels have remained near the land surface, and only slight water-level declines have occurred regionally. Water-level trends in the Jasper aquifer for several representative wells are shown in Figure 10. Some of these wells are in pumping centers, whereas others are away from such centers. The hydrographs show that there have been, for the most part, only slight declines of 10-l5 feet in 20 years in the potentiometric surface at those sites.

The potentiometric surface of the Jasper aquifer prior to well development has been approximated on the basis of the earliest available water levels. To approximate predevelopment conditions, the hydraulic heads have been adjusted upward in varying amounts by backward projection of hydrographs and, in some areas, by considering heads measured in nearby wells that represented pressures little affected by pumping stresses. The potentiometric contours reflect these adjustments, while the well data indicate actual measured water levels prior to any adjustment (Figure 11).

DESCRIPTION OF THE DIGITAL MODEL

The digital model that was developed to simulate the ground-water hydrology of the Jasper aquifer is a mathematical, two-dimensional, finite-difference program that was documented by Trescott, Pinder, and Larson (1976). The iterative-numerical technique used to solve the simultaneous equations is the strongly implicit procedure (SIP). This procedure was originally described by Stone (1968) for problems in two dimensions.

The steady-state approach was used to simulate the hydrologic conditions in the aquifer. This approach was taken because, on a regional basis, the aquifer is only slightly stressed from pumping, and in many places, groundwater levels are virtually static, which indicates a nearly steady-state condition. For this reason, no attempt was made to develop a transient model to simulate the small regional water-level changes that have occurred since pumping began. The steady-state model developed for the project area, therefore, represents hydrologic conditions prior to development by wells, when natural recharge equaled natural discharge and water levels varied little during long periods.

The Jasper aquifer is part of an extensive and continuous hydrologic system in the Gulf Coastal Plain; its lateral boundaries are far beyond the modeled area. The aquifer contains freshwater for varying distances downdip beyond which the aquifer contains saltwater. For modeling purposes, however, only the part of the aquifer containing fresh to slightly saline water was considered. Under steady-state conditions, the interface between the fresh to slightly saline water and saltwater is assumed to be static and is considered to be a no-flow boundary. Beyond the interface on the downdip side, the saltwater is virtually motionless, whereas on the updip side, the fresh to slightly saline water is circulating throughout the aquifer. From the outcrop, water as recharge (a finite flux or constant recharge boundary in the model) moves downdip beneath the Burkeville confining system. Here two components of movement are in effect. One is a downdip component, and the other is an upward component. Where the Jasper is overlain by the Burkeville, water is being discharged through the Burkeville as steady leakage, with the sum of the leakage equal to the sum of the net recharge. The contact of the base of the Jasper with the underlying Catahoula confining system (restricted) is treated as a no-flow or zero-flux boundary, as the Catahoula functions in the hydrologic system as a confining layer of mostlyclayor tuff that for all practical purposes prevents any significant interchange of water between the Jasper and underlying aquifers. (See Figure 12.)

The model has a grid pattern of 15 x 24 nodes representing an area of about 20,000 square miles as shown in Figure 13. In the outcrop of the Jasper aquifer, the grids have dimensions of 5 x 10 miles and are the smallest in the model. The purpose of using the smaller grids is to provide a better distribution of net recharge on the relatively narrow outcrop of the aquifer. Downdip from the outcrop, where the aquifer is beneath the Burkeville confining system, the model has grid dimensions of 10 x 10 miles. Within any one grid, the aquifer properties are assumed to be uniform.

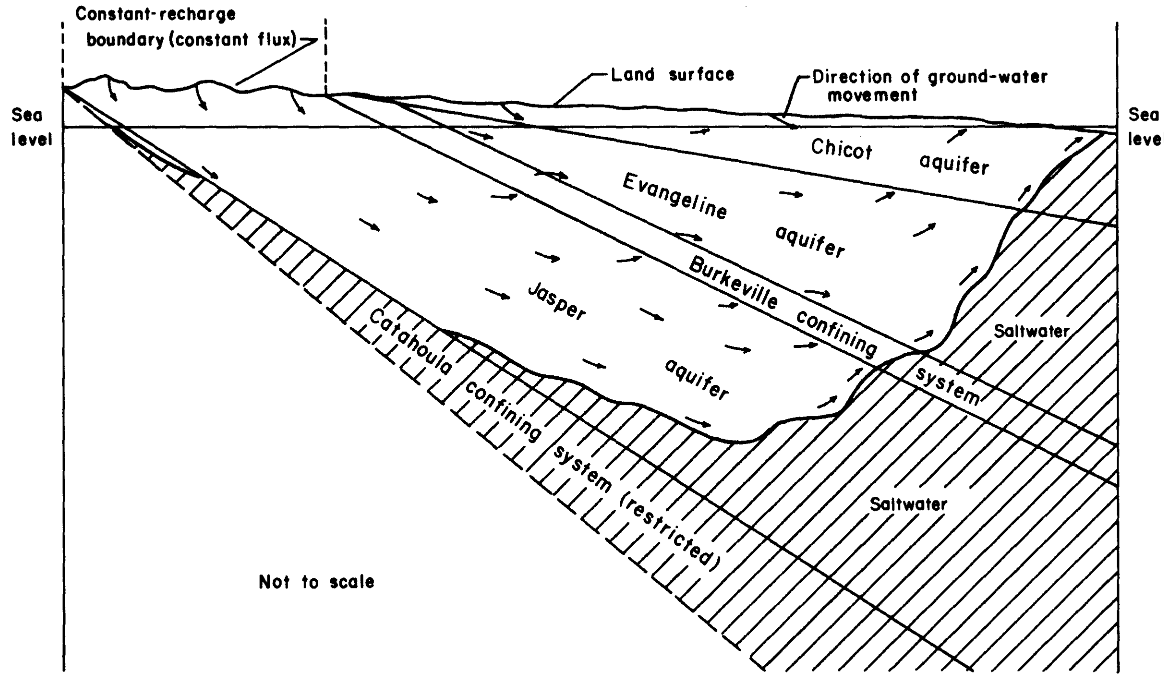

Figure 12.—Conceptual Model of the Ground-Water Hydrology of the Texas Coastal Plain Prior to Development by Wells

Impermeable (no-flow) boundaries were placed at the two lateral extremities of the model sufficiently far beyond the main study area to decrease any boundary effects in the area of interest. At the downdip edge of the model, a no-flow boundary also was placed sufficiently far enough into the part of the aquifer containing saltwater so that the boundary would have negligible effect on the part of the aquifer containing fresh to slightly saline water. The updip edge of the outcrop was a natural physical boundary having zero flow.

The boundary effects in the model were tested by substituting constant-head boundaries for the no-flow boundaries at the two lateral extremities on the east and west and on the downdip extremity on the south. Hydraulic heads representing the approximate potentiometric surface of the Jasper aquifer prior to development by wells (Figure 11) constituted the starting-head matrix. The results showed very little difference (less than 2 feet) even within 10 miles of the adjacent constant-head boundaries. Most nodes showed no differences, and where differences did occur, they were rises of no more than 1 foot.

Aquifer Properties and Parameters Modeled

Transmissivity of the Aquifer

All known aquifer tests conducted in wells completed in the Jasper aquifer within the modeled area were examined. From these tests, horizontal hydraulic conductivities were computed, and horizontal hydraulic-conductivity maps and sand-thickness maps were prepared. The areal distribution of transmissivity of the Jasper was then determined (Figure 14).

The transmissivity of the Jasper aquifer ranges from less than 2,500 ft^2/d in places in the outcrop and near the downdip limit of fresh to slightly saline water to about 35,000 ft^2/d east of the Sabine River. Outcrop transmissivities increase eastward as do transmissivities in the artesian part beneath the Burkeville confining system. These increases are attributed primarily to eastward increases in sand thicknesses. Conversely, the decreases in transmissivities near the downdip limit of fresh to slightly saline water are due to the fact that the thickness of sand with this quality water decreases to zero at this southern interface.

Recharge to the Aquifer

Precipitation on the outcrop of the Jasper aquifer is the source of recharge to the aquifer. Only a small part of the total precipitation, however, does not run off directly or is not evapotranspired, and a large part of the precipitation that reaches the zone of saturation in the outcrop moves to streams where it is discharged as seepage and springflow. Therefore, only a small quantity of water from precipitation becomes net recharge, or that quantity of water that moves into the downdip part of the aquifer south of the outcrop. Under steady-state conditions in the Jasper as conceptualized prior to development by wells, this net quantity of recharge is equal to the quantity of discharge by vertical leakage through the Burkeville confining system.

In the model, the outcrop was treated as a constant-recharge (constant-flux) boundary with each node constantly recharging a given volume of water. The total net recharge was determined incrementally for each 10-mile length of the Jasper aquifer's outcrop using the Darcy flow equation in the following form:

$$Q = TIL, \tag{1}$$

where Q = flow rate, in cubic feet per day;

T = transmissivity, in square feet per day;

I = hydraulic gradient, in feet per mile; and

L = length of aquifer (in miles) across which the flow moves.

The 10-mile cross-sectional length of the outcrop, which the flow moves across, was chosen at the outcrop's contact with the overlying Burkeville confining system. The flow thus determined to be moving into the downdip artesian parts of the aquifer can be equated with the total net recharge for the incremental area of the outcrop. This volume of recharge was then apportioned to the nodes within that part of the outcrop. The distribution of total net recharge as equivalent precipitation on the outcrop of the Jasper is shown in Figure 15.

The quantity of water as net recharge to the Jasper aquifer is equivalent to 0.9 inch of precipitation on the sandy part of the outcrop, about 2 percent of the average precipitation. In addition to this quantity, according to Wood (1956, p. 30-33), about 1 inch or more of precipitation enters the outcrop but is discharged to streams crossing the outcrop as base flow or rejected recharge.

Leakage Through the Burkeville Confining System

Water in the Jasper aquifer downdip from the outcrop is discharged upward through the Burkeville confining system. This process is simulated in the model by considering the vertical-hydraulic conductivity of the Burkeville, the thickness of the Burkeville, and the hydraulic head on the upper side of the Burkeville which is the predevelopment potentiometric surface of water in the Evangeline aquifer.

Vertical-Hydraulic Conductivity of the Burkeville Confining System

The effective vertical-hydraulic conductivity of the Burkeville confining system is a function of the composite intergranular flow characteristics of the predominantly silt and clay beds that compose this hydrologic unit. Hydraulic-conductivity values, which were determined by calibration of the model, range from 1.0×10^{-5} to 2.5×10^{-3} ft/d. These values are similar to those determined for the clay beds in the Chicot and Evangeline aquifers by previous model studies in the Houston area and in other areas along the Gulf Coast of Texas (Jorgensen, 1975, p. 54; Meyer and Carr, 1979, p. 17; and Carr and others, 1985). In these areas, the vertical-hydraulic conductivity of the Chicot and Evangeline, which is controlled primarily by the clay beds that occur within the vertical sequence of sand beds, ranges from 9.2×10^{-5} to 2.3×10^{-4} ft/d.

The larger values of vertical-hydraulic conductivity of the Burkeville confining system are associated with the outcrop and updip parts of the hydrologic unit, and the smaller values are associated with the downdip parts. This pattern of differing vertical hydraulic conductivities is shown in Figure 16. Sedimentation features of the Burkeville support this pattern as increasingly finer grained sediments were deposited in the downdip direction (Baker, 1979, p. 40).

Thickness of the Burkeville Confining System

Large variations in the thickness of the Burkeville confining system affect the leakage at each node in the model where the confining system overlies the Jasper aquifer. All areas of the Jasper south of its outcrop are overlain by the Burkeville, and in no place are the Evangeline or Chicot aquifers, which overlie the Burkeville, in contact with the Jasper.

Large thicknesses of the Burkeville confining system of more than 600 feet are present in several grids near the southeastern boundary of the model, and even larger thicknesses of more than 900 feet are present in a few grids along the western boundary near the downdip limit of fresh to slightly saline water in the Jasper aquifer. In other places between these two areas-chiefly in the outcrop of the Burkeville where it thins to extinction-the thickness of the confining system, is less than 100 feet as shown in Figure 17. Leakage is facilitated along the outcrop where the vertical-hydraulic conductivity generally is greater than elsewhere and where the confining layers are relatively thin.

Head Differences Across the Burkeville Confining System

The flux across the Burkeville confining system in the model is controlled in part by the hydraulic head differences in the Evangeline and Jasper aquifers. In the steady-state model, the predevelopment potentiometric surfaces were approximated for the two aquifers using available water-level data, and the hydraulic head differences were determined. The approximate predevelopment potentiometric surface of the Evangeline aquifer is shown in Figure 18. The map is based on the oldest available water levels adjusted upward by varying amounts for some sites to account for the effects of development. The predevelopment potentiometric surface of the Jasper aquifer is shown in Figure 11.

Hydraulic-head differences between the Evangeline and Jasper aquifers varied significantly prior to well development. As simulated in the model, these differences were less than 15 feet for most nodes near the updip reaches of the overlying Evangeline aquifer, and gradually increased downdip ranging from 70 to 130 feet at nodes along the southern limit of fresh to slightly saline water in the Jasper. At all nodes, the predevelopment head in the Jasper was greater than the predevelopment hydraulic head in the Evangeline. It should be noted that postdevelopment hydraulic head changes in the Evangeline as well as in the Jasper could alter the magnitude of the hydraulic head differences across the Burkeville confining system or possibly even reverse the direction of water movement. These changes would have to be considered in any leakage determinations for a transient model.

Calibration of the Model

The model was calibrated by simulating the predevelopment hydrologic conditions of the Jasper aquifer and comparing the computed potentiometric surface with the predevelopment surface that was based on historical water-level measurements. Where the computed surface differed significantly from the measured surface, vertical-hydraulic conductivity of the Burkeville confining system was modified, and the model was tested again. Transmissivity of the Jasper aquifer was modified in some areas, but to a much lesser extent than vertical-hydraulic conductivity of the Burkeville, because aquifer-test results were available for computing transmissivity. This trial and error procedure was continued using reasonable modifications until a satisfactory match with the approximate potentiometric surface shown in Figure 11 was obtained (Figure 19).

Results of the calibration show that the simulation basically agrees in most areas with the historical records of water levels. A good match was achieved in the artesian part of the aquifer south of the outcrop. In the outcrop, the influence of semiartesian conditions in combination with rolling topography and associated variable transmissivity in short distances creates an irregular potentiometric surface. For these reasons, simulations of the potentiometric surface are less exact in the outcrop than elsewhere.

The water-level data in Figure 19 are the oldest available data that represent approximate predevelopment conditions. Actual predevelopment water levels were greater in some areas, but the data presented give a basis for comparison with the simulated water-level contours.

Sensitivity Analysis

Sensitivity of the model was demonstrated by hydrologic analysis primarily using a single model column or cross section. This procedure simulated a one-dimensional flow tube along a line of ground-water flow from the outcrop of the Jasper aquifer into the part of the aquifer that contains saltwater. The position of this cross section and arrangement of cells from node 2 on the outcrop to node 27, which is about 60 miles downdip from the limit of the fresh to slightly saline water, are shown in Figure 20. The calibrated values of transmissivity of the Jasper aquifer, of vertical-hydraulic conductivity and thickness of the Burkeville confining system, and of potentiometric heads within the Jasper and Evangeline aquifers for appropriate nodes along the cross section are illustrated in Figure 21. Using these calibrated data and by varying the data values, as well as extending them beyond the model's downdip no-flow boundary at node 16, head values were simulated to show the changes in water levels that resulted from such modifications. Although the resulting changes in water levels pertain to the line of section represented by the flow tube, similar effects are expected to apply elsewhere in the model.

The sensitivity analysis for transmissivity showed that a uniform 25-percent increase in this parameter from that of the calibrated model resulted in a maximum decrease in head of 11 feet in the updip limit of the aquifer's outcrop at node 2 and a maximum increase in head of 10 feet at the downdip limit of water containing less than 3,000 mg/l of dissolved solids at node 16. A uniform decrease of 25 percent in transmissivity resulted in a maximum increase in head of 18 feet at the updip limit of the aquifer's outcrop to a maximum decrease in head of 13 feet at the downdip limit of 3,000 mg/l water. If the calibrated values of transmissivity that are uniformly decreasing from node 6 to 12 are extended as a straight-line projection to node 16, then this results in an increase in transmissivity of as much as about 7,500 ft^2/d over the calibrated model, which, in turn, causes a maximum increase in head of 4 feet. (See Figure 22.) The projected increase in transmissivity from nodes 12 to 16 negates the gradual decrease in transmissivity of the calibrated model as the downdip limit of fresh to slightly saline water, which serves as a no-flow boundary, is approached. This procedure compares the sensitivity of the no-flow boundary as an interface of fresh to slightly saline water with more highly saline water.

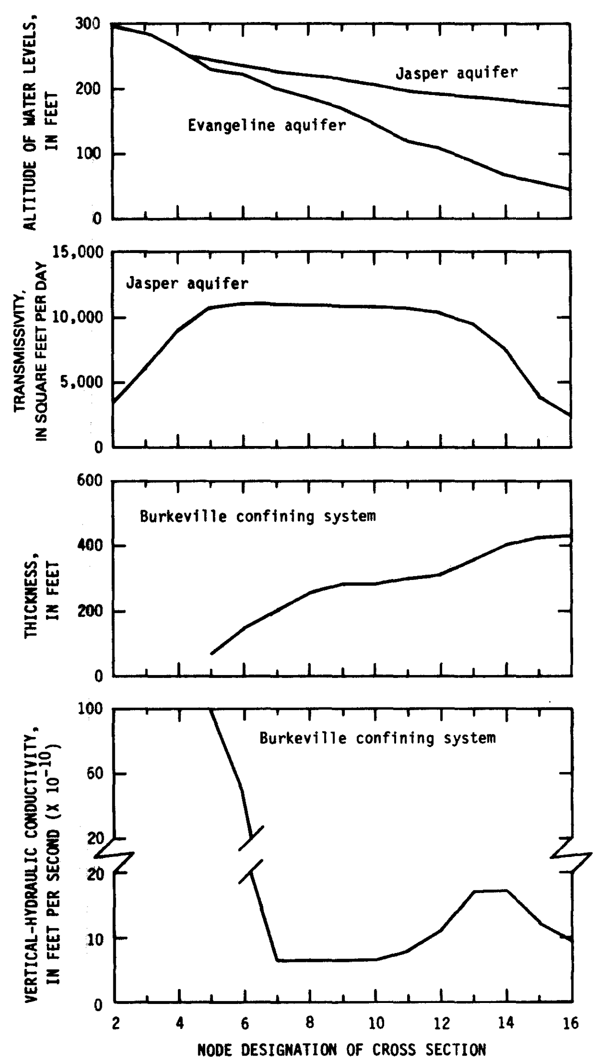

Figure 21.—Hydrologic Parameters and Hydraulic Heads of the Calibrated Model for the Cross Section Used for Sensitivity Analysis

The changes in hydraulic head represent the result of new equilibriums being established in the aquifer from the uniform increases and decreases in transmissivity. A uniform 25-percent increase in transmissivity caused a decrease in the hydraulic gradient (a flattening of the potentiometric surface),

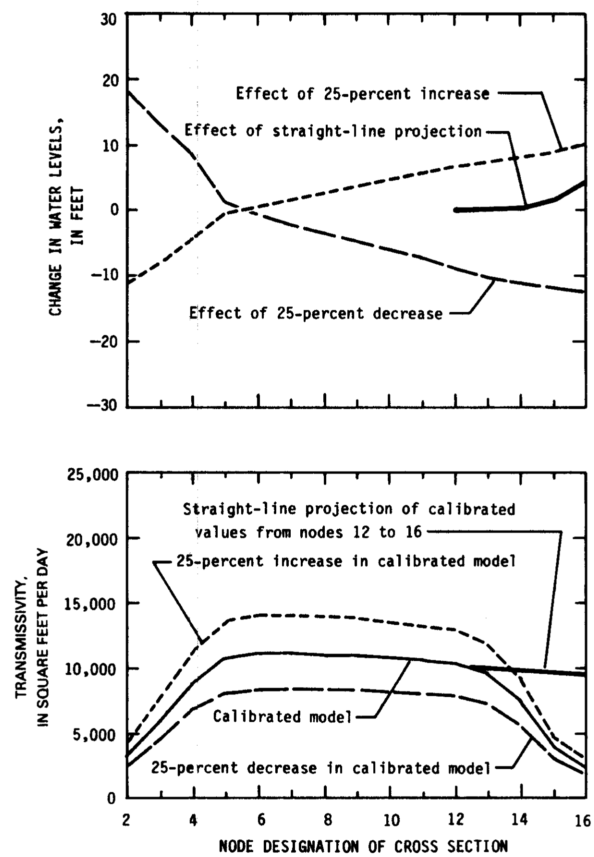

Figure 22.—Sensitivity of Calibrated Model to Variations in Transmissivity of the Jasper Aquifer

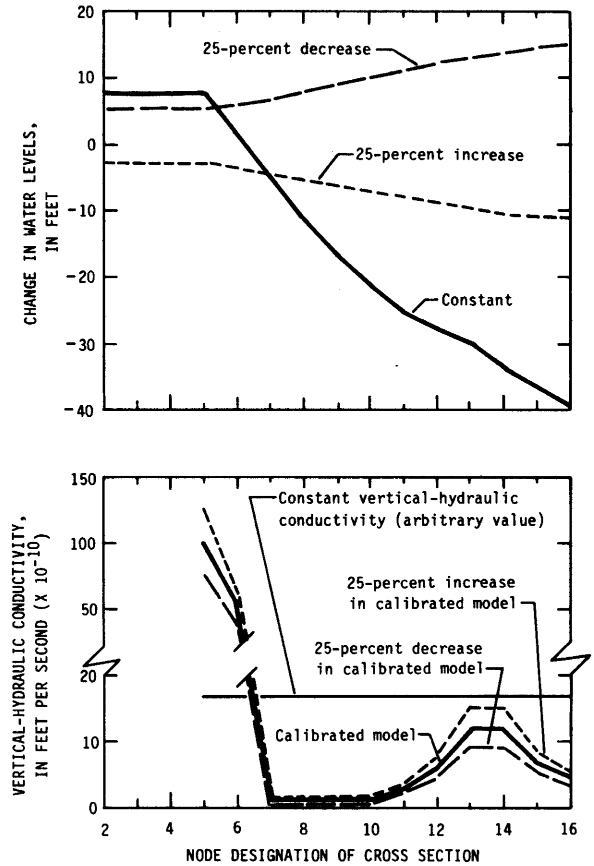

Figure 23.—Sensitivity of Calibrated Model to Variations in Vertical-Hydraulic Conductivity of the Burkeville Confining System

whereas a 25-percent decrease in transmissivity caused an increase in the hydraulic gradient (a steepening of the potentiometric surface). This is in accordance with the Darcy flow equation (equation 1) where the hydraulic gradient is inversely proportional to the transmissivity. The decrease in hydraulic head in the outcrop (with a uniform 25-percent increase in transmissivity) necessitates a rise in hydraulic head downdip, and conversely, with a 25-percent decrease in transmissivity, the increase in hydraulic head in the outcrop requires a decrease in hydraulic head downdip—the flow rate or recharge being held constant.

A uniform 25-percent increase in the vertical-hydraulic conductivity of the Burkeville confining system from that of the calibrated model resulted in a decrease in water levels from 3 feet in the outcrop of the aquifer to 11 feet near the downdip limit of 3,000 mg/l water at node 16. A uniform 25-percent decrease in the vertical-hydraulic conductivity resulted in an increase in water levels that ranged from 5 feet in the aquifer's outcrop to 15 feet at node 16. If the vertical-hydraulic conductivity remains constant throughout the model at 16.7×10^{-10} ft/s, the water levels show a rise of as much as 8 feet above the calibrated amount in the aquifer's outcrop, and show a steady decrease from the 8-foot rise near the outcrop to as much as 40 feet below the calibrated amount at the downdip limit of 3,000 mg/l water at node 16. (See Figure 23.)

The changes in water levels that resulted from the uniform changes in vertical-hydraulic conductivity of the Burkeville confining system constitute the response of the Jasper aquifer to changes in one of the three leakage parameters in this case, vertical-hydraulic conductivity. With the other two leakage parameters-thickness of the Burkeville and hydraulic head on the upper side of the Burkeville (base of Evangeline aquifer) not changing in value, the 25-percent increase in vertical-hydraulic conductivity over the calibrated value of each node necessitated a decrease in hydraulic head (water-level decrease) in the Jasper in order to maintain steady-state conditions. Conversely, the 25-percent decrease in vertical-hydraulic conductivity necessitated an increase in hydraulic head in the Jasper.

The application of a constant value of 16.7×10^{-10} ft/s for vertical-hydraulic conductivity caused the aquifer to adjust its hydraulic head at each node by increasing or decreasing the head so as to keep the volumes of recharge and discharge equal in the steady-state simulation. The constant value utilized in the sensitivity analysis was between the two extreme calibrated values of 100×10^{-10} ft/s and 1.5×10^{-10} ft/s. The 8-foot rise in hydraulic head in the outcrop of the Jasper aquifer was due to the constant value of vertical-hydraulic conductivity being six times smaller than the calibrated vertical-hydraulic conductivity of the Burkeville at node 5 adjacent to the outcrop of the aquifer. The steady decline in hydraulic head downdip from the 8-foot rise in the outcrop of the aquifer to 40 feet below the calibrated value at the downdip limit of 3,000 mg/l water at node 16 was due to the constant vertical-hydraulic conductivity being about 1.5 to 11 times greater than the calibrated vertical-hydraulic conductivities of most of the Burkeville nodes downdip from its outcrop.

The distribution of leakage and sensitivity of water levels to a reduction in recharge on the Jasper outcrop and a reduction in vertical-hydraulic conductivity on and near the outcrop of the Burkeville confining system are shown in Figure 24. A large reduction in vertical-hydraulic conductivity on and near the outcrop of the Burkeville from calibrated values of 100×10^{-10} and 50×10^{-10} ft/s for nodes 5 and 6, respectively, to a uniform value of 1.2×10^{-10} ft/s for those nodes, which coupled with a decrease in recharge of 58 percent from an average calibrated value of 10.5×10^{-10} ft/s resulted in leakage being reduced from 30 to 100 times as much as that which would result from the calibrated model. The leakage reduction affected only nodes 5 and 6 on and near the outcrop of the Burkeville.

Figure 24 also demonstrates that hydraulic head losses occurred when large reductions in vertical-hydraulic conductivity of the Burkeville on and near its outcrop were coupled with a recharge reduction of 58 percent from the calibrated value. The losses in hydraulic head varied from 0 to 30 feet and only affected water levels on the outcrop of the Jasper aquifer at nodes 2-4. Water levels at nodes 5-16 from the downdip edge of the aquifer's outcrop to the limit of 3,000 mg/l water were unchanged from those of the calibrated model. It is significant to note that the normal effect of water levels rising in the Jasper from a decrease in vertical-hydraulic conductivity of the Burkeville (in this case a large decrease of several orders of magnitude) was reversed by the greater effect of a decrease in recharge (in this case a 58 percent decrease), and the net result was that water levels declined.

The sensitivity of the calibrated model to an experimental 60-mile extension further downdip of the actual downdip limit of fresh to slightly saline water (the no-flow boundary) into the part of the Jasper aquifer that contains moderately saline water to brine is illustrated in Figure 25. The hydrologic parameters that were extended beyond the calibrated model's no-flow boundary at the downdip limit of fresh to slightly saline water included the transmissivity of the Jasper aquifer, vertical-hydraulic conductivity of the Burkeville confining system, thickness of the Burkeville, and

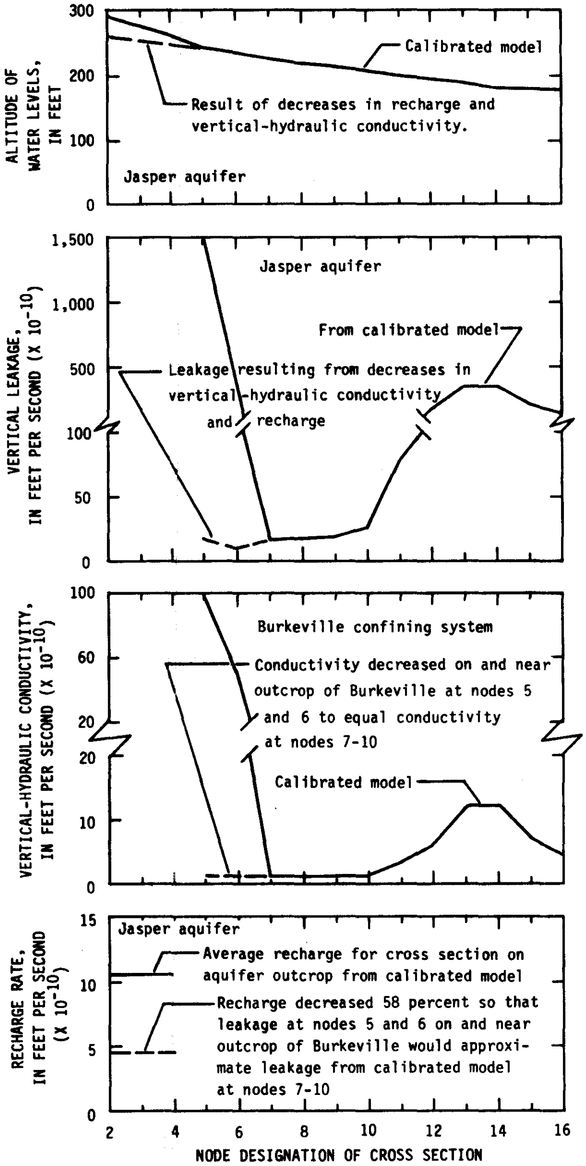

Figure 24.—Distribution of Leakage and Sensitivity of Water Levels to Reductions in Recharge and Vertical-Hydraulic Conductivity on and Near the Outcrop of the Jasper Aquifer and Burkeville Confining System

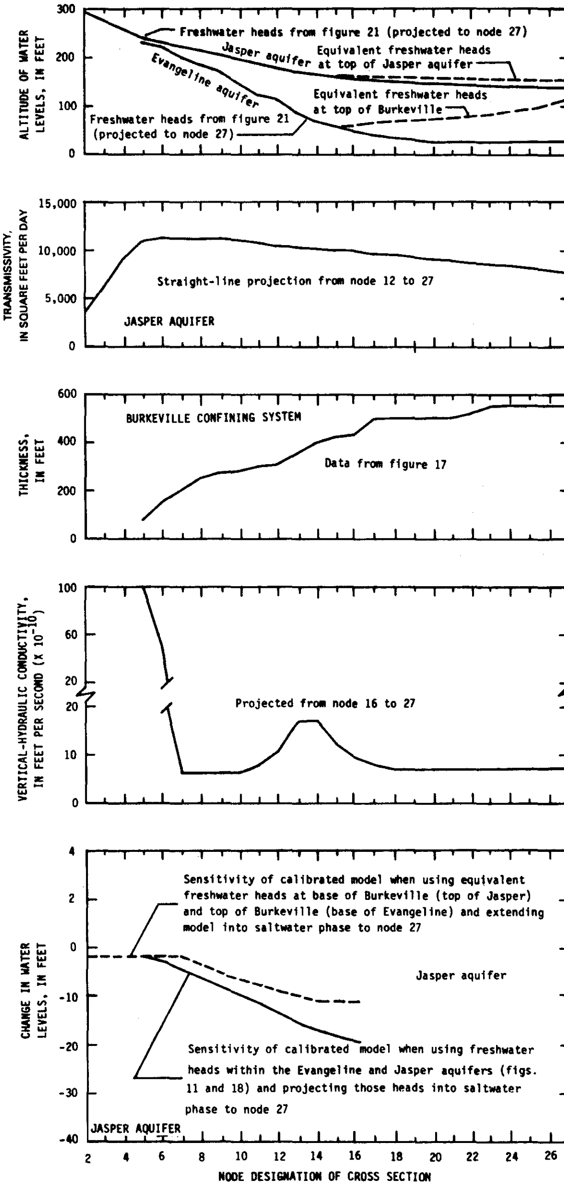

Figure 25.—Hydrologic Parameters for the Cross Section of the Model Extended Into the Part of the Aquifer Containing Saltwater and Sensitivity of the Calibrated Model to the Downdip Extension

freshwater hydraulic heads of the Jasper and Evangeline aquifers. The available freshwater hydraulic heads within the Jasper and Evangeline aquifers were projected to node 27 in the cross section using the aquifer's established hydraulic gradients from Figures 11 and 18. Equivalent freshwater hydraulic heads at the base of the Evangeline aquifer (top of the Burkeville confining system) were computed as well as the equivalent freshwater hydraulic heads at the top of the Jasper aquifer (base of Burkeville). These computations of equivalent freshwater hydraulic heads were necessary due to the presence of saltwater at the base of the Evangeline and top of the Jasper in the downdip extension of the calibrated model's boundary. The equivalent freshwater hydraulic heads were approximated using the Ghyben-Herzberg principle, which states that freshwater will extend 40 feet below sea level for every foot of freshwater above sea level provided that an environment where seawater, with a specific gravity of 1.025, is in good hydraulic connection with freshwater in the aquifer (Winslow and others, 1957, p. 381-383).

The effect of the calibrated model's no-flow boundary at the downdip limit of fresh to slightly saline water if the model is extended 60 miles into the part of the Jasper aquifer that contains saltwater is shown in Figure 25. The change in water levels of the calibrated model (if saltwater effects were not a factor in the downdip extension of the model) ranged from a decrease of 2 feet on the outcrop of the Jasper aquifer to a decrease of 11 feet at the no-flow boundary at node 16, when considering equivalent freshwater hydraulic heads in the top of the Jasper and base of the Evangeline aquifers. When considering the projections of the freshwater potentiometric surfaces within the Jasper and Evangeline aquifers (from Figures 11 and 18) downdip beyond the limit of fresh to slightly saline water in the Jasper to node 27 of the cross section, the net change in water levels in the calibrated model also decreased 2 feet in the Jasper's outcrop and decreased to 19 feet at the model's no-flow boundary at node 16.

In conclusion, the sensitivity analysis indicated that the calibrated model of the Jasper aquifer was more sensitive to certain hydrologic properties than to others, but was similar in sensitivity to various other modifications.

The shape of the potentiometric surface in the outcrop and downdip was affected to a greater degree by increasing and decreasing the value of transmissivity a specified percentage than by increasing and decreasing vertical-hydraulic conductivity the same percentage. By modifying transmissivity, either by 25-percent increases or decreases, the water level changed 20 to 30 feet, which flattened or steepened the slope of the potentiometric surface considerably. An increase and decrease of vertical-hydraulic conductivity by 25 percent, which lowered and raised the potentiometric surface less than the same percentage changes in transmissivity, did not alter the shape or slope of the potentiometric surface significantly.

The experimentation with leakage showed that modifications in the volume of recharge affected the water levels substantially when compared to effects from modifications in vertical-hydraulic conductivity of the Burkeville confining system. Only relatively slight changes in recharge are required to equal the effect on water levels from very large changes in vertical-hydraulic conductivity.

The sensitivity of most of the calibrated model to an extension of the downdip limit of water containing 3,000 mg/l of dissolved solids into more highly saline water was about the same as a reduction of 25 percent in transmissivity and an increase of 25 percent in vertical-hydraulic conductivity. All three experimentations caused water-level decreases of similar magnitude in the downdip part of the aquifer.

IMPROVEMENT OF THE MODEL AND FUTURE MODELING STUDIES

Rational values of hydraulic and hydrologic properties were built into the model of the aquifer system. Nevertheless, as additional data become available more accurate values can be used.

An extensive network of observation wells will be required to provide long-term responses of the aquifer to pumping stresses. At present (1983), the aquifer is only slightly to moderately developed by mostly small-capacity wells, and consequently, it is stressed only slightly. Larger withdrawals of water are anticipated from an increasing number of large-capacity wells, which are expected to be drilled to the aquifer. This is predicated on the economic advantage offered by the relatively high artesian pressure in the aquifer. Such well development, coupled with adequate records of aquifer responses and of pumpage, will allow for development of a transient flow model and for verification of the model by simulating different pumping periods. A transient model will provide a means of determining or verifying the aquifer's storage coefficient and will permit predictions of the potentiometric surface from proposed pumping.

It is important to remember that the Texas Coastal Plain sediments constitute a stacked series of hydrologic units including aquifers and confining systems. Future modeling efforts should not simply consider the effects of pumping stresses on individual aquifers, but should make provision to simulate the net effect of multiple stresses acting within a group of hydrologic units that mutually interact. Three-dimensional flow models will be required, and they should have the capability of considering the influence of different salinities within the hydrologic system.

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APPENDIX 5

Kasmarek, M.C., 2013, Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas 1891-2009. U.S. Geological Survey, Scientific Investigation Report 2012-5154, Version 1.1, November 2013 and December 2013.

Prepared in cooperation with the Harris–Galveston Subsidence District, the Fort Bend Subsidence District, and the Lone Star Groundwater Conservation District

Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas, 1891–2009

Scientific Investigations Report 2012–5154

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Contents

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Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Pressure	
pound per square foot (lb/ft^2)	0.04788	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

SI to Inch/Pound

Multiply	By	To obtain
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2] ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas, 1891–2009

By Mark C. Kasmarek

Abstract

In cooperation with the Harris–Galveston Subsidence District, Fort Bend Subsidence District, and Lone Star Groundwater Conservation District, the U.S. Geological Survey developed and calibrated the Houston Area Groundwater Model (HAGM), which simulates groundwater flow and land-surface subsidence in the northern part of the Gulf Coast aquifer system in Texas from predevelopment (before 1891) through 2009. Withdrawal of groundwater since development of the aquifer system has resulted in potentiometric surface (hydraulic head, or head) declines in the Gulf Coast aquifer system and land-surface subsidence (primarily in the Houston area) from depressurization and compaction of clay layers interbedded in the aquifer sediments.

The MODFLOW-2000 groundwater flow model described in this report comprises four layers, one for each of the hydrogeologic units of the aquifer system except the Catahoula confining system, the assumed no-flow base of the system. The HAGM is composed of 137 rows and 245 columns of 1-square-mile grid cells with lateral no-flow boundaries at the extent of each hydrogeologic unit to the northwest, at groundwater divides associated with large rivers to the southwest and northeast, and at the downdip limit of freshwater to the southeast. The model was calibrated within the specified criteria by using trial-and-error adjustment of selected model-input data in a series of transient simulations until the model output (potentiometric surfaces, land-surface subsidence, and selected water-budget components) acceptably reproduced field measured (or estimated) aquifer responses including water level and subsidence. The HAGM-simulated subsidence generally compared well to 26 Predictions Relating Effective Stress to Subsidence (PRESS) models in Harris, Galveston, and Fort Bend Counties. Simulated HAGM results indicate that as much as 10 feet (ft) of subsidence has occurred in southeastern Harris County. Measured subsidence and model results indicate that a larger geographic area encompassing this area of maximum subsidence and much of central to southeastern Harris County has subsided at least 6 ft. For the western part of the study area, the HAGM simulated as much as 3 ft of subsidence in Wharton, Jackson, and Matagorda Counties. For the eastern part of the study area, the HAGM simulated as much as 3 ft of subsidence at the boundary of Hardin and Jasper Counties. Additionally, in the southeastern part of the study area in Orange County, the HAGM simulated as much as 3 ft of subsidence. Measured subsidence for these areas in the western and eastern parts of the HAGM has not been documented.

Introduction

The availability of groundwater for municipal, industrial, and agricultural uses, as well as the potential subsidence associated with groundwater use, has been of concern in the Houston, Texas, area for decades (Lang and Winslow, 1950; Doyel and Winslow, 1954; Wood, 1956; Wood and others, 1963; Wood and Gabrysch, 1965; Jorgenson, 1975; Gabrysch and Bonnett, 1975; Gabrysch, 1982). In 2004, in cooperation with Texas Water Development Board and Harris–Galveston Coastal Subsidence District (now known as the Harris–Galveston Subsidence District), the U.S. Geological Survey (USGS) developed a groundwater flow model referred to as the "Northern Gulf Coast Groundwater Availability Model" (GAM) (Kasmarek and Robinson, 2004), which simulated the potentiometric surface (hydraulic head, or head) and clay compaction in the main water-bearing units of the Gulf Coast aquifer system from 1891 to 2000. Because areal distribution of groundwater withdrawals has changed in the study area (and subsequently, areas undergoing land-surface subsidence as a result) since 2000, a need was identified by water managers in the greater Houston area to update the GAM (Kasmarek and Robinson, 2004) to more accurately reflect recent (2009) conditions. Accordingly, the USGS, in cooperation with the Harris–Galveston Subsidence District (HGSD), the Fort Bend Subsidence District (FBSD), and the Lone Star Groundwater Conservation District (LSGCD), prepared a groundwater model of the Houston area, referred to hereinafter as the Houston Area Groundwater Model (HAGM). The objective of the HAGM is to accurately simulate and provide reliable, timely data on groundwater availability and land-surface subsidence in the Houston area through 2009. Local and regional water managers can use the HAGM as a tool to simulate aquifer response (changes in water levels and clay compaction) to future estimated water demands. The previous model (GAM) simulated groundwater flow in the Chicot and Evangeline aquifers and in parts of the Burkeville confining unit and Jasper aquifer that contain freshwater (Kasmarek and Robinson, 2004, figs. 20 and 21) and simulated land-surface subsidence in the Chicot and Evangeline aquifers. Like the GAM, the HAGM simulates groundwater flow in the Chicot and Evangeline aquifers and parts of the Jasper aquifer and Burkeville confining unit, but unlike the GAM the HAGM also simulates subsidence in the Jasper aquifer and the Burkeville confining unit.

Purpose and Scope

The purpose of this report is to describe the hydrogeology and simulation of groundwater flow and land-surface subsidence in the northern part of the Gulf Coast aquifer system in the HAGM study area (fig. 1). Additionally, this report documents changes made to the previous model (GAM), the parent model of the HAGM. For this report, “predevelopment” refers to conditions prior to 1891, and “postdevelopment” refers to 1891–2009. The hydrogeologic units, hydraulic properties, flow conditions, and development (groundwater withdrawals) of the HAGM are based on available information and have been modified from the original GAM as necessary. The hydrogeologic units from land surface downward are the Chicot aquifer, Evangeline aquifer, Burkeville confining unit, Jasper aquifer, and Catahoula confining system. Little mention of the Catahoula confining system is included because it was not simulated in the model. Groundwater flow was simulated for parts of the hydrogeologic units that contain freshwater.

Previous Studies

The Gulf Coast aquifer system in the Houston region has been extensively studied. Nine previous groundwater-flow-modeling studies, including two that simulated land-surface subsidence, have been completed in all or parts of the HAGM study area. From the earliest to most recent, the models were authored by Wood and Gabrysch (1965); Jorgensen (1975); Meyer and Carr (1979); Trescott (1975); Espey, Huston and Associates, Inc. (1982); Carr and others (1985); LBG-Guyton Associates (1997); Kasmarek and Strom (2002); and Kasmarek and Robinson (2004). LBG-Guyton Associates (1997) were the first to use the USGS groundwater-flow model MODFLOW to simulate water levels (heads) in the Houston area (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996).

The first model to simulate land-surface subsidence is known as the Predictions Relating Effective Stress to Subsidence (PRESS) model, which uses a modified version of the compaction (COMPAC) code developed by Helm (1975; 1976a, b; 1978). A model of land-surface subsidence (Fugro–McClelland [Southwest], Inc., 1997) was designed to be used with, but was not part of, the LBG-Guyton Associates (1997) groundwater-flow model. Similar to the model by Espey, Huston and Associates, Inc. (1982), the model by Fugro–McClelland (Southwest), Inc. (1997), used the PRESS code to simulate land-surface subsidence. The simulated water-level declines from the LBG-Guyton Associates (1997) groundwater-flow model were used as input data for PRESS models at 22 separate sites in the Houston area. Kasmarek and Strom (2002) and Kasmarek and Robinson (2004) used MODFLOW (Harbaugh and McDonald, 1996) to simulate groundwater flow in the Chicot and Evangeline aquifers of the Houston–Galveston region and the northern part of the Gulf Coast aquifer system, respectively, and the Interbed-Storage (IBS) package (Leake and Prudic, 1991) was used to simulate clay compaction and storage in the aquifers. Additional summary information about the previous models described in this section is presented in Kasmarek and Robinson (2004).

Description of Study Area for the Houston Area Groundwater Model

The HAGM study area (fig. 1) includes all or parts of 38 counties in southeastern Texas. The HAGM area is a gently sloping coastal plain, and land-surface elevations are topographically highest along the northwestern boundary. The vegetation in the northern parts of the HAGM area generally is composed of hardwood and pine forests, but as land-surface altitude decreases toward the coast, the vegetation becomes increasingly dominated by shrubs and grasses. Numerous constructed lakes and reservoirs are in the HAGM area, but those surficial water bodies generally only influence the water table on a local scale. The Gulf of Mexico and Galveston Bay have a large effect on the downdip groundwater-flow system and climate of the area. Winters in the HAGM area are mild with few days of freezing temperatures. During winter, moisture-laden Pacific and Canadian air masses produce regionally extensive bands of moderate rainfall. Summers are hot with high relative humidity, and prevailing winds are from the south to southwest (Kasmarek and Robinson, 2004). During summer, atmospheric convective cells can produce rates of precipitation from light to extreme (0.01 inches [in.] per hour to 2.0 in. per hour or more) (Federal Aviation Agency, 2007). Infrequently, moisture-laden tropical air masses produce light to extreme rates of precipitation with a reported rate of 38.8 in. being recorded from June 5 to June 9, 2001, related to Tropical Storm Allison (National Oceanic and Atmospheric Administration, 2012a). The average annual rainfall for the greater Houston area is 47.84 in., and the average annual temperature is about 68.8 degrees Fahrenheit (National Oceanic and Atmospheric Administration, 2012).

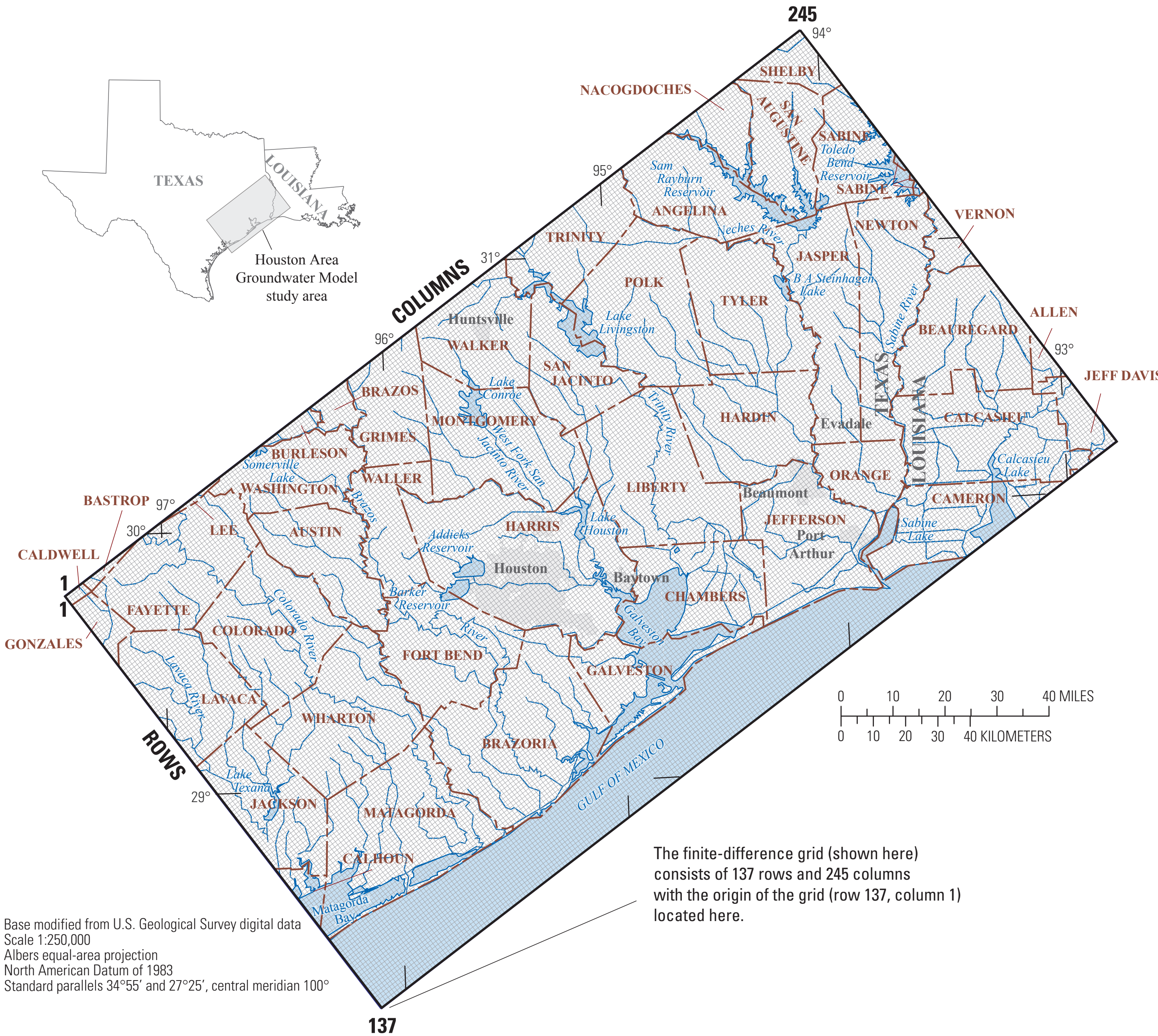


Figure 1. Location of the Houston Area Groundwater Model study area and finite-difference grid, southeastern Texas and southwestern Louisiana.

Hydrogeology

In a generalized conceptual model of the Gulf Coast aquifer system, the fraction of precipitation that does not evaporate, transpire through plants, or run off the land surface to streams enters the groundwater-flow system in topographically high updip outcrop areas of the hydrogeologic units in the northwestern part of the system. Most precipitation infiltrating into the saturated zone flows relatively short distances through shallow zones and then discharges to streams. The remainder of the water flows to intermediate and deep zones of the system southeastward of the outcrop areas where it is discharged by wells (in the developed system) and by upward leakage in topographically low areas near or along the coast (in both predevelopment and postdevelopment, but appreciably less in postdevelopment). Near the coast and at depth, saline water is present. The saline water causes less-dense freshwater that has not been captured and discharged by wells to be redirected upward as diffuse leakage to shallow zones of the aquifer system and ultimately to be discharged to coastal water bodies. Because groundwater flow was simulated in the HAGM only as far as the downdip limit of freshwater, only the parts of the hydrogeologic units containing freshwater are described in this report (Kasmarek and Robinson, 2004).

Hydrogeologic Units and Geologic Setting

The thicknesses of the four stratigraphic units used in the HAGM coincide with the GAM of Kasmarek and Robinson (2004) and originated from Strom and others (2003c). From land surface downward, the Chicot aquifer, the Evangeline aquifer, the Burkeville confining unit, the Jasper aquifer, and the Catahoula confining system are the hydrogeologic units of the Gulf Coast aquifer system (fig. 2), as described by Baker (1979, 1986) and by Ashworth and Hopkins (1995). In general, where the hydrogeologic units crop out, they do so parallel to the coast and thicken downdip to the southeast with the older units having a greater dip angle (fig. 2). The correlation of hydrogeologic units with stratigraphic units is shown in figure 3. The Chicot aquifer comprises (youngest to oldest) the alluvium, Beaumont Formation, Montgomery Formation, Bentley Formation, and Willis Formation. The Evangeline aquifer comprises (youngest to oldest) the Goliad Sand and the upper part of the Fleming Formation. The Burkeville confining unit consists entirely of the Fleming Formation. The Jasper aquifer comprises (youngest to oldest) the lower part of the Fleming Formation throughout its subsurface extent and the upper part of the Catahoula Sandstone in its outcrop and updip parts (fig. 3). The basal unit for this report is the Catahoula confining system, which comprises the Catahoula Sandstone and, downdip, the Anahuac and Frio Formations (Kasmarek and Robinson, 2004).

The updip limit of the Chicot aquifer is an undulating boundary approximately parallel to the coast and extending as far north as Lavaca, Colorado, Austin, Waller, Grimes, Montgomery, San Jacinto, Polk, Tyler, Jasper, and Newton Counties (fig. 4). To the southeast, the freshwater part of the aquifer extends beneath the Gulf of Mexico. The altitude of the top of the Chicot aquifer in the HAGM study area approximates the land-surface altitude and ranges from the North American Vertical Datum of 1988 (NAVD 88, hereinafter, datum) at the coast to as much as 445 feet (ft) above datum at its updip limit (Kasmarek and Robinson, 2004, fig. 9). The altitude of the base of the Chicot aquifer in the HAGM study area (Kasmarek and Robinson, 2004, fig. 10) ranges from more than 1,500 ft below Datum southeast of the coast to more than 420 ft above Datum in the outcrop area and varies locally because of numerous salt domes in the study area (Kasmarek and Robinson, 2004, fig. 27). The altitude of the base of the Chicot aquifer was constructed from hydrogeologic digital data of Strom and others (2003a). The original cumulative clay thickness of the Chicot aquifer (Kasmarek and Robinson, 2004, fig. 12) was subtracted from aquifer thickness to construct cumulative sand thickness (Kasmarek and Robinson, 2004, fig. 13).

The updip limit of the Evangeline aquifer is an undulating boundary approximately parallel to the coast and extending as far north as Lavaca, Fayette, Austin, Washington, Grimes, Montgomery, Walker, San Jacinto, Polk, Tyler, Jasper, and Newton Counties (fig. 5). The downdip limit of freshwater is approximately coincident with the coast. The altitude of the top of the Evangeline aquifer in the HAGM study area ranges from more than 1,440 ft below datum to as much as 469 ft above datum at its updip limit (Kasmarek and Robinson, 2004, fig. 15). The altitude of the base of the Evangeline aquifer in the HAGM study area (Kasmarek and Robinson, 2004, fig. 16) ranges from more than 5,300 ft below datum at the coast to 430 ft above datum in the outcrop area and varies locally because of numerous salt domes (Kasmarek and Robinson, 2004, fig. 27). The base of the Evangeline aquifer transgresses the stratigraphic boundary between the Goliad Sand and the Fleming Formation. (This transgression is not shown in the section depicted in figure 2, as only outcropping stratigraphic units are shown.) The altitude of the base of the Evangeline aquifer is presented in Strom and others (2003b). The original cumulative clay thickness of the Evangeline aquifer (Kasmarek and Robinson, 2004, fig. 18) is from Gabrysch (1982, fig. 37) and was subtracted from aquifer thickness to construct cumulative sand thickness (Kasmarek and Robinson, 2004, fig. 19).

The updip limit of the Burkeville confining unit is an undulating boundary approximately parallel to the coast and extending as far north as Lavaca, Fayette, Austin, Washington, Grimes, Montgomery, Walker, San Jacinto, Polk, Tyler, Jasper, and Newton Counties (fig. 6). The Burkeville confining unit lies stratigraphically below the Evangeline aquifer and above the Jasper aquifer (fig. 2) and restricts flow between the Evangeline and Jasper aquifers because of its relatively large percentage of silt and clay compared to the percentages of the adjacent aquifers (Baker, 1979). Southeast of the

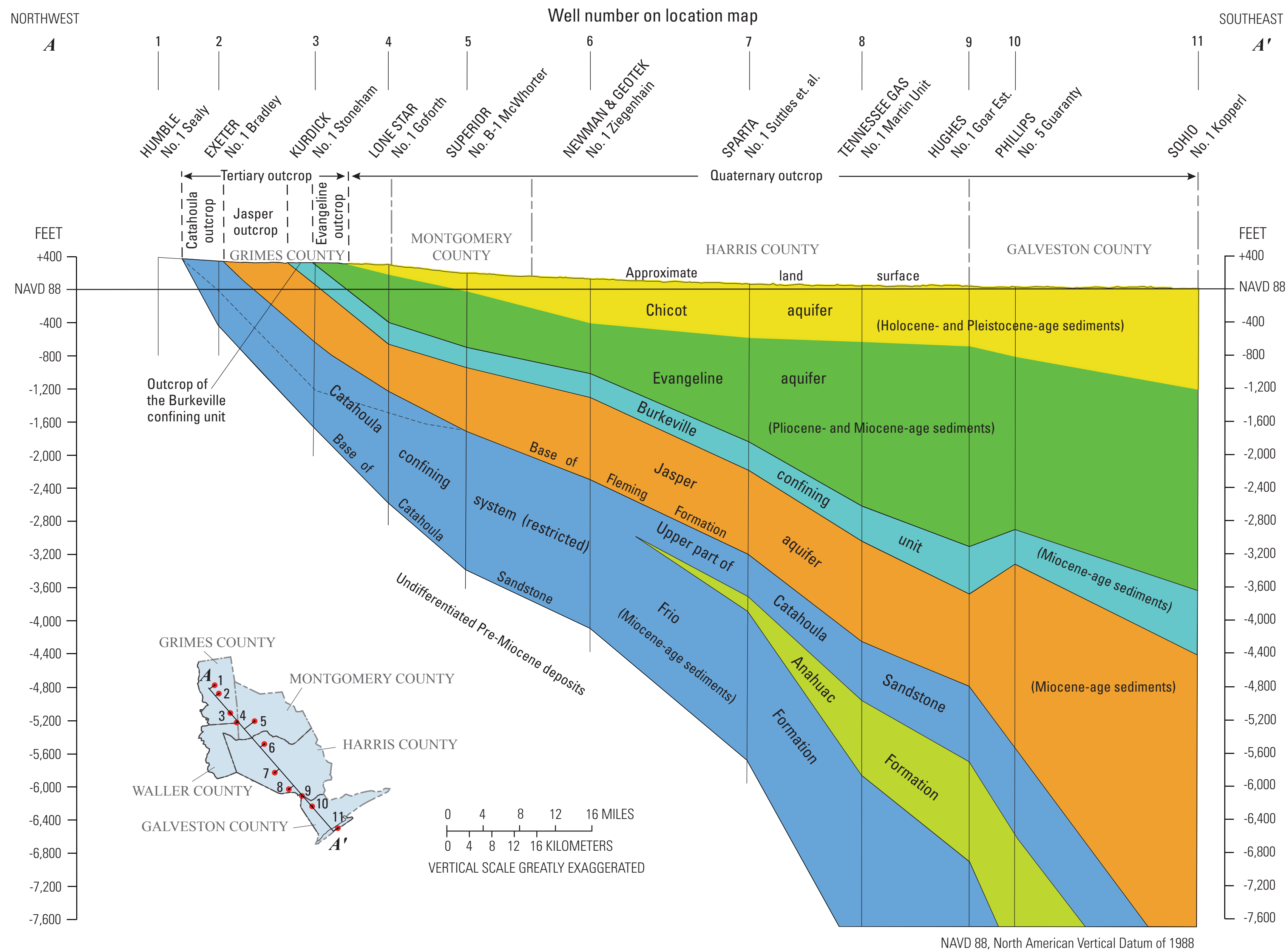
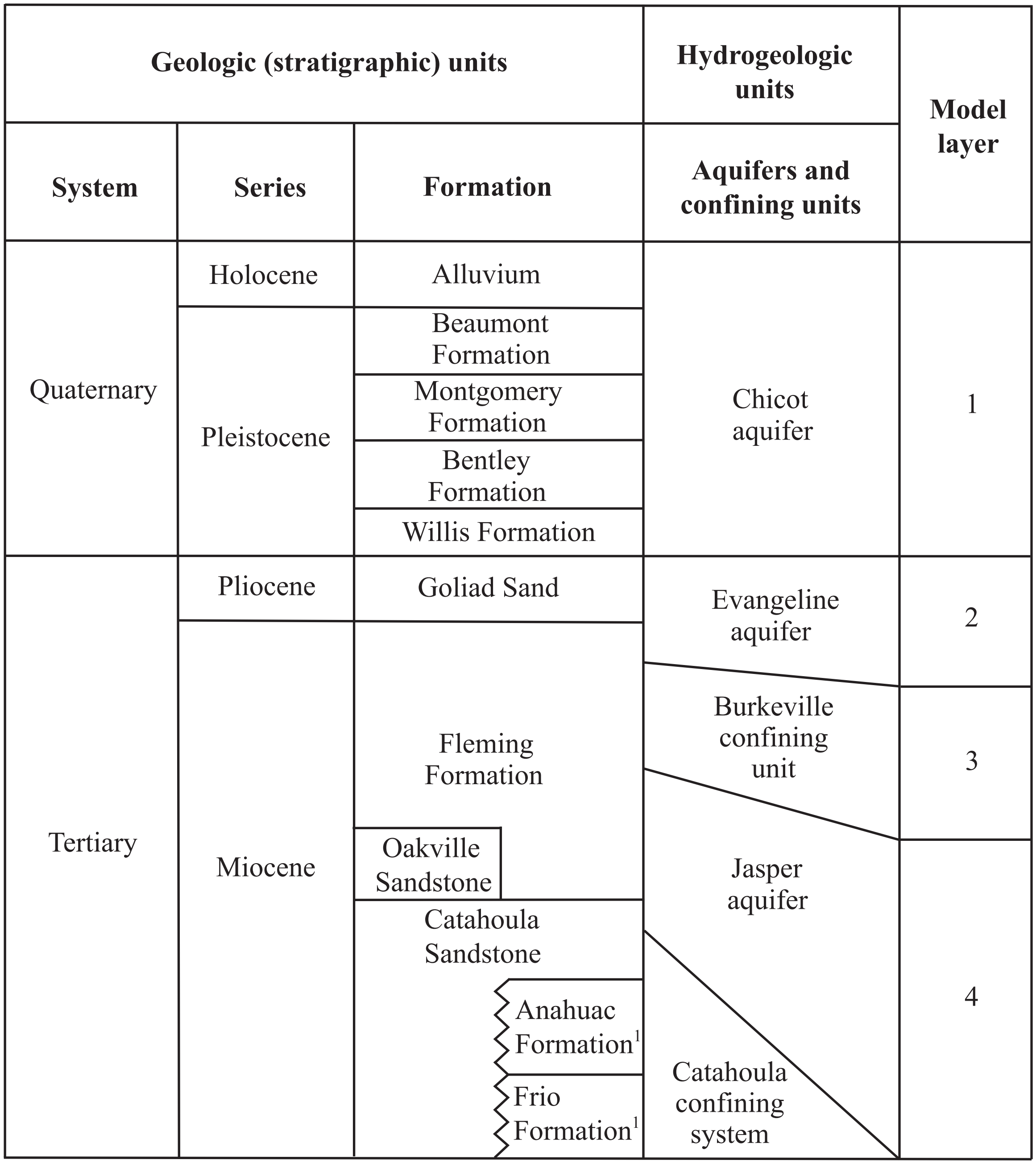


Figure 2. Hydrogeologic section of the Gulf Coast aquifer system in Harris County and adjacent counties, Texas.



[1]Present only in subsurface.

Figure 3. Correlation of stratigraphic and hydrogeologic units in the Houston Area Groundwater Model study area.

downdip limit of freshwater (fig. 6), this unit is considered (for HAGM simulation purposes) a no-flow unit that prevents diffuse upward leakage of saline water from the Jasper aquifer. In updip areas of the Burkeville confining unit (fig. 6), the sediments are slightly more transmissive and thus able to supply small quantities of water for domestic use. In the outcrop area, the altitude of the top of the Burkeville confining unit is equal to the land-surface altitude, and in the subcrop area, the top of the Burkeville confining unit is coincident with the base of the Evangeline aquifer. The altitude of the base of the Burkeville confining unit is coincident with the top of the Jasper aquifer and varies locally because of the numerous salt domes in the area (Kasmarek and Robinson, 2004, fig. 27).

The updip limit of the Jasper aquifer is an undulating boundary approximately parallel to the coast and extending as far north as Lavaca, Gonzales, Fayette, Washington,

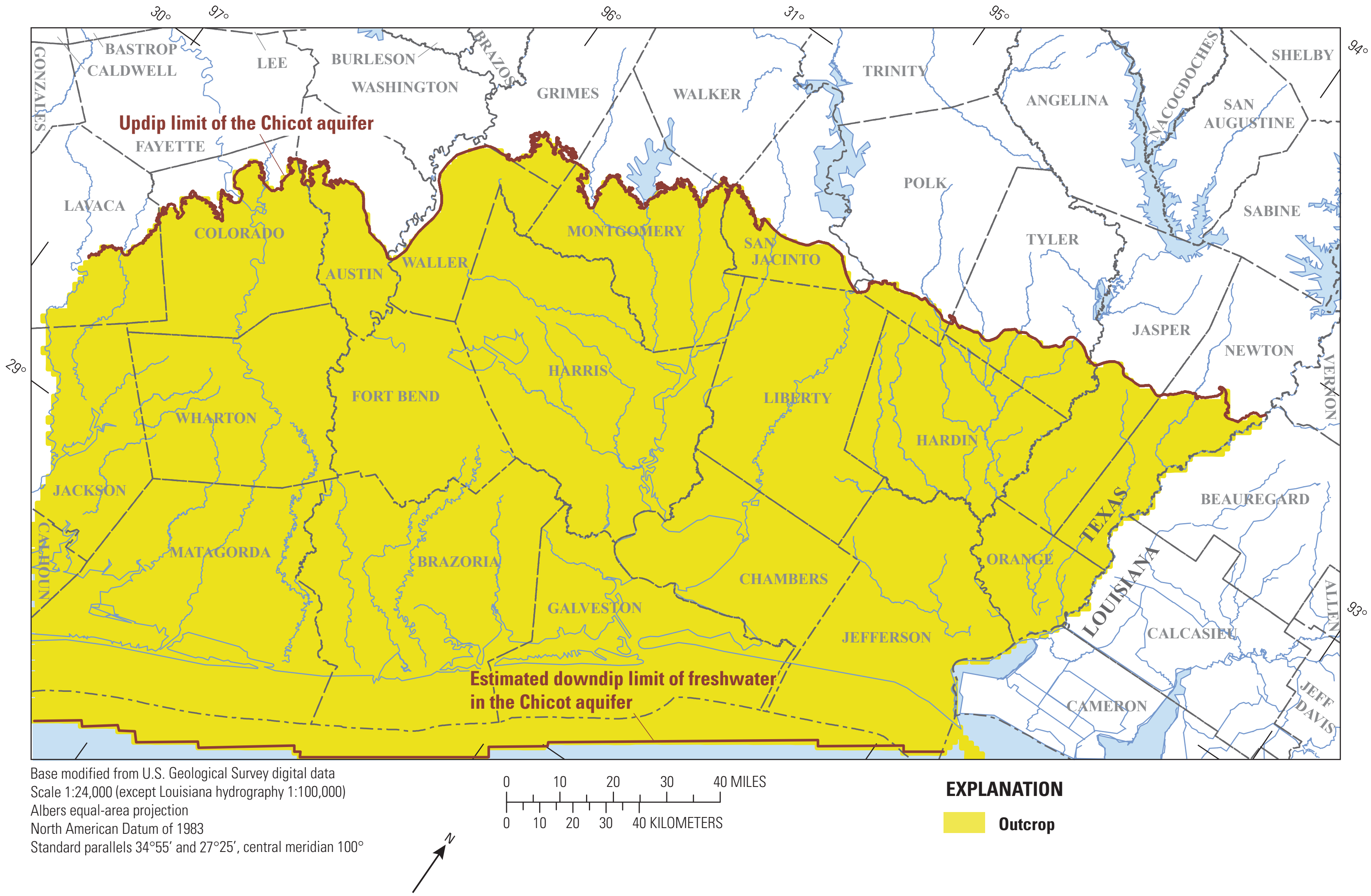


Figure 4. Extent and outcrop area of the Chicot aquifer in the Houston Area Groundwater Model study area.

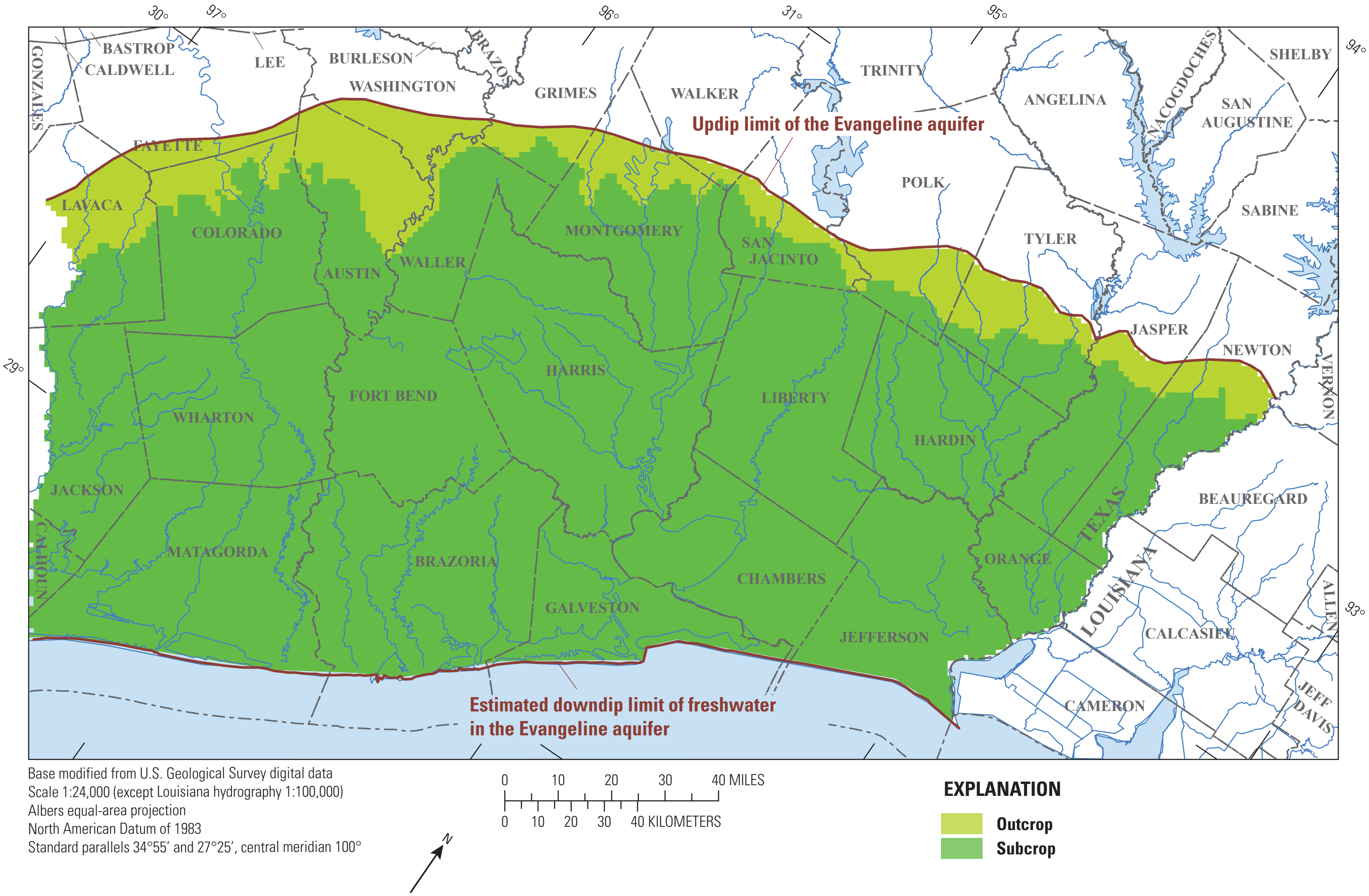


Figure 5. Extent, outcrop area, and subcrop area of the Evangeline aquifer in the Houston Area Groundwater Model study area.

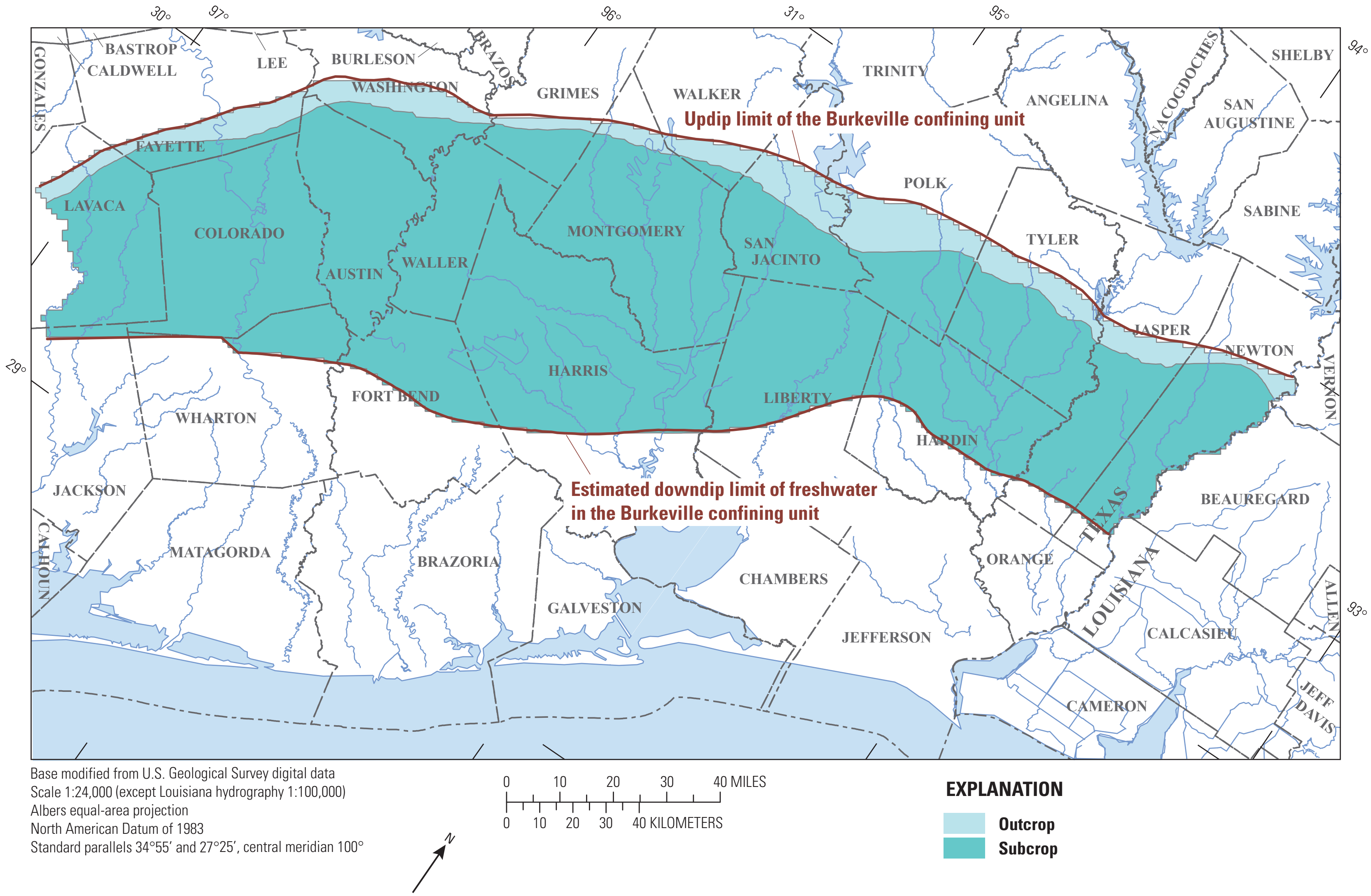


Figure 6. Extent, outcrop area, and subcrop area of the Burkeville confining unit in the Houston Area Groundwater Model study area.

Brazos, Grimes, Walker, Trinity, Polk, Tyler, Angelina, Jasper, Newton, and Sabine Counties (fig. 7). Southeast of the downdip limit of freshwater, this unit is considered (for HAGM simulation purposes) a no-flow unit that prevents diffuse upward leakage of saline water. The altitude of the top of the Jasper aquifer in the HAGM study area ranges from less than 2,800 ft below datum to about 900 ft above datum at its updip limit (Kasmarek and Robinson, 2004, fig. 22). The altitude of the base of the freshwater part of the Jasper aquifer (Kasmarek and Robinson, 2004, fig. 23) ranges from about 3,800 ft below datum near the downdip limit of freshwater to about 500 ft above datum in the outcrop area and varies locally because of numerous salt domes (Kasmarek and Robinson, 2004, fig. 27). The base of the Jasper aquifer in updip areas transgresses the stratigraphic boundary between the Fleming Formation and the Catahoula Sandstone (figs. 2 and 3). Strom and others (2003c) estimated the altitudes of the top and base of the Jasper aquifer and evaluated the thickness of the aquifer (Kasmarek and Robinson, 2004, fig. 24). The original cumulative clay thickness of the Jasper aquifer (Kasmarek and Robinson, 2004, fig. 25) was subtracted from aquifer thickness to construct the cumulative sand thickness (Kasmarek and Robinson, 2004, fig. 26). The basal unit for the HAGM (fig. 2) is the Catahoula confining system, which comprises the Catahoula Sandstone and, downdip, the Anahuac and Frio Formations. The Jasper aquifer is underlain by the Catahoula confining system, which is composed mostly of clay or tuff. The Catahoula confining system impedes substantial exchange of water between the Jasper aquifer and underlying units (Baker, 1986).

The paleodepositional environment of the sediments that formed the Gulf Coast aquifer system was a fluvial-deltaic or shallow-marine environment that produced interlayered, discontinuous sequences of clay, silt, sand, and gravel (Kasmarek and Robinson, 2004). (In this report, the term “sand” refers to coarse-grained sand and gravel sediments, whereas “clay” refers to fine-grained sediments including clay and silt.) 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 the predominantly continental sediments that compose the aquifers to the predominantly marine sediments that compose the confining units and clay layers within aquifers; therefore, the Gulf Coast aquifer system has a high degree of heterogeneity in both lateral and vertical extents (Sellards and others, 1932).

Normal growth faults are common throughout the unconsolidated sediments of the HAGM study area, and traces of some of these faults have been mapped and named. Based on the study of well logs and seismic-line data, these faults have been delineated to depths of 3,000–12,000 ft below land surface (Verbeek and others, 1979). The presence of most of these faults is associated with natural geologic processes. The scale of fault movement is insufficient to completely offset entire hydrogeologic units; however, if an offset results in the juxtaposition of relatively more permeable sediments against relatively less permeable sediments, the rate and direction of groundwater flow could be affected. Although growth faults are common in the study area, the exact locations and frequency with which associated offsets appreciably affect groundwater flow is unknown. Because the distribution and magnitude of such occurrences in the study area are unknown, accounting for them in the HAGM was not possible. Numerous salt domes originating from the Jurassic-age Louann Salt have risen through the overlying strata (Halbouty, 1967) and have been mapped in the HAGM area (Beckman and Williamson, 1990). In some areas, the salt domes have penetrated the aquifers. The upward intrusions of the salt domes decrease the thickness of the adjacent aquifer sediments and radially alter the prevailing hydraulic characteristics and flow paths in the adjacent aquifer sediments. These widely distributed salt domes increase the heterogeneity of the hydraulic characteristics of the aquifers (Kasmarek and Robinson, 2004).

Hydraulic Properties

Carr and others (1985) estimated transmissivity and storativity of the Chicot and Evangeline aquifers from simulation and are approximately the same as that used in the HAGM. Estimated transmissivity of the Chicot aquifer ranged from about 3,000 to about 50,000 square feet per day (ft^2/d), and storativity ranged from about 0.0004 to 0.1(dimensionless). Estimated transmissivity of the Evangeline aquifer ranges from about 3,000 to about 15,000 ft^2/d, and storativity ranged from about 0.00005 to 0.1. For both aquifers, the simulations indicated that the larger storativities are in the updip outcrop areas that are under water-table conditions; the smaller storativities are in downdip areas that are under confined conditions. Baker (1986) estimated transmissivity of the Jasper aquifer from simulation for an area coincident with most of the Jasper aquifer in the HAGM area; the transmissivity of the Jasper aquifer simulated in that study ranged from less than 2,500 to about 35,000 ft^2/d. Wesselman (1967) estimated transmissivity for all three aquifers and storativity for the Chicot and Evangeline aquifers from aquifer tests in Jasper, Newton, Orange, and Hardin Counties. Transmissivities of the Chicot aquifer ranged from 12,300 to 68,000 ft^2/d; the Evangeline aquifer, 2,130 to 14,800 ft^2/d; and the Jasper aquifer, 1,070 to 14,000 ft^2/d. Wesselman (1967) also estimated storativities of the Evangeline aquifer ranging from 0.00063 to 0.0015 and of the Jasper aquifer ranging from 0.000382 to 0.00119. Strom and others (2003c) reported storativities for the Jasper aquifer as large as 0.2. Several other previous studies (for example Jorgensen, 1975) estimated transmissivity in aquifers for parts of counties in the HAGM study area; those estimates generally are within the ranges listed above.

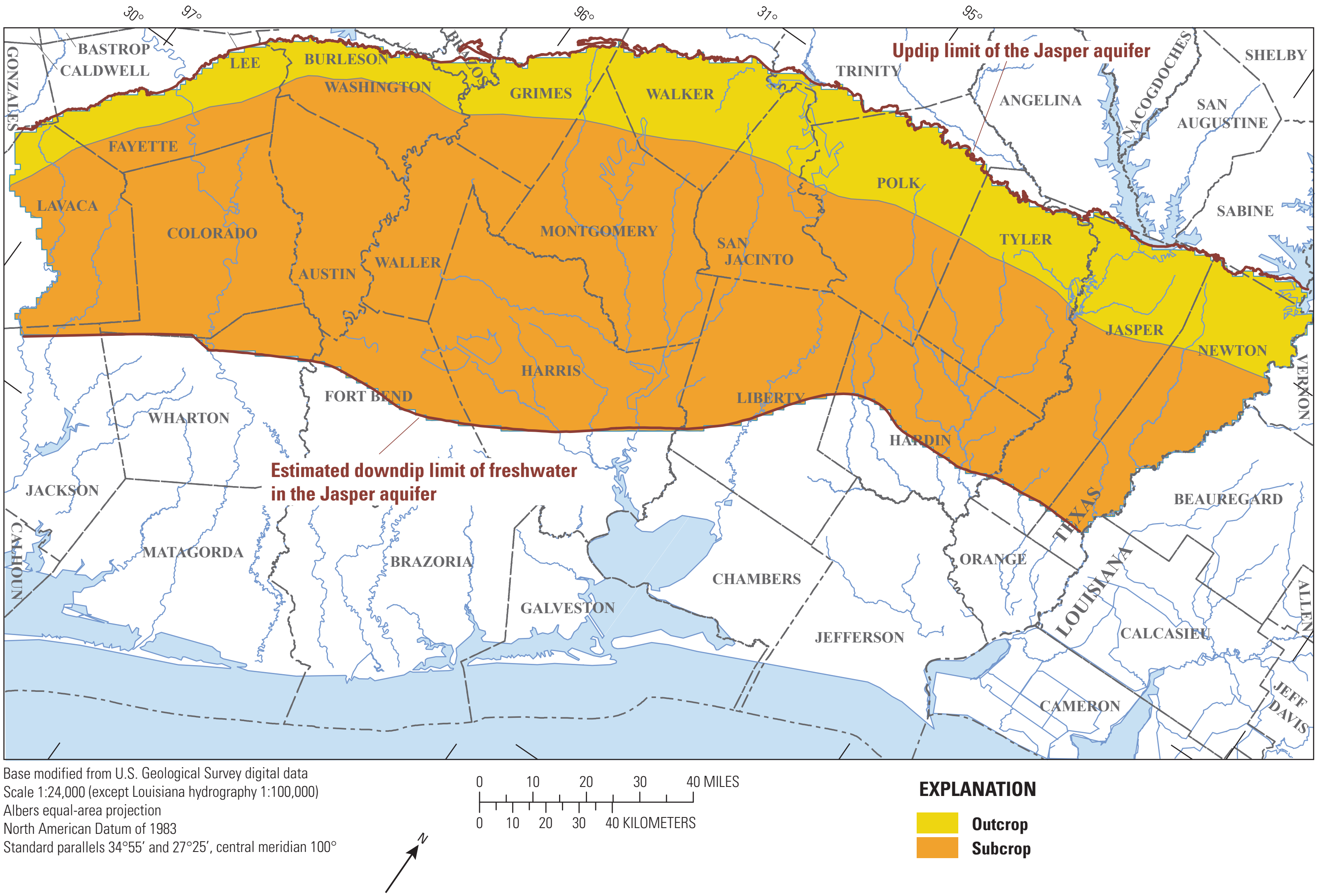


Figure 7. Extent, outcrop area, and subcrop area of the Jasper aquifer in the Houston Area Groundwater Model study area.

The transmissivity of an aquifer is equal to the hydraulic conductivity multiplied by the thickness of the aquifer (Freeze and Cherry, 1979, p. 59); "hydraulic conductivity" is used extensively in this report. Initial transmissivity distributions for the aquifers were constructed with data from Wesselman (1967), Carr and others (1985), Baker (1986), and Kasmarek and Strom (2002) by using geographic information system (GIS) applications. The initial transmissivity of the Burkeville confining unit was computed by multiplying values of hydraulic conductivity representative of a midrange between silty sand and marine clay (average of 0.01 foot per day [ft/d]) (Freeze and Cherry, 1979, table 2.2, p. 29) by the areally distributed thickness of the confining unit. In this report, hydraulic conductivity refers to horizontal hydraulic conductivity, unless otherwise noted.

Groundwater Flow Conditions, Recharge, and Discharge

The uppermost parts of the Gulf Coast aquifer system (shallow zones), which include outcrop areas, are under shallow, unconfined water-table conditions. As depth increases in the aquifer system and the cumulative thicknesses of the interbedded sand and clay increase, water-table conditions transition to confined potentiometric conditions. Thus, the lowermost parts of the aquifer system (deep zones) are under confined conditions. The middle parts of the aquifer system (intermediate zones) therefore are under semiconfined conditions. Because the transition from water table to confined conditions incrementally increases with depth, assigning specific depth horizons to shallow, intermediate, and deep zones is problematic (Kasmarek and Robinson, 2004).

Assuming that groundwater flows downgradient and perpendicular to equipotential lines, simulated predevelopment potentiometric surfaces of the Chicot, Evangeline, and Jasper aquifers (Kasmarek and Robinson, 2004, figs. 62–64) confirm the generalized conceptual model of the natural groundwater-flow system. Recharge enters the system in topographically high updip outcrops of the hydrogeologic units in the northwestern parts of the HAGM study area and either flows relatively short distances discharging into topographically lower areas to features such as streams or flows longer distances southeastward through deeper zones, where it is discharged by diffuse-upward leakage in topographically low areas along coastal areas.

As first described by Tóth (1963) and summarized by Johnston (1999) relative to regional aquifer systems, natural (predevelopment) groundwater flow can be subdivided into local, intermediate, and regional flow systems. Local flow follows relatively short flow paths in shallow zones and is controlled mainly by topography. Recharge to local flow systems occurs in topographically high areas, and discharge occurs in nearby, topographically low areas. Intermediate flow moves along relatively deeper flow paths compared to local flow, with groundwater flowing from recharge areas through intermediate zones to downgradient discharge areas. Regional flow follows relatively long flow paths from regional recharge areas through deep zones to distal discharge areas such as the downgradient limits of an aquifer system. Referring to the local, intermediate, and deep flow systems of the aquifer is a basic way to explain the groundwater flow in the aquifer system, but the true nature of the flow system is more complex because of the paleodepositional environment and the stresses of groundwater withdrawals on the aquifer. Tóth (1963) noted that to assume an exact, one-to-one correspondence among local, intermediate, and regional flow systems would be an oversimplification.

If this concept of subdividing natural groundwater flow is applied to the Gulf Coast aquifer system, the implications are that an appreciable amount of the precipitation that infiltrates the subsurface (total recharge) in the relatively topographically high outcrop areas of the hydrogeologic units joins local flow systems. Thus, much of the total precipitation enters from and exits to the shallow subsurface by streams and in topographically low areas. A proportionally smaller amount of the total recharge joins intermediate flow systems, and an even smaller amount of the total recharge joins regional flow systems. Wood (1956, p. 30–33), in an early study of the availability of groundwater in the Gulf Coast region of Texas, stated that, "Within the rainfall belts of 40–50 inches per year, probably 1 inch or more of the water that enters the outcrop of the aquifers updip from the heavily pumped areas is discharged to the streams in the outcrop area as base flow or rejected recharge."

The natural groundwater-flow system has been altered in places (the Houston area, for example) by decades of substantial and concentrated withdrawals in the Chicot and Evangeline aquifers. By 1977, water levels had declined to as much as 250 ft and 350 ft below datum in the Chicot and Evangeline aquifers, respectively (Gabrysch, 1979). Because the Chicot and Evangeline aquifers are hydraulically connected, in these areas, withdrawals have increased vertical-head gradients and have induced downward flow from local and intermediate flow systems into the regional flow system, thus capturing some flow that would have discharged naturally (Gabrysch, 1979).

Few studies that focus specifically on recharge to the system in the HAGM study area are available. For example, Baker (1986) and a study of potential recharge in the Houston area by the U.S. Geological Survey Robert K. Gabrysch [retired] and Fred Liscum [retired], U.S. Geological Survey, written commun., 1995) estimated that the recharge rate across the area ranged from 0.25 in. per year (in./yr) to 7 in./yr. A few additional studies report recharge rates within this range (Tarver, 1968; Sandeen, 1972; Loskot and others, 1982). An in-depth discussion of the results from previous recharge studies in the study area is available in Kasmarek and Robinson (2004).

Groundwater Development

Rates of recharge to and discharge from the Chicot, Evangeline, and Jasper aquifers are affected by groundwater withdrawals from those aquifers. “Predevelopment” relative to the HAGM refers to aquifer conditions before 1891 or before the aquifers were measurably stressed by groundwater withdrawals; “postdevelopment” refers to aquifer conditions after the stress of withdrawals became measurable. Initially, the principal areas of concentrated groundwater withdrawals from the aquifer system in the HAGM study area were located in Harris, Galveston, and Fort Bend Counties (the Houston area). Much of the early groundwater-use information for the area, as summarized here, is from Lang and Winslow (1950) and Wood and Gabrysch (1965).

In the area of Houston (founded in 1836), surface water was initially used to meet water-supply demands. In 1886, the first well was drilled to a depth of 140 ft and was reported as free flowing at more than 1,000 gallons per minute (gal/min) (Lang and Winslow, 1950). By 1906, groundwater withdrawals had the capacity of as much as 19 million gallons per day (Mgal/d). By 1935, withdrawals averaged 24.5 Mgal/d and by 1941 had increased to 27.2 Mgal/d. From 1941 to 1950, groundwater use more than doubled. In 1954, water released from the newly constructed Lake Houston began to be used to augment groundwater supplies. The additional surface-water supply from Lake Houston resulted in reduced groundwater withdrawals from 1954 to 1960. From the early 1960s to the mid-1970s, however, groundwater withdrawals increased at rates comparable to pre-1954 rates (Lang and Winslow, 1950). In 1975, because of increasing groundwater withdrawals and subsequent land-surface subsidence in Harris and Galveston Counties, the Harris–Galveston Coastal Subsidence District (HGCSD) was created and began to control land-surface subsidence by regulating groundwater withdrawals. In late 1976, groundwater withdrawals began to decrease in eastern Harris County because part of the demand began to be supplied by water from Lake Livingston. The policies of the newly created HGCSD resulted in decreased groundwater withdrawals in the Baytown and southeastern Harris County areas. The groundwater withdrawal rate exceeded 450 Mgal/d in 1976 and decreased to about 390 Mgal/d in the early 1980s, but the trend reversed, and by 1990, withdrawals had increased to 493 Mgal/d. A downward trend began again in the 1990s when withdrawals were about 463 Mgal/d by 1996. By 2000, withdrawals were about 895 Mgal/d (Harris–Galveston Subsidence District, 2012).

Potentiometric Surfaces and Land-Surface Subsidence

In the updip outcrop area of the Chicot aquifer and the outcrop areas of the Evangeline and Jasper aquifers and Burkeville confining unit (figs. 4–7), water-table conditions generally exist. The water table is assumed to be a subdued replica of the topography (Williams and Williamson, 1989). In outcrops of the Chicot and Evangeline aquifers in parts of Harris and Montgomery Counties, a seismic refraction investigation indicated that the water table ranges from about 10 to 30 ft below land surface (Noble and others, 1996). Hydrographs of water levels in wells screened in the water table of the Chicot and Evangeline aquifers indicate that the water levels were not influenced by increased groundwater withdrawal in the area and have remained fairly stable (Kasmarek and Robinson, 2004, fig. 28). The USGS annually has measured water levels in wells and constructed maps of potentiometric surfaces of the Chicot and Evangeline aquifers in the greater Houston area since 1977 (Gabrysch, 1979) and of the Jasper aquifer since 2000. Related to groundwater withdrawal in the HAGM study area, the 2009 report (Kasmarek, Houston, and Ramage, 2009) in this series indicates that water-level-altitude contours ranged from 250 ft below datum (hereinafter, datum) in a small area in southwestern Harris County to 200 ft above datum in central to southwestern Montgomery County in the Chicot aquifer; from 300 ft below datum in south-central Montgomery County to 200 ft above datum at the intersecting borders of Waller, Montgomery, and Grimes Counties in the Evangeline aquifer; and from 175 ft below datum in south-central Montgomery County to 250 ft above datum in east-central Grimes County in the Jasper aquifer (Kasmarek, Houston, and Ramage, 2009).

In the 1830s, before groundwater withdrawals from the aquifer system occurred in the HAGM study area, the potentiometric surfaces in the confined parts of the aquifers were higher than land surface. This was demonstrated by a well in Houston that was drilled to 140 ft and flowed at more than 1,000 gal/min. Groundwater development has caused substantial declines of as much as 350 ft below datum (Gabrysch, 1979) of the potentiometric surfaces of the aquifers (and subsequent land-surface subsidence), primarily in Harris, Galveston, and Fort Bend Counties (Kasmarek and Robinson, 2004, figs. 48 and 49). These potentiometric-surface declines in unconsolidated confined aquifers cause a decrease in hydraulic pressure that creates a load on the skeletal matrix of the aquifer (Galloway and others, 1999, p. 9). Because coarse-grained sediments (sand layers) are more transmissive and less compressible than are fine-grained sediments (clay layers), the depressurization of sand layers is relatively rapid compared to that of clay layers and causes only slight skeletal-matrix consolidation. The depressuring and subsequent dewatering of clay layers requires more time compared to that of the sand layers, however, and is dependent on the thickness of the clay layers, the hydraulic characteristics of the clay layers, and the vertical-stress load of the sediment overburden. The delayed drainage of the clay layers continues to occur until the residual 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 reorientation of the individual clay grains occurs, becoming perpendicular to the applied vertical load (Galloway and others, 1999, p. 9). Therefore, the dewatering caused by the depressurization of the clay layers combined with clay-grain realignment reduces the porosity and groundwater-storage capacity of the clay layers, which in turn allows them to inelastically and permanently compact. More than 10 ft of land-surface subsidence has been documented in the Baytown area in southwestern Harris County (Gabrysch and Neighbors, 2005; Kasmarek, Gabrysch, and Johnson, 2009). Because of the weight (sediment load) of the overburden and the inelastic compaction characteristics of the clay layers, about 90 percent of the compaction is permanent (Gabrysch and Bonnett, 1975). Thus, when potentiometric surfaces rise and repressure compacted clay layers, there is little, if any, rebound of the land surface (Gabrysch and Bonnett, 1975). Although the compaction of one clay layer generally will not cause a noticeable decrease in the land-surface altitude, if numerous stacked clay-layer sequences (which are characteristic of the Gulf Coast aquifer system) depressure and compact, then appreciable decreases in land-surface altitude can and do occur (Gabrysch and Bonnett, 1975). A substantial amount of the total water withdrawn is derived from dewatering of the numerous clay layers of the aquifer: model simulations indicated that as much as 19 and 10 percent of the total water budget of the Chicot and Evangeline aquifers, respectively, is derived from the dewatering of the clay layers of the aquifers (Kasmarek and Strom, 2002).

Simulation of Groundwater Flow and Land-Surface Subsidence

Model Description

The finite-difference computer code MODFLOW-2000 (Harbaugh and others, 2000) was used to create and calibrate the HAGM to simulate groundwater flow and land-surface subsidence in the northern Gulf Coast aquifer system from predevelopment (1891) through 2009. The Subsidence and Aquifer-System Compaction (SUB) package designed for the MODFLOW-2000 model (Hoffman and others, 2003) was used to simulate clay compaction and storage, and thus land-surface subsidence, in the Chicot, Evangeline, and Jasper aquifers and the Burkeville confining unit. The Chicot, Evangeline, and Jasper aquifers and the Burkeville confining unit were simulated as four separate layers and discretized into two-dimensional finite-difference grids (fig. 1). By using GIS applications, model input data were georeferenced and assigned to model grid cells.

Mathematical Representation

The MODFLOW-2000 model uses finite-difference methods to solve the partial differential equation for three-dimensional movement of groundwater of constant density through heterogeneous, anisotropic porous materials. The equation can be written as follows:

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right)- W = Ss\frac{\partial h}{\partial t} \qquad (1)$$

where

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

h is hydraulic head (Lt^{-1});

W is a volumetric flux per unit volume representing sources and/or sinks of water, with $W < 0.0$ for flow out of the groundwater system and $W > 0.0$ for flow in (Lt^{-1});

S_s is specific storage of the porous material (L^{-1});

L is length;

t is time; and

Lt^{-1} is length divided by time

(Harbaugh and McDonald, 1996). This equation, with specification of appropriate boundary and initial conditions, constitutes a mathematical representation of the groundwater-flow system. In this application, the aquifer system was assumed to be horizontally isotropic; thus, there was no preferred direction of hydraulic conductivity in the horizontal.

The storage coefficient (S_s) in equation 1 is particularly important in a confined and unlithified aquifer system like the Gulf Coast aquifer system. Because the aquifers do not have a rigid skeletal matrix, water is released not only from coarse-grained sediments like sand and gravel but also from fine-grained sediments like clay and silt. Therefore, the compressibility of water (S_w) is necessarily considered, computed as

$$S_w = S_{sw} \times b, \qquad (2)$$

where

S_{sw} is specific storage due to compressibility of water (L);

S_{sw} is computed as S_{sw} = q×g_w/E_w (L); and

b is thickness of the layer (L)

where

θ is porosity (dimensionless);

γ_w is unit weight of water (62.4 pounds [lb] per cubic foot [ft^3]);

E_w is the bulk modulus of elasticity of water (4.5×10^7 lb/ft^2); and

L is length (modified from Leake and Prudic, 1991).

An additional important component of the aquifer system is the compressibility of the sediment skeleton, or S_k, computed as

$$S_k = S_{sk} \times b, \tag{3}$$

where

S_{sk} is specific storage due to compressibility of water, and

b is thickness of sediments (L) (modified from Leake and Prudic, 1991).

As in equation 2, equation 3 is relevant to coarse- and fine-grained sediments, and thickness of the aquifer (b) is present. Thus, as the thickness of the aquifer increases, the storage coefficient from compressibility of water (S_w) and storage coefficient from compressibility of the sediment skeleton (S_k) correspondingly increase, providing a greater volume of water from storage in the downdip areas of the aquifers along the coast. In the Layer-Property Flow package of MODFLOW (LPF), a single combined specific storage value, $S_s = S_{sw} + S_{sk}$, is specified and multiplied by layer thickness for the case where head is above the top of a model layer (confined conditions). Where the aquifer is unconfined (head is below the top of the layer), LPF applies a value of specific yield in formulation of the equations for groundwater flow. Use of the confined storage coefficient, $S = S_s \times b$, is appropriate where compression and expansion of the aquifer skeleton and water are elastic; however, if inelastic (nonrecoverable) compaction of fine-grained sediments occurs and is important, an add-on package such as the SUB package (Hoffman and others, 2003) should be used with the no-delay interbeds option for the Gulf Coast aquifer system. For details on representing all storage properties in a model with aquifer-system compaction, see Leake and Prudic (1991).

Grid Design

The finite-difference grid (fig. 1) for the HAGM covers 33,565 square miles (mi^2) in southeastern Texas and southwestern Louisiana. The model grid was rotated 37.6 degrees clockwise so that the orientation of the model closely coincides with the natural groundwater divides, model boundaries, and predevelopment and postdevelopment flow paths. The four layers of the model together contain 134,260 grid blocks. Each layer consists of 137 rows and 245 columns. Layer 1 represents the Chicot aquifer, layer 2 the Evangeline aquifer, layer 3 the Burkeville confining unit, and layer 4 the Jasper aquifer. The grid blocks are uniformly spaced with each model cell area equal to 1 mi^2.

Boundaries

Model boundaries control where and how much water enters and exits the simulated aquifer system. The selection of model boundaries for the aquifers in this model was based on a conceptual interpretation of the flow system developed by using information reported by Meyer and Carr (1979), Carr and others (1985), Williamson and others (1990), and Strom and others (2003a, b, c). The northwestern boundaries of the three aquifers and the Burkeville confining unit are the northwestern extent of the updip outcrop sediments for each unit (Kasmarek and Robinson, 2004, figs. 8, 14, 20, 21). Northwest of these boundaries, the model grid blocks were assigned a hydraulic conductivity of zero to simulate no-flow boundaries. The downdip limit of freshwater (defined for this study as the location where the dissolved solids concentration is as much as 10,000 milligrams per liter [mg/L]) was chosen as the southeastern boundary of flow in each hydrogeologic unit. Southeast of these limits, the model grid blocks were assigned a hydraulic conductivity of zero to simulate no-flow boundaries. The location of the 10,000-mg/L line in each hydrogeologic unit was estimated from geophysical log data and from the coastward extent of freshwater withdrawals (Kasmarek and Robinson, 2004). A no-flow boundary at specified locations reflects an assumption of a stable downdip freshwater/saline-water interface. Along the coast in most of the HAGM study area, this assumption probably is valid: little or no human-induced stresses on the aquifer system in most of the coastal region likely have allowed long-term equilibrium to be established between the freshwater and the slightly more dense saline water that lies laterally adjacent to and beneath the freshwater. The southwestern and northeastern lateral boundaries for the Chicot, Evangeline, and Jasper aquifers and the Burkeville confining unit were selected to coincide with groundwater-flow divides associated with major rivers in the study area. The southwestern lateral boundary was located generally along the Lavaca River, and the northeastern lateral boundary was located in the general vicinity of the Sabine River (fig. 1). The assumption is that little lateral flow occurs across these boundaries, and thus they can reasonably be simulated as no-flow boundaries. The Catahoula confining system underlies the Jasper aquifer. The assumption is that the brackish water within the Catahoula confining system sufficiently impedes the exchange of water between the Jasper aquifer and deeper units, so the Catahoula confining system can reasonably be simulated as a no-flow base-of-system boundary.

Recharge and Discharge

The MODFLOW General-Head Boundary (GHB) package was used to simulate recharge and discharge in the outcrops of the Chicot, Evangeline, and Jasper aquifers and the Burkeville confining unit. This package allows the simulated water table of an aquifer system to function as a head-dependent flux (flow per unit area) boundary (Franke and others, 1987); that is, a condition in which the rate of flow between the water table and the adjacent deeper zone of the system is controlled by the difference between the water table (constant head) and the head in the adjacent deeper zone (which changes with model simulation time) and by the vertical hydraulic conductance between the water table and the immediately adjacent deeper zone. In interstream outcrop areas, the head differences indicate general downward flow or areas of recharge, and in stream and downdip areas along the coast, the head differences generally indicate upward flow or areas of discharge. Simulating the water table as a constant-head source (or sink) of water to the system requires an assumption that no long-term trends in the water table are indicated, as shown in the example hydrographs in Kasmarek and Robinson (2004, fig. 28). These hydrographs indicate that the water table remains stable even during documented periods of drought that occurred during 1932–34, 1938–40, 1947–48, 1950–57, and 1960–67 (State of Texas Drought Preparedness Council, 2006). Water-table-altitude data for the shallow zones of the hydrogeologic units from the model of Kasmarek and Robinson (2004) were used for HAGM model grid blocks in areas where the two models are coincident. These water-table-altitude data were originally created by using the method described by Williams and Williamson (1989) that used multiple linear regressions of depth-to-water data and topographic data to derive relations between depth to water and topography. This assumption is believed reasonable over most of the HAGM study area.

Flow between streams and the aquifer system (essentially discharge from aquifers to incised streams in outcrops) was not explicitly simulated in the model. The rationale for this approach is that the GHB package, assuming that the model is adequately calibrated, would account for stream discharge to the level of accuracy that such discharge is known. Additionally, few measured data are available on streamflow gains or losses for the major streams that flow across the outcrops of the Gulf Coast aquifer system. Because aquifer discharge to streams is not well known, such data are not particularly helpful for comparison with simulated data for purposes of calibration; there was little incentive to add more complexity to an already complex model by explicitly computing flow between streams to the aquifers. Although some additional recharge rates have recently been determined (Tarver, 1968; Sandeen, 1972; Loskot and others, 1982; Baker, 1986; and Kasmarek and Robinson, 2004), the additional complexity of including that information specifically, by substituting the GHB package with the River or Stream package and the Recharge package, was determined to be beyond the scope of this report.

Initial Conditions

Initial conditions, including heads and spatial distributions of hydraulic conductivity, leakance, sand storativity, clay storativity, and general-head boundary conductance from Kasmarek and Robinson (2004), provided the initial data before model calibration began. The leakance parameter is equivalent to vertical hydraulic conductivity divided by the vertical distance between the centers of model layers. The spatial distributions of head in each hydrogeologic unit for the initial predevelopment steady-state simulation also were coincident with Kasmarek and Robinson (2004). Additionally, the simulated values of head from the stress period associated with the year 2000 in the GAM (Kasmarek and Robinson, 2004) were consistent with the initial heads of the HAGM in year 2001. For more detailed information on the initial development of these datasets, refer to Kasmarek and Robinson (2004).

Land-Surface Subsidence and Storage in Clays

Simulation of land-surface subsidence (actually, compaction of clays) and release of water from storage in the clays of the Chicot, Evangeline, and Jasper aquifers and the Burkeville confining unit was accomplished by using the SUB package designed for use with MODFLOW-2000 by Hoffman and others (2003). As explained in Leake and Prudic (1991), effective stress is defined as the difference between geostatic pressure (overburden load) and fluid pressure (head). Head decreases in a confined aquifer do not change geostatic pressure if, as assumed in this application, water-table heads remain constant. With constant geostatic pressure, effective stress thus will increase by the same amount that heads decrease. Previous studies (Riley, 1969; Helm, 1975) indicate that compaction (or expansion) of interbedded clays is proportional, or nearly so, to change in effective stress. For sediments in confined aquifers with constant geostatic pressure, compaction also is proportional, or nearly so, to change in head. The relation is

$$\Delta b = \Delta h S_s b_o, \tag{4}$$

where

Δb is the amount of compaction or expansion (L);
Δh is the change in head (L);
S_s is the skeletal (sand and clay) component of elastic or inelastic specific storage (L^{-1});
b_o is the thickness of the interbed (L); and
L is length (modified from Leake and Prudic, 1991).

For changes in hydraulic head in which head remains above preconsolidation head, an elastic response is computed. For changes in head in which head declines below preconsolidation head, an inelastic response is computed, permanent clay compaction is calculated, and the preconsolidation head is reset to the new head value. For the HAGM, an initial value of preconsolidation head of about 70 ft below the starting head was used.

A preconsolidation head of about 70 ft was used by Meyer and Carr (1979), Carr and others (1985), Kasmarek and Strom (2002), and Kasmarek and Robinson (2004). For the Chicot and Evangeline aquifers in the HAGM study area, the initial values of elastic- and inelastic-clay storativity were coincident with the model of Kasmarek and Robinson (2004). The initial values of elastic-clay storativity used in the HAGM for the Burkeville confining unit and the Jasper aquifer were calculated by multiplying existing GAM values of clay thickness by 1.0×10^{-6}. The initial values of inelastic-clay storativity for the Burkeville confining unit and Jasper aquifer were derived by multiplying the values of elastic-clay storativity by 100.

Withdrawals

The primary sources of updated water-use data used in the HAGM are as follows: the Harris–Galveston Subsidence District (Harris and Galveston Counties); the Fort Bend Subsidence District (Fort Bend County); and the Lone Star Groundwater Conservation District, the Texas Water Development Board, and the San Jacinto River Authority (Montgomery County). HAGM simulations were made under transient conditions from 10,000 years before 1891 through 2009 for 78 groundwater withdrawal (stress) periods of variable length (fig. 8 and table 1). Stress period 1 has a long duration without withdrawals, thereby enhancing model stability prior to actual withdrawals that began in stress period 2. For the years 1980, 1982, and 1988, monthly stress periods were applied. Substantially lower than average precipitation was recorded in the HAGM study area for those years. Monthly rather than annual stress periods allows the model to represent groundwater withdrawals on a monthly or seasonal basis if the model is used to simulate hypothetical drought scenarios in the future. Total groundwater withdrawals increased from an estimated 41 Mgal/d in 1891 to about 1,130 Mgal/d in 1976, peaked at about 1,135 Mgal/d in 1980, and varied during the next 20 years but generally trended downward to about 895 Mgal/d in 2000. Evaluation of these data indicates that groundwater withdrawals varied from 799 Mgal/d in 2001 to 869 Mgal/d in 2009. The lowest withdrawals, 747 Mgal/d, occurred in 2007, and the highest withdrawals, 876 Mgal/d, occurred in 2005. Historical water-use data supplied by the Texas Water Development Board (compiled by LBG-Guyton Associates) were used to update the 2001–9 data in Austin, Brazoria, Chambers, Hardin, Jefferson, Liberty, Matagorda, Walker, Waller, and Wharton Counties. For the remaining counties of the HAGM study area, water-use data were not updated for the period 2001–9 but were equal to and held constant during 2001–9 at the 2000 value of the GAM water-use data of Kasmarek and Robinson (2004). Additional water-use data were combined with the water-use data of the GAM for the Evangeline and Jasper aquifers in Montgomery County for the periods 1955–2000 and 1969–2000, respectively.

Model Calibration

Before calibration began, an initial predevelopment (no withdrawals) steady-state simulation was run to obtain starting heads for the hydrogeologic units for transient calibration simulations. Periodically during calibration, predevelopment steady-state simulations were run with the most current input data to obtain starting heads for successive transient calibration simulations. The input data that were adjusted from initial values on the basis of model output from successive transient simulations were hydraulic conductivity (transmissivity divided by aquifer thickness) of the aquifers, storativity of sands, vertical hydraulic conductance (leakance) between the water table and deeper zones of each hydrogeologic unit in outcrop areas, leakance between hydrogeologic units in subcrop areas, and inelastic-clay storativity (actually, inelastic-clay-specific storage, which is multiplied by aquifer or confining unit thickness) in the Chicot, Evangeline, and Jasper aquifers and the Burkeville confining unit. Water-table heads, hydraulic conductivity, and storativity of the Burkeville confining unit, storativity of the Jasper aquifer, and temporal and spatial distributions of withdrawals were adjusted. Elastic-specific storage of clays in the Chicot and Evangeline aquifers were computed by multiplying inelastic-clay storativities by 0.01.

The HAGM was calibrated by an iterative trial-and-error adjustment of selected model input data (the aquifer properties that control water flow, recharge, discharge, and storage) in a series of transient simulations until the model output (simulated heads and land-surface subsidence and selected water-budget components) reasonably reproduced field measured (or estimated) aquifer responses and specified model calibration criteria. Transient model calibration comprised eight elements:

1. qualitative comparison of simulated and measured potentiometric surfaces of the Chicot, Evangeline, and Jasper aquifers for 2009 (Kasmarek, Houston, and Ramage, 2009);
2. quantitative comparison of simulated water levels and annually measured water levels of selected wells screened in the Chicot, Evangeline, and Jasper aquifers (calibration targets) by computing and evaluating the areal distribution of the root-mean-square error (RMSE) (square root of the sum of the squares of the differences between simulated and measured heads divided by the total number of calibration targets) of 497 sites for the three aquifers for 2009;
3. qualitative comparison of hydrographs of simulated and measured water levels for each aquifer;
4. quantitative comparison of simulated and measured subsidence by computation and areal distribution of the RMSE for 474 calibration target sites was performed—RMSE values were calculated by using standard GIS techniques, whereby a gridded surface of the 2000 land-surface subsidence data (Gabrysch and Neighbors, 2005) was intersected with the simulated subsidence data for model cells coinciding with the locations of the 474 calibration targets, providing a spatial distribution of RMSE;
5. qualitative comparison of simulated subsidence from the 1890s through 2000 was compared to measured cumulative long-term land-surface subsidence from 1906 to 2000 (Gabrysch and Neighbors, 2005);
6. qualitative comparison of simulated predevelopment potentiometric surfaces of the aquifers to conceptualized configurations of the predevelopment surfaces based on hydrogeologic knowledge of the Gulf Coast aquifer system;

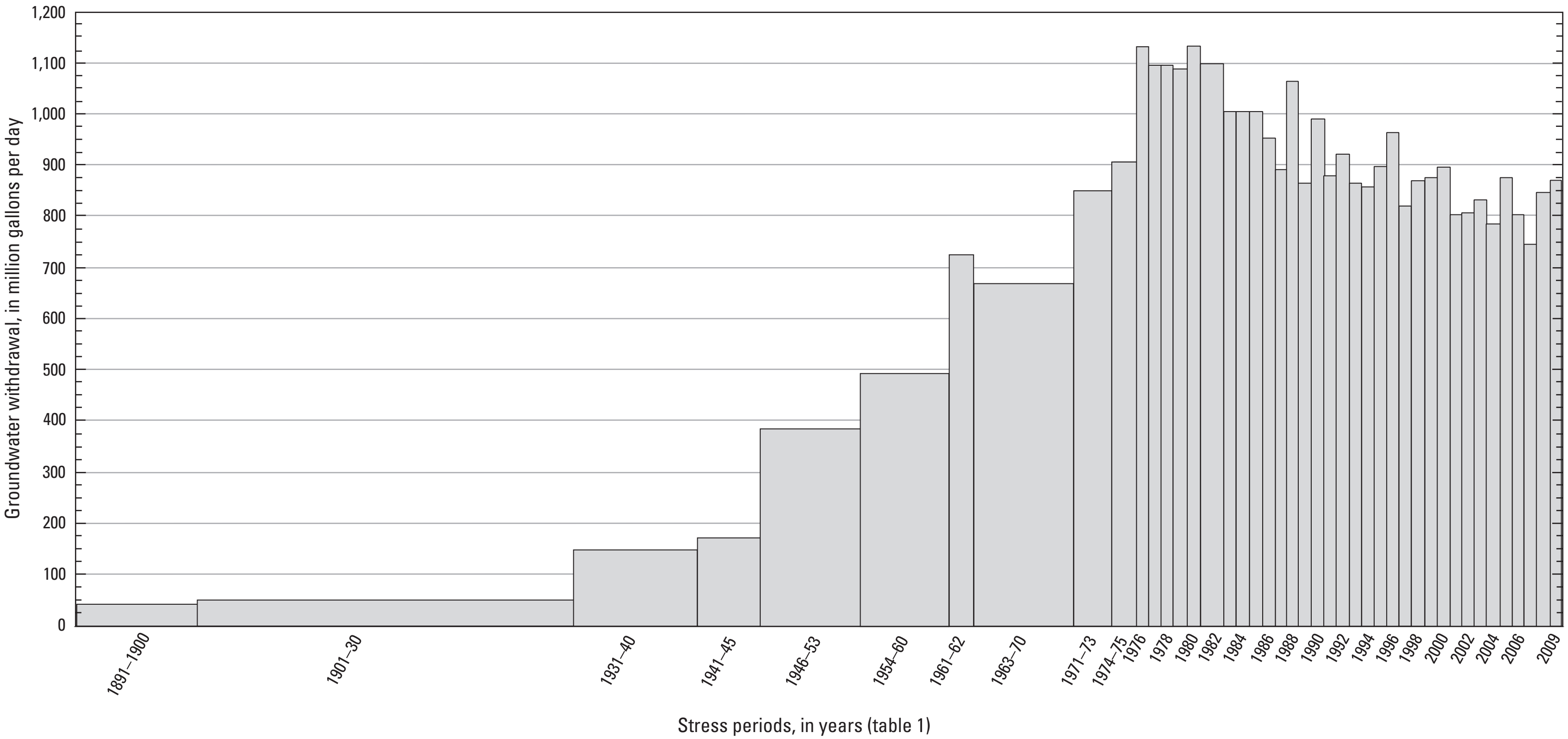


Figure 8. Total groundwater withdrawals used during transient Houston Area Groundwater Model simulations, by stress periods, 1891–2009.

Table 1. Groundwater withdrawal (stress) periods used in the Houston Area Groundwater Model.

Stress period	Length of time (years)	Time interval	Stress period	Length of time (years)	Time interval	Stress period	Length of time (years)	Time interval
1	Steady state[1]	10,000 years	27	0.085	Dec. 1980	53	0.085	Aug. 1988
2	10	1891–1900	28	1	1981	54	0.082	Sept. 1988
3	30	1901–30	29	0.085	Jan. 1982	55	0.085	Oct. 1988
4	10	1931–40	30	0.077	Feb. 1982	56	0.082	Nov. 1988
5	5	1941–45	31	0.085	Mar. 1982	57	0.085	Dec. 1988
6	8	1946–53	32	0.082	Apr. 1982	58	1	1989
7	7	1954–60	33	0.085	May 1982	59	1	1990
8	2	1961–62	34	0.082	June 1982	60	1	1991
9	8	1963–70	35	0.085	July 1982	61	1	1992
10	3	1971–73	36	0.085	Aug. 1982	62	1	1993
11	2	1974–75	37	0.082	Sept. 1982	63	1	1994
12	1	1976	38	0.085	Oct. 1982	64	1	1995
13	1	1977	39	0.082	Nov. 1982	65	1	1996
14	1	1978	40	0.085	Dec. 1982	66	1	1997
15	1	1979	41	1	1983	67	1	1998
16	0.085	Jan. 1980	42	1	1984	68	1	1999
17	0.077	Feb. 1980	43	1	1985	69	1	2000
18	0.085	Mar. 1980	44	1	1986	70	1	2001
19	0.082	Apr. 1980	45	1	1987	71	1	2002
20	0.085	May 1980	46	0.085	Jan. 1988	72	1	2003
21	0.082	June 1980	47	0.077	Feb. 1988	73	1	2004
22	0.085	July 1980	48	0.085	Mar. 1988	74	1	2005
23	0.085	Aug. 1980	49	0.082	Apr. 1988	75	1	2006
24	0.082	Sept. 1980	50	0.085	May 1988	76	1	2007
25	0.085	Oct. 1980	51	0.082	June 1988	77	1	2008
26	0.082	Nov. 1980	52	0.085	July 1988	78	1	2009

[1]A 10,000-year steady-state period was used for model stability.

7. quantitative comparison of simulated water-budget components—primarily recharge and withdrawal rates. The simulated recharge rate was compared to the range of rates from previous recharge studies (see “Ground-Water-Flow Conditions, Recharge, and Discharge” section in Kasmarek and Robinson, 2004) to ensure that the value was reasonable. Similarly, simulated groundwater withdrawal rates were compared to the cumulative withdrawal rates published by HGSD, FBSD, and LSGCD for accuracy. Additionally, comparisons of simulated spatial distributions of recharge and discharge in the outcrops of aquifers to estimates of physically reasonable distributions based on knowledge of the hydrology of the Gulf Coast aquifer system also were used.

8. quantitative determination to ensure that the calibrated RMSE for each aquifer is 10 percent or less of the total range of calibrated simulated head.

Calibrated model parameters of the four layers of the GAM (Kasmarek and Robinson, 2004) and HAGM were compared to quantify the parameter differences (table 2). The additional water-use data (2001–9) used in the HAGM since the GAM was finalized required modification of the calibrated parameters, particularly in layer 4 (Jasper aquifer), to achieve recalibration.

The maximum value of simulated GHB conductance in layer 1 (Chicot aquifer) was decreased by more than two orders of magnitude, but the minimum value was increased by two orders of magnitude. All other maximum and minimum values of conductance in layer 2 (Evangeline aquifer), layer 3 (Burkeville confining unit), and layer 4 (Jasper aquifer) were unchanged (table 2).

The maximum value of inelastic-clay storativity (inelastic storage coefficient) was increased by about one order of magnitude in layer 1 and was increased by about two

Table 2. Comparison of calibrated-parameter values used in the Groundwater Availability Model (GAM) (2004) and the Houston Area Groundwater Model (HAGM).

[min, minimum; max, maximum; GHB, general head boundary; ICS, inelastic-clay storativity; HC, hydraulic conductivity; ft, feet; ft^2/day, square feet per day; n/s, not simulated; <, less than; n/a, not applicable; ft^3/day, cubic feet per day]

Simulated parameter	GAM min	GAM max	HAGM min	HAGM max
GHB conductance, in ft^2/day				
Chicot aquifer GHB	1.0×10^{-6}	51,776	1.46×10^{-4}	199
Evangeline aquifer GHB	1.202	69,700	1.202	69,700
Burkeville confining unit GHB	2.2×10^{-2}	9.4×10^{-1}	2.2×10^{-2}	9.4×10^{-1}
Jasper aquifer GHB	6.34	1,500	6.34	1,500
ICS (dimensionless)				
Chicot aquifer ISC	2.06×10^{-7}	5.18×10^{-3}	5.3×10^{-6}	1.49×10^{-2}
Evangeline aquifer ISC	1.03×10^{-6}	1.08×10^{-3}	2.28×10^{-7}	1.49×10^{-1}
Burkeville confining unit ISC	n/s	n/s	2.05×10^{-6}	9.24×10^{-5}
Jasper aquifer ISC	n/s	n/s	1.0×10^{-6}	9.47×10^{-4}
HC, in ft^2/day				
Chicot aquifer HC	1.0×10^{-1}	2,877	4.0×10^{-3}	39.9
Evangline aquifer HC	2.0×10^{-1}	49.5	3.9×10^{-1}	30.8
Burkeville confining unit HC	9.0×10^{-6}	2.1×10^{-2}	9.0×10^{-6}	2.1×10^{-2}
Jasper aquifer HC	9.1×10^{-5}	47.6	8.64×10^{-1}	21.23
Storativity (dimensionless)				
Chicot aquifer storativity	2.0×10^{-3}	1.578×10^{-1}	2.0×10^{-3}	1.56×10^{-1}
Evangeline aquifer storativity	2.0×10^{-4}	1.8×10^{-1}	1.0×10^{-3}	1.82×10^{-1}
Burkeville confining unit storativity	1.0×10^{-5}	5.0×10^{-2}	1.0×10^{-5}	5.0×10^{-2}
Jasper aquifer storativity	2.0×10^{-5}	2.0×10^{-2}	4.1×10^{-6}	2.01×10^{-1}
Leakance, in foot per day per foot				
Chicot aquifer leakance	$2.0.0\times10^{-11}$	4.43×10^{-4}	1.1×10^{-7}	4.43×10^{-4}
Evangeline aquifer leakance	$5.0.0\times10^{-11}$	5.0×10^{-3}	9.0×10^{-8}	5.0×10^{-3}
Burkeville confining unit leakance	$4.47.0\times10^{-11}$	2.06×10^{-4}	$7.18.0\times10^{-11}$	2.06×10^{-5}
Jasper aquifer leakance	n/a	n/a	n/a	n/a
Total groundwater withdrawals for each aquifer	Chicot aquifer	Evangeline aquifer	Burkeville confining unit	Jasper aquifer
Total 2000 withdrawal, ft^3/day	48,986,631	64,250,796	Negligible	5,048,086
Total 2009 withdrawal, ft^3/day	50,095,831	55,623,263	Negligible	9,041,220
Change in withdrawls from 2000 to 2009	1,109,200	-8,627,533		3,993,134

orders of magnitude for layer 2. The minimum inelastic-clay storativity was increased by about one order of magnitude in layer 1 but decreased by about one order of magnitude in layer 2. A comparison of inelastic-clay storativity values for layers 3 and 4 was not possible because clay compaction was not simulated for these layers in the GAM.

The maximum value of simulated hydraulic conductivity (HC) value decreased about two orders of magnitude in layer 1, decreased slightly for layer 2, remained constant in layer 3, and decreased by about half in layer 4. The minimum HC was decreased by about two orders of magnitude for the layer 1, increased slightly for layer 2, remained the same for the layer 3, and increased by about three orders of magnitude for layer 4.

The maximum value of simulated storativity (sand storage) remained about constant for layers 1, 2, and 3 but increased by about one order of magnitude for layer 4. The minimum values of storativity for layers 1 and 3 remained constant, increased by about one order of magnitude for layer 2, and decreased by about one order of magnitude for layer 4.

The maximum value of simulated leakance for layers 1, 2, and 3 remained constant between the GAM and HAGM calibrated models. The minimum leakance in layer 1 was increased by about four orders of magnitude, was increased by about three orders of magnitude in layer 2, and remained about constant in layer 3. Additionally, a comparison of groundwater withdrawals for 2000 and 2009 for the four model layers indicates withdrawals increased by 1,109,200 cubic feet per day (ft^3/d) for layer 1, decreased by 8,627,533 ft^3/d for layer 2, and increased by 3,993,134 ft^3/day for layer 4. Water-use data for the Burkeville confining unit were unreported, therefore unknown, but are thought to be negligible.

Model Results

Simulated Hydraulic Properties Associated with Groundwater Flow and Subsidence

The calibrated spatial distributions of simulated hydraulic conductivity in the Chicot, Evangeline, and Jasper aquifers are shown in figures 9–11 and listed in table 2. Hydraulic conductivities of the Chicot aquifer ranged from 4.0×10^{-3} to 39.91 ft/d, with the larger values located in Harris, Fort Bend, Liberty, Chambers, Galveston, Wharton, Colorado, Tyler, Jasper, and Newton Counties. Hydraulic conductivities of the Evangeline aquifer ranged from 3.9×10^{-1} to 30.79 ft/d, with largest values located in southeast Fort Bend County. Hydraulic conductivities of the Burkeville confining unit are coincident with values used in the GAM (Kasmarek and Robinson, 2004). Hydraulic conductivities of the Jasper aquifer ranged from 8.64×10^{-1} to 21.23 ft/d, with the larger values located in northern Harris and Montgomery Counties. Spatial distributions of hydraulic conductivity indicate that, generally, the largest values are coincident with areas of large withdrawals and are consistent with previous studies (Wesselman, 1972; Jorgensen, 1975; Carr and others, 1985; Baker, 1986; Kasmarek and Strom, 2002; Ryder and Ardis, 2002; see "Initial Conditions," Kasmarek and Robinson, 2004).

Simulated sand storativities of the Chicot and Evangeline aquifers (2.0×10^{-3} to 1.56×10^{-1} and 1.0×10^{-3} to 1.82×10^{-1}, figs. 12 and 13, respectively) reflect aquifer conditions from confined to semiconfined to water table. Sand storativities of the Chicot and Evangeline aquifers (figs. 12 and 13) generally are largest in the updip, outcrop areas, where water-table conditions prevail. Storativities of the Burkeville confining unit are coincident with values used in the GAM (Kasmarek and Robinson, 2004). Storativities of the Jasper aquifer (4.1×10^{-6} to 2.01×10^{-1}) are generally largest in the updip, outcrop areas associated with water-table conditions (fig. 14).

The simulated calibrated spatial distributions of inelastic-clay storativity for the Chicot aquifer, the Evangeline aquifer, the Burkeville confining unit, and the Jasper aquifer are shown in figures 15–18, respectively. Because a large area of land-surface subsidence has been documented (Gabrysch and Neighbors, 2005; Kasmarek, Gabrysch, and Johnson, 2009) in Harris County and parts of Galveston, Fort Bend, Montgomery, Brazoria, Waller, Liberty, and Chambers Counties, only these areas of the model study area can be considered calibrated for elastic- and inelastic-clay storativity. Inelastic-clay storativities for the Chicot aquifer, the Evangeline aquifer, the Burkeville confining unit, and the Jasper aquifer range from 5.3×10^{-6} to 1.49×10^{-2}, from 2.28×10^{-7} to 1.49×10^{-1}, from 2.05×10^{-6} to 9.24×10^{-5}, and from 1.0×10^{-6} to 9.47×10^{-4}, respectively. A total of 474 calibration-target sites in Harris and surrounding counties were used to evaluate simulated subsidence compared to measured subsidence. After numerous iterative trial-and-error transient model simulations, the final RMSE was 0.37 ft.

The simulated potentiometric surfaces of the Chicot, Evangeline, and Jasper aquifers for 2009 (figs. 19–21; also shown are the selected wells used as calibration targets) indicate general agreement with measured potentiometric surfaces from Kasmarek, Houston, and Ramage (2009). The simulated 2009 potentiometric surfaces of the aquifers are shown in this report, but the simulated potentiometric surfaces for 1977, 1990, and 2000 compare favorably with coincident published water-level-altitude maps for 1977 (Gabrysch, 1979); 1990 (Kasmarek, 1997); and 2000 (Coplin and Santos, 2000: Chicot and Evangeline aquifer water-level altitudes; Kasmarek and Houston, 2007: 2000 Jasper aquifer water-level altitude). The RMSE of the simulated water levels for the three aquifers for 2009 were about 31.06 ft for the Chicot aquifer, about 33.73 ft for the Evangeline aquifer, and about 23.50 ft for the Jasper aquifer (table 3). The RMSE were calculated to be about 6, 5, and 4 percent, respectively, for the total range in simulated heads for the three aquifers, with a -0.03 percent water-budget difference between the total simulated inflow and the total simulated outflow.

Water levels were measured from December 2008 through March 2009 in wells completed in the Chicot, Evangeline, and Jasper aquifers (Kasmarek, Houston, and Ramage, 2009). Simulated heads were compared to measured heads to evaluate the calibration validity of the groundwater-flow model. This comparison of simulated and measured heads of the Chicot aquifer, 2009 (fig. 22), indicates that the model is acceptable throughout the range of measured heads; however, simulated heads are lower than measured heads for values of measured head from about +60 ft to about -120 ft. Similarly, for the simulated and measured heads of the Evangeline aquifer, 2009 (fig. 22), the model is acceptable throughout the range of heads, but simulated heads are lower than measured heads for values of measured head from about -105 ft to about -235 ft. Comparisons of simulated and measured heads for the Jasper aquifer, 2009 (fig. 22), indicate close correlation. These graphical comparisons between the simulated and measured heads correlate well with the RMSE shown in table 3.

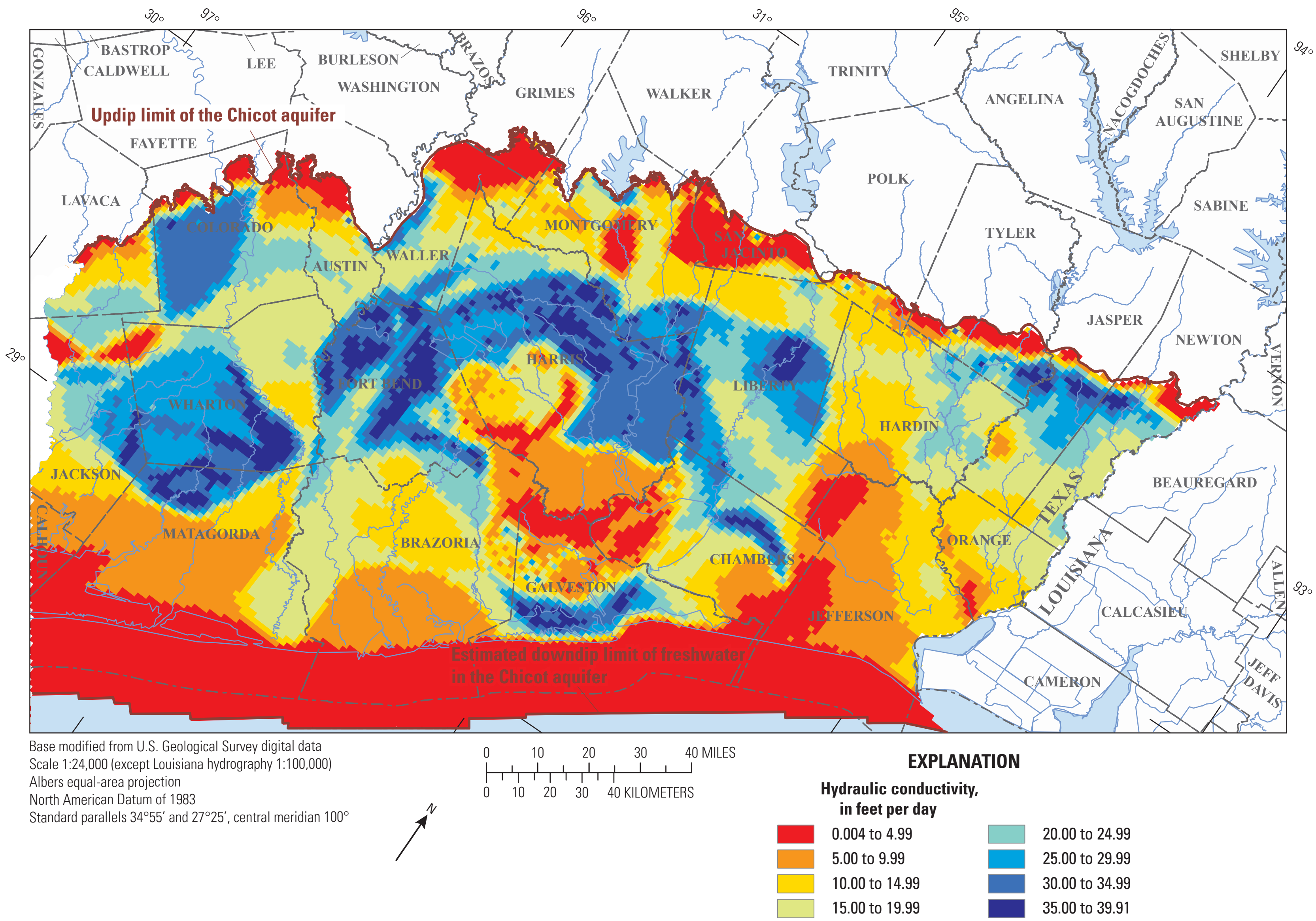


Figure 9. Simulated hydraulic conductivity of the Chicot aquifer in the Houston Area Groundwater Model study area.

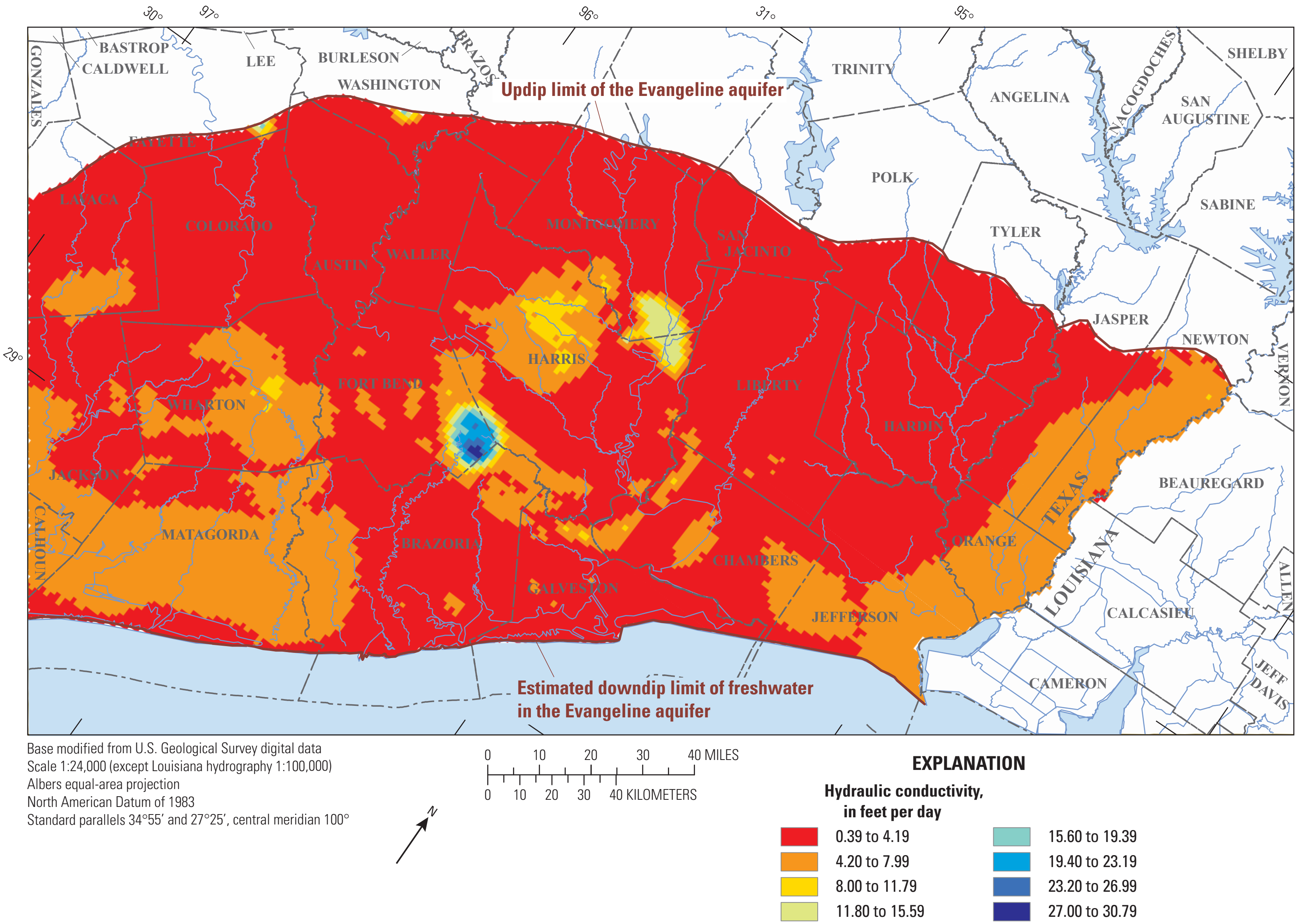


Figure 10. Simulated hydraulic conductivity of the Evangeline aquifer in Houston Area Groundwater Model study area.

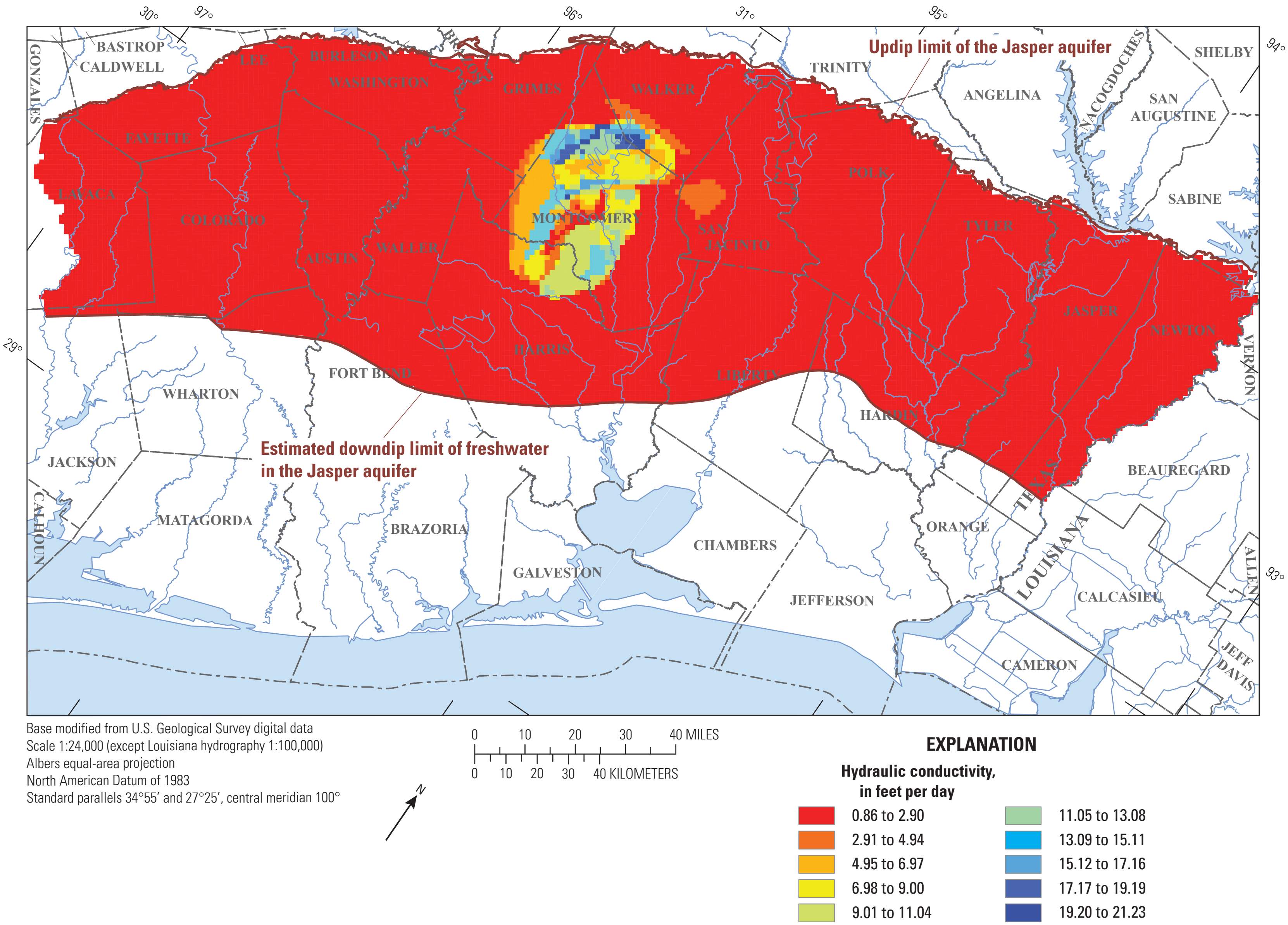


Figure 11. Simulated hydraulic conductivity of the Jasper aquifer in the Houston Area Groundwater Model study area.

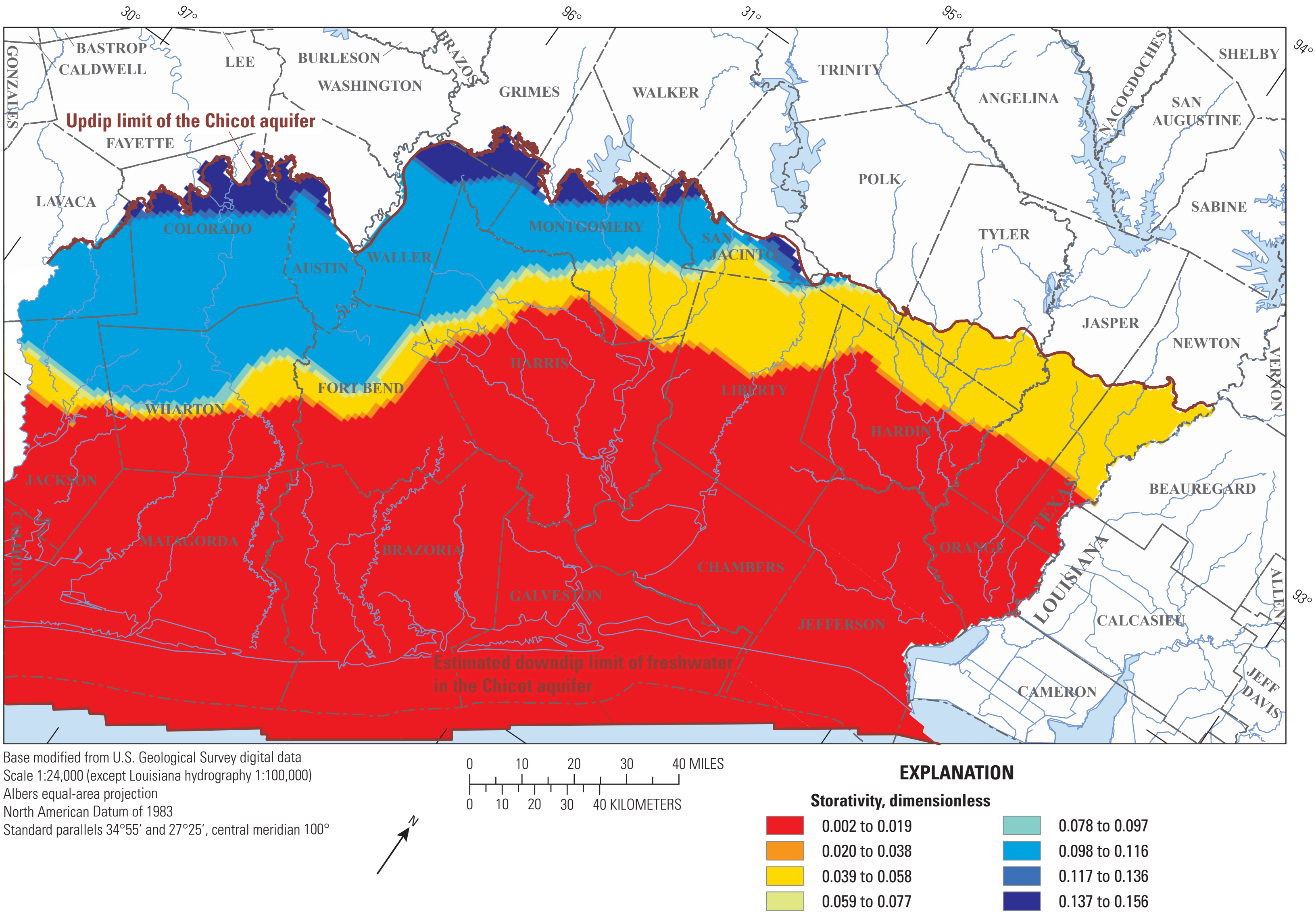


Figure 12. Simulated sand storativity of the Chicot aquifer in the Houston Area Groundwater Model study area.

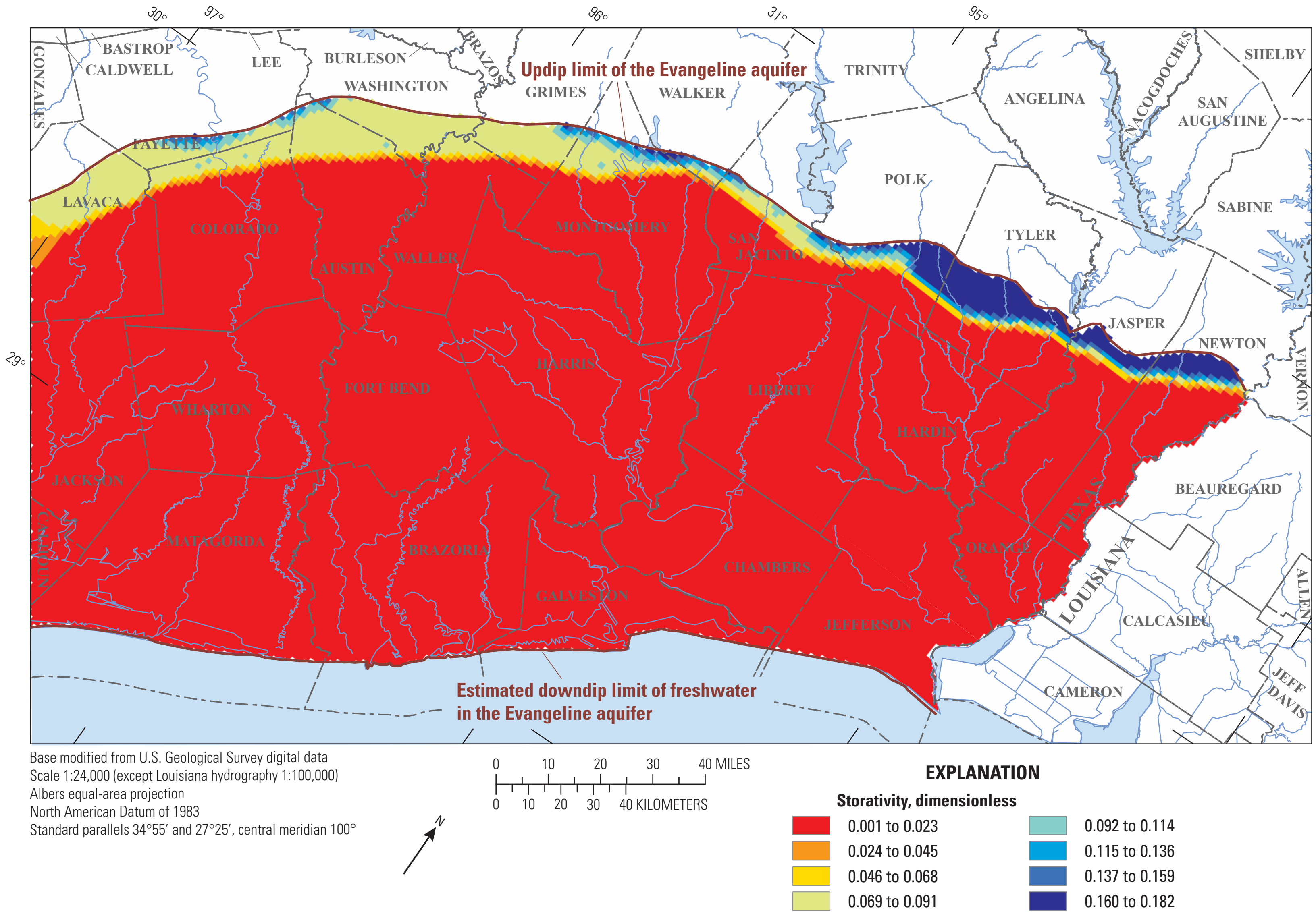


Figure 13. Simulated sand storativity of the Evangeline aquifer in the Houston Area Groundwater Model study area.

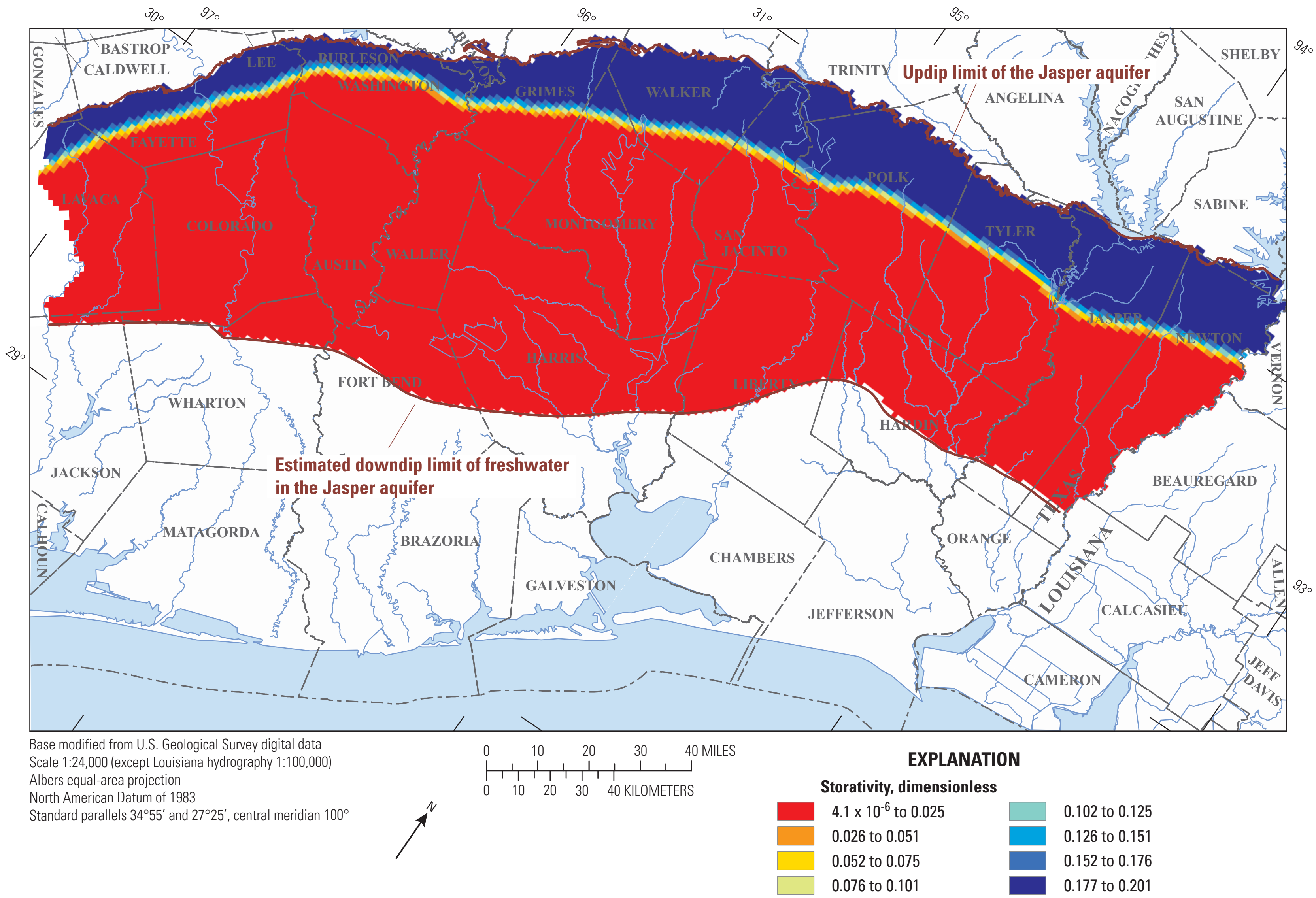
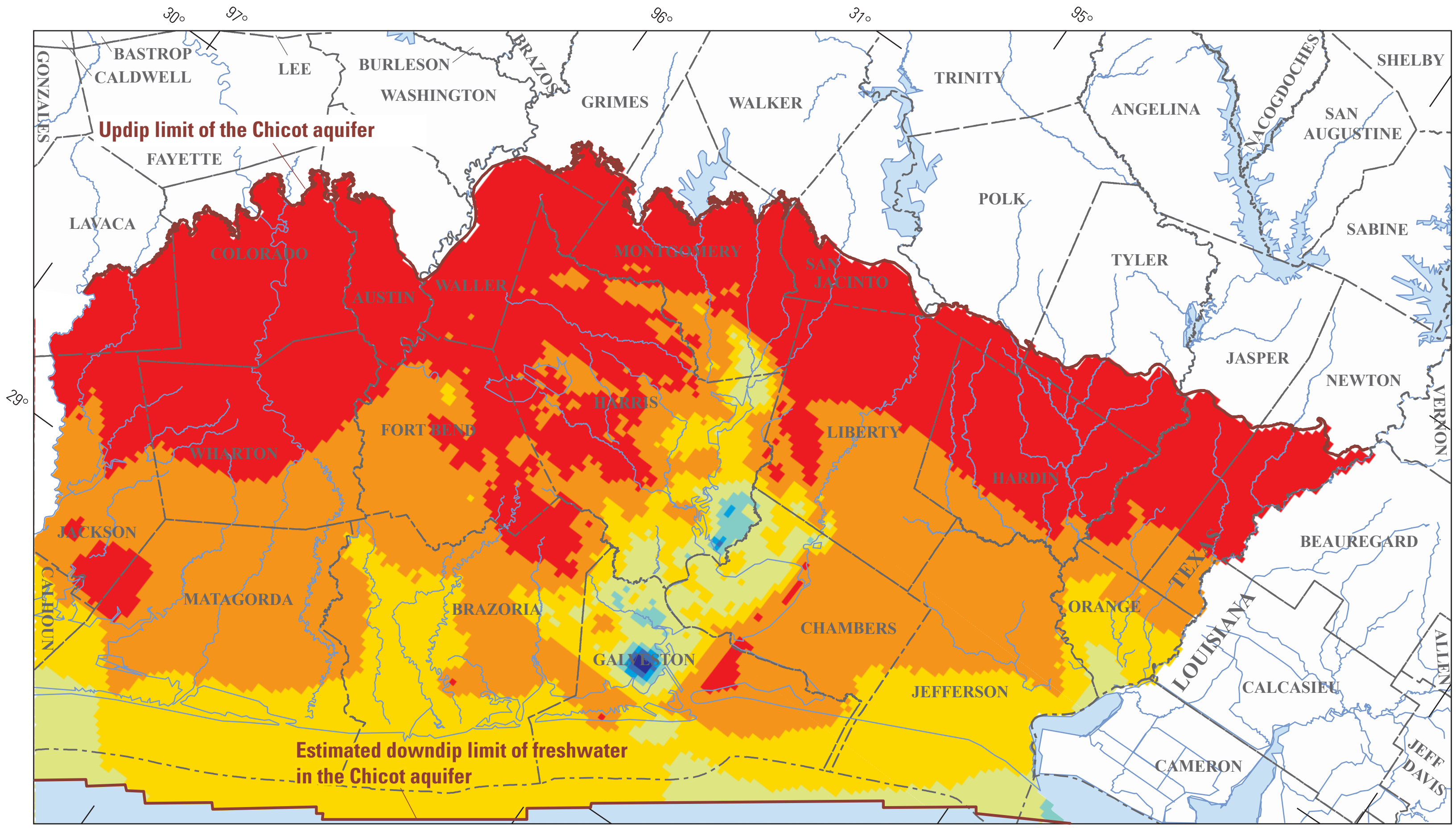


Figure 14. Simulated sand storativity of the Jasper aquifer in the Houston Area Groundwater Model study area.



Base modified from U.S. Geological Survey digital data
Scale 1:24,000 (except Louisiana hydrography 1:100,000)
Albers equal-area projection
North American Datum of 1983
Standard parallels 34°55′ and 27°25′, central meridian 100°

0 10 20 30 40 MILES

0 10 20 30 40 KILOMETERS

N

EXPLANATION

Inelastic storativity, dimensionless

5.30×10^{-6} to 1.85×10^{-2}	7.46×10^{-2} to 9.31×10^{-2}
1.86×10^{-2} to 3.72×10^{-2}	9.32×10^{-2} to 1.11×10^{-1}
3.73×10^{-2} to 5.58×10^{-2}	1.12×10^{-1} to 1.30×10^{-1}
5.59×10^{-2} to 7.45×10^{-2}	1.31×10^{-1} to 1.49×10^{-1}

Figure 15. Simulated inelastic-clay storativity of the Chicot aquifer in the Houston Area Groundwater Model study area.

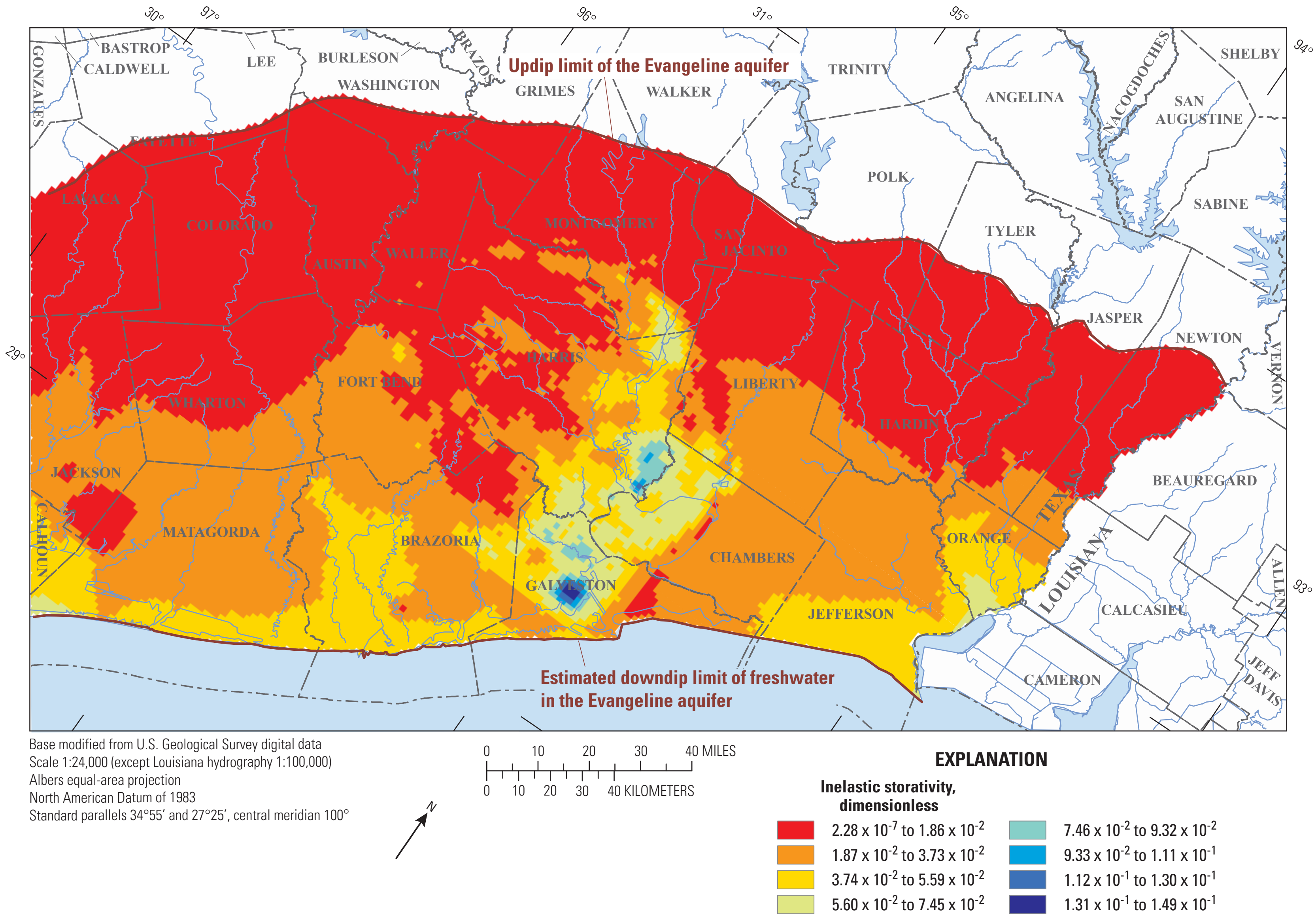


Figure 16. Simulated inelastic-clay storativity of the Evangeline aquifer in the Houston Area Groundwater Model study area.

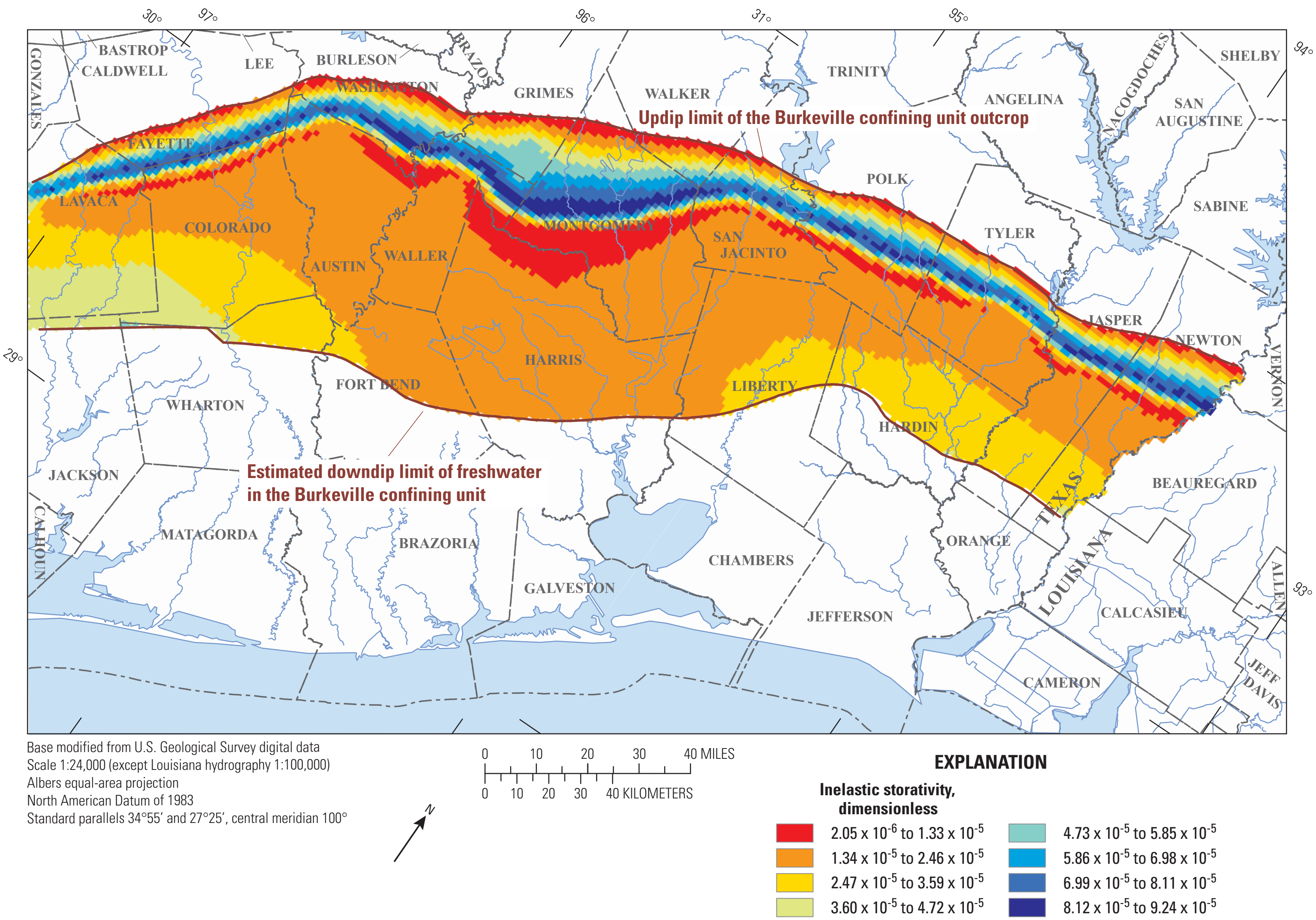


Figure 17. Simulated inelastic-clay storativity of the Burkeville confining unit in the Houston Area Groundwater Model study area.

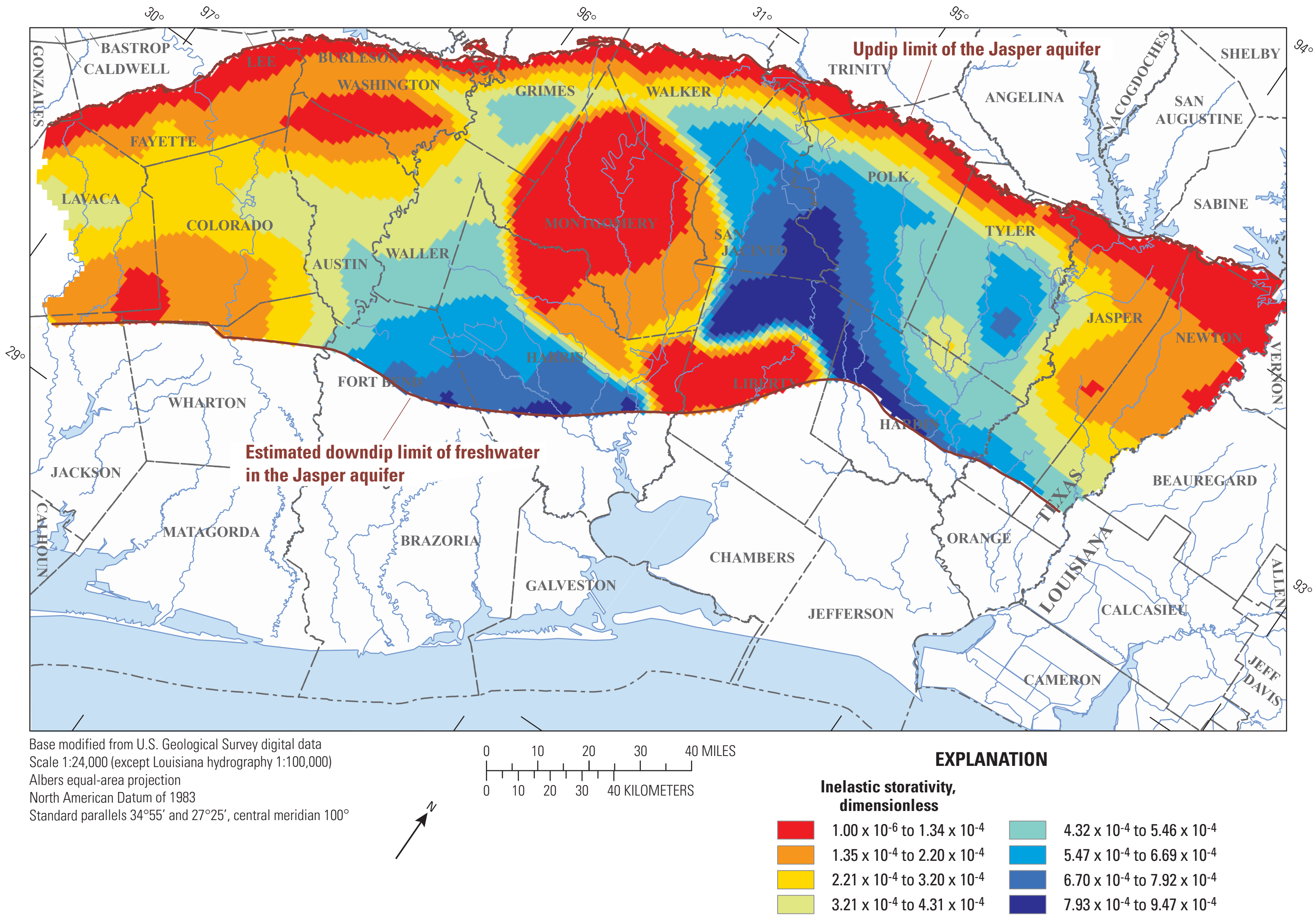
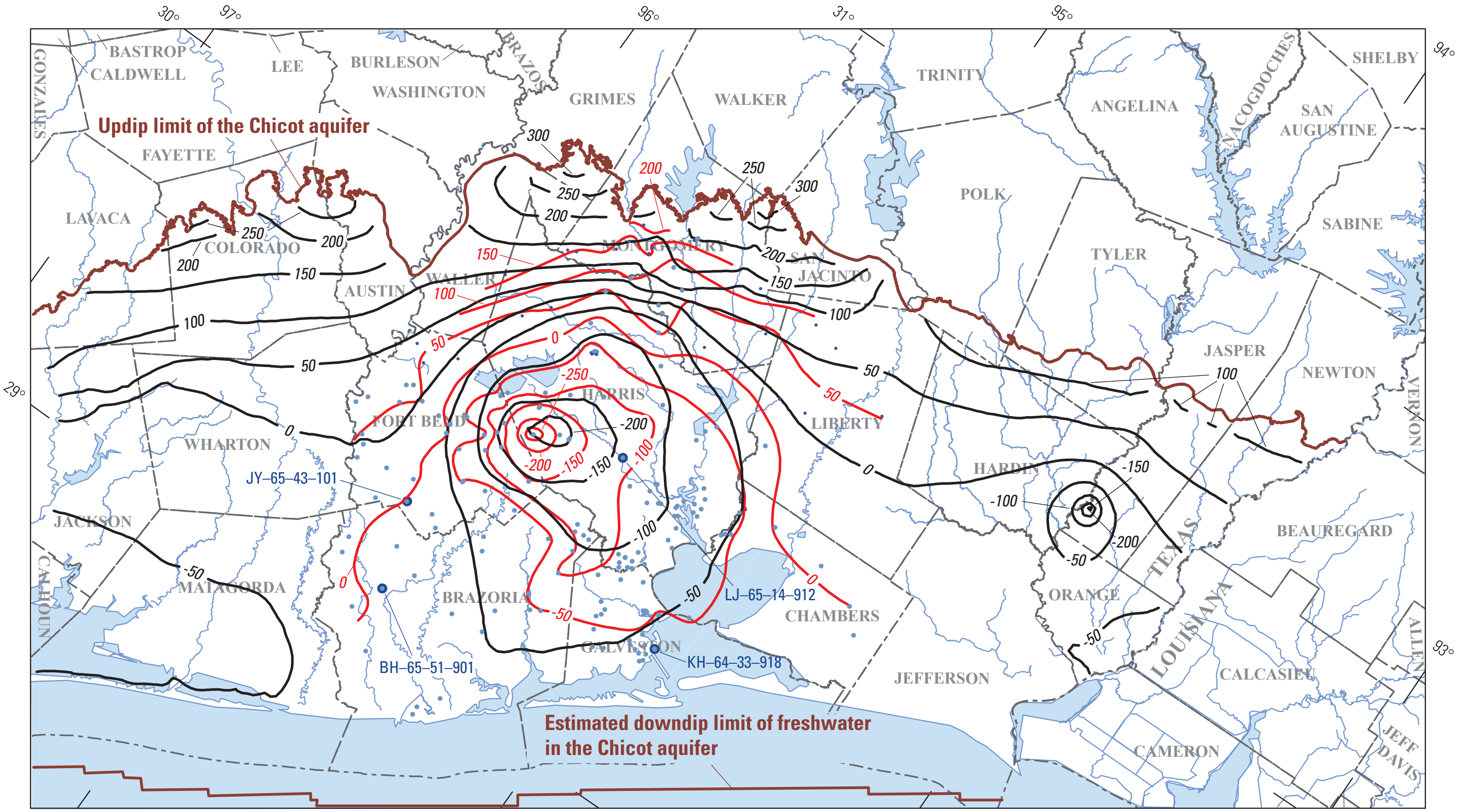


Figure 18. Simulated inelastic-clay storativity of the Jasper aquifer in the Houston Area Groundwater Model study area.



Base modified from U.S. Geological Survey digital data
Scale 1:24,000 (except Louisiana hydrography 1:100,000)
Albers equal-area projection
North American Datum of 1983
Standard parallels 34°55′ and 27°25′, central meridian 100°

0 10 20 30 40 MILES
0 10 20 30 40 KILOMETERS

N

EXPLANATION

-50 — **Simulated potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Interval 50 feet. Datum is NAVD 88

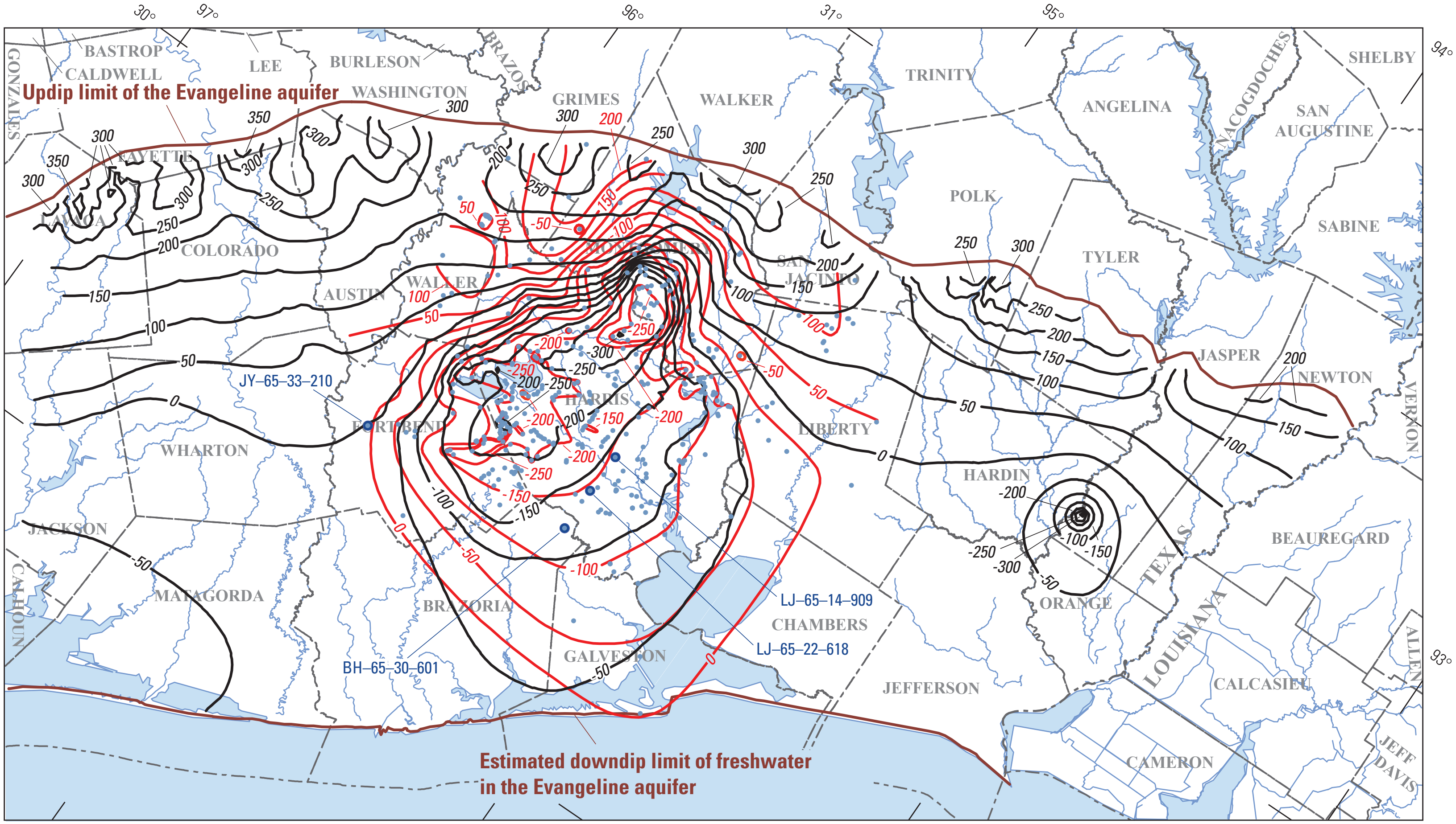
-50 — **Measured potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Interval 50 feet. Datum is NAVD 88

Data point—Well in which water-level measurement was made

LJ–65–14–912 **Data point and well number**—Well in which water-level measurement was made and for which hydrograph is shown on figure 26

NAVD 88, North American Vertical Datum of 1988

Figure 19. Simulated and measured potentiometric surfaces of the Chicot aquifer, 2009, and location of monitoring wells in the Houston Area Groundwater Model study area.



Base modified from U.S. Geological Survey digital data
Scale 1:24,000 (except Louisiana hydrography 1:100,000)
Albers equal-area projection
North American Datum of 1983
Standard parallels 34°55′ and 27°25′, central meridian 100°

0 10 20 30 40 MILES
0 10 20 30 40 KILOMETERS

N

EXPLANATION

-50 **Simulated potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Interval 50 feet. Datum is NAVD 88

-50 **Measured potentiometric contour**—Shows altitude at which water would have stood in tightly cased well. Intervals 50, 100, and 250 feet. Datum is NAVD 88

Data point—Well in which water-level measurement was made

LJ–65–14–909 **Data point and well number**—Well in which water-level measurement was made and for which hydrograph is shown on figure 27

NAVD 88, North American Vertical Datum of 1988

Figure 20. Simulated and measured potentiometric surfaces of the Evangeline aquifer, 2009, and location of monitoring wells in the Houston Area Groundwater Model study area.

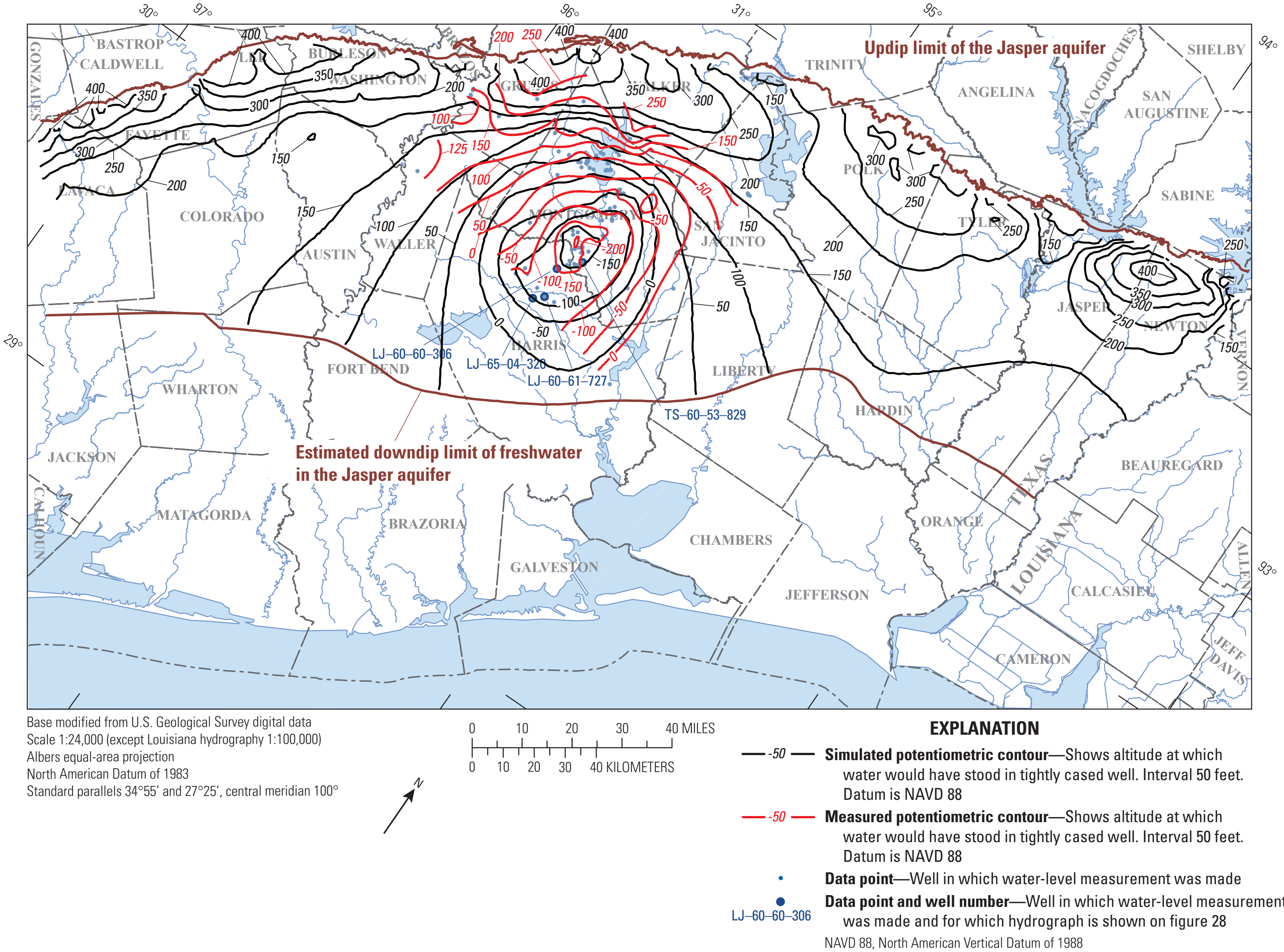


Figure 21. Simulated and measured potentiometric surfaces of the Jasper aquifer, 2009, and location of monitoring wells in the Houston Area Groundwater Model study area.

Table 3. Number of water-level (head) measurements, root-mean-square errors of simulated head, and range of total simulated head in the Chicot, Evangeline, and Jasper aquifers, 2009.

Aquifer	Number of water-level measurements	Root-mean-square error of simulated water levels (feet)	Range of total simulated head (feet)
Chicot	165	31.06	366
Evangeline	251	33.73	541
Jasper	81	23.50	631

The spatial distribution of water-level residuals (measured values of head minus simulated values of head) for the Chicot aquifer (fig. 23) indicates that most residuals are positive in the area of the model that contains monitoring wells, which means that the model computes head below the measured value. In other areas of the Fort Bend, Brazoria, Galveston, southwest Harris, Chambers, Liberty and Montgomery Counties, areas of negative and positive residual values are prevalent, which means that the model computes head above the measured value in these areas. From a spatial distribution of water-level (head) residuals for the Evangeline aquifer (fig. 24), most of the residuals are positive, with isolated areas of negative residuals in southeast Harris, northern Galveston, western Chambers, northern Waller, and southeast Grimes Counties; an area of negative residuals also extends from northern Waller County into Montgomery County. The spatial distribution of water-level (head) residuals for the Jasper aquifer (fig. 25) indicates an almost even distribution between negative and positive residuals. These residual values are less than residual values of the Chicot and Evangeline aquifers (figs. 23 and 24).

Simulated and Measured Hydrographs

Hydrographs of simulated and measured water levels for observation wells in Brazoria, Galveston, Harris, and Fort Bend Counties in wells screened in the Chicot aquifer (fig. 26) indicate that simulated and measured water levels match closely. The hydrographs for Galveston and Harris Counties (fig. 26*B* and *C*) reflect generally declining heads through the mid- to late 1970s followed by rises associated with decreased withdrawals. The hydrographs of simulated and measured water levels in observation wells in Brazoria and Fort Bend Counties for the Evangeline aquifer (fig. 27*A* and *B*) also match closely. The two hydrographs from wells in Harris County (fig. 27*C* and *D*) indicate similar matches between simulated and measured water levels from about 1998 through 2009, which spans the calibration period used for the HAGM. The hydrographs of simulated heads and measured heads in observation wells in Harris and Montgomery Counties for the Jasper aquifer (fig. 28) have similar water-level trends and become almost coincident in the mid-2000s.

Simulated and Estimated Water-Budget Components

Simulated recharge and discharge in outcrops of the hydrogeologic units, vertical leakage between units, changes in storage, and withdrawals for 2009 are summarized in figure 29. The diagram indicates a net recharge (total recharge minus natural discharge) of 779.6 cubic feet per second (ft^3/s) (about 0.56 in./yr) in the Chicot aquifer outcrop, 35.0 ft^3/s (about 0.23 in./yr) in the Evangeline aquifer outcrop, negligible net recharge in the Burkeville confining unit outcrop, and 16.5 ft^3/s (about 0.07 in./yr) in the Jasper aquifer outcrop. For the entire system, the simulated total net recharge for 2009 was 831.1 ft^3/s (about 0.45 in./yr) in the outcrop areas. As a comparison, the simulated total recharge for the GAM in 2000 was 995 ft^3/s (about 0.54 in./yr) (Kasmarek and Robinson, 2004, p. 90). In terms of a water-budget balance (within 0.4 ft^3/s because of rounding error) for the entire system in 2009, 945.2 ft^3/s of total recharge plus 391.9 ft^3/s from depletion of water in coarse-grained sediments (sands) and 104.8 ft^3/s from inelastic compaction of clays is offset by 114.1 ft^3/s of natural discharge and 1,328.2 ft^3/s (about 858.4 Mgal/d) of groundwater withdrawal. The net difference between total recharge (945.2 ft^3/s) and withdrawal (1,328.2 ft^3/s) is 383.0 ft^3/s (about 247.5 Mgal/d), and the volume of withdrawal from the Chicot, Evangeline, and Jasper aquifers was about 44, 48, and 8 percent, respectively. The volumetric budget (expressed in cubic feet per day) for the transient simulation for the HAGM in 2009, at the end of stress period 78, is shown in table 4.

Simulated and Measured Land-Surface Subsidence

Simulated land-surface subsidence from 1891 (predevelopment) to 2000 and measured land-surface subsidence from 1906 to 2000 is shown in figure 30. In Harris County and counties immediately adjacent, where the main area of subsidence has been measured, the simulated and measured values of subsidence match closely. As much as 10 ft of measured subsidence has occurred in southeastern Harris County. A larger geographic area encompassing the maximum measured land-surface subsidence area and much of central to southeastern Harris County has subsided at least 6 ft. In the western part of the HAGM study area, another area of simulated subsidence centered in Wharton County has as much as 3 ft of subsidence. In the eastern part of the HAGM study area, at the boundary of Hardin and Jasper Counties, an area of subsidence with as much as 3 ft of subsidence was simulated. An isolated area with as much as 3 ft of simulated subsidence is located in southeast Orange County. Measured subsidence has not been

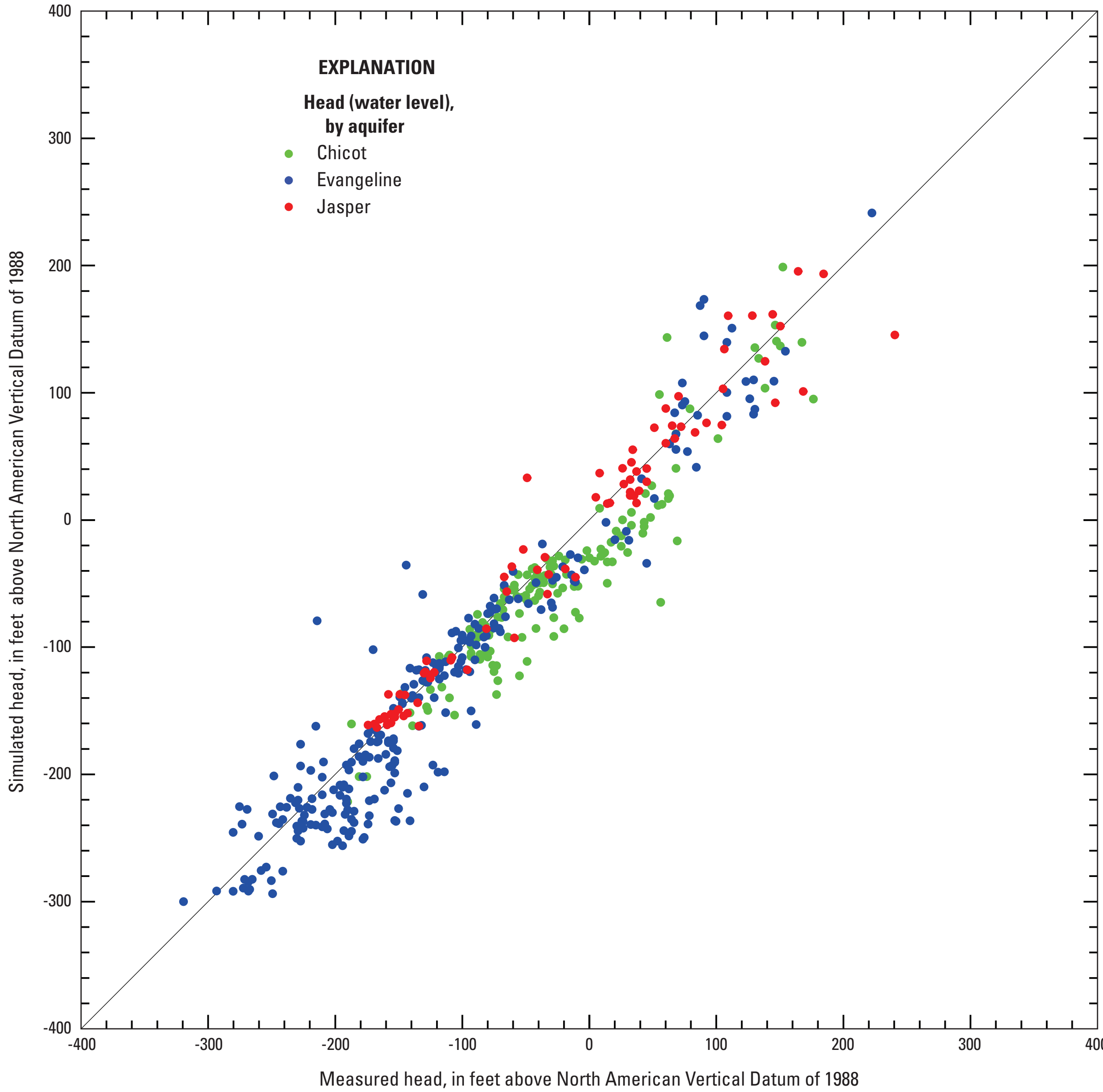


Figure 22. Relation between simulated and measured heads for the Chicot, Evangeline, and Jasper aquifers, 2009, in the Houston Area Groundwater Model study area.

documented for these western and eastern areas of the HAGM study area. Measured compaction of subsurface sediments at 11 borehole extensometer sites in Harris and Galveston Counties has been continually recorded since as early as 1973 (Kasmarek and others, 2009).

Simulated land-surface subsidence (1891–2009) and measured land-surface subsidence (1906–2000) is shown in figure 31. For these periods in Harris County and counties immediately adjacent, where the main area of measured subsidence is present, the simulated and measured subsidence match closely, but not as closely as in figure 30. The most recent areas of simulated subsidence are generally in southern Montgomery, northwest Harris, and Fort Bend Counties, where water demand has increased and has resulted in sustained groundwater withdrawals during 2001–9. The two distal areas with as much as 3 ft of simulated subsidence in the eastern and western areas of the HAGM study area depicted in figure 31 are similar to the areal extent of simulated subsidence shown for 2000 in figure 30.

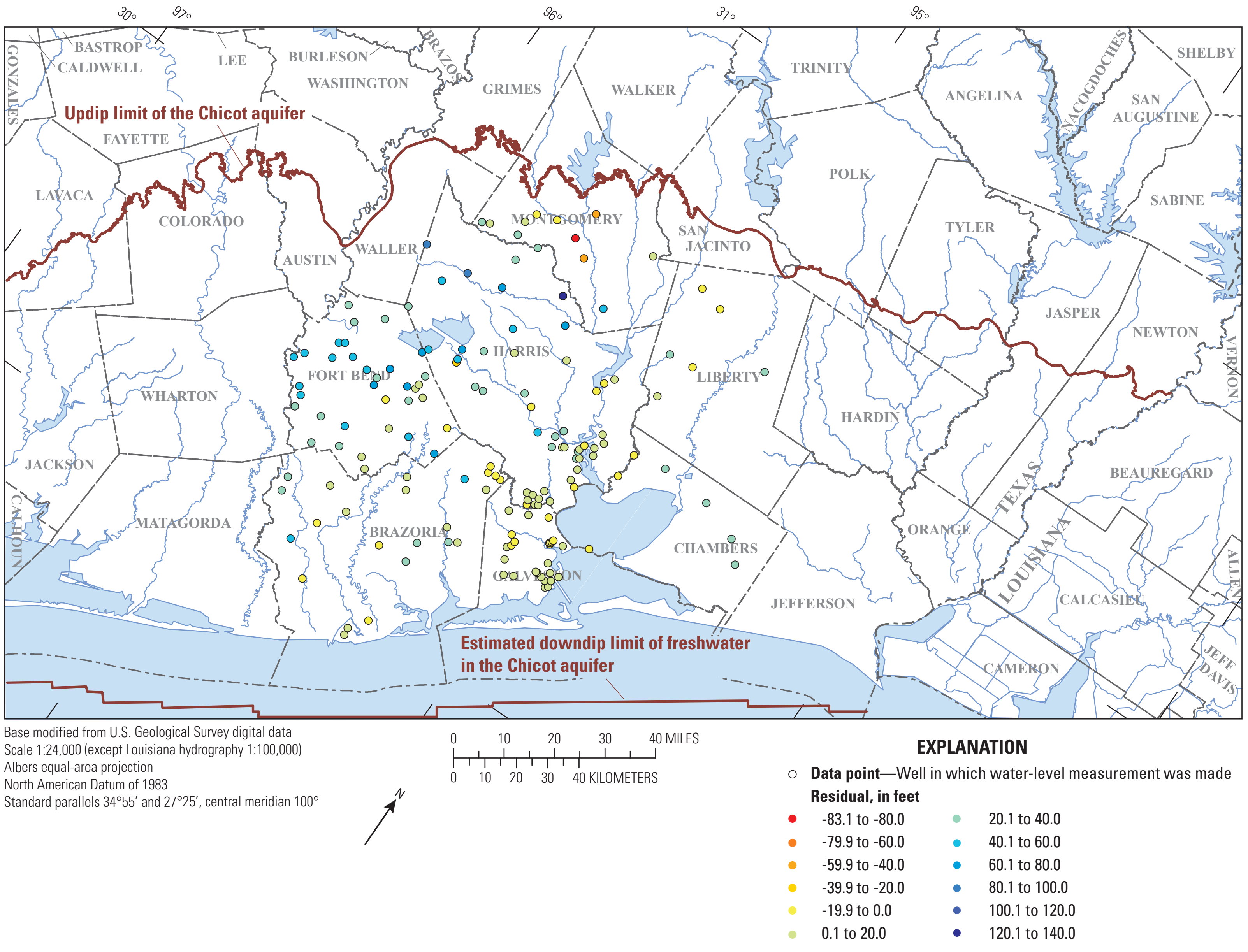


Figure 23. Spatial distribution of water-level (head) residuals (measured minus simulated heads) for the Chicot aquifer, 2009, in the Houston Area Groundwater Model study area.

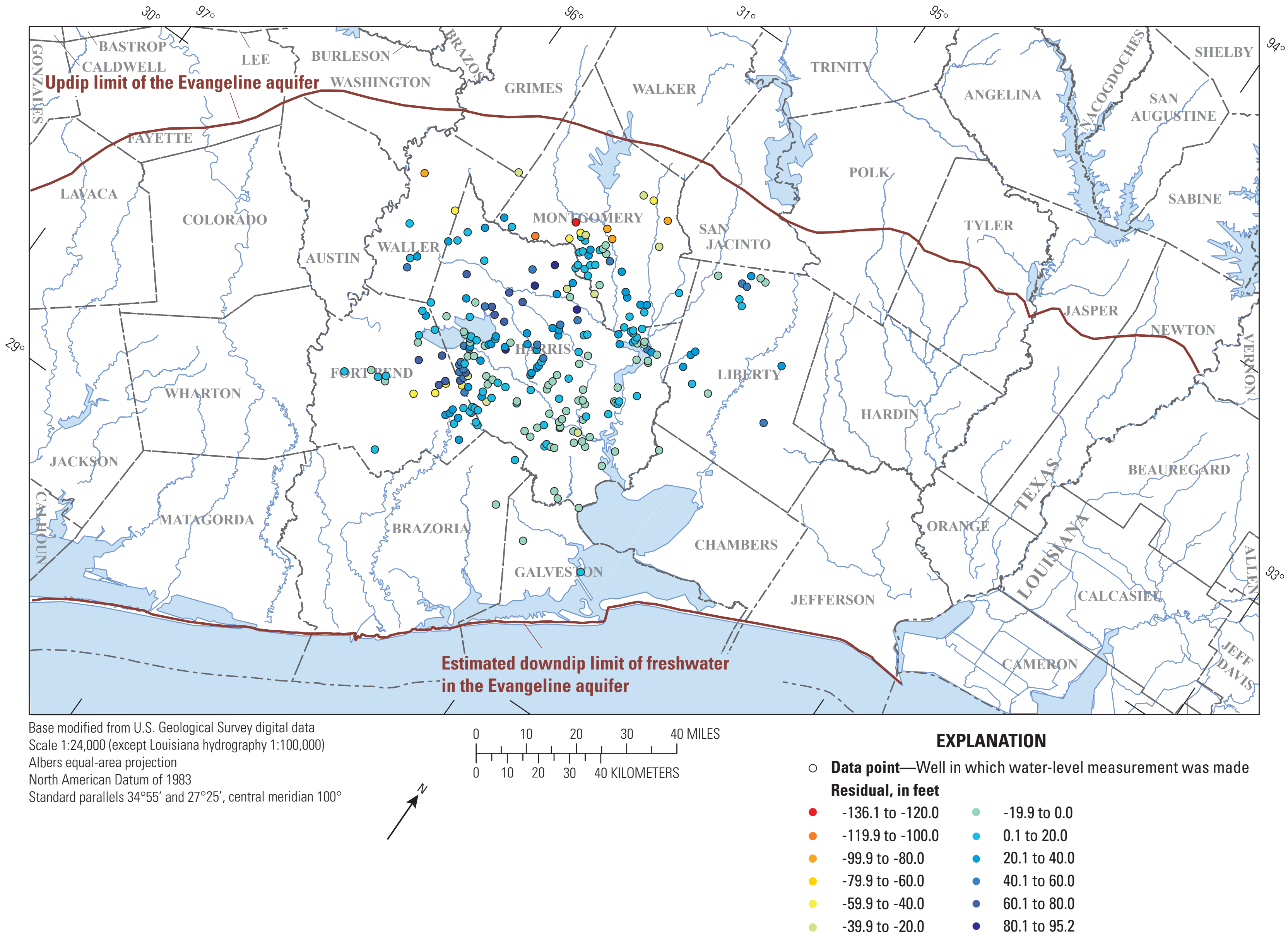


Figure 24. Spatial distribution of water-level (head) residuals (measured minus simulated heads) for the Evangeline aquifer, 2009, in the Houston Area Groundwater Model study area.

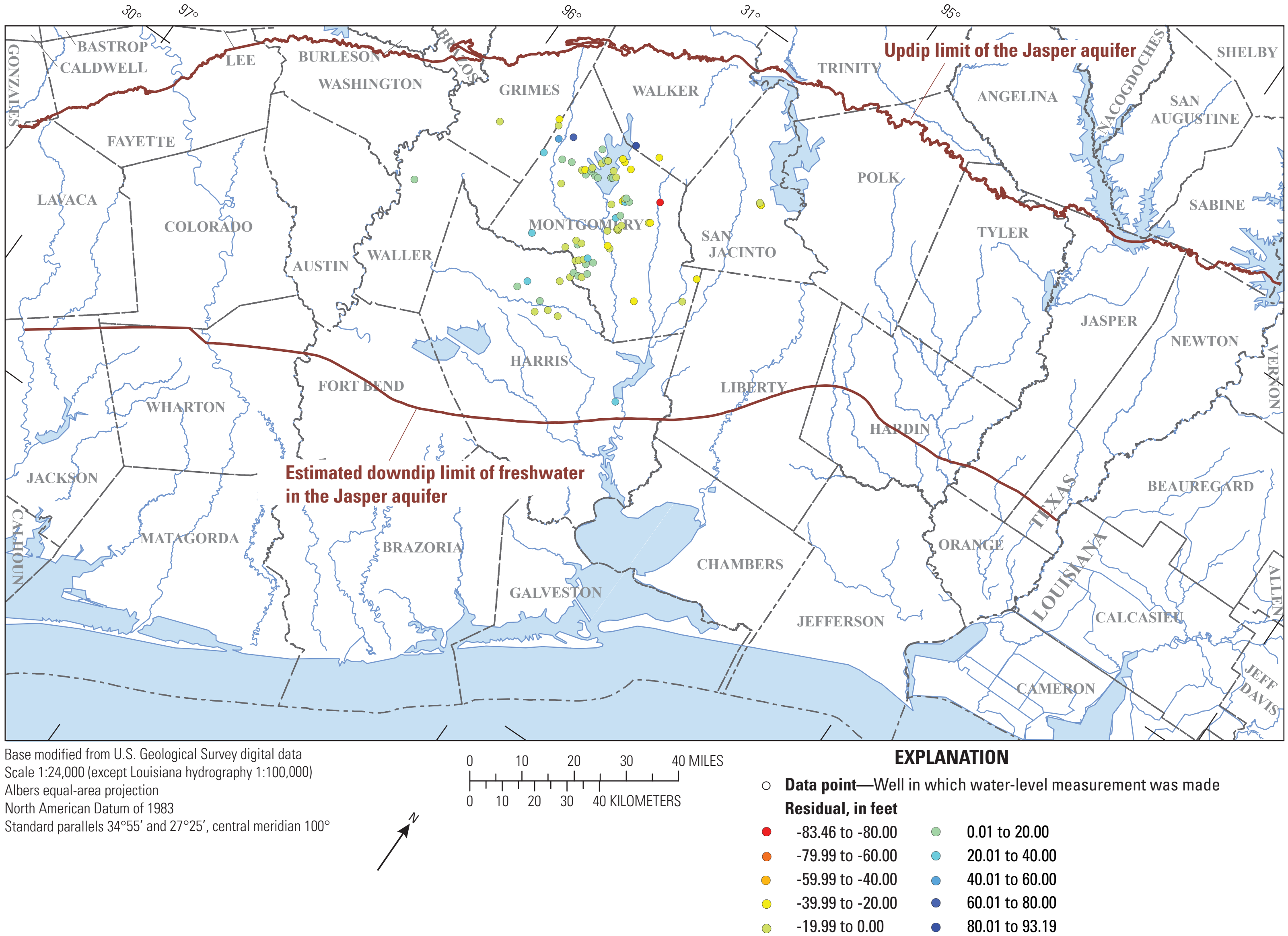


Figure 25. Spatial distribution of water-level (head) residuals (measured minus simulated heads) for the Jasper aquifer, 2009, in the Houston Area Groundwater Model study area.

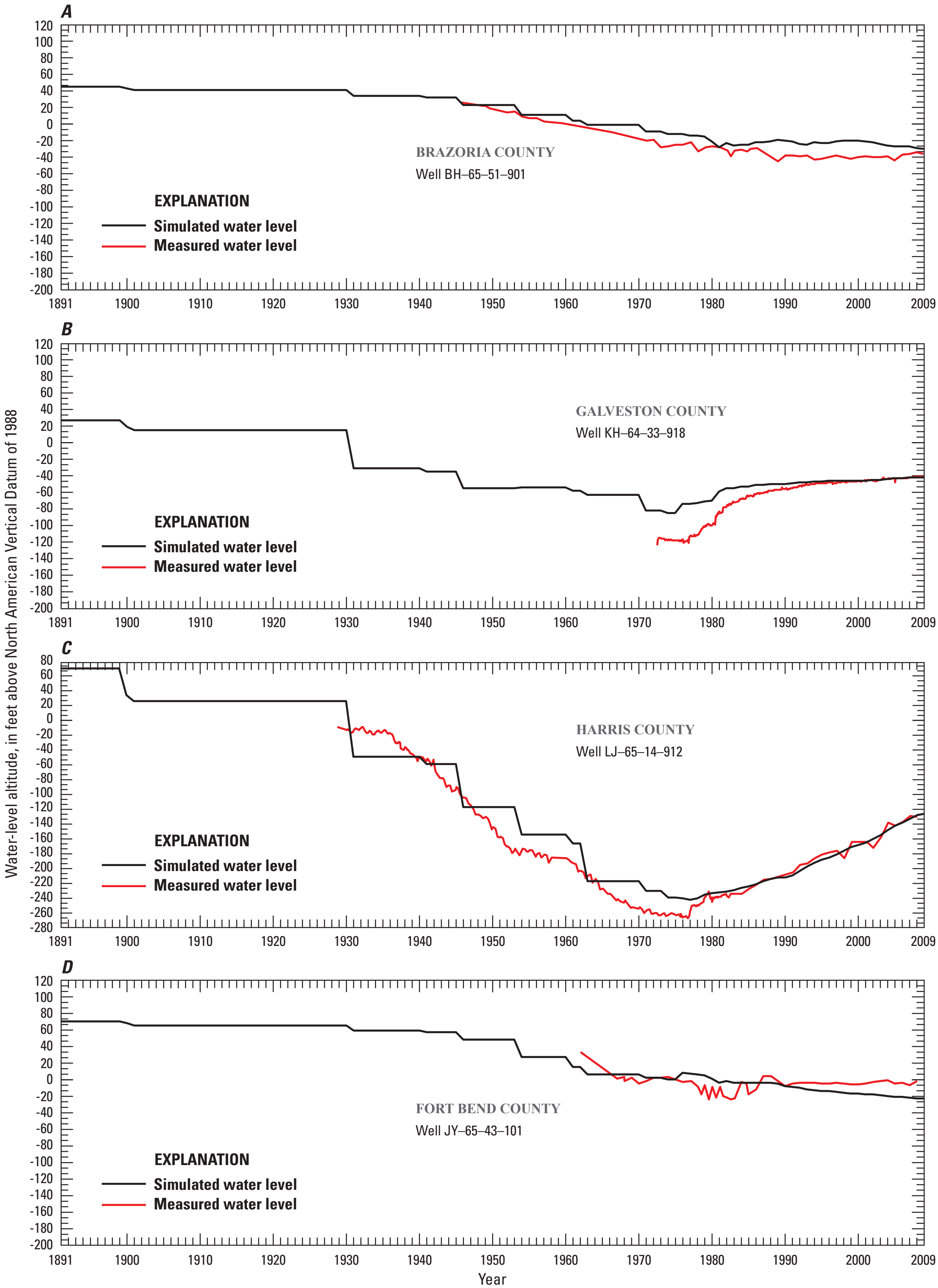


Figure 26. Hydrographs showing simulated and measured water levels in selected observation wells screened in the Chicot aquifer in *A*, Brazoria, *B*, Galveston, *C*, Harris, and *D*, Fort Bend Counties in the Houston Area Groundwater Model study area.

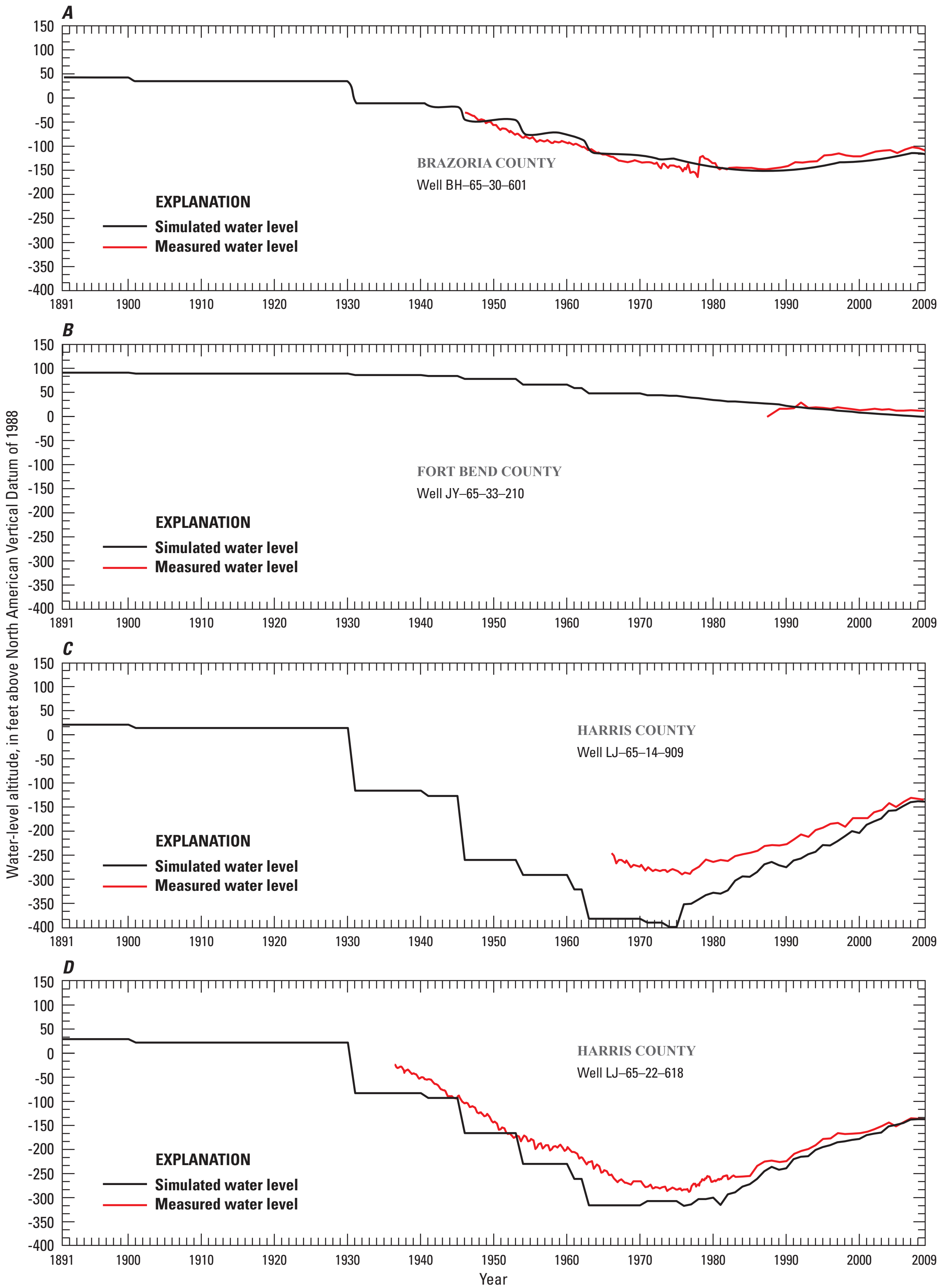


Figure 27. Hydrographs showing simulated and measured water levels in selected observation wells screened in the Evangeline aquifer in *A*, Brazoria, *B*, Fort Bend, and *C*, *D*, Harris Counties in the Houston Area Groundwater Model study area.

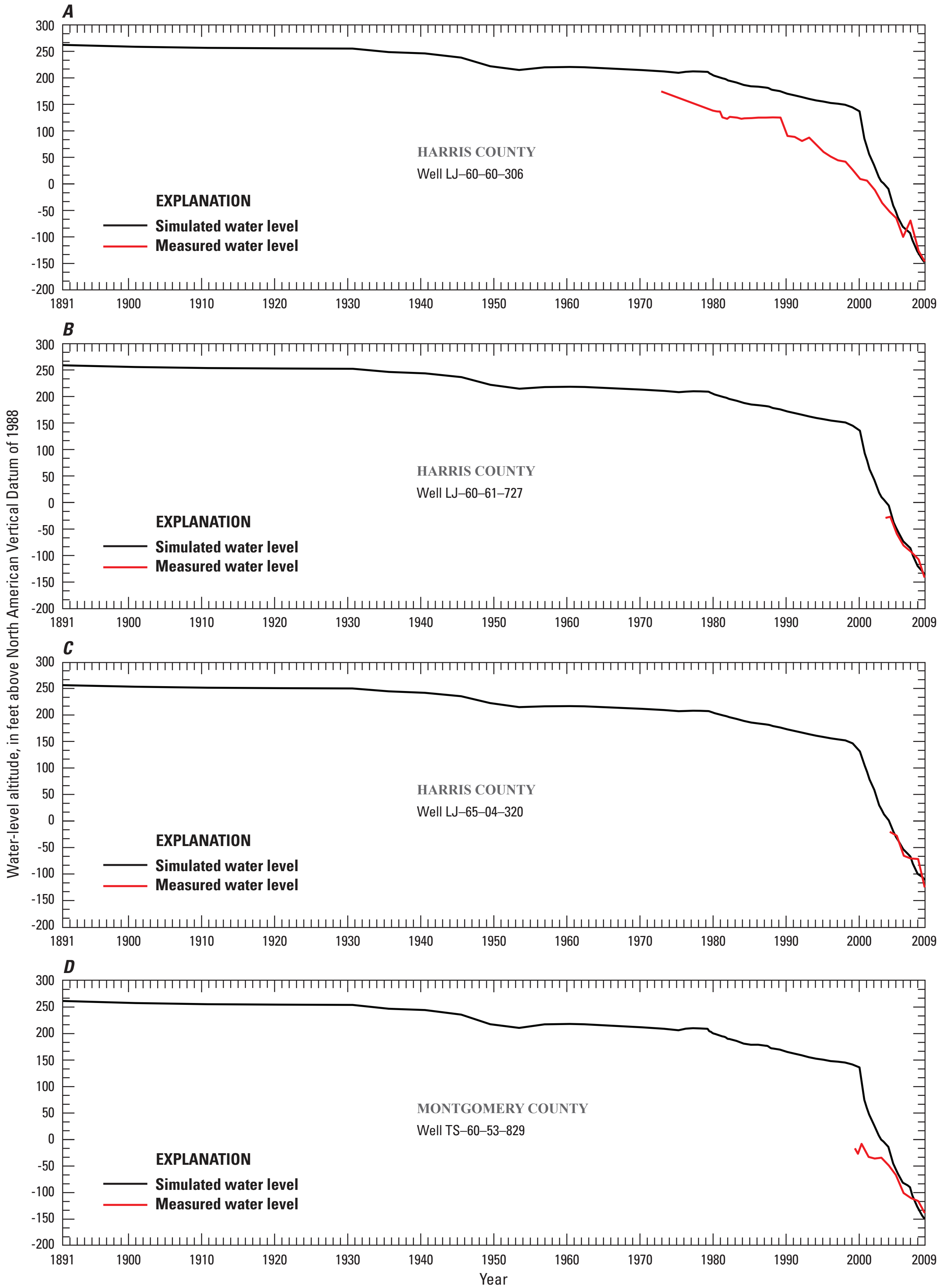


Figure 28. Hydrographs showing simulated and measured water levels in selected observation wells screened in the Jasper aquifer in *A*, *B*, *C*, Harris and *D*, Montgomery Counties in the Houston Area Groundwater Model study area.

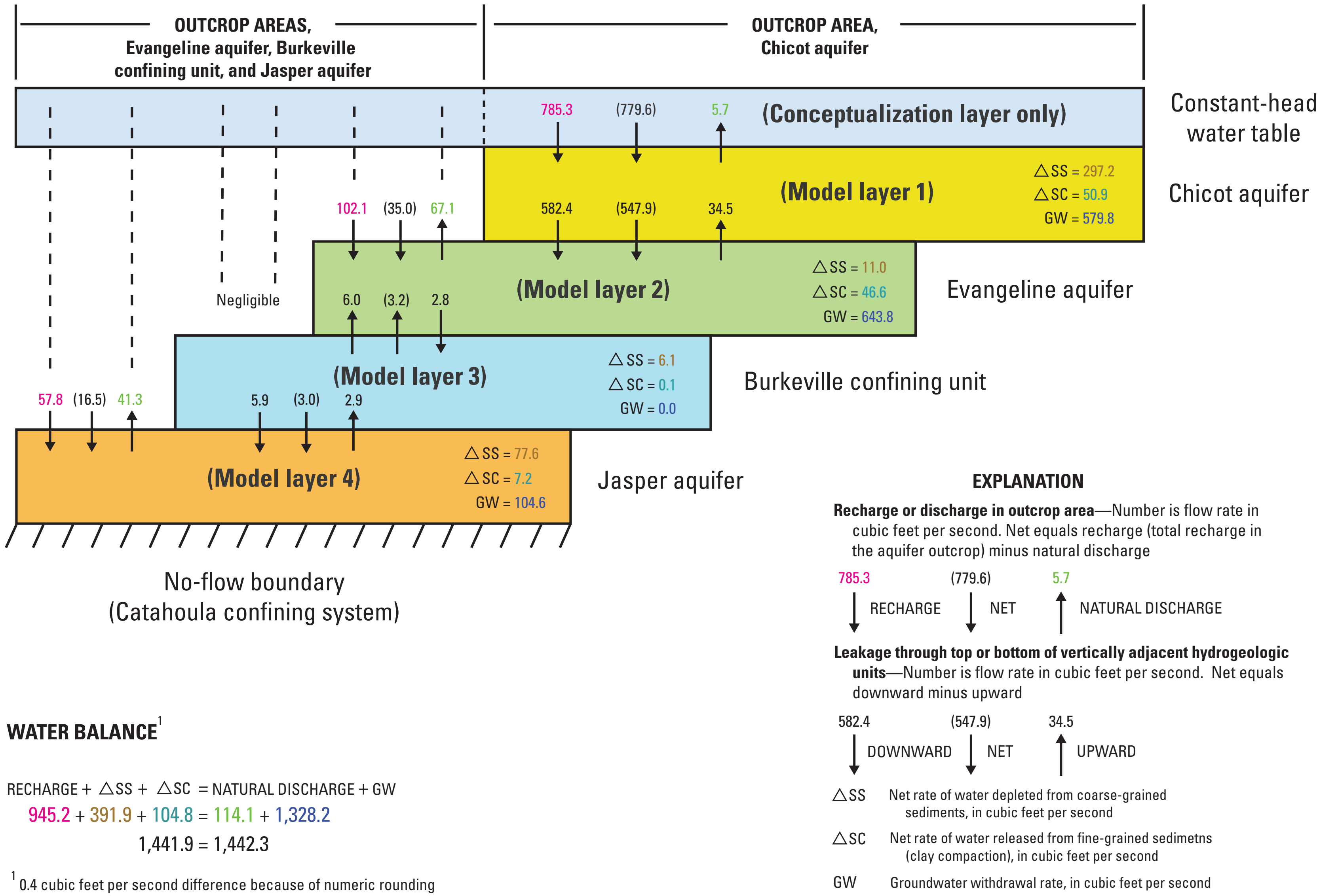


Figure 29. Simulated 2009 water-budget components of the hydrogeologic units of the Houston Area Groundwater Model.

Table 4. Volumetric budget for the Houston Area Groundwater Model at the end of stress period 78, 2009.

[ft^3/day, cubic feet per day; E, exponent]

Cumulative volumetric budget	Sand storage	Groundwater withdrawal	Recharge and natural discharge	Clay storage	Total volume
Volume inflow (ft^3/day)	1.000E+12	0.000E+00	7.690E+13	4.414E+11	7.834E+13
Volume outflow (ft^3/day)	5.562E+10	2.580E+12	7.570E+13	5.234E+09	7.834E+13
Cumulative volumetric percent error					0.00
2009 volumetric budget					
Volume inflow (ft^3/day)	3.478E+07	0.000E+00	8.166E+07	9.102E+06	1.255E+08
Volume outflow (ft^3/day)	9.166E+05	1.148E+08	9.859E+06	4.233E+04	1.256E+08
2009 volumetric percent error					-0.03

An additional approach of simulating subsidence in Harris, Galveston, and Fort Bend Counties was the use of PRESS models developed by Helm (1975; 1976a, b; 1978). This model solves the Terzaghi equations of consolidation based on constant, one-dimensional total stress and transient changes of pore pressure at specific sites (Kasmarek and Strom, 2002). PRESS models were developed for 26 sites (fig. 32) by Freese and Nichols Inc. (Mike Reedy, Freese and Nichols Inc., written commun., 2011). For each PRESS site, a hydrograph was created by using coincident model cells of the simulated water-level data of the HAGM, and a value of subsidence was determined. A good correlation exists between the PRESS and HAGM simulated subsidence values. For example, the Pasadena site (fig. 32) indicates a PRESS determined subsidence value of 10.523 ft, and immediately adjacent to that site is a HAGM-simulated isolated 10-ft contour. Because the PRESS site locations (shown as polygons on fig. 32) encompass numerous model cells and may or may not extend across individual subsidence contours, a direct cell-by-cell or contour comparison is not a feasible evaluation. Instead, a more general areal comparison is appropriate.

Sensitivity Analysis

The sensitivity of calibrated model responses to changes in input data (the aquifer properties that control flow, recharge [general head boundary in the HAGM], discharge, subsidence, and storage, plus withdrawals) was evaluated. The values of selected model input data were iteratively and individually varied over ranges that may reflect plausible uncertainty (potential lack of accuracy of estimated or simulated values) in a series of simulations to present the effects of the uncertainty on simulated heads and subsidence. The effects of those changes on simulated 2009 water levels and land-surface subsidence were measured in terms of increases in RMSE (figs. 33 and 34, respectively). The plots depicting sensitivity of simulated water levels to changes in selected calibrated model input data (fig. 33) indicate that the model is more sensitive to groundwater withdrawals than to inelastic-clay storativity. In contrast, the plots depicting sensitivity of simulated land-surface subsidence to changes in selected calibrated model input data (fig. 34) indicate that the model is more sensitive to both groundwater withdrawals and sand storativity than to leakance. This analysis has implications if the HAGM is used for prediction of aquifer responses to future stresses. For example, the plots on figures 33 and 34 indicate that accurate estimates of withdrawals are more important to reliable predictions of heads and subsidence compared to accurate estimates of sand storativity.

Model Limitations

Several factors limit, or detract from, the ability of the HAGM to reliably simulate aquifer responses to groundwater withdrawals. The HAGM, like any nonlinear numeric model, is a simplification of the actual, complex aquifer system it simulates. As Brooks and others (1994) explain, simplification not only is necessary to make the problem tractable but also is necessary because the structure, properties, modeled boundaries, and stresses on the aquifer system can never be fully known. Simplifications involve assumptions about the actual system and the way it functions. Knowledge (or lack of knowledge) of the system is reflected in the quality and quantity of input data. The scale of the model, which is associated with the necessity to discretize a continuous system in space, also affects the ability of a model to produce reliable results.

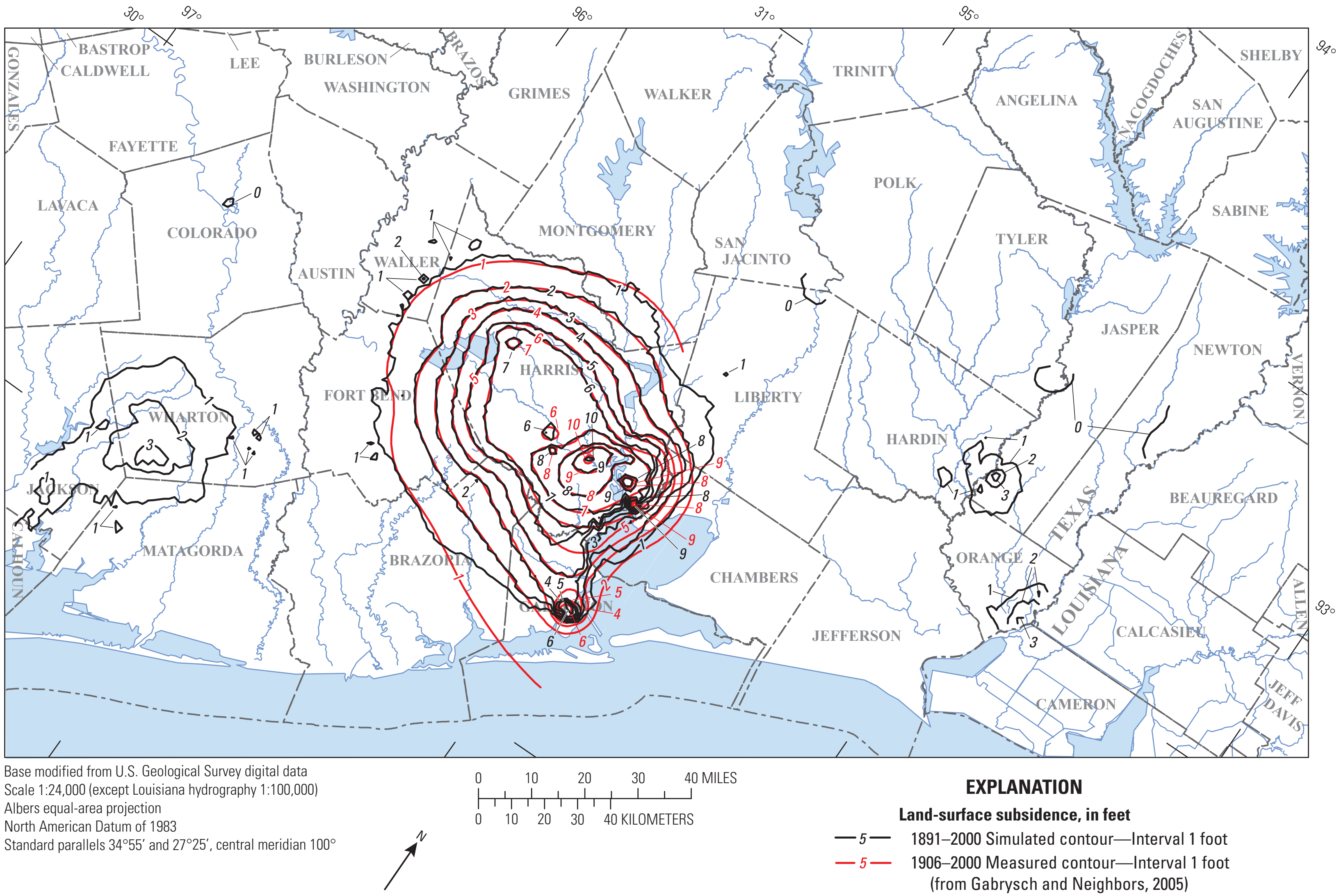


Figure 30. Simulated (1891–2000) and measured (1906–2000) land-surface subsidence in the Houston Area Groundwater Model study area.

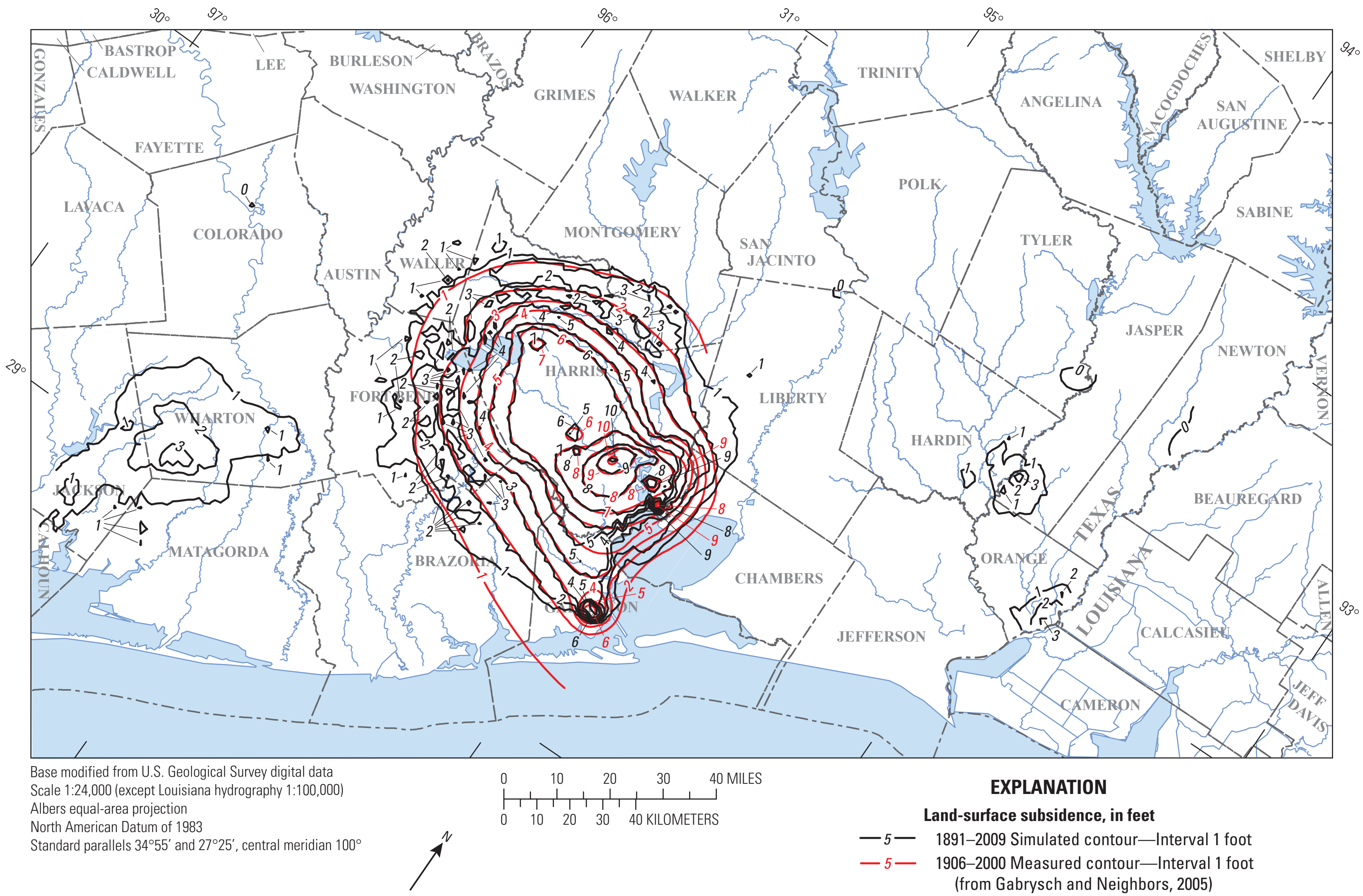


Figure 31. Simulated (1891–2009) and measured (1906–2000) land-surface subsidence in the Houston Area Groundwater Model study area.

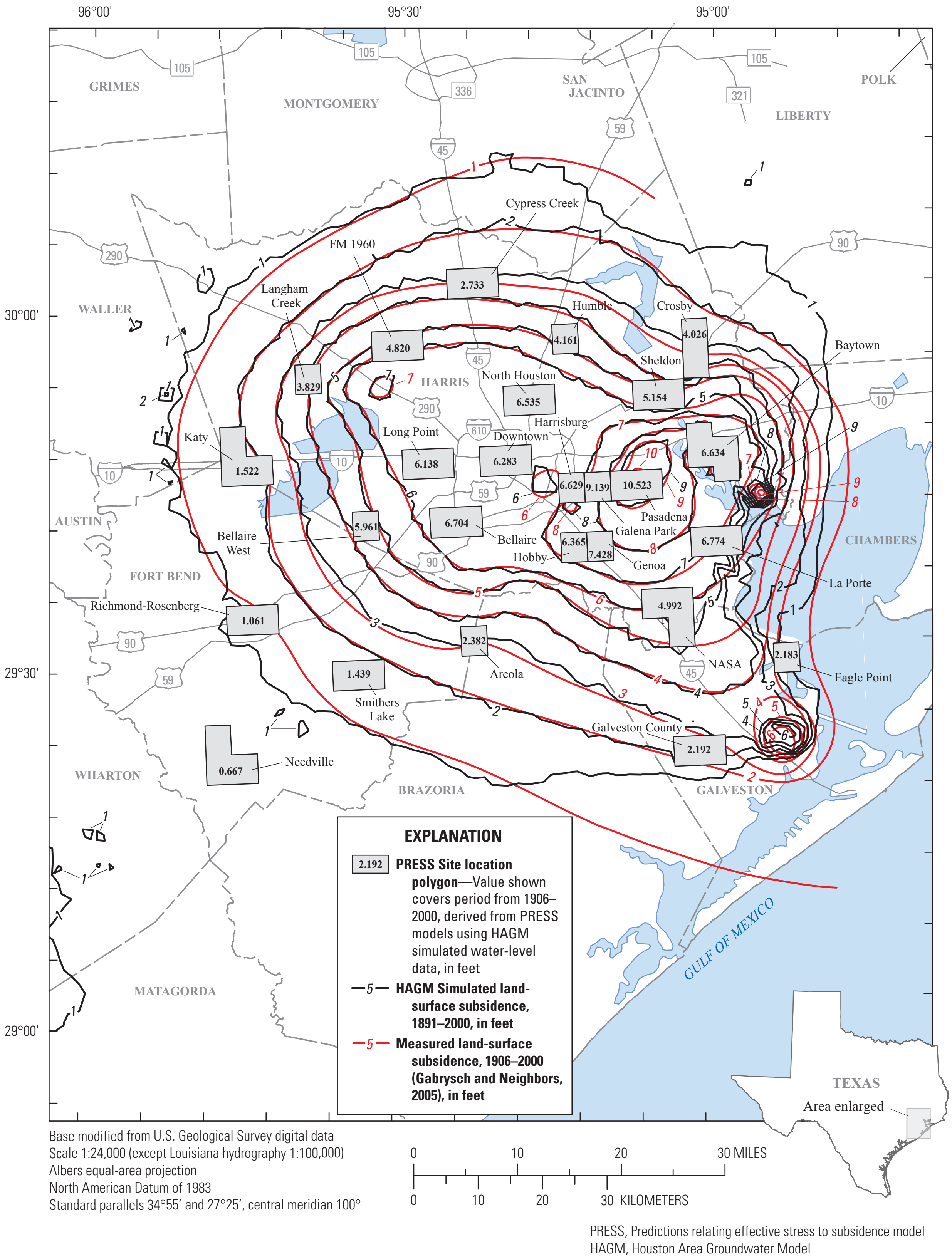


Figure 32. Predictions Relating Effective Stress to Subsidence (PRESS) model site locations and PRESS simulated land-surface subsidence, 1906–2000 (Mike Reedy, Freese and Nichols Inc., written commun., 2011), and Houston Area Groundwater Model simulated land-surface subsidence (1891–2009) and measured land-surface subsidence (1906–2000) in the Houston Area Groundwater Model study area.

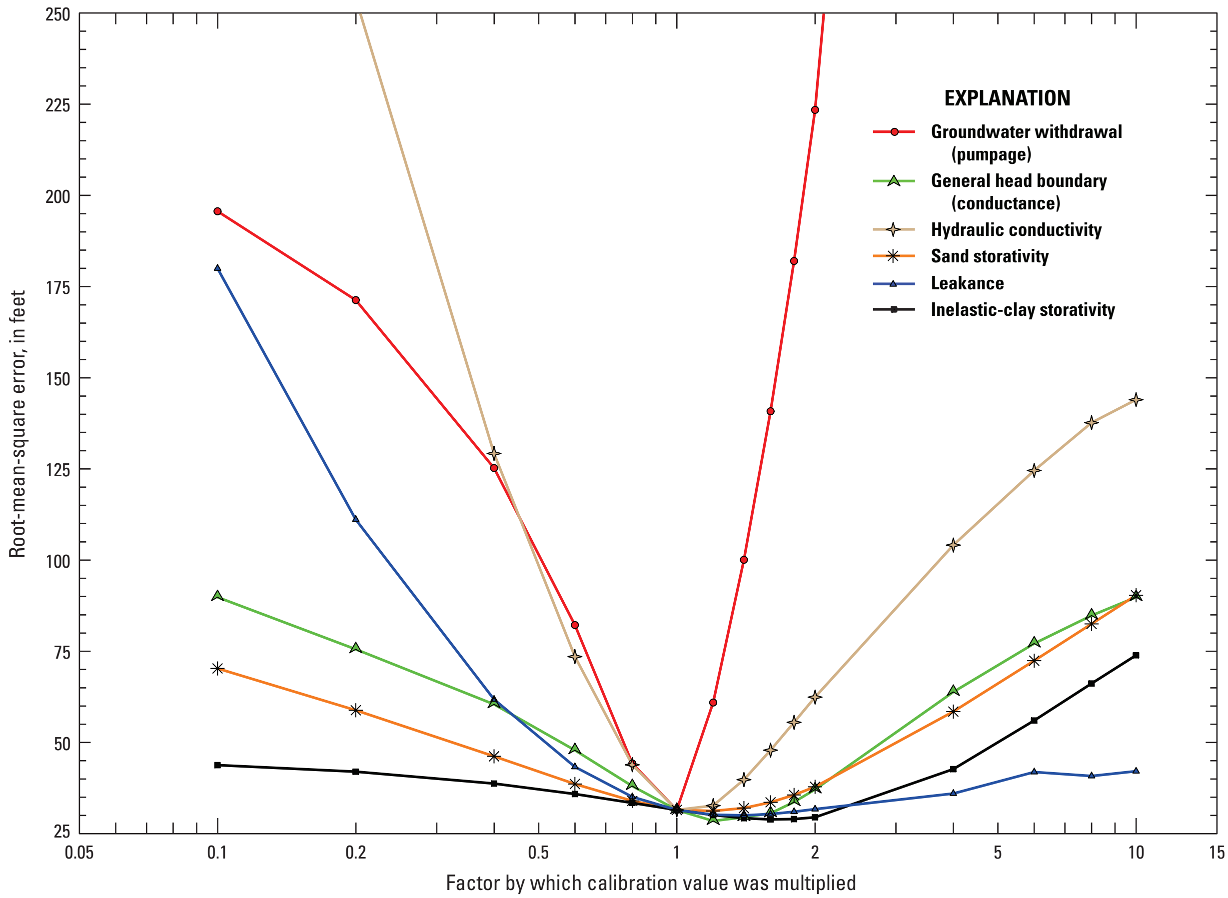


Figure 33. Sensitivity of simulated water levels to changes in selected calibrated model input data of the Houston Area Groundwater Model.

Assumption

A basic assumption is that the hydrogeologic units of the Gulf Coast aquifer system can be adequately represented by four discrete layers. This simplification is made because in the actual aquifer system the change from one aquifer to another with depth likely is transitional rather than abrupt. Other assumptions pertain to the boundary conditions. The conceptualization of the downdip boundaries of each hydrogeologic unit as the downdip limit of freshwater flow probably is realistic—salinity increases and flow becomes increasingly sluggish with distance downdip in each unit; however, the simplifying assumption that the downdip limit of freshwater flow in each unit is a sharp interface across which no flow occurs, the position of which is known and static over time, is more tenuous, as was discussed in the section "Hydrogeologic Units and Geologic Setting." The assumption of the southwestern and northeastern aquifer-system boundaries as no-flow, coincident with the Lavaca and Sabine Rivers, respectively, is not entirely realistic. Although those rivers likely represent effective groundwater-flow divides in the shallow subsurface, the vertical extent of their influence on groundwater flow is unknown. Those lateral boundaries are far enough from areas of major withdrawals, however, so that they likely have negligible influence on the simulated response of the aquifer to withdrawals. The base of the Jasper aquifer is assumed to be a no-flow boundary, although in the actual aquifer system, a relatively small amount of water probably flows between the Jasper aquifer and the underlying Catahoula confining system. Another assumption is that in areas of large withdrawals and substantial declines in the potentiometric surface of an aquifer, the overlying water table has not declined in response to increased downward gradients; water-table heads are held constant during simulations. If this assumption is not valid, then more recharge than actually occurs in the actual system could be simulated in such areas, which also could result in simulated heads higher than actual heads. Although the validity of this assumption has not been studied, that annual rainfall is likely sufficient to keep any actual long-term water-table declines to a minimum. As noted in the section on "Land-Surface Subsidence and Storage in Clays," assuming a constant-head water table also means constant geostatic pressure, which in turn makes changes in effective stress a function only of changes in head. If the

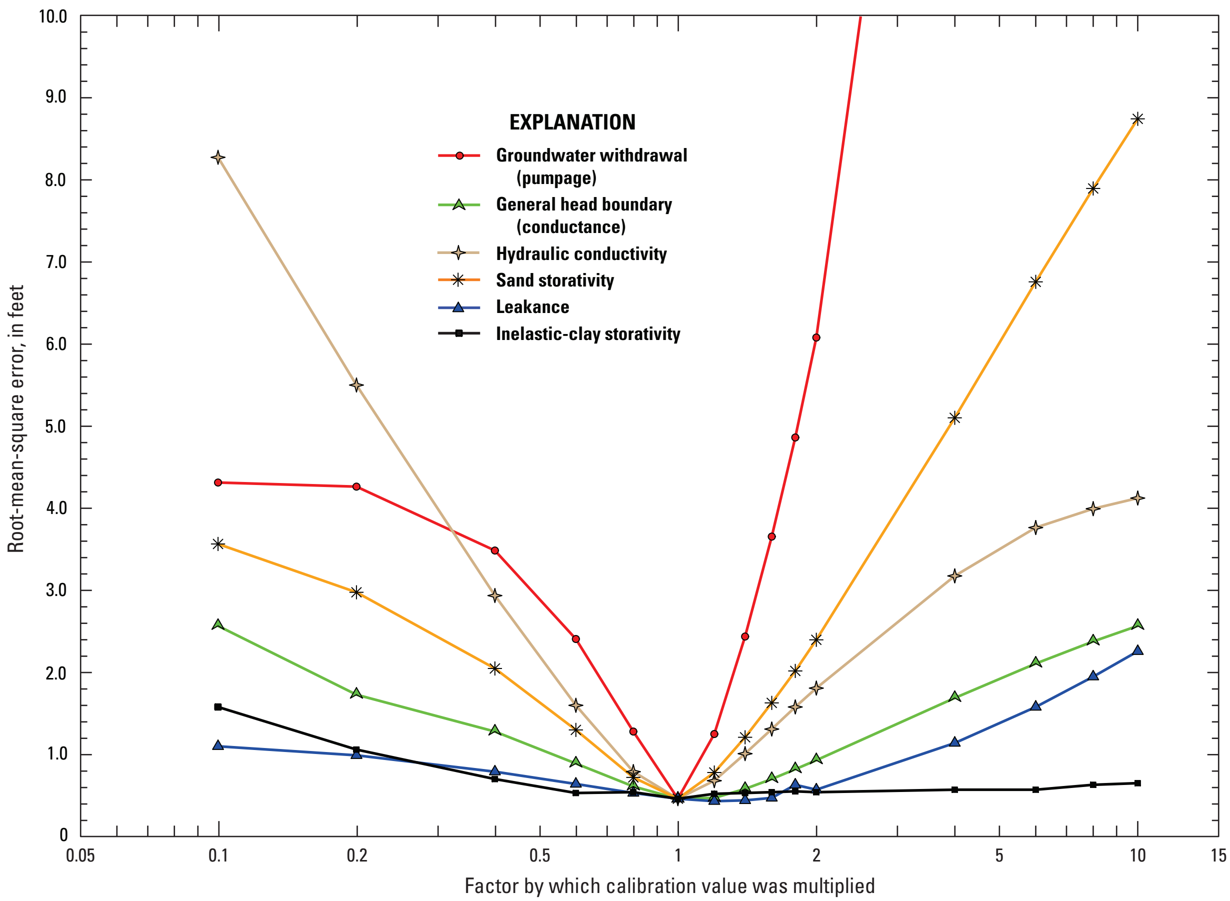


Figure 34. Sensitivity of simulated land-surface subsidence to changes in selected calibrated model input data of the Houston Area Groundwater Model.

assumption of a constant water table was not valid and the water table in the actual system was to decline appreciably, then the model could overestimate effective stress and thus overestimate compaction (subsidence). Also pertaining to the simulation of land-surface subsidence, the assumption was made that head changes within a model time step in the aquifer sands are the same as those in the interbedded clays; in other words, head changes in the clays do not lag those in the sands. If simulated time steps are too short to allow for dissipation of all excess-residual-pore pressure in the clays of the actual system, then the amount of water released by the clays in the simulated system will be unrealistically large for the time step. Leake and Prudic (1991, p. 7) provide an equation for the upper limit on the time required for excess-residual-pore pressure in the actual system to dissipate on the basis of interbedded clay properties, which can be compared to the length of model time steps. Computations for the interbedded clays in the aquifer system indicate that excess-residual-pore pressure will dissipate in about 300 days. Thus the 1-year model time steps that were applied for all of the transient period except for 1980, 1982, and 1988 appear to be adequate, but the 1-month model time steps during those 3 years probably are not, which implies that the simulated amount of water released by the clays for each of those 3 years probably is greater than the actual amount.

Input Data

Associated with each of the input datasets is a level of uncertainty and a degree of bias, neither of which is quantitatively known. The uncertainty arises from the fact that point measurements or estimates of the input data represent regions around the points. The bias originates from the facts that some properties are better known than others are and individual properties are better known in some areas than in others (data points commonly are concentrated in some areas and are sparse in others). The result is that the optimum (but non-unique) spatial distributions of input data arrived at through calibration, or history matching, are distributions of effective properties, not actual properties; that is, the set of property distributions for the calibrated model is one of potentially many plausible sets that would allow simulated heads, subsidence, and water-budget components to reasonably match those of the actual system under selected conditions. In all likelihood, the property distributions reflect the order of magnitude of the actual-system properties but not the true distributions of the actual-system properties. For example, the simulated spatial distributions of hydraulic conductivity of the Chicot, Evangeline, and Jasper aquifers (figs. 9–11), while generally of the correct orders of magnitude, indicate larger values and generally more “definition” in areas coincident with large withdrawals. The distributions reflect the availability of more historical information for those areas and thus more attention to those areas during calibration. It is likely that if comparable groundwater development, subsurface information, head data, and calibration attention were focused on the system in other parts of the HAGM study area, the distributions of hydraulic conductivity in those areas would reflect that situation and be different from the distributions of figures 9, 10, and 11. What can be said about the spatial distributions of aquifer-system properties after calibration is that, collectively, they are one set of probably multiple sets of input data that allows the model to reasonably reproduce selected historical heads, land-surface subsidence, and groundwater flow. The possibility of multiple sets of input data implies that the reliability of the model for predictive simulation is uncertain.

Scale of Application

The HAGM is a regional-scale model, and as such, it is intended for regional-scale rather than local-scale analyses. Discretization of the HAGM area into 1-mi^2 grid blocks in which aquifer properties and conditions are assumed to be averages over the area of each grid block precludes site-specific analyses. For example, the simulated head in a grid block encompassing one or more pumping wells will represent an average head in the actual grid-block area rather than the head at or near the pumping well, which is much lower. An implication of simulated areal average heads is that, for calibration, comparison of simulated heads to measured heads might not always be comparable. Although explicit care is taken to ensure that static (nonpumping) water-level data are collected, undoubtedly some measured heads are influenced by nearby pumping or by antecedent pumping conditions or for other reasons are not representative of an average head in the grid-block area. Another scale-related issue—the “scale problem” as defined by Johnston (1999)—was described in the “Groundwater-Flow Conditions, Recharge, and Discharge” section. Because flow that enters and exits the actual system within the area encompassed by a single grid block cannot be simulated except by superposition of sources or sinks, which would be impractical over a regional area, the model does not simulate total recharge (and thus total [actual-system] groundwater flow). The fraction of total flow simulated is unknown, but the fraction of total flow simulated decreases as the grid-block size increases. This unknown flow fraction implies that any simulated components of flow not explicitly specified (for example, natural recharge and discharge) will be less than their actual-system counterparts. Explicitly specified components (for example, withdrawals) are based on measured or estimated actual-system data and therefore will more closely approximate actual-system magnitudes.

Summary

The availability of groundwater for municipal, industrial, and agricultural uses, as well as the potential subsidence associated with groundwater use, has been a concern in the Houston, Texas, area for decades. In cooperation with the Harris–Galveston Subsidence District, Fort Bend Subsidence District, and Lone Star Groundwater Conservation District, the U.S. Geological Survey developed and calibrated the Houston Area Groundwater Model (HAGM). Groundwater flow and land-surface subsidence in the northern part of the Gulf Coast aquifer system in Texas from predevelopment (before 1891) through 2009 were simulated; the objective of the HAGM is to accurately simulate and provide reliable, timely data on groundwater availability and land-surface subsidence in the Houston area through 2009. Results from the HAGM can be used to simulate aquifer response (changes in water levels and clay compaction) to future estimated water demands.

In a generalized conceptual model of the Gulf Coast aquifer system, the fraction of precipitation that does not evaporate, transpire through plants, or run off the land surface to streams enters the groundwater-flow system in topographically high updip outcrop areas of the hydrogeologic units in the northwestern part of the system. Most precipitation infiltrating into the saturated zone flows relatively short distances through shallow zones and then discharges to streams. The remainder of the water flows to intermediate and deep zones of the system southeastward of the outcrop areas where it is discharged by wells (in the developed system) and by upward leakage in topographically low areas near or along the coast. Because groundwater flow was simulated in the HAGM only as far as the downdip limit of freshwater, only the parts of the hydrogeologic units containing freshwater are described in this report.

The HAGM was developed to simulate groundwater flow and land-surface subsidence in the northern Gulf Coast aquifer system (Chicot aquifer, Evangeline aquifer, Burkeville confining unit, and Jasper aquifer) from predevelopment (1891) through 2009. The finite-difference computer code MODFLOW-2000 was used in this application. The finite-difference grid for the numerical model covers 33,565 square miles in southeastern Texas and southwestern Louisiana. The model grid was rotated 37.6 degrees clockwise so that the orientation of the model closely coincides with the natural groundwater divides, model boundaries, and predevelopment and postdevelopment flow paths. The four layers of the model together contain 134,260 grid blocks. Each layer consists of 137 rows and 245 columns. Layer 1 represents the Chicot aquifer, layer 2 the Evangeline aquifer, layer 3 the Burkeville confining unit, and layer 4 the Jasper aquifer. The grid blocks are uniformly spaced with each model cell area equal to

1 square mile. The MODFLOW General-Head Boundary package was used to simulate recharge and discharge in the outcrops of the Chicot, Evangeline, and Jasper aquifers and the Burkeville confining unit. This package allows the water table of an aquifer system to function as a head-dependent flux. Initial conditions, including heads and hydraulic properties, provided a starting point for the model simulation. The initial conditions for head and hydraulic properties were coincident with the calibrated groundwater flow model previously created (2004) for the northern Gulf Coast by the USGS and cooperators.

Simulation of land-surface subsidence (actually, compaction of clays) and release of water from storage in the clays of the Chicot, Evangeline, and Jasper aquifers and the Burkeville confining unit was accomplished by using the Subsidence and Aquifer-System Compaction package designed for use with MODFLOW-2000. Simulations were made under transient conditions from 1891 through 2009 for 78 withdrawal (stress) periods of variable length. Total groundwater withdrawals increased from an estimated 41 million gallons per day in 1891 to about 869 million gallons per day in 2009.

The HAGM was calibrated by an iterative trial-and-error adjustment of selected model input data (the aquifer properties that control water flow, recharge, discharge, and storage) in a series of transient simulations until the model output (simulated heads, land-surface subsidence, selected water-budget components) reasonably reproduced field measured aquifer responses.

Calibrated model parameters from each layer within the GAM and HAGM were compared to identify any differences in values. Generally, the additional data available in the model area since the development of the GAM required substantial modification of GAM parameters, particularly in the Jasper aquifer, for a complete calibration. Maximum general-head boundary conductance in the Chicot aquifer was reduced by more than two orders of magnitude, whereas general-head boundary conductance values in the other model layers remained unchanged. Inelastic-clay storativity maximum and minimum values varied slightly between the two models in the Chicot and Evangeline aquifers but were of a consistent magnitude. Minimum hydraulic conductivity values decreased about two orders of magnitude in the Chicot aquifer, increased less than an order of magnitude in the Evangeline aquifer, and increased about three orders of magnitude in the Jasper aquifer. Maximum hydraulic conductivity values decreased nearly two orders of magnitude in the Chicot and less than one order of magnitude in the Evangeline and Jasper aquifers. Spatial distributions of simulated parameters of specific storage and leakance were similar between the GAM and HAGM calibrated models.

Hydraulic conductivities of the Chicot aquifer ranged from 4.0×10^{-3} to 39.91 feet per day (ft/d), with the larger values located in Harris, Fort Bend, Liberty, Chambers, Galveston, Wharton, Colorado Tyler, Jasper, and Newton Counties. Hydraulic conductivities of the Evangeline aquifer ranged from 3.9×10^{-1} to 30.79 ft/d, with largest values located in northeast Fort Bend County. Hydraulic conductivities of the Burkeville confining unit are coincident with values used in the GAM. Hydraulic conductivities of the Jasper aquifer ranged from 8.64×10^{-1} to 21.23 ft/d, with the larger values located in northern Harris and Montgomery Counties.

Simulated sand storativities of the Chicot and Evangeline aquifers (2×10^{-3} to 1.56×10^{-1} and 1×10^{-3} to 1.82×10^{-1}, respectively) reflect aquifer conditions from confined to semiconfined to water table. Sand storativities of the Chicot and Evangeline aquifers generally are largest in the updip, outcrop areas where water-table conditions prevail. Storativities of the Burkeville confining unit are coincident with values used in the GAM. Storativities of the Jasper aquifer (4.1×10^{-6} to 2.01×10^{-1}) are generally largest in the updip, outcrop areas associated with water-table conditions.

Because a large area of land-surface subsidence has been documented in Harris County and parts of Galveston, Fort Bend, Montgomery, Brazoria, Waller, Liberty, and Chambers Counties, only these areas of the HAGM can be considered calibrated for elastic- and inelastic-clay storativity. Inelastic-clay storativities for the Chicot aquifer, the Evangeline aquifer, the Burkeville confining unit, and the Jasper aquifer range from 5.3×10^{-6} to 1.49×10^{-2}, from 2.28×10^{-7} to 1.49×10^{-1}, from 2.05×10^{-6} to 9.24×10^{-5}, and from 1.0×10^{-6} to 9.47×10^{-4}, respectively. A total of 474 sites located in Harris and surrounding counties were used to evaluate simulated subsidence compared to measured subsidence. After numerous iterative trial-and-error transient model simulations, the final land-surface subsidence RMSE was 0.37 ft.

The simulated potentiometric surfaces of the Chicot, Evangeline, and Jasper aquifers for 2009 indicate general agreement with the measured potentiometric surfaces. The RMSE of the three aquifer potentiometric surfaces for 2009 were 31.06 ft for the Chicot aquifer, 33.73 ft for the Evangeline aquifer, and 23.50 ft for the Jasper aquifer. The RMSE were about 6, 5, and 4 percent, respectively, for the total range in simulated heads for the three aquifers, with a -0.03 percent water-budget discrepancy between the total simulated inflow and the total simulated outflow.

Hydrographs were used to compare simulated and measured water levels; selected water wells with screened intervals in the Chicot, Evangeline, and Jasper aquifers match closely relative to the ranges of water-level change. Simulated water budget components for 2009 indicate that a net recharge (total recharge minus natural discharge) of 779.6 cubic feet per second (ft^3/s) (about 0.56 inches per year [in./yr]) in the Chicot aquifer outcrop, 35.0 ft^3/s (about 0.23 in./yr) in the Evangeline aquifer outcrop, negligible net recharge in the Burkeville confining unit outcrop, and 16.5 ft^3/s (about 0.07 in./yr) in the Jasper aquifer outcrop. For the entire system, the simulated total net recharge for 2009 was 831.1 ft^3/s (about 0.45 in./yr).

In Harris County and counties immediately adjacent, where the main area of subsidence has been measured, the 1891–2000 simulated subsidence matches closely with the 1906–2000 measured subsidence. As much as 10 ft of subsidence has occurred in southeastern Harris County near the northern end of Galveston Bay. A larger geographic area encompassing the maximum land-surface subsidence area and much of central to southeastern Harris County has subsided at least 6 ft. Again, in Harris County and counties immediately adjacent, where the main area of subsidence is present, the 1891–2009 simulated subsidence matches closely with the 1906–2000 measured subsidence, but not as closely as the simulated subsidence for 1891–2000. The most recent areas of subsidence are approximately located in southern Montgomery, northwest Harris, and Fort Bend Counties, where development has occurred and required sustained groundwater withdrawals during 2001–9.

An additional approach of simulating and predicting subsidence in Harris, Galveston, and Fort Bend Counties was the use of Predictions Relating Effective Stress to Subsidence (PRESS) model. For each PRESS site, a hydrograph was created by using coincident model cells of the simulated water-level data of the HAGM, and a value of subsidence was determined. A good correlation exists between the PRESS and HAGM simulated subsidence values. For example, at the Pasadena PRESS site, the simulated value is 10.523 ft and the site is located immediately adjacent to a HAGM-simulated isolated 10 ft contour.

The sensitivity of calibrated-model responses to changes in input data (the aquifer properties that control flow, recharge, discharge, subsidence, and storage, plus withdrawals) was evaluated. The HAGM sensitivity results indicate that accurate estimates of hydraulic conductivity and withdrawals are more important to reliable predictions of heads and subsidence compared to accurate estimates of sand storativity.

Several factors limit, or detract from, the ability of the HAGM to reliably predict aquifer responses to future conditions. The HAGM, like any nonlinear numeric model, is a simplification of the actual, complex aquifer system it simulates. Additionally, the HAGM is a regional-scale model, and as such, it is intended for regional-scale rather than local-scale analyses. Discretization of the HAGM study area into 1-square-mile grid blocks in which aquifer properties and conditions are assumed to be averages over the area of each grid block precludes site-specific analyses.

Associated with each of the input datasets are a level of uncertainty and a degree of bias, neither of which is quantitatively known. The uncertainty arises from the fact that point measurements or estimates of the input data represent regions around the points. The bias originates from the facts that some properties are better known than others are and individual properties are better known in some areas than in others (data points commonly are concentrated in some areas and are sparse in others). The result is that the optimum (but non-unique) spatial distributions of input data arrived at through calibration, or history matching, are distributions of effective properties, not actual properties; that is, the set of property distributions for the calibrated model is one of potentially many plausible sets that would allow simulated heads, subsidence, and water-budget components to reasonably match those of the actual system under selected conditions.

A basic assumption is that the hydrogeologic units of the Gulf Coast aquifer system can be adequately represented by four discrete layers, a simplification because, in the actual system, the change from one aquifer to another with depth likely is transitional rather than abrupt. Downdip salinity changes and lateral boundary conditions also are not absolutely known.

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APPENDIX 6

Extended Houston Area Groundwater Model MODFLOW Files

APPENDIX 7

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A Formula for Computing Transmissibility Causing Maximum Possible Drawdown Due to Pumping

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1536-F

A Formula for Computing Transmissibility Causing Maximum Possible Drawdown Due to Pumping

By G. M. ROBINSON *and* H. E. SKIBITZKE

GROUND-WATER HYDRAULICS

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1536-F

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

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GEOLOGICAL SURVEY

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CONTENTS

ILLUSTRATIONS

A FORMULA FOR COMPUTING TRANSMISSIBILITY CAUSING MAXIMUM POSSIBLE DRAWDOWN DUE TO PUMPING

By G. M. Robinson and H. E. Skibitzke

ABSTRACT

By modifying the Theis nonequilibrium formula a relation is found in which the maximum possible drawdown is expressed in terms of a unique value for the aquifer coefficient of transmissibility. The relation is valid for any specified period and rate of pumping, for a given aquifer coefficient of storage, and for any desired radial distance from the center of pumping.

INTRODUCTION

When planning ground-water investigations, it is often desirable to analyze the manner in which the release of ground water from storage affects the time required for changes in head to migrate from a center of pumping to the area of natural discharge. In many instances the effects of release would predominate over such a long period of time that the water from storage would become the controlling feature of the ground-water development in the region. Many ground-water reservoirs are of such large areal extent that pumping throughout any foreseeable economic or practicable pumping period would not cause drawdowns sufficient to recover water from the region of natural discharge. The purpose of this paper is to show the development of a formula describing—for any desired pumping rate, pumping period, and distance from the pumped well—the particular aquifer transmissibility at which the greatest possible drawdown occurs.

It is recognized that in studying any real hydrologic problem, a detailing of the effects of pumping and the release of water from storage requires knowledge of the variation in the coefficients of transmissibility and of storage throughout the region. If these data were known, it would be possible to describe the drawdown that would occur throughout the region because of any given pumping regimen. In the usual absence of such detailed data, however, highly significant perspectives of the hydrologic problem can be obtained through some idealization of the aquifer and use of the equation developed and described in this paper.

EFFECTS OF PUMPING

If a water-table aquifer were infinite in areal extent and transmissibility, pumping from the aquifer would cause no drawdown anywhere. If such an aquifer were infinite in transmissibility but not infinite in areal extent, the effect of pumping would be a uniform drawdown throughout the aquifer and the water table would remain a plane surface. If the aquifer were not infinite in transmissibility there would be a cone of depression that is somewhat steep sided near the well and that flattens out with distance from the well (Theis, 1940); if the aquifer material were relatively impermeable, the drawdown cone near the well would be very steep sided. The relatively steep sides of the drawndown cone would flare out and intersect the horizontal or nearly horizontal water tables representative of the first two sets of conditions postulated in this paragraph.

DEVELOPMENT OF FORMULA

Obviously, for a specified rate and period of pumping, the drawdown near the pumped well increases as successively smaller aquifer

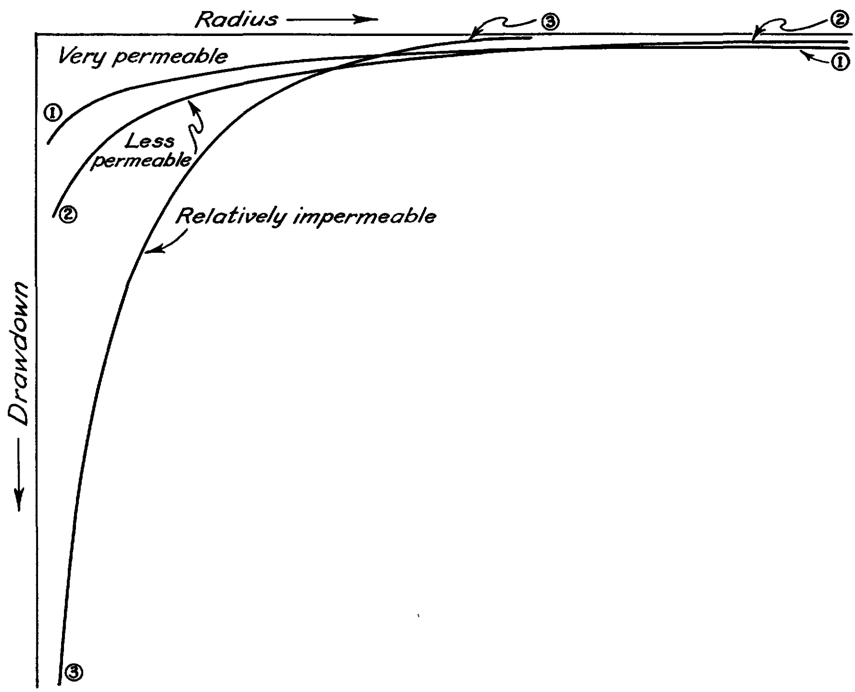

FIGURE 46.—Profiles of drawdown cones near a pumped well.

transmissibilities are considered. Furthermore, as shown in figure 46, the intersection of the drawdown profiles with the plane of the water table occurs at distances that are progressively nearer to the pumped well as successively smaller transmissibilities are considered. The preceding statements suggest that for a specified steady and continuous rate of pumping, from an aquifer having a specified coefficient of storage, there is a unique combination of maximum possible drawdown and aquifer transmissibility for any given elapsed pumping time and distance from the pumped well. The expression for the maximum drawdown, in terms of the coefficient of transmissibility, can be found by differentiating the familiar Theis (1935) formula, which has the nondimensional form (Brown, 1953, p. 851)

$$s=\frac{Q}{4\pi T}W\ (u),\ \text{where}\ u=\frac{Sr^2}{4Tt}.$$

Differentiating

$$\frac{\partial s}{\partial T}=-\frac{Q}{4\pi T^2}\,W(u)+\frac{Q}{4\pi T}\,\frac{\partial W(u)}{\partial u}\cdot\frac{du}{dT}$$

$$\frac{du}{dT}=-\frac{r^2S}{4T^2t}=-\frac{u}{T}$$

$$\frac{\partial s}{\partial T}=-\frac{Q}{4\pi T^2}\left[W(u)+u\,\frac{\partial W(u)}{\partial u}\right].$$

The maximum or minimum may be found by setting $\frac{\partial s}{\partial T}=0$, or

$$W(u)+u\,\frac{\partial W(u)}{\partial u}=0,$$

but

$$\frac{\partial W(u)}{\partial u}=\frac{e^{-u}}{u}$$

Hence

$$W(u)=e^{-u}=-Ei(-u) \qquad \text{(Wenzel, 1942).}$$

The value of u where $e^{-u}=W(u)$ is obtained graphically, as shown in figure 47. The intersection of the two lines, representing plots of $W(u)$ versus u and e^{-u} versus u, occurs at values of $W(u)=0.64738$ and $u=0.43482$. From this value of u the transmissibility can be calculated for specified values of storage coefficient, elapsed pumping time, and distance from the pumped well. This value of transmissibility can be used to compute the maximum possible drawdown for a given rate of pumping. Thus the Theis formula can conveniently be rewritten in nondimensional form to give an expression for the maximum drawdown in terms of the aquifer transmissibility:

$$s_{\max}=(0.647)\frac{Q}{4\pi T}, \tag{1}$$

where

$$T=\frac{(2.30)r^2S}{4t}.$$

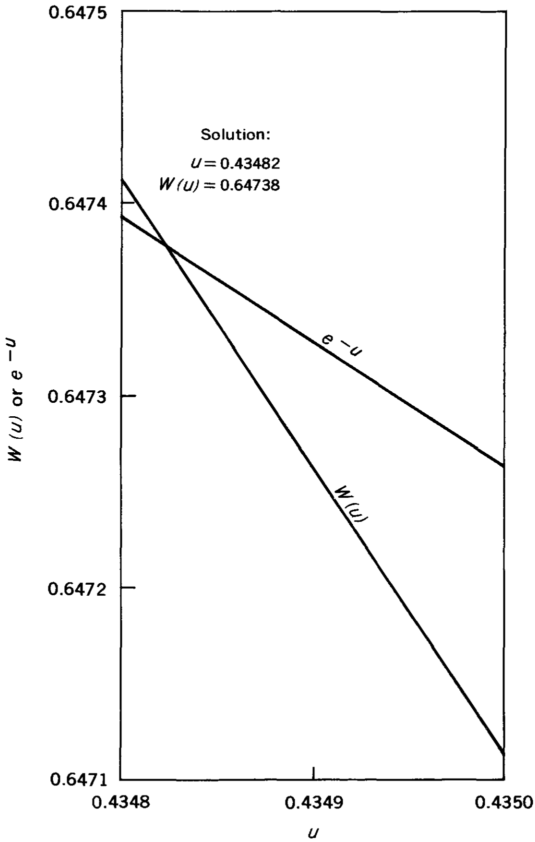

FIGURE 47.—Graph showing point at which $e^{-u}=W(u)$.

ILLUSTRATION OF FORMULA

The implications of equation 1 are illustrated in figure 48, where the maximum possible drawdown is plotted as a function of radius and time, and for the particular value of transmissibility determined for each selected combination of radius and time. The plot is for a pumping rate of 1,000 gpm (gallons per minute) and an aquifer

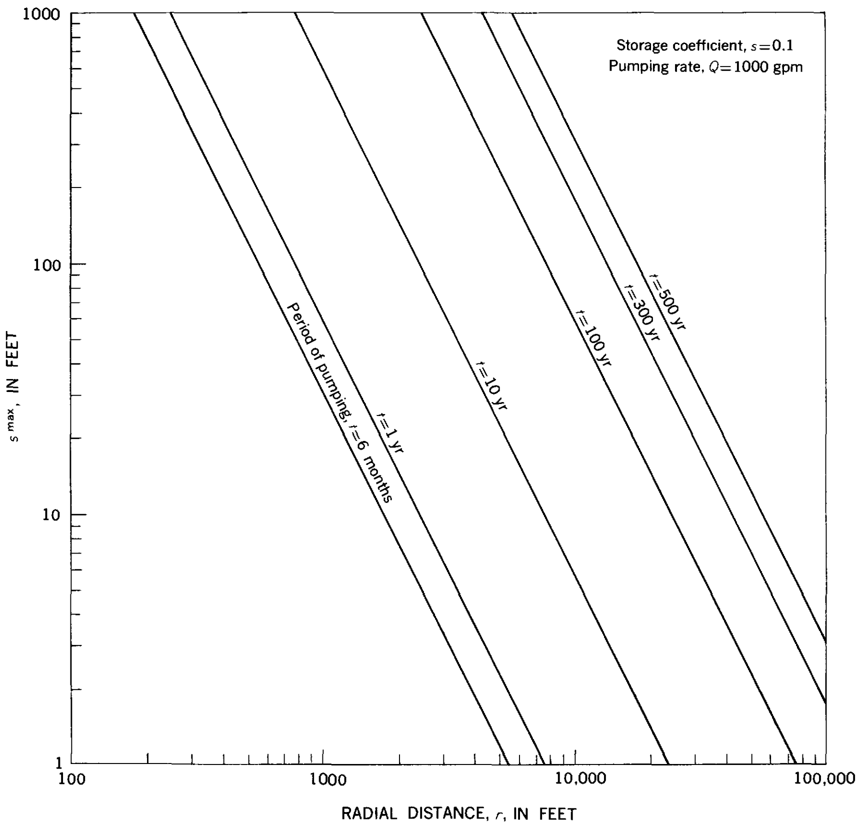

FIGURE 48.—Graph showing maximum possible drawdown for a given radius and time.

storage coefficient of 0.10. Figure 49 also illustrates the significance of equation 1 by showing the transmissibility associated with the maximum drawdown for a given radius and time. This plot is also computed for a pumping rate of 1,000 gpm and a storage coefficient of 0.10. Equation 1 can be used to plot graphs similar to figures 48 and 49 for any other given values of storage coefficient and pumping rate.

SUMMARY

The relation shown as equation 1 can be used to determine quickly the maximum effects of proposed or predicted pumping in a region and to analyze the significance of these effects before proceeding with a hydrologic study. For example, if the maximum possible drawdowns at various points of interest in a very extensive aquifer indicate no drawdown in the region of recharge, it could be concluded

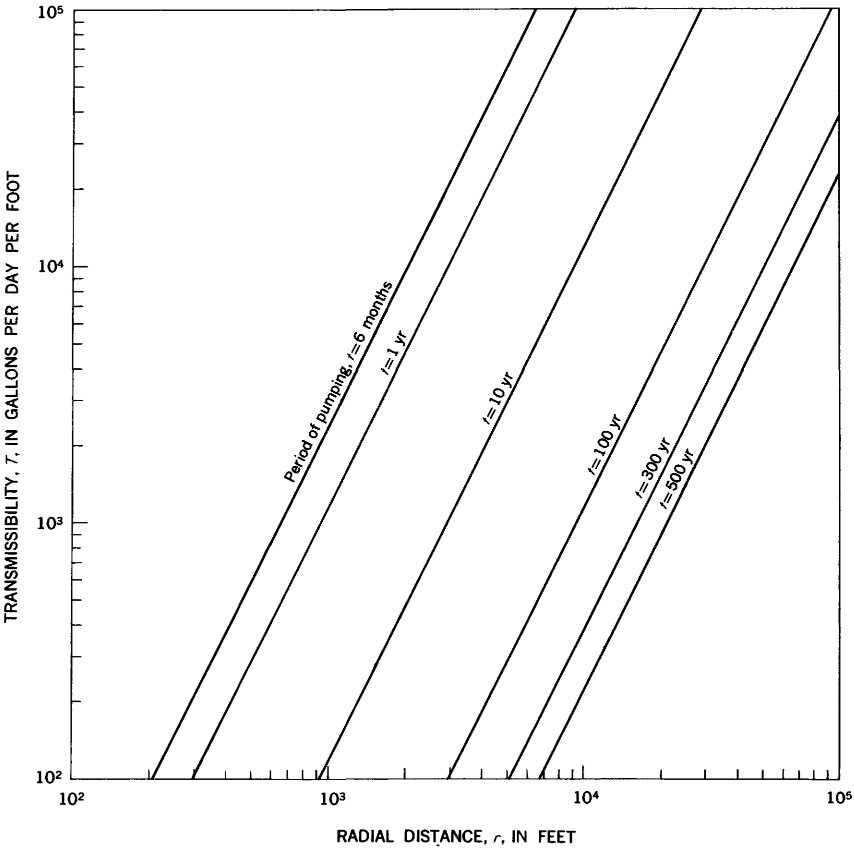

FIGURE 49.—Graph of transmissibility at which drawdown is at a maximum for a given radius and time.

that the problem always would be one of developing ground water from storage and would be independent of any relationships between recharge and the coefficient of transmissibility of the aquifer.

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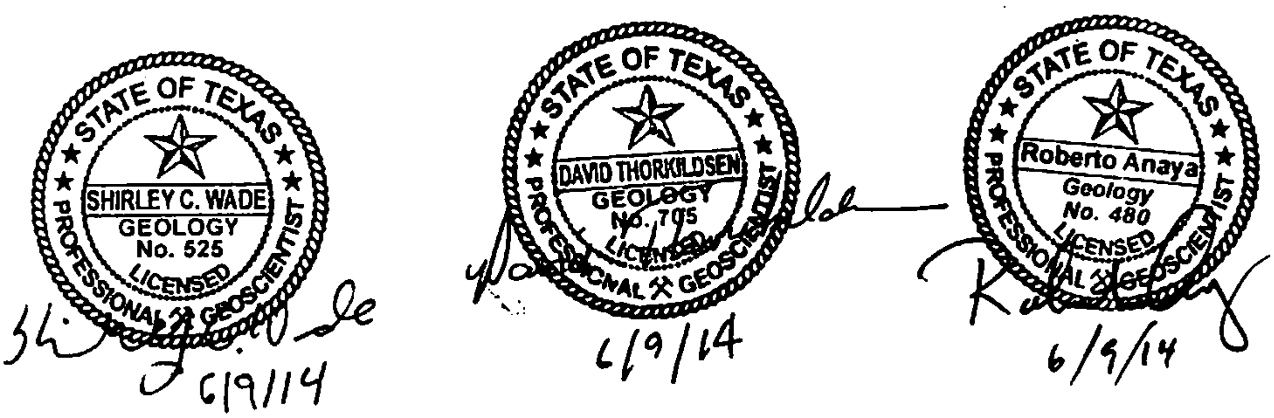
APPENDIX 8

Wade, S., Thorkildsen, D., and Anaya, R., 2014, Texas Water Development Board, Groundwater Resources Division, June 9, 2014

GAM Task 13-037: Total Estimated Recoverable Storage for Aquifers in Groundwater Management Area 14

by Shirley Wade, Ph.D., P.G., David Thorkildsen, P.G., and Roberto Anaya, P.G.
Texas Water Development Board
Groundwater Resources Division
(512) 463-6115[1]
June 09, 2014



The seal appearing on this document were authorized by Shirley C. Wade, P.G. 525, and David Thorkildsen, P.G. 705, and Roberto Anaya, P.G. 480 on June 09, 2014.

The total estimated recoverable storage in this report was calculated as follows: the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson aquifers, the Gulf Coast Aquifer System and the Brazos River Alluvium Aquifer (Shirley Wade); and the San Bernard, Navasota, San Jacinto, and Trinity river alluviums determined as relevant (David Thorkildsen), quality assurance and report preparation (Roberto Anaya).

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[1] Contact information is for Roberto Anaya

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GAM TASK 13-037: TOTAL ESTIMATED RECOVERABLE STORAGE FOR AQUIFERS IN GROUNDWATER MANAGEMENT AREA 14

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Texas Water Development Board
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June 09, 2014

EXECUTIVE SUMMARY:

Texas Water Code, §36.108 (d) (Texas Water Code, 2011) states that, before voting on the proposed desired future conditions for a relevant aquifer within a groundwater management area, the groundwater conservation districts shall consider the total estimated recoverable storage as provided by the executive administrator of the Texas Water Development Board (TWDB) along with other factors listed in §36.108 (d). Texas Administrative Code Rule §356.10 (Texas Administrative Code, 2011) defines the total estimated recoverable storage as the estimated amount of groundwater within an aquifer that accounts for recovery scenarios that range between 25 percent and 75 percent of the porosity-adjusted aquifer volume.

This report discusses the methods, assumptions, and results of an analysis to estimate the total recoverable storage for the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, Gulf Coast, and Brazos River Alluvium aquifers in addition to water-bearing alluvial sediments determined as relevant by Groundwater Management Area 14 groundwater conservation districts for the San Bernard, Navasota, San Jacinto, and Trinity rivers within Groundwater Management Area 14. Tables 1 through 20 summarize the total estimated recoverable storage required by the statute. The total estimated recoverable storage values are for areas within the official extent of the aquifers (and other portions deemed relevant by the groundwater conservation districts) in Groundwater Management Area 14. In addition, areas that currently have adopted desired future conditions but may be declared to be non-relevant are included

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[1] Contact information is for Roberto Anaya

as the total estimated recoverable storage values are needed for the associated explanatory report per Texas Administrative Code Rule §356.31 (b) (Texas Administrative Code, 2011).

DEFINITION OF TOTAL ESTIMATED RECOVERABLE STORAGE:

The total estimated recoverable storage is defined as the estimated amount of groundwater within an aquifer that accounts for recovery scenarios that range between 25 percent and 75 percent of the porosity-adjusted aquifer volume. In other words, we assume that only 25 to 75 percent of groundwater held within an aquifer can be removed by pumping.

The total recoverable storage was estimated for the portion of the aquifers within Groundwater Management Area 14 that lie within the official lateral aquifer boundaries as delineated by George and others (2011). If portions of aquifers outside these boundaries were defined as relevant in the resolution dated August 25, 2010, that adopted the current desired future conditions, then estimates of total recoverable storage reported here include these specific areas. Total estimated recoverable storage values may include a mixture of water quality types, including fresh, brackish, and saline groundwater, because the available data and the existing groundwater availability models do not permit the differentiation between different water quality types. The total estimated recoverable storage values do not take into account the effects of land surface subsidence, degradation of water quality, or any changes to surface water-groundwater interaction that may occur as the result of extracting groundwater from the aquifer.

METHODS:

To estimate the total recoverable storage of an aquifer, we first calculated the total storage in an aquifer within the official and/or relevant aquifer boundary. The total storage is the volume of groundwater removed by pumping that completely drains the aquifer.

Aquifers can be either unconfined or confined (Figure 1). A well screened in an unconfined aquifer will have a water level equal to the water level outside the well or in the aquifer. Thus, unconfined aquifers have water levels within the aquifers. A confined aquifer is bounded by low permeable geologic units at the top and bottom, and the aquifer is under hydraulic pressure above the ambient atmospheric pressure. The water level at a well screened in a confined aquifer will be above the top of the aquifer. As a result, calculation of total storage is also different between unconfined and confined aquifers. For an unconfined aquifer, the total storage is equal to the volume of groundwater removed by pumping that makes the water level fall to the aquifer bottom. For a confined aquifer, the total storage contains two parts. The first part is the groundwater released from the aquifer when the water level falls from above the top of the aquifer to the top of the aquifer. The reduction of hydraulic pressure in the aquifer by pumping causes expansion of groundwater and deformation of aquifer solids. The aquifer is still fully saturated to this point. The second part, just like unconfined aquifer, is the groundwater released from the aquifer when the water level falls from the top to the bottom of the aquifer. Given the same aquifer area and water level drop, the amount of water released in the second part is much greater than the first part. The difference is quantified by two parameters: storativity related to confined aquifers and specific yield related to unconfined aquifers. For example, storativity values range from 10^{-5} to 10^{-3} for most confined aquifers, while the specific yield values can be 0.01 to 0.3 for most unconfined aquifers. The equations for calculating the total storage are presented below:

- for unconfined aquifers

$$Total\ Storage\ = V_{drained} = Area \times S_y \times (Water\ Level - Bottom)$$

- for confined aquifers

$$Total\ Storage\ = V_{confined} + V_{drained}$$

  - confined part

$$V_{confined} = \ Area \times [\ S \times (Water\ Level - Top)]$$

or

$$V_{confined} = \ Area \times [\ S_s\ \times (\mathrm{Top} - \mathrm{Bottom}) \times (Water\ Level - Top)]$$

  - unconfined part

$$V_{drained} = \ Area \times \left[S_y \times (Top - Bottom)\right]$$

where:

- $V_{drained}$ = storage volume due to water draining from the formation (acre-feet)
- $V_{confined}$ = storage volume due to elastic properties of the aquifer and water(acre-feet)
- *Area* = area of aquifer (acre)
- *Water Level* = groundwater elevation (feet above mean sea level)

- *Top* = elevation of aquifer top (feet above mean sea level)
- *Bottom* = elevation of aquifer bottom (feet above mean sea level)
- S_y = specific yield (no units)
- S_s = specific storage (1/feet)
- S = storativity or storage coefficient (no units)

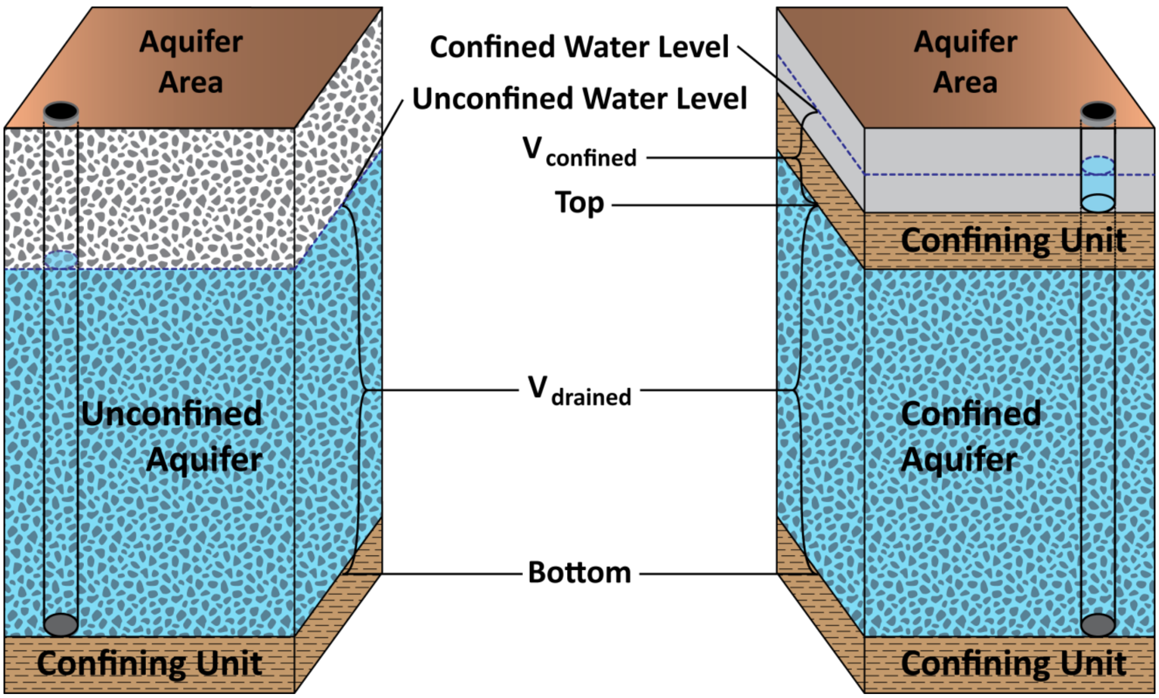

FIGURE 1. SCHEMATIC GRAPH SHOWING THE DIFFERENCE BETWEEN UNCONFINED AND CONFINED AQUIFERS.

As presented in the equations, calculation of the total storage requires data, such as aquifer top, aquifer bottom, aquifer storage properties, and water level. For the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Gulf Coast aquifers we extracted this information from existing groundwater availability model input and output files on a cell-by-cell basis.

For the Brazos River Alluvium Aquifer which does not have a groundwater availability model, we used an analytical approach. For each county, ArcMAP™ was used to estimate the Brazos River Alluvium Aquifer thickness (assuming base of the alluvium and land surface) and average water table depth (Shah and others, 2007; TWDB, 2013). Average Brazos River Alluvium Aquifer saturated thickness for each county was then calculated from average thickness minus average water table depth. Finally we estimated the total storage of the Brazos River

Alluvium Aquifer from average saturated thickness multiplied with area and an assumed specific yield value.

For the water bearing alluvial sediments determined as relevant for the San Bernard, Navasota, San Jacinto, and Trinity rivers, which do not have a groundwater availability model, we used an analytical approach. For each county, ArcMAP™ was used to calculate the acreage area for the delineated spatial extents of each of the river alluvia. The saturated thickness was then estimated based on water well and water-level data from the TWDB groundwater database for each of the acreage areas of the water bearing alluvial sediments determined as relevant (TWDB, 2011). Finally, we estimated the total storage for each of the river alluvia using average saturated thicknesses multiplied with associated areas and an assumed uniformly distributed specific yield values reported in the literature (Baker and others, 1974; Bradley, 2011; Cronin and Wilson, 1967; Johnson, 1967; Wilson, 1967).

The recoverable storage for each of the aquifers listed above was the product of its total storage and an estimated factor ranging from 25 percent to 75 percent.

PARAMETERS AND ASSUMPTIONS:

Carrizo-Wilcox, Queen City, and Sparta aquifers

- We used version 2.02 of the groundwater availability model for the central part of the Carrizo-Wilcox, Queen City, and Sparta aquifers to estimate the total recoverable storage for the Carrizo-Wilcox, Queen City, and Sparta aquifers. See Dutton and others (2003) and Kelley and others (2004) for assumptions and limitations of the groundwater availability model.
- This groundwater availability model includes eight layers which generally represent the Sparta Aquifer (Layer 1), the Weches Confining Unit (Layer 2), the Queen City Aquifer (Layer 3), the Reklaw Confining Unit (Layer 4), the Carrizo Formation (Layer 5), the Upper Wilcox Formation or Calvert Bluff Formation (Layer 6), the Middle Wilcox Formation or Simsboro Formation (Layer 7), and the Lower Wilcox Formation or Hooper Formation (Layer 8). To develop the estimates for the total estimated recoverable storage, we used Layer 1 (Sparta Aquifer), Layer 3 (Queen City Aquifer), and Layers 5 through 8 (Carrizo-Wilcox Aquifer system).

- The down-dip boundary of the model is based on the location of the Wilcox Growth Fault Zone, which is considered to be a barrier to flow (Kelley and others, 2004). This boundary is relatively deep and in the portion of the aquifer that is characterized as brackish to saline; consequently, the model includes parts of the formation beyond potable portions of the aquifer (Dutton and others, 2003). The groundwater in the official extent of the Carrizo-Wilcox, Queen City, and Sparta aquifers ranges from fresh to brackish in composition (Kelley and others, 2004).
- The groundwater availability model for the northern part of the Carrizo-Wilcox, Queen City, and Sparta aquifers was not considered for analysis because the active model area was more adequately covered by the overlap of the active model area for the central part of the Carrizo-Wilcox, Queen City, and Sparta aquifers.

Yegua-Jackson Aquifer and the Catahoula Formation portion of the Gulf Coast Aquifer System

- We used version 1.01 of the groundwater availability model for the Yegua-Jackson Aquifer to estimate the total recoverable storages of the Yegua-Jackson Aquifer. See Deeds and others (2010) for assumptions and limitations of the groundwater availability model.
- This groundwater availability model includes five layers which represent the outcrop section for the Yegua-Jackson Aquifer and the Catahoula Formation and other younger overlying units (Layer 1), the upper portion of the Jackson Group (Layer 2), the lower portion of the Jackson Group (Layer 3), the upper portion of the Yegua Group (Layer 4), and the lower portion of the Yegua Group (Layer 5). To develop the estimates for the total estimated recoverable storage in the Yegua-Jackson Aquifer, we used layers 1 through 5; however, we only used model cells in Layer 1 that represent the outcrop area of the Yegua-Jackson Aquifer.
- The down-dip boundary for the Yegua-Jackson Aquifer in this model was set to approximately coincide with the extent of the available geologic data, well beyond any active portion (groundwater use) of the aquifer (Deeds and others, 2010). Consequently, the model extends into zones of brackish and saline groundwater. The groundwater in the official extent of the Yegua-Jackson Aquifer ranges from fresh to brackish in composition (Deeds and others, 2010).

- For Jasper, Newton, Polk, Tyler, and Washington counties we used the official active areas of the groundwater availability model to estimate the total recoverable storage for the Yegua-Jackson Aquifer. However, for Grimes and Walker counties the desired future condition statement adopted on August 25, 2010,o included confined and brackish confined areas outside of the official aquifer area. Geographic information for those areas was submitted with the desired future condition statement. We used that information in this assessment to estimate the total recoverable storage for Grimes and Walker counties for layers 2 through 5 which represent the confined parts of the Yegua-Jackson units.

Gulf Coast Aquifer System

- We used version 3.01 of the groundwater availability model for the northern portion of the Gulf Coast Aquifer system for this analysis. See Kasmarek (2013) for assumptions and limitations of the model.
- The model has four layers which represent the Chicot Aquifer (Layer 1), the Evangeline Aquifer (Layer 2), the Burkeville confining unit (Layer 3), and the Jasper Aquifer and parts of the Catahoula Formation in direct hydrologic communication with the Jasper Aquifer (Layer 4).
- The southeastern boundary of flow in each hydrogeologic unit of the model was set at the down-dip limit of freshwater (defined in this case to be up to 10,000 milligrams per liter of total dissolved solids; Kasmarek, 2013).

Brazos River Alluvium Aquifer

- The Brazos River Alluvium Aquifer is under water table conditions in most places (George and others, 2011).
- The thickness of the Brazos River Alluvium Aquifer is based on a U.S. Geological Survey electromagnetic and resistivity imaging project (Shah and others, 2007).
- Water levels are from the TWDB groundwater database http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp accessed in July 2013. The three latest years of water level data were used to estimate the average water table depth for each county.
- We used a specific yield value of 0.15 from Cronin and others (1967).

San Bernard River Alluvium

- The areal extent of the San Bernard River Alluvium within Austin County was calculated to be 2,792 acres (USGS and TWDB, 2006).
- Average saturated thickness of the water bearing alluvium determined as relevant was calculated to be 20 feet (Thorkildsen and Backhouse, 2011).
- We used a specific yield value of 0.15 (Wilson, 1967).

Navasota River Alluvium

- The areal extent of the Navasota River Alluvium within Grimes County was calculated to be 12,004 acres (USGS and TWDB, 2006).
- Based on water well and water-level data from the TWDB groundwater database near the confluence of the Navasota and Brazos Rivers the water bearing alluvium determined as relevant has an average saturated thickness of 32 feet (TWDB, 2011).
- We used a specific yield value of 0.15 (Baker and others, 1974; Bradley, 2011; Johnson, 1967).

San Jacinto River Alluvium

- The areal extent of the San Jacinto River Alluvium within Walker County was calculated to be 7,399 acres (USGS and TWDB, 2006).
- Based on water well and water-level data from the TWDB groundwater database the water bearing alluvium determined as relevant has an average saturated thickness of 20 feet (TWDB, 2011).
- We used a specific yield value of 0.15 (Cronin and Wilson, 1967; Johnson, 1967).

Trinity River Alluvium

- The areal extent of the Trinity River Alluvium within Walker County was calculated to be 19,873 acres (USGS and TWDB, 2006).
- Based on water well and water-level data from the TWDB groundwater database the water bearing alluvium determined as relevant has an average saturated thickness of 23 feet (TWDB, 2011).

- We used a specific yield value of 0.15 (Cronin and Wilson, 1967; Johnson, 1967).

RESULTS:

Tables 1 through 20 summarize the total estimated recoverable storage required by statute. The county and groundwater conservation district total storage estimates are rounded to two or three significant digits. Figures 2 through 11 indicate the extent of the groundwater availability models or aquifer boundaries deemed relevant by the groundwater conservation districts in Groundwater Management Area 14 for the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, Gulf Coast, and Brazos River Alluvium aquifers as well as the water bearing alluvial sediments determined as relevant by Groundwater Management Area 14 groundwater conservation districts for the San Bernard, Navasota, San Jacinto, and Trinity rivers.

TABLE 1. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE CARRIZO-WILCOX AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Grimes	14,500,000	3,625,000	10,875,000
Walker	5,040,000	1,260,000	3,780,000
Washington	264,000	66,000	198,000
Total	19,804,000	4,951,000	14,853,000

TABLE 2. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT[2] FOR THE CARRIZO-WILCOX AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
No District	264,000	66,000	198,000
Bluebonnet GCD	19,500,000	4,875,000	14,625,000
Total	19,764,000	4,941,000	14,823,000

[2] The total estimated recoverable storage values by groundwater conservation district and county for an aquifer may not be the same because the numbers have been rounded to three significant digits.

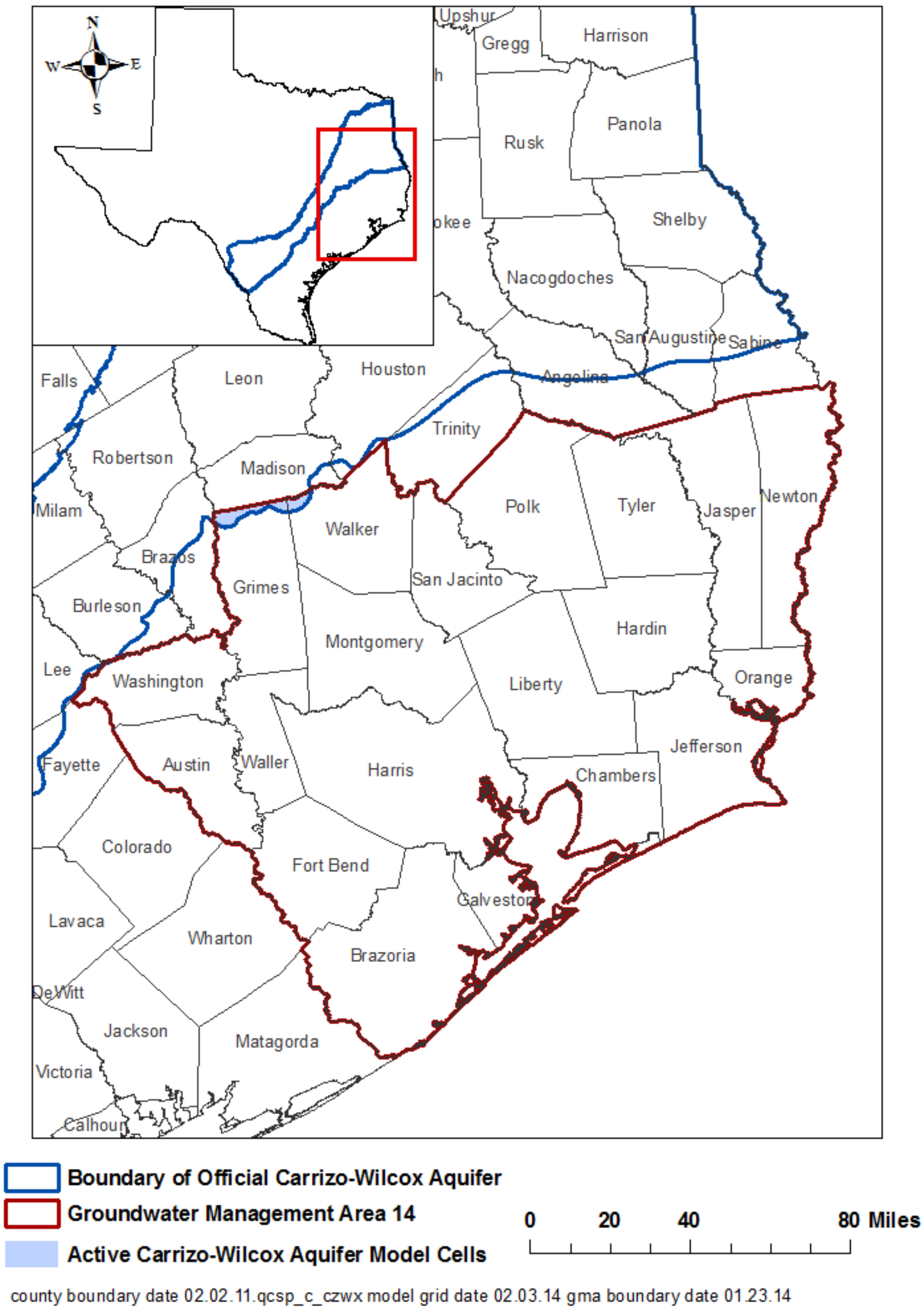

FIGURE 2. EXTENT OF THE GROUNDWATER AVAILABILITY MODEL FOR THE CENTRAL PART OF THE CARRIZO-WILCOX, QUEEN CITY, AND SPARTA AQUIFERS USED TO ESTIMATE TOTAL RECOVERABLE STORAGE FOR THE CARRIZO-WILCOX AQUIFER (TABLES 1 AND 2) WITHIN GROUNDWATER MANAGEMENT AREA 14.

TABLE 3. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE QUEEN CITY AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Grimes	4,970,000	1,242,500	3,727,500
Walker	624,000	156,000	468,000
Washington	4,330,000	1,082,500	3,247,500
Total	9,924,000	2,481,000	7,443,000

TABLE 4. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT[3] FOR THE QUEEN CITY AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
No District	4,330,000	1,082,500	3,247,500
Bluebonnet GCD	5,590,000	1,397,500	4,192,500
Total	9,920,000	2,480,000	7,440,000

[3] The total estimated recoverable storage values by groundwater conservation district and county for an aquifer may not be the same because the numbers have been rounded to three significant digits.

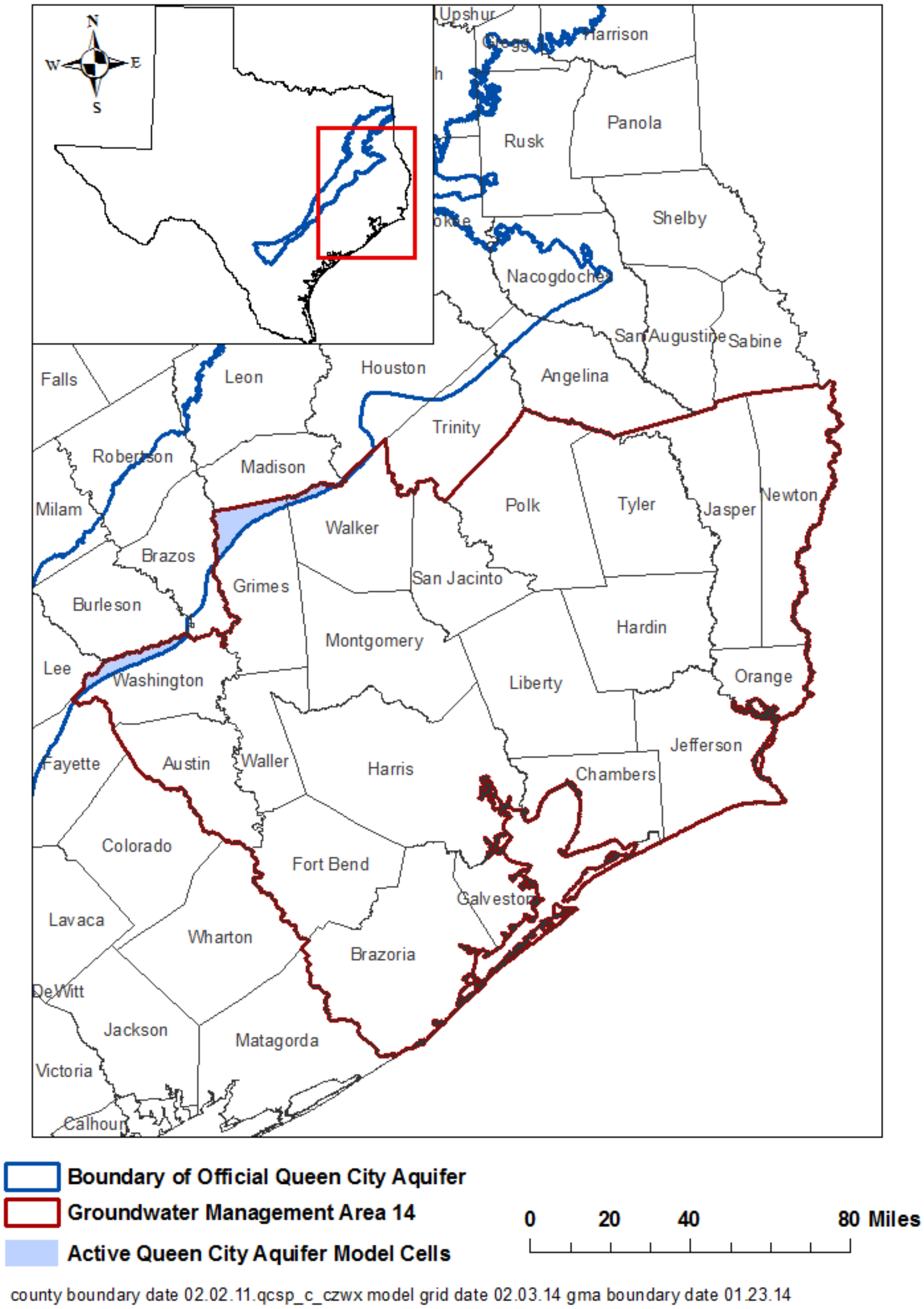

FIGURE 3. EXTENT OF THE GROUNDWATER AVAILABILITY MODEL FOR THE CENTRAL PART OF THE CARRIZO-WILCOX, QUEEN CITY, AND SPARTA AQUIFERS USED TO ESTIMATE TOTAL RECOVERABLE STORAGE FOR THE QUEEN CITY AQUIFER (TABLES 3 AND 4) WITHIN GROUNDWATER MANAGEMENT AREA 14.

TABLE 5. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE SPARTA AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Grimes	11,600,000	2,900,000	8,700,000
Walker	8,550,000	2,137,500	6,412,500
Washington	1,860,000	465,000	1,395,000
Total	22,010,000	5,502,500	16,507,500

TABLE 6. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT[4] FOR THE SPARTA AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
No District	1,860,000	465,000	1,395,000
Bluebonnet GCD	20,100,000	5,025,000	15,075,000
Total	21,960,000	5,490,000	16,470,000

[4] The total estimated recoverable storage values by groundwater conservation district and county for an aquifer may not be the same because the numbers have been rounded to three significant digits.

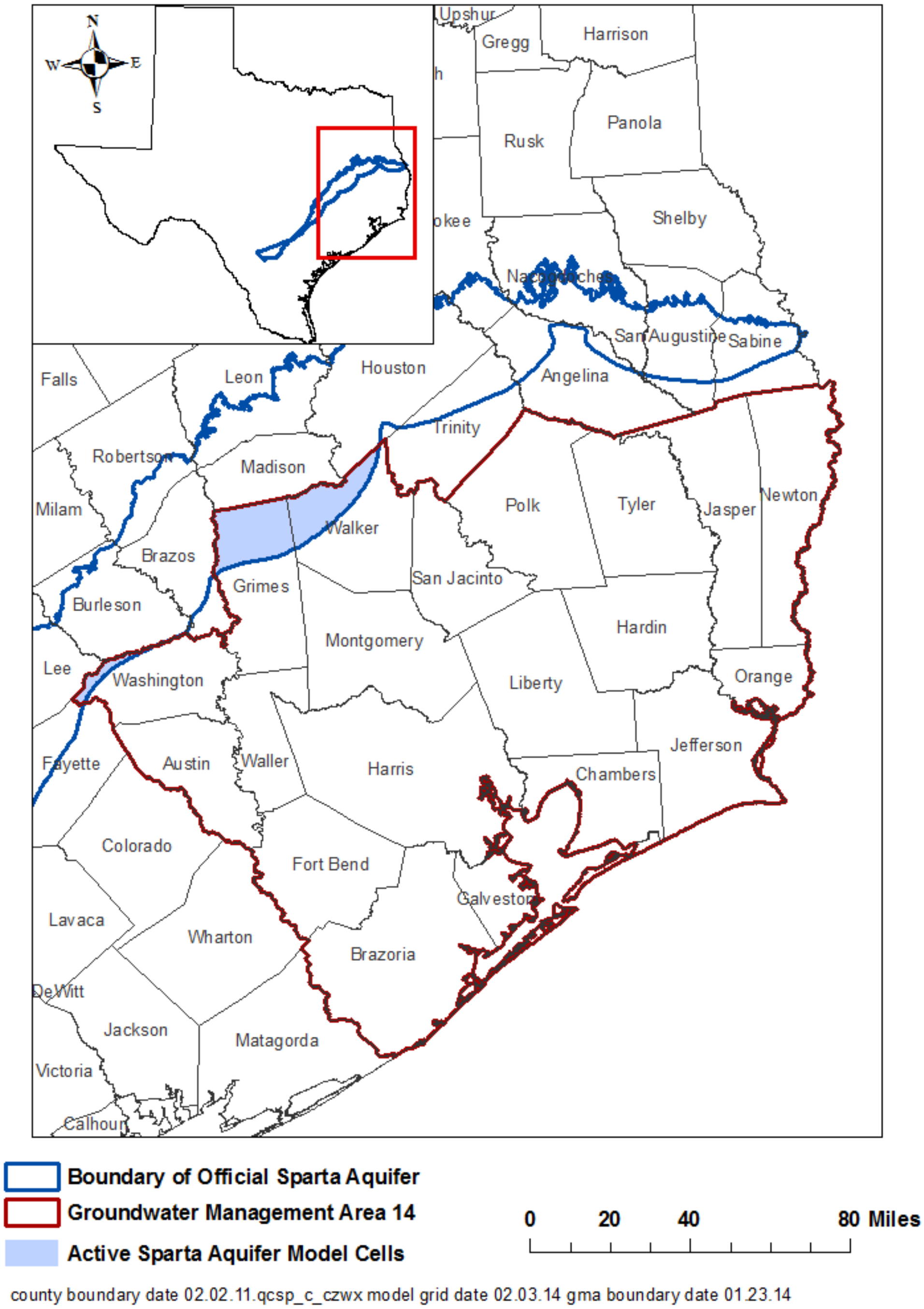

FIGURE 4. EXTENT OF THE GROUNDWATER AVAILABILITY MODEL FOR THE CENTRAL PART OF THE CARRIZO-WILCOX, QUEEN CITY, AND SPARTA AQUIFERS USED TO ESTIMATE TOTAL RECOVERABLE STORAGE FOR THE SPARTA AQUIFER (TABLES 5 AND 6) WITHIN GROUNDWATER MANAGEMENT AREA 14.

TABLE 7. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE YEGUA-JACKSON AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Grimes	94,900,000	23,725,000	71,175,000
Jasper	6,930,000	1,732,500	5,197,500
Newton	1,270,000	317,500	952,500
Polk	27,900,000	6,975,000	20,925,000
Tyler	8,650,000	2,162,500	6,487,500
Walker	103,000,000	25,750,000	77,250,000
Washington	12,400,000	3,100,000	9,300,000
Total	255,050,000	63,762,500	191,287,500

TABLE 8. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT[5] FOR THE YEGUA-JACKSON AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
No District	12,400,000	3,100,000	9,300,000
Bluebonnet GCD	198,000,000	49,500,000	148,500,000
Lower Trinity GCD	28,000,000	7,000,000	21,000,000
Southeast Texas GCD	16,900,000	4,225,000	12,675,000
Total	255,300,000	63,825,000	191,475,000

[5] The total estimated recoverable storage values by groundwater conservation district and county for an aquifer may not be the same because the numbers have been rounded to three significant digits.

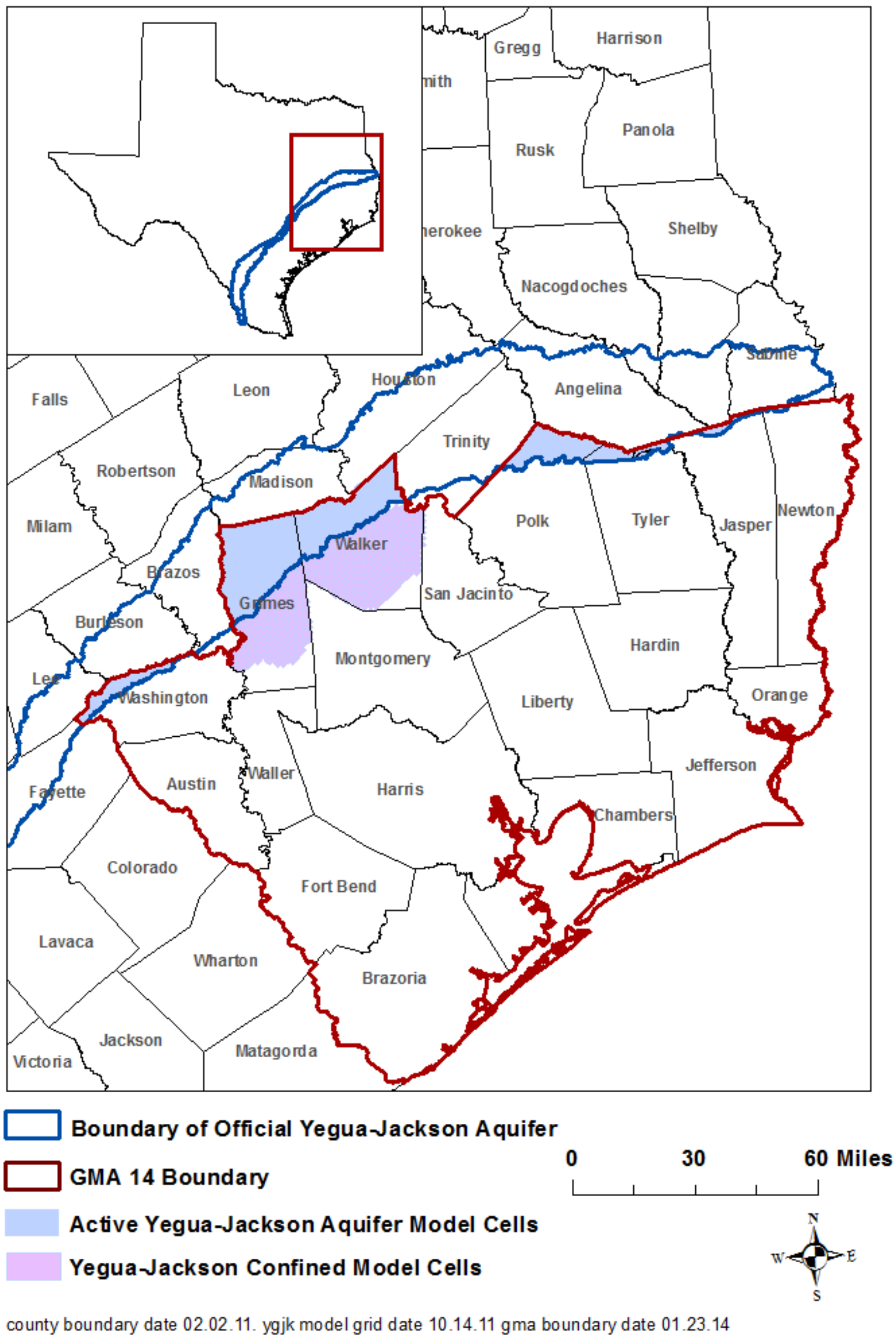

FIGURE 5. EXTENT OF THE GROUNDWATER AVAILABILITY MODEL FOR THE YEGUA-JACKSON AQUIFER USED TO ESTIMATE TOTAL RECOVERABLE STORAGE (TABLES 7 AND 8) FOR THE YEGUA-JACKSON AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14.

TABLE 9. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE GULF COAST AQUIFER SYSTEM WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Austin	80,000,000	20,000,000	60,000,000
Brazoria	330,000,000	82,500,000	247,500,000
Chambers	130,000,000	32,500,000	97,500,000
Fort Bend	170,000,000	42,500,000	127,500,000
Galveston	81,000,000	20,250,000	60,750,000
Grimes	35,000,000	8,750,000	26,250,000
Hardin	190,000,000	47,500,000	142,500,000
Harris	380,000,000	95,000,000	285,000,000
Jasper	140,000,000	35,000,000	105,000,000
Jefferson	170,000,000	42,500,000	127,500,000
Liberty	250,000,000	62,500,000	187,500,000
Montgomery	180,000,000	45,000,000	135,000,000
Newton	120,000,000	30,000,000	90,000,000
Orange	61,000,000	15,250,000	45,750,000
Polk	110,000,000	27,500,000	82,500,000
San Jacinto	95,000,000	23,750,000	71,250,000
Tyler	120,000,000	30,000,000	90,000,000
Walker	32,000,000	8,000,000	24,000,000
Waller	80,000,000	20,000,000	60,000,000
Washington	22,000,000	5,500,000	16,500,000
Total	2,776,000,000	694,000,000	2,082,000,000

TABLE 10. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT[6] FOR THE GULF COAST AQUIFER SYSTEM WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
No District	640,000,000	160,000,000	480,000,000
Bluebonnet GCD	230,000,000	57,500,000	172,500,000
Brazoria County GCD	330,000,000	82,500,000	247,500,000
Fort Bend Subsidence District	170,000,000	42,500,000	127,500,000
Harris-Galveston Coastal Subsidence District	460,000,000	115,000,000	345,000,000
Lone Star GCD	180,000,000	45,000,000	135,000,000
Lower Trinity GCD	200,000,000	50,000,000	150,000,000
Southeast Texas GCD	570,000,000	142,500,000	427,500,000
Total	2,780,000,000	695,000,000	2,085,000,000

[6] The total estimated recoverable storage values by groundwater conservation district and county for an aquifer may not be the same because the numbers have been rounded to two significant digits.

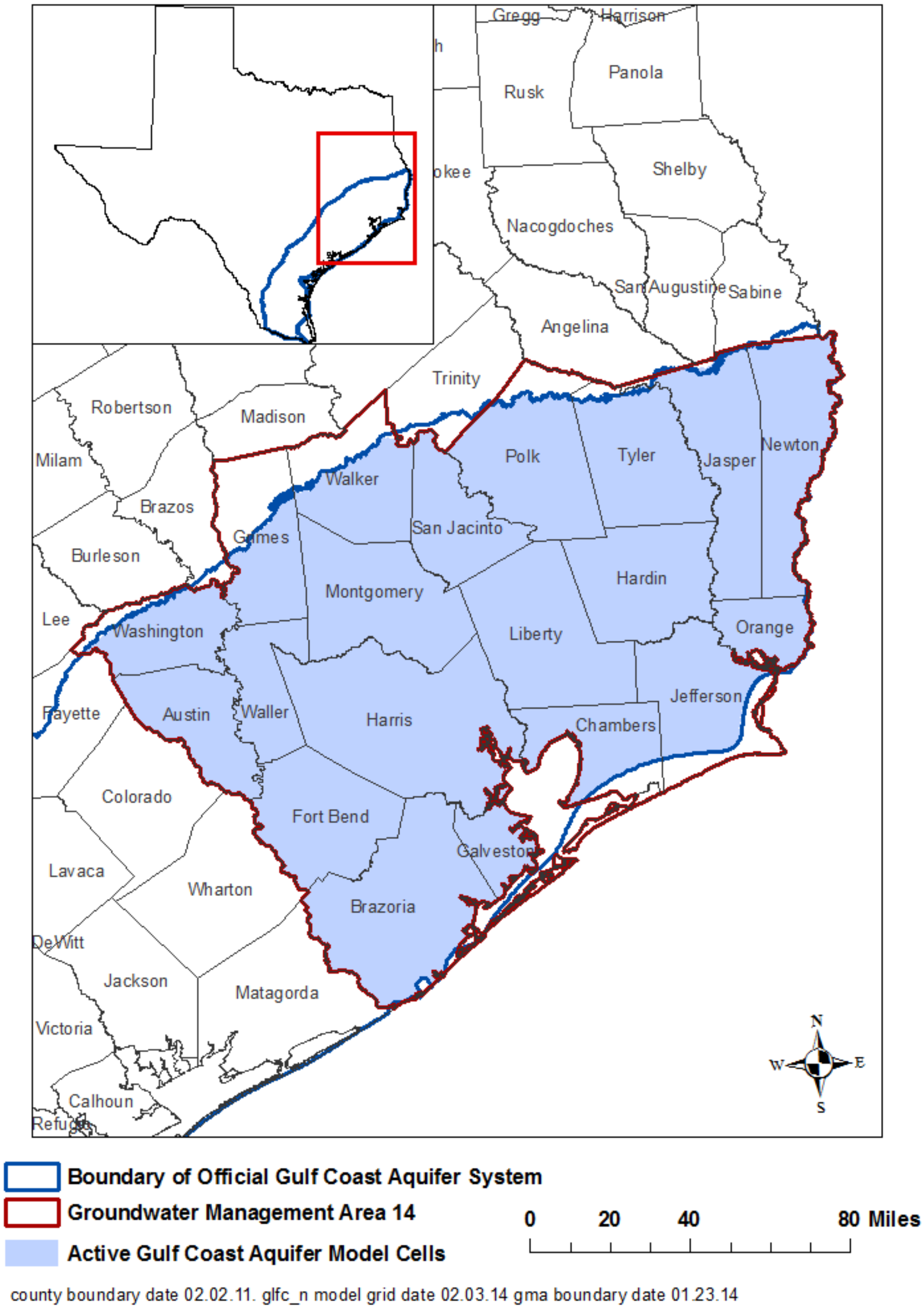

FIGURE 6. EXTENT OF THE GROUNDWATER AVAILABILITY MODEL FOR THE NORTHERN PART OF THE GULF COAST AQUIFER SYSTEM USED TO ESTIMATE TOTAL RECOVERABLE STORAGE (TABLES 9 AND 10) FOR THE GULF COAST AQUIFER SYSTEM WITHIN GROUNDWATER MANAGEMENT AREA 14.

TABLE 11. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE BRAZOS RIVER ALLUVIUM AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Austin	220,000	55,000	165,000
Fort Bend	1,010,000	252,500	757,500
Grimes	74,700	18,675	56,025
Waller	412,000	103,000	309,000
Washington	179,000	44,750	134,250
Total	1,895,700	473,925	1,421,775

TABLE 12. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT[7] FOR THE BRAZOS RIVER ALLUVIUM AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO THREE SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
No District	179,140	179,000	44,750
Bluebonnet GCD	707,000	176,750	530,250
Fort Bend Subsidence District	1,010,000	252,500	757,500
Total	1,896,000	474,000	1,422,000

[7] The total estimated recoverable storage values by groundwater conservation district and county for an aquifer may not be the same because the numbers have been rounded to three significant digits.

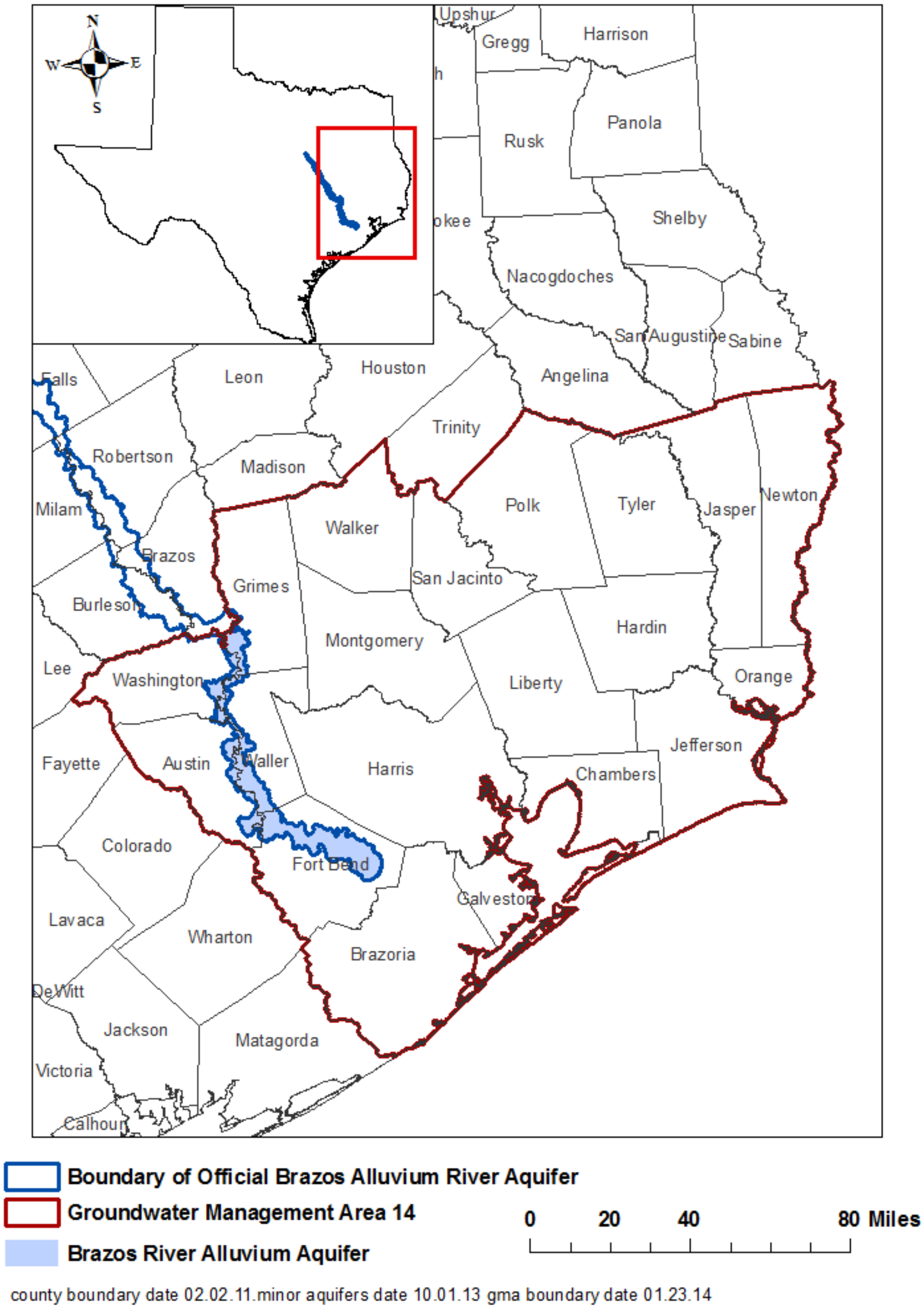

FIGURE 7. EXTENT OF THE BRAZOS RIVER ALLUVIUM AQUIFER USED TO ESTIMATE TOTAL RECOVERABLE STORAGE (TABLES 11 AND 12) FOR THE BRAZOS RIVER ALLUVIUM AQUIFER WITHIN GROUNDWATER MANAGEMENT AREA 14.

TABLE 13. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE SAN BERNARD RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Austin	8,400	2,100	6,300
Total	8,400	2,100	6,300

TABLE 14. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT FOR THE SAN BERNARD RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Bluebonnet GCD	8,400	2,100	6,300
Total	8,400	2,100	6,300

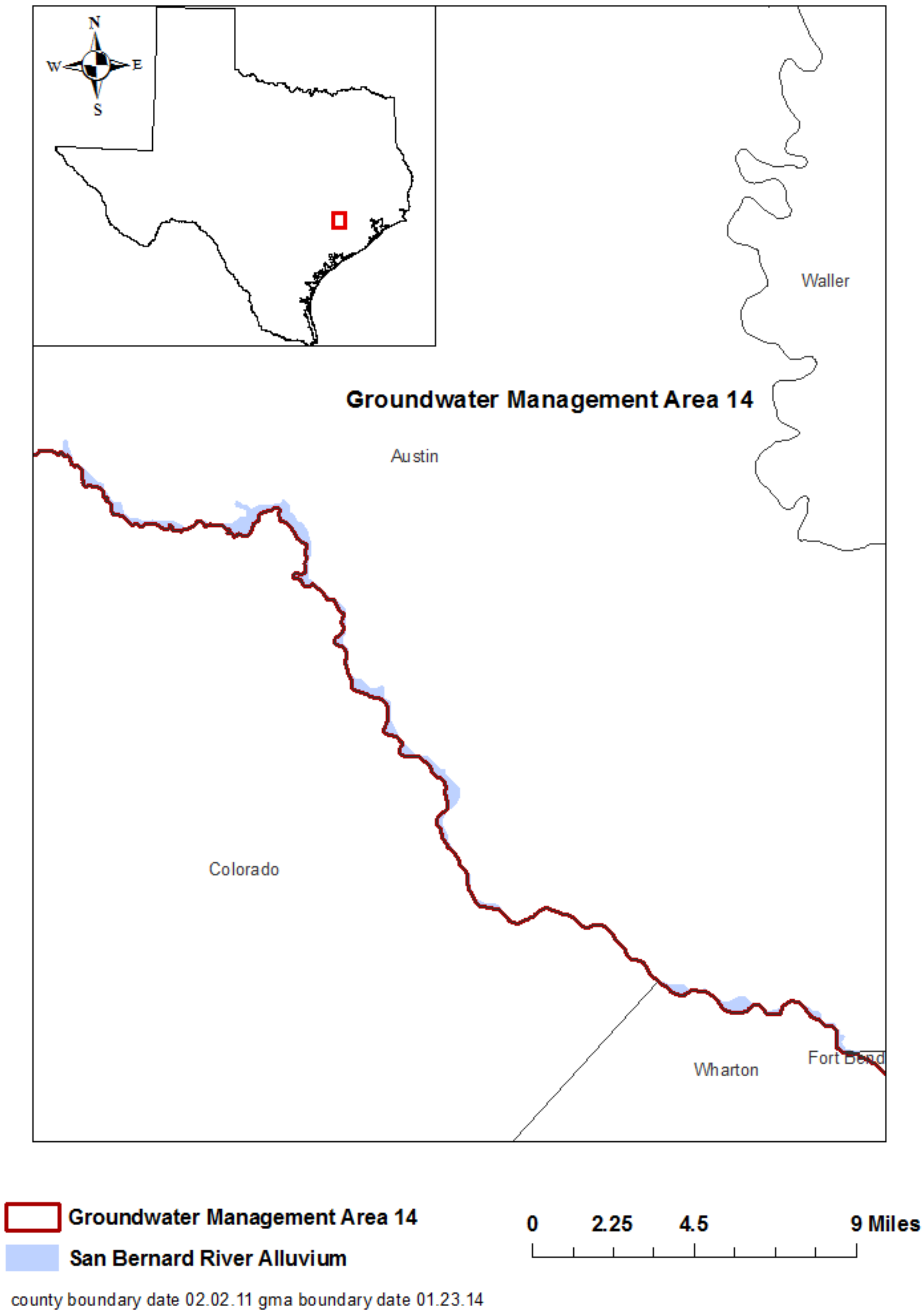

FIGURE 8. EXTENT OF THE SAN BERNARD RIVER ALLUVIUM DETERMINED AS RELEVANT IN AUSTIN COUNTY USED TO ESTIMATE TOTAL RECOVERABLE STORAGE (TABLES 13 AND 14) FOR THE SAN BERNARD RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14.

TABLE 15. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE NAVASOTA RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Grimes	58,000	14,500	43,500
Total	58,000	14,500	43,500

TABLE 16. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT FOR THE NAVASOTA RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Bluebonnet GCD	58,000	14,500	43,500
Total	58,000	14,500	43,500

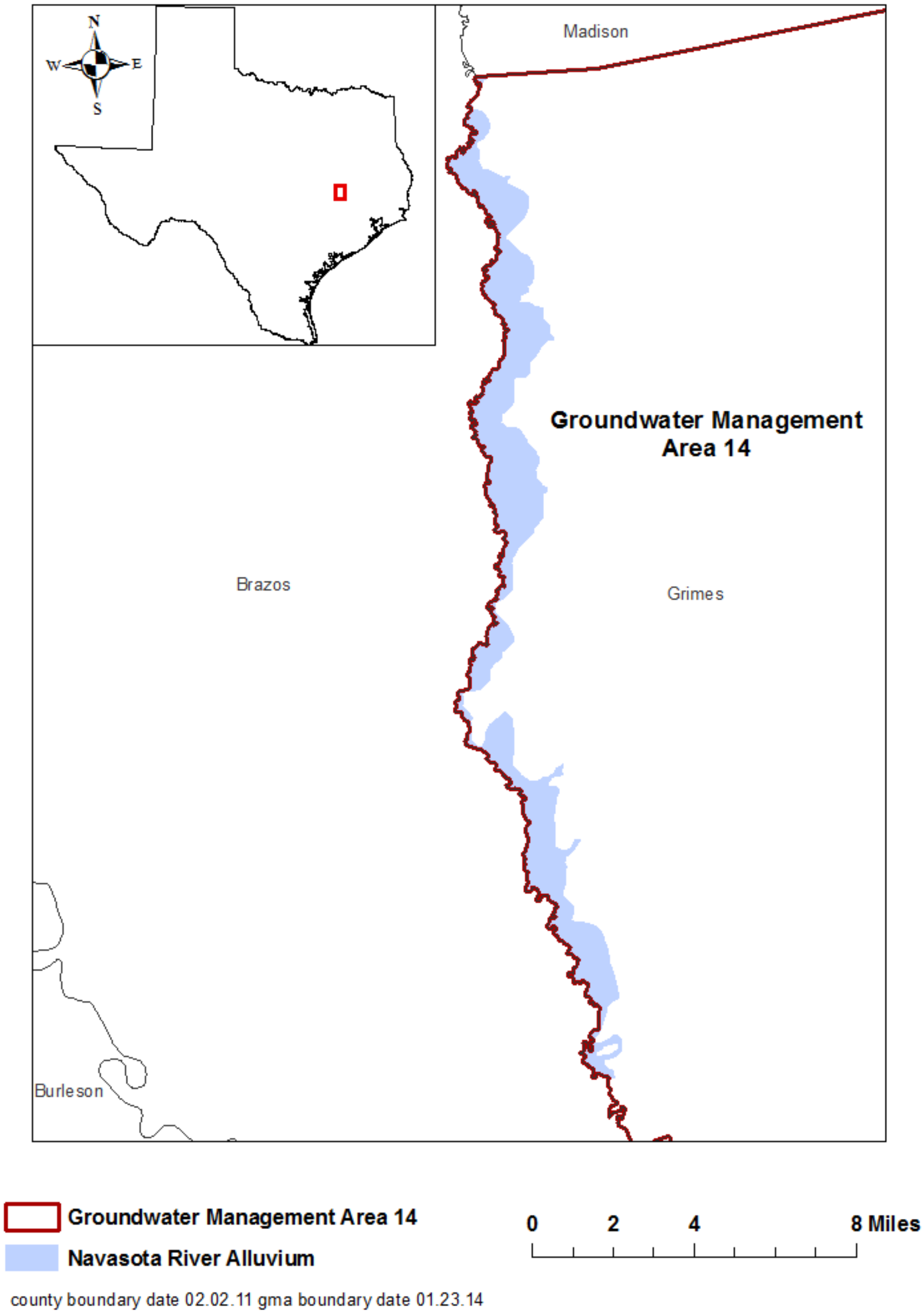

FIGURE 9. EXTENT OF THE NAVASOTA RIVER ALLUVIUM DETERMINED AS RELEVANT IN GRIMES COUNTY USED TO ESTIMATE TOTAL RECOVERABLE STORAGE (TABLES 15 AND 16) FOR NAVASOTA RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14.

TABLE 17. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE SAN JACINTO RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Walker	22,000	5,500	16,500
Total	22,000	5,500	16,500

TABLE 18. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT FOR THE SAN JACINTO RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Bluebonnet GCD	22,000	5,500	16,500
Total	22,000	5,500	16,500

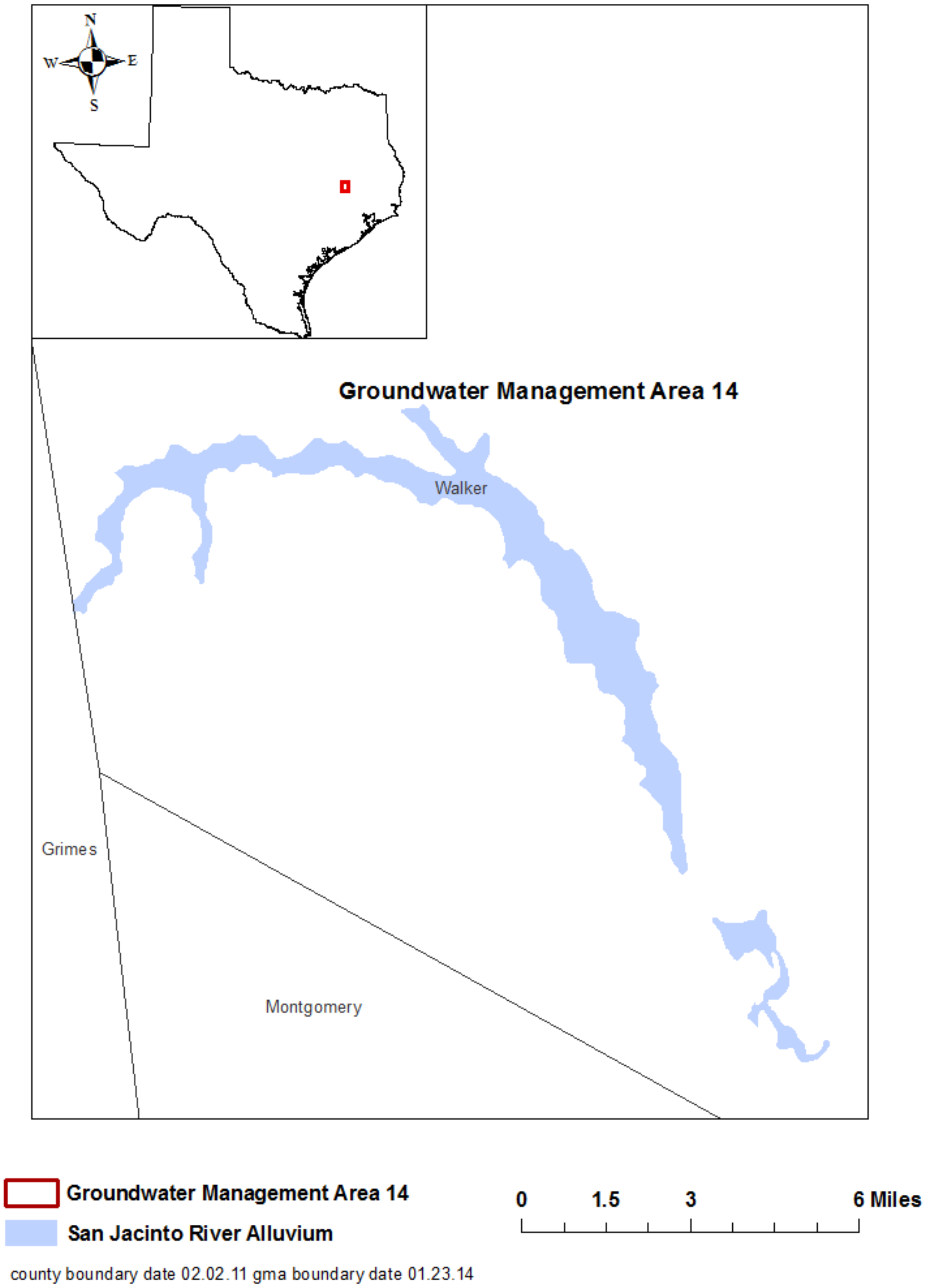

FIGURE 10. EXTENT OF THE SAN JACINTO RIVER ALLUVIUM DETERMINED AS RELEVANT IN WALKER COUNTY USED TO ESTIMATE TOTAL RECOVERABLE STORAGE (TABLES 17 AND 18) FOR THE SAN JACINTO RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14.

TABLE 19. TOTAL ESTIMATED RECOVERABLE STORAGE BY COUNTY FOR THE TRINITY RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14. COUNTY TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

County	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Walker	69,000	17,250	51,750
Total	69,000	17,250	51,750

TABLE 20. TOTAL ESTIMATED RECOVERABLE STORAGE BY GROUNDWATER CONSERVATION DISTRICT FOR THE TRINTY RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14. GROUNDWATER CONSERVATION DISTRICT TOTAL ESTIMATES ARE ROUNDED TO TWO SIGNIFICANT DIGITS.

Groundwater Conservation District (GCD)	*Total Storage (acre-feet)*	*25 percent of Total Storage (acre-feet)*	*75 percent of Total Storage (acre-feet)*
Bluebonnet GCD	69,000	17,250	51,750
Total	69,000	17,250	51,750

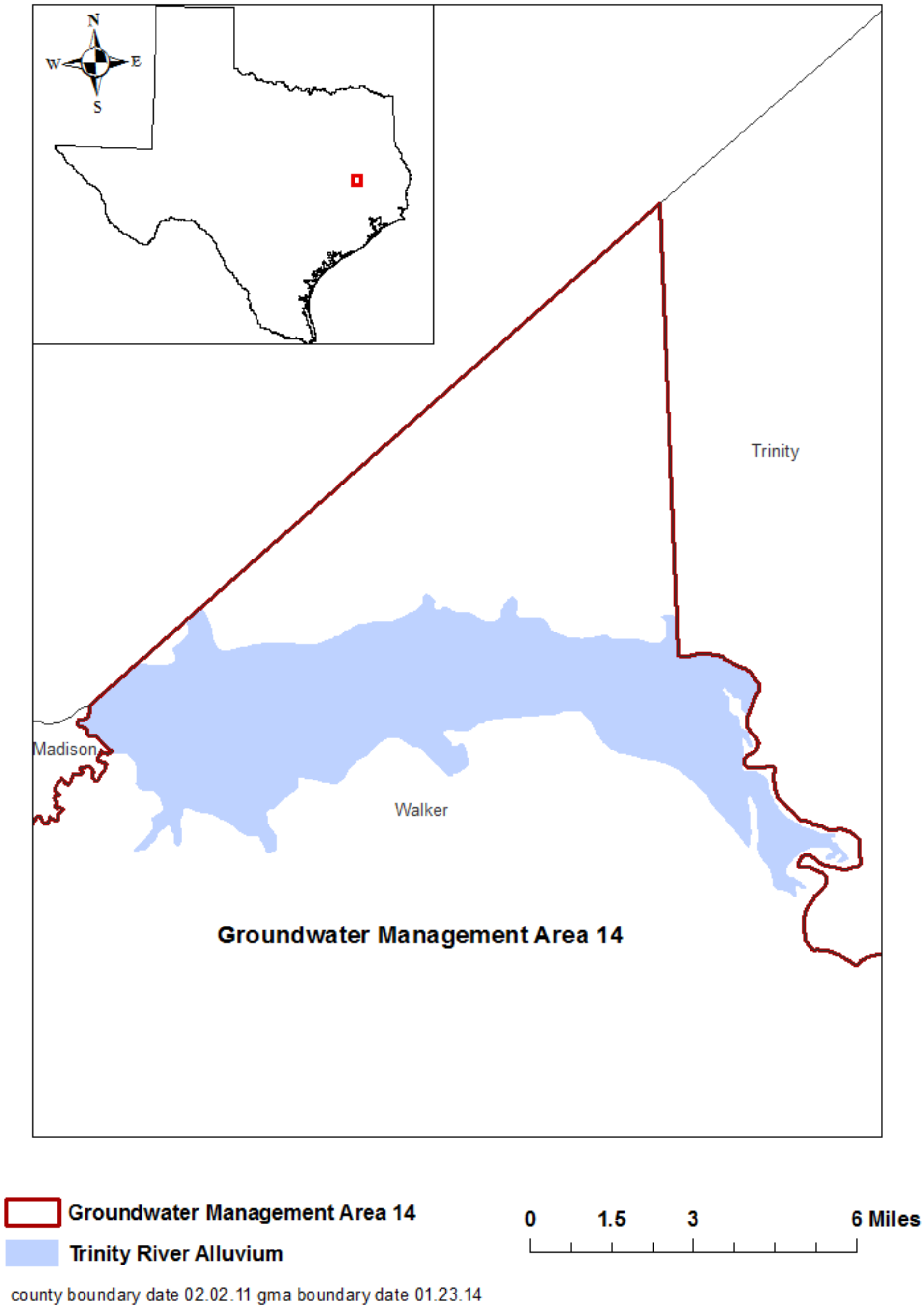

FIGURE 11. EXTENT OF THE TRINITY RIVER ALLUVIUM DETERMINED AS RELEVANT IN WALKER COUNTY USED TO ESTIMATE TOTAL RECOVERABLE STORAGE (TABLES 19 AND 20) FOR THE TRINITY RIVER ALLUVIUM DETERMINED AS RELEVANT WITHIN GROUNDWATER MANAGEMENT AREA 14.

LIMITATIONS

The groundwater models used in completing this analysis are the best available scientific tools that can be used to meet the stated objective(s). To the extent that this analysis will be used for planning purposes and/or regulatory purposes related to pumping in the past and into the future, it is important to recognize the assumptions and limitations associated with the use of the results. In reviewing the use of models in environmental regulatory decision making, the National Research Council (2007) noted:

> *"Models will always be constrained by computational limitations, assumptions, and knowledge gaps. They can best be viewed as tools to help inform decisions rather than as machines to generate truth or make decisions. Scientific advances will never make it possible to build a perfect model that accounts for every aspect of reality or to prove that a given model is correct in all respects for a particular regulatory application. These characteristics make evaluation of a regulatory model more complex than solely a comparison of measurement data with model results."*

Because the application of the groundwater model was designed to address regional scale questions, the results are most effective on a regional scale. The TWDB makes no warranties or representations relating to the actual conditions of any aquifer at a particular location or at a particular time.

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Thorkildsen, D., and Backhouse, S., 2011, GTA Aquifer Assessment 10-33 MAG: Texas Water Development Board, GTA Aquifer Assessment 10-33 MAG Report, 11 p.

USGS and TWDB, 2006, Digital Geologic Atlas of Texas: U.S. Geological Survey and Texas Natural Resources Information System., http://www.twdb.texas.gov/groundwater/aquifer/GAT/index.asp.

Wilson, C. A., 1967, Ground-water resources of Austin and Waller counties, Texas: Texas Water Development Board Report 68, 231 p., http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R68/report68.asp.

Exhibit 5

WATER SUPPLY AGREEMENT

This Water Supply Agreement ("Agreement") is made and entered into effective as of the ____ day of ___________________ 2015 ("Effective Date"), by and between Daniel Ayres dba Wild Springs Ranch ("Supplier"), a ____________________________, and __________________________ ("Purchaser"), a ________________________________.

RECITALS

1. Supplier has the right to drill and produce water from wells on the Wild Springs Ranch Property in Newton County, Texas ("Property") identified on the attached Exhibit "A".

2. Purchaser is willing to purchase, and Supplier is willing to make available, water produced from the Wild Springs Ranch Property subject to the terms and conditions of this Agreement.

3. Purchaser will take and use water produced from the Wild Springs Ranch Property subject to all-applicable rules and regulations of state and federal agencies.

AGREEMENT

For and in consideration of the mutual promises, covenants, obligations, and benefits described in this Agreement, Supplier and Purchaser agree as follows:

SECTION 1. TERM

This Agreement shall remain in force and effect for a period of ten (10) years commencing on the Effective Date (the "Initial Term") unless terminated sooner as provided herein. Purchaser shall have an option of renewing this Agreement for a period of ten (10) years at the end of the Initial Term (the "Extended Term") subject to Supplier and Purchaser agreeing to the amount of any payments to Supplier during the Extended Term. However, if Purchaser is producing water at the end of the Initial Term, the contract will continue to be in force under the same terms and conditions established in the Initial Term. This will be considered a "hold by production" lease. The lease will be in force after the Initial Term as long as production is maintained on a yearly basis or Monthly Minimum Payments are paid to Supplier.

SECTION 2. AGREED SUSTAINABLE PRODUCTION AMOUNT

Supplier will undertake to drill and complete wells on the Wild Spring Ranch Property to provide water to Purchaser in an amount not to exceed Six Hundred and Fifty Four (654) acre-feet of water per year unless otherwise agreed to. Subsequent to drilling and completing each well Supplier and Purchaser shall have the annual estimated sustainable production capacity in acre-feet of the well field determined by a registered professional engineer or a certified groundwater professional with expertise in hydraulics and hydrogeology based upon an aquifer performance test(s) performed in accordance with accepted best hydrogeological practices. The length of the pump test(s) will be 48 hours of pumping followed by 96 hours of recovery data including recovery data measured every minute for 24 hours following cessation of pumping.

The annual estimated sustainable production capacity so determined, for the well field on the Wild Springs Ranch Property that has been completed is connected to the water transportation facilities, and is capable of delivering water is hereinafter referred to as the "Agreed Sustainable Production

Amount" for such well field. The Agreed Sustainable Production Amount shall continue in effect for so long as the actual aggregate production for all Wild Springs Ranch Property wells is equal to or less than the aggregate total of the Agreed Production Rates for all Wild Springs Ranch Property wells to which this Agreement applies. If the actual aggregate production for all Wild Springs Ranch Property is less than the Agreed Sustainable Production Amount during any twelve (12) month period from the Effective Date of this Agreement, then, upon written request by Purchaser, Supplier and Purchaser shall have the Agreed Sustainable Production Amount re-determined by a registered professional engineer or certified ground-water professional and performed in accordance with accepted best practices. The "Agreed Sustainable Production Amount" of six hundred and fifty four (654) acre-feet of water per year may be exceeded during the term of this Agreement by agreement of the parties.

SECTION 3. CONSTRUCTION OF WATER WELLS AND OTHER FACILITIES

Purchaser acknowledges that in order to have the capability of delivering the Agreed Sustainable Production Amount to Purchaser, Supplier will have to construct the Water Wells and water transportation facilities to a point of delivery at the boundary of the Wild Springs Ranch property, jointly determined by Supplier and Purchaser, and that the commencement of construction of the Water Wells and transportation facilities by Supplier is done in reliance upon the agreements of Purchaser herein.

SECTION 4. POINT OF DELIVERY

Supplier will deliver water produced from the Wild Springs Ranch Property to Purchaser at the Point of Delivery, which shall be at a bulk water delivery terminal on the property boundary of the Wild Springs Ranch Property as described in Exhibit 1 (the "Point of Delivery").

SECTION 5. VOLUME

Subject to the limitations and conditions described in this Agreement, Supplier agrees to sell to Purchaser up to the Agreed Sustainable Production Amount, not to exceed six hundred and fifty four (654) acre-feet per year of untreated water produced from the Wild Springs Ranch Property at the Point of Delivery described in this Agreement. Subject to the Standby Payment for lack of market, as set forth in Section 8 and the Monthly Minimum Payment; as established in Section 8, the volume of water actually purchased depends upon Purchaser's demand and the amount of water that can be produced from the Wild Springs Ranch Property. Purchaser shall also have the right to limit the amount of water purchased based on system demand, aquifer conditions, and meteorological conditions, subject however to the monthly minimum payment. Purchaser shall have full operational control over all facilities during the term of this Agreement subject to the Monthly Minimum Payment.

SECTION 6. JASPER AQUIFER WATER ONLY

This Agreement is intended to cover and apply only to water produced from the Wild Springs Ranch Property, which will extract water from the Jasper formations only. Purchaser acknowledges that it has special expertise in the development, conservation and distribution of water resources and warrants and represents that it has consulted and is aware of the available technical and geological data regarding the Jasper Formation and aquifer.

SECTION 7. REGULATORY REQUIREMENTS

This Agreement is subject to all applicable federal, state, and local laws and any applicable ordinances, rules, orders, and regulations of any local, state, or federal governmental authority having jurisdiction. However, nothing contained in this Agreement shall be construed as a waiver of any right to question or contest any law, ordinance, order, rule, or regulation in any forum having jurisdiction, and Supplier and Purchaser each agree to make a good faith effort to support proposed laws and regulations which would be consistent with the performance of this Agreement in accordance with its terms.

Purchaser agrees to conform to all regulatory requirements to report pumping volumes, water quality information and such other data and information as may now or in the future be required by any governmental or regulatory body having jurisdiction for continuation and establishment of pumping rights under any laws or regulations now existing or that in the future may exist. To the extent filings are in the future required to establish water production volumes for purposes of issuance of permits or for water conservation purposes, Purchaser shall provide Supplier with records and data as may be necessary to establish or preserve Supplier's production rights. In any such permitting process, Purchaser and Supplier shall make a good faith effort to maximize the efficient pumping volume to which the Wild Springs Ranch Property Wells.

Purchaser's actions in making any reports of production volume, water quality, water use, historic use for permitting or any other purpose, shall be deemed to have been performed as agent for Supplier. All historic use under the terms of this Agreement shall inure to the benefit of Supplier and shall remain attached to the Wild Springs Ranch Property Water Wells regardless of whether this Agreement is terminated. Purchaser agrees to take such actions as may in the future be necessary to assist Supplier in carrying out the purposes and intent of this provision including executing, delivering and recording regulatory filings, assignments, transfer or other documents should that prove necessary or appropriate under any laws or regulations that may be enacted or promulgated by any authority having jurisdiction.

SECTION 8. PRICE AND TERMS

A. Standby Payments

Where water from one or more water wells on the Wild Springs Ranch property capable of producing water is not sold or used because of a lack of market or lack of access to market because of Federal or State laws, executive orders, rules or regulations, or lack of installed infrastructure to convey the produced water to market, this Agreement shall continue in full force and effect through its primary term as though water were being produced, captured, saved, marketed, and sold by Purchaser on the payment of a monthly payment of Twenty Thousand and No One Hundredths Dollars ($20,000.00) beginning January 1, 2016 said payments to be subject to increase according to terms set forth in Subsection C of this Section 8, said Standby Payment not to be credited toward future purchases and lack of market being generally defined as the absence of pipeline, storage, and treatment facilities.

B. Payment by Purchaser

Subject to the Monthly Minimum Payment provision in Subsection F of this Section 8, Purchaser shall pay Supplier monthly at the price established in Subsection C of this Section 8 for all water produced by Purchaser. Purchaser will remit payment to Supplier for water produced by Purchaser during the preceding month no later than thirty (30) days after the end of the preceding month. All sums payable under this Agreement shall be payable to Supplier at its address set forth herein.

If Purchaser fails to make any payment under this Agreement in the required amount and when due, the Supplier may, without prejudice to any other right or remedy it may have under this Agreement, provide notice to Purchaser in writing that Purchaser has thirty (30) days from receipt of the notice within which to remedy the breach of payment terms. In the event Purchaser fails to make required payment by the 30-day deadline set forth in the notice under this paragraph, Supplier may, at its option, immediately terminate this Agreement by providing written notice to Purchaser such notice shall be conclusive and may be relied upon by any subsequent purchaser with whom Supplier contracts. Purchaser agrees that upon termination of this Agreement pursuant to this paragraph, that it shall provide such documentation as may be reasonably requested to confirm termination of this Agreement. The exercise by Supplier of its right to terminate this Agreement shall not limit in any way Supplier's right to seek payment of all amounts due to it from Purchaser under the terms of this Agreement.

C. Rates

The price to be paid for water during the first year of this Agreement shall be Four Cents per Gallon ($0.04/gal) (Wild Springs Ranch Property "Initial Rate"). For each year thereafter on the anniversary date of this Agreement, over the twenty-year term (and/or any extended period), the price for water (the "Adjusted Rate") shall be adjusted annually based upon percentage increases or decreases in the Producer Price Index ("PPI") from the 2015 base reported by the U.S. Department of Labor on December 31, 2014.

D. Facilities

As further consideration for this Agreement, Supplier hereby leases and lets exclusively to Purchaser the real and personal property comprising the Freisenhahn Property wells, pipelines, pumping and transportation equipment (the "Facilities") during the term of this Agreement. If this Agreement is terminated pursuant to the terms and provisions set forth herein, all of Purchasers rights to the Facilities shall terminate.

E. Operation and Maintenance Costs

Purchaser agrees that it shall bear all costs associated with operation and maintenance of wells and equipment and production, transportation, treatment and marketing of water hereunder and equipment replacement; and that Supplier shall not be required to pay, and the amounts to be paid to Supplier hereunder shall never bear, directly or indirectly, any such costs.

F. Monthly Minimum Payment

Providing availability of market, for each month of this Agreement, Purchaser agrees to pay a fee for the use of the property for water production. For purposes of this Agreement, the Monthly Minimum Payment shall be Forty Thousand and No Hundredths Dollars ($40,000.00). Beginning on the availability to market, and continuing throughout the term of this Agreement, the Monthly Minimum Payment shall be applicable and will be reduced by payment for actual water produced and paid for until water payment exceeds the Minimum Monthly Payment. If, in any month, Purchaser produces less than the Monthly Minimum Payment from all of the Wild Springs Ranch Property Water Wells, Purchaser shall nonetheless pay for the Monthly Minimum Payment. Said difference is defined as the Monthly Production Credit. Monthly Production Credits accumulated on a month to month basis shall be applied on a first-in, first-out basis over a period not to exceed twelve (12) months from the month the credit arises to offset amounts produced in excess of the Monthly Minimum Payment where Actual Monthly Production exceeds the Monthly Minimum Payment. Monthly Production Credits shall be applied on an equal volume basis and shall thereby reduce in subsequent months the Actual Monthly Production payment by the amount that Actual Monthly Production payment the Monthly Minimum Payment, not to exceed the amount of the Monthly Production Credits available. Provided, further however, that these Monthly Production Credits shall in no way reduce the Monthly Minimum Payments hereunder.

G. Dispute

If Purchaser at any time disputes the amount to be paid by it to Supplier, Purchaser shall nevertheless promptly make the disputed payment or payments; but if it is subsequently determined by agreement or court decision that the disputed amount paid by Purchaser should have been less or more, Supplier shall promptly adjust Purchaser's account in a manner that Purchaser or Supplier will recover the amount due plus interest at Purchaser's most recent permanent financing rate.

By signing this Agreement, Purchaser stipulates and agrees that Supplier will be prejudiced if Purchaser avoids the obligation to pay for the Monthly Minimum Payment or the actual production at the rates for water specified in this Agreement while accepting the benefits of obtaining water from Supplier. Nothing in this Agreement shall be construed as constituting an undertaking by Supplier to furnish water to Purchaser except pursuant to the terms and provisions of this Agreement. Purchaser stipulates and agrees that the terms, rates and policies specified in this Agreement are just, reasonable, and without discrimination.

SECTION 9. <u>MEASUREMENT</u>

Supplier shall provide, and Purchaser shall operate, maintain, and read totalizing flow meters that record the total production of water taken by Purchaser from Supplier at the wellhead of each Wild Springs Ranch Property Water Well. Water shall be measured through a conventional type of approved totalizing flow meter. Purchaser shall keep accurate records of all measurements of water required under this Agreement, and the measuring device(s) and such records shall be open for Supplier's inspection at all times. Purchaser shall have access to Supplier's metering equipment at all reasonable times. This access shall include authorization for Supplier to install, inspect, adjust, or test measuring and recording equipment. Upon written request of Supplier, Purchaser will give Supplier copies of such records or permit Supplier to have access to the same in Purchaser's office during reasonable business hours. If requested in writing by Supplier and not more than once in each calendar year, on a date as near the end of a calendar month as practical, Purchaser shall calibrate the water meter(s) in the presence of a Supplier representative, and Supplier and Purchaser shall jointly observe any adjustments that shall be necessary. If Supplier shall, in writing, request Purchaser to calibrate its water meter(s), Purchaser shall give Supplier notice of the time when any such calibration is to be made and, if a representative of Supplier is not present at the time set, Purchaser may proceed with the calibration and adjustment in the absence of any representative of Supplier.

The accuracy of any meter shall be determined by application of a orifice plate port permanently installed on the discharge line from the well which orifice plate port has been calibrated or by other testing procedures promulgated by ASTM or other technical oversight body applicable to the specific measuring device in question, under the supervision of a registered professional engineer acceptable to Supplier. If, upon any test of the water meter(s), the percentage of inaccuracy of such metering equipment is found to be in excess of one percent (1 %), registration thereof shall be corrected for a period extending back to the time when such inaccuracy began, if such time is ascertainable. If such time is not ascertainable, then registration thereof shall be corrected for a period extending back one-half (1/2) of the time elapsed since the last date of calibration, but in no event further back than a period of six (6) months. If any meter(s) are out of service or out of repair so that the amount of water delivered cannot be ascertained or computed from the reading thereof, the water delivered through the period such meter(s) are out of service or out of repair shall be estimated and agreed upon by Supplier and Purchaser upon the basis of the best data available. Supplier shall install new meter(s) or repair existing meter(s) within a reasonable time not to exceed one hundred eighty (180) days. If Supplier and Purchaser fail to agree on the amount of water delivered during such period, the amount of water delivered may be estimated by:

(1) correcting the error if the percentage of the error is ascertainable by calibration tests or mathematical calculation; or

(2) estimating the quantity of delivery by deliveries during the preceding periods under similar conditions when the meter or meters were registering accurately.

All books and records pertaining to this Agreement shall be open and available for copying, inspection, and audit by Supplier, their successor and assigns.

SECTION 10. <u>SOURCE AND ADEQUACY OF SUPPLY</u>

Water supplied by Supplier to Purchaser under this Agreement shall be water produced by Supplier from the Jasper Formation Aquifer on the Wild Springs Ranch Property and from no other source. Supplier will use reasonable efforts to remain in a position to furnish water sufficient for the reasonable demands of Purchaser up to the Agreed Sustainable Production Amount. Supplier's agreement to provide water to Purchaser shall not be deemed a guarantee on Supplier's part that any particular quantity or quality of water will be available, nor shall any penalties accrue if the quantity and quality of water do not meet the requirements of Purchaser. The quantity of water taken shall at all times be subject to the right of Supplier to reduce said quantity of water as Supplier in its sole judgment may deem necessary to comply with any order of any court or administrative body having appropriate jurisdiction. Purchaser acknowledges that Supplier's source of water under this Agreement is dependent upon (i) the continued existence of one or more underlying leases which Supplier has secured for the production of water and (ii) the forces of nature. In the event Supplier is unable to deliver water to Purchaser in the Agreed Sustainable Production Amount as a result of a failure or default under one or more of the existing leases or as result of any other event or condition out of Supplier's control including but not limited to force majeure, Supplier shall notify Purchaser as soon as reasonably practical. Upon Purchaser's receipt of such notice and for a period of ten days (10) thereafter, either party shall have the right to immediately terminate this Agreement upon written notice to the other and thereafter neither party shall have any further rights or obligations under this Agreement.

SECTION 11: FORCE MAJEURE

Supplier shall be held harmless and shall not be held to any penalty(ies) for its inability to deliver water in the maximum amount contracted for or to deliver water of any particular quality that may be caused by strike, insurrection, civil disobedience, war, governmental regulation or action, actions at law, and any Act of God including but not limited to failure of the wells, alteration of the underground groundwater flow regime, change in underground water quality, corrosion, lightning, contamination from any source or sources, and changing groundwater level in the presence of underground karstic features.

SECTION 12. WATER QUALITY

The water, which Supplier offers to sell to Purchaser at the wellhead, is untreated groundwater in its natural condition. Purchaser has satisfied itself that such water at the wellhead is suitable for its needs and meets the requirements of the Federal Safe Drinking Water Act and any applicable water requirements of the State of Texas. Supplier expressly disclaims any warranty as to the quality of the water or suitability of the water for its intended purpose. Supplier expressly disclaims the warranties of merchantability and fitness. Purchaser agrees that any variation in the quality or characteristics of the water offered for sale as provided by this agreement shall not entitle Purchaser to avoid or limit its obligation to make payments provided for by this agreement for a period of two (2) years from the effective date of this agreement, provided there is no negligence on the part of the Supplier, well head protection is maintained, and a sanitary easement of no less than 150 feet radius measured from each well is maintained appropriately. After said two (2) year period, if the water quality at the wellhead fails to meet the requirements of the federal Safe Drinking Water Act or other applicable Texas regulations precludes use of the water, after conventional treatment, for drinking water, then Purchaser shall be entitled to avoid or limit its obligation to make payments provided for by this agreement or Purchaser may elect to terminate this agreement with the payment of liquidated damages equivalent to the unamortized capital costs of wells and pipelines on the Wild Springs Ranch Property. If Purchaser elects to terminate this agreement because of the water quality, as analyzed at the wellhead, Purchaser shall deliver written notice of the decision to terminate this agreement to Supplier. Purchaser shall discontinue production of water from the Wild Springs Ranch Property sixty (60) days after receipt of said written notice. There are no warranties that extend beyond the description contained in this agreement. Purchaser represents and warrants that it is a water purveyor having special expertise in the area of water development and distribution, including the standards of quality applicable to drinking water under state and federal law and regulation; that it is not relying upon any statement or representation of Supplier as to the qualities, quantities or characteristics of the water at the wellhead; and that it will undertake such tests and investigations as it may deem necessary and appropriate and as may be required by law to assure that the water it accepts is suitable for its intended purpose.

SECTION 13. TITLE

Purchaser shall take legal and equitable title to the water at the wellhead on an as is basis. The point of delivery shall be the bulk water terminal. The parties hereto agree to save and hold each other party hereto harmless from all claims, demands, and causes of action which may be asserted by anyone on account of the transportation and delivery of said water while title for liability purposes remains in the other party. The parties hereto further agree to hold harmless and indemnify owners of non-operating interests from all claims.

SECTION 14. OTHER CHARGES

In the event that any user fees, assessments, or charges of any similar nature are imposed on diverting, storing, gathering delivering, impounding, taking, marketing, selling, using, or consuming the water received by Purchaser from the Wild Springs Ranch Property, the amount of the user fee, assessment, or charge shall be borne by Purchaser, in addition to all other charges, and whenever Supplier shall be required to pay, collect, or remit any user fee, assessment, or charge on water received by Purchaser, then Purchaser shall promptly pay or reimburse Supplier for the user fee, assessment, or charge in the manner directed by Supplier.

SECTION 15. DEFAULT IN PAYMENTS

All amounts due and owing to Supplier by Purchaser shall, if not paid within thirty (30) days after being invoiced, bear interest at the Texas post¬judgment interest rate set out in Texas Revised Civil Statutes, Article 5069-1.05 or any successor statute from the date when due until paid, but not accruing interest during the judicial proceedings, provided that such rate shall never be usurious or exceed the maximum rate permitted by law. If any amount due and owing by Purchaser to Supplier is placed with an attorney for collection, Purchaser shall pay to Supplier, in addition to all other payments provided for by this Agreement, including interest, Supplier's collection expenses, including court costs and attorneys' fees. Supplier shall, to the extent permitted by law, suspend production of water from the Jasper Aquifer on the Wild Springs Ranch Property by Purchaser if Purchaser remains delinquent in any payments due hereunder for a period of sixty (60) days and Purchaser shall not resume production of water while Purchaser is so delinquent and Supplier may, at its option, terminate this contract without further liability to Purchaser except for payment of the unamortized capital costs of wells and facilities incurred by Supplier as liquidated damages caused by virtue of construction and maintenance costs less any offsets If judicial proceedings are initiated, Supplier and Purchaser agree to use a mediator selected from an appropriate Mediation Company to mediate the dispute and agree to mediate the dispute until a mutually agreeable solution is reached without further civil proceedings. The mediator will be selected from a panel of no less than three mediators submitted by the appropriate Mediation Company.

SECTION 16. WAIVER AND AMENDMENT

Failure to enforce or the waiver of any provision of this Agreement or any breach or nonperformance by Supplier or Purchaser shall not be deemed a waiver by Purchaser or Supplier of the right in the future to demand strict compliance and performance of any provision of this Agreement. Regardless of any provision contained in this Agreement to the contrary, any right or remedy or any default under this Agreement, except the right of Supplier to receive the payment provided herein which shall never be determined to be waived, shall be deemed to be conclusively waived unless asserted by a proper proceeding at law or in equity within 0 three (3) years plus one (1) day after the occurrence of the default.

No officer or agent of Supplier or Purchaser is authorized to waive or modify any provision of this Agreement. No modifications to or rescission of this Agreement may be made except by a written document signed by both Supplier's and Purchaser's authorized representatives.

SECTION 17. REMEDIES

It is not intended hereby to specify (and this Agreement shall not be considered as specifying) an exclusive remedy for any default, but all such other remedies (other than termination) existing at law or in equity may be availed of by any party hereto and shall be cumulative. Recognizing, however, that failure in the performance of any party's obligations hereunder could not be adequately compensated in money damages alone, each party agrees in the event of any default on its part that each party shall have available to it the equitable remedy of (mandamus can only be had against a government or official) specific performance, in addition to any other legal or equitable remedies (other than termination) which also may be available to Supplier.

SECTION 18. INDEMNITY

A. Defense

By signing this Agreement, Purchaser agrees on behalf of itself and its successors and assigns, that it relinquishes and discharges and will, to the fullest extent permitted by law, defend and protect Supplier and Supplier's officers, directors, employees, agents, and consultants, successors and assigns from and against all claims, expenses, costs, demands, judgments, causes of action, suits, and liability in tort, contract or any other basis and of every kind and character whatsoever (including but not limited to all costs of defense, such as fees and charges of attorneys, expert witnesses, and other professionals incurred by Supplier and all court or arbitration or other dispute resolution costs) arising out of or incident to, directly or indirectly, this Agreement, including but not limited to, any such claim for bodily injury, death, property damage, consequential damage, or economic loss and any claim that may arise in connection with the quality, quantity, use, misuse, impoundment, diversion, transportation and measurement of Supplier water and any claim that may arise as a result of installation, inspection, adjusting, or testing of measuring and recording equipment involving Purchaser's diversion of Supplier water, as well as any claim that may arise from any condition of Purchaser's facilities, separate operations being conducted on Purchaser's facilities, or the imperfection or defective condition, whether latent or patent, of any material or equipment sold, supplied, or furnished by Supplier.

B. Indemnity for Environmental Conditions

Supplier shall construct and deliver all facilities and Purchaser shall use reasonable efforts to maintain and operate all equipment and conduct all operations in an environmentally sound manner, in accordance with all applicable regulations of the Texas Natural Resources Conservation Commission, the Environmental Protection Agency and any other governmental authorities. Purchaser shall not use, store, transport to or from or dispose of any hazardous materials or wastes upon the Wild Spring Ranch Property, except to the extent such substances are contemporaneously required for actual water treatment in connection with the Wild Springs Ranch Property, and any such substances shall be used, stored and thereafter disposed of off of the Wild Springs Ranch Property in a safe manner, in compliance with all applicable governmental regulations and Purchaser assumes all liability with the transportation and disposal of said substances and holds Supplier harmless. Upon the occurrence of a spill or release of waste or any hazardous materials on the Wild Springs Ranch Property, Purchaser shall promptly report same to the Supplier and to the appropriate governmental agency having jurisdiction over the particular type of spill or release which has occurred, and then promptly abate and clean-up the release. Purchaser shall assure that all contractors comply with the terms of this Subsection. In the event Purchaser is notified of any environmentally harmful or dangerous conditions on the Wild Springs Ranch Property resulting from Purchaser's operations, including conditions that create an imminent threat of a release that could pose an unjustified risk of harm to human health or the environment, Purchaser shall promptly take all actions required to clean-up and correct such dangerous or harmful conditions, in accordance with applicable laws, rules and regulations and sound engineering practices. Purchaser has the absolute responsibility and liability for the clean-up of all pollution or contamination caused by Purchaser's operations and the reclamation of the Wild Springs Ranch Property, including the bearing of all costs and expenses thereof. Supplier shall have no responsibility to inspect or oversee Purchaser's operations or to identify or correct any potentially harmful, dangerous or damaging conditions, and Supplier shall have the right to retain expert consultants to review all activities of Purchaser control any details of Purchaser's operations, nor to designate or control Purchaser's contractors. Neither Purchaser nor any of Purchaser's contractors shall have any right of contribution or indemnity from Supplier for any matters relating to operations on the Wild Springs Property or conditions on the Wild Springs Ranch Property.

C. Environmental Site Assessment

Prior to assumption of operation and maintenance of the well field, Purchaser shall have prepared for the benefit of the Supplier an Environmental Site Assessment to establish baseline environmental conditions of the well field.

D. Insurance

(1) Prior to any entrance upon the Wild Springs Ranch Property, Purchaser, its contractor(s) and subcontractor(s) shall deliver to the Supplier evidence of Workman's' Compensation, Auto and General Liability Coverage. The insurance referenced under this Subsection shall be obtained at the sole cost of Purchaser, its contractor(s), and subcontractor(s), and shall name the Supplier, its affiliates and Purchaser as additional insureds, and protect the Supplier, its affiliates and Purchaser against any and all liability for injury to or death of a person or persons, and for damage to or destruction of property occasioned by or arising out of or in connection with the actions of Purchaser, its employees, its contractor(s), or subcontractor(s), or by anyone directly or indirectly employed by any of them, or by anyone for whose acts any of them may be liable. Additionally, notice that said insurance carriers are licensed to sell insurance in the State of Texas and have designated Texas agent(s) to receive notices required pursuant to the policies shall be delivered to the Supplier. Supplier's affiliates for the purposes of this Agreement are $1,000,000, its shareholders, officers and directors.

(2) Workman's' Compensation, Auto and General Liability coverage insurance policy or policies described under this Section 17, and required of Purchaser, its contractor(s) and subcontractor(s), shall be in an amount not less than $250,000.00 per individual and $1,000,000.00 per occurrence, and an amount of not less than $1,000,000.00 in respect to property damaged or destroyed in anyone occurrence.

SECTION 19. <u>ASSIGNABILITY</u>

Purchaser understands and agrees that any assignment of rights or delegation of duties under this Agreement is void without the prior written consent of Supplier.

Purchaser may not assign its interest under this Agreement without the written approval of the Supplier, said written approval not to be unreasonably withheld.

SECTION 20. SOLE AGREEMENT

This Agreement constitutes the sole and only agreement of Purchaser and Supplier and supersedes any prior understanding or oral or written agreements between Supplier and Purchaser respecting the subject matter of this Agreement, including any oral or written agreement with Supplier that Purchaser obtained by assignment.

SECTION 21. SEVERABILITY

The provisions of this Agreement are severable and if, for any reason, any one or more of the provisions contained in the Agreement shall be held to be invalid, illegal, or unenforceable in any respect, the invalidity, illegality, or unenforceability shall not affect any other provision of this Agreement, and this Agreement shall remain in effect and be construed as if the invalid, illegal, or unenforceable provision had never been contained in the Agreement.

SECTION 22. PLACE OF PERFORMANCE

This Agreement shall be performed in Newton County, Texas. All amounts due under this Agreement, including but not limited to payments due under this Agreement or damages for the breach of this Agreement, shall be paid and be due in Newton County, Texas.

SECTION 23. DUPLICATE ORIGINALS

Purchaser and Supplier shall authorize the execution of this Agreement in several counterparts, each of which shall be an original. Purchaser shall submit written evidence in the form of bylaws, charters, resolutions, or other written documentation specifying the authority of Purchaser's representative to sign this Agreement which evidence shall be attached to this Agreement as Exhibit 2.

SECTION 24. CAPTIONS AND HEADINGS

The captions and headings used herein are for reference purposes only and shall not affect the meaning or interpretation of the terms and provisions of this Agreement.

SECTION 25. NOTICES

Any notice provided or permitted to be given under this Agreement must be in writing and may be served by depositing same in the United States mail, addressed to the party to be notified, postage prepaid and registered or certified with return receipt requested; by delivering the same in person to such party; or by facsimile transmission/telecopy. Notice given in accordance herewith shall be effective upon receipt at the address of the addressee. For purposes of notice, the addresses of the parties shall be as follows:

If to Supplier, to:

Daniel Ayres, dba Wild Springs Ranch

811 C.R. 2076, Newton, Texas, 75988

Telephone: 409-384-0832

Email: d.ayres@msvmobile.com

If to Purchaser, to:

____

____

SECTION 26. FINANCING PROVISIONS

A. Purchaser's Estoppel Certificate

Purchaser agrees to furnish, from time to time, within ten (10) days after written request from the Supplier or the Supplier's lender or prospective lender, a certificate certifying to such lender or prospective lender the following:

(1) This Agreement is in full force and effect;

(2) Except as disclosed in such certificate, this Agreement (as reflected in a copy of this Agreement attached to the certificate) is unmodified;

(3) There is no offset against any amounts owing under this Agreement to Purchaser;

(4) Amounts owing or to become owing to Purchaser under this Agreement have not been and will not be prepaid for more than one (1) month in advance;

(5) Except as disclosed in such certificate, to the knowledge of Purchaser, there is no existing default under this Agreement by reason of some act or omission by the Supplier;

(6) Except as disclosed in such certificate, there is no existing default by the Purchaser under this Agreement, and no event has occurred or condition exists which, with the passage of time or the giving of notice, or both, would constitute a default by the Purchaser under this Agreement;

(7) Except as disclosed in such certificate, that Supplier has performed all obligations required of Supplier in connection with this Agreement; and

(8) Such lender or prospective lender may reasonably require such other matters as.

B. Assignability to Lender

This Agreement and any and all rights of Supplier under this Agreement are assignable to any lender of Supplier and to any purchaser at any foreclosure sale with respect to any lien or security interest in favor of any such lender on this Agreement and/or on any rights of Supplier under this Agreement. Such right of assignment includes (without limitation) the right of Supplier to grant a security interest in, or make an absolute assignment of, the rights to payments under this Agreement to any lender of Supplier.

C. Designation of Designated Lender and Other Interest Owner(s) and Notice of Default to Designated Lender

Supplier may designate to Purchaser in writing a lender and other Interest owners (the "Designated Lender" and "Designated Interest Owner" hereinafter "Designated Parties"), and Purchaser shall thereafter provide Designated Parties with written notice of any default by Supplier under this Agreement known to Purchaser. Such notice shall provide that the Designated Parties shall have not less than 60 days after the giving of such notice to cure or cause to be cured such default before Purchaser may exercise any rights or remedies it may have with respect to such default (other than any right Purchaser may have pursuant to this Agreement to itself cure such default). Once a Designated Party is designated to Purchaser, such designation shall not be changed or terminated without the consent of the then current Designated Parties.

D. Payments to Designated Parties upon Notice

Upon receipt of written notice from the Designated Parties stating that Supplier is in default under the loan or payment documents for the loan or loans from Designated Parties to Supplier and directing that all payments under this Agreement be sent to Designated Parties, Purchaser shall make such payments to the Designated Parties in accordance with the instructions therefor set forth in such notice. Purchaser shall not be further liable to Supplier or any other person with respect to payments it makes to the Designated Parties in reliance on any such notice.

E. Consent by Designated Parties to Terminations and Amendments, and Limitation on Remedies

If a lender or other party has been designated as the Designated Party, and such designation has not been terminated as provided herein, (a) Purchaser and Supplier cannot amend this Agreement without the written consent of the Designated Parties, and (b) Purchaser's sole remedy for any breach or default of this Agreement by Supplier shall be to itself cure such breach or default and/or bring suit against Supplier for damages resulting from such breach or default.

F. Recordation of Memorandum of Agreement

Upon the request of the Designated Parties or the Supplier, Purchaser will execute and acknowledge a Memorandum of Agreement in recordable form setting forth the basic terms of this Agreement in form and substance reasonably satisfactory to the Designated Parties.

IN WITNESS WHEREOF, this instrument is executed as of the Effective Date.

SUPPLIER:

Daniel Ayres dba Wild Springs Ranch

By:____

Name (Print):____________________________________

Title:____

PURCHASER:

____

By:____

Name (Print):__________________________________

Title:____

ACKNOWLEDGEMENTS

State of Texas)

)ss.

County of Newton)

This instrument was acknowledged before me on the _____ day of _____________________, 2015, by _________________________.

(Seal)

____

My Commission expires: _____________________

State of Texas)

)ss.

County of ___________________)

This instrument was acknowledged before me on the _____ day of _____________________, 2015, by _________________________, a Corporation, on behalf of said corporation.

(Seal)

____

My Commission expires: _____________________