HEADWATERS GROUNDWATER CONSERVATION DISTRICT

DISTRICT GROUNDWATER MANAGEMENT PLAN

REVISED 2016

Headwaters Groundwater Conservation District Groundwater Management Plan – 2016

The Headwaters Groundwater Conservation District (the "District") is a governmental agency and a body politic and corporate. The District was created to serve a public use and benefit, and is essential to accomplish the objectives set forth in Section 59, Article XVI, of the Texas Constitution. The District's boundaries are coextensive with the boundaries of Kerr County, Texas, and all lands and other property within these boundaries will benefit from the works and projects that will be accomplished by the District.

Purpose of Management Plan

The 75th Texas Legislature in 1997 enacted Senate Bill 1 ("SB 1") to establish a comprehensive statewide water planning process. In particular, SB 1 contained provisions that required groundwater conservation districts to prepare management plans to identify the water supply resources and water demands that will shape the decisions of each district. SB 1 designed the management plans to include management goals for each district to manage and conserve the groundwater resources within their boundaries. In 2001, the Texas Legislature Enacted Senate Bill 2 ("SB 2") to build on the planning requirements of SB 1 and to further clarify the actions necessary for districts to manage and conserve the groundwater resources of the state of Texas.

The Texas Legislature enacted significant changes to the management of groundwater resources in Texas with the passage of House Bill 1763 (HB 1763) in 2005. HB 1763 created a long-term planning process in which groundwater conservation districts (GCDs) in each Groundwater Management Area (GMA) are required to meet and determine the Desired Future Conditions (DFCs) for the groundwater resources within their boundaries by September 1, 2010. In addition, HB 1763 required GCDs to share management plans with the other GCDs in the GMA for review by the other GCDs.

The Headwaters Groundwater Conservation District's management plan satisfies the requirements of SB 1, SB 2, HB 1763, the statutory requirements of Chapter 36 of the Texas Water Code, and the administrative requirements of the Texas Water Development Board's (TWDB) rules.

District Creation and History

Under Article XVI, Section 59, of the Texas Constitution, the Headwaters Groundwater Conservation District was created by the 72nd Legislature House Bill (HB) No. 1463 and approved by the Governor of Texas on June 16, 1991. The 77th Legislature HB 3543 amended the enabling legislation and was approved by the Secretary of State on May 23, 2001. And in accordance with Chapter 36 of the Texas Water Code, by the Act of May 25, 2009, 81st Legislature, Special District Local Laws Code, Title 6. Water and Wastewater, Subtitle H. Districts Governing Groundwater Chapter 8842 effective April 1, 2011 this plan is submitted.

District Mission

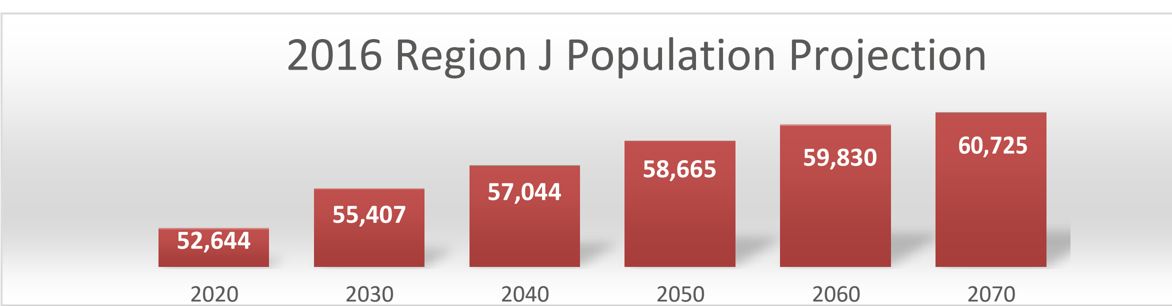
The Mission of the Headwaters Groundwater Conservation District is to develop rules to provide protection to existing wells, prevent waste, promote conservation, provide a framework that will allow availability and accessibility of groundwater for future generations, protect the quality of the groundwater in the recharge zone of the aquifer, ensure that the residents of Kerr County maintain local control over their groundwater, and operate the District in a fair and equitable manner for all residents of the District. The District is committed to manage and protect the groundwater resources within its jurisdiction and to work with others to ensure a sustainable, adequate, high quality and cost effective supply of water, now and in the future. The District will strive to develop, promote, and implement water conservation, augmentation, and management strategies to protect water resources for the benefit of the citizens, economy and environment of the District. The preservation of this most valuable resource can be managed in a prudent and cost effective manner through conservation, public education, and management. Any action taken by the District shall only be after full considerations and respect has been afforded to the individual property rights of all citizens of the District. This management plan is intended as a tool to focus the thoughts and actions of those given the responsibility for the execution of District activities. The District Board of Directors will review the status of all performance standards in this plan annually.

Time period for this plan

This plan will become effective upon adoption by the Headwaters Groundwater Conservation District Board of Directors and approved as administratively complete by the Texas Water Development Board. The plan will remain in effect for five (5) years after the date of approval or until a revised plan is adopted and approved.

Demographics

The District boundaries are contiguous with that of Kerr County, Texas. Kerr County encompasses 1,106 square miles and is located in the hill country of southwest central Texas. The county is bounded on the north by Kimble and Gillespie counties, on the east by Kendall County, on the west by Edwards and Real counties and on the south by Bandera and Real counties. Kerrville, the largest city in the county, is also the county seat for Kerr County. Retirement living, private camps, resorts, hunting, medical services, and private higher education dominate the economy in Kerr County. Agriculture, light industry, and manufacturing contribute to the economy to a lesser extent. The Kerr County population is displayed in the table below according to population estimates prepared by data developed and submitted by the Regional Water Planning Group (RWPG) Region J. These estimates include Ingram, Kerrville, and County-Other.



Topography and Climatic Conditions

The predominantly rough and rolling topography of Kerr County is characteristic of the Edwards Plateau or Hill Country region. In the western part of Kerr County, the land surface is gently rolling, interrupted by steep slopes and narrow valleys caused by the erosion of resistant limestone beds. Extensive dissection of the plateau in the eastern part of the county has formed wide valleys separated by high hills of generally uniform altitude. The altitude of the land surface ranges from about 1,400 ft. above mean sea level (MSL) at the southeastern edge of the county to about 2,400 feet in the western part (Reeves, 1969). Historically, the vegetative cover was considered to be an oak and juniper savannah. Presently, second and third growth juniper is increasing in density to the point of being dominant.

Most of Kerr County is drained by the upper Guadalupe River (approximately 75%), which rises in the western part of the county and flows eastward for approximately 40 miles before exiting the county. The Llano and Pedernales Rivers to the north and the Medina River to the south drain small peripheral areas of the county amounting to less than 25 percent of the total area (Reeves, 1969). Kerr County has a sub humid to semiarid climate coupled with mild winters and hot summers. Average annual rainfall recorded by the United States Department of Agriculture – Agriculture Research Service (USDA-ARS) –Knipling-Bushland US Livestock Insects Laboratory, Kerrville, TX. for the years (1985 to 2014) [1] is 31.14 inches. Net lake surface evaporation ranges from approximately 45 inches per year in the eastern part of the county to about 55 inches per year in the western part.

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[1] http://www.ars.usda.gov/SP2UserFiles/Place/30940500/Avg_Rain.pdf

Water Resources of Kerr County

Groundwater Resources of Kerr County

The Trinity Aquifer is the principal source of groundwater in Kerr County. The Trinity Aquifer in the Hill Country is an extension of the lower part of the Edwards-Trinity Aquifer of the Edwards Plateau, with the Edwards group and its equivalents mostly removed (see Strata Geological Services Report Hydrogeology of Kerr County 2008.[2]) The Trinity Aquifer yields water from Cretaceous limestone and sand of the Trinity Group. The Trinity Aquifer is composed of three permeable zones separated by two relatively impermeable horizontal barriers. The Upper Trinity is made up of the upper member of the Glen Rose Limestone formation. The Middle Trinity is composed of the Lower Glen Rose Limestone, the Hensell Sand, and the Cow Creek Limestone formations. The Lower Trinity consists of the Hosston and Sligo Formations. Relatively impermeable tight sediments within the Glen Rose Limestone separate the Upper and Middle Trinity. The Hammett Shale separates the Middle and Lower Trinity. Recharge of the Trinity Aquifer occurs through lateral flow of water from the Edwards Plateau, infiltration of precipitation on the outcrop area, and surface water leakage from shallow tributary streams in upland areas. Relatively impermeable inner beds in the Upper and Middle Glen Rose Limestone generally impede the downward percolation of precipitation. A second, less reliable, aquifer in Kerr County is the Fort Terrett Formation of the Edwards Group. Erosion caused by stream flow off the edge of the Edwards Plateau trending eastward across Kerr County has removed most of the Fredericksburg and Washita strata. Unconfined conditions prevail over parts of the county, varying greatly in response to diverse geologic conditions and topographic effects. The production of wells in the Fort Terrett Formation is usually confined to domestic and stock use, but the Fort Terrett is essential in maintaining stream flow of the Guadalupe River.

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[2] http://hgcd.org/wp-content/uploads/2015/07/2008-Kerr-Hydrogeology-Report-.pdf

Surface Water Resources of Kerr County

The Guadalupe River predominately (70%) originates as spring flow from the Edwards Trinity (Plateau) Aquifer within Kerr County. The larger springs range in flow from 5 -15 cubic feet per second (CFS) and chemically reflect the limestone geology of Kerr County. Originally, streams in Kerr County were characterized by shallow, swift flow over bedrock, but construction of surface water impoundments has restricted this flow. The primary surface water source available in Kerr County is the Upper Guadalupe River Basin. Considering the complexity of the diversion rights system and variations in the flows of the river, the river alone is not a sustainable long-term source for municipal, industrial and irrigation use when drought conditions or conservation plans are considered. However, prudent use of available supplies in the Guadalupe River should be made in order to protect and extend the capabilities of the groundwater system. Headwaters Groundwater Conservation District has agreed to and signed a Memorandum of Understanding (MOU) with Kerr County, the City of Kerrville, the City of Ingram, and the Upper Guadalupe River Authority to cooperate regarding the development of regional surface water supply, treatment, storage and transmission facilities.

Municipal Water Rights for Kerrville and UGRA

Water Rights Permit	Authorized Diversion (ac-ft/yr)	Permit Holder	Priority Date	Storage (ac-ft)	Restrictions
1996 (amended 4/10/98)	150 (mun) 75 (irr)	Kerrville	April 4, 1914		
3505	3,603	Kerrville	May 23, 1977	840	Max diversion rate = 9.7 cfs divert only when reservoir is above 1908 ft msl
5394 (amended 4/10/98)	2,169	Kerrville (Kerrville Municipal Use)	January 6, 1992	Utilizes the storage authorized for Permit 3505	Max combined diversion rate for water rights # 3505 and # 5394 = 15.5 cfs. Minimum instream flow requirements vary from 30 to 50 cfs during year.
	2,000	UGRA (County Municipal use)			

Source: Plateau Region Water Plan 2016

Technical District Information Required by Texas Administrative Code

Estimate of Modeled Available Groundwater in the District Based on Desired Future Conditions

Texas Water Code § 36.001 defines modeled available groundwater as “the amount of water that the executive administrator determines may be produced on an average annual basis to achieve a desired future condition established under Section 36.108”. The joint planning process set forth in Texas Water Code § 36.108 must be collectively conducted by all groundwater conservation districts within the same GMA. The District is a member of GMA 9. In the second round of planning (Water Code 36 Sec. 108 d.) on April 18, 2016, GMA9 voted to propose portions of certain major and minor aquifers within GMA-9 be classified as non-relevant for the purposes of joint planning and adopted DFCs for the relevant aquifers. For Headwaters Groundwater Conservation District, the DFC for the Hill Country Trinity Aquifer remained as stated in GAM Run 10-005. The Edwards Group of Edwards-Trinity (Plateau) Aquifer in Kerr County was proposed as non-relevant. The adopted DFCs, non-relevant aquifers and the GMA-9 Explanatory Report were then forwarded to the TWDB for approval and development of the MAG calculations.

Draft GAM Task 10-005 & GAM Task 10-031: Supplement for DFCs for Kerr County	Please Refer to Appendix A

GAM Run 10-049 MAG Report Version 2, for Modeled Available Groundwater for the Edwards Group of the Edwards-Trinity (Plateau) Aquifer	Please Refer to Appendix B

GAM Run 10-050 MAG Report Version 2, for Modeled Available Groundwater for the Trinity Aquifer.	Please Refer to Appendix C

Amount of Groundwater Being Used within the District on an Annual Basis. *"TWDB Estimated Historical Water Use"*	Please refer to Appendix D

Annual Amount of Recharge from Precipitation to the Groundwater Resources within the District. *"GAM Run 16-019"*	Please refer to Appendix E

Annual Volume of Water that discharges from the Aquifer to Springs and Surface Water Bodies. *"GAM Run 16-019"*	Please refer to Appendix E

Estimates of the Annual Volume of Flow into the District, out of the District, and between Aquifers in the District. *"GAM Run 16-019"*	Please refer to Appendix E

Projected Surface Water Supply within the District *"Texas 2017 State Water Plan"*	Please refer to Appendix D

Projected Total Demand for Water within the District *"Texas 2017 State Water Plan"*	Please refer to Appendix D

Water Supply Needs *"Texas 2017 State Water Plan"*	Please refer to Appendix D

Water Management Strategies *"Texas 2017 State Water Plan"*	Please refer to Appendix D

Groundwater Availability Model for the Hill Country Portion of the Trinity Aquifer System, Texas - Updated Model *"Report 377. June 2011"*	Please refer to Appendix F

Methodology to Track District Progress in Achieving Management Goals

An annual report ("Annual Report") will be created by the general manager and staff of the District and provided to the members of the Board of the District. The Annual Report will cover the activities of the District including information on the District's performance in regards to achieving the District's management goals and objectives. A copy of the Annual Report will be kept on file and will be available for public inspection at the District's offices upon adoption.

Action, Procedures, Performance and Avoidance for Plan Implementation and Details on How the District Will Manage Groundwater Supplies.

The District has adopted rules and policies relating to the permitting of wells and the production of groundwater. The rules and policies adopted by the District are pursuant to Texas Water Code Chapter 36 and the provisions of this plan, based on the best technical evidence available[3]. The District will strive to enforce all rules and policies in a fair and equitable way, the rules may be viewed at [http://hgcd.org/resources/rules-plans.](http://hgcd.org/resources/rules-plans) The District shall treat all citizens with equality. Citizens may apply to the District for discretion in enforcement of the rules on grounds of adverse economic effect or unique local conditions. In granting of discretion to any rule the District Board shall consider the potential for adverse effect on adjacent landowners. The exercise of said discretion shall not be construed as limiting the power of the District Board. The District will utilize the provisions of this management plan to determine the direction or priority for District activities. Operations of the District, agreements entered into by the District and any additional planning efforts in which the District may participate will be consistent with the provisions of this plan.

In the implementation of this plan and the management of groundwater supplies activities of the District will be undertaken in cooperation and coordination with

- [3] Update GAM for the Hill Country Portion of the Trinity Aquifer System, Texas, Report 377 June 2011, Appendix F of this report.

the appropriate state, regional or local water management entity and in compliance with State and Regional Water Plans.

Management Goals

A. Provide the most efficient use of groundwater

A.1. Objective – Implement a program to improve understanding of usable groundwater supplies in Kerr County.

A.1. Performance Standard -

The District has an ongoing program to gather data from Kerr County aquifers and supervise the drilling, logging, and completion of monitor wells. Also the District has rules in place to require aquifer tests for all new drilled Public Supply Wells and provide all monitor well data and aquifer test data to the TWDB groundwater database.

A.2. Objective - Establish an aquifer monitoring program.

A.2. Performance Standard -

The District has a Monitoring Well drilling program; to date HGCD has drilled 16 Monitoring Wells. Aquifer levels are monitored in the 16 District Monitoring Wells and approximately 25 private wells monthly in the Middle and Lower Trinity Aquifer., 13 wells are monitored quarterly in the Edwards Group of the Edwards-Trinity (Plateau) aquifers. A table and hydrograph of each individual monitor well as well as the number of wells measured will be reported to the District Board and displayed on the District website monthly.

A.3. Objective - Regulate and account for groundwater withdrawal in Kerr County.

A.3. Performance Standard -

Register all new wells drilled and maintain a well database. Provide an annual report to the District Board which includes the number of new wells drilled in the District during the past year. Perform well site inspections before, during, and after the drilling of each new well in the District. Require State Well Logs, certified statements of completion from water well Drillers and Pump Installers within 30 days of completion. Require non-exempt wells to be metered and the production reported annually to the District. Provide an annual groundwater report to the District Board.

B. Controlling and Preventing Waste of Groundwater

B.1. Objective - Make and enforce rules to ensure that groundwater is used solely for beneficial purposes and prohibit activities that contribute to waste of groundwater.

B.1. Performance Standard -
Review all well registrations and applications for intended use and production capacities (gallons per minute). The number of wells and a list of intended uses and production capacities for the previous calendar year will be included in the annual management plan tracking report to the District Board. Promote Public Education in conservation matters on the District website and publish one article on the prevention of wasteful water practices in one newspaper within the District annually. Identify, document, and investigate occurrences of waste of groundwater and include in the annual tracking report.

C. Addressing conjunctive surface water management issues.

C.1. Objective - Assess the availability of surface water resources that may be used as an alternative to groundwater.

C.1. Performance Standard -
Participate in the Plateau Regional Planning group scope of work projects to promote strategies for increasing surface water use in Kerr County. Meet once a year with the City of Kerrville to report on surface water use and aquifer storage and recovery projects. The District has signed a

memorandum of understanding with the cities of Kerrville and Ingram, the Kerr County Commissioners, and the Upper Guadalupe River Authority, to maximize surface water use in the District.

D. Address Natural Resource Issues

D.1. Objective - Prevent contamination/pollution of the aquifers from other natural resources being produced within the District.

D.1. Performance Standard -
Monitor any oil and gas drilling or mining operations for potential sources of pollution of the aquifers in the District. The annual tracking report will include the number of currently existing oil and gas wells, the number of new oil and gas wells drilled, and an estimate of the total amount of groundwater being used by these operations. District Rules require any water wells drilled associated with oil and gas drilling or production be registered with the District and are required to comply with District construction standards and reporting.

E. Addressing Drought Conditions

E.1. Objective - Monitor Drought Conditions

E.1. Performance Standard -
Review aquifer data monthly and declare drought stages based on the District's defined drought triggers. Inform the public and permitted well owners regarding declared drought stages, appropriate non-essential water use restrictions and recommended restrictions during drought. Publish information when drought stages are triggered by way of the HGCD website, local newspaper notices, and mail-outs to Permitted well owners. The TWDB drought conditions section may be viewed at http://www.waterdatafortexas.org/drought/ The number of website notices, newspaper notices, and mail-outs will be included in the annual tracking report to the District Board.

F. Addressing Conservation

F.1. Objective - Conservation

F.1. Performance Standard -

Distribute water conservation material by newspaper articles and the HGCD website. The District will publish a minimum of one article on conservation practices in one newspaper within the District annually. The District Conservation Plan is available to the public on the District website and at the District office. View the Water Conservation Advisory Council website at http://www.savetexaswater.org

G. Addressing Rainwater Harvesting

G.1. Objective - Rainwater Harvesting

G.1. Performance Standard

Provide Rainwater Harvesting links to the public on the HGCD website. Publish at least one newspaper article annually discussing the benefits of rainwater harvesting.

H. Address the Desired Future Conditions of the Groundwater Resources.

H.1. Objective - Based on the Modeled Available Groundwater (MAG), issue permits up to the point that the total volume of exempt and permitted production achieve the Desired Future Condition for the Hill Country Middle and Lower Trinity Aquifers adopted by GMA 9 and for the non-relevant Edwards Group of the Edwards Trinity (Plateau) Aquifer.

H.1. Performance Standard -

GMA 9 declared the Edwards Group of the Edwards-Trinity (Plateau) to be not relevant for joint planning in Kerr County. At this time the District does not allow non-exempt wells in the Edwards Aquifer.

The combined annual operating permit volume and the estimated exempt pumping volume provided by the Texas Water Development Board will be evaluated and compared to the Modeled Available Groundwater stated in report GAM Run 10-050 MAG Version 2, March 30 2012.

Complete an annual groundwater report that details groundwater production from non-exempt wells combined with exempt well pumping estimates supplied by the Texas Water Development Board. This report will be included in the annual report provided to the District's Board of Directors.

I. Management Goals Not Applicable to the District

I.1. Controlling and Preventing Subsidence -

This goal is not applicable to the District due to a rigid geologic framework. Accordingly, the District's plan does not contain a "Management Objective" or "Performance Standard" to address this issue.

I.2. Recharge Enhancement - is not within the District's ability to be cost effective. This goal is not applicable at this time.

I.3. Precipitation Enhancement is not within the District's ability to be cost effective. This goal is not applicable at this time.

I.4. Brush Control is not within the District's ability to be cost effective. This goal is not applicable at this time.

APPENDIX A

GAM TASK 10-005

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September 3, 2010

GAM Task 10-005

by William R. Hutchison, Ph. D, P.E., P.G.
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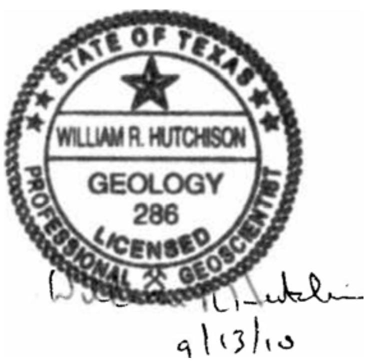
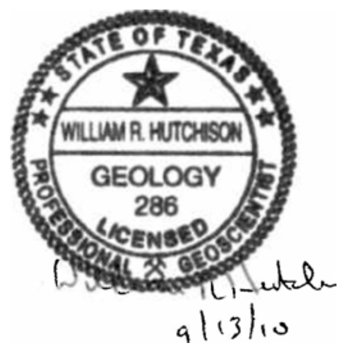
(512) 463-5067
September 3, 2010

The seal appearing on this document was authorized by William R. Hutchison, P.E. 96287, P.G. 286 on September 3, 2010.





EXECUTIVE SUMMARY

This report presents results of a GAM Task that was requested at the May 10, 2010 Groundwater Management Area 9 meeting in Kerrville. This task represents an expansion of the GAM run requested by Groundwater Management Area 9 (Chowdhury, 2010) and the supplement of that GAM run request (Hutchison, 2010), both of which were discussed at the May 10, 2010 Groundwater Management Area 9 meeting.

The simulations completed as part of this task include seven pumping scenarios of the Trinity Aquifer that range from zero pumping to about twice current pumping. Each scenario included running 387 50-year simulations. The 387 50-year simulations were developed based on tree-ring precipitation estimates from 1537 to 1972 for the Edwards Plateau (Cleveland, 2006). The results were used to evaluate the relationships between pumping versus drawdown, spring and base flow and outflow across the Balcones Fault Zone.

Results from the Task were summarized Groundwater Management Area-wide, by county, and by three areas designated by Mr. Ron Fieseler, General Manager of the Blanco-Pedernales Groundwater Conservation District. Because each scenario consisted of 387 50-year simulations, the results can also be expressed in terms of minimum, average, and maximum, as well as values that are exceeded 5 percent of the time and values that are exceeded 95 percent of the time.

ORIGIN OF TASK:

During the course of the May 10, 2010 Groundwater Management Area 9 meeting, there was consensus to complete these 50-year simulations to provide additional information to the groundwater conservation districts in Groundwater Management Area 9

DESCRIPTION OF TASK:

The simulations completed as part of this task include seven pumping scenarios of the Trinity Aquifer that range from zero pumping to about twice current pumping. Each scenario included running 387 50-year simulations. The 387 50-year simulations were developed based on tree-ring precipitation estimates from 1537 to 1972 for the Edwards Plateau (Cleaveland, 2006). The results were used to evaluate the relationships between pumping versus drawdown, spring and base flow and outflow across the Balcones Fault Zone.

METHODS:

The original request (Chowdhury, 2010) included model runs that included predictive simulations using the Hill Country portion of the Trinity Aquifer model to assess the effects of drought and increased pumping on water levels, base flow, and flow across the Balcones Fault Zone. The requested runs consisted of 50-year simulations, some with 50 years of average recharge, and some with 43 years of average recharge followed by 7 years of drought-of-record conditions. The runs also included various combinations of pumping at 2008 levels, one and a half times the 2008 pumping levels, and one and a half times 2008 pumping levels which were reduced to 2008 pumping levels during droughts.

The supplement (Hutchison, 2010) included seven separate scenarios. Three of the scenarios assumed constant pumping (i.e. no drought reduction), and four scenarios assumed a 33 percent pumping reduction during drought years. Each scenario included 430 7-year simulations based on tree-ring precipitation estimates from 1537 to 1972 for the Edwards Plateau (Cleveland, 2006).

These simulations involve varying recharge based on the Cleveland (2006) tree-ring dataset, but include 387 50-years simulations, as detailed below.

Precipitation and Recharge

The 50-year running average of the tree-ring precipitation is presented in Figure 1. Note that the precipitation for the 50-year period ending in 1593 is about 96 percent of average, and represents the driest 50-year period in the record. Aside from the generally dry conditions in the late 1500s and early 1600s, there are three other relatively dry periods in the early 1800s, the early 1900s, and the most recent period that ended in 1972 (at the end of the record).

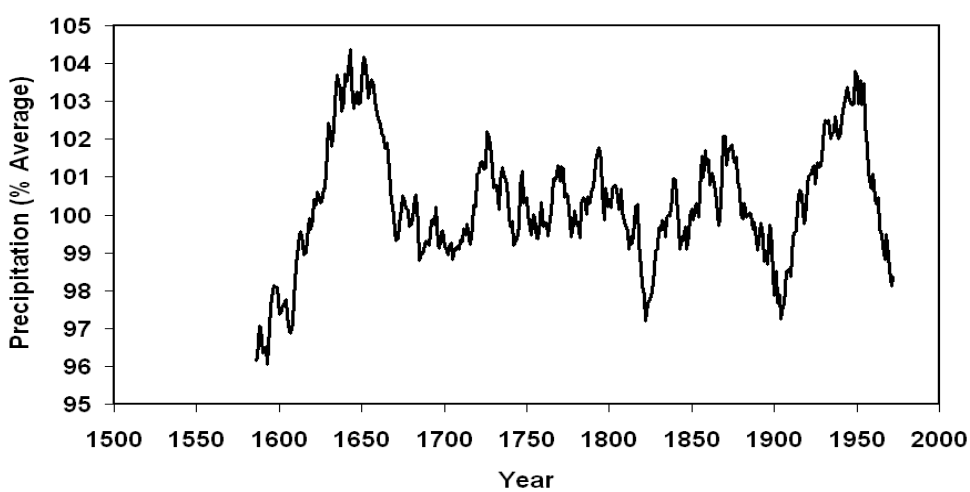


Figure 1. 50-year running average precipitation in the Edwards Plateau region of Texas based on tree-ring data (data from Cleveland, 2006).

These tree-ring precipitation data were used to develop 387 separate recharge input files based on the relationship between precipitation and recharge during the model calibration period as shown in Figure 2.

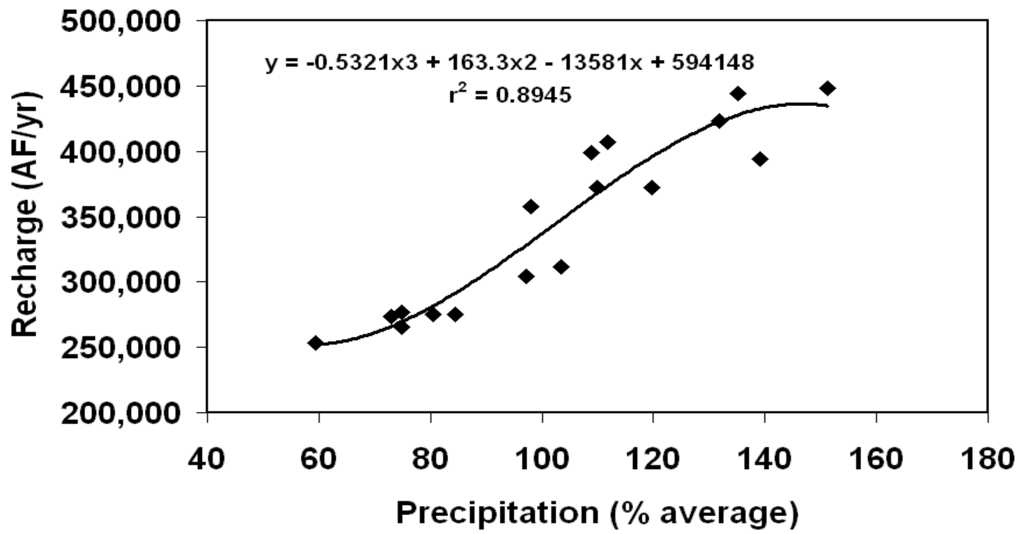


Figure 2. Precipitation versus recharge in Hill Country model from 1981 to 1997

Pumping

Pumping in the original request was based on 2008 pumping, and in some runs, was increased to one-and-a-half times the 2008 pumping. As reported in the main report (Chowdhury, 2010) 2008 pumping totaled 61,248 acre-feet per year. One-and-a-half times 2008 pumping totaled 89,921 acre-feet per year. Pumping scenarios in the supplemental runs (Hutchison, 2010) were based on an analysis of 2008 pumping and 2007 State Water Plan groundwater availability estimates. Pumping ranged from about 64,000 acre-feet per year to about 119,000 acre-feet per year.

For this Task, seven pumping scenarios were developed. The groundwater districts in Groundwater Management Area 9 updated their estimates of 2008 pumping, as detailed in Table 1. Total 2008 pumping is about 60,000 acre-feet per year.

The seven scenarios were based on varying the 2008 pumping as follows (all pumping amounts are from the Trinity Aquifer and are approximate):

- Scenario 1 = 0 acre-feet per year
- Scenario 2 = 20,000 acre-feet per year
- Scenario 3 = 40,000 acre-feet per year
- Scenario 4 = 60,000 acre-feet per year (2008 conditions)
- Scenario 5 = 80,000 acre-feet per year
- Scenario 6 = 100,000 acre-feet per year
- Scenario 7 = 120,000 acre-feet per year

Table 2. Estimated 2008 Pumping as Provided by Groundwater Conservation Districts in Groundwater Management Area 9

County	Edwards Group of the Edwards-Trinity (Plateau) Aquifer	Upper Trinity Aquifer	Middle Trinity Aquifer	Lower Trinity Aquifer	Total Pumping (County)
Bandera	631	288	3567	515	**5,000**
Bexar	0	693	14110	197	**15,000**
Blanco	0	77	1,477	0	**1,554**
Comal	0	398	5,788	0	**6,186**
Hays	0	416	4,800	449	**5,665**
Kendall	315	300	6,060	325	**7,000**
Kerr	1,035	213	6,263	5,534	**13,045**
Medina	0	0	500	1000	**1,500**
Travis	0	551	4,967	0	**5,518**
Total pumping (aquifer)	**1,981**	**2,936**	**47,532**	**8,020**	**60,468**

PARAMETERS AND ASSUMPTIONS:

- As in the requested runs and the supplemental runs, the recently updated groundwater availability model (version 2.01) for the Hill Country portion of the Trinity Aquifer developed by Jones and others (2009) was used for these simulations (see Mace and others (2000) and Jones and others (2009) for details on model construction, recharge, discharge, assumptions, and limitations of the model).

- The model has four layers: layer 1 represents the Edwards Group of the Edwards-Trinity (Plateau) Aquifer, layer 2 represents the Upper Trinity Aquifer, layer 3 represents the Middle Trinity Aquifer, and layer 4 represents the Lower Trinity Aquifer.

- The rivers, streams, and springs were simulated in the model using MODFLOW's Drain package. MODFLOW's Drain package was also used to simulate spring discharge along bedding contacts of the Edwards Group (Plateau) and the Upper

Trinity Aquifer in the northwestern parts of the model area. This resulted in the assignment of numerous drain cells along this outcrop contact.

- Seven different pumping scenarios were used as described above

- 387 recharge input files were developed as described above.

- Each simulation consisted of 50 stress periods. Initial conditions were assumed to be equivalent to 2008 conditions.

- The model was run with MODFLOW-96 (Harbaugh and McDonald, 1996)

RESULTS:

Similar to the supplemental runs (Hutchison, 2010), results from this Task focused on drawdown impacts, impacts to spring and base flow, and impacts to outflow across the Balcones Fault Zone. Results are summarized Groundwater Management Area-wide and by county. In addition, results are presented for three areas within Groundwater Management Area 9 as designated by Mr. Ron Fieseler, General Manager of the Blanco-Pedernales Groundwater Conservation District. These areas are defined as follows:

- Area 1 – Comal, Hays and Travis Counties
- Area 2 – Bexar and Medina Counties
- Area 3 – Bandera, Blanco, Kendall and Kerr Counties

Because each scenario consisted of 387 50-year simulations, the results can also be expressed in terms of minimum, average, and maximum, as well as values that are exceeded 5 percent of the time and values that are exceeded 95 percent of the time.

All drawdown results are expressed as drawdown from 2008 initial conditions at the end of the simulation (50 years). All flow data (spring flow, base flow, outflow across the Balcones Fault Zone) are calculated using the results from each year of the 387 50-year simulations.

Summary tables of all results (for all of Groundwater Management Area 9, by the portions of the counties located within the model, and by area) are presented in Appendix A.

Figure 3 summarizes the relationship between Groundwater Management Area 9 pumping and overall Trinity Aquifer drawdown after 50 years (averaged over the entire Groundwater Management Area) for all seven pumping scenarios. For purposes of this analysis, overall Trinity Aquifer drawdown includes the Trinity Aquifer and the Trinity portion of the Edwards-Trinity (Plateau) Aquifer.

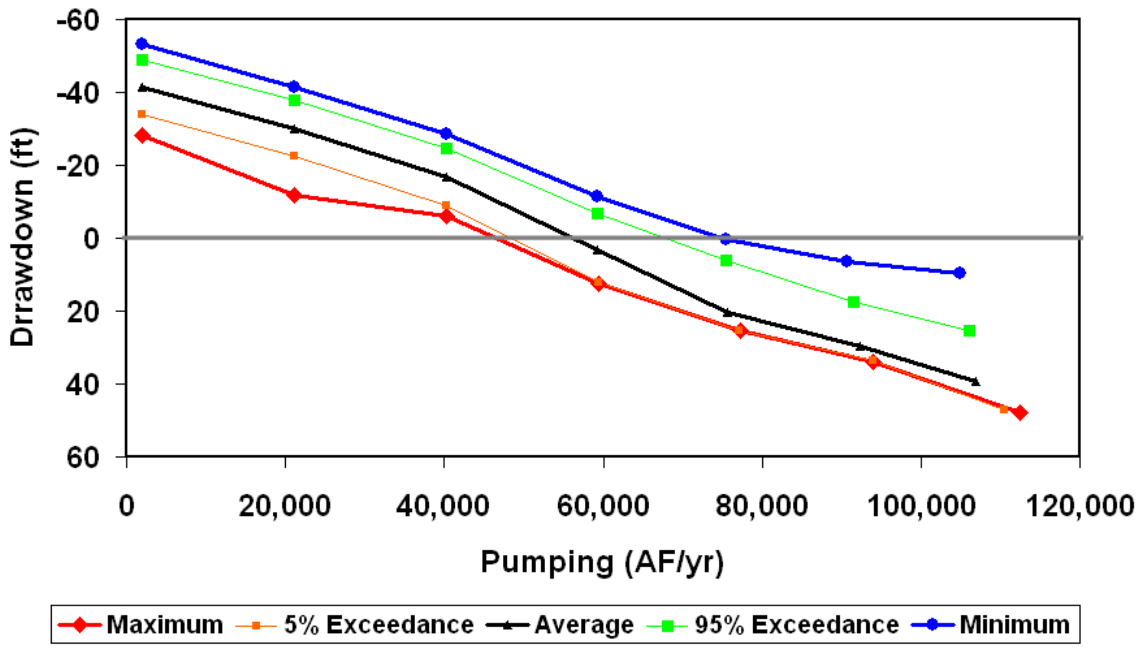


Figure 3. Pumping versus overall Trinity Aquifer drawdown after 50 years for all scenarios for Groundwater Management Area 9

Note that, as expected, increases in pumping result in increases in drawdown. The nature of these simulations provides an opportunity to evaluate drawdown in terms of the minimum value (out of all 387 simulations), 95 percent exceedance value (drawdown that is exceeded 95 percent of the time based on the 387 simulations), the average drawdown (out of all 387 simulations), 5 percent exceedance value (drawdown that is exceeded 5 percent of the time based on the 387 simulations), and the maximum value (out of all 387 simulations).

When pumping is about 60,000 acre-feet per year (the estimated 2008 pumping), average drawdown is near zero, which is expected since this pumping represents no change from 2008 conditions. However, it ranges from 12 feet of drawdown (representative of when a 50-year period ends in dry conditions) to about 12 feet of recovery (representative of when a 50-year period ends in wet conditions).

When pumping is about 1.5 times current pumping (92,000 acre-feet per year), average drawdown is about 29 feet after 50 years, with a range of between 6 to 33 feet depending on conditions at the end of the 50-year period.

Figure 4 summarizes the relationship between pumping and spring and base flow (averaged over the entire Groundwater Management Area) for all seven scenarios.

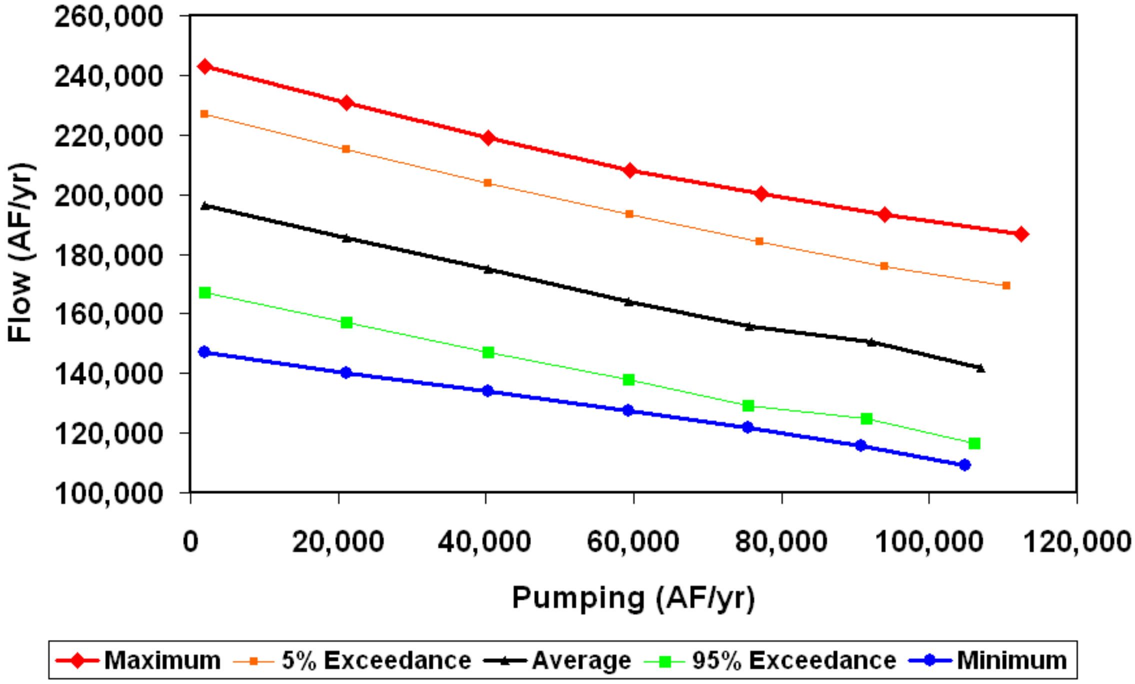


Figure 4. Pumping versus spring and base flow for all scenarios for Groundwater Management Area 9

As expected, pumping increases result in reductions in spring and base flow as the pumping captures this water prior to its discharge. It can be seen that, based on average values, 2008 pumping rates (approximately 60,000 acre-feet per year) result in an average spring and base flow of about 164,000 acre-feet per year. Zero pumping would result in a spring and base flow of about 197,000 acre-feet per year. Thus the impact of pumping 60,000 acre-feet per year includes a reduction in spring and base flow of about 33,000 acre-feet per year. If pumping were increased to 92,000 acre-feet per year (about 1.5 times the 2008 pumping rate), spring and base flow would be reduced, on average, to about 150,000 acre-feet per year. Thus an increase in pumping from 2008 levels of about 32,000 acre-feet per year would result in a reduction of 14,000 acre-feet per year in spring and base flow.

Figure 5 summarizes the relationship between pumping and outflow across the Balcones Fault Zone (averaged over the entire Groundwater Management Area) for all seven scenarios. As expected, pumping increases result in reductions in outflow across the Balcones Fault Zone as the pumping captures this water prior to its discharge. It can be seen that, based on average values, 2008 pumping rates result in an average outflow of 62,000 acre-feet per year. Zero pumping would result in a spring and base flow of about 81,000 acre-feet per year. Thus, the impact of pumping 60,000 acre-feet per year includes a reduction in Balcones Fault Zone outflow of about 19,000 acre-feet per year. If pumping were increased to 92,000 acre-feet per year (about 1.5 times the 2008 pumping rate), Balcones Fault Zone outflow would be reduced, on average, to about

50,000 acre-feet per year. Thus an increase in pumping from 2008 levels of about 32,000 acre-feet would result in a reduction of about 12,000 acre-feet per year in Balcones Fault Zone outflow.

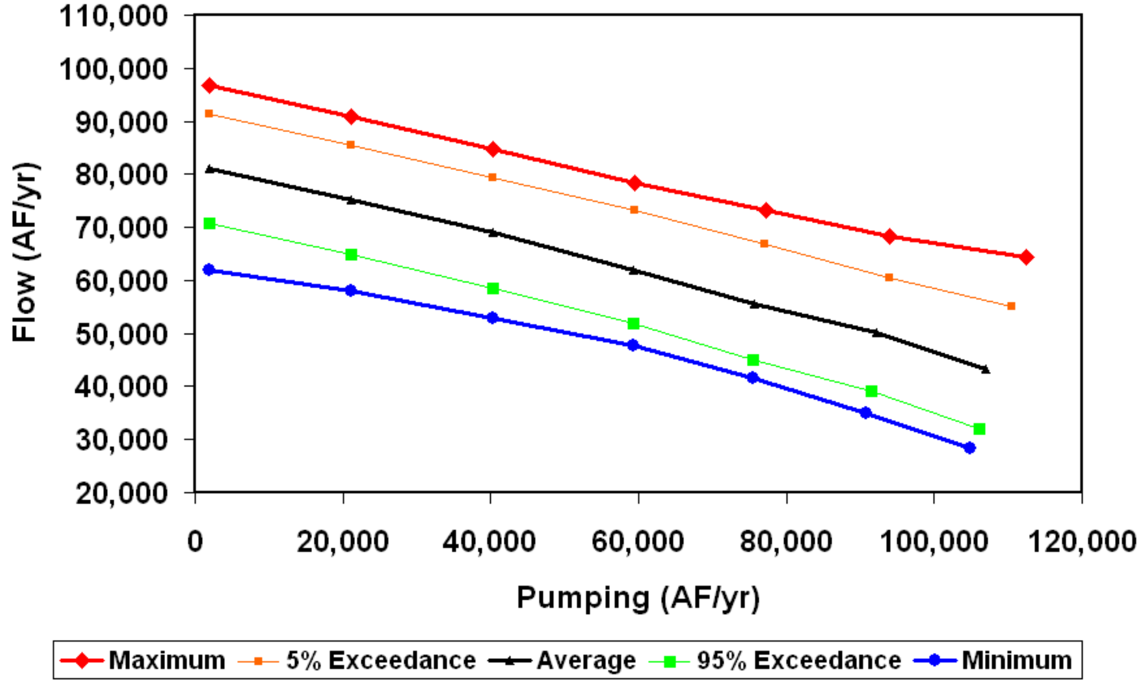


Figure 5. Pumping versus outflow across the Balcones Fault Zone for all scenarios for Groundwater Management Area 9

Figures 6, 7 and 8 summarize pumping versus the average Groundwater Management Area 9 drawdown in the upper, middle and lower Trinity Aquifer, respectively. Note that increases in pumping have less impact in the Upper Trinity Aquifer drawdown, presumably due to the buffering effect of surface water and the smaller amount of pumping in this aquifer compared with the Middle and Lower Trinity units.

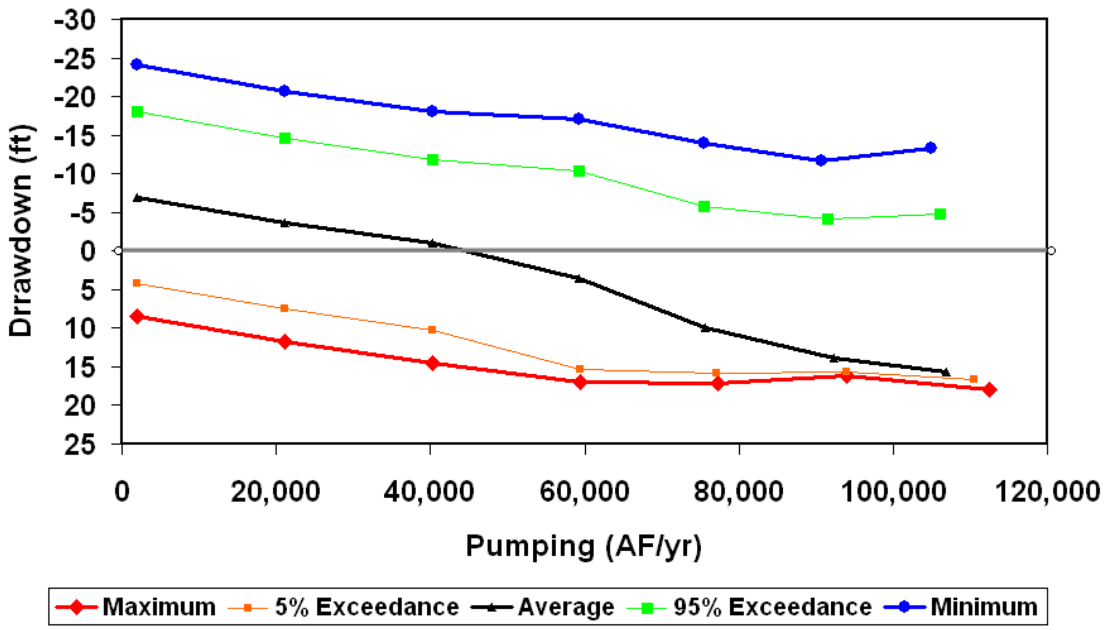


Figure 6. Pumping versus drawdown after 50 years in the Upper Trinity Aquifer for all scenarios for Groundwater Management Area 9

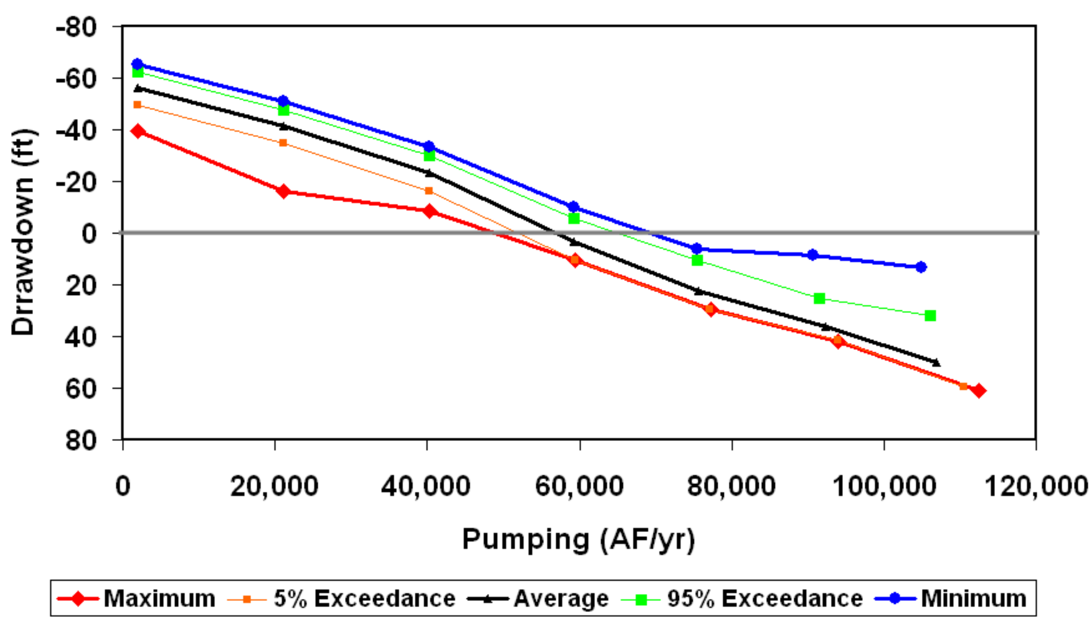


Figure 7. Pumping versus drawdown after 50 years in the Middle Trinity Aquifer for all scenarios for Groundwater Management Area 9

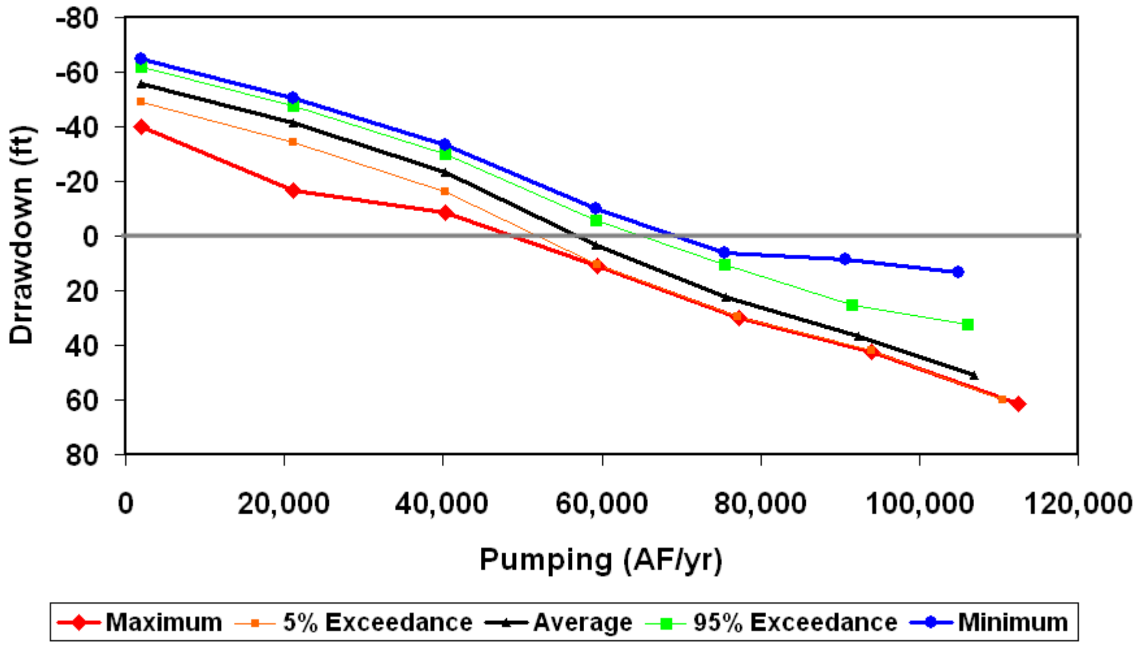


Figure 10. Pumping versus drawdown after 50 years in the Lower Trinity Aquifer for all scenarios for Groundwater Management Area 9

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Appendix A
Results Summary:
GMA 9
Bandera County
Bexar County
Blanco County
Comal County
Hays County
Kendall County
Kerr County
Medina County
Travis County
Area 1 (Comal, Hays, Travis Counties)
Area 2 (Bexar and Medina Counties)
Area 3 (Bandera, Blanco, Kendall and Kerr Counties)

GMA 9

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	1,969	21,117	40,270	59,344	75,424	90,727	104,940
	Exceeded 95% of years	1,969	21,117	40,270	59,344	75,524	91,479	106,022
	Average	1,969	21,117	40,270	59,344	75,624	92,261	106,982
	Exceeded 5% of years	1,969	21,117	40,270	59,418	77,094	94,042	110,485
	Maximum	1,969	21,117	40,270	59,418	77,193	94,042	112,454
Spring and River Base Flow (AF/yr)	Minimum	147,208	140,310	133,845	127,663	121,697	115,641	109,250
	Exceeded 95% of years	166,965	156,950	147,187	137,975	129,301	125,017	116,465
	Average	196,565	185,496	174,835	164,295	155,854	150,359	141,829
	Exceeded 5% of years	226,855	215,184	203,683	193,362	184,292	175,822	169,517
	Maximum	242,887	230,903	218,873	208,311	200,390	193,276	186,668
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	61,911	58,009	52,906	47,691	41,702	34,904	28,372
	Exceeded 95% of years	70,712	64,824	58,595	51,782	45,097	39,036	32,054
	Average	81,036	75,275	69,101	62,023	55,633	50,163	43,208
	Exceeded 5% of years	91,297	85,499	79,377	73,150	66,955	60,524	54,981
	Maximum	96,699	90,900	84,783	78,421	73,289	68,380	64,497
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-53.1	-41.6	-28.6	-11.6	0.4	6.4	9.8
	Exceeded 95% of years	-49.1	-37.8	-24.5	-6.9	6.0	17.6	25.4
	Average	-41.6	-30.1	-16.9	3.2	20.2	29.8	39.4
	Exceeded 5% of years	-33.8	-22.4	-8.8	12.0	25.4	33.7	47.0
	Maximum	-28.1	-11.8	-6.1	12.5	25.5	34.0	48.0
Edwards Group Drawdown after 50 Years (ft)	Minimum	-8.1	-8.1	-8.1	-8.1	-6.5	-6.1	-6.5
	Exceeded 95% of years	-6.2	-6.1	-6.1	-5.9	-4.8	-4.4	-4.7
	Average	-3.0	-3.0	-3.1	-2.1	0.2	0.5	0.2
	Exceeded 5% of years	0.2	0.2	0.2	0.7	3.5	2.5	3.4
	Maximum	1.7	1.3	1.7	3.3	3.9	3.4	3.9
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-24.1	-20.7	-18.0	-17.0	-14.0	-11.6	-13.3
	Exceeded 95% of years	-18.0	-14.6	-11.8	-10.4	-5.7	-4.1	-4.8
	Average	-7.0	-3.7	-1.0	3.6	9.9	13.9	15.6
	Exceeded 5% of years	4.2	7.5	10.2	15.4	15.8	15.6	16.6
	Maximum	8.4	11.8	14.5	16.9	17.2	16.2	18.0
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-65.1	-50.8	-33.4	-9.9	6.3	8.5	13.2
	Exceeded 95% of years	-62.2	-47.7	-29.9	-5.9	10.5	25.0	31.9
	Average	-56.0	-41.3	-23.4	3.1	22.4	36.4	50.2
	Exceeded 5% of years	-49.5	-34.6	-16.4	10.5	29.4	41.6	59.5
	Maximum	-39.5	-16.3	-8.6	10.7	29.6	42.0	60.9
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-64.8	-50.6	-33.4	-10.0	6.3	8.7	13.5
	Exceeded 95% of years	-61.9	-47.5	-29.9	-5.9	10.6	25.4	32.5
	Average	-55.7	-41.2	-23.4	3.1	22.6	36.7	50.8
	Exceeded 5% of years	-49.2	-34.4	-16.4	10.6	29.5	42.0	60.0
	Maximum	-40.0	-16.6	-8.8	10.8	29.8	42.3	61.5

Bandera County

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	625	2,082	3,540	4,996	6,452	7,910	9,349
	Exceeded 95% of years	625	2,082	3,540	4,996	6,452	7,910	9,361
	Average	625	2,082	3,540	4,996	6,452	7,910	9,367
	Exceeded 5% of years	625	2,082	3,540	4,996	6,452	7,910	9,367
	Maximum	625	2,082	3,540	4,996	6,452	7,910	9,367
Spring and River Base Flow (AF/yr)	Minimum	30,247	29,115	28,013	26,929	25,691	24,868	23,201
	Exceeded 95% of years	35,570	33,352	31,201	28,948	27,337	26,502	25,120
	Average	40,975	38,469	35,883	33,402	31,735	30,620	29,204
	Exceeded 5% of years	46,187	43,494	40,716	38,187	36,489	34,773	33,648
	Maximum	48,851	46,055	43,093	40,337	39,037	37,946	36,910
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	1,217	1,081	887	673	323	5	-445
	Exceeded 95% of years	1,763	1,505	1,197	819	499	165	-225
	Average	2,148	1,856	1,531	1,122	823	535	169
	Exceeded 5% of years	2,457	2,168	1,838	1,443	1,154	924	681
	Maximum	2,622	2,336	2,006	1,611	1,413	1,259	1,125
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-48.9	-39.2	-26.7	-8.0	5.5	4.5	6.7
	Exceeded 95% of years	-46.5	-36.4	-23.6	-4.2	8.8	18.6	21.6
	Average	-41.2	-31.1	-18.2	3.2	18.7	29.3	42.7
	Exceeded 5% of years	-35.9	-25.5	-12.3	9.7	24.4	34.6	51.1
	Maximum	-25.0	-8.0	-3.9	9.9	24.6	35.0	52.7
Edwards Group Drawdown after 50 Years (ft)	Minimum	-7.1	-7.1	-7.1	-7.1	-5.9	-5.4	-5.9
	Exceeded 95% of years	-5.5	-5.4	-5.4	-5.2	-4.2	-3.7	-3.9
	Average	-2.5	-2.5	-2.5	-1.5	0.6	0.8	0.6
	Exceeded 5% of years	0.5	0.5	0.5	0.9	3.1	2.4	3.0
	Maximum	1.8	1.4	1.8	3.1	3.3	3.1	3.3
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-20.7	-18.2	-15.9	-15.3	-12.6	-10.6	-12.1
	Exceeded 95% of years	-15.3	-12.7	-10.4	-9.1	-5.2	-3.8	-4.5
	Average	-5.5	-3.0	-0.8	3.5	13.7	12.6	14.2
	Exceeded 5% of years	4.6	7.1	9.6	14.2	14.5	14.1	15.1
	Maximum	8.3	11.0	13.5	15.6	15.8	14.7	16.3
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-62.2	-49.3	-32.2	-5.3	11.0	6.2	9.2
	Exceeded 95% of years	-60.8	-47.4	-29.9	-2.5	13.9	21.2	25.6
	Average	-57.6	-43.9	-26.1	3.3	21.3	37.8	58.3
	Exceeded 5% of years	-54.1	-40.2	-21.8	7.7	29.1	44.6	67.6
	Maximum	-36.8	-11.6	-5.9	8.9	29.5	45.1	70.1
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-62.2	-49.3	-32.2	-5.3	11.0	6.2	9.2
	Exceeded 95% of years	-60.8	-47.4	-29.9	-2.5	13.9	21.2	25.6
	Average	-57.6	-43.9	-26.1	3.3	21.3	37.8	58.3
	Exceeded 5% of years	-54.2	-40.2	-21.8	7.7	29.1	44.6	67.7
	Maximum	-36.8	-11.6	-5.9	8.9	29.5	45.1	70.1

Bexar County

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	0	4,970	9,943	14,913	19,884	24,856	29,246
	Exceeded 95% of years	0	4,970	9,943	14,913	19,884	24,856	29,358
	Average	0	4,970	9,943	14,913	19,884	24,856	29,589
	Exceeded 5% of years	0	4,970	9,943	14,913	19,884	24,856	29,827
	Maximum	0	4,970	9,943	14,913	19,884	24,856	29,827
Spring and River Base Flow (AF/yr)	Minimum	9,527	9,466	9,405	9,344	9,284	9,225	9,167
	Exceeded 95% of years	9,790	9,730	9,671	9,596	9,519	9,455	9,392
	Average	10,647	10,581	10,515	10,444	10,340	10,319	10,233
	Exceeded 5% of years	11,492	11,424	11,365	11,301	11,224	11,104	11,092
	Maximum	11,867	11,798	11,730	11,665	11,600	11,536	11,471
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	33,298	31,221	28,595	25,917	23,139	20,183	17,228
	Exceeded 95% of years	36,683	34,038	31,225	28,227	25,103	22,220	19,009
	Average	42,130	39,459	36,714	33,626	30,583	28,131	24,650
	Exceeded 5% of years	47,585	44,946	42,210	39,560	36,613	33,455	30,948
	Maximum	50,232	47,632	44,964	42,271	39,633	37,091	34,721
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-69.2	-56.9	-44.3	-31.0	-13.3	4.7	14.6
	Exceeded 95% of years	-59.9	-47.5	-34.5	-20.2	0.1	16.3	29.2
	Average	-43.7	-31.2	-18.2	1.5	33.7	46.0	62.9
	Exceeded 5% of years	-27.0	-13.9	-0.4	20.6	35.2	49.4	64.2
	Maximum	-20.8	-7.6	6.1	22.8	36.1	49.4	64.4
Edwards Group Drawdown after 50 Years (ft)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-24.5	-23.7	-22.9	-22.1	-17.7	-15.9	-16.1
	Exceeded 95% of years	-17.9	-16.5	-15.7	-14.0	-9.2	-6.2	-6.9
	Average	-4.2	-3.4	-2.7	3.4	16.0	15.1	17.4
	Exceeded 5% of years	10.7	11.5	12.3	17.2	18.0	17.5	19.5
	Maximum	14.8	15.6	16.4	17.6	18.3	17.7	19.8
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-87.6	-70.6	-53.0	-34.7	-11.6	13.1	27.1
	Exceeded 95% of years	-77.0	-60.0	-42.4	-21.9	3.9	25.6	44.5
	Average	-60.1	-43.0	-24.6	0.7	40.6	58.6	81.1
	Exceeded 5% of years	-42.3	-24.3	-5.5	22.1	42.3	62.5	82.6
	Maximum	-35.4	-17.1	1.9	24.9	43.4	62.6	82.8
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-87.5	-70.5	-53.0	-34.7	-11.6	13.1	27.1
	Exceeded 95% of years	-76.9	-59.9	-42.3	-21.9	3.9	25.5	44.5
	Average	-60.0	-42.9	-24.6	0.7	40.6	58.6	81.5
	Exceeded 5% of years	-42.3	-24.3	-5.5	22.1	42.3	62.5	83.0
	Maximum	-35.3	-17.1	1.9	24.9	43.4	62.6	83.2

Blanco County

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	0	515	1,029	1,544	2,059	2,573	3,088
	Exceeded 95% of years	0	515	1,029	1,544	2,059	2,573	3,088
	Average	0	515	1,029	1,544	2,059	2,573	3,088
	Exceeded 5% of years	0	515	1,029	1,544	2,059	2,573	3,088
	Maximum	0	515	1,029	1,544	2,059	2,573	3,088
Spring and River Base Flow (AF/yr)	Minimum	13,690	13,313	12,942	12,594	12,221	11,845	11,411
	Exceeded 95% of years	15,263	14,849	14,353	13,847	13,187	12,913	12,310
	Average	18,762	18,259	17,710	17,092	16,489	16,312	15,606
	Exceeded 5% of years	22,508	21,879	21,285	20,783	20,208	19,556	19,181
	Maximum	24,353	23,748	23,128	22,617	22,122	21,702	21,319
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-23.0	-19.9	-16.6	-13.1	-7.9	-1.4	-0.4
	Exceeded 95% of years	-18.1	-14.9	-11.6	-7.4	-0.2	4.1	7.4
	Average	-9.4	-6.1	-2.7	4.0	16.7	19.2	23.6
	Exceeded 5% of years	-0.1	3.0	6.7	13.3	18.5	21.0	27.1
	Maximum	2.9	6.2	9.6	14.8	18.5	22.1	27.2
Edwards Group Drawdown after 50 Years (ft)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-19.7	-19.1	-18.6	-18.1	-14.3	-12.6	-13.5
	Exceeded 95% of years	-13.2	-12.5	-11.9	-10.5	-6.2	-4.0	-5.4
	Average	-1.0	-0.5	-0.1	4.9	16.0	14.8	16.2
	Exceeded 5% of years	12.1	12.6	13.0	17.3	17.6	16.7	18.1
	Maximum	16.0	16.5	16.9	17.8	18.0	16.9	18.4
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-24.1	-20.1	-15.9	-11.3	-5.6	2.7	4.4
	Exceeded 95% of years	-20.1	-16.0	-11.7	-6.4	1.5	7.0	11.6
	Average	-12.6	-8.2	-3.6	3.5	16.7	20.6	26.0
	Exceeded 5% of years	-4.3	0.2	5.0	11.8	19.6	23.4	31.4
	Maximum	-1.8	2.7	7.5	13.7	19.7	24.5	31.4
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-24.4	-20.3	-16.0	-11.4	-5.5	2.9	4.6
	Exceeded 95% of years	-20.4	-16.1	-11.8	-6.4	1.6	7.2	11.8
	Average	-12.7	-8.3	-3.6	3.6	16.8	20.7	26.2
	Exceeded 5% of years	-4.5	0.1	4.9	11.8	19.6	23.4	31.3
	Maximum	-2.0	2.6	7.4	13.7	19.6	24.4	31.3

Comal County

Component	Case	Scenario						
		1	**2**	**3**	**4**	**5**	**6**	**7**
Pumping (AF/yr)	Minimum	0	2,042	4,086	6,128	8,170	10,214	11,924
	Exceeded 95% of years	0	2,042	4,086	6,128	8,170	10,214	12,068
	Average	0	2,042	4,086	6,128	8,170	10,214	12,225
	Exceeded 5% of years	0	2,042	4,086	6,128	8,170	10,214	12,256
	Maximum	0	2,042	4,086	6,128	8,170	10,214	12,256
Spring and River Base Flow (AF/yr)	Minimum	5,309	3,693	1,918	124	-1,730	-3,623	-5,496
	Exceeded 95% of years	8,017	5,663	3,509	1,592	-576	-2,387	-4,498
	Average	12,794	10,322	7,883	5,319	3,114	1,477	-823
	Exceeded 5% of years	17,638	15,165	12,669	10,228	7,669	5,079	3,287
	Maximum	19,973	17,503	15,001	12,558	10,192	8,010	6,277
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	33,808	32,833	31,781	30,711	29,604	28,442	27,279
	Exceeded 95% of years	35,331	34,298	33,261	32,094	30,871	29,689	28,480
	Average	39,283	38,316	37,292	36,131	34,913	33,948	32,577
	Exceeded 5% of years	43,101	42,124	41,128	40,215	39,082	37,888	36,897
	Maximum	44,814	43,864	42,898	41,927	40,960	40,011	39,046
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-27.8	-23.6	-19.4	-15.0	-7.9	-1.3	2.3
	Exceeded 95% of years	-22.8	-18.6	-14.3	-9.2	-0.7	5.9	10.8
	Average	-14.2	-10.1	-5.3	2.9	19.2	23.9	31.1
	Exceeded 5% of years	-4.9	-0.3	4.6	14.4	20.3	25.7	31.9
	Maximum	-1.7	3.1	8.5	15.2	20.7	25.7	32.0
Edwards Group Drawdown after 50 Years (ft)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-21.8	-21.1	-20.5	-19.9	-16.0	-14.3	-14.8
	Exceeded 95% of years	-14.8	-14.0	-13.5	-11.9	-7.5	-4.2	-5.2
	Average	-1.4	-0.9	-0.3	5.4	16.4	15.4	17.5
	Exceeded 5% of years	12.6	13.1	13.7	17.9	18.5	17.9	19.6
	Maximum	16.3	16.8	17.4	17.9	18.5	17.9	19.6
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-29.1	-24.2	-19.1	-13.9	-6.3	1.6	5.9
	Exceeded 95% of years	-24.6	-19.6	-14.6	-8.7	0.6	8.4	14.3
	Average	-17.0	-11.9	-6.4	2.4	19.8	25.5	33.7
	Exceeded 5% of years	-8.9	-3.2	2.8	13.6	20.7	27.5	34.3
	Maximum	-5.7	0.1	6.6	14.7	21.2	27.5	34.4
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-29.1	-24.2	-19.1	-13.9	-6.3	1.6	6.0
	Exceeded 95% of years	-24.7	-19.7	-14.6	-8.7	0.6	8.4	14.4
	Average	-17.0	-11.9	-6.4	2.4	19.7	25.5	34.3
	Exceeded 5% of years	-9.0	-3.2	2.8	13.6	20.7	27.5	35.1
	Maximum	-5.7	0.1	6.5	14.7	21.2	27.5	35.3

Hays County

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	0	1,826	3,652	5,478	7,304	9,115	10,486
	Exceeded 95% of years	0	1,826	3,652	5,478	7,304	9,115	10,492
	Average	0	1,826	3,652	5,478	7,304	9,115	10,938
	Exceeded 5% of years	0	1,826	3,652	5,478	7,304	9,130	10,956
	Maximum	0	1,826	3,652	5,478	7,304	9,130	10,956
Spring and River Base Flow (AF/yr)	Minimum	17,976	17,239	16,474	15,709	14,913	14,104	13,345
	Exceeded 95% of years	18,900	18,203	17,417	16,552	15,690	14,938	14,154
	Average	21,917	21,133	20,364	19,599	18,694	18,025	17,140
	Exceeded 5% of years	25,016	24,230	23,451	22,686	21,850	20,971	20,286
	Maximum	26,427	25,620	24,832	24,080	23,346	22,630	21,854
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	5,832	5,290	4,623	3,894	3,046	2,155	1,418
	Exceeded 95% of years	6,889	6,029	5,235	4,355	3,371	2,600	1,838
	Average	8,252	7,409	6,557	5,668	4,774	3,995	3,179
	Exceeded 5% of years	9,628	8,772	7,907	7,105	6,214	5,335	4,665
	Maximum	10,263	9,405	8,542	7,743	7,039	6,509	5,978
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-21.5	-16.8	-12.1	-7.3	-1.3	5.4	6.6
	Exceeded 95% of years	-18.3	-13.6	-8.8	-3.5	3.9	9.2	12.2
	Average	-12.5	-7.7	-3.0	4.0	15.1	19.2	23.5
	Exceeded 5% of years	-6.6	-1.9	3.2	10.2	15.9	20.3	24.5
	Maximum	-4.7	0.2	5.2	10.9	15.9	20.8	24.6
Edwards Group Drawdown after 50 Years (ft)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-12.0	-11.7	-11.3	-11.0	-8.2	-7.3	-7.8
	Exceeded 95% of years	-8.0	-7.1	-6.7	-5.8	-2.9	-1.1	-2.2
	Average	0.5	0.9	1.2	4.8	12.2	11.4	12.7
	Exceeded 5% of years	9.4	9.7	10.1	13.0	13.4	12.9	14.0
	Maximum	12.0	12.3	12.7	13.1	13.5	13.0	14.1
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-25.4	-19.0	-12.6	-6.0	1.5	8.2	11.8
	Exceeded 95% of years	-22.8	-16.3	-9.7	-2.9	6.2	13.5	17.4
	Average	-17.9	-11.4	-4.7	3.7	16.0	22.4	27.5
	Exceeded 5% of years	-12.7	-6.1	0.9	9.1	17.6	23.8	29.2
	Maximum	-11.1	-4.3	2.6	10.0	17.6	24.3	29.4
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-25.4	-19.0	-12.6	-6.0	1.5	8.2	11.8
	Exceeded 95% of years	-22.8	-16.3	-9.7	-2.9	6.2	13.5	17.5
	Average	-17.9	-11.4	-4.7	3.7	16.0	22.4	27.7
	Exceeded 5% of years	-12.7	-6.1	0.9	9.1	17.6	23.8	29.5
	Maximum	-11.1	-4.4	2.6	10.0	17.6	24.4	29.6

Kendall County

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	310	2,539	4,766	6,994	9,223	11,450	13,678
	Exceeded 95% of years	310	2,539	4,766	6,994	9,223	11,450	13,678
	Average	310	2,539	4,766	6,994	9,223	11,450	13,678
	Exceeded 5% of years	310	2,539	4,766	6,994	9,223	11,450	13,678
	Maximum	310	2,539	4,766	6,994	9,223	11,450	13,678
Spring and River Base Flow (AF/yr)	Minimum	25,159	23,558	22,071	20,736	19,214	17,848	15,899
	Exceeded 95% of years	29,988	27,651	25,150	22,814	20,790	19,421	17,739
	Average	36,424	33,737	31,034	28,183	26,184	24,753	22,688
	Exceeded 5% of years	43,318	40,422	37,390	34,466	32,253	30,160	28,629
	Maximum	47,156	44,178	40,989	38,030	36,010	34,442	32,978
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-41.3	-35.0	-28.0	-20.0	-11.5	-0.2	2.7
	Exceeded 95% of years	-34.5	-27.9	-21.1	-12.9	-0.9	7.7	13.5
	Average	-22.0	-15.7	-8.6	3.4	23.5	28.6	36.8
	Exceeded 5% of years	-9.1	-2.8	4.4	17.1	26.6	31.7	41.9
	Maximum	-5.0	1.5	8.6	19.6	26.6	32.5	42.0
Edwards Group Drawdown after 50 Years (ft)	Minimum	-3.5	-3.5	-3.5	-3.5	-3.1	-2.3	-3.1
	Exceeded 95% of years	-2.3	-2.3	-2.3	-2.3	-1.4	-1.1	-1.2
	Average	-0.3	-0.4	-0.3	0.2	2.1	2.0	2.0
	Exceeded 5% of years	1.7	1.7	1.7	2.1	2.7	2.3	2.7
	Maximum	2.3	2.3	2.3	2.7	2.7	2.7	2.7
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-45.0	-42.8	-41.0	-39.5	-32.9	-27.1	-31.4
	Exceeded 95% of years	-30.6	-28.3	-26.5	-24.3	-14.9	-11.5	-12.6
	Average	-7.1	-5.2	-3.7	5.2	29.1	26.3	30.3
	Exceeded 5% of years	17.9	19.4	21.0	30.4	31.1	30.3	32.4
	Maximum	26.1	28.0	29.4	33.3	33.9	31.0	34.9
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-40.2	-32.3	-23.9	-14.1	-4.3	7.4	11.1
	Exceeded 95% of years	-35.6	-27.8	-19.2	-8.8	3.7	13.6	22.5
	Average	-27.0	-19.1	-10.4	3.1	21.3	29.3	38.8
	Exceeded 5% of years	-18.2	-10.0	-0.8	12.5	25.6	32.8	45.7
	Maximum	-15.3	-7.0	2.2	14.9	25.6	33.3	45.8
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-40.1	-32.3	-23.9	-14.2	-4.3	7.4	11.2
	Exceeded 95% of years	-35.5	-27.8	-19.3	-8.8	3.7	13.7	22.5
	Average	-26.9	-19.0	-10.4	3.0	21.3	29.4	39.0
	Exceeded 5% of years	-18.1	-9.9	-0.8	12.6	25.6	32.9	45.8
	Maximum	-15.2	-6.9	2.2	15.0	25.6	33.4	45.9

Kerr County

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	1,033	5,030	9,029	13,026	14,180	14,594	15,656
	Exceeded 95% of years	1,033	5,030	9,029	13,026	14,180	15,170	16,614
	Average	1,033	5,030	9,029	13,026	14,180	15,952	16,614
	Exceeded 5% of years	1,033	5,030	9,029	13,026	15,650	17,468	18,935
	Maximum	1,033	5,030	9,029	13,026	15,650	17,468	20,755
Spring and River Base Flow (AF/yr)	Minimum	31,354	31,284	31,168	31,102	31,097	31,127	31,040
	Exceeded 95% of years	34,569	33,772	33,361	33,242	33,121	33,421	33,125
	Average	39,213	38,159	37,582	37,349	37,351	37,559	37,294
	Exceeded 5% of years	44,116	42,936	42,155	42,132	41,972	41,641	41,844
	Maximum	46,635	45,388	44,438	44,272	44,256	44,225	44,193
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-103.0	-78.8	-49.0	-9.0	11.6	5.6	9.8
	Exceeded 95% of years	-100.1	-75.4	-45.2	-5.2	13.4	21.0	25.1
	Average	-94.7	-70.2	-40.1	2.7	21.3	39.2	58.5
	Exceeded 5% of years	-89.1	-64.4	-33.8	7.9	33.1	46.6	69.2
	Maximum	-57.2	-18.5	-9.8	11.5	33.6	47.5	72.0
Edwards Group Drawdown after 50 Years (ft)	Minimum	-9.0	-9.0	-9.0	-9.0	-7.1	-6.9	-7.1
	Exceeded 95% of years	-7.0	-6.9	-6.9	-6.6	-5.4	-5.2	-5.3
	Average	-3.5	-3.5	-3.6	-2.5	-0.2	0.2	-0.2
	Exceeded 5% of years	0.1	0.1	0.1	0.4	3.7	2.6	3.5
	Maximum	1.6	1.1	1.6	3.4	4.2	3.6	4.2
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-27.3	-19.0	-12.5	-10.5	-9.1	-7.2	-8.7
	Exceeded 95% of years	-23.7	-15.4	-9.1	-6.9	-4.6	-3.7	-3.8
	Average	-17.0	-9.0	-2.8	0.7	6.9	6.7	7.1
	Exceeded 5% of years	-10.3	-2.2	3.7	6.9	9.4	8.3	9.6
	Maximum	-3.1	-0.1	5.9	9.4	9.7	9.5	10.1
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-142.2	-109.5	-67.6	-8.1	13.2	8.3	14.4
	Exceeded 95% of years	-139.9	-106.3	-64.5	-4.8	21.0	27.6	34.1
	Average	-135.1	-101.8	-59.4	3.6	29.1	56.8	86.6
	Exceeded 5% of years	-130.1	-96.1	-52.1	9.5	45.1	66.4	99.8
	Maximum	-84.1	-27.0	-14.1	16.9	45.8	68.1	103.5
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-142.7	-110.4	-68.5	-8.2	13.8	8.6	15.0
	Exceeded 95% of years	-140.2	-107.2	-65.4	-4.8	21.3	28.5	35.5
	Average	-135.6	-102.8	-60.2	3.8	29.7	58.2	88.8
	Exceeded 5% of years	-130.7	-97.1	-53.0	9.7	46.0	68.0	102.4
	Maximum	-86.7	-28.3	-14.8	17.2	46.7	69.8	106.3

Medina County

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	0	500	1,000	1,500	2,000	2,500	3,000
	Exceeded 95% of years	0	500	1,000	1,500	2,000	2,500	3,000
	Average	0	500	1,000	1,500	2,000	2,500	3,000
	Exceeded 5% of years	0	500	1,000	1,500	2,000	2,500	3,000
	Maximum	0	500	1,000	1,500	2,000	2,500	3,000
Spring and River Base Flow (AF/yr)	Minimum	4,991	4,985	4,978	4,971	4,965	4,955	4,943
	Exceeded 95% of years	5,112	5,096	5,083	5,070	5,056	5,049	5,037
	Average	5,463	5,443	5,428	5,413	5,398	5,395	5,378
	Exceeded 5% of years	5,810	5,789	5,773	5,776	5,750	5,734	5,729
	Maximum	5,961	5,940	5,922	5,911	5,904	5,896	5,889
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	10,930	9,947	8,705	7,361	5,365	3,375	915
	Exceeded 95% of years	14,040	12,286	10,422	8,214	6,305	4,318	2,065
	Average	16,304	14,499	12,538	10,236	8,380	6,647	4,483
	Exceeded 5% of years	18,400	16,589	14,611	12,344	10,570	8,903	7,233
	Maximum	19,533	17,731	15,726	13,475	12,099	10,924	9,948
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-24.2	-18.9	-12.7	-4.9	1.6	5.0	7.4
	Exceeded 95% of years	-22.4	-17.0	-10.9	-2.9	4.3	10.7	15.4
	Average	-18.9	-13.6	-7.4	1.6	10.8	16.1	22.1
	Exceeded 5% of years	-15.3	-9.9	-3.8	5.7	12.4	17.9	25.0
	Maximum	-13.7	-6.8	-2.5	5.8	12.4	17.9	25.4
Edwards Group Drawdown after 50 Years (ft)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-8.2	-8.0	-7.8	-7.5	-6.0	-5.3	-5.7
	Exceeded 95% of years	-5.5	-5.2	-4.9	-4.4	-2.6	-1.7	-2.2
	Average	-0.5	-0.3	-0.1	2.0	6.8	6.4	7.0
	Exceeded 5% of years	5.0	5.2	5.4	7.3	7.5	7.2	7.9
	Maximum	6.6	6.9	7.1	7.6	7.7	7.2	7.9
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-32.5	-24.6	-15.7	-4.1	5.4	7.3	10.9
	Exceeded 95% of years	-31.1	-23.2	-14.1	-2.4	7.5	16.0	20.8
	Average	-28.4	-20.4	-11.3	1.5	12.8	21.0	30.3
	Exceeded 5% of years	-25.5	-17.5	-8.3	4.8	15.3	23.5	34.2
	Maximum	-21.4	-10.4	-5.4	4.9	15.4	23.8	34.8
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-32.6	-24.7	-15.7	-4.1	5.5	7.3	10.9
	Exceeded 95% of years	-31.2	-23.3	-14.2	-2.4	7.5	16.1	20.9
	Average	-28.5	-20.5	-11.3	1.5	12.8	21.1	30.4
	Exceeded 5% of years	-25.6	-17.5	-8.3	4.8	15.4	23.6	34.3
	Maximum	-21.4	-10.5	-5.4	4.9	15.4	23.9	34.9

Travis County

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	0	1,814	3,629	5,368	6,958	8,521	9,405
	Exceeded 95% of years	0	1,814	3,629	5,368	7,058	8,521	9,561
	Average	0	1,814	3,629	5,368	7,158	8,697	9,692
	Exceeded 5% of years	0	1,814	3,629	5,443	7,158	8,947	10,437
	Maximum	0	1,814	3,629	5,443	7,257	8,947	10,736
Spring and River Base Flow (AF/yr)	Minimum	13,039	12,019	10,762	9,511	8,171	6,895	5,915
	Exceeded 95% of years	14,452	12,938	11,495	10,032	8,549	7,343	6,337
	Average	16,216	14,699	13,180	11,666	10,197	9,050	7,959
	Exceeded 5% of years	18,024	16,480	14,936	13,469	12,022	10,687	9,792
	Maximum	18,883	17,348	15,798	14,389	13,230	12,312	11,359
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	1,565	1,377	1,132	855	521	171	-147
	Exceeded 95% of years	1,966	1,643	1,314	973	613	290	-28
	Average	2,341	2,006	1,672	1,321	980	670	341
	Exceeded 5% of years	2,717	2,377	2,034	1,700	1,384	1,057	777
	Maximum	2,914	2,571	2,226	1,917	1,695	1,510	1,324
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-24.8	-18.4	-11.7	-5.1	2.9	11.1	12.5
	Exceeded 95% of years	-21.3	-14.8	-8.1	-1.0	8.9	16.6	19.1
	Average	-15.2	-8.6	-1.9	6.9	20.7	27.6	31.5
	Exceeded 5% of years	-9.0	-2.6	4.4	13.4	22.0	28.8	32.9
	Maximum	-7.1	-0.6	6.3	13.9	22.0	29.4	33.4
Edwards Group Drawdown after 50 Years (ft)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-14.2	-12.6	-11.0	-9.5	-4.3	-0.1	-3.8
	Exceeded 95% of years	-6.6	-5.0	-3.4	-1.3	4.9	8.0	6.4
	Average	5.9	7.4	8.9	14.8	28.0	28.2	29.4
	Exceeded 5% of years	18.7	20.3	21.8	28.1	29.3	29.7	31.0
	Maximum	23.5	25.1	26.7	28.3	29.6	30.8	32.9
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-28.7	-20.6	-12.2	-3.8	5.7	11.3	16.1
	Exceeded 95% of years	-26.6	-18.3	-9.8	-1.1	9.7	19.8	23.3
	Average	-22.8	-14.5	-5.9	4.1	17.8	27.6	31.5
	Exceeded 5% of years	-18.9	-10.6	-1.8	8.1	19.8	29.0	33.5
	Maximum	-17.8	-9.4	-0.6	8.7	19.8	29.5	33.8
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-28.9	-20.7	-12.3	-3.9	5.4	11.4	16.1
	Exceeded 95% of years	-26.8	-18.5	-9.9	-1.3	9.6	19.4	23.3
	Average	-23.0	-14.6	-5.9	4.0	17.8	27.6	32.5
	Exceeded 5% of years	-19.0	-10.6	-1.7	8.2	19.9	29.0	34.8
	Maximum	-17.9	-9.4	-0.5	8.8	19.9	29.5	35.3

Area 1 (Comal, Hays and Travis Counties)

Component	Case	Scenario 1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	0	5,682	11,367	16,974	22,432	27,850	31,828
	Exceeded 95% of years	0	5,682	11,367	16,974	22,532	27,850	32,131
	Average	0	5,682	11,367	16,974	22,632	28,026	32,855
	Exceeded 5% of years	0	5,682	11,367	17,049	22,632	28,291	33,649
	Maximum	0	5,682	11,367	17,049	22,731	28,291	33,948
Spring and River Base Flow (AF/yr)	Minimum	36,382	33,020	29,161	25,397	21,452	17,392	13,798
	Exceeded 95% of years	41,415	36,777	32,250	28,088	23,579	19,904	15,872
	Average	50,919	46,177	41,514	36,563	32,043	28,588	24,313
	Exceeded 5% of years	60,615	55,827	51,004	46,460	41,599	36,704	33,352
	Maximum	65,283	60,471	55,624	51,000	46,618	42,766	39,484
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	41,232	39,579	37,536	35,479	33,228	30,775	28,578
	Exceeded 95% of years	44,158	41,949	39,692	37,286	34,837	32,611	30,270
	Average	49,847	47,750	45,517	43,107	40,642	38,643	36,144
	Exceeded 5% of years	55,375	53,220	51,036	48,980	46,694	44,199	42,358
	Maximum	57,991	55,840	53,666	51,582	49,641	47,778	46,271
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-24.5	-19.6	-14.5	-9.4	-2.6	4.8	6.5
	Exceeded 95% of years	-20.4	-15.4	-10.4	-4.7	3.6	10.0	13.4
	Average	-13.6	-8.8	-3.6	4.3	18.0	23.0	28.1
	Exceeded 5% of years	-6.7	-1.4	4.1	12.5	18.6	24.3	29.0
	Maximum	-4.3	1.0	6.6	13.1	18.6	24.5	29.3
Edwards Group Drawdown after 50 Years (ft)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-15.1	-14.4	-13.6	-12.9	-9.0	-7.2	-8.3
	Exceeded 95% of years	-9.7	-8.3	-7.5	-6.0	-1.9	0.7	-0.8
	Average	1.4	2.1	2.9	7.7	17.6	17.0	18.6
	Exceeded 5% of years	12.8	13.5	14.2	18.4	19.0	18.7	20.0
	Maximum	16.2	16.9	17.7	18.5	19.2	19.0	20.6
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-27.5	-21.2	-14.8	-8.3	-0.4	8.7	11.4
	Exceeded 95% of years	-24.4	-18.0	-11.5	-4.6	5.1	13.1	18.0
	Average	-18.7	-12.3	-5.6	3.3	17.9	24.7	30.8
	Exceeded 5% of years	-12.8	-6.2	0.8	10.5	19.0	26.1	32.1
	Maximum	-10.9	-4.2	3.0	11.4	19.0	26.7	32.1
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-27.6	-21.3	-14.8	-8.3	-0.5	8.6	11.4
	Exceeded 95% of years	-24.5	-18.1	-11.6	-4.6	5.1	13.0	18.2
	Average	-18.8	-12.4	-5.7	3.3	18.0	24.8	31.4
	Exceeded 5% of years	-12.9	-6.3	0.8	10.5	19.0	26.1	32.7
	Maximum	-11.0	-4.2	3.0	11.4	19.0	26.7	32.8

Area 2 (Medina and Bexar Counties)

Component	Case	Scenario						
		1	2	3	4	5	6	7
Pumping (AF/yr)	Minimum	0	5,470	10,943	16,413	21,884	27,356	32,246
	Exceeded 95% of years	0	5,470	10,943	16,413	21,884	27,356	32,358
	Average	0	5,470	10,943	16,413	21,884	27,356	32,589
	Exceeded 5% of years	0	5,470	10,943	16,413	21,884	27,356	32,827
	Maximum	0	5,470	10,943	16,413	21,884	27,356	32,827
Spring and River Base Flow (AF/yr)	Minimum	14,518	14,451	14,383	14,315	14,249	14,183	14,119
	Exceeded 95% of years	14,893	14,824	14,752	14,649	14,574	14,501	14,429
	Average	16,113	16,027	15,946	15,865	15,737	15,718	15,612
	Exceeded 5% of years	17,305	17,216	17,134	17,078	16,977	16,841	16,825
	Maximum	17,828	17,738	17,652	17,576	17,504	17,432	17,360
Outflow Across the Balcones Fault Zone (AF/yr)	Minimum	44,228	41,198	37,300	33,278	28,805	23,593	18,313
	Exceeded 95% of years	50,933	46,428	41,743	36,416	31,309	26,651	21,169
	Average	58,350	53,918	49,236	43,765	38,878	34,722	29,275
	Exceeded 5% of years	65,785	61,372	56,704	51,861	47,188	42,165	37,851
	Maximum	69,765	65,363	60,690	55,746	51,732	47,886	44,669
Overall Trinity Drawdown after 50 Years (ft)	Minimum	-54.3	-44.3	-33.8	-22.4	-8.4	6.1	14.5
	Exceeded 95% of years	-47.5	-37.2	-26.6	-14.1	1.5	14.4	25.1
	Average	-35.6	-25.4	-14.6	1.6	26.2	36.3	49.2
	Exceeded 5% of years	-23.1	-12.6	-1.6	15.6	27.4	38.9	50.8
	Maximum	-18.6	-8.0	3.2	17.1	27.4	39.0	51.1
Edwards Group Drawdown after 50 Years (ft)	Minimum	NA	NA	NA	NA	NA	NA	NA
	Exceeded 95% of years	NA	NA	NA	NA	NA	NA	NA
	Average	NA	NA	NA	NA	NA	NA	NA
	Exceeded 5% of years	NA	NA	NA	NA	NA	NA	NA
	Maximum	NA	NA	NA	NA	NA	NA	NA
Upper Trinity Drawdown after 50 Years(ft)	Minimum	-18.6	-18.0	-17.4	-16.8	-13.3	-12.0	-12.2
	Exceeded 95% of years	-13.4	-12.4	-11.8	-10.4	-6.8	-4.5	-5.2
	Average	-2.9	-2.3	-1.8	2.9	12.6	11.9	13.7
	Exceeded 5% of years	8.6	9.2	9.8	13.6	14.2	13.7	15.2
	Maximum	11.8	12.4	13.0	13.9	14.4	13.9	15.5
Middle Trinity Drawdown after 50 Years(ft)	Minimum	-70.2	-56.0	-41.1	-24.8	-6.2	14.0	26.3
	Exceeded 95% of years	-62.6	-48.3	-33.5	-15.8	5.2	23.1	38.9
	Average	-50.2	-35.8	-20.5	0.9	31.9	46.9	64.4
	Exceeded 5% of years	-37.1	-22.4	-6.4	16.5	33.4	50.1	67.0
	Maximum	-32.1	-17.1	-1.1	18.6	33.5	50.2	67.3
Lower Trinity Drawdown after 50 Years (ft)	Minimum	-70.1	-56.0	-41.1	-24.8	-6.2	14.0	26.4
	Exceeded 95% of years	-62.6	-48.3	-33.4	-15.8	5.2	23.1	39.0
	Average	-50.2	-35.8	-20.5	0.9	31.9	46.9	65.0
	Exceeded 5% of years	-37.1	-22.3	-6.4	16.5	33.4	50.1	67.6
	Maximum	-32.0	-17.1	-1.1	18.6	33.5	50.2	67.8

Area 3 (Bandera, Blanco, Kendall and Kerr Counties)

Component **Case**

Scenario

Component	Case	1	2	3	4	5	6
Pumping (AF/yr)	Minimum	1,968	10,16	18,36	26,56	31,91	36,52
	Exceeded 95% of	1,968	10,16	18,36	26,56	31,91	37,10
	Average	1,968	10,16	18,36	26,56	31,91	37,88
	Exceeded 5% of	1,968	10,16	18,36	26,56	33,38	39,40
	Maximum	1,968	10,16	18,36	26,56	33,38	39,40
Spring and River Base Flow (AF/yr)	Minimum	100,4	97,27	94,25	91,43	88,68	86,24
	Exceeded 95% of	115,6	109,8	104,2	98,85	94,46	92,52
	Average	135,5	128,7	122,1	116,0	111,7	109,2
	Exceeded 5% of	155,8	148,5	141,2	135,1	130,5	126,1
	Maximum	166,2	158,5	150,9	144,5	140,6	137,1
Outflow Across the Balcones Fault Zone	Minimum	1,217	1,081	887	673	323	5
	Exceeded 95% of	1,763	1,505	1,197	819	499	165
	Average	2,148	1,856	1,531	1,122	823	535
	Exceeded 5% of	2,457	2,168	1,838	1,443	1,154	924
	Maximum	2,622	2,336	2,006	1,611	1,413	1,259
Overall Trinity Drawdown after 50	Minimum	-62.3	-49.1	-33.1	-11.4	2.5	5.0
	Exceeded 95% of	-58.8	-45.4	-29.0	-6.8	7.1	19.6
	Average	-51.5	-38.0	-21.7	3.2	20.0	31.1
	Exceeded 5% of	-43.9	-30.4	-13.8	11.2	27.3	36.3
	Maximum	-32.7	-11.9	-6.3	11.6	27.5	36.6
Edwards Group Drawdown after 50	Minimum	-8.1	-8.1	-8.1	-8.1	-6.5	-6.1
	Exceeded 95% of	-6.2	-6.1	-6.1	-5.9	-4.8	-4.4
	Average	-3.0	-3.0	-3.1	-2.1	0.2	0.5
	Exceeded 5% of	0.2	0.2	0.2	0.7	3.5	2.5
	Maximum	1.7	1.3	1.7	3.3	3.9	3.4
Upper Trinity Drawdown after 50	Minimum	-27.3	-22.8	-19.3	-18.2	-15.5	-12.8
	Exceeded 95% of	-21.3	-16.8	-13.2	-10.9	-6.9	-5.2
	Average	-9.8	-5.5	-2.1	2.8	14.4	13.2
	Exceeded 5% of	1.8	5.9	9.8	14.9	15.5	15.1
	Maximum	5.8	10.4	13.9	16.9	17.2	15.8
Middle Trinity Drawdown after 50	Minimum	-77.6	-60.7	-39.3	-9.1	9.7	7.0
	Exceeded 95% of	-74.9	-57.6	-35.9	-4.9	13.0	24.4
	Average	-69.4	-51.8	-29.9	3.2	22.5	38.9
	Exceeded 5% of	-63.6	-45.7	-23.5	9.6	32.2	45.8
	Maximum	-46.0	-16.4	-8.6	10.6	32.6	46.3
Lower Trinity Drawdown after 50	Minimum	-78.1	-61.2	-39.8	-9.1	10.0	7.2
	Exceeded 95% of	-75.4	-58.2	-36.4	-4.9	13.2	24.8
	Average	-69.9	-52.4	-30.4	3.3	22.8	39.6
	Exceeded 5% of	-64.2	-46.3	-24.0	9.7	32.6	46.7
	Maximum	-47.1	-16.9	-8.9	10.7	33.0	47.1

GAM Task 10-031: Supplement to GAM Task 10-005

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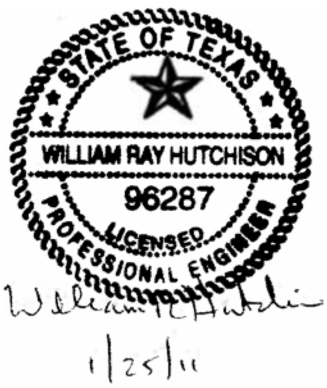
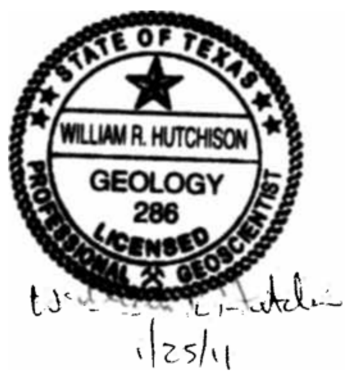
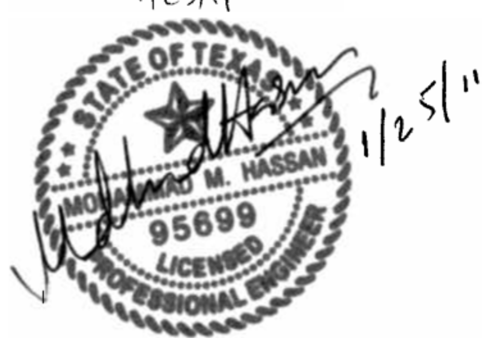
January 25, 2011







The seals appearing on this document were authorized by William R. Hutchison, P.E. 96287,
P.O. 286 and Mohammad Masud Hassan, P.E. 95699 on January 25, 2011.

DESCRIPTION OF TASK:

This report presents additional results associated with the analysis described in GAM Task 10-005. The simulations used as part of this task include four of the seven pumping scenarios (GAM Task 10-005) of the Trinity Aquifer that range from current estimated pumping representing 2008 to about twice the estimated 2008 level of pumping. Each scenario included running 387 50-year simulations. The 387 50-year simulations were developed based on tree-ring precipitation estimates from 1537 to 1972 for the Edwards Plateau (Cleaveland, 2006). The results were used to evaluate averaged water budgets per county and to develop contour maps of average drawdown in water levels for each scenario.

METHODS:

The seven pumping scenarios in GAM Task 10-005 (Hutchison, 2010) ranged from no pumping in the Trinity Aquifer (Scenario 1), to 2008 levels of pumping (about 60,000 acre-feet in Scenario 4) to about twice the pumping experienced in 2008 (about 120,000 acre-feet in Scenario 7) as summarized below:.

- Scenario 1 = 0 acre-feet per year
- Scenario 2 = 20,000 acre-feet per year
- Scenario 3 = 40,000 acre-feet per year
- Scenario 4 = 60,000 acre-feet per year (2008 conditions)
- Scenario 5 = 80,000 acre-feet per year
- Scenario 6 = 100,000 acre-feet per year
- Scenario 7 = 120,000 acre-feet per year

Table 1 summarizes the estimated pumping by county and by aquifer in 2008. These estimates were provided by groundwater conservation districts in Groundwater Management Area 9.

Table 1. Estimated 2008 pumping as provided by the groundwater conservation districts in Groundwater Management Area 9

County	Edwards Group of the Edwards-Trinity (Plateau) Aquifer	Upper Trinity Aquifer	Middle Trinity Aquifer	Lower Trinity Aquifer	Total Pumping (County)
Bandera	631	288	3567	515	**5,000**
Bexar	0	693	14110	197	**15,000**
Blanco	0	77	1,477	0	**1,554**
Comal	0	398	5,788	0	**6,186**
Hays	0	416	4,800	449	**5,665**
Kendall	315	300	6,060	325	**7,000**
Kerr	1,035	213	6,263	5,534	**13,045**
Medina	0	0	500	1000	**1,500**
Travis	0	551	4,967	0	**5,518**
Total pumping (aquifer)	**1,981**	**2,936**	**47,532**	**8,020**	**60,468**

PARAMETERS AND ASSUMPTIONS:

- See GAM Task 10-005 (Hutchison, 2010) for additional information of the assumptions used for recharge, starting conditions, and pumping for the 387 50 year simulations.
- The recently updated Hill Country portion of the Trinity Aquifer developed by Jones and others (2009) was used for these simulations. See Mace and others (2000) and Jones and others (2009) for details on model construction, recharge distribution, discharge, assumptions, and limitations of the model.
- Pumping scenarios 4, 5, 6, and 7 were used as described above
- The model has four layers: layer 1 represents the Edwards Group of the Edwards-Trinity (Plateau) Aquifer, layer 2 represents the Upper Trinity Aquifer, layer 3 represents the Middle Trinity Aquifer, and layer 4 represents the Lower Trinity Aquifer.
- The rivers, streams, and springs were simulated in the model using MODFLOW's Drain package. MODFLOW's Drain package was also used to simulate spring discharge along bedding contacts of the Edwards Group (Plateau) and the Upper

Trinity Aquifer in the northwestern parts of the model area. This resulted in the assignment of numerous drain cells along this outcropcontact.

- The model was run with MODFLOW-96 (Harbaugh and McDonald, 1996).

- Drawdowns were calculated by subtracting the final;water levels at the end ofthe 50 year simulations from the 2008 initial conditions..

RESULTS:

Summary tables of all groundwater budget results (by county and aquifer are presented in Appendix A. Because each scenario consisted of 387 50-year simulations, the groundwater budget results are expressed in terms of average of all 387 simulations for each scenario.

Figures 1 through 4 show the contour maps of the average drawdown for the Trinity Aquifer within Groundwater Management Area 9. In scenario 4 the drawdown is a maximum of about 14.5 feet to a minimum of 3.3 feet water rise in elevation compared to 2008 starting water level elevations. In scenario 5, 6 and 7 the drawdown ranges from:

- zero feet to 54.6 feet,
- zero feet to 74.0 feet, and
- zero feet to 87.9 feet respectively.

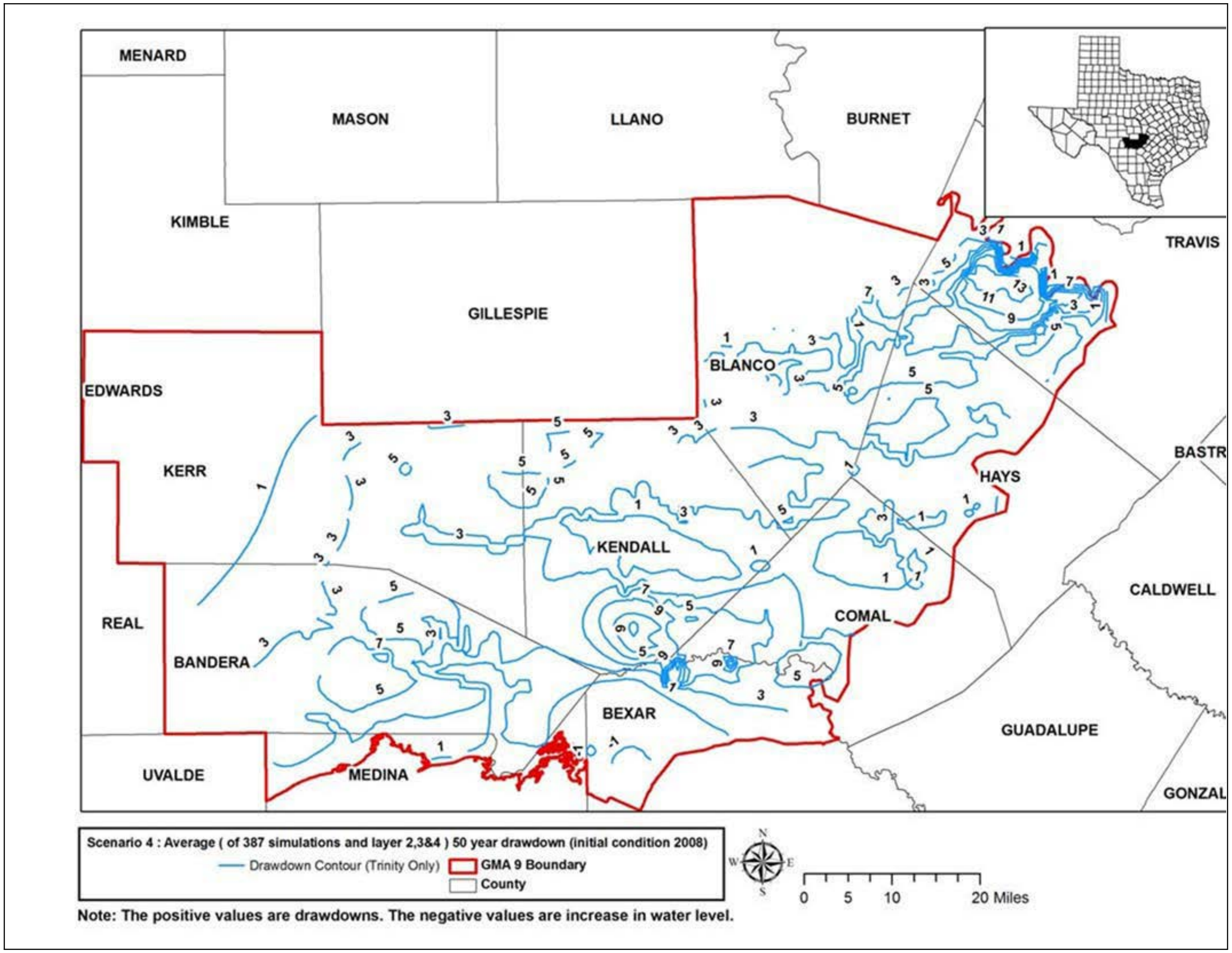


Figure 13: Average water level drawdown contour map for scenario 4 for Groundwater Management Area (GMA) 9 using 2008 water levels for the calculation.

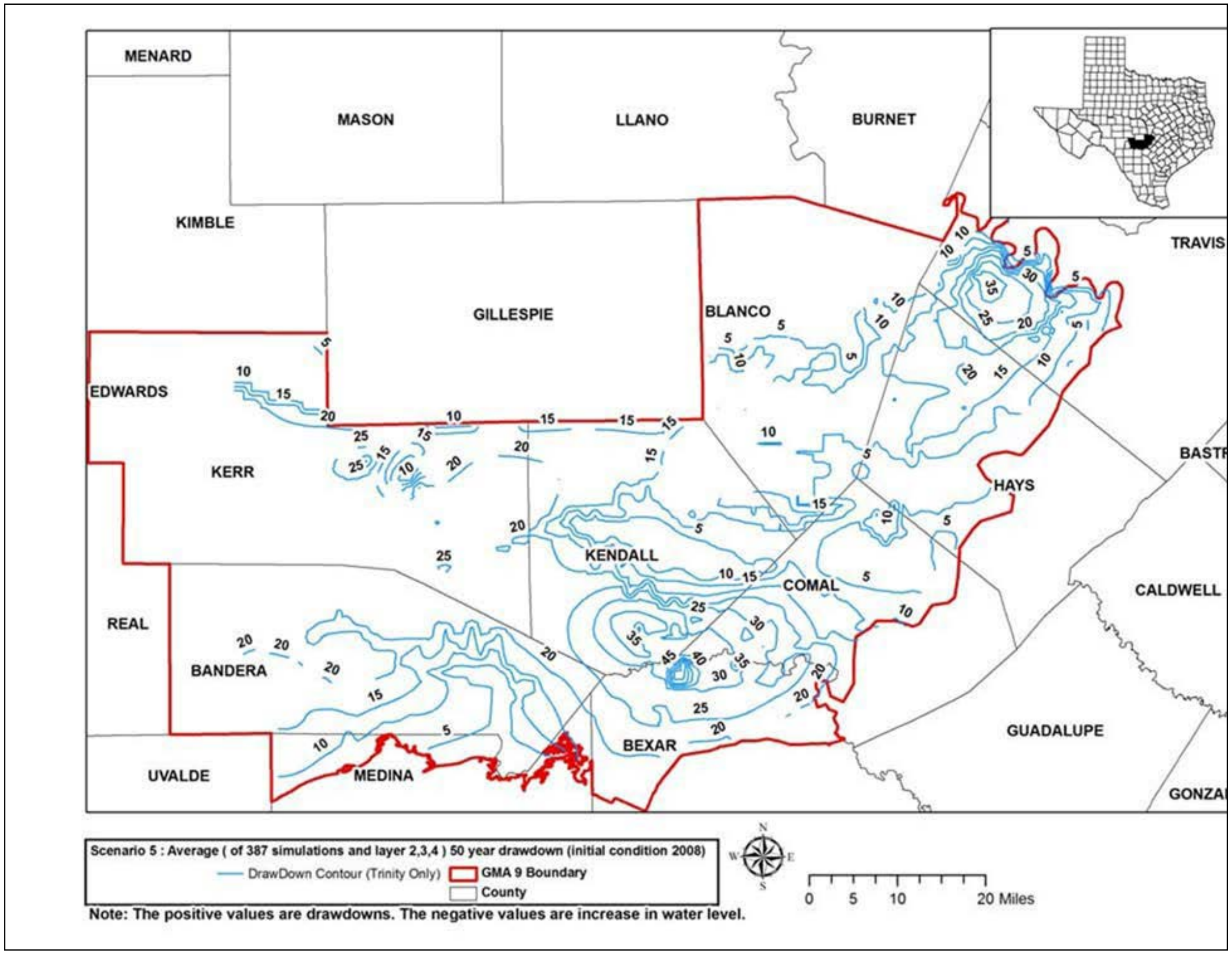


Figure 14: Average water level drawdown contour map for scenario 5 for Groundwater Management Area (GMA) 9 using 2008 water levels for the calculation.

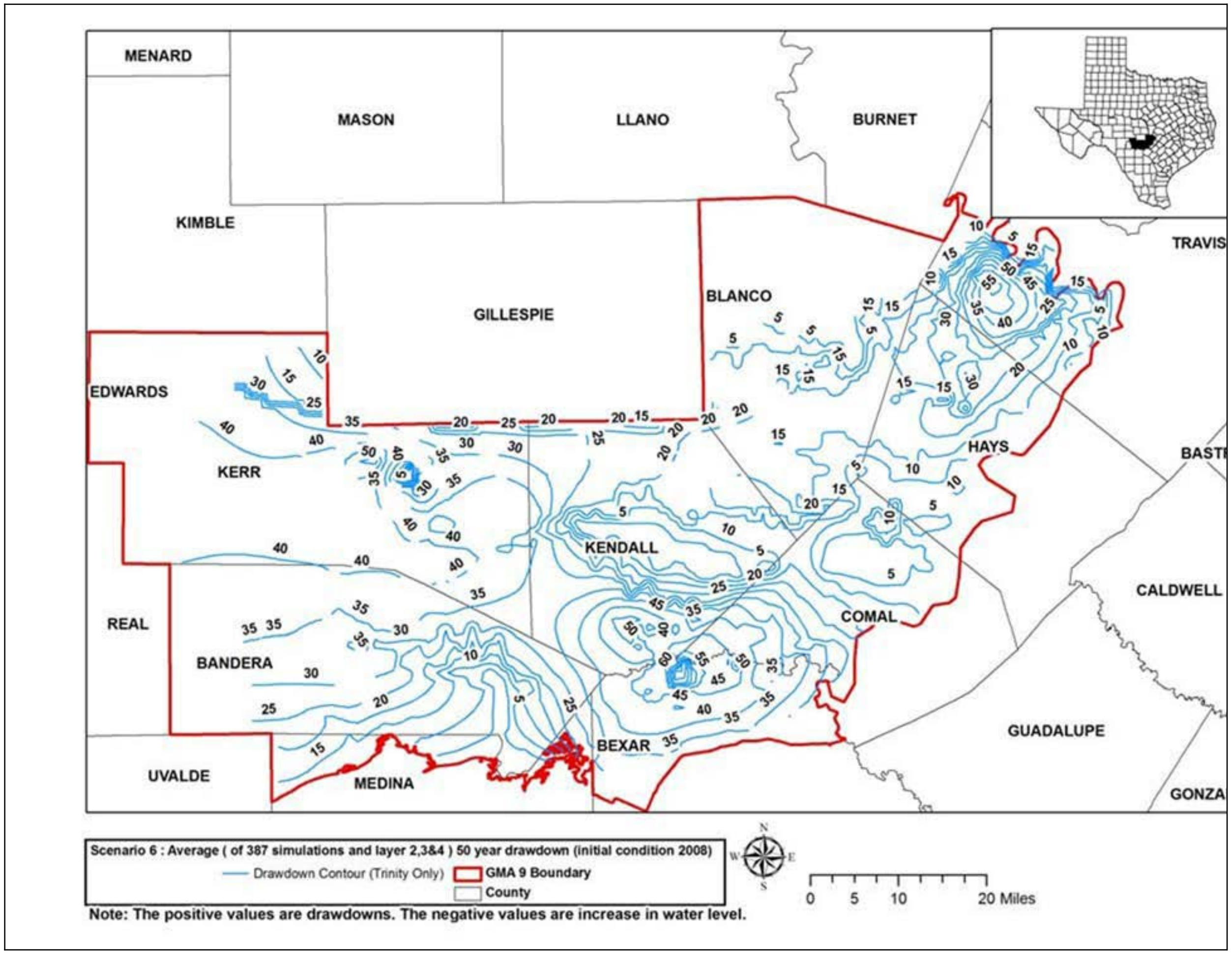


Figure 15: Average water level drawdown contour map for scenario 6 for Groundwater Management Area (GMA) 9 using 2008 water levels for the calculation.

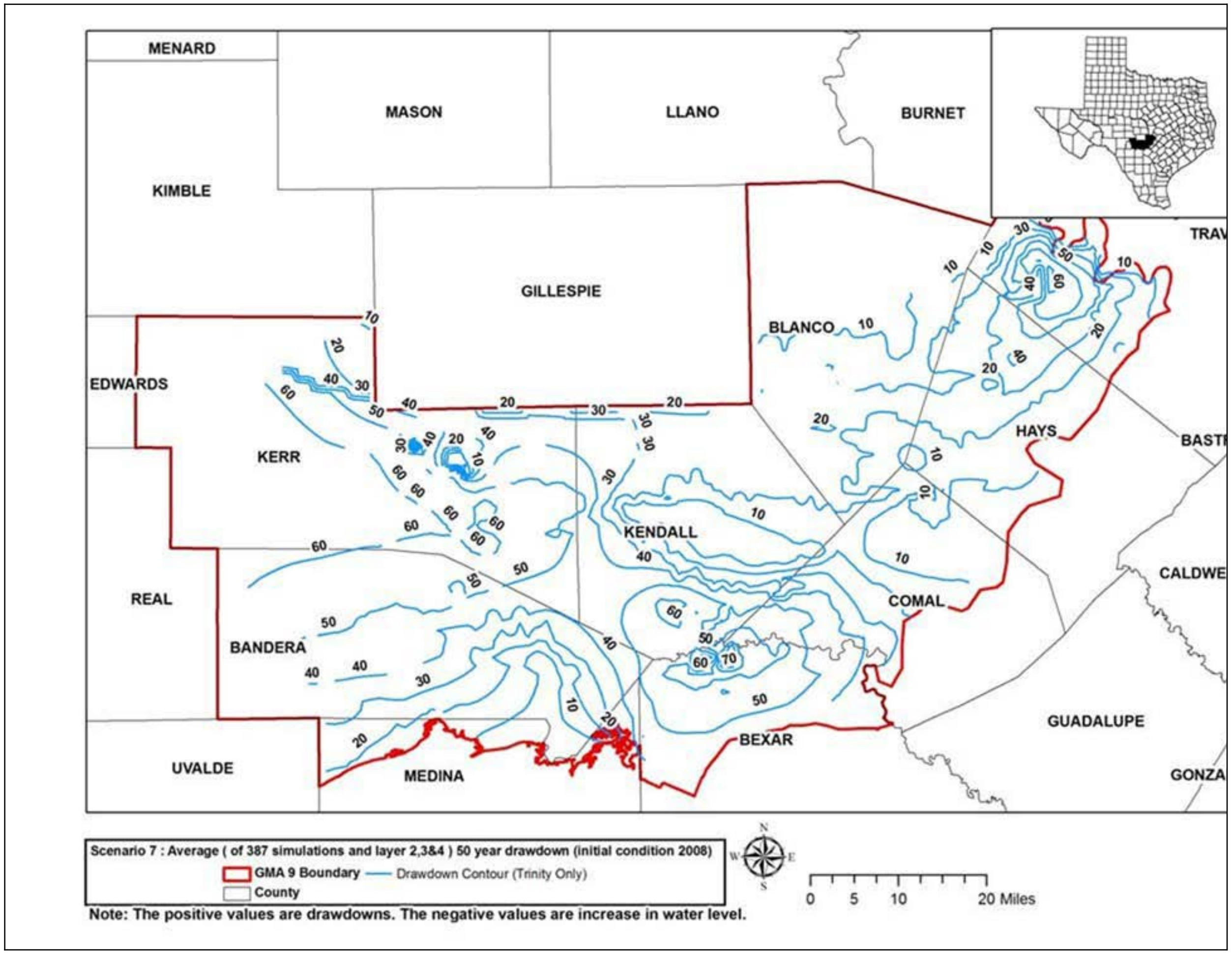


Figure 16: Average water level drawdown contour map for scenario 7 for Groundwater Management Area (GMA) 9 using 2008 water levels for the calculation.

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Appendix A

Water budgets per county for:

Bandera
County Bexar
County Blanco
County Comal
County Hays
County
Kendall
County Kerr
County
Medina
County Travis
County

Table: Bandera County (Edward Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	9,604	9,460	9,435	9,405
INFLOW FROM KERR COUNTY	3,422	3,392	3,386	3,383
TOTAL INFLOW	13,026	12,852	12,821	12,788
OUTFLOW				
PUMPING	626	626	626	626
OUTFLOW TO SURFACE WATER	11,678	11,568	11,560	11,535
OUTFLOW TO TRINITY AQUIFER	707	704	704	703
TOTAL OUTFLOW	13,011	12,898	12,890	12,864
TOTAL INFLOW- TOTAL OUTFLOW	15	-46	-69	-76
STORAGE CHANGE	15	-45	-68	-75
MODEL ERROR	0	-1	-1	-1

Table: Bandera County (Trinity Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	31,787	31,310	31,227	31,129
INFLOW FROM KENDALL COUNTY	5,686	5,391	5,165	4,906
INFLOW FROM KERR COUNTY	7,415	6,655	6,070	5,459
INFLOW FROM EDWARD AQUIFER	707	704	704	703
TOTAL INFLOW	45,595	44,060	43,166	42,197
OUTFLOW				
PUMPING	4,373	5,831	7,290	8,746
OUTFLOW TO SURFACE WATER	21,680	19,892	18,672	17,436
OUTFLOW TO EDWARD AQUIFER (BALCONES FALT ZONE)	1,118	807	543	217
OUTFLOW TO OTHER AREA	470	381	324	237
OUTFLOW TO BEXAR COUNTY	1,742	1,754	1,775	1,779
OUTFLOW TO MEDINA COUNTY	16,295	15,870	15,579	15,033
TOTAL OUTFLOW	45,678	44,535	44,183	43,448
TOTAL INFLOW- TOTAL OUTFLOW	-83	-475	-1,017	-1,251
STORAGE CHANGE	-82	-475	-1,018	-1,251
MODEL ERROR	-1	0	1	0

Table: Bexar County (Trinity Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	41,294	40,673	40,566	40,439
INFLOW FROM BANDERA COUNTY	1,742	1,754	1,775	1,779
INFLOW FROM COMAL COUNTY	10,621	11,273	11,896	12,446
INFLOW FROM KENDALL COUNTY	10,392	10,086	9,844	9,480
INFLOW FROM MEDINA COUNTY	4,831	5,788	6,688	7,583
TOTAL INFLOW	68,880	69,574	70,769	71,727
OUTFLOW				
PUMPING	14,922	19,897	24,872	29,682
OUTFLOW TO SURFACE WATER	10,412	10,285	10,214	10,139
OUTFLOW TO EDWARD AQUIFER (BALCONES FALT ZONE)	33,705	30,389	27,484	24,436
OUTFLOW TO OTHER AREA	9,878	9,216	8,638	8,028
TOTAL OUTFLOW	68,917	69,787	71,208	72,285
TOTAL INFLOW- TOTAL OUTFLOW	-37	-213	-439	-558
STORAGE CHANGE	-37	-209	-434	-554
MODEL ERROR	0	-4	-5	-4

Table: Blanco County (Trinity Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	23,316	22,966	22,906	22,834
INFLOW FROM OTHER AREA	1,796	1,761	1,731	1,696
INFLOW FROM KENDALL COUNTY	2,738	2,704	2,690	2,670
TOTAL INFLOW	27,850	27,431	27,327	27,200
OUTFLOW				
PUMPING	1,545	2,060	2,575	3,090
OUTFLOW TO SURFACE WATER	17,127	16,380	15,928	15,419
OUTFLOW TO COMAL COUNTY	3,799	3,683	3,597	3,487
OUTFLOW TO HAYS COUNTY	5,434	5,482	5,532	5,558
TOTAL OUTFLOW	27,905	27,605	27,632	27,554
TOTAL INFLOW- TOTAL OUTFLOW	-55	-174	-305	-354
STORAGE CHANGE	-46	-164	-297	-344
MODEL ERROR	-9	-10	-8	-10

Table: Comal County (Trinity Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	39,793	39,195	39,092	38,969
INFLOW FROM SURFACE WATER	0	0	0	959
INFLOW FROM BLANCO COUNTY	3,799	3,683	3,597	3,487
INFLOW FROM KENDALL COUNTY	7,799	7,823	7,855	7,822
TOTAL INFLOW	51,391	50,701	50,544	51,237
OUTFLOW				
PUMPING	5,716	7,622	9,527	11,380
OUTFLOW TO SURFACE WATER	5,492	3,044	1,055	0
OUTFLOW TO EDWARD AQUIFER (BALCONES FALT ZONE)	15,384	14,796	14,315	13,803
OUTFLOW TO OTHER AREA	8,208	8,202	8,232	8,254
OUTFLOW TO BEXAR COUNTY	10,621	11,273	11,896	12,446
OUTFLOW TO HAYS COUNTY	6,016	5,958	5,890	5,809
TOTAL OUTFLOW	51,437	50,895	50,915	51,692
TOTAL INFLOW- TOTAL OUTFLOW	-46	-194	-371	-455
STORAGE CHANGE	-47	-192	-370	-452
MODEL ERROR	1	-2	-1	-3

Table: Hays County (Trinity Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	24,363	23,997	23,934	23,859
INFLOW FROM BLANCO COUNTY	5,434	5,482	5,532	5,558
INFLOW FROM COMAL COUNTY	6,016	5,958	5,890	5,809
TOTAL INFLOW	35,813	35,437	35,356	35,226
OUTFLOW				
PUMPING	5,397	7,196	8,985	10,620
OUTFLOW TO SURFACE WATER	19,490	18,462	17,658	16,837
OUTFLOW TO EDWARD AQUIFER (BALCONES FALT ZONE)	2,610	1,782	1,073	412
OUTFLOW TO OTHER AREA	2,417	2,330	2,252	2,180
OUTFLOW TO TRAVIS COUNTY	5,951	5,863	5,770	5,624
TOTAL OUTFLOW	35,865	35,633	35,738	35,673
TOTAL INFLOW- TOTAL OUTFLOW	-52	-196	-382	-447
STORAGE CHANGE	-51	-195	-382	-447
MODEL ERROR	-1	-1	0	0

Table: Kendall County (Edwards Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	5,446	5,364	5,350	5,333
INFLOW FROM KERR COUNTY	101	101	101	101
TOTAL INFLOW	5,547	5,465	5,451	5,434
OUTFLOW				
PUMPING	311	311	311	311
OUTFLOW TO SURFACE WATER	4,879	4,833	4,838	4,820
OUTFLOW TO OTHER AREA	217	216	216	215
OUTFLOW TO TRINITY AQUIFER	153	153	153	152
TOTAL OUTFLOW	5,560	5,513	5,518	5,498
TOTAL INFLOW- TOTAL OUTFLOW	-13	-48	-67	-64
STORAGE CHANGE	-13	-47	-66	-65
MODEL ERROR	0	-1	-1	1

Table: Kendall County (Trinity Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	52,346	51,559	51,424	51,262
INFLOW FROM OTHER AREA	4,087	4,048	4,034	4,009
INFLOW FROM KERR COUNTY	3	0	0	0
INFLOW FROM EDWARD AQUIFER	153	153	153	152
TOTAL INFLOW	56,589	55,760	55,611	55,423
OUTFLOW				
PUMPING	6,688	8,919	11,147	13,376
OUTFLOW TO SURFACE WATER	23,405	21,129	19,477	17,704
OUTFLOW TO BANDERA COUNTY	5,686	5,391	5,165	4,906
OUTFLOW TO BEXAR COUNTY	10,392	10,086	9,844	9,480
OUTFLOW TO BLANCO COUNTY	2,738	2,704	2,690	2,670
OUTFLOW TO COMAL COUNTY	7,799	7,823	7,855	7,822
OUTFLOW TO KERR COUNTY	0	223	404	619
TOTAL OUTFLOW	56,708	56,275	56,582	56,577
TOTAL INFLOW- TOTAL OUTFLOW	-119	-515	-971	-1,154
STORAGE CHANGE	-118	-511	-971	-1,153
MODEL ERROR	-1	-4	0	-1

Table: Kerr County (Edward Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	35,483	34,950	34,858	34,748
INFLOW FROM OTHER AREA	973	969	971	968
TOTAL INFLOW	36,456	35,919	35,829	35,716
OUTFLOW				
PUMPING	1,034	1,034	1,034	1,034
OUTFLOW TO SURFACE WATER	26,268	26,040	26,036	25,977
OUTFLOW TO BANDERA COUNTY	3,422	3,392	3,386	3,383
OUTFLOW TO KENDALL COUNTY	101	101	101	101
OUTFLOW TO TRINITY AQUIFER	5,494	5,473	5,470	5,466
TOTAL OUTFLOW	36,319	36,040	36,027	35,961
TOTAL INFLOW- TOTAL OUTFLOW	137	-121	-198	-245
STORAGE CHANGE	137	-121	-198	-245
MODEL ERROR	0	0	0	0

Table: Kerr County (Trinity Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	16,952	16,697	16,653	16,601
INFLOW FROM OTHER AREA	7,962	7,905	7,923	7,827
INFLOW FROM KENDALL COUNTY	0	223	404	619
INFLOW FROM EDWARD AQUIFER	5,494	5,473	5,470	5,466
TOTAL INFLOW	30,408	30,298	30,450	30,513
OUTFLOW				
PUMPING	12,001	13,544	15,302	16,428
OUTFLOW TO SURFACE WATER	11,063	10,863	10,826	10,746
OUTFLOW TO BANDERA COUNTY	7,415	6,655	6,070	5,459
OUTFLOW TO KENDALL COUNTY	3	0	0	0
TOTAL OUTFLOW	30,482	31,062	32,198	32,633
TOTAL INFLOW- TOTAL OUTFLOW	-74	-764	-1,748	-2,120
STORAGE CHANGE	-74	-762	-1,748	-2,118
MODEL ERROR	0	-2	0	-2

Table: Medina County (Trinity Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	6,084	5,993	5,977	5,958
INFLOW FROM BANDERA COUNTY	16,295	15,870	15,579	15,033
TOTAL INFLOW	22,379	21,863	21,556	20,991
OUTFLOW				
PUMPING	1,405	1,873	2,341	2,810
OUTFLOW TO SURFACE WATER	6,275	6,243	6,232	6,217
OUTFLOW TO EDWARD AQUIFER (BALCONES FALT ZONE)	7,998	6,486	5,185	3,619
OUTFLOW TO OTHER AREA	1,874	1,503	1,175	844
OUTFLOW TO BEXAR COUNTY	4,831	5,788	6,688	7,583
TOTAL OUTFLOW	22,383	21,893	21,621	21,073
TOTAL INFLOW- TOTAL OUTFLOW	-4	-30	-65	-82
STORAGE CHANGE	-6	-31	-66	-84
MODEL ERROR	2	1	1	2

Table: Travis County (Trinity Aquifer. 2008 to 2060)				
INFLOW	Scen 4	Scen 5	Scen 6	Scen 7
RECHARGE FROM PRECIPITATION	11,194	11,026	10,997	10,963
INFLOW FROM HAYS COUNTY	5,951	5,863	5,770	5,624
TOTAL INFLOW	17,145	16,889	16,767	16,587
OUTFLOW				
PUMPING	5,375	7,120	8,714	9,890
OUTFLOW TO SURFACE WATER	7,419	6,466	5,748	5,201
OUTFLOW TO EDWARD AQUIFER (BALCONES FALT ZONE)	1,327	969	657	354
OUTFLOW TO OTHER AREA	3,079	2,513	2,001	1,547
TOTAL OUTFLOW	17,200	17,068	17,120	16,992
TOTAL INFLOW- TOTAL OUTFLOW	-55	-179	-353	-405
STORAGE CHANGE	-43	-166	-341	-393
MODEL ERROR	-12	-13	-12	-12

APPENDIX B

GAM Run 10-049 Mag Version 2

By Mohammad Masud Hassan, P. E.
Edited by Marius Jigmond to reflect statutory
Changes effective September 1, 2011

Updated to version 2 by Wade Oliver and Radu Boghici to reflect refined modeled available groundwater estimates

Texas Water Development Board
Groundwater Availability Modeling Section
(512) 463- 8499

March 28, 2012

GAM Run 10-049 MAG Version 2

By Mohammad Masud Hassan, P.E.

Edited by Marius Jigmond to reflect statutory changes effective September 1, 2011

Updated to version 2 by Wade Oliver and Radu Boghici to reflect refined modeled available groundwater estimates

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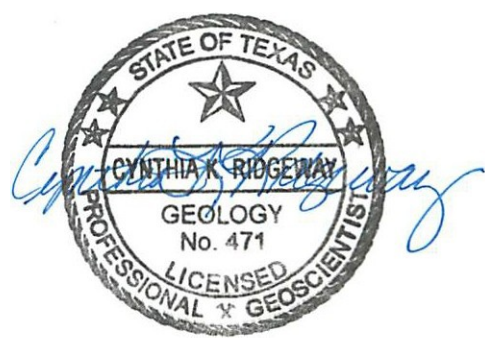
March 28, 2012



Cynthia K. Ridgeway is the Manager of the Groundwater Availability Modeling Section and is responsible for oversight of work performed by employees under her direct supervision. The seal appearing on this document was authorized by Cynthia K. Ridgeway, P.G. 471 on March 28, 2012

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EXECUTIVE SUMMARY:

The modeled available groundwater for the Edwards Group of the Edwards-Trinity (Plateau) Aquifer as a result of the desired future condition adopted by the members of Groundwater Management Area 9 is approximately 1,001 acre-feet per year between 2010 and 2060. This is shown divided by county, regional water planning area, and river basin in Table 1 for use in the regional water planning process. Modeled available groundwater is summarized by county, regional water planning area, river basin, and groundwater conservation district in tables 2 through 5. The estimates were extracted from the previous Groundwater Availability Model Run 08-90mag (Chowdhury, 2009), which meets the desired future condition adopted by the members of Groundwater Management Area 9.

The first version of this report showed modeled available groundwater for Bandera, Kendall, and Kerr counties based on the pumping assumed in the groundwater availability model simulation. However, Groundwater Management Area 9 declared Kerr County "not relevant" for joint planning purposes. Since modeled available groundwater only applies to areas with a specified desired future condition, we updated this report to only depict modeled available groundwater in Kendall and Bandera counties.

REQUESTOR:

Mr. Ronald G. Fieseler of the Blanco Pedernales Groundwater Conservation District on behalf of Groundwater Management Area 9

DESCRIPTION OF REQUEST:

In a letter dated August 26, 2010 and received August 30, 2010, Mr. Ronald G. Fieseler provided the Texas Water Development Board (TWDB) with the desired future condition of the Edwards Group of Edwards-Trinity (Plateau) Aquifer adopted by the members of Groundwater Management Area 9. As described in Resolution #072610-01, the desired future condition for the Edwards Group of the Edwards-Trinity (Plateau) Aquifer in Groundwater Management Area 9 is:

"[…] Allow for no net increase in average drawdown in the Edwards Group of the Edward-Trinity (Plateau) Aquifer in Kendall and Bandera [c]ounties.

In addition, GMA 9 declared the Edward Group of the Edward-Trinity (Plateau) to be "Not Relevant" in Kerr and Blanco [c]ounties"

In response to receiving the adopted desired future condition, the Texas Water Development Board has estimated the modeled available groundwater for the Edwards Group of the Edwards-Trinity (Plateau) Aquifer for Kendall and Bandera counties.

METHODS:

The Texas Water Development Board previously completed Groundwater Availability Model (GAM) Run 08-90mag (Chowdhury, 2009) containing "managed available groundwater" information based on the desired future conditions adopted on August 28, 2008 by the groundwater

conservation districts in Groundwater Management Area 9. Subsequent to the release of GAM Run 08-90mag, the desired future conditions for the Edwards Group of the Edwards-Trinity (Plateau) Aquifer were petitioned, and presented to the Texas Water Development Board at a special meeting on January 21, 2010. At that meeting, the Board found that the adopted desired future condition of zero drawdown was not reasonable. The Board further recommended that the desired future condition in Kerr County be 9 feet of drawdown and that the Edwards Group of the Edwards-Trinity (Plateau) Aquifer be found not relevant in Bandera and Kendall counties. The Board's recommended desired future condition was discussed at a meeting for Groundwater Management Area 9 on February 22, 2010, and a public hearing was held during that same meeting. At their July 26, 2010, meeting, the districts adopted new desired future conditions for the Edwards Group of the Edwards-Trinity (Plateau) Aquifer. In Bandera and Kendall counties, the new desired future condition is the same as the original desired future condition: zero drawdown.
Because no changes were made to the desired future condition in Bandera and Kendall counties, the results in the GAM Run 08-90mag report were still applicable to the "new" desired future condition.

The location of Groundwater Management Area 9, the Edwards Group of the Edwards-Trinity (Plateau) Aquifer, and the groundwater availability model cells that represent the aquifer are shown in Figure 1. The pumping was divided by county, regional water planning area, river basin, and groundwater conservation district (Figure 2).

PARAMETERS AND ASSUMPTIONS:

The parameters and assumptions for the model run using the groundwater availability model for the Hill Country portion of the Trinity Aquifer, which contains a portion representing the Edwards Group of the Edwards-Trinity (Plateau) Aquifer, are described below:

- Version 1.03 of the groundwater availability model for the Hill Country portion of the Trinity Aquifer developed by Mace and others (2000) was used for this analysis. See Mace and others (2000) for details on model construction, recharge, discharge, assumptions and limitations of the model.
- The model has three layers: layer 1 represents the Edwards Group, layer 2 represents the Upper Trinity Aquifer, and layer 3 represents the Middle Trinity Aquifer.
- The model has a total of 79 stress periods with 2 stress periods representing pre-development conditions, 24 monthly stress periods for representing transient conditions (1996 to 1997), and 53 predictive annual stress periods (2008 to 2060).

- The root-mean squared error of the model (a measure of the difference between simulated and measured water levels) is approximately 56 feet. This represents 5 percent of the range of measured water levels across the modelarea.
- We assigned the baseline pumping to the first predictive stress period in the model to represent 2008 pumping conditions based on the assumption that the aquifers in the area recharge rapidly and groundwater movement is fast enough to quickly bring about a dynamic equilibrium. Comparisons of water level changes in selected hydrographs in the predictive period suggest that the aquifer attains a dynamic equilibrium within a year (Chowdhury, 2009).
- Average recharge was used throughout the predictive period for this model run. Average recharge in the model was estimated for normal climatic conditions by using the average precipitation for the period 1960 to 1990 and the recharge coefficients estimated from baseflow analyses for each model cell (Mace and others, 2000).
- The model was run in Processing MODFLOW for Windows (version 5.3; Chiang and Kinzelbach, 1998).

Modeled Available Groundwater and Permitting

As defined in Chapter 36 of the Texas Water Code, "modeled available groundwater" is the estimated average amount of water that may be produced annually to achieve a desired future condition. This is distinct from "managed available groundwater," shown in the draft version of this report dated January 31, 2011, which was a permitting value and accounted for the estimated use of the aquifer exempt from permitting. This change was made to reflect changes in statute by the 82nd Texas Legislature, effective September 1, 2011.

Groundwater conservation districts are required to consider modeled available groundwater, along with several other factors, when issuing permits in order to manage groundwater production to achieve the desired future condition(s). The other factors districts must consider include annual precipitation and production patterns, the estimated amount of pumping exempt from permitting, existing permits, and a reasonable estimate of actual groundwater production under existing permits. The estimated amount of pumping exempt from permitting, which the Texas Water Development Board is now required to develop after soliciting input from applicable groundwater conservation districts, will be provided in a separate report.

RESULTS:

The modeled available groundwater for the Edwards Group of the Edward-Trinity (Plateau) Aquifer consistent as a result of the desired future condition adopted by the members of Groundwater Management Area 9 is approximately 1,001 acre-feet per year between 2010 and 2060. This is subdivided by county, regional water planning area, and river basin as shown in Table 1. The modeled available groundwater is also summarized by county, regional water planning area, river basin, and groundwater conservation district as shown in tables 2, 3, 4, and 5, respectively.

LIMITATIONS:

The groundwater model used in developing estimates of modeled available groundwater is the best available scientific tool that can be used to estimate the pumping that will achieve the desired future conditions. Although the groundwater model used in this analysis is the best available scientific tool for this purpose, it, like all models, has limitations. 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 modelresults."

A key aspect of using the groundwater model to develop estimates of modeled available groundwater is the need to make assumptions about the location in the aquifer where future pumping will occur. As actual pumping changes in the future, it will be necessary to evaluate the amount of that pumping as well as its location in the context of the assumptions associated with this analysis. Evaluating the amount and location of future pumping is as important as evaluating the changes in groundwater levels, spring flows, and other metrics that describe the condition of the groundwater resources in the area that relate to the adopted desired future condition(s).

Given these limitations, users of this information are cautioned that the modeled available groundwater numbers should not be considered a definitive, permanent description of the amount of groundwater that can be pumped to meet the adopted desired future condition. 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.

It is important for groundwater conservation districts to monitor future groundwater pumping as well as whether or not they are achieving their desired future conditions. Because of the limitations of the model and the assumptions in this analysis, it is important that the groundwater conservation districts work with the TWDB to refine the modeled available groundwater numbers given the reality of how the aquifer responds to the actual amount and location of pumping now and in the future.

REFERENCES:

Chiang, W.H. and Kinzelbach, W., 1998, Processing Modflow: A simulation system for modeling groundwater flow and pollution: Hamburgh, Zurich, variously paginated.

Chowdhury, A.H., 2009, GAM Run 08-090mag, Texas Water Development Board, GAM Run 09-80mag Report, 8 p.

Mace, R.E., Chowdhury, A.H., Anaya, R., and Way, S-C., 2000, Groundwater availability of the Trinity Aquifer, Hill Country Area, Texas—Numerical simulations through 2050: Texas Water Development Board Report 353, 119 p.

Table 1. Modeled available groundwater for the Edwards Group of Edwards-Trinity (Plateau) Aquifer in Groundwater Management Area 9. Results are in acre-feet per year and are divided by county, regional water planning area, and river basin.

County	Regional Water Planning Area	River Basin	Year					
			2010	2020	2030	2040	2050	2060
Bandera	J	Guadalupe	21	21	21	21	21	21
		Nueces	101	101	101	101	101	101
		San Antonio	561	561	561	561	561	561
Kendall	L	Colorado	46	46	46	46	46	46
		Guadalupe	103	103	103	103	103	103
		San Antonio	169	169	169	169	169	169
Total			**1,001**	**1,001**	**1,001**	**1,001**	**1,001**	**1,001**

Table 2. Modeled available groundwater for the Edwards Group of Edwards-Trinity (Plateau) Aquifer in Groundwater Management Area 9. Results are in acre-feet per year and are summarized by county.

County	Year					
	2010	2020	2030	2040	2050	2060
Bandera	683	683	683	683	683	683
Kendall	318	318	318	318	318	318
Total	**1,001**	**1,001**	**1,001**	**1,001**	**1,001**	**1,001**

Table 3. Modeled available groundwater for the Edwards Group of Edwards-Trinity (Plateau) Aquifer in Groundwater Management Area 9. Results are in acre-feet per year and are summarized by regional water planning area.

Regional Water Planning Area	Year					
	2010	2020	2030	2040	2050	2060
J	683	683	683	683	683	683
L	318	318	318	318	318	318
Total	**1,001**	**1,001**	**1,001**	**1,001**	**1,001**	**1,001**

Table 4: Modeled available groundwater for the Edwards Group of Edwards-Trinity (Plateau) Aquifer in Groundwater Management Area 9. Results are in acre-feet per year and summarized by river basin.

River Basin	Year					
	2010	2020	2030	2040	2050	2060
Colorado	46	46	46	46	46	46
Guadalupe	124	124	124	124	124	124
Nueces	101	101	101	101	101	101
San Antonio	730	730	730	730	730	730
Total	**1,001**	**1,001**	**1,001**	**1,001**	**1,001**	**1,001**

Table 5: Modeled available groundwater for the Edwards Group of Edwards-Trinity (Plateau) Aquifer in Groundwater Management Area 9. Results are in acre-feet per year and summarized by groundwater conservation district (GCD). RA refers to River Authority. GWD refers to Groundwater District.

Groundwater Conservation District	Year					
	2010	2020	2030	2040	2050	2060
Bandera County RA & GWD	683	683	683	683	683	683
Cow Creek GCD	318	318	318	318	318	318
Total	**1,001**	**1,001**	**1,001**	**1,001**	**1,001**	**1,001**

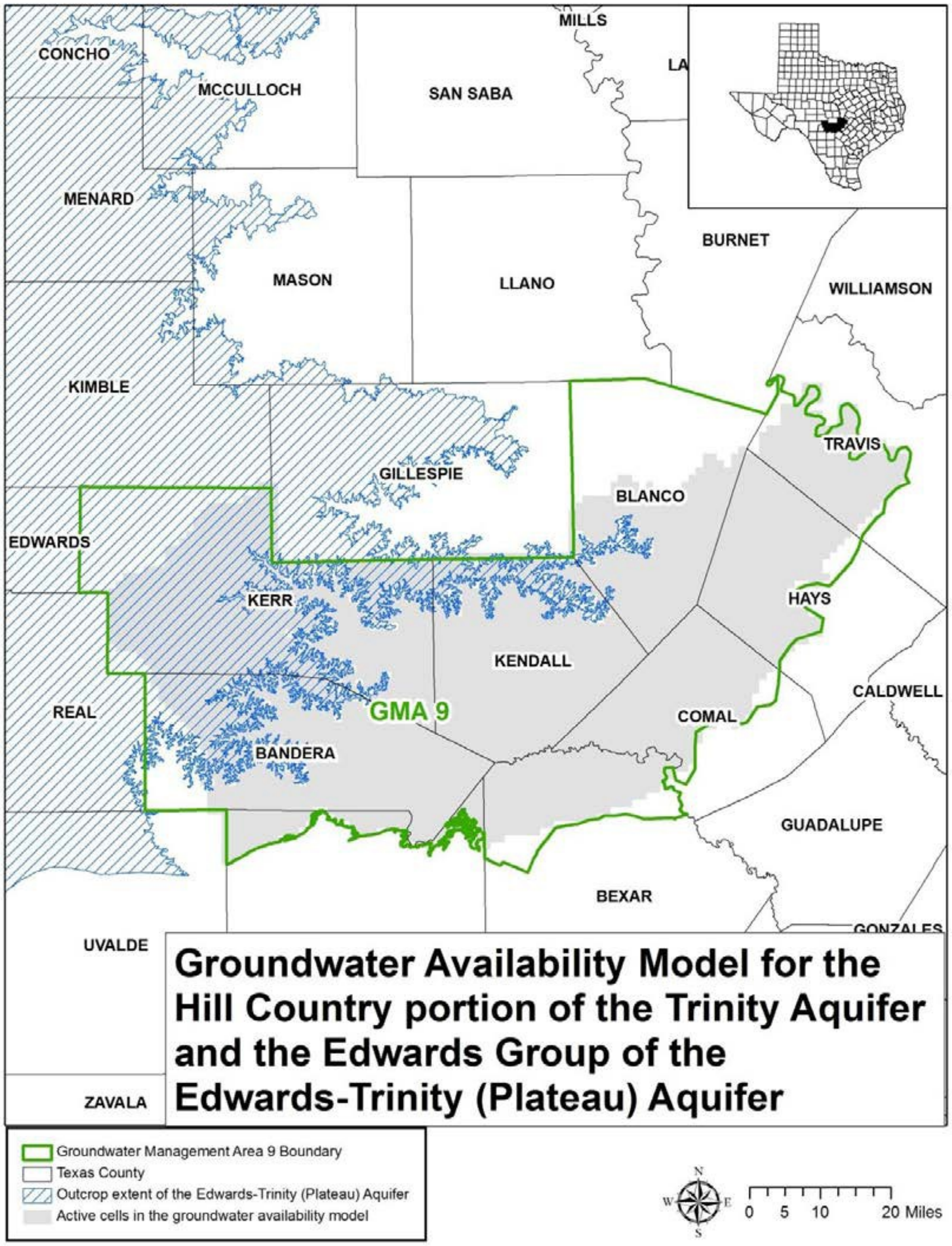

Figure 1: Map showing the areas covered by the groundwater availability model for the Hill Country portion of the Trinity Aquifer, which also contains the Edwards group of the Edwards-Trinity (Plateau) Aquifer.

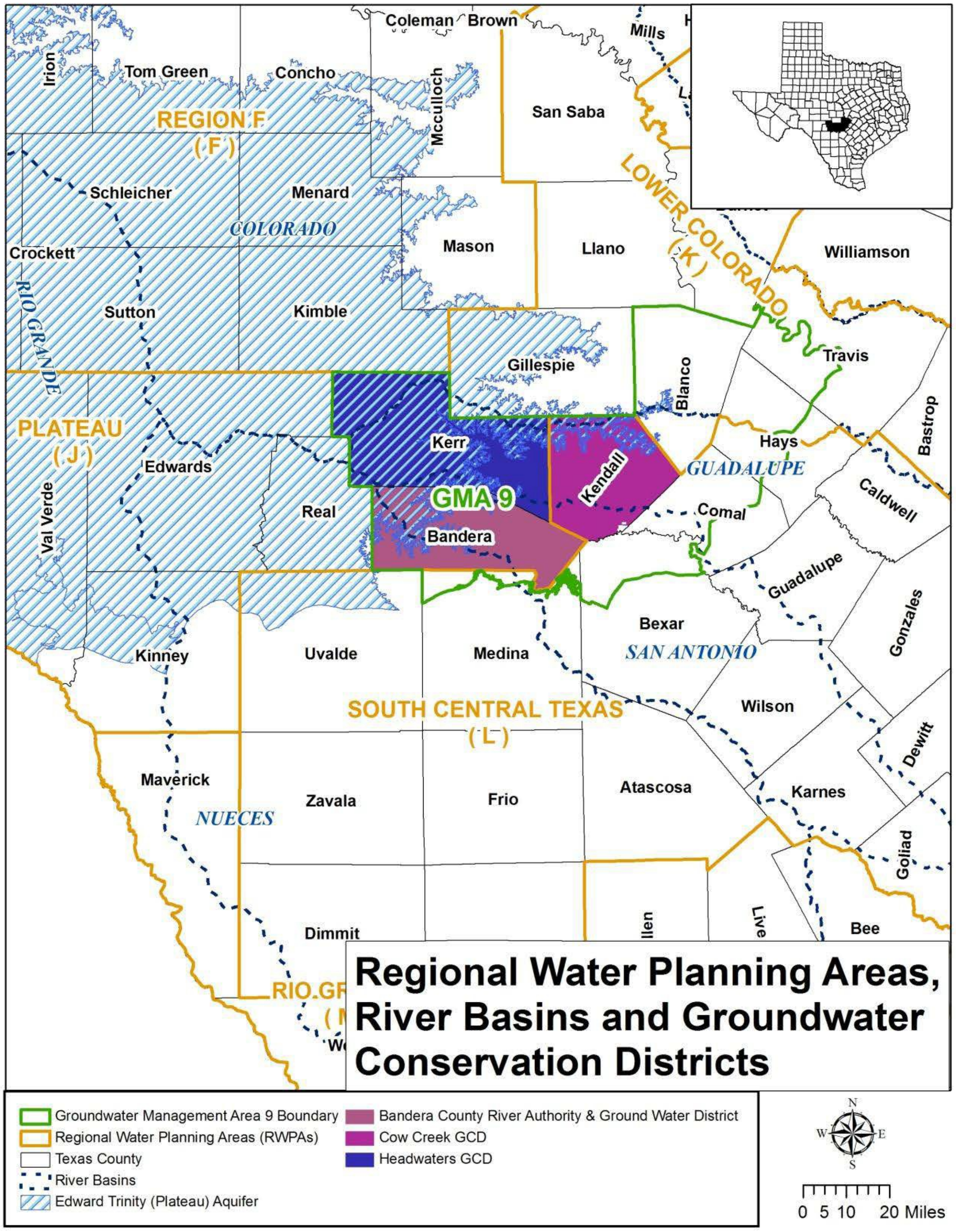

Figure 2: Map showing regional water planning areas (RWPAs), groundwater conservation districts (GCDs), counties, and river basins in Groundwater Management Area 9.

APPENDIX C

GAM Run 10-050 MAG version 2

By Mohammad Masud Hassan, P. E.

Edited and finalized by Radu Boghici to reflect statutory changes effective September 1, 2011

Texas Water Development Board
Groundwater Availability Modeling Section
(512) 463-5808

March 30, 2012

GAM Run 10-050 MAG version 2

By Mohammad Masud Hassan, P.E.

Edited and finalized by Radu Boghici to reflect statutory changes effective September 1, 201 1

Texas Water Development Board
Groundwater Availability Modeling Section
(512) 463-5808

March 30, 2012

Cynthia K. Ridgeway, the Manager of the Groundwater Availability Modeling Section is responsible for oversight of work performed by employees under her direct supervision. The seal appearing on this document was authorized by Cynthia K. Ridgeway, P.G. 471 on March 30, 2012

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EXECUTIVE SUMMARY:

The modeled available groundwater for the Trinity Aquifer as a result of the desired future condition adopted by the members of Groundwater Management Area 9 declines from approximately 93,000 acre-feet per year to approximately 90,500 acre-feet per year between 2010 and 2060. This is shown divided by county, regional water planning area, and river basin in Table 1 for use in the regional water planning process. Modeled available groundwater is summarized by county, regional water planning area, river basin, and groundwater conservation district in tables 2 though 5. The estimates were extracted from Scenario 6 of Groundwater Availability Modeling Task 10-005 (Hutchison, 2010), which meets the desired future condition adopted by the members of Groundwater Management Area 9.

REQUESTOR:

Mr. Ronald G. Fieseler of the Blanco Pedernales Groundwater Conservation District on behalf of Groundwater Management Area 9

DESCRIPTION OF REQUEST:

In a letter dated August 26, 2010 and received August 30, 2010, Mr. Ronald G. Fieseler provided the Texas Water Development Board (TWDB) with the desired future condition of the Trinity Aquifer adopted by the members of Groundwater Management Area 9. The desired future condition for the Trinity Aquifer in Groundwater Management Area 9, as described in Resolution No. 07-26-10-1, is:

"Hill Country Trinity Aquifer - allow for an increase in average drawdown of approximately 30 feet through 2060 consistent with "Scenario 6" in TWDB Draft GAM Task 10-005"

The TWDB has used this adopted desired future condition to estimate the modeled available groundwater for the Trinity Aquifer for each groundwater conservation district within Groundwater Management Area 9.

METHODS:

The TWDB previously completed several predictive groundwater availability model simulations of the Trinity Aquifer to assist the members of Groundwater Management Area 9 in developing a desired future condition. The location of Groundwater Management Area 9, the Trinity Aquifer, and the groundwater availability model cells that represent the aquifer are shown in Figure 1. As stated in Resolution No. 07-26-10-1, the management area considered Groundwater Availability Modeling (GAM) Task 10-005 (Hutchison, 2010) when developing a desired future condition for the Trinity Aquifer. Since the desired future condition above is met in Scenario 6 of GAM Task 10-005, the modeled available groundwater for Groundwater Management Area 9 presented here was taken directly from that simulation. Please note that in GAM Task 10-005 the pumping was presented as an average of all years (2010 to 2060). We have reported this pumping by decade in the results shown in tables 1-5. The modeled available groundwater was then divided by county, regional water planning area, river basin, and groundwater conservation district (Figure 2).

PARAMETERS AND ASSUMPTIONS:

The parameters and assumptions for the model run using the groundwater availability model for the Trinity Aquifer are described below:

- The results presented in this report are based on Scenario 6 of GAM Task 10-005 (Hutchison, 2010). See Hutchison (2010) for a full description of the methods, assumptions, and results of the model simulations.
- The recently updated groundwater availability model (version 2.01) for the Hill Country portion of the Trinity Aquifer developed by Jones and others (2009) was used for the simulations in GAM Task 10-005. See Mace and others (2000) and Jones and others (2009) for details on model construction, recharge, discharge, assumptions, andlimitations.
- The model has four layers: Layer 1 represents the Edwards Group of the Edwards-Trinity (Plateau) Aquifer, Layer 2 represents the Upper Trinity Aquifer, Layer 3 represents the Middle Trinity Aquifer, and Layer 4 represents the Lower Trinity Aquifer. Each scenario in GAM Task 10-005 consisted of a series of 387 separate 50-year model simulations, each with a different recharge configuration. Though the pumping input to the model was the same for each of the 387 simulations, the pumping output differed depending on the occurrence of inactive (or dry) cells. The results below represent the average pumping for the year shown among the simulations comprising Scenario 6 in Hutchison (2010).

Modeled Available Groundwater and Permitting

As defined in Chapter 36 of the Texas Water Code, “modeled available groundwater” is the estimated average amount of water that may be produced annually to achieve a desired future condition. This is distinct from “managed available groundwater”, shown in the draft version of this report dated December 1, 2010, which was a permitting value, and accounted for the estimated use of the aquifer exempt from permitting.

Groundwater conservation districts are required to consider modeled available groundwater, along with several other factors, when issuing permits in order to manage groundwater production to achieve the desired future condition(s). The other factors the districts must consider include annual precipitation and production patterns, the estimated amount of pumping exempt from permitting, existing permits, and a reasonable estimate of actual groundwater production under existing permits. The estimated amount of pumping exempt from permitting, which the Texas Water Development Board is now required to develop after soliciting input from applicable groundwater conservation districts, will be provided in a separate report.

RESULTS:

The modeled available groundwater for the Trinity Aquifer in Groundwater Management Area 9 consistent with the desired future condition decreases from 93,052 acre-feet per year in 2010 to 90,503 acre-feet per year in 2060. The modeled available groundwater has been divided by county, regional water planning area, and river basin for each decade between 2010 and 2060 for use in the regional water planning process (Table 1).

The modeled available groundwater is also summarized by county, regional water planning area, river basin, and groundwater conservation district as shown in tables 2, 3, 4, and 5, respectively. In Table 5, note that modeled available groundwater is totaled for both groundwater conservation district areas and areas without groundwater conservation districts.

REFERENCES:

Hutchison, William R., 2010, GAM Task 10-005, Texas Water Development Board GAM Task 10-005 Report, 13 p.

Jones, I.C., Anaya, R. and Wade, S., 2009, Groundwater Availability Model for the Hill Country portion of the Trinity Aquifer System, Texas, Texas Water Development Board unpublished report,193 p.

Mace, R.E., Chowdhury, A.H., Anaya, R., and Way, S-C., 2000, Groundwater availability of the Trinity Aquifer, Hill Country Area, Texas—Numerical simulations through 2050: Texas Water Development Board Report 353, 119 p.

TABLE 1. MODELED AVAILABLE GROUNDWATER FOR THE TRINITY AQUIFER IN GROUNDWATER MANAGEMENT AREA 9 DIVIDED BY COUNTY, REGIONAL WATER PLANNING AREA, AND RIVER BASIN. RESULTS ARE IN ACRE-FEET PER YEAR.

County	Regional Water Planning Area	River Basin	Year					
			2010	2020	2030	2040	2050	2060
Bandera	J	Guadalupe	76	76	76	76	76	76
		Nueces	903	903	903	903	903	903
		San Antonio	6,305	6,305	6,305	6,305	6,305	6,305
Bexar	L	San Antonio	24,856	24,856	24,856	24,856	24,856	24,856
Blanco	K	Colorado	1,322	1,322	1,322	1,322	1,322	1,322
		Guadalupe	1,251	1,251	1,251	1,251	1,251	1,251
Comal	L	Guadalupe	6,906	6,906	6,906	6,906	6,906	6,906
		San Antonio	3,308	3,308	3,308	3,308	3,308	3,308
Hays	K	Colorado	4,721	4,710	4,707	4,706	4,706	4,706
	L	Guadalupe	4,410	4,410	4,410	4,410	4,410	4,410
Kendall	L	Colorado	135	135	135	135	135	135
		Guadalupe	6,028	6,028	6,028	6,028	6,028	6,028
		San Antonio	4,976	4,976	4,976	4,976	4,976	4,976
Kerr	J	Colorado	318	318	318	318	318	318
		Guadalupe	15,646	14,129	14,056	13,767	13,450	13,434
		Nueces	0	0	0	0	0	0
		San Antonio	471	471	471	471	471	471
Medina	L	Nueces	1,575	1,575	1,575	1,575	1,575	1,575
		San Antonio	925	925	925	925	925	925
Travis	K	Colorado	8,920	8,672	8,655	8,643	8,627	8,598
Total			**93,052**	**91,276**	**91,183**	**90,881**	**90,548**	**90,503**

TABLE 2: MODELED AVAILABLE GROUNDWATER FOR THE TRINITY AQUIFER SUMMARIZED BY COUNTY IN GROUNDWATER MANAGEMENT AREA 9 FOR EACH DECADE BETWEEN 2010 AND 2060. RESULTS ARE IN ACRE-FEET PER YEAR.

County	Year					
	2010	**2020**	**2030**	**2040**	**2050**	**2060**
Bandera	7,284	7,284	7,284	7,284	7,284	7,284
Bexar	24,856	24,856	24,856	24,856	24,856	24,856
Blanco	2,573	2,573	2,573	2,573	2,573	2,573
Comal	10,214	10,214	10,214	10,214	10,214	10,214
Hays	9,131	9,120	9,117	9,116	9,116	9,116
Kendall	11,139	11,139	11,139	11,139	11,139	11,139
Kerr	16,435	14,918	14,845	14,556	14,239	14,223
Medina	2,500	2,500	2,500	2,500	2,500	2,500
Travis	8,920	8,672	8,655	8,643	8,627	8,598
Total	**93,052**	**91,276**	**91,183**	**90,881**	**90,548**	**90,503**

TABLE 3: MODELED AVAILABLE GROUNDWATER FOR THE TRINITY AQUIFER SUMMARIZED BY REGIONAL WATER PLANNING AREA IN GROUNDWATER MANAGEMENT AREA 9 FOR EACH DECADE BETWEEN 2010 AND 2060. RESULTS ARE IN ACRE-FEET PER YEAR.

Regional Water Planning Area	Year					
	2010	**2020**	**2030**	**2040**	**2050**	**2060**
J	23,719	22,202	22,129	21,840	21,523	21,507
K	16,214	15,955	15,935	15,922	15,906	15,877
L	53,119	53,119	53,119	53,119	53,119	53,119
Total	**93,052**	**91,276**	**91,183**	**90,881**	**90,548**	**90,503**

TABLE 4: MODELED AVAILABLE GROUNDWATER FOR THE TRINITY AQUIFER SUMMARIZED BY RIVER BASIN IN GROUNDWATER MANAGEMENT AREA 9 FOR EACH DECADE BETWEEN 2010 AND 2060. RESULTS ARE IN ACRE-FEET PER YEAR.

River Basin	Year					
	2010	**2020**	**2030**	**2040**	**2050**	**2060**
Colorado	15,416	15,157	15,137	15,124	15,108	15,079
Guadalupe	34,317	32,800	32,727	32,438	32,121	32,105
Nueces	2,478	2,478	2,478	2,478	2,478	2,478
San Antonio	40,841	40,841	40,841	40,841	40,841	40,841
Total	**93,052**	**91,276**	**91,183**	**90,881**	**90,548**	**90,503**

TABLE 5: MODELED AVAILABLE GROUNDWATER FOR THE TRINITY AQUIFER SUMMARIZED BY GROUNDWATER CONSERVATION DISTRICT (GCD) IN GROUNDWATER MANAGEMENT AREA 9 FOR EACH DECADE BETWEEN 2010 AND 2060. RESULTS ARE IN ACRE-FEET PER YEAR. RA REFERS TO RIVER AUTHORITY. GWD REFERS TO GROUNDWATER DISTRICT.

Groundwater Conservation District	Year					
	2010	**2020**	**2030**	**2040**	**2050**	**2060**
Bandera County RA & GWD	7,284	7,284	7,284	7,284	7,284	7,284
Blanco-Pedernales GCD	2,573	2,573	2,573	2,573	2,573	2,573
Cow Creek GCD	10,622	10,622	10,622	10,622	10,622	10,622
Hays Trinity GCD	9,109	9,098	9,095	9,094	9,094	9,094
Headwaters GCD	16,435	14,918	14,845	14,556	14,239	14,223
Medina County GCD	2,500	2,500	2,500	2,500	2,500	2,500
Trinity Glen Rose GCD	25,511	25,511	25,511	25,511	25,511	25,511
Total (district areas)	**74,034**	**72,506**	**72,430**	**72,140**	**71,823**	**71,807**
No District	19,018	18,770	18,753	18,741	18,725	18,696
Total (including non-district areas)	**93,052**	**91,276**	**91,183**	**90,881**	**90,548**	**90,503**

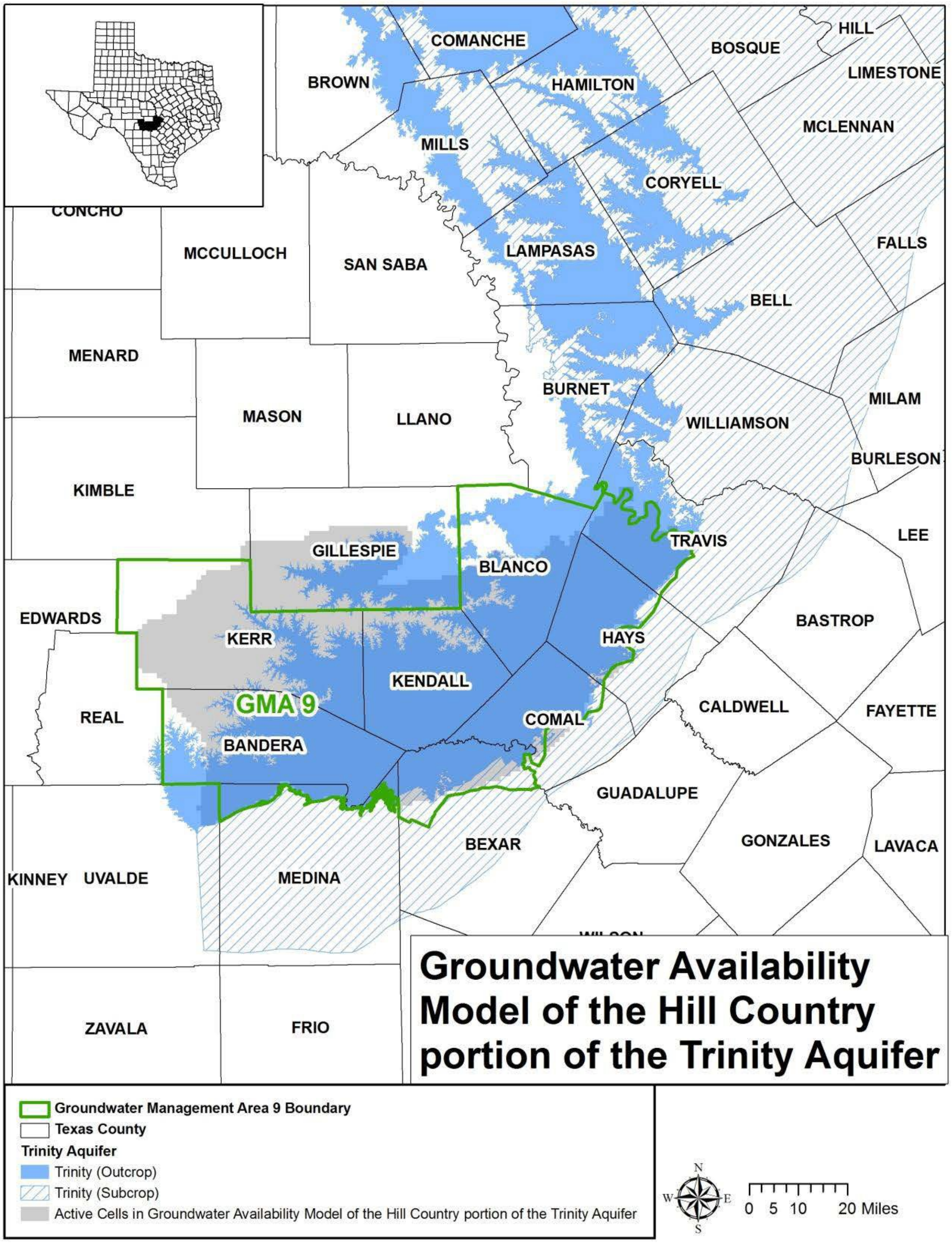

Figure 1: Map showing the areas covered by the groundwater availability model for the Trinity Aquifer.

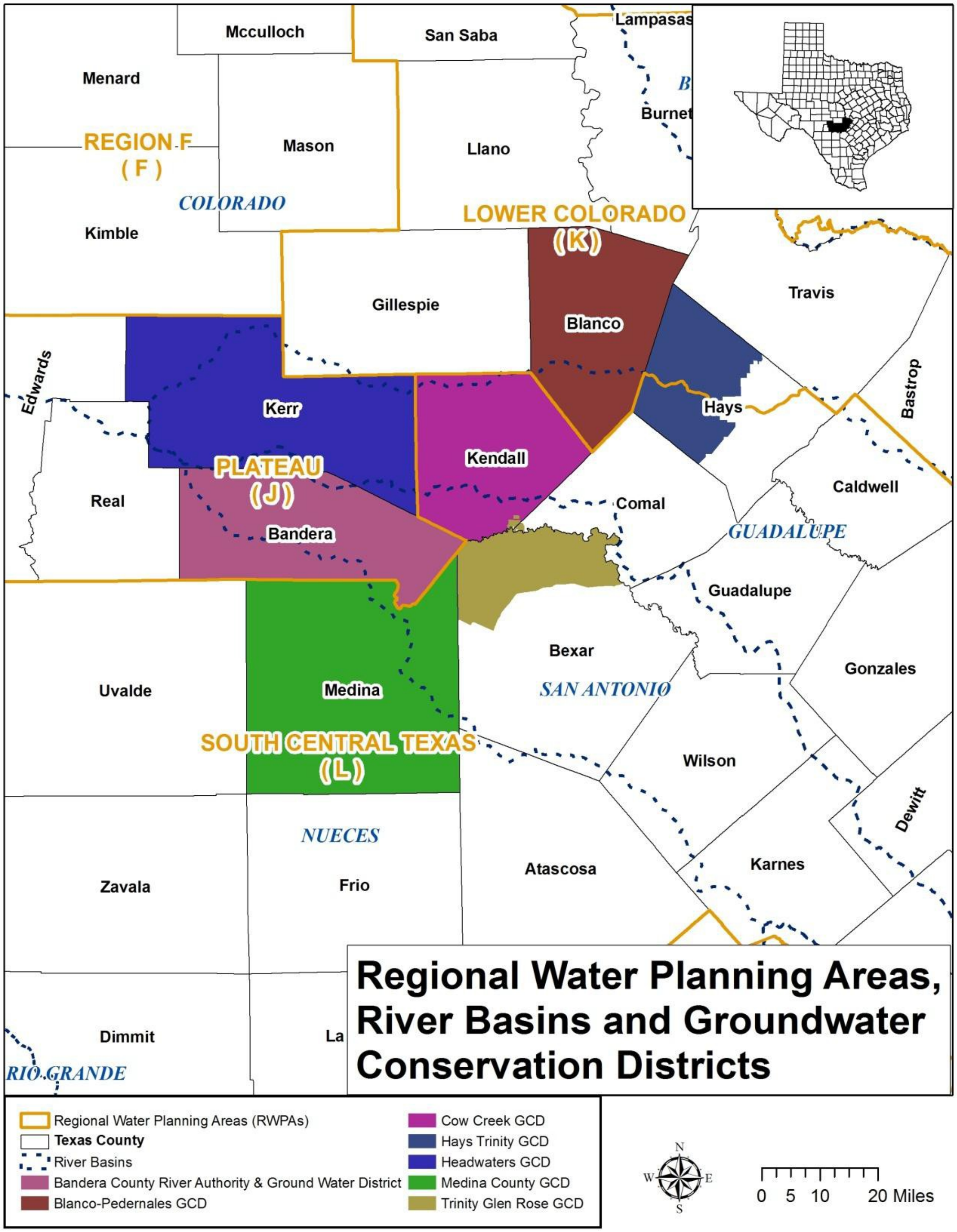

Figure 2: Map showing regional water planning areas (RWPAs), groundwater conservation districts (GCDs), counties, and river basins in Groundwater Management Area 9.

APPENDIX D

Estimated Historical Water Use And 2017 State Water Plan Datasets:

Headwaters Groundwater Conservation District

by Stephen Allen Texas Water Development Board Groundwater Division
Groundwater Technical Assistance Section stephen.allen@twdb.texas.gov (512) 463-7317
September 2, 2016

Estimated Historical Water Use And 2017 State Water Plan Datasets:

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September 2, 2016

GROUNDWATER MANAGEMENT PLAN DATA:

This package of water data reports (part 1 of a 2-part package of information) is being provided to groundwater conservation districts to help them meet the requirements for approval of their five-year groundwater management plan. Each report in the package addresses a specific numbered requirement in the Texas Water Development Board's groundwater management plan checklist. The checklist can be viewed and downloaded from this web address:

http://www.twdb.texas.gov/groundwater/docs/GCD/GMPChecklist0113.pdf

The five reports included in this part are:

1. Estimated Historical Water Use (checklist item 2)

   from the TWDB Historical Water Use Survey (WUS)

2. Projected Surface Water Supplies (checklist item 6)
3. Projected Water Demands (checklist item 7)
4. Projected Water Supply Needs (checklist item 8)
5. Projected Water Management Strategies (checklist item 9)

   from the 2017 Texas State Water Plan (SWP)

Part 2 of the 2-part package is the groundwater availability model (GAM) report for the District (checklist items 3 through 5). The District should have received, or will receive, this report from the Groundwater Availability Modeling Section. Questions about the GAM can be directed to Dr. Shirley Wade, shirley.wade@twdb.texas.gov, (512) 936-0883.

DISCLAIMER:

The data presented in this report represents the most up-to-date WUS and 2017 SWP data available as of 9/2/2016. Although it does not happen frequently, either of these datasets are subject to change pending the availability of more accurate WUS data or an amendment to the 2017 SWP. District personnel must review these datasets and correct any discrepancies in order to ensure approval of their groundwater management plan.

The WUS dataset can be verified at this web address:

http://www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/

The 2017 SWP dataset can be verified by contacting Sabrina Anderson (sabrina.anderson@twdb.texas.gov or 512-936-0886).

For additional questions regarding this data, please contact Stephen Allen (stephen.allen@twdb.texas.gov or 512-463-7317) or Rima Petrossian (rima.petrossian@twdb.texas.gov or 512-936-2420).

Estimated Historical Water Use
TWDB Historical Water Use Survey (WUS) Data

Groundwater and surface water historical use estimates are currently unavailable for calendar year 2015. TWDB staff anticipates the calculation and posting of these estimates at a later date.

KERR COUNTY

All values are in acre-feet

Year	Source	Municipal	Manufacturing	Mining	Steam Electric	Irrigation	Livestock	Total
2014	GW	4,656	0	30	0	1,509	279	6,474
	SW	2,880	0	137	0	519	372	3,908
2013	GW	4,886	0	31	0	1,077	251	6,245
	SW	3,245	0	126	0	624	401	4,396
2012	GW	5,607	20	30	0	459	299	6,415
	SW	3,316	0	76	0	855	402	4,649
2011	GW	5,800	8	14	0	293	433	6,548
	SW	3,475	0	45	0	362	457	4,339
2010	GW	4,681	6	17	0	447	428	5,579
	SW	4,635	0	54	0	567	462	5,718
2009	GW	4,091	23	16	0	246	343	4,719
	SW	4,255	0	49	0	807	459	5,570
2008	GW	4,885	24	15	0	73	367	5,364
	SW	3,498	0	44	0	1,015	430	4,987
2007	GW	4,623	23	0	0	133	327	5,106
	SW	3,529	0	0	0	1,035	287	4,851
2006	GW	4,625	7	0	0	120	328	5,080
	SW	3,814	0	0	0	400	291	4,505
2005	GW	3,847	6	0	0	76	314	4,243
	SW	3,981	0	0	0	450	230	4,661
2004	GW	4,475	6	0	0	47	171	4,699
	SW	4,347	0	0	0	478	461	5,286
2003	GW	3,439	8	0	0	77	171	3,695
	SW	4,347	0	0	0	772	515	5,634
2002	GW	3,741	9	0	0	113	171	4,034
	SW	4,708	0	0	0	1,776	515	6,999
2001	GW	3,981	25	0	0	113	186	4,305
	SW	3,784	0	0	0	1,778	522	6,084
2000	GW	3,851	25	0	0	107	389	4,372
	SW	3,583	0	0	0	1,773	356	5,712

Projected Surface Water Supplies
TWDB 2017 State Water Plan Data

KERR COUNTY

All values are in acre-feet

RWPG	WUG	WUG Basin	Source Name	2020	2030	2040	2050	2060	2070
J	COUNTY-OTHER, KERR	GUADALUPE	GUADALUPE RUN-OF-RIVER	15	15	15	15	15	15
J	IRRIGATION, KERR	GUADALUPE	GUADALUPE RUN-OF-RIVER	958	958	958	958	958	958
J	KERRVILLE	GUADALUPE	GUADALUPE RUN-OF-RIVER	150	150	150	150	150	150
J	LIVESTOCK, KERR	COLORADO	COLORADO OTHER LOCAL SUPPLY	46	46	46	46	46	46
J	LIVESTOCK, KERR	GUADALUPE	GUADALUPE OTHER LOCAL SUPPLY	393	393	393	393	393	393
J	LIVESTOCK, KERR	SAN ANTONIO	SAN ANTONIO OTHER LOCAL SUPPLY	23	23	23	23	23	23
J	MANUFACTURING, KERR	GUADALUPE	GUADALUPE RUN-OF-RIVER	9	9	9	9	9	9
J	MINING, KERR	GUADALUPE	GUADALUPE RUN-OF-RIVER	89	89	89	89	89	89
	Sum of Projected Surface Water Supplies (acre-feet)			**1,683**	**1,683**	**1,683**	**1,683**	**1,683**	**1,683**

Projected Water Demands
TWDB 2017 State Water Plan Data

Please note that the demand numbers presented here include the plumbing code savings found in the Regional and State Water Plans.

KERR COUNTY

All values are in acre-feet

RWPG	WUG	WUG Basin	2020	2030	2040	2050	2060	2070
J	COUNTY-OTHER, KERR	COLORADO	53	53	53	53	54	55
J	COUNTY-OTHER, KERR	GUADALUPE	1,946	1,986	1,994	2,029	2,072	2,110
J	COUNTY-OTHER, KERR	NUECES	1	1	1	1	1	1
J	COUNTY-OTHER, KERR	SAN ANTONIO	29	29	28	29	29	30
J	INGRAM	GUADALUPE	165	160	155	153	154	155
J	IRRIGATION, KERR	COLORADO	23	22	21	21	20	19
J	IRRIGATION, KERR	GUADALUPE	804	779	755	730	708	687
J	IRRIGATION, KERR	SAN ANTONIO	15	15	14	14	13	13
J	KERRVILLE	GUADALUPE	4,619	4,688	4,706	4,759	4,821	4,875
J	LIVESTOCK, KERR	COLORADO	195	195	195	195	195	195
J	LIVESTOCK, KERR	GUADALUPE	642	642	642	642	642	642
J	LIVESTOCK, KERR	NUECES	11	11	11	11	11	11
J	LIVESTOCK, KERR	SAN ANTONIO	42	42	42	42	42	42
J	LOMA VISTA WATER SYSTEM	GUADALUPE	417	424	425	431	438	444
J	MANUFACTURING, KERR	GUADALUPE	25	27	29	30	32	34
J	MINING, KERR	COLORADO	14	15	19	19	21	23
J	MINING, KERR	GUADALUPE	62	65	81	83	90	97
		Sum of Projected Water Demands (acre-feet)	**9,063**	**9,154**	**9,171**	**9,242**	**9,343**	**9,433**

Projected Water Supply Needs
TWDB 2017 State Water Plan Data

Negative values (in red) reflect a projected water supply need, positive values a surplus.

KERR COUNTY

All values are in acre-feet

RWPG	WUG	WUG Basin	2020	2030	2040	2050	2060	2070
J	COUNTY-OTHER, KERR	COLORADO	-5	-5	-5	-5	-6	-7
J	COUNTY-OTHER, KERR	GUADALUPE	3,242	3,202	3,194	3,159	3,116	3,078
J	COUNTY-OTHER, KERR	NUECES	-1	-1	-1	-1	-1	-1
J	COUNTY-OTHER, KERR	SAN ANTONIO	84	84	85	84	84	83
J	INGRAM	GUADALUPE	387	392	397	399	398	397
J	IRRIGATION, KERR	COLORADO	21	22	23	23	24	25
J	IRRIGATION, KERR	GUADALUPE	556	581	605	630	652	673
J	IRRIGATION, KERR	SAN ANTONIO	-14	-14	-13	-13	-12	-12
J	KERRVILLE	GUADALUPE	-3,194	-3,263	-3,281	-3,334	-3,396	-3,450
J	LIVESTOCK, KERR	COLORADO	-106	-106	-106	-106	-106	-106
J	LIVESTOCK, KERR	GUADALUPE	131	131	131	131	131	131
J	LIVESTOCK, KERR	NUECES	-6	-6	-6	-6	-6	-6
J	LIVESTOCK, KERR	SAN ANTONIO	-18	-18	-18	-18	-18	-18
J	LOMA VISTA WATER SYSTEM	GUADALUPE	-30	-37	-38	-44	-51	-57
J	MANUFACTURING, KERR	GUADALUPE	9	7	5	4	2	0
J	MINING, KERR	COLORADO	-12	-13	-17	-17	-19	-21
J	MINING, KERR	GUADALUPE	42	39	23	21	14	7
	Sum of Projected Water Supply Needs (acre-feet)		**-3,386**	**-3,463**	**-3,485**	**-3,544**	**-3,615**	**-3,678**

KERR COUNTY

WUG, Basin (RWPG) All values are in acre-feet

Water Management Strategy	Source Name [Origin]	2020	2030	2040	2050	2060	2070
COUNTY-OTHER, KERR, COLORADO (J)							
MUNICIPAL AND COUNTY OTHER CONSERVATION FOR UGRA	DEMAND REDUCTION [KERR]	5	5	5	5	6	7
		5	**5**	**5**	**5**	**6**	**7**
COUNTY-OTHER, KERR, GUADALUPE (J)							
CCP/UGRA - ELLENBURGER AQUIFER WATER SUPPLY WELL	ELLENBURGER AQUIFER [KERR]	108	108	108	108	108	108
CCP/UGRA - WELL FIELD FOR DENSE, RURAL AREAS	TRINITY AQUIFER [KERR]	994	994	994	994	994	994
CENTER POINT WWW - WATER LOSS AUDIT AND MAIN-LINE REPAIR	DEMAND REDUCTION [KERR]	1	1	1	1	1	1
EKC/UGRA - ACQUISITION OF SURFACE WATER RIGHTS	GUADALUPE RUN-OF-RIVER [KERR]	1,029	1,029	1,029	1,029	1,029	1,029
EKC/UGRA - ASR FACILITY	TRINITY AQUIFER ASR [KERR]	1,124	1,124	1,124	1,124	1,124	1,124
EKC/UGRA - CONSTRUCTION OF AN OFF-CHANNEL SURFACE WATER STORAGE	GUADALUPE RIVER OFF-CHANNEL LAKE/RESERVOIR [KERR]	1,121	1,121	1,121	1,121	1,121	1,121
EKC/UGRA - CONSTRUCTION OF SURFACE WATER TREATMENT FACILITIES AND DISTRIBUTION LINES	GUADALUPE RUN-OF-RIVER [KERR]	15	15	15	15	15	15
HILLS AND DALES WWW - WATER LOSS AUDIT AND MAIN-LINE REPAIR	DEMAND REDUCTION [KERR]	1	1	1	1	1	1
KERR COUNTY OTHER - VEGETATIVE MANAGEMENT - ASHE JUNIPER	TRINITY AQUIFER [KERR]	0	0	0	0	0	0
MUNICIPAL AND COUNTY OTHER CONSERVATION FOR UGRA	DEMAND REDUCTION [KERR]	9	9	9	10	9	8
RUSTIC HILLS WATER - WATER LOSS AUDIT AND MAIN-LINE REPAIR	DEMAND REDUCTION [KERR]	1	1	1	1	1	1
VERDE PARK ESTATES WWW - WATER LOSS AUDIT AND MAIN-LINE REPAIR	DEMAND REDUCTION [KERR]	1	1	1	1	1	1
		4,404	**4,404**	**4,404**	**4,405**	**4,404**	**4,403**
COUNTY-OTHER, KERR, NUECES (J)							
MUNICIPAL AND COUNTY OTHER CONSERVATION FOR UGRA	DEMAND REDUCTION [KERR]	1	1	1	1	1	1
		1	**1**	**1**	**1**	**1**	**1**
IRRIGATION, KERR, SAN ANTONIO (J)							
KERR COUNTY IRRIGATION - ADDITIONAL GROUNDWATER WELL	TRINITY AQUIFER [KERR]	20	20	20	20	20	20
		20	**20**	**20**	**20**	**20**	**20**

WUG, Basin (RWPG) — All values are in acre-feet

Water Management Strategy	Source Name [Origin]	2020	2030	2040	2050	2060	2070
KERRVILLE, GUADALUPE (J)							
CITY OF KERRVILLE - INCREASE WASTEWATER REUSE	GUADALUPE RUN-OF-RIVER [KERR]	5,041	5,041	5,041	5,041	5,041	5,041
CITY OF KERRVILLE - INCREASED WATER TREATMENT AND ASR CAPACITY	TRINITY AQUIFER ASR [KERR]	3,360	3,360	3,360	3,360	3,360	3,360
CITY OF KERRVILLE - PURCHASE WATER FROM UGRA	GUADALUPE RUN-OF-RIVER [KERR]	0	0	0	0	0	0
CITY OF KERRVILLE - WATER LOSS AUDIT AND MAIN-LINE REPAIR	DEMAND REDUCTION [KERR]	147	147	147	147	147	147
		8,548	**8,548**	**8,548**	**8,548**	**8,548**	**8,548**
LIVESTOCK, KERR, COLORADO (J)							
KERR COUNTY LIVESTOCK - ADDITIONAL GROUNDWATER WELLS	EDWARDS-TRINITY-PLATEAU AQUIFER [KERR]	108	108	108	108	108	108
KERR COUNTY LIVESTOCK - ADDITIONAL GROUNDWATER WELLS - GUADALUPE RIVER BASIN	EDWARDS-TRINITY-PLATEAU AQUIFER [KERR]	10	10	10	10	10	10
		118	**118**	**118**	**118**	**118**	**118**
LIVESTOCK, KERR, NUECES (J)							
KERR COUNTY LIVESTOCK - ADDITIONAL GROUNDWATER WELLS - GUADALUPE RIVER BASIN	EDWARDS-TRINITY-PLATEAU AQUIFER [KERR]	10	10	10	10	10	10
		10	**10**	**10**	**10**	**10**	**10**
LIVESTOCK, KERR, SAN ANTONIO (J)							
KERR COUNTY LIVESTOCK - ADDITIONAL GROUNDWATER WELL	TRINITY AQUIFER [KERR]	20	20	20	20	20	20
		20	**20**	**20**	**20**	**20**	**20**
LOMA VISTA WATER SYSTEM, GUADALUPE (J)							
LOMA VISTA WSC - ADDITIONAL GROUNDWATER WELL	TRINITY AQUIFER [KERR]	57	57	57	57	57	57
LOMA VISTA WSC - CONSERVATION PUBLIC INFORMATION	DEMAND REDUCTION [KERR]	4	4	4	4	4	4
		61	**61**	**61**	**61**	**61**	**61**
MINING, KERR, COLORADO (J)							

KERR COUNTY MINING - ADDITIONAL TRINITY AQUIFER [KERR] GROUNDWATER WELL	30	30	30	30	30	30
	30	**30**	**30**	**30**	**30**	**30**
Sum of Projected Water Management Strategies (acre-feet)	**13,217** **13,218**	**13,217**	**13,217**	**13,218**	**13,218**	

APPENDIX E

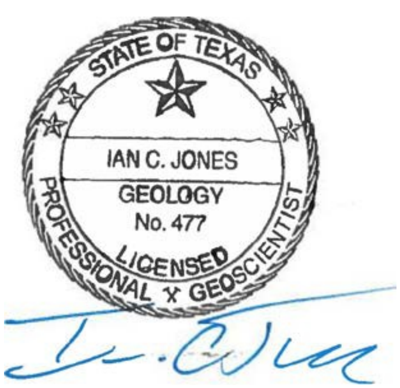
GAM RUN 16-019

HEADWATERS GROUNDWATER CONSERVATION DISTRICT MANAGEMENT PLAN

by Ian C. Jones, Ph.D., P.G.
Texas water Development Board
Groundwater Resources Division
Groundwater Availability Modeling Section
(512) 463-6641
August 31, 2016

GAM RUN 16-019: HEADWATERS GROUNDWATER CONSERVATION DISTRICT MANAGEMENT PLAN

Ian C. Jones, Ph.D., P.G. Texas Water Development Board
Groundwater Division Groundwater Availability Modeling Section
(512) 463-6641
August 31, 2016



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GAM RUN 16-019: HEADWATERS GROUNDWATER CONSERVATION DISTRICT MANAGEMENT PLAN

Ian C. Jones, Ph.D., P.G. Texas Water Development Board
Groundwater Division Groundwater Availability Modeling Section
(512) 463-6641
August 31, 2016

EXECUTIVE SUMMARY:

Texas Water Code, Section 36.1071, Subsection (h) (Texas Water Code, 2015), states that, in developing its groundwater management plan, a groundwater conservation district shall use groundwater availability modeling information provided by the Executive Administrator of the Texas Water Development Board (TWDB) in conjunction with any available site-specific information provided by the district for review and comment to the Executive Administrator.

The TWDB provides data and information to the Headwaters Groundwater Conservation District in two parts. Part 1 is the Estimated Historical Water Use/State Water Plan dataset report which will be provided to you separately by the TWDB Groundwater Technical Assistance Section. Please direct questions about the water data report to Mr. Stephen Allen at (512) 463-7317 or stephen.allen@twdb.texas.gov. Part 2 is the required groundwater availability modeling information. This information includes:

1. the annual amount of recharge from precipitation, if any, to the groundwater resources within the district;
2. for each aquifer within the district, the annual volume of water that discharges from the aquifer to springs and any surface-water bodies, including lakes, streams, and rivers; and
3. the annual volume of flow into and out of the district within each aquifer and between aquifers in the district.

The groundwater management plan for the Headwaters Groundwater Conservation District should be adopted by the district on or before November 15, 2017, and submitted to the Executive Administrator of the TWDB on or before December 15, 2017. The current management plan for the Headwaters Groundwater Conservation District expires on February 13, 2018.

The Edwards-Trinity (Plateau), Trinity, Ellenburger-San Saba, and Hickory aquifers are identified by the TWDB as being located within the Headwaters Groundwater Conservation District. Information for the Edwards-Trinity (Plateau) and Trinity aquifers were extracted from version 1.01 of the groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009), while information for the Ellenburger-San Saba and Hickory aquifers were extracted from draft version 1.01 of the groundwater availability model for the minor aquifers of the Llano Uplift area (Shi and others, 2016).

This report discusses the methods, assumptions, and results from model runs using the groundwater availability models for the Edwards-Trinity (Plateau) Aquifer and the minor aquifers of the Llano Uplift area (Anaya and Jones, 2009; Shi and others, 2016). This model run replaces GAM Run 12-021 (Jones, 2012). GAM Run 16-019 meets current standards set after the release of GAM Run 12-021 and includes information from the draft groundwater availability model for the minor aquifers of the Llano Uplift area (Shi and others, 2016). Tables 1 through 4 summarize the groundwater availability model data required by statute, and Figures 1 through 3 show the areas of the respective models from which the values in the tables were extracted. If after review of the figures, Headwaters Groundwater Conservation District determines that the district boundaries used in the assessment do not reflect current conditions, please notify the TWDB at your earliest convenience.

METHODS:

In accordance with the provisions of the Texas State Water Code, Section 36.1071, Subsections (e) and (h), the groundwater availability models for the Edwards- Trinity (Plateau) Aquifer and the aquifers of the Llano Uplift were run for this analysis. The water budget for the Headwaters Groundwater Conservation District was extracted for the historical model periods of 1981 through 2000 and 1981 through 2010 for the Edwards-Trinity (Plateau) and Llano Uplift models, respectively, using ZONEBUDGET Version 3.01 (Harbaugh, 2009). The average annual water budget values for recharge, surface water outflow, inflow to the district, outflow from the district, net inter-aquifer flow (upper), and net inter- aquifer flow (lower) for the portion of the aquifer system located within the district are summarized in this report.

1. *PARAMETERS AND ASSUMPTIONS:*

Edwards-Trinity (Plateau) Aquifer

- We used version 1.01 of the groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers. See Anaya and Jones (2009) for assumptions and limitations of the groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers. The Pecos Valley Aquifer does not occur within the Headwaters Groundwater Conservation District and therefore no groundwater budget values are included for it in this report.

- This groundwater availability model includes two layers within Headwaters Groundwater Conservation District, which generally represent the Edwards Group (Layer 1**)** and the Trinity Group (Layer 2) of the Edwards-Trinity (Plateau) Aquifer. Individual water budgets for the District were determined for the Edwards-Trinity (Plateau) Aquifer (Layer 1 and Layer 2 combined) and for the Trinity Aquifer (Layer 2).

- The model was run with MODFLOW-96 (Harbaugh and McDonald, 1996).

2. *Marble Falls, Ellenburger-San Saba, and Hickory Aquifers*

- We used version 1.01 of the draft groundwater availability model for the minor aquifers in the Llano Uplift area. See Shi and others (2016) for assumptions and limitations of the model.

- The draft groundwater availability model for the minor aquifers in Llano Uplift area contains eight layers: Layer 1 (the Trinity Aquifer, Edwards-Trinity (Plateau) Aquifer, and younger alluvium deposits), Layer 2 (confining units), Layer 3 (the Marble Falls Aquifer and equivalent unit), Layer 4 (confining units), Layer 5 (Ellenburger-San Saba Aquifer and equivalent unit), Layer 6 (confining units), Layer 7 (the Hickory Aquifer and equivalent unit), and Layer 8 (Precambrian units).

- Perennial rivers and reservoirs were simulated using MODFLOW-USG river package. Springs were simulated using MODFLOW-USG drain package. For this management plan, groundwater discharge to surface water includes groundwater leakage to the river and drain boundaries.

- The model was run with MODFLOW-USG beta (development) version (Panday and others, 2013).

RESULTS:

A groundwater budget summarizes the amount of water entering and leaving the aquifer according to the groundwater availability model. Selected groundwater budget components listed below were extracted from the model results for the aquifers located within the district and averaged over the duration of the calibration and verification portion of the model run in the district, as shown in Table 1.

- Precipitation recharge—The areally distributed recharge sourced from precipitation falling on the outcrop areas of the aquifers (where the aquifer is exposed at land surface) within the district.
- Surface water outflow—The total water discharging from the aquifer (outflow) to surface water features such as streams, reservoirs, and springs.
- Flow into and out of district—The lateral flow within the aquifer between the district and adjacent counties.
- Flow between aquifers—The net vertical flow between the aquifer and adjacent aquifers or confining units. This flow is controlled by the relative water levels in each aquifer or confining unit and aquifer properties of each aquifer or confining unit that define the amount of leakage that occurs.

The information needed for the District's management plan is summarized in Tables 1 through 4. It is important to note that sub-regional water budgets are not exact. This is due to the size of the model cells and the approach used to extract data from the model. To avoid double accounting, a model cell that straddles a political boundary, such as a district or county boundary, is assigned to one side of the boundary based on the location of the centroid of the model cell. For example, if a cell contains two counties, the cell is assigned to the county where the centroid of the cell is located.

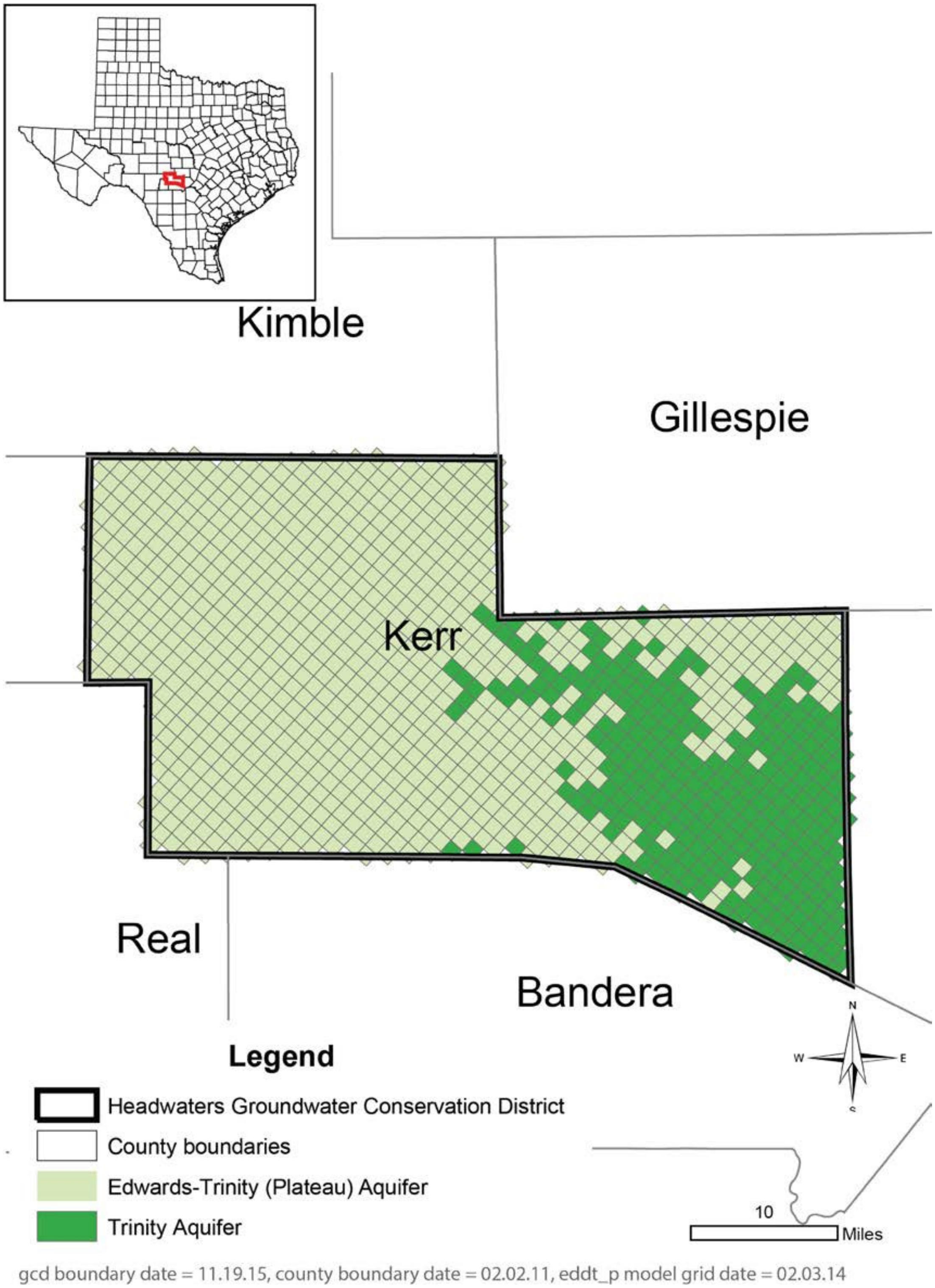

FIGURE 1: AREA OF THE GROUNDWATER AVAILABILITY MODEL FOR THE EDWARDS-TRINITY (PLATEAU) AQUIFER FROM WHICH THE INFORMATION IN TABLES 1 AND 2 WAS EXTRACTED.

TABLE 1: SUMMARIZED INFORMATION FOR THE EDWARDS-TRINITY (PLATEAU) AQUIFER THAT IS NEEDED FOR HEADWATERS GROUNDWATER CONSERVATION DISTRICT'S GROUNDWATER MANAGEMENT PLAN. ALL VALUES ARE REPORTED IN ACRE-FEET PER YEAR AND ROUNDED TO THE NEAREST ONE ACRE-FOOT.

Management Plan requirement	Aquifer or confining unit	Results
Estimated annual amount of recharge from precipitation to the district	Edwards-Trinity (Plateau) Aquifer	26,419
Estimated annual volume of water that discharges from the aquifer to springs and any surface water body including lakes, streams, and rivers	Edwards-Trinity (Plateau) Aquifer	17,697
Estimated annual volume of flow into the district within each aquifer in the district	Edwards-Trinity (Plateau) Aquifer	8,311
Estimated annual volume of flow out of the district within each aquifer in the district	Edwards-Trinity (Plateau) Aquifer	20,066
Estimated net annual volume of flow between each aquifer in the district	From the Edwards-Trinity (Plateau) Aquifer to the Trinity Aquifer	5,831

TABLE 2: SUMMARIZED INFORMATION FOR THE HILL COUNTRY PORTION OF THE TRINITY AQUIFER SYSTEM THAT IS NEEDED FOR HEADWATERS GROUNDWATER CONSERVATION DISTRICT'S GROUNDWATER MANAGEMENT PLAN. ALL VALUES ARE REPORTED IN ACRE-FEET PER YEAR AND ROUNDED TO THE NEAREST ONE ACRE-FOOT.

Management Plan requirement	Aquifer or confining unit	Results
Estimated annual amount of recharge from precipitation to the district	Trinity Aquifer	21,331
Estimated annual volume of water that discharges from the aquifer to springs and any surface water body including lakes, streams, and rivers	Trinity Aquifer	18,473
Estimated annual volume of flow into the district within each aquifer in the district	Trinity Aquifer	2,238
Estimated annual volume of flow out of the district within each aquifer in the district	Trinity Aquifer	8,264
Estimated net annual volume of flow between each aquifer in the district	From the Edwards-Trinity (Plateau) Aquifer to the Trinity Aquifer	5,831

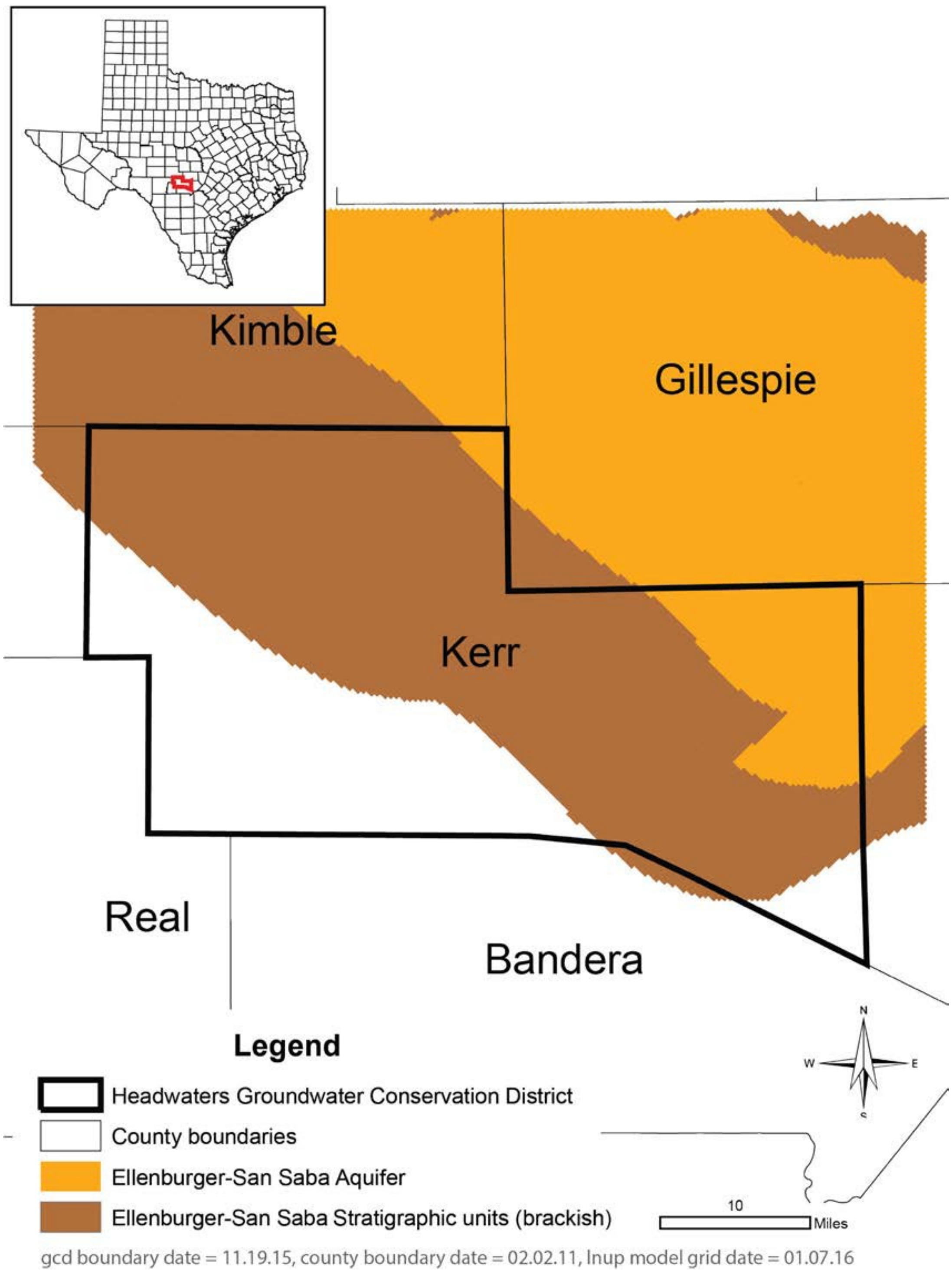

FIGURE 2: AREA OF THE DRAFT GROUNDWATER AVAILABILITY MODEL FOR THE MINOR AQUIFERS IN THE LLANO UPLIFT AREA FROM WHICH THE INFORMATION IN TABLE 3 WAS EXTRACTED (THE ELLENBURGER-SAN SABA AQUIFER EXTENT WITHIN THE DISTRICT BOUNDARY).

TABLE 3: SUMMARIZED INFORMATION FOR THE ELLENBURGER-SAN SABA AQUIFER THAT IS NEEDED FOR HEADWATERS GROUNDWATER CONSERVATION DISTRICT'S GROUNDWATER MANAGEMENT PLAN. ALL VALUES ARE REPORTED IN ACRE-FEET PER YEAR AND ROUNDED TO THE NEAREST ONE ACRE- FOOT.

Management Plan requirement	Aquifer or confining unit	Results
Estimated annual amount of recharge from precipitation to the district	Ellenburger-San Saba Aquifer	0
Estimated annual volume of water that discharges from the aquifer to springs and any surface water body including lakes, streams, and rivers	Ellenburger-San Saba Aquifer	0
Estimated annual volume of flow into the district within each aquifer in the district	Ellenburger-San Saba Aquifer	3,967
Estimated annual volume of flow out of the district within each aquifer in the district	Ellenburger-San Saba Aquifer	4,031
Estimated net annual volume of flow between each aquifer in the district	From the Hickory Aquifer to the Ellenburger-San Saba Aquifer	238
	From the Ellenburger-San Saba Aquifer to the brackish Ellenburger-San Saba stratigraphic unit	1,189

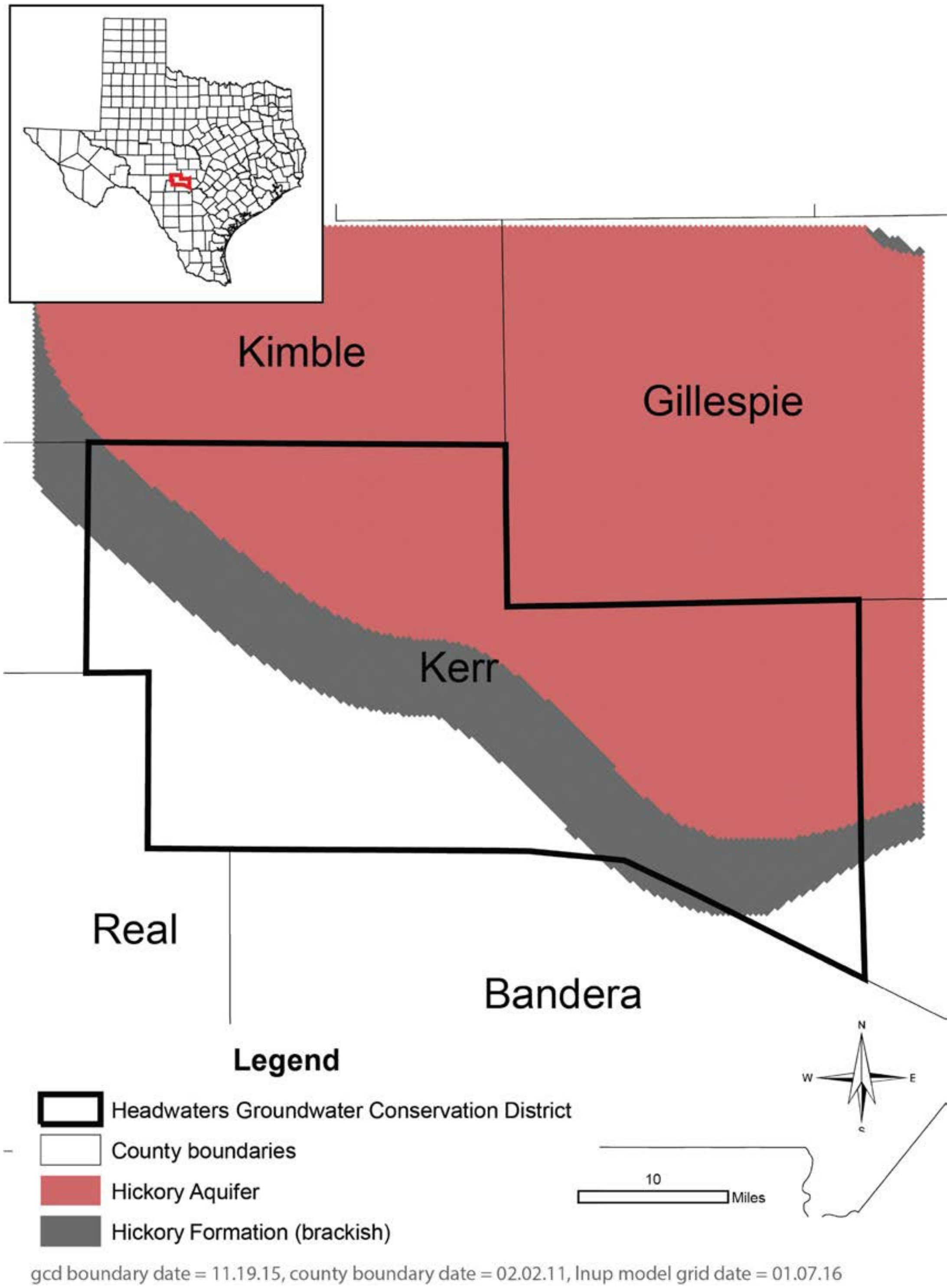

FIGURE 3: AREA OF THE DRAFT GROUNDWATER AVAILABILITY MODEL FOR THE MINOR AQUIFERS IN THE LLANO UPLIFT AREA FROM WHICH THE INFORMATION IN TABLE 4 WAS EXTRACTED (THE HICKORY AQUIFER EXTENT WITHIN THE DISTRICT BOUNDARY).

TABLE 4: SUMMARIZED INFORMATION FOR THE HICKORY AQUIFER THAT IS NEEDED FOR HEADWATERS GROUNDWATER CONSERVATION DISTRICT'S GROUNDWATER MANAGEMENT PLAN. ALL VALUES ARE REPORTED IN ACRE-FEET PER YEAR AND ROUNDED TO THE NEAREST ONE ACRE-FOOT.

Management Plan requirement	Aquifer or confining unit	Results
Estimated annual amount of recharge from precipitation to the district	Hickory Aquifer	0
Estimated annual volume of water that discharges from the aquifer to springs and any surface water body including lakes, streams, and rivers	Hickory Aquifer	0
Estimated annual volume of flow into the district within each aquifer in the district	Hickory Aquifer	4,831
Estimated annual volume of flow out of the district within each aquifer in the district	Hickory Aquifer	2,347
Estimated net annual volume of flow between each aquifer in the district	From the Hickory Aquifer to the Ellenburger-San Saba Aquifer	213
	From the Hickory Aquifer to the brackish Ellenburger-San Saba stratigraphic unit	2,113
	From the Hickory Aquifer to the brackish Hickory Formation	3,933

LIMITATIONS:

The groundwater model(s) used in completing this analysis is the best available scientific tool 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."

A key aspect of using the groundwater model to evaluate historic groundwater flow conditions includes the assumptions about the location in the aquifer where historic pumping was placed. Understanding the amount and location of historic pumping is as important as evaluating the volume of groundwater flow into and out of the district, between aquifers within the district (as applicable), interactions with surface water (as applicable), recharge to the aquifer system (as applicable), and other metrics that describe the impacts of that pumping. In addition, assumptions regarding precipitation, recharge, and interaction with streams are specific to particular historic time periods.

Because the application of the groundwater models was designed to address regional scale questions, the results are most effective on a regional scale. The TWDB makes no warranties or representations related to the actual conditions of any aquifer at a particular location or at a particular time.

It is important for groundwater conservation districts to monitor groundwater pumping and overall conditions of the aquifer. Because of the limitations of the groundwater model and the assumptions in this analysis, it is important that the groundwater conservation districts work with the TWDB to refine this analysis in the future given the reality of how the aquifer responds to the actual amount and location of pumping now and in the future. Historic precipitation patterns also need to be placed in context as future climatic conditions, such as dry and wet year precipitation patterns, may differ and affect groundwater flow conditions.

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Texas Water Code, 2015, http://www.statutes.legis.state.tx.us/docs/WA/pdf/WA.36.pdf.

APPENDIX F:

Groundwater Availability Model: Hill Country Portion of the Trinity Aquifer of, Texas

Report 377 June 2011

By Ian. C Jones, Ph.D., P.G.

Roberto Anaya, P. G.

Shirley Wade, Ph.D., P.G.

Groundwater Availability Model: Hill Country Portion of the Trinity Aquifer of Texas

by Ian C. Jones, Ph.D., P.G. • Roberto Anaya, P.G. • Shirley C. Wade, Ph.D., P.G.

Report 377
June 2011

Texas Water Development Board
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Report 377

Groundwater Availability Model: Hill Country Portion of the Trinity Aquifer of Texas

by
Ian C. Jones, Ph.D., P.G.
Roberto Anaya, P.G.
Shirley C. Wade, Ph.D., P.G.

June 2011

Geoscientist Seal

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

Ian C. Jones, Ph.D., P.G. No. 477
Dr. Jones was the project manager for this work and was responsible for oversight of the project, organization of the report, the modeling approach, and the steady-state and transient model calibration.

The seal appearing on this document was authorized on June 22, 2011 by

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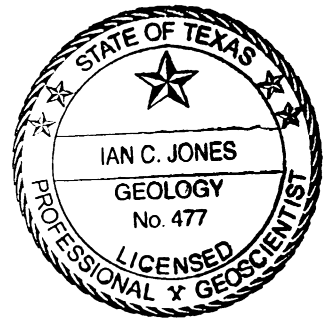
Ian. C. Jones



Roberto Anaya, P.G No. 480
Mr. Anaya changed the map projection of the model and assisted with revising the structural geology.

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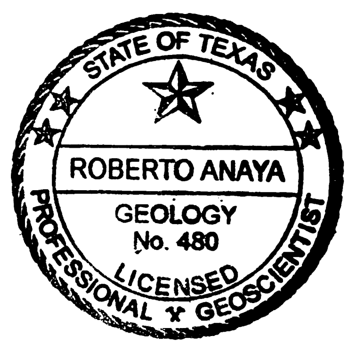

Shirley C. Wade, Ph.D., P.G. No. 525
Dr. Wade revised the structural geology used in the model.

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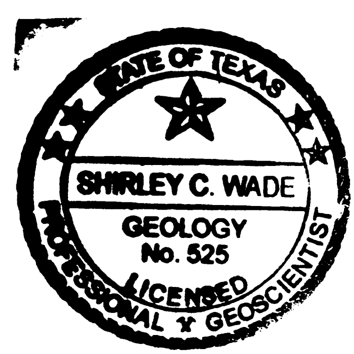
Shirley C. Wade



Cover photo: Jacob's Well ©Todd Seibel

Edited by Susann Doenges

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1.0 Executive Summary

Mace and others (2000) constructed a groundwater availability model simulating groundwater flow through the Hill Country portion of the Trinity Aquifer System as a groundwater resource management tool. The purpose of this report is to document updates to this earlier model. We updated the model by (1) adding the Lower Trinity Aquifer as another layer to the model, (2) revising the spatial distribution of parameters, such as recharge and pumping, and (3) calibrating to steady-state water level and river discharge conditions for 1980 and historical transient water level and discharge conditions for 1981 through 1997. The calibrated model can be used to predict future water level changes that may result from various projected pumping rates and/or changes in climatic conditions.

Our conceptual model subdivides the Hill Country portion of the Trinity Aquifer System into three main components: the Upper, Middle, and Lower Trinity aquifers. The Upper Trinity Aquifer is composed of the upper member of the Glen Rose Limestone. The Middle Trinity Aquifer is composed of the lower member of the Glen Rose Limestone, Hensell Sand, and Cow Creek Limestone. The Lower Trinity Aquifer is composed of the Sycamore Sand, Sligo Formation, and Hosston Formation. The Middle and Lower Trinity aquifers are separated by the Hammett Shale, which acts as a confining unit and is not explicitly included in the model. The model study area also includes easternmost parts of the Edwards-Trinity (Plateau) Aquifer.

Recharge in the updated model is a combination of infiltration of precipitation that falls on the aquifer outcrop and infiltration from losing intermittent streams within the model area. Estimates of recharge due to infiltration of precipitation in this updated model vary spatially and are equivalent to 3.5 to 5 percent of average annual precipitation. The highest of these recharge rates coincide with the Balcones Fault Zone. In addition to recharge from precipitation, recharge of about 70,000 acre-feet per year results from streamflow losses in the downstream parts of the Cibolo Creek watershed to the underlying aquifers.

Groundwater in the aquifer generally flows toward the south and east. The Hill Country portion of the Trinity Aquifer System discharges naturally as base flow to gaining streams, such as the Guadalupe, Blanco, and Medina rivers, and as cross-formational flow to the adjacent Edwards (Balcones Fault Zone) Aquifer. This cross-formational flow accounts for about 100,000 acre-feet per year of discharge. Pumping discharge from the Hill Country portion of the Trinity Aquifer System increased over the period 1980 through 1997. This increase in pumping is most apparent in Bexar, Hays, Kendall, and Kerr counties—counties adjacent to the two largest metropolitan areas in the region, San Antonio and Austin. In some of these counties pumping has doubled during this period.

The updated model does a good job of reproducing observed water level fluctuations. Comparison of measured and simulated 1997 water levels indicates a mean absolute error of 57 feet, or approximately 5.3 percent of the range of measured water levels. This precision is a slight improvement over that of the original model. Overall, the updated model also does a good job of mimicking base-flow fluctuations. The ability of the model to simulate spring discharge varies widely. Simulating discharge to springs using a regional-scale model is commonly difficult because of spatial and temporal scale issues. Of 17 springs, 6 display a good comparison between measured and simulated discharge values.

The main improvements in the updated model over the original model are due to the addition of the Lower Trinity Aquifer to the model and the revised recharge distribution. The addition of the Lower Trinity Aquifer is important because the Lower Trinity Aquifer is an increasingly important source of groundwater in the study area. The revision of the recharge distribution in the updated model, along with associated changes in the hydraulic conductivity distribution, takes into consideration the major contribution to recharge from Cibolo Creek and will result in better simulation of groundwater flow in Bexar and surrounding counties.

2.0 Introduction

This report describes updates to the earlier developed groundwater availability model for the Hill Country portion of the Trinity Aquifer System by Mace and others (2000). These updates include (1) addition of the Lower Trinity Aquifer to the model, (2) revisions to the model layers' structural geometry, and recharge, hydraulic conductivity, and pumping distribution, and (3) changes to the model calibration periods to bring the model in line with Texas Water Development Board (TWDB) groundwater availability modeling standards that were developed after the earlier model was constructed (http://www.twdb.state.tx.us/gam/gam_documents/GAM_RFQ_Oct2005.pdf).

In this report, we use the term *Trinity Aquifer System.* The term *aquifer system* has not previously been used in TWDB publications but is commonly used by the U.S. Geological Survey, for example, the Edwards-Trinity Aquifer System (Barker and others, 1994), where multiple aquifers are grouped together. In this case, the Hill Country portion of the Trinity Aquifer System is subdivided into the Upper, Middle, and Lower Trinity aquifers.

The Trinity Aquifer System is an important source of groundwater to municipalities, industries, and landowners in the Hill Country. Rapid population growth and recent droughts have increased interest in the Trinity Aquifer System and led to a greater need for quantitative tools to assist in the estimation of groundwater availability in the area. Many groundwater conservation districts and the groundwater management area in the region need to assess the impacts of groundwater pumping and drought on the groundwater resources of the area. Regional water planning groups are required to plan for future water needs under drought conditions and are similarly interested in the groundwater availability of the Hill Country.

Several studies have noted the vulnerability of the Hill Country portion of the Trinity Aquifer System to drought and increased pumping. Ashworth (1983) concluded that heavy pumping is resulting in rapid water level declines in certain areas and that continued growth would result in continued water level declines. Bluntzer (1992), Simpson Company Limited and Guyton and Associates (1993), and Kalaswad and Mills (2000) noted that intense pumping has resulted in water level declines, decreased well yields, increased potential for the encroachment of saline groundwater into the aquifer, and depletion of base flow in nearby streams.

Calibrated groundwater flow models are simplified mathematical representations of groundwater flow systems that can be used to refine and confirm the conceptual understanding of a groundwater flow system. Once the model is successfully calibrated, it can be used as a quantitative tool to investigate the effects of pumping, drought, and different water management scenarios on the groundwater flow system.

In this study, we enhanced and recalibrated the three-dimensional finite-difference groundwater flow model for the Hill Country portion of the Trinity Aquifer System to improve our conceptual understanding of groundwater flow in the region. Our goal was to develop a management tool to support water planning efforts for regional water planning groups, groundwater conservation districts, groundwater management areas, and river authorities in the study area. This report describes the construction and recalibration of the numerical model owing to the addition of the Lower Trinity Aquifer and revisions to recharge, hydraulic conductivity, and pumping distribution in the earlier model.

Our general approach involved (1) revising the conceptual groundwater flow model, (2) organizing and distributing aquifer parameters for the model, (3) calibrating a steady-state model for 1980 water level conditions, and (4) calibrating a transient model for the period 1981 through 1997. This report describes the study area, previous work, the hydrogeologic setting used to develop the conceptual model, and model calibration results.

3.0 Study Area

The study area is located in the Hill Country of south-central Texas and includes all or parts of Bandera, Bexar, Blanco, Comal, Gillespie, Hays, Kendall, Kerr, Kimble, Medina, Travis, and Uvalde counties (Figure 3-1). Hydrologic boundaries define the extent of the study area. These boundaries include (1) major faults of the Balcones Fault Zone in the east and south, (2) presumed groundwater flow paths in the west, and (3) aquifer outcrops and/or rivers in the north (Figure 3-1). Because we selected groundwater flow paths to the west to assign a model boundary, the study area does not include the entire Hill Country area, such as parts of western Bandera and northeastern Uvalde counties, and includes the easternmost parts of the Edwards-Trinity (Plateau) Aquifer System (Ashworth and Hopkins, 1995) in Bandera, Gillespie, Kendall, and Kerr counties (Figure 3-2).

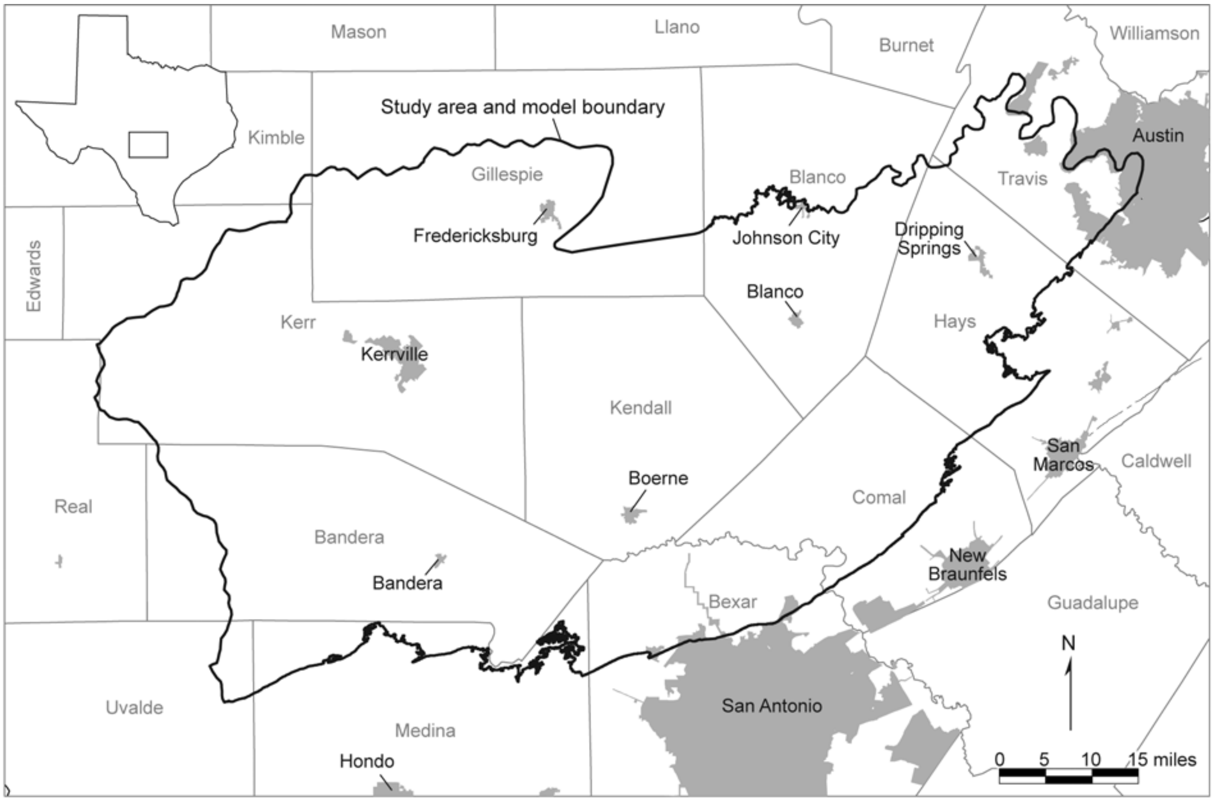


Figure 3-1. Location of the study area relative to major cities and towns (modified from Mace and others, 2000).

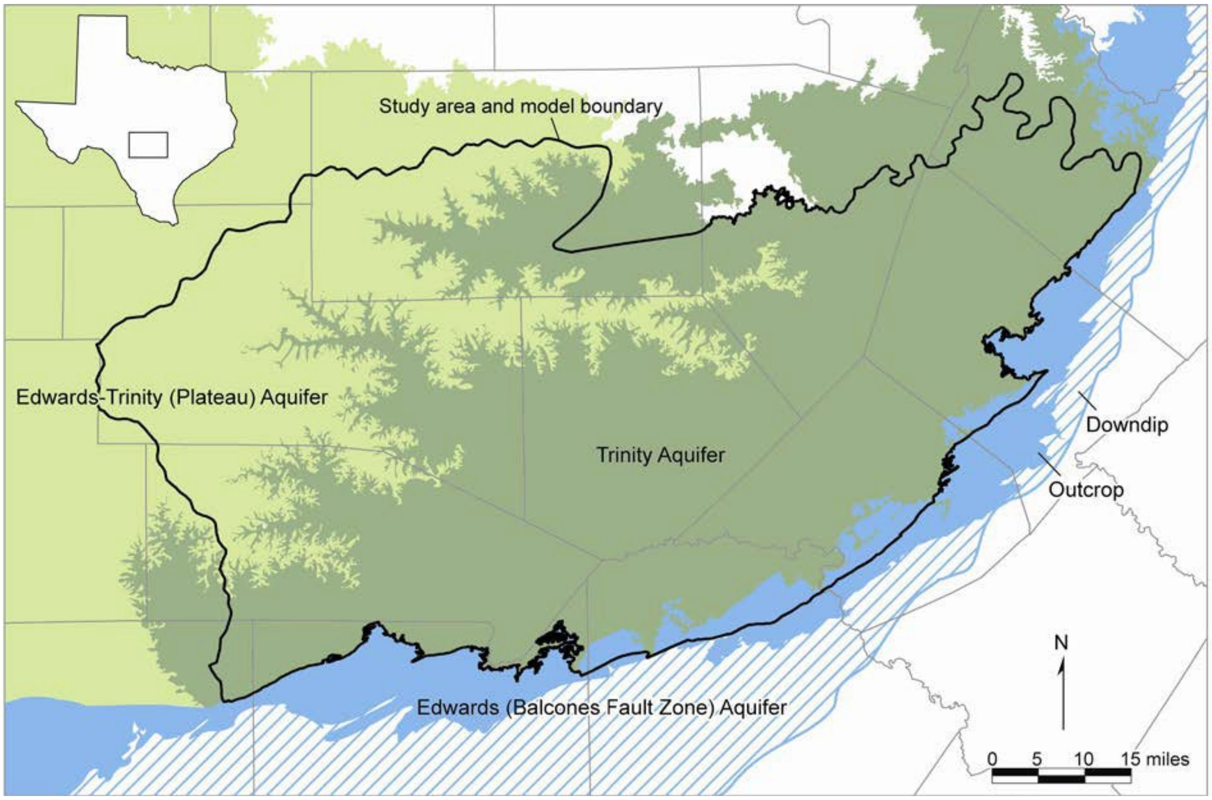


Figure 3-2. Map of outcrop of the major aquifers in the study area. Trinity sediments in the study area include sediments that are part of the Edwards-Trinity (Plateau) Aquifer System to the west and underlie the Edwards (Balcones Fault Zone) Aquifer to the south and east (modified from Mace and others, 2000).

The study area includes parts of three regional water planning areas: the Lower Colorado Region (Region K), the South Central Texas Region (Region L), and the Plateau Region (Region J) (Figure 3-3). The study area includes all or parts of several groundwater conservation districts, including Bandera County River Authority and Groundwater District, Blanco-Pedernales Groundwater Conservation District, Cow Creek Groundwater Conservation District, Edwards Aquifer Authority, Hays Trinity Groundwater Conservation District, Headwaters Groundwater Conservation District, Hill Country Underground Water Conservation District, Kimble County Groundwater Conservation District, Medina County Groundwater Conservation District, Trinity Glen Rose Groundwater Conservation District, and Uvalde County Underground Water Conservation District (Figure 3-4). The study area approximately coincides with Groundwater Management Area 9 (Figure 3-5). The study area also extends over four major river basins—the Colorado, Guadalupe, San Antonio, and Nueces rivers—and five river authorities—the Lower Colorado River Authority (that includes Blanco and Travis counties in the study area), the Guadalupe-Blanco River Authority (that includes Comal, Hays, and Kendall counties in the study area), the Upper Guadalupe River Authority (that includes Kerr County), the Nueces River Authority (that includes Bandera, Medina, and Uvalde counties), and the San Antonio River Authority (that includes Bexar County in the study area) (Figure 3-6).

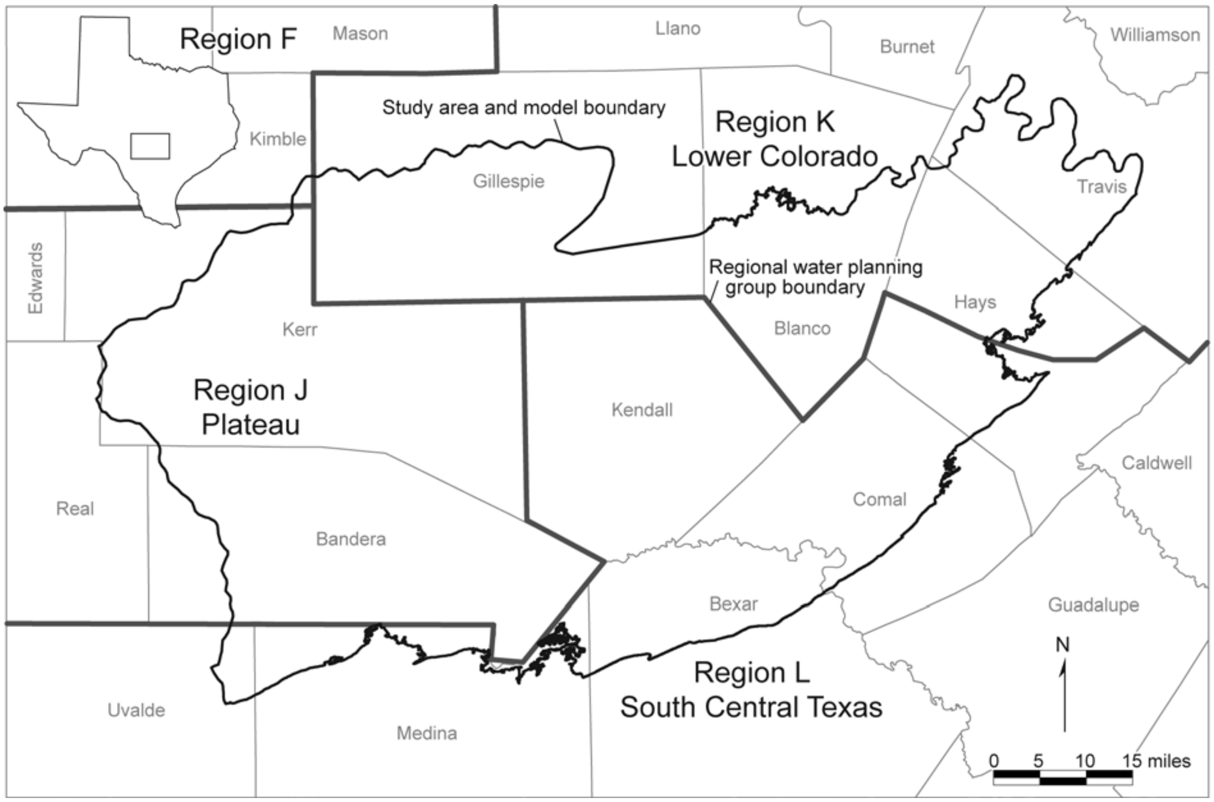


Figure 3-3. Regional water planning groups in the study area (modified from Mace and others, 2000).

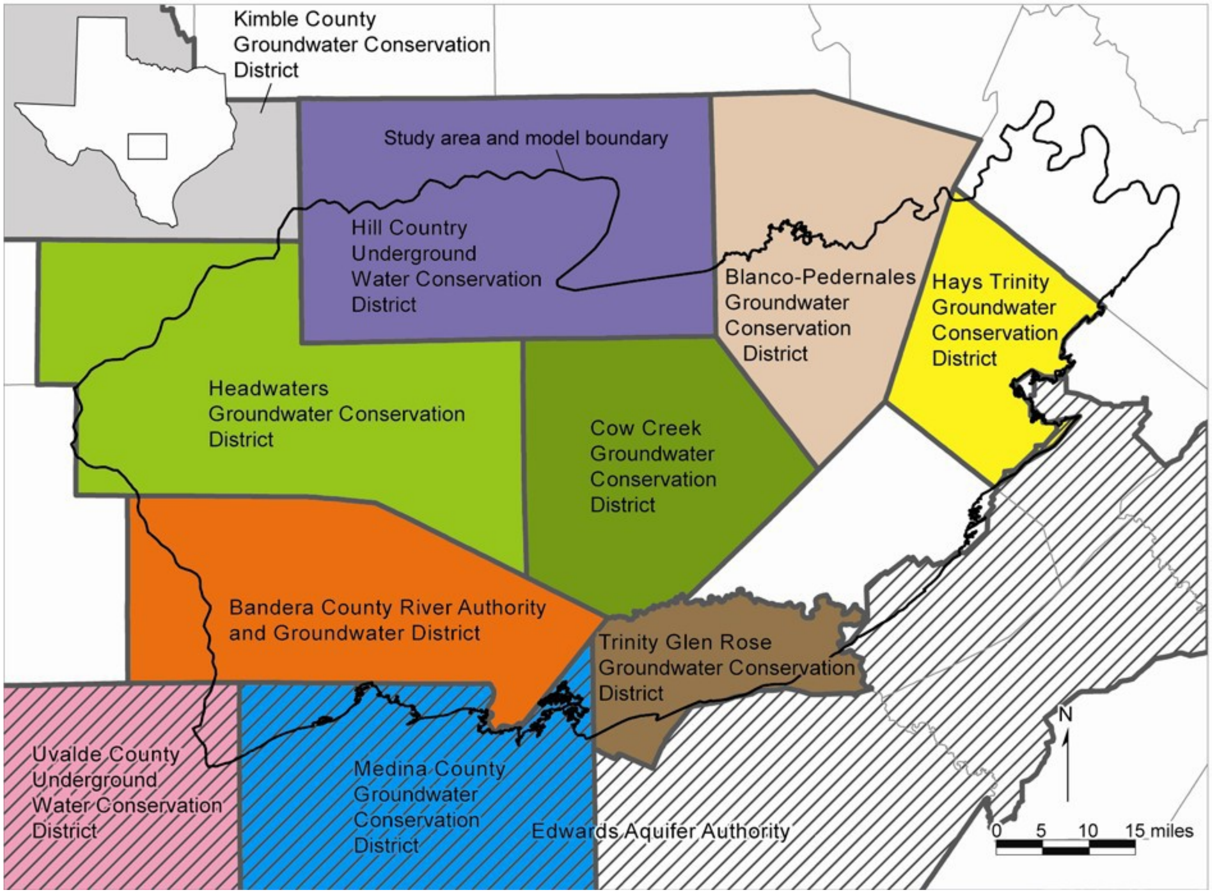


Figure 3-4. **Groundwater conservation districts in the study area as of June 2011 (area with diagonal hatch lines represents the Edwards Aquifer Authority).**

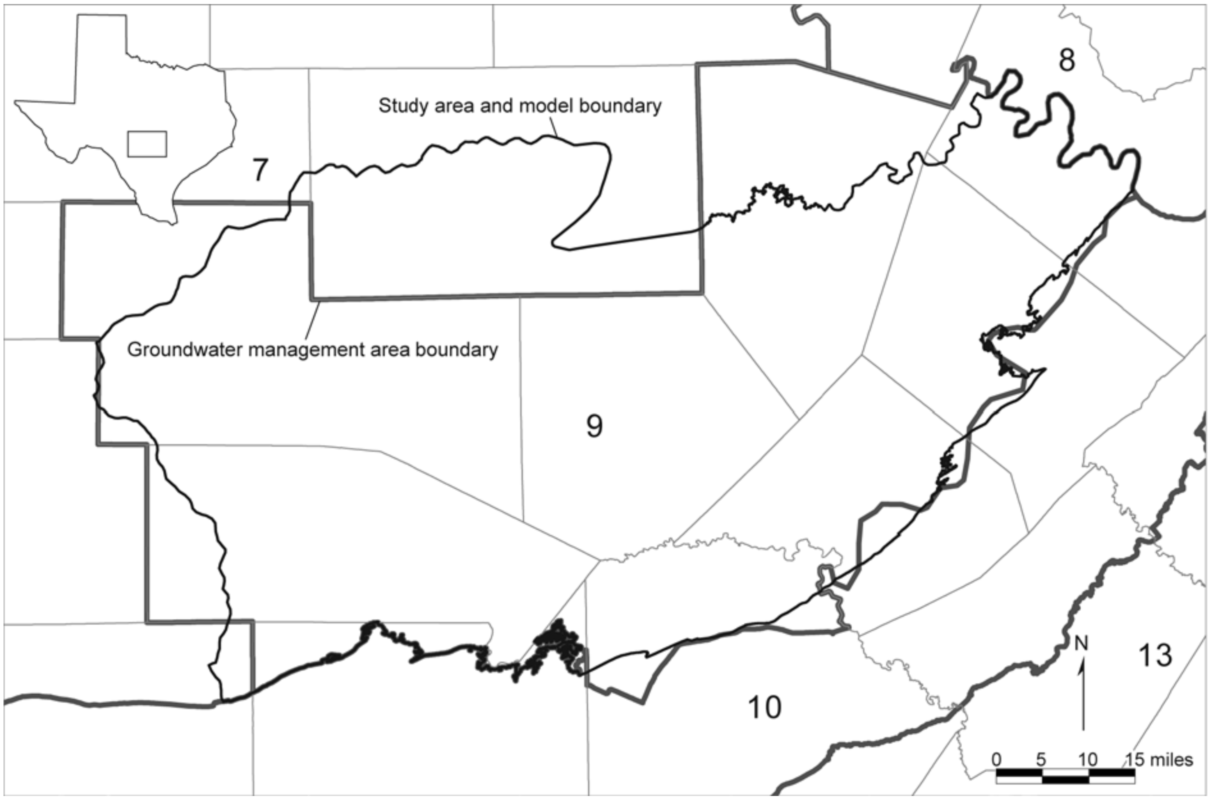
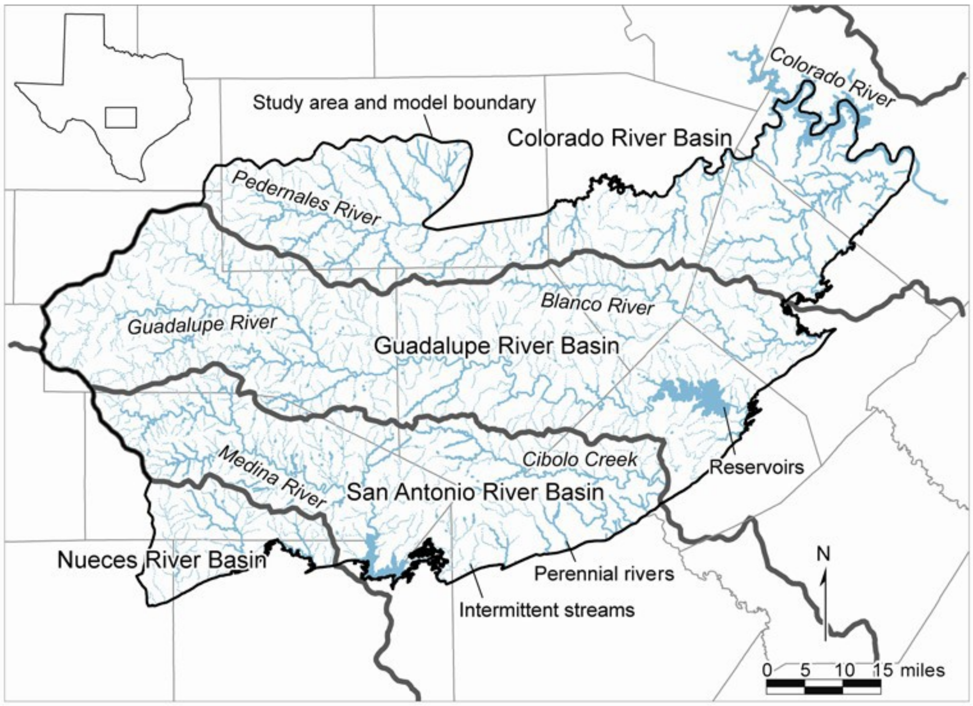
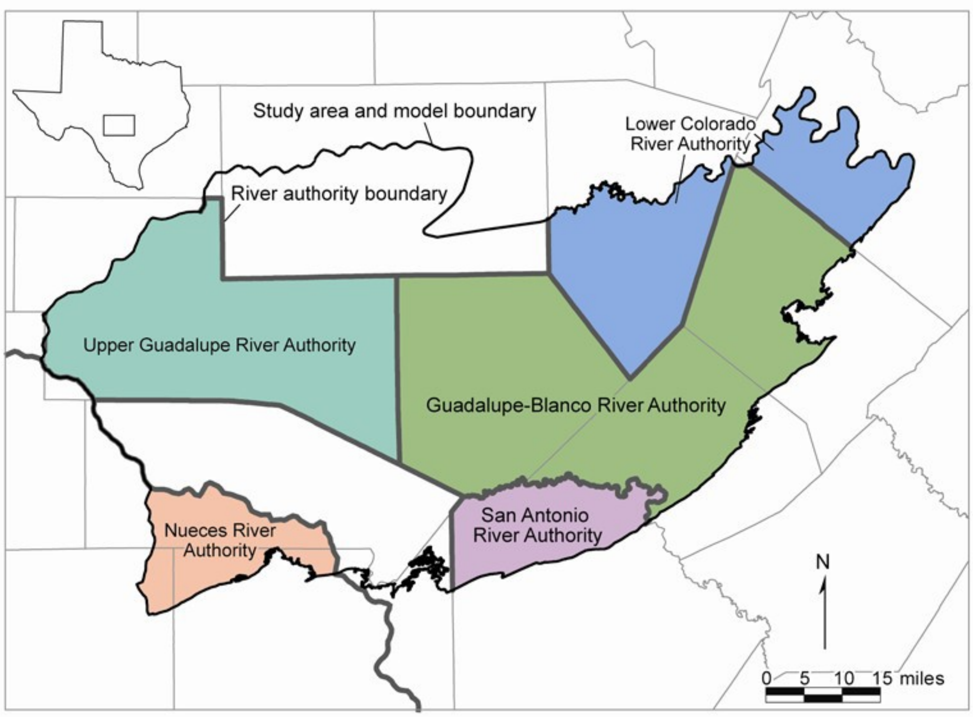


Figure 3-5. Groundwater management areas in the study area.



(a)



(b)

Figure 3-6. (a) Major perennial and intermittent rivers and streams in the study area. (b) River authorities in the study area.

3.1 Physiography and Climate

The study area is located along the southeastern margin of the Edwards Plateau region in a region commonly referred to as the Texas Hill Country (Figure 3-7). The Texas Hill Country is also known as the Balcones Canyonlands subregion, a deeply dissected terrain formed by the headward erosion of major streams between the Edwards Plateau and the Balcones Escarpment (Thornbury, 1965; Riskind and Diamond, 1986). Land surface elevations across the study area range from 2,400 feet above sea level in the west to about 600 feet along the eastern margin of the study area (Figure 3-8).

The more massive and resistant carbonate members of the Edwards Group form the nearly flat uplands of the Edwards Plateau in the west and the topographic divides in the central portion of the study area (Figure 3-7). The differential weathering of alternating beds of limestone and dolostone with soft marl and shale in the upper member of the Glen Rose Limestone forms the characteristic stair-step topography of the Balcones Canyonlands. In general, the upper member of the Glen Rose Limestone is much less resistant to erosion than the overlying Edwards Group caprock.

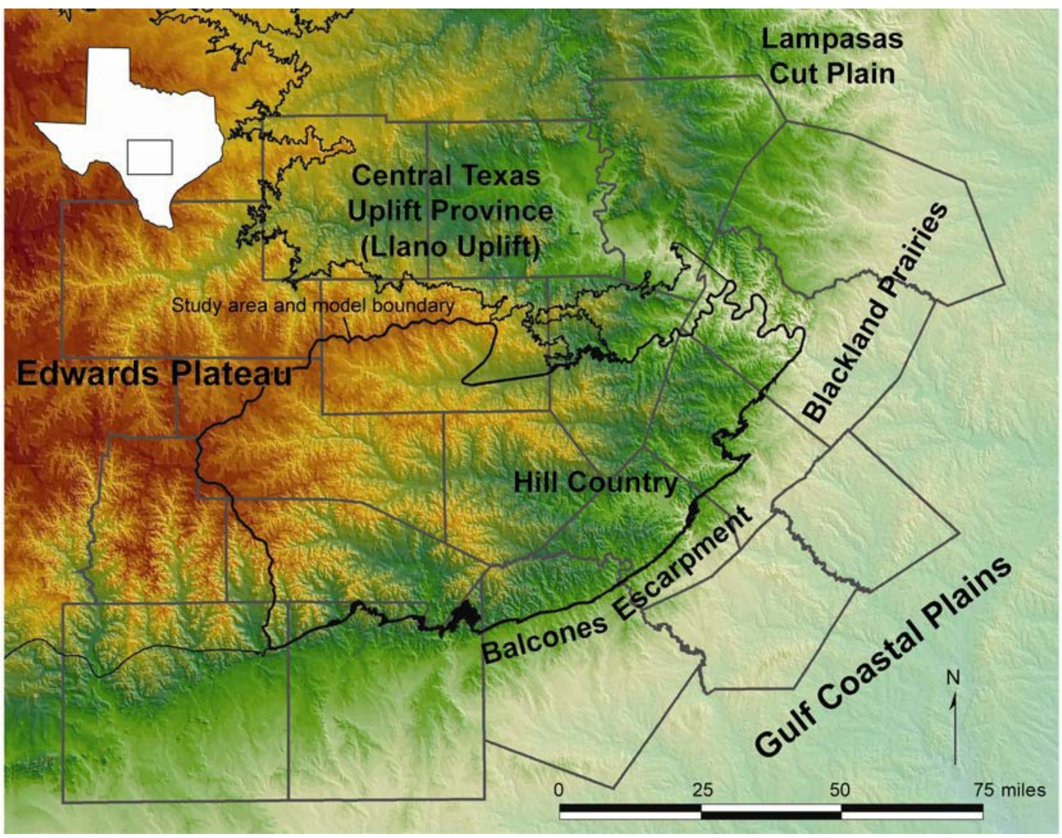


Figure 3-7. Physiographic provinces in the study area (modified from Anaya and Jones, 2009).

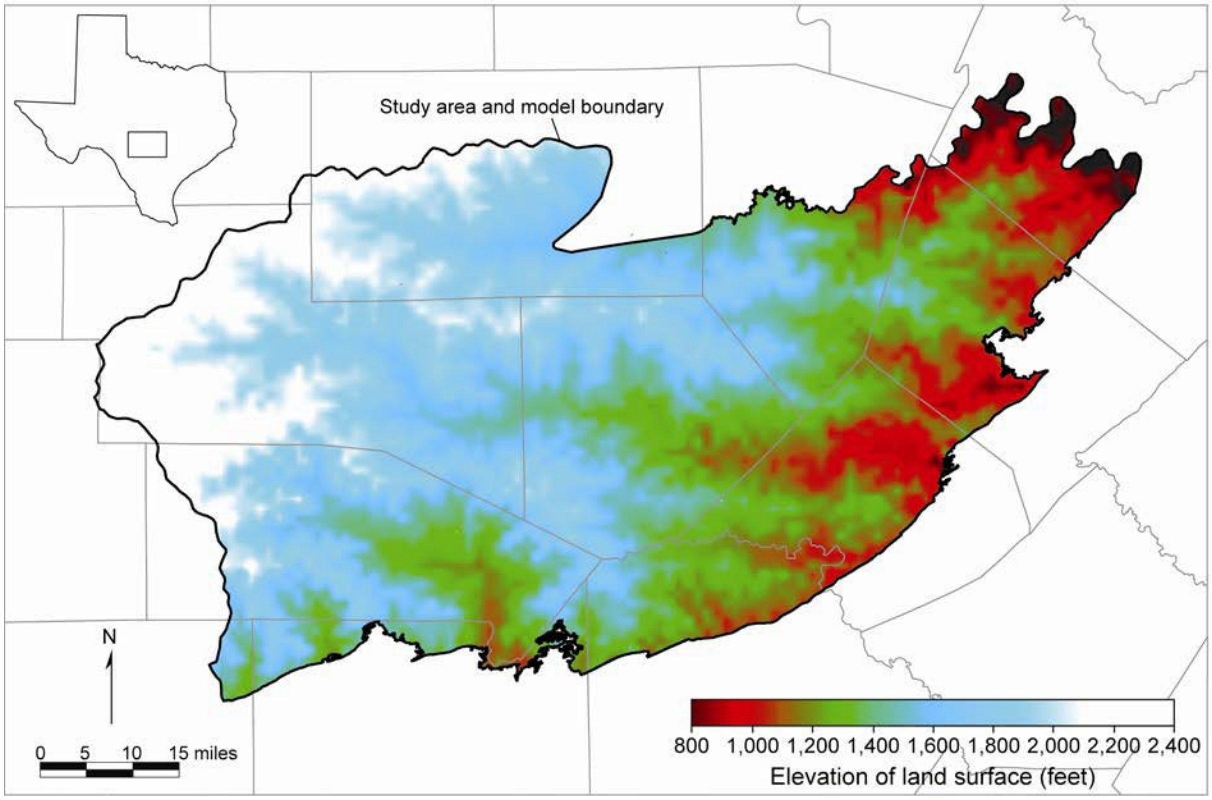


Figure 3-8. Land surface elevation in the study area (modified from Mace and others, 2000).

The study area is characterized by a subhumid to semiarid climate. Average annual precipitation gradually decreases from east to west (35 to 25 inches) owing to increasing distance from the Gulf of Mexico (Carr, 1967) (Figure 3-9). Additionally, local precipitation is highest in the central part of the study area and decreases to the north and south. Historical annual precipitation ranges from less than 10 inches to more than 60 inches (Figure 3-10). Precipitation has a bimodal distribution during the year with most of the rainfall occurring in the spring and fall (Figure 3-11). During the spring, weak cold fronts begin to stall and interact with warm moist air from the Gulf of Mexico. During the summer, sparse rainfall is due to infrequent convectional thunderstorms. In early fall, rainfall is due to more frequent convectional thunderstorms and occasional tropical cyclones that make landfall along the Texas coast. Rainfall frequency continues to increase in late fall as cold fronts once again begin to strengthen and interact with the warm moist air masses of the Gulf of Mexico.

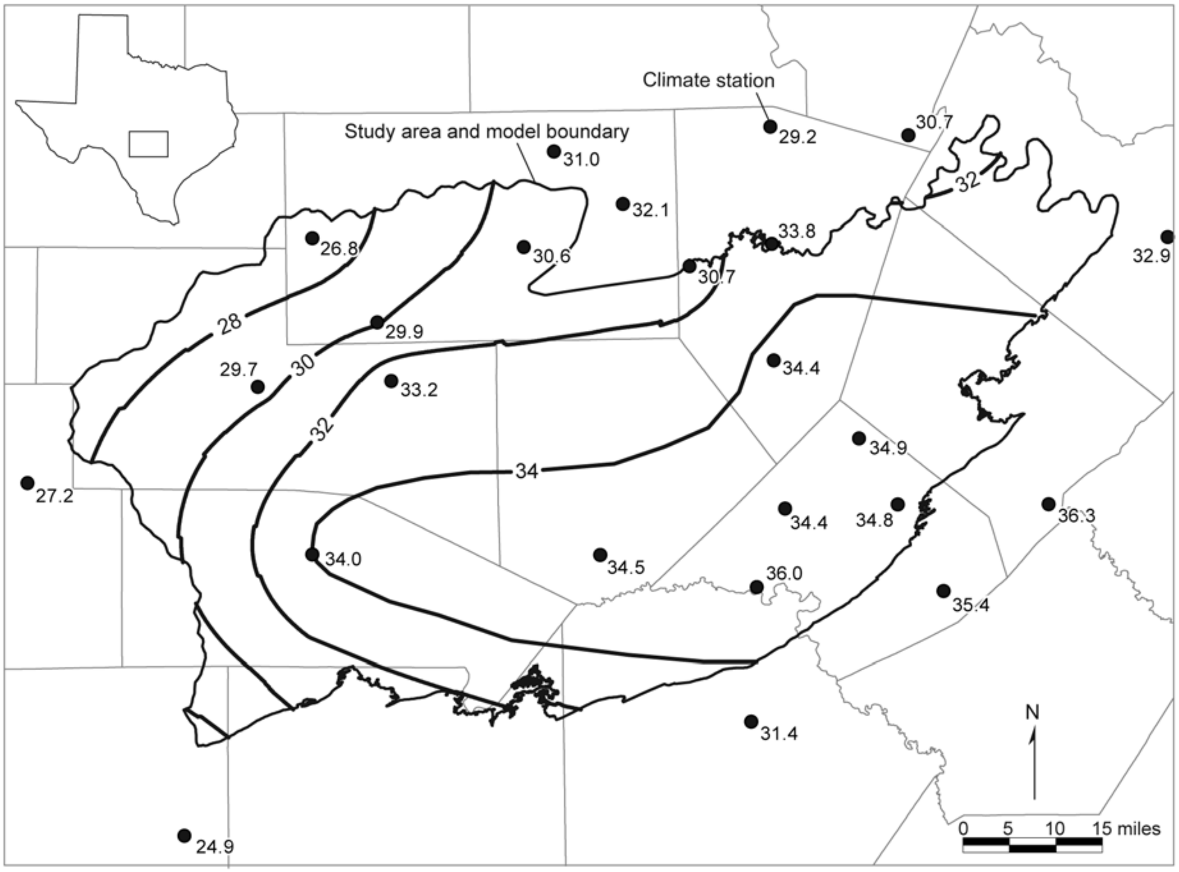


Figure 3-9. **Average annual rainfall distribution for the period 1960 through 1996 (data from National Climate Data Center). Contours represent annual precipitation in inches.**

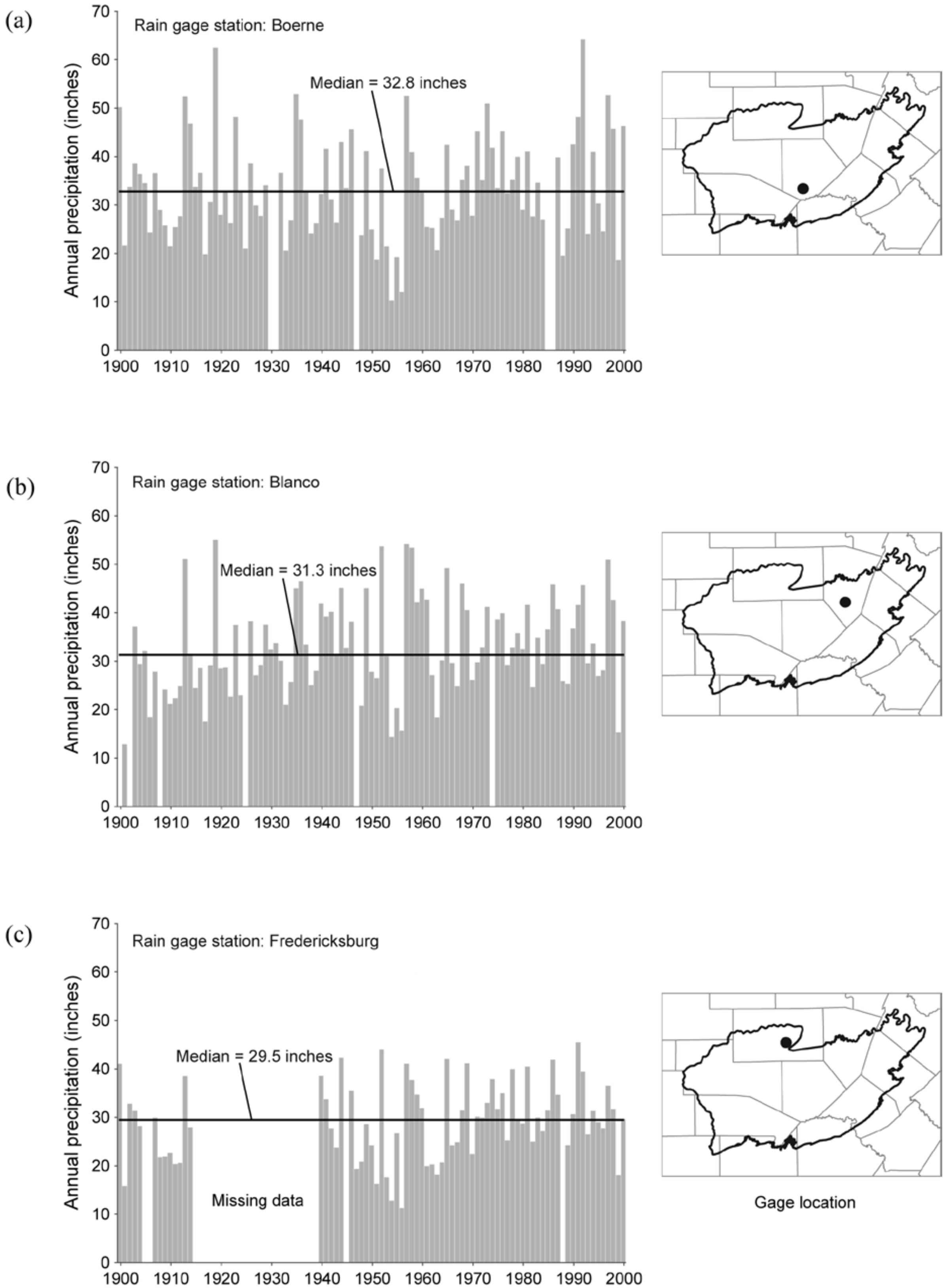


Figure 3-10. **Historical annual precipitation for three rain gage stations in the study area (modified from Mace and others, 2000).**

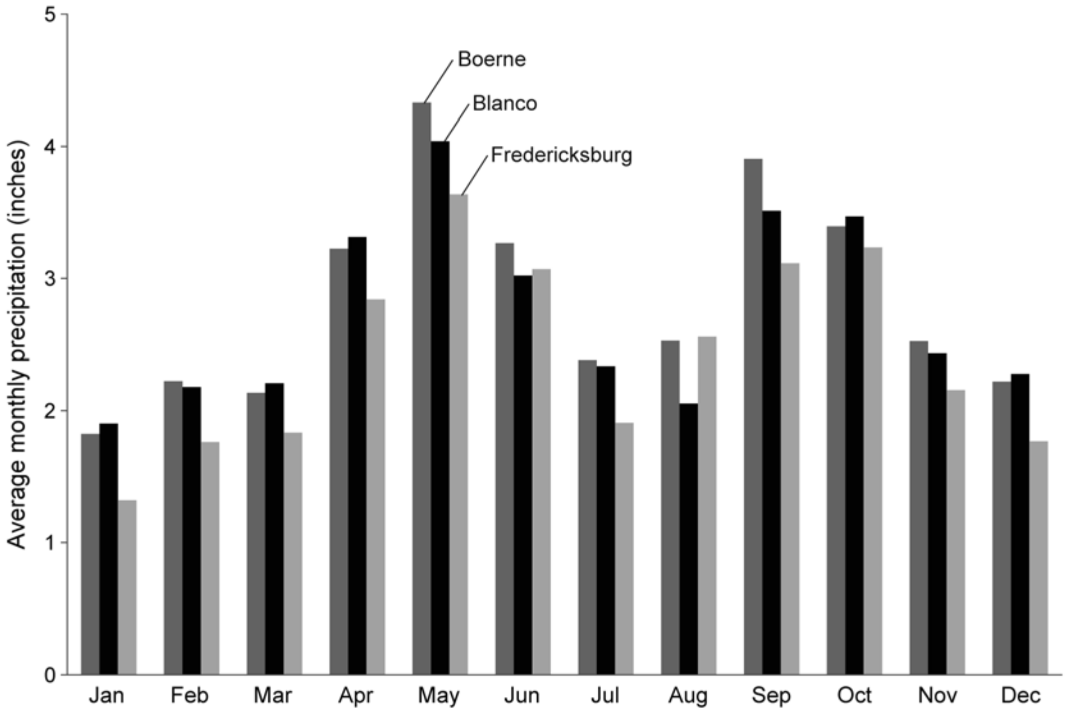


Figure 3-11. Average monthly precipitation for three rain gages in the study area for the period 1960 through 1996 (data from National Climate Data Center).

The average annual maximum temperature ranges from 76°F in the west to 78°F in the east and south (Figure 3-12). Average monthly temperatures range from about 60°F during winter months to about 95°F during summer months (Larkin and Bomar, 1983). The average annual (1950 to 1979) gross lake surface evaporation is more than twice the average annual precipitation and ranges from 63 inches in the east to 68 inches in the west (Figure 3-13). Seasonally, average monthly gross lake surface evaporation ranges from about 2.5 inches during winter months to more than 9 inches during summer months (Larkin and Bomar, 1983).

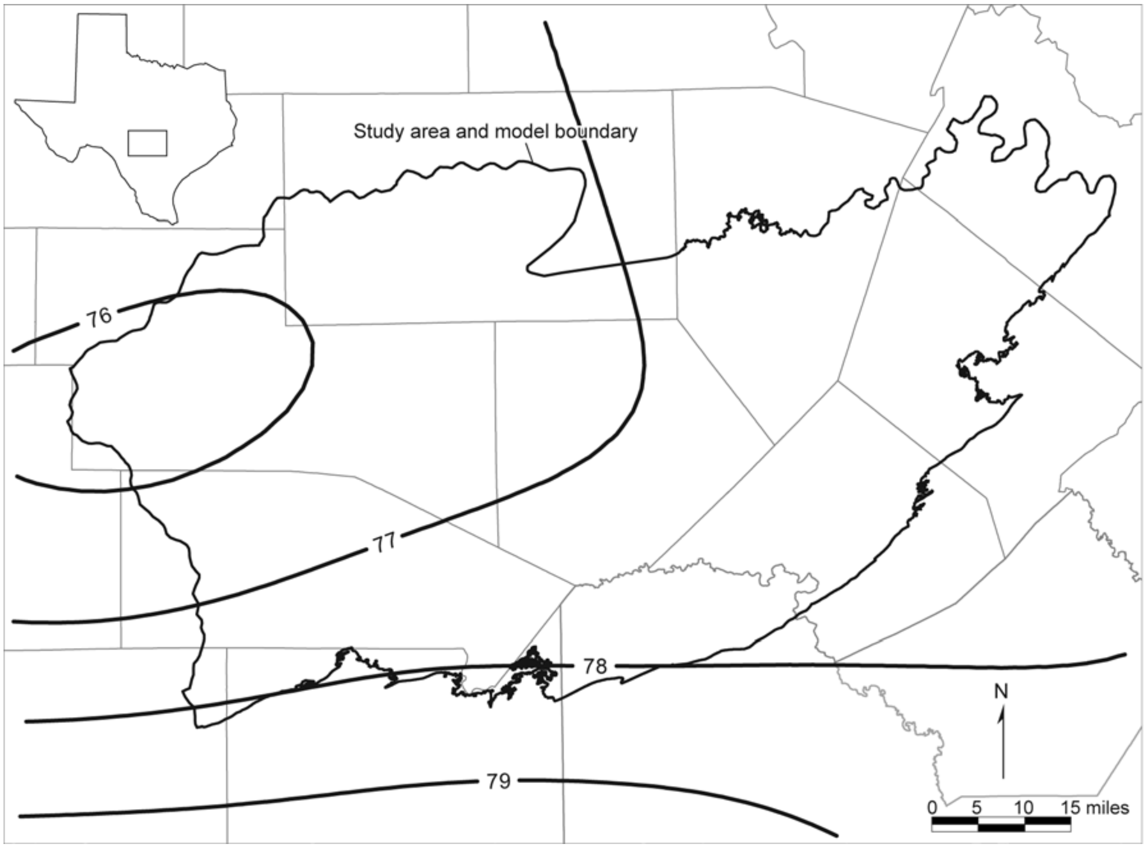


Figure 3-12. **Average annual maximum temperature for 1971 through 2000. The contours are expressed in degrees Fahrenheit (modified from data from Spatial Climate Analysis Service, 2004).**

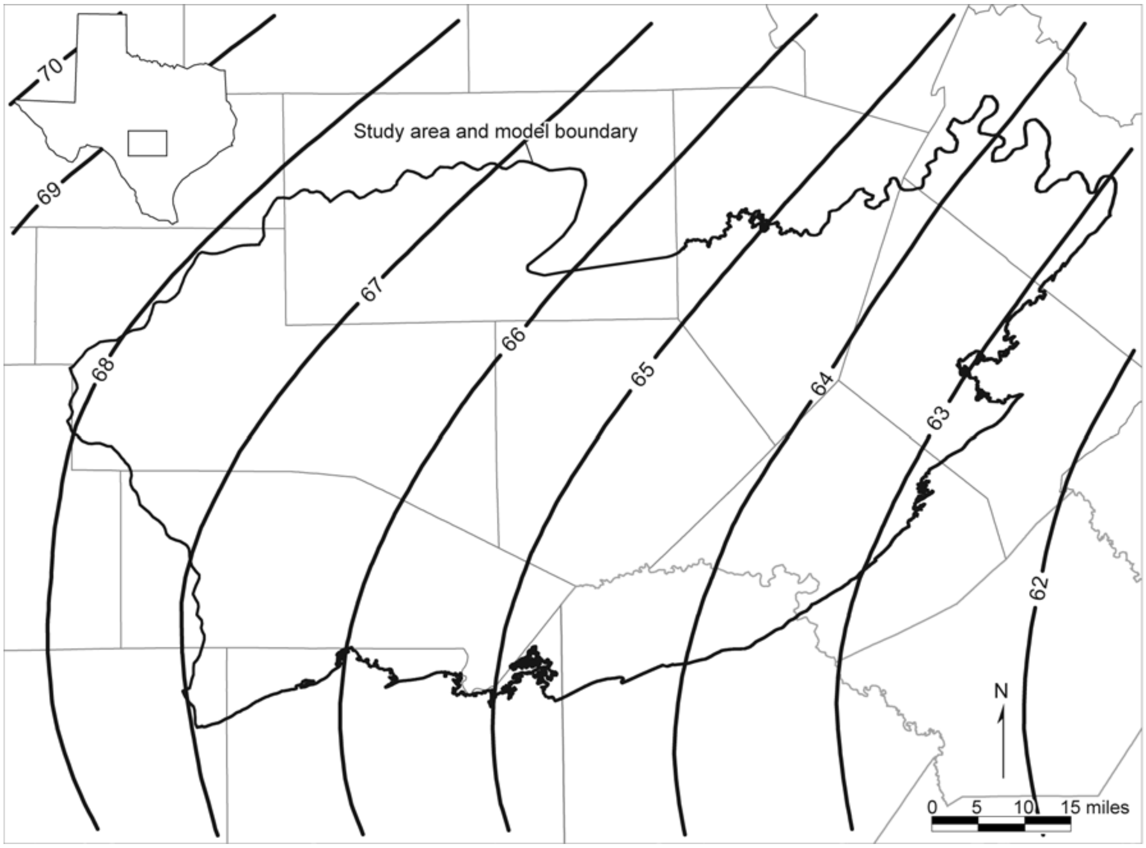


Figure 3-13. Average annual gross lake evaporation for 1950 through 1979. Contours are expressed in inches (modified from Larkin and Bomar, 1983).

3.2 Geology

Lower Cretaceous rocks of the Trinity Group that compose the Hill Country portion of the Trinity Aquifer System unconformably overlie Paleozoic rocks in the study area (Figure 3-14). These Lower Cretaceous rocks consist of (from oldest to youngest) the Hosston Formation (known as Sycamore Sand where it crops out at the surface), Sligo Formation, Hammett Shale, Cow Creek Limestone, Hensell Sand, lower and upper members of the Glen Rose Limestone, and the Fort Terrett and Segovia Formations of the Edwards Group (Figure 3-14). The Trinity Group sediments are locally covered by Quaternary alluvium along streams and rivers and capped by Edwards Group sediments in the west.

Era	System	Group	Stratigraphic unit		Hydrologic unit	
Cenozoic	Quaternary		Alluvium		Alluvium	
Mesozoic	Cretaceous	Edwards	Segovia Formation		Edwards Group	
			Fort Terrett Formation			
		Trinity	Glen Rose Limestone	Upper Member	Trinity Aquifer System	Upper Trinity
				Lower Member		Middle Trinity
			Hensell Sand/Bexar Shale			
			Cow Creek Limestone			
			Hammett Shale			Confining unit
			Sligo Formation			Lower Trinity
			Sycamore Sand/Hosston Formation			
Paleozoic			Undifferentiated Pre-Cretaceous rock			

Figure 3-14. Stratigraphic and hydrostratigraphic column of the Hill Country area.

The stratigraphic units of the Hill Country portion of the Trinity Aquifer System were deposited during a period of rifting and subsidence in the ancestral Gulf of Mexico (Barker and others, 1994). These units were deposited on the landward margin of a broad continental shelf under shallow marine conditions. The Llano Uplift was a dominant structural high, forming islands of Precambrian metamorphic and igneous rock and Paleozoic sedimentary rock that were sources of terrigenous sediment occurring in the Trinity Group (Figure 3-15).

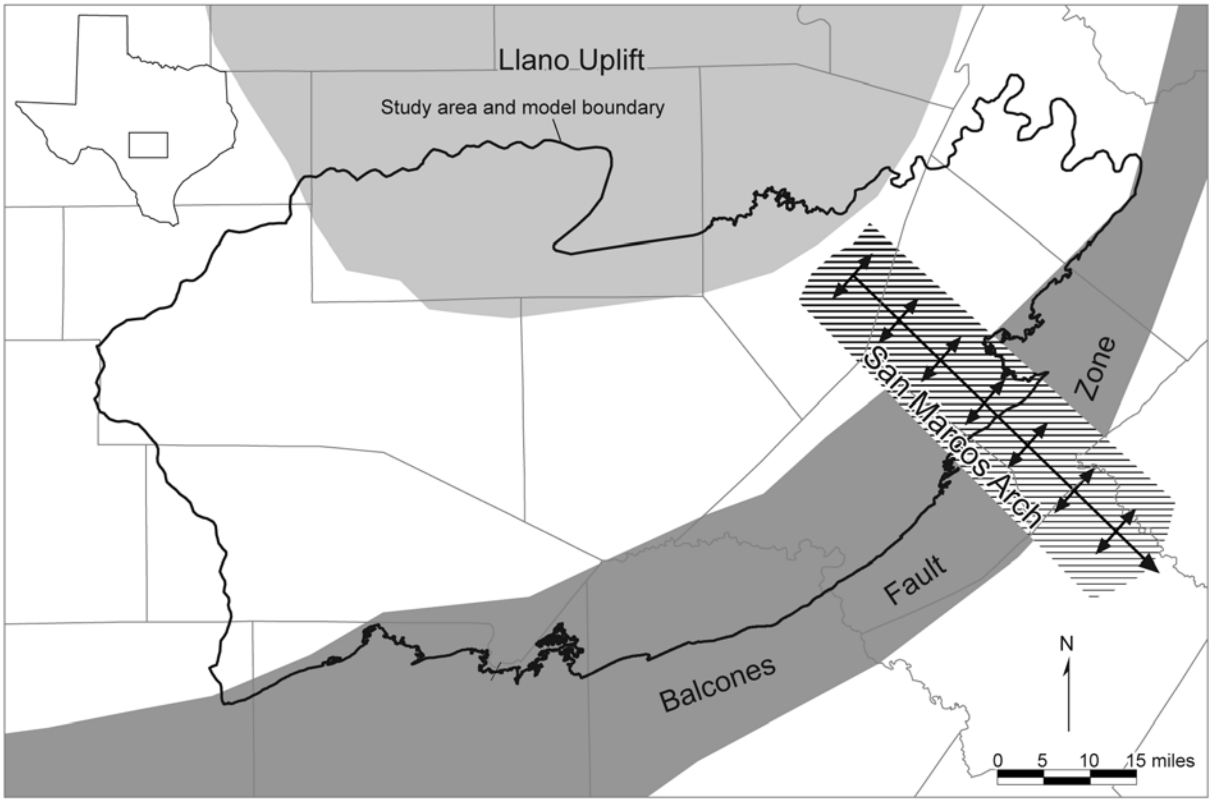


Figure 3-15. Main geologic structures in the study area (modified from Mace and others, 2000).

The Hosston Formation is dominantly composed of siliciclastic siltstone and sandstone in updip areas and dolomitic mudstone and grainstone downdip derived from the Llano Uplift (Barker and others, 1994). This formation, which is as much as 900 feet thick, grades upward into the Sligo Formation and where it is exposed at the surface is known as the Sycamore Sand. The Sycamore Sand is composed of quartz sand and gravel as much as 50 feet thick (Barker and others, 1994). The Sycamore Sand also contains some feldspar and dolomite derived from the Llano Uplift.

The Sligo Formation is composed of as much as 250 feet of evaporites, limestone, and dolostone (Barker and others, 1994). The evaporites were deposited in a supratidal environment, whereas the limestone and dolostone were deposited in an intertidal environment. In the updip regions, the Sligo Formation sediments display a greater contribution of terrestrial sediments from the Llano Uplift (Barker and others, 1994).

The Hammett Shale is highly burrowed and is made up of mixed clay, silt, and calcareous mud as much as 130 feet thick (Barker and others, 1994). This stratigraphic unit interfingers vertically with the overlying Cow Creek Limestone.

The Cow Creek Limestone, a beach deposit on the southern flank of the Llano Uplift, is as much as 90 feet thick (Barker and others, 1994). The lower part of the Cow Creek Limestone is composed of fine- to coarse-grained calcareous sandstone. The middle part of the Cow Creek Limestone is composed of silty calcareous sandstone, and the upper part is composed of coarse-grained fossiliferous calcareous sandstone with poorly sorted quartz grains and chert pebbles.

The Hensell Sand crops out in the northern part of the study area in Gillespie County (Figure 3-16). The Hensell Sand is composed of poorly cemented clay, quartz, and calcareous sand and chert and dolomite gravel as much as 200 feet thick (Barker and others, 1994). The gravel beds occur at the base of this stratigraphic unit. The shallow marine deposits of the Bexar Shale Member of the Pearsall Formation are the downdip equivalent of the Hensell Sand (Barker and others, 1994).

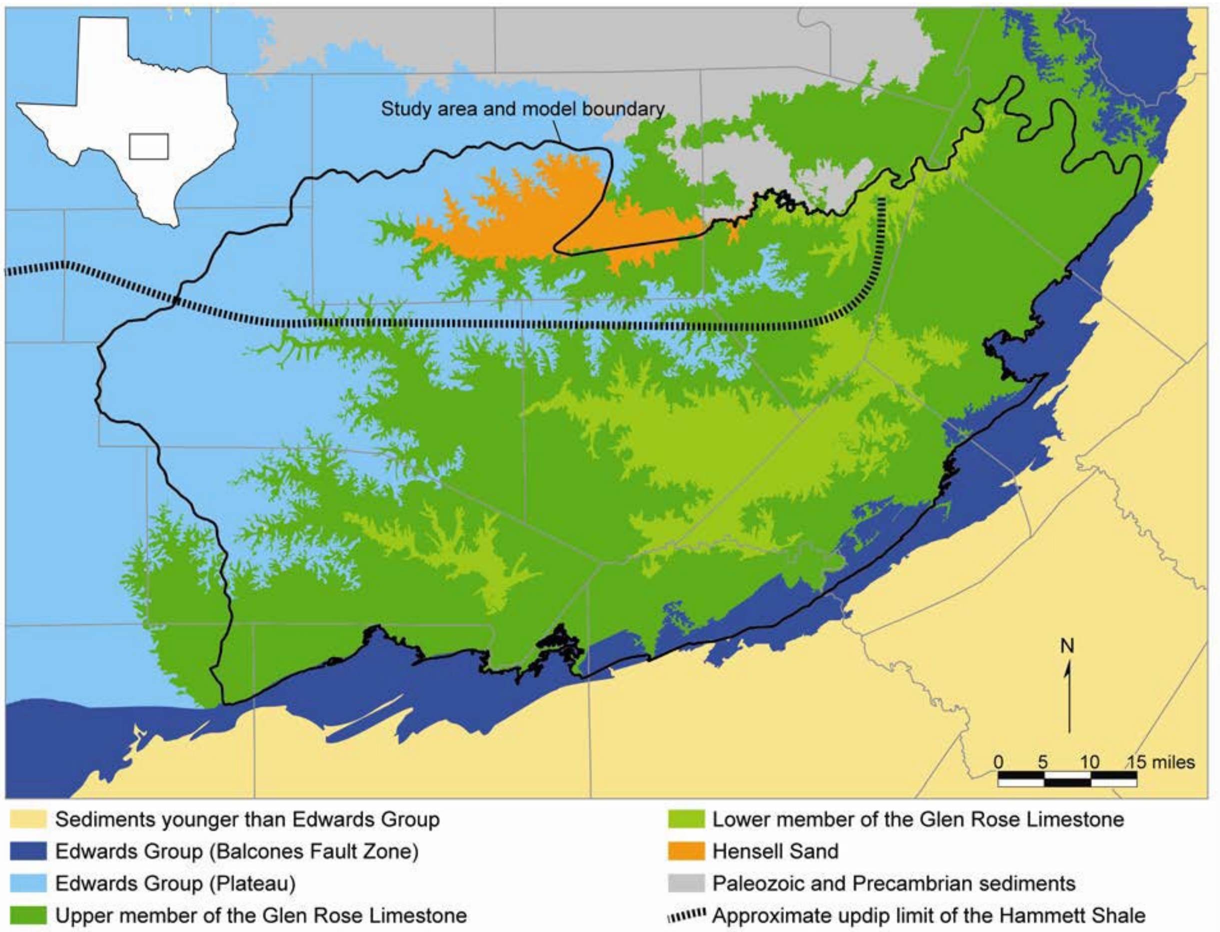


Figure 3-16. Surface geology of the study area (modified from Mace and others, 2000). Please note that this map excludes isolated outliers of the Edwards Group that overlie the upper member of the Glen Rose Limestone, some of which are included in the original and updated models. Approximate updip limit of Hammett Shale is modified from Amsbury (1974) and Barker and others (1994).

The Glen Rose Limestone is composed of sandy fossiliferous limestone and dolostone that are characterized by beds of calcareous marl, clay, and shale and include thin layers of gypsum and anhydrite (Barker and others, 1994). The Glen Rose Limestone has a maximum thickness of 1,500 feet. The lower member of the Glen Rose Limestone is composed of medium-thick beds of limestone, dolostone, and fossiliferous dolomitic limestone (Barker and others, 1994). The Glen Rose Limestone was deposited in a shallow marine to intertidal environment and grades northward into the terrestrial Hensell Sand. The upper member of the Glen Rose Limestone is exposed at land surface in most of the study area except where it is (1) removed by erosion exposing the lower member of the Glen Rose Limestone and (2) overlain by the Edwards Group in the Edwards Plateau to the west and in the Balcones Fault Zone to the south and east (Figure 3-16). The upper member of the Glen Rose Limestone is characterized by a thin- to medium-bedded sequence of alternating nonresistant marl and resistant limestone and dolostone. The alternating layers of resistant and nonresistant rock result in uneven erosion that produces the stair-step topography characteristic of much of the Hill Country.

The basal parts of the Hosston Formation, the Sycamore Sand, and updip parts of the Hensell Sand are mostly sandy and contain some of the most permeable sediments in the Hill Country portion of the Trinity Aquifer System (Barker and others, 1994). The Cow Creek Limestone is highly permeable in the outcrop owing to carbonate dissolution and preservation of the pores but has relatively low permeability in the subsurface owing to precipitation of calcite cements (Barker and others, 1994). Similarly, the lower member of the Glen Rose Limestone is more permeable in the outcrop than at depth (Barker and others, 1994). The Sligo Formation may yield small to large quantities of water (Ashworth, 1983).

The Lower Trinity Aquifer is not exposed at land surface within the study area and exists only in the southern half of the study area (Figures 3-14 and 3-16). The study area is completely underlain by sediments of the Middle Trinity Aquifer. The Upper Trinity Aquifer exists in most of the study area except where it has been removed by erosion along and near the lower reaches of the Pedernales, Blanco, Guadalupe, Cibolo, and Medina rivers (Figure 3-16). In the western part of the study area, the Fort Terrett and Segovia formations of the Edwards Group (Figure 3-16) cap the Trinity Aquifer sediments. The Edwards Group may produce large amounts of water where it is saturated and has high transmissivity.

The Llano Uplift is a regional dome formed by a massive Precambrian granitic pluton (Figure 3-15). The Llano Uplift remained a structural high throughout the Ouachita Orogeny that folded and uplifted the Paleozoic rocks of this area and provided a source of sediments for terrigenous and near-shore facies of the Trinity Group (Ashworth, 1983; Barker and others, 1994). The San Marcos Arch is a broad anticlinal (upward-folded ridge) extension of the Llano Uplift with a southeast-plunging axis. The San Marcos Arch extends through central Blanco and southwest Hays counties (Ashworth, 1983) (Figure 3-15). This arch contributed to the formation of a carbonate platform with thinning sediments along the anticlinal axis. The Balcones Fault Zone is a northeast-southwest-trending system of high-angle normal faults with downthrown blocks toward the Gulf of Mexico (Figure 3-15). The faulting occurred along the subsurface axis of the Ouachita Fold Belt as a result of extensional forces created by the subsidence of basin sediments in the Gulf of Mexico during the Tertiary Period. The last episode of movement in the fault zone is thought to have occurred in the late Early Miocene, approximately 15 million years ago (Young, 1972). The Balcones Fault Zone is a structural feature that laterally juxtaposes Trinity Group sediments against Edwards Group sediments of the Edwards (Balcones Fault Zone) Aquifer (Figures 3-15 and 3-17).

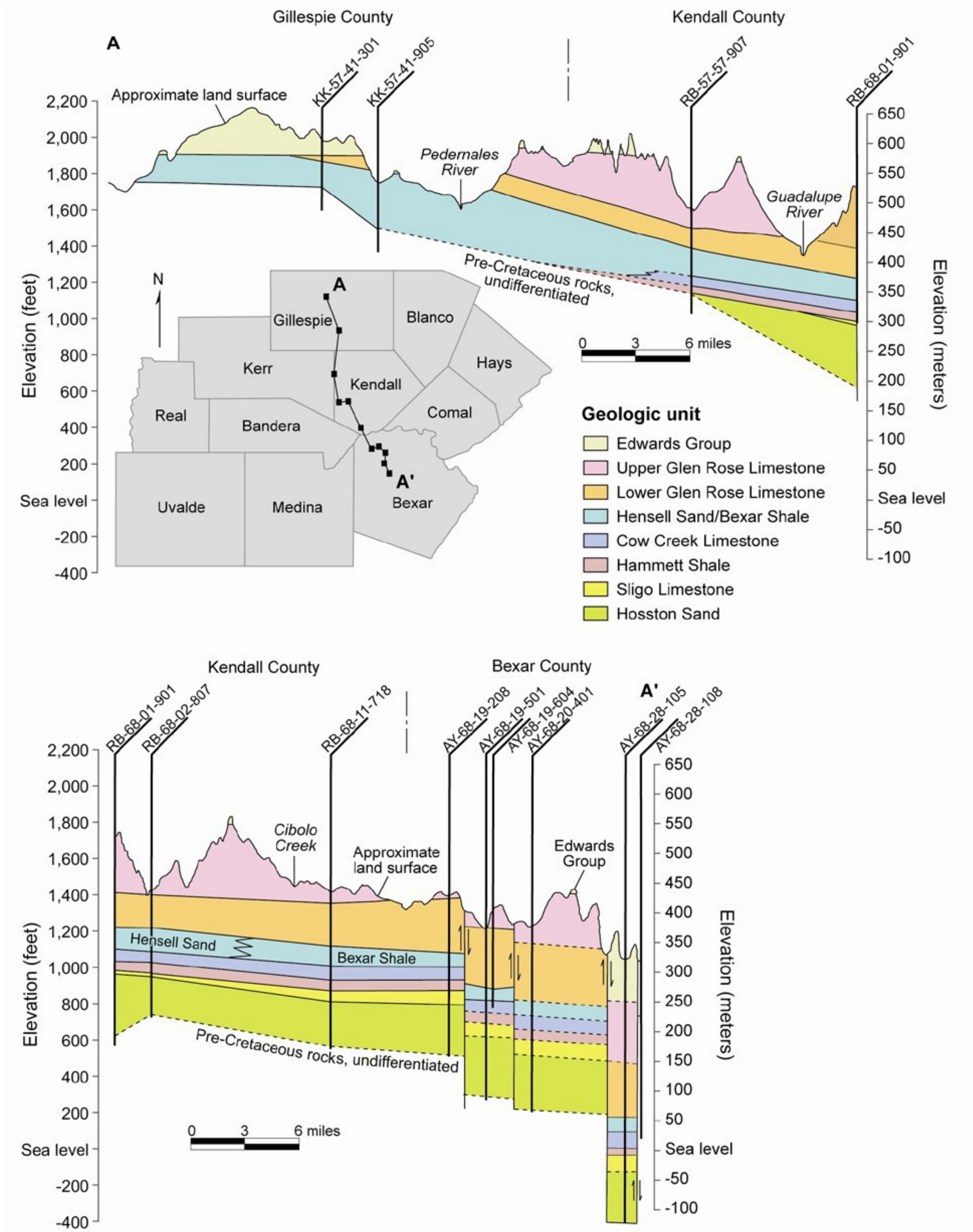


Figure 3-17. **Geologic cross sections through the study area (modified from Ashworth, 1983; Mace and others, 2000). Inset map shows cross-section line A-A´.**

The structural geometry of Lower Cretaceous sediments in the study area is characterized by (1) a southeast regional dip, (2) an uneven base of the Trinity Group, and (3) the occurrence of the San Marcos Arch in the southeast, Llano Uplift to the north, and Balcones Fault Zone to the south and east (Figures 3-15 and 3-17). Both Trinity Group and Edwards Group sediments have a regional dip to the south and southeast. The dip increases from a rate of about 10 to 15 feet per mile near the Llano Uplift to about 100 feet per mile near the Balcones Fault Zone (Ashworth, 1983). These Lower Cretaceous sediments may be described as a series of stacked wedges that pinch out against the Llano Uplift and thicken downdip toward the Gulf of Mexico (Figure 3-17). At the base of the Trinity Group sediments, underlying Paleozoic rocks have been moderately folded, uplifted, and eroded to form an unconformable surface upon which the Trinity Group sediments were deposited (Figure 3-17). Along the northern margin of the study area, the Middle and Upper Trinity sediments directly overlie Paleozoic and Precambrian rocks (Figure3-17).

4.0 Previous Work

The TWDB and the U.S. Geological Survey have conducted a number of hydrogeologic studies in the Hill Country area. Ashworth (1983), Bluntzer (1992), and Barker and others (1994) provided a thorough review of much of the previous geologic and hydrogeologic work done in the area.

A regional numerical groundwater flow model was developed and published for the area by the U.S. Geological Survey (Kuniansky and Holligan, 1994). Besides the Trinity Aquifer in the Hill Country, this U.S. Geological Survey model includes the Edwards-Trinity (Plateau) and Edwards (Balcones Fault Zone) aquifers and extends almost 400 miles across the state (Figure 4-1). The purpose of the U.S. Geological Survey model was to better understand and describe the regional groundwater flow system. Using the model, Kuniansky and Holligan (1994) defined transmissivity ranges, estimated total flow through and recharge to the aquifer system, and simulated groundwater flow from the Trinity Aquifer into the Edwards (Balcones Fault Zone) Aquifer. The two-dimensional, finite-element, steady-state model was developed as the simplest approximation of the regional flow system. The U.S. Geological Survey model is inappropriate for regional water planning because (1) it does not simulate water level changes with time, and (2) it simulates all aquifers in the study area as a single layer. Subsequently, Anaya and Jones (2009) developed a transient finite-difference model covering a study area similar to that used in the model by Kuniansky and Holligan (1994). The model by Anaya and Jones (2009) simulates the Trinity Aquifer System as a single layer (Figure 4-1).

The TWDB developed a regional transient groundwater flow model for the Hill Country area of the Trinity Aquifer (Mace and others, 2000) (Figure 4-1). Mace and others (2000) calibrated this model to 1975 steady-state conditions and 1996 through 1997 transient conditions. This model simulates groundwater flow through the Edwards Group and the Upper and Middle Trinity aquifers. Our updated model includes the Lower Trinity Aquifer previously excluded from the model by Mace and others (2000).

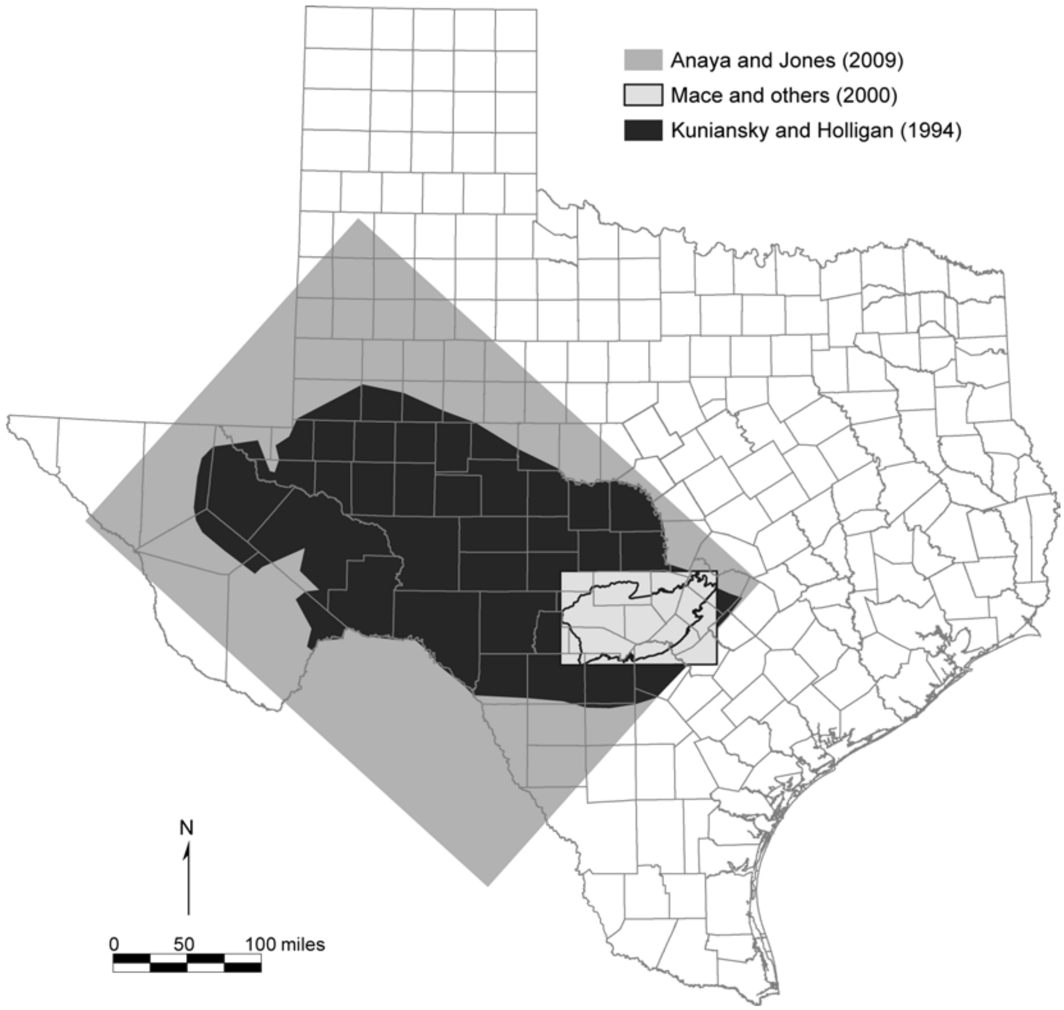


Figure 4-1. **Approximate extents of previous model grids for models used for simulating groundwater flow through the study area.**

5.0 Hydrogeologic Setting

The hydrogeologic setting describes the aquifer, hydrologic features, and hydraulic properties that influence groundwater flow in the aquifer. We based the hydrogeologic setting for the Hill Country portion of the Trinity Aquifer System on previous work (for example, Ashworth, 1983; Bluntzer, 1992; Barker and others, 1994; Kuniansky and Holligan, 1994) and additional studies we conducted in support of the modeling effort (Mace and others, 2000). These additional studies included assembling structure maps, developing water level maps and hydrographs, estimating base flow to streams, investigating recharge rates, conducting aquifer tests, and assembling pumping information.

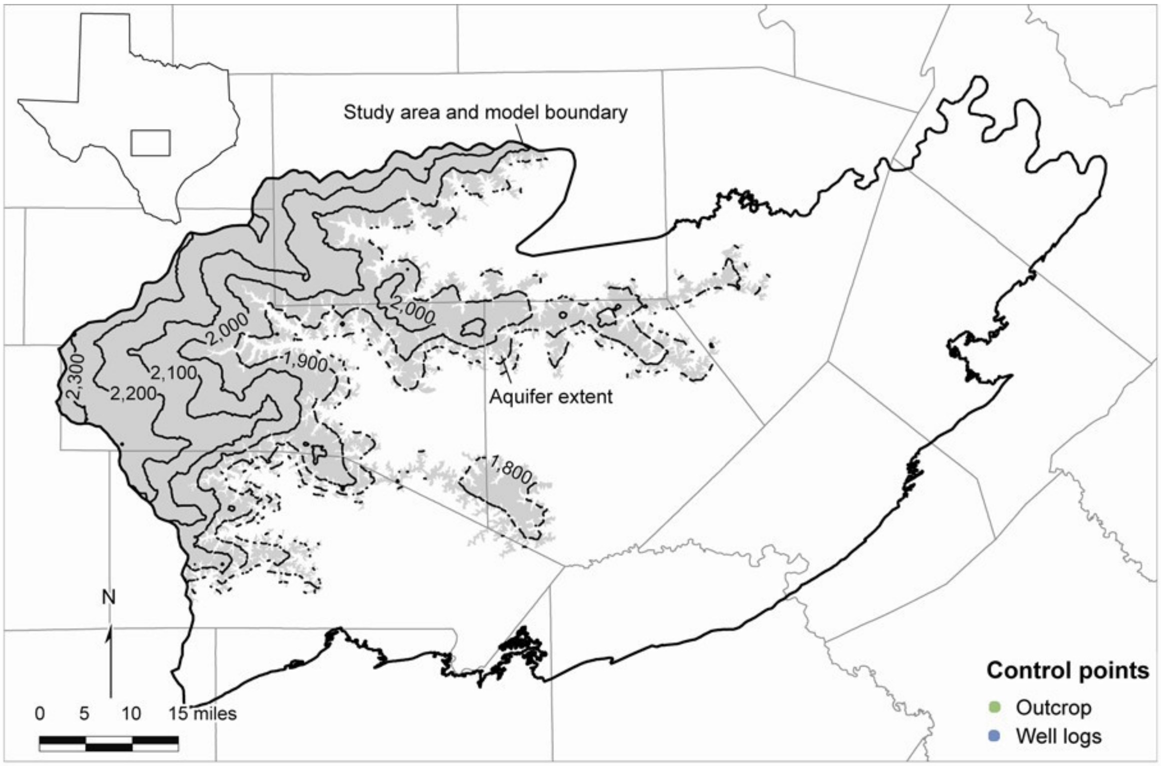
5.1 Hydrostratigraphy

The Hill Country portion of the Trinity Aquifer System comprises sediments of the Trinity Group and is divided into lower, middle, and upper aquifers (Figure 3-14) on the basis of hydraulic characteristics of the sediments (Barker and others, 1994). The Lower Trinity Aquifer consists of the Hosston (and the Sycamore Sand in outcrop) and Sligo formations; the Middle Trinity Aquifer consists of the Cow Creek Limestone, the Hensell Sand, and the lower member of the Glen Rose Limestone; and the Upper Trinity Aquifer consists of the upper member of the Glen Rose Limestone. Low-permeability sediments throughout the upper member of the Glen Rose Limestone separate the Middle and Upper Trinity aquifers. The Lower and Middle Trinity aquifers are separated by the low-permeability Hammett Shale, except where the Hammett Shale pinches out in the northern part of the study area (Amsbury, 1974; Barker and Ardis, 1996) (Figure 3-16).

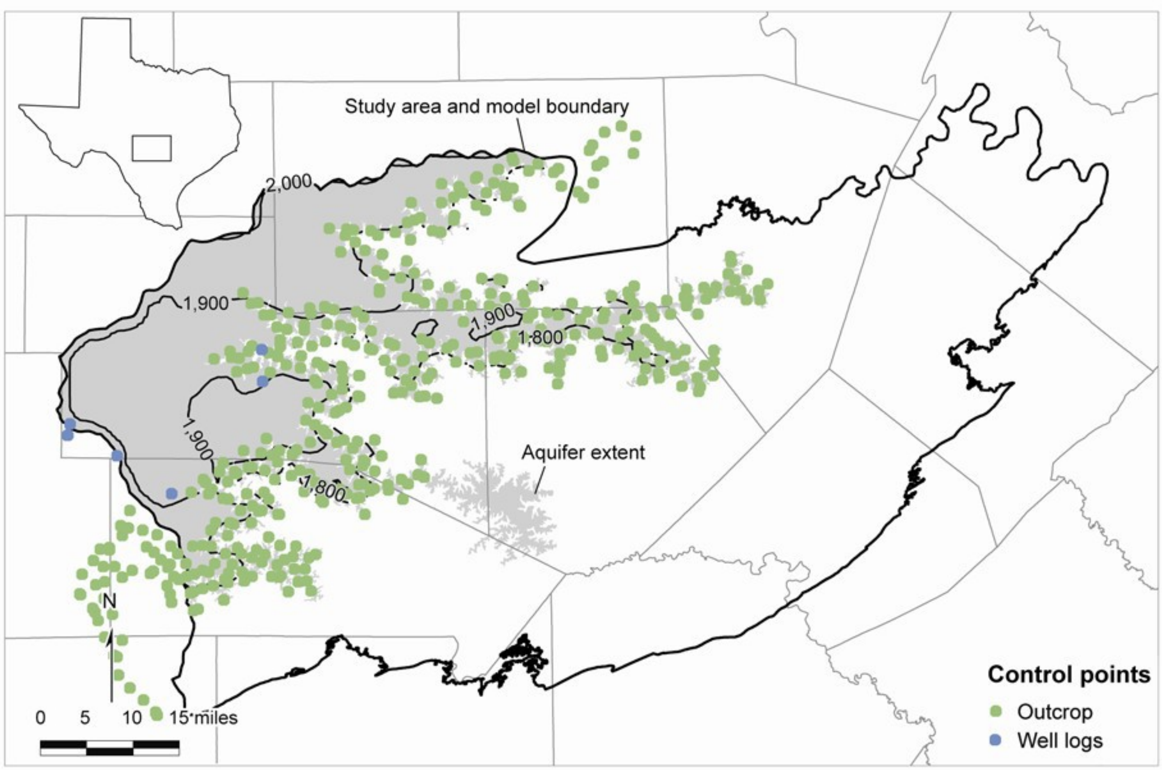
5.2 Structure

Building on the structural interpretations of Ashworth (1983) and using available drilling logs from the Hill Country Underground Water Conservation District, geophysical logs, and locations of outcrop areas, Mace and others (2000) developed structural elevation maps for the bases of the Edwards Group and the Upper and Middle Trinity aquifers (Figures 5-1 through 5-4). Mace and others (2000) collected geophysical logs from the TWDB, Edwards Aquifer Authority, Bandera County River Authority and Groundwater District, and private collections and used natural gamma logs to locate (1) the base of the Edwards Group, (2) the contact between the upper and lower members of the Glen Rose Limestone (as defined by the lower evaporite beds just above the Corbula marker bed or correlated equivalent), and (3) the base of the Middle Trinity sediments. Mace and others (2000) used resistivity logs to add control points in parts of the study area in the absence of gamma logs to complete the structure surfaces.

To further enhance the control of structural elevation point data, Mace and others (2000) supplemented the geophysical-log-based data with outcrop elevation points. Mace and others (2000) digitized the appropriate formation contacts for the base of the Edwards Group and Upper and Middle Trinity sediments from 1:250,000-scale maps of surface geology in the area (Brown and others, 1974; Proctor and others, 1974a, b; Barnes, 1981) using AutoCAD® (Autodesk, 1997) and converted the digitized contacts into an ArcInfo® (ESRI, 1991) geographic information system line coverage. Mace and others (2000) then georeferenced the line coverage, converted it into a point coverage from the arc vertices, and intersected it with a triangulated irregular network constructed from a U.S. Geological Survey 3-arc-second digital elevation model to determine their point elevations. Mace and others (2000) compiled the structural elevation information and organized it into ArcInfo® for the base of the Middle Trinity Aquifer, the base of the Upper Trinity Aquifer, and the base of the Edwards Group sediments. Mace and others (2000) then exported the point elevations from ArcInfo® into point coordinates and imported them into Surfer® (Golden Software, 1995) for spatial interpolation (Figures 5-1 through 5-4).

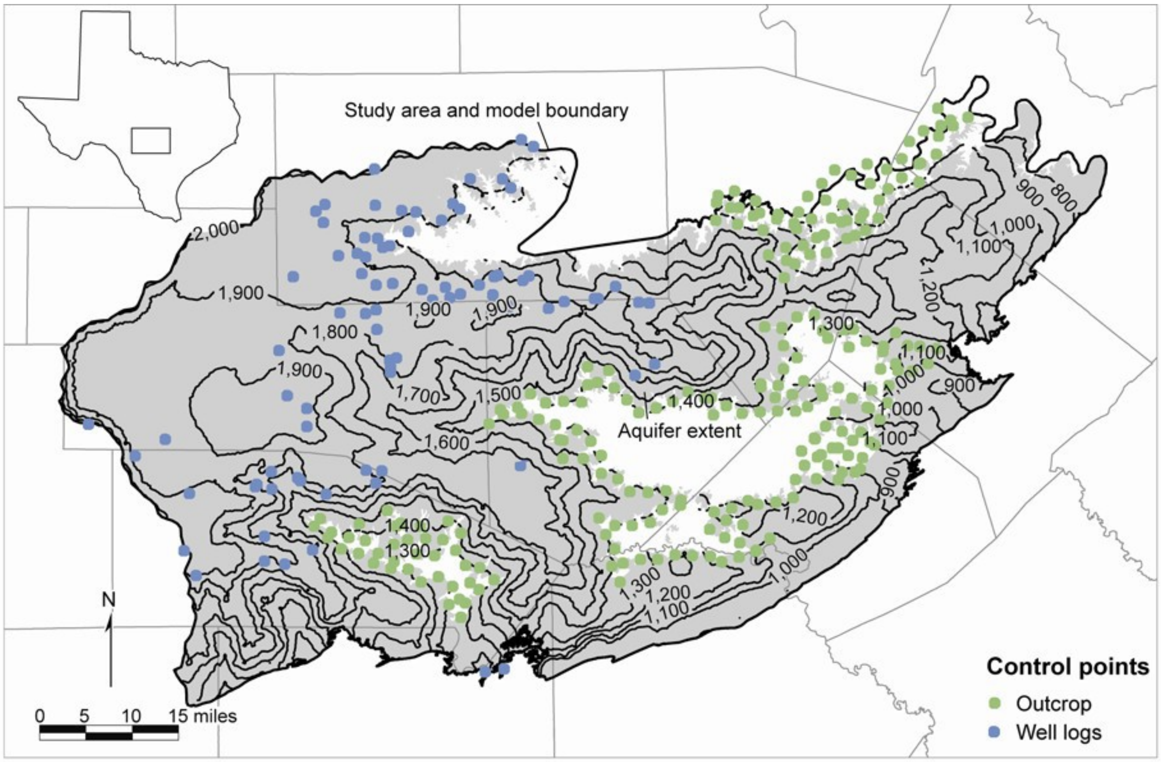


(a)

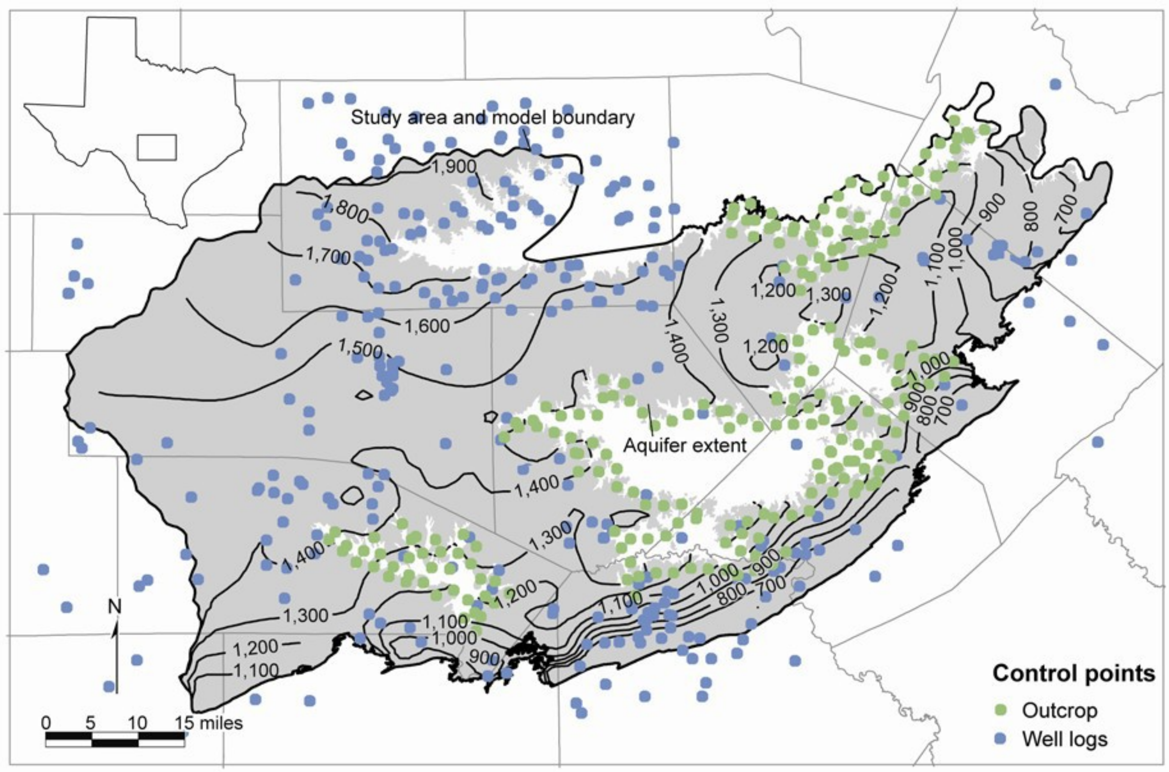


(b)

Figure 5-1. **Elevations of (a) the top and (b) the base of the Edwards Group. The contour interval is 100 feet (modified from Ashworth, 1983; Mace and others, 2000).**



(a)



(b)

Figure 5-2. Elevations of (a) the top and (b) the base of the Upper Trinity Aquifer. The contour interval is 100 feet (modified from Ashworth, 1983; Mace and others, 2000).

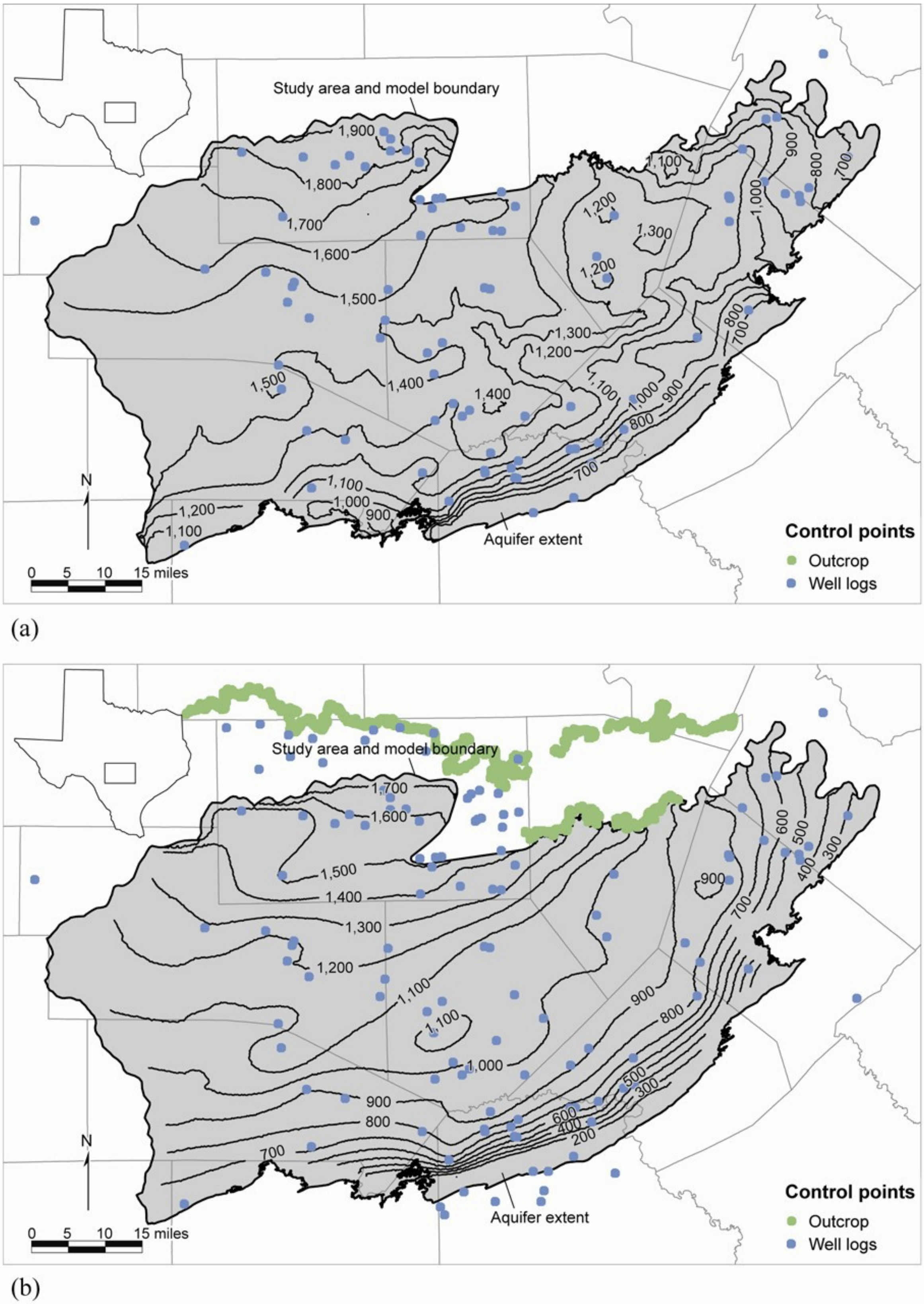
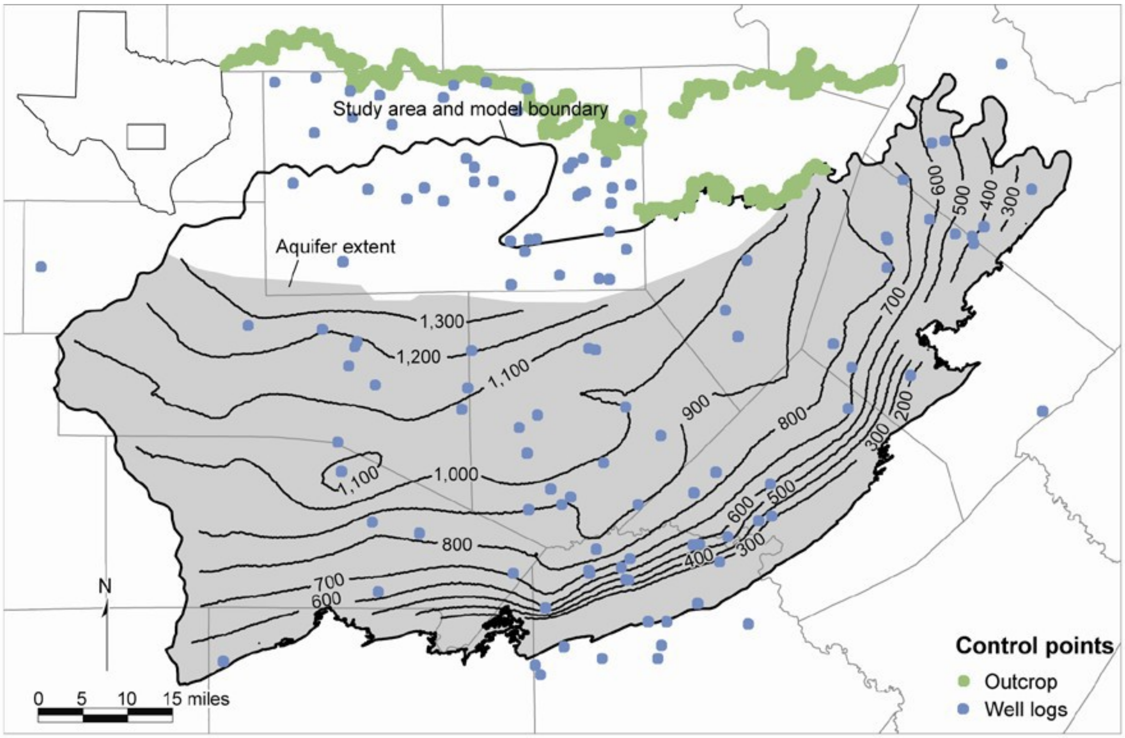
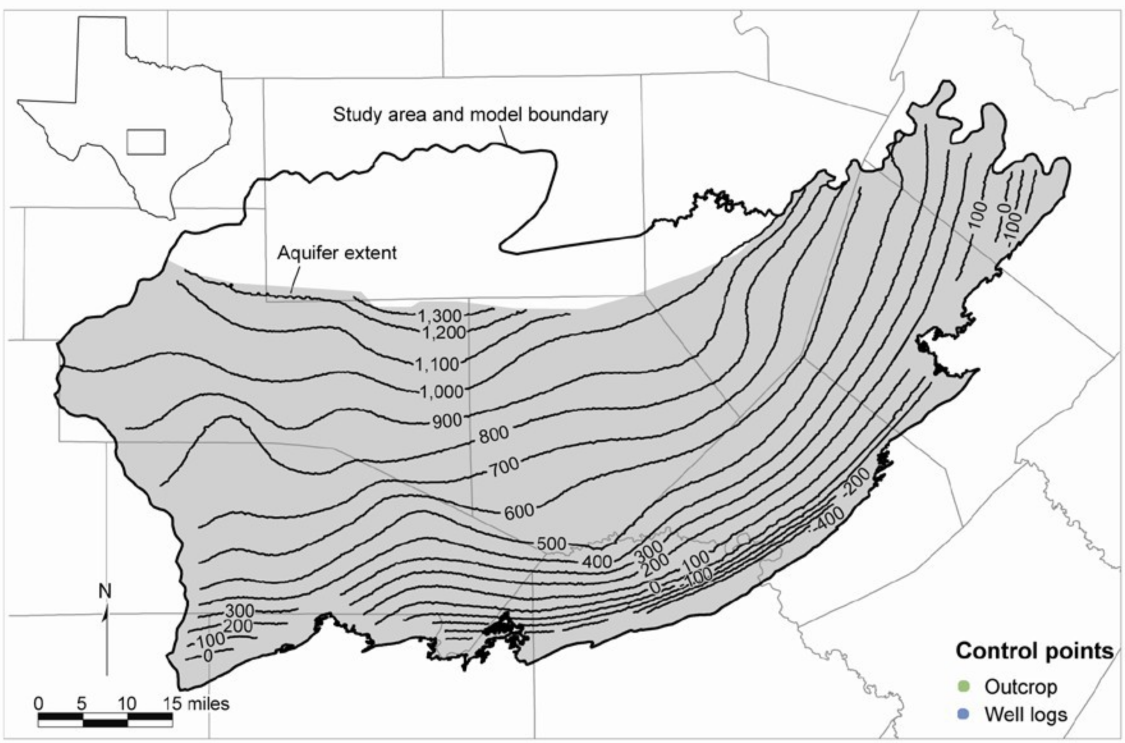


Figure 5-3. Elevations of (a) the top and (b) the base of the Middle Trinity Aquifer. The contour interval is 100 feet (modified from Ashworth, 1983; Mace and others, 2000).



(a)



(b)

Figure 5-4. **Elevations of (a) the top (modified from Ashworth, 1983; Mace and others, 2000) and (b) the base of the Lower Trinity Aquifer. The contour interval is 100 feet. Please note: the top of the Lower Trinity Aquifer coincides with the base of the Hammett Shale and thus differs from the base of the Middle Trinity Aquifer.**

As part of this project, we updated the model structure of Mace and others (2000) by revising the structure of the Middle Trinity Aquifer and adding the Lower Trinity Aquifer as a fourth layer. These changes were aided by structural interpretations from the Hays Trinity Groundwater Conservation District. The base of the Lower Trinity Aquifer was taken from the base of the Edwards-Trinity Aquifer System used in the groundwater availability model for the Edwards-Trinity (Plateau) Aquifer System by Anaya and Jones (2009). When we compared the base elevation of the Middle Trinity Aquifer from the original model (Mace and others, 2000) with the base elevation of the Lower Trinity from the Edwards-Trinity (Plateau) Aquifer System model (Anaya and Jones, 2009), we noticed that the structures were not consistent because the base of the Middle Trinity dipped below the base of the Lower Trinity in Blanco County. To resolve this inconsistency between the two structures we revised the base of the Middle Trinity Aquifer using data from the Texas Commission on Environmental Quality Source Water Assessment and Protection geographic information system database developed by the U.S. Geological Survey. We used the Source Water Assessment and Protection data for the base of the Middle Trinity in Blanco County and merged it with the structural surface data from the original model (Mace and others, 2000) for the rest of the model. The two surfaces were merged through the use of a linear smoothing algorithm in ArcGIS® version 9.1 (ESRI, 2005).

We developed thickness maps by subtracting elevations for the tops and bases of the respective model layers using ArcGIS® 9.1 (Figures 5-5 through 5-8). The thickness of the relatively flat lying beds of the Edwards Group is controlled by the dendritic erosional pattern of the surface topography (Figures 5-1 and 5-5). Although mostly masked by the dendritic erosional pattern of the surface topography in the central and eastern portions of the study area, sediments of the Upper Trinity Aquifer thicken toward the Balcones Fault Zone (Figure 5-6). Sediments of the Middle and Lower Trinity aquifers also generally increase in thickness toward the Balcones Fault Zone (Figures 5-7 and 5-8).

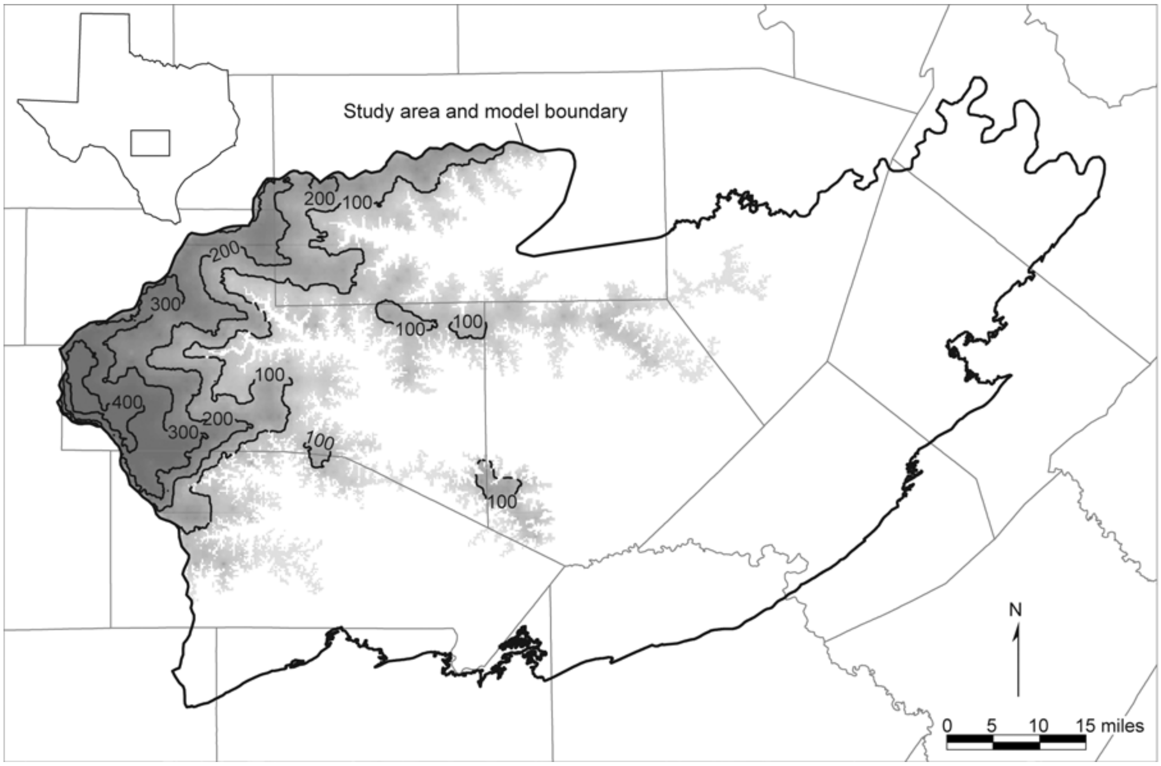


Figure 5-5. **Approximate thickness of the Edwards Group in the study area. The contour interval is 100 feet.**

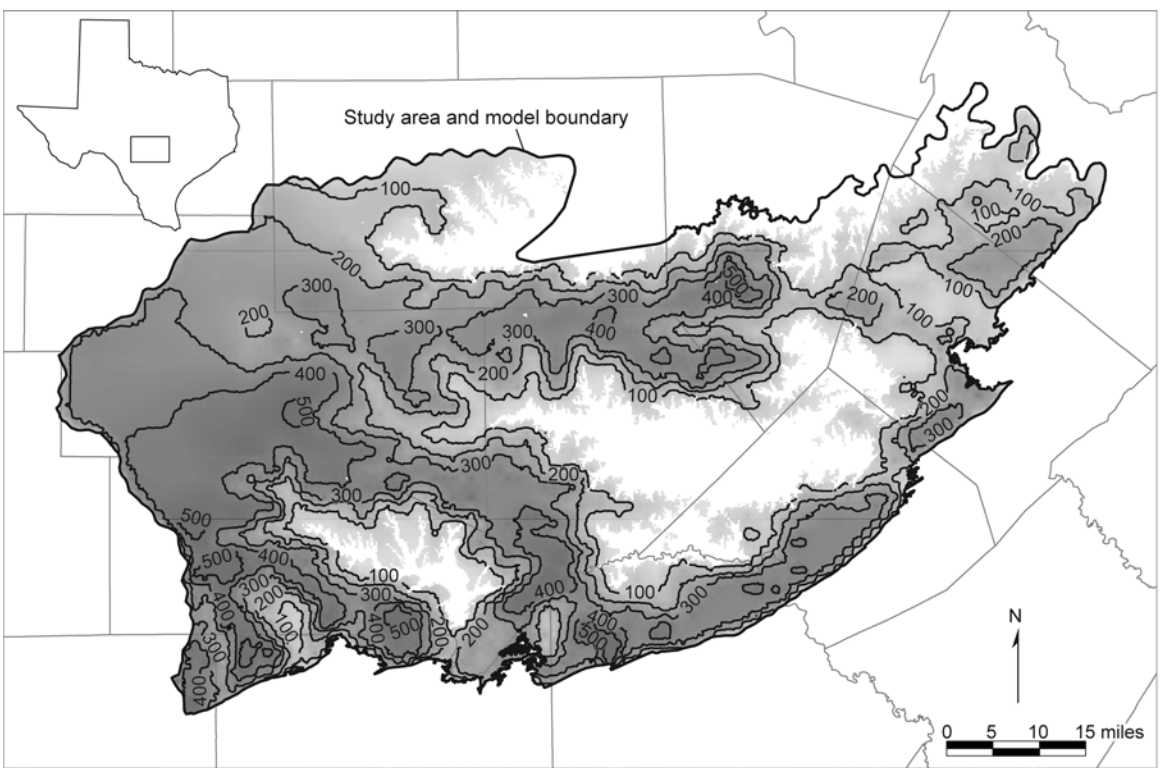


Figure 5-6. **Approximate thickness of the Upper Trinity Aquifer in the study area. The contour interval is 100 feet.**

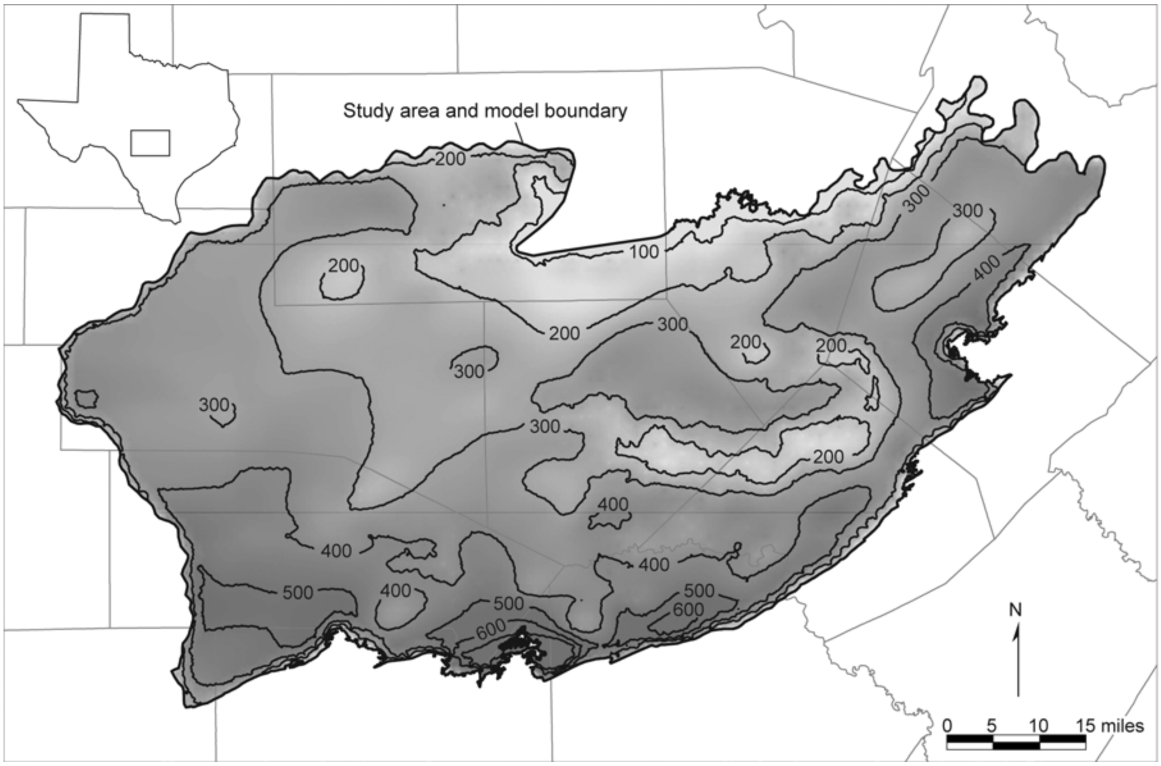


Figure 5-7. **Approximate thickness of the Middle Trinity Aquifer in the study area. The contour interval is 100 feet.**

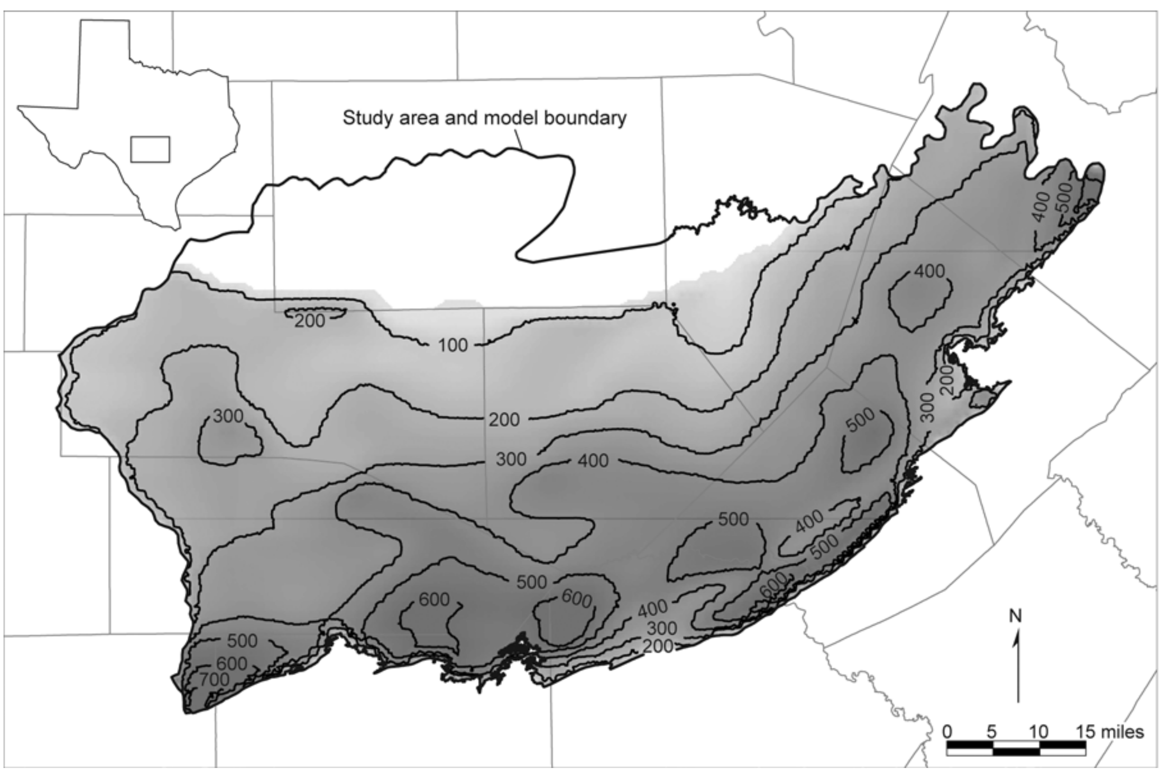


Figure 5-8. **Approximate thickness of the Lower Trinity Aquifer in the study area. The contour interval is 100 feet.**

5.3 Water Levels and Regional Groundwater Flow

We compiled water level measurements and developed generalized steady-state water level maps for the Edwards Group and the Upper, Middle, and Lower Trinity aquifers in the study area. To increase the number of measurement points, we expanded our time interval to lie between 1977 and 1985 to approximate steady-state water levels for the period about 1980. If a well had multiple water level measurements, we chose the average measurement for contouring the water level map.

Water levels in the aquifers generally follow topography (Figures 5-9 through 5-12). Kuniansky and Holligan (1994) noted that water levels in this area are a subdued representation of surface topography due to recharge in the uplands and discharge in the lowlands. Water level maps indicate that water levels are influenced by the location of rivers and springs. For example, the water level maps show that groundwater in the aquifer flows toward most of the rivers in the study area (Figures 5-9 through 5-12). In the case of the Edwards Group, groundwater flows east toward the escarpment, where there are numerous springs at the geologic contact between the Edwards Group and the upper member of the Glen Rose Limestone (Figure 5-9). Barker and Ardis (1996) also noted that water level elevations and the direction of groundwater flow in the Trinity Aquifer System are largely controlled by the position of springs and streams.

Groundwater flows from higher water level elevations toward lower water level elevations. The water level maps show that regional groundwater flow is from the northwest toward the southeast and east (Figures 5-9 through 5-12). Water level maps also show that groundwater in the Upper, Middle, and Lower Trinity aquifers flows out of the study area to the south and east into the Edwards (Balcones Fault Zone) Aquifer (Figures 5-10 through 5-12). Section 5.7 (Discharge) of this report discusses the estimated amount of groundwater flow from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer.

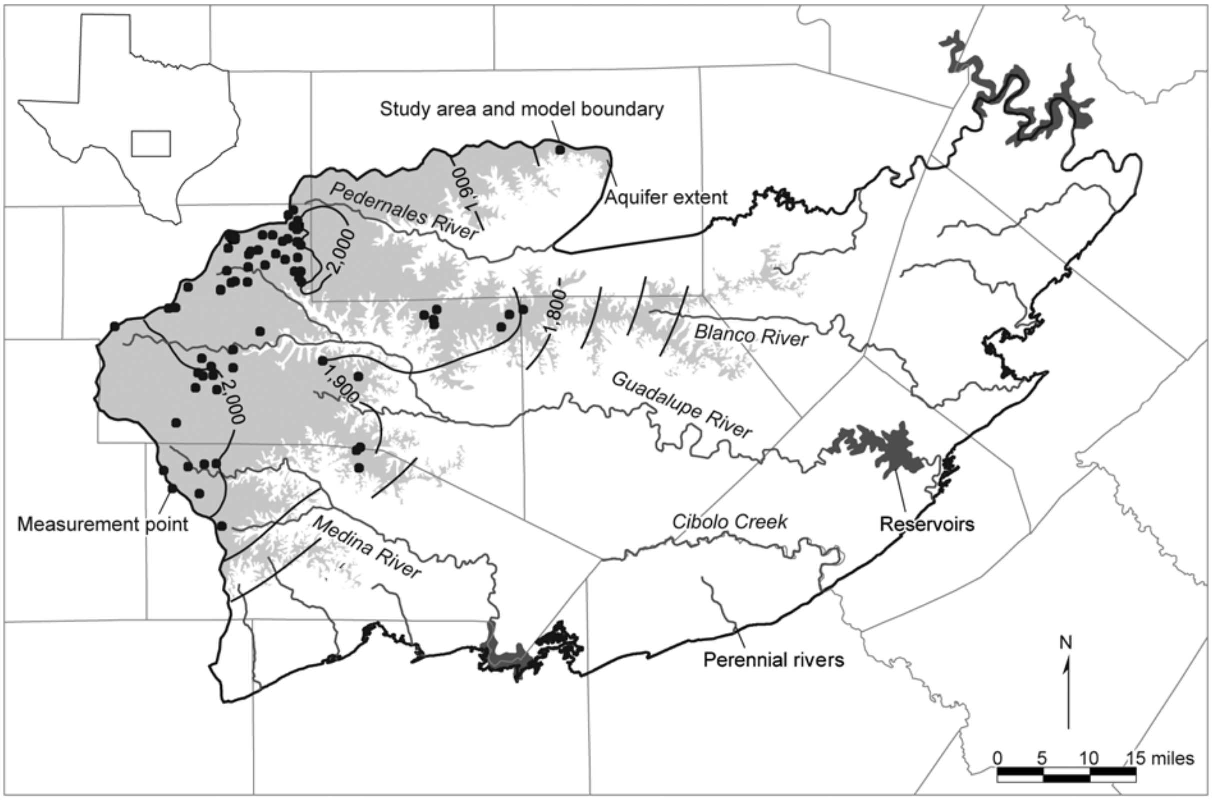


Figure 5-9. **Average water level elevations in the Edwards Group in the study area for the period 1977 through 1985. The contour interval is 100 feet.**

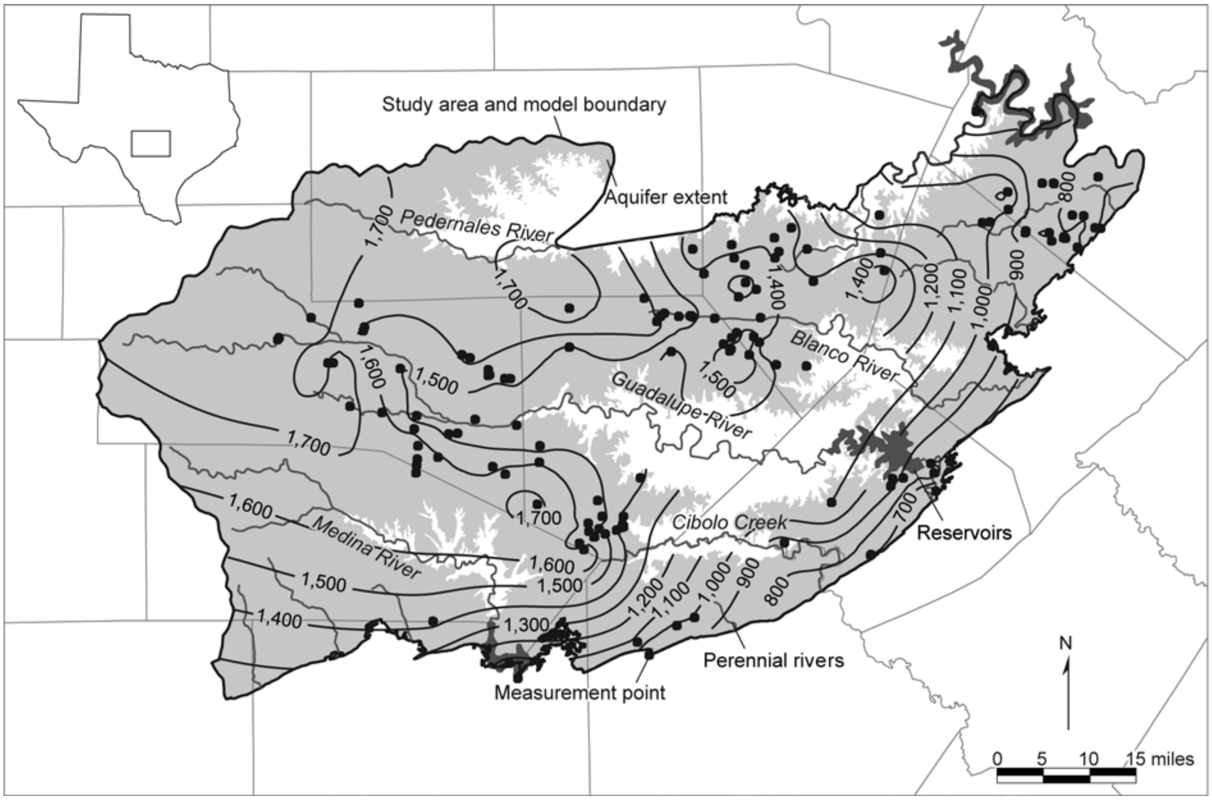


Figure 5-10. **Average water level elevations in the Upper Trinity Aquifer in the study area for the period 1977 through 1985. The contour interval is 100 feet.**

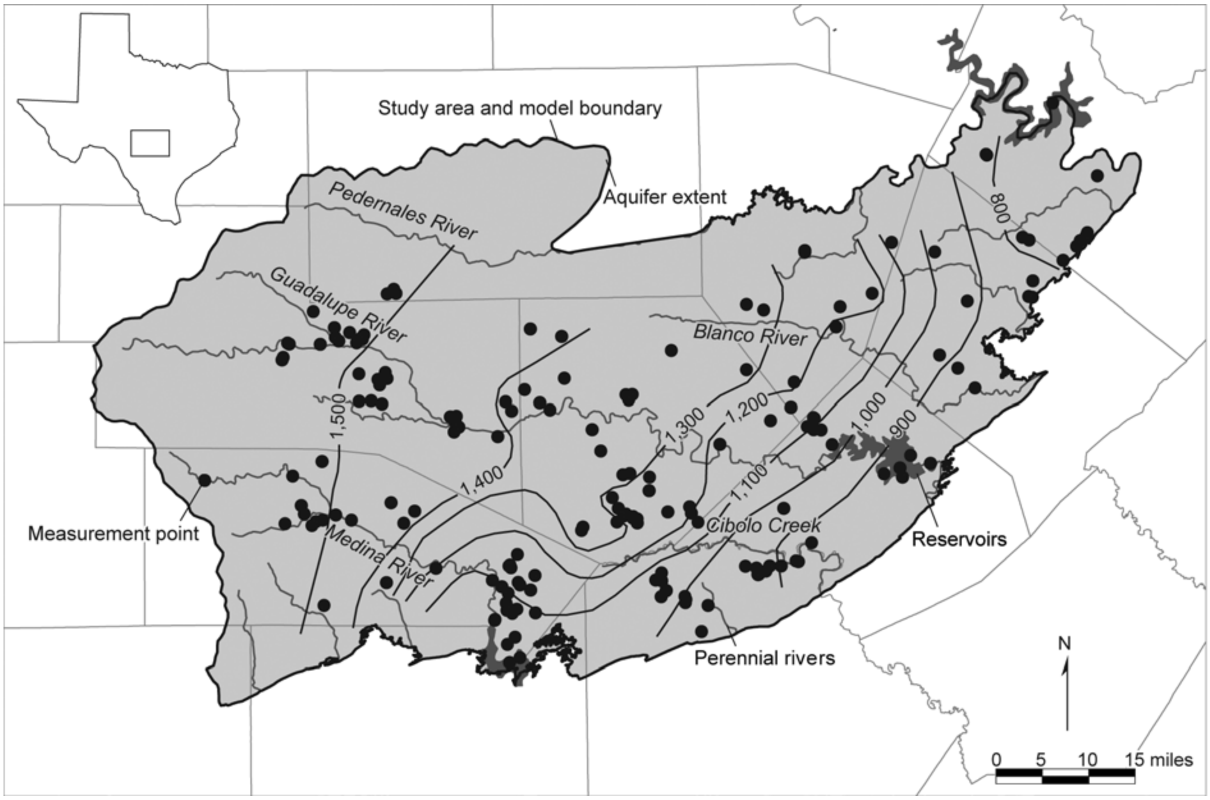


Figure 5-11. **Average water level elevations in the Middle Trinity Aquifer in the study area for the period 1977 through 1985. The contour interval is 100 feet.**

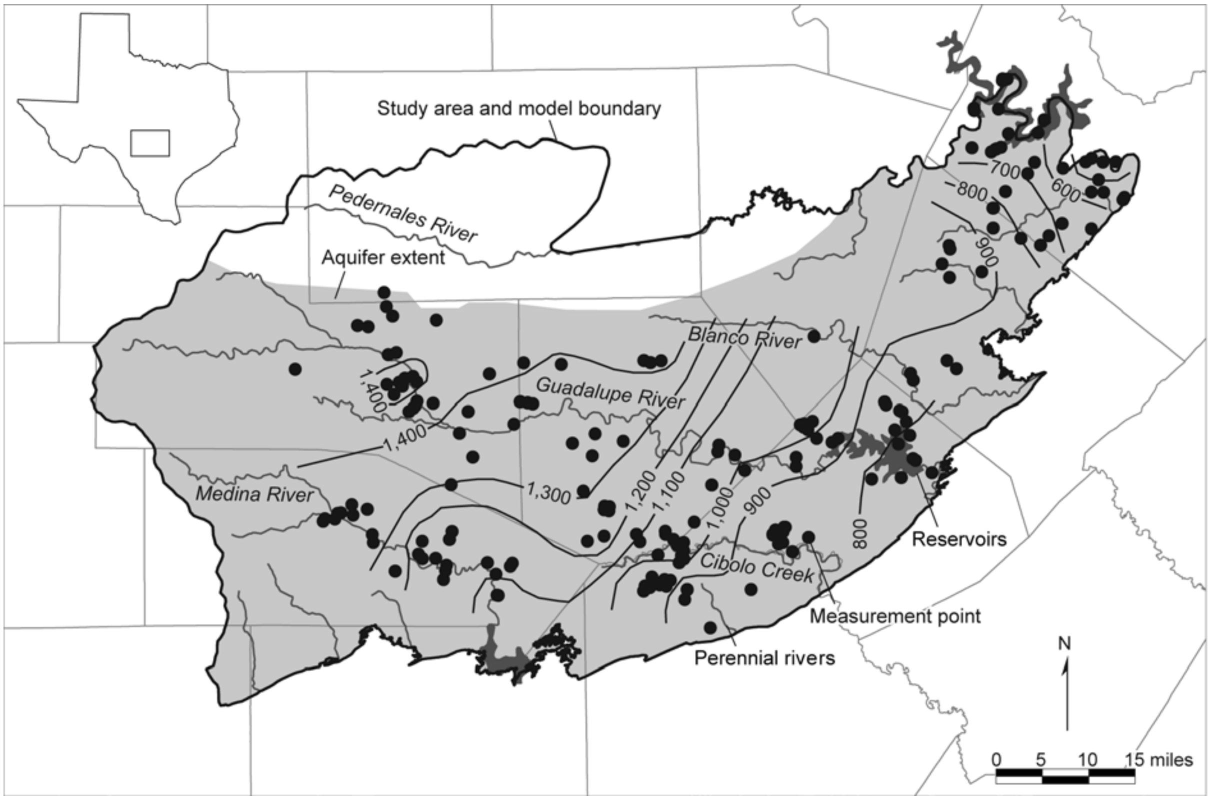


Figure 5-12. Average water level elevations in the Lower Trinity Aquifer in the study area for the period 1977 through 1985. The contour interval is 100 feet.

Water levels, especially in shallow wells (less than 100 feet deep), can seasonally vary by as much as 50 feet (Barker and Ardis, 1996) in response to rainfall events. Some wells show relatively small changes in water level over time, for example, wells 69-04-502, 56-48-301, 57-61-803, and 58-50-120, whereas others show large fluctuations, for example, wells 68-19-806 and 56-63-604 (Figures 5-13 through 5-16). Wells with detailed measurements, for example, wells 68-19-806, 68-02-609, and 68-01-314, show seasonal fluctuations (Figures 5-15 and 5-16). Figures 5-13 through 5-16 suggest that overall there are no long-term trends of declining or rising water levels in the Hill Country portion of the Trinity Aquifer System; thus, water levels in the 1990s will be similar to those for the period 1977 through 1985 (Figures 5-9 through 5-12).

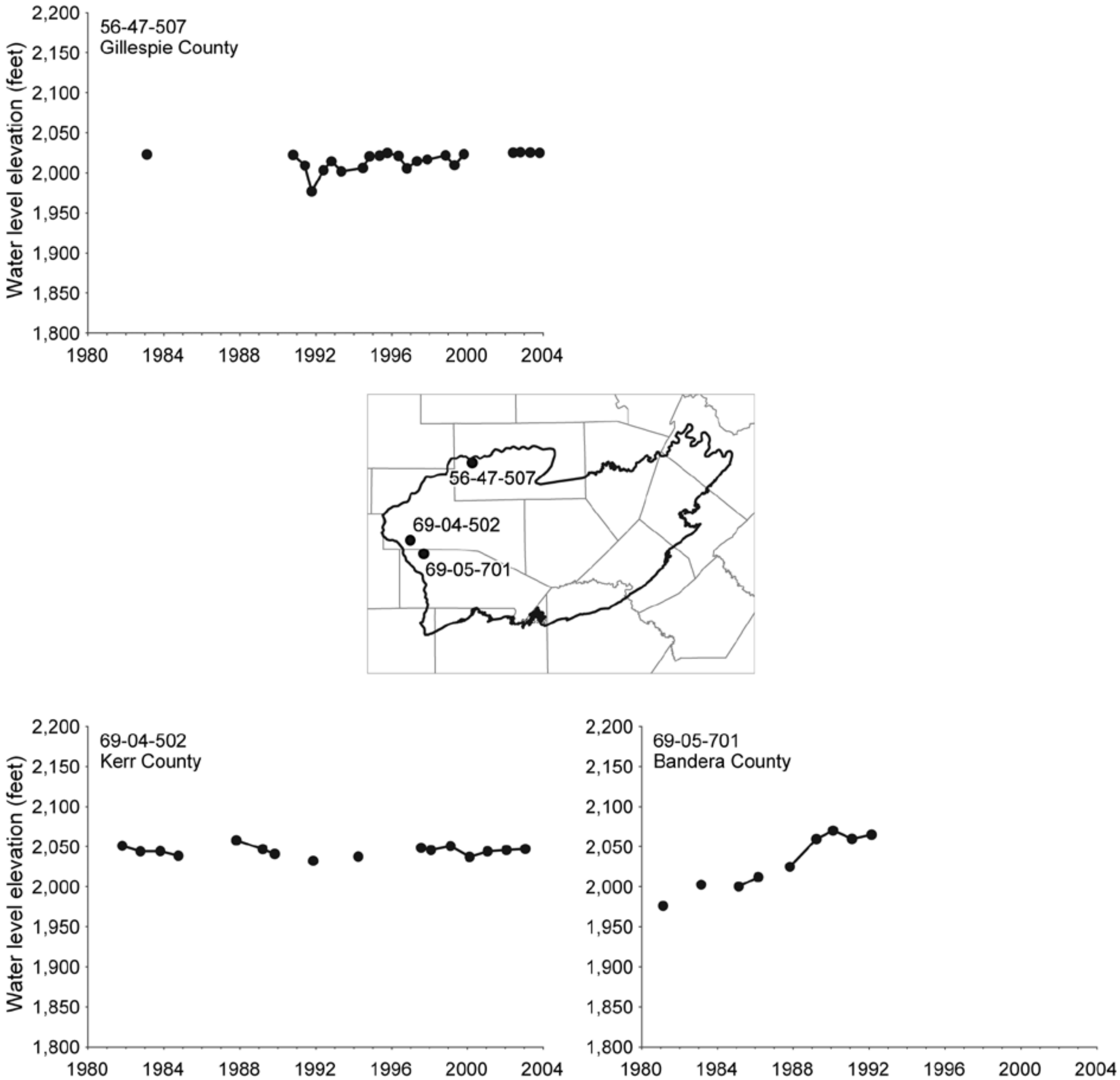


Figure 5-13. Hydrographs from selected Edwards Group wells in the study area.

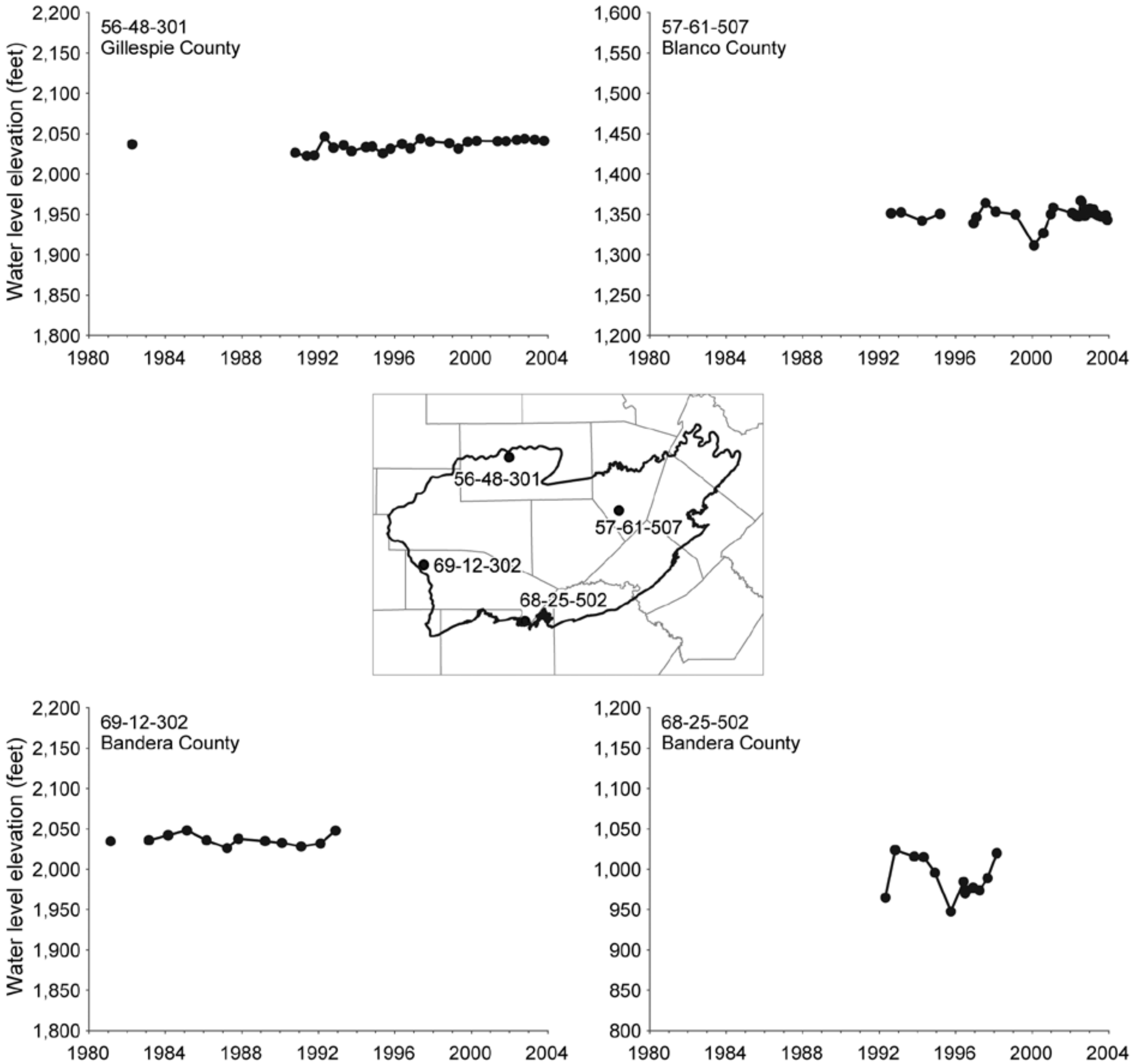


Figure 5-14. Hydrographs from selected Upper Trinity Aquifer wells in the study area.

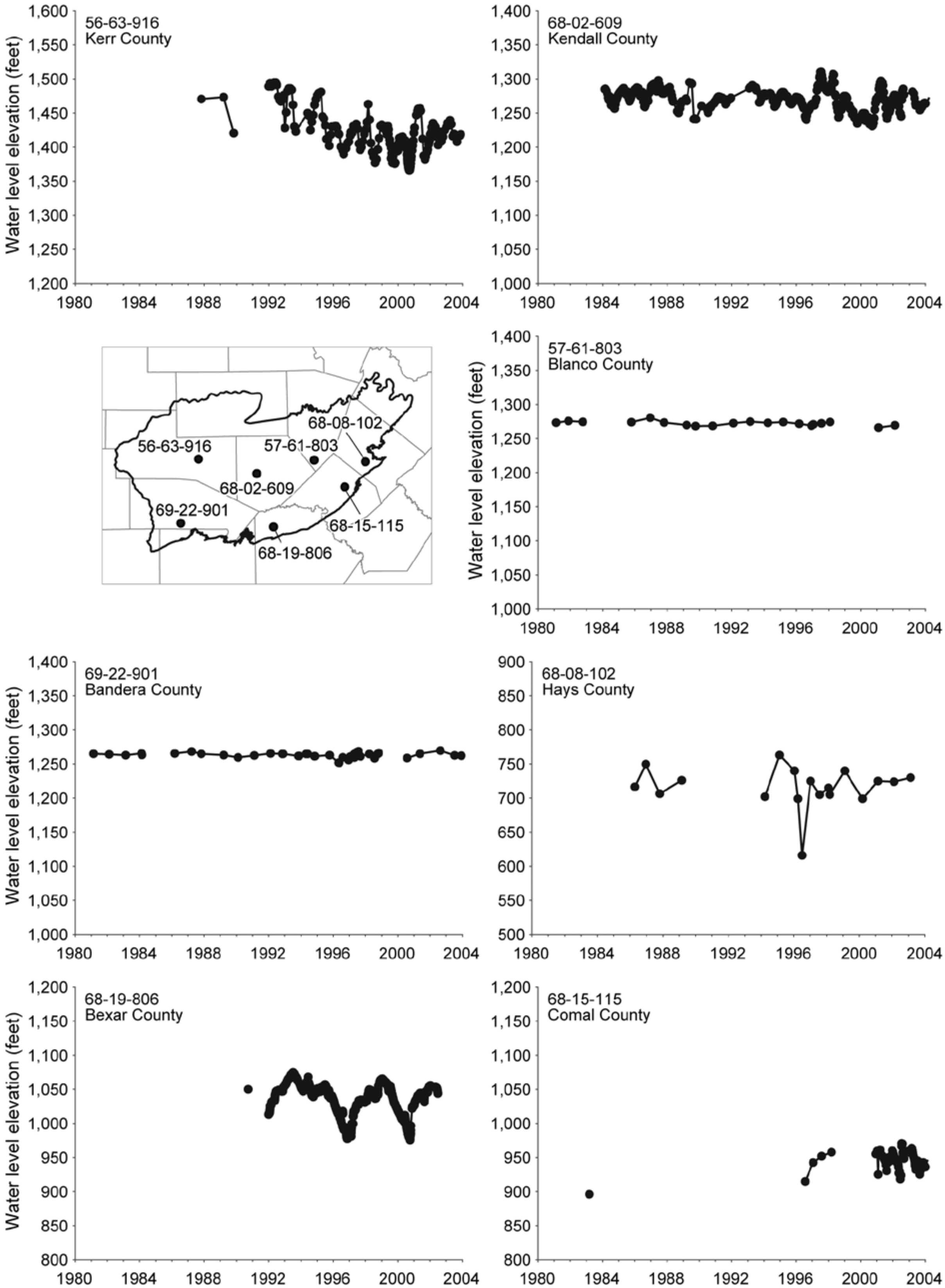


Figure 5-15. Hydrographs from selected Middle Trinity Aquifer wells in the study area.

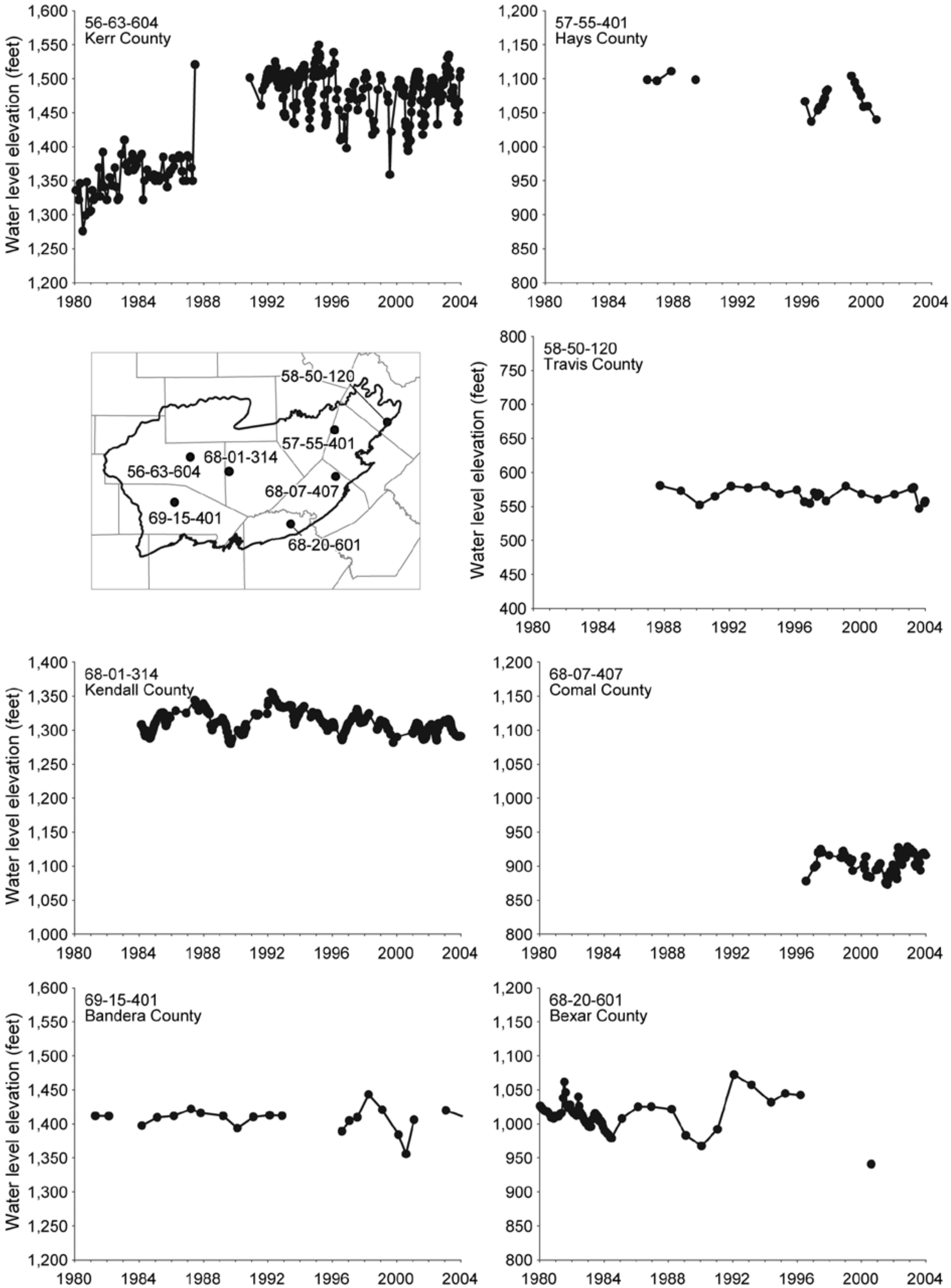


Figure 5-16. Hydrographs from selected Lower Trinity Aquifer wells in the study area.

From 1980 to 1997, water levels generally rose in the Upper Trinity Aquifer of Bexar County (Figure 5-17). Over the same period, water levels generally declined in the Middle and Lower Trinity aquifers in Bandera, Blanco, Kendall, and Kerr counties and rose, at least locally, in Bexar and Comal counties (Figure 5-18). In other parts of the study area, water levels show seasonal fluctuations but have remained fairly constant since 1980. The area having the most significant water level decline is near the city of Kerrville in Kerr County. The largest water level decline is approximately 40 feet in the Middle Trinity Aquifer and 85 feet in the Lower Trinity Aquifer (Figures 5-15 and 5-16). The 128-foot water level rise in Kerr County (Well 56-63-604) can be attributed to a reduction in pumping by the City of Kerrville. Well 68-08-102, which is located near the city of Wimberley (Hays County), shows a water level decline of approximately 45 feet between 1980 and 2000 (Figure 5-15).

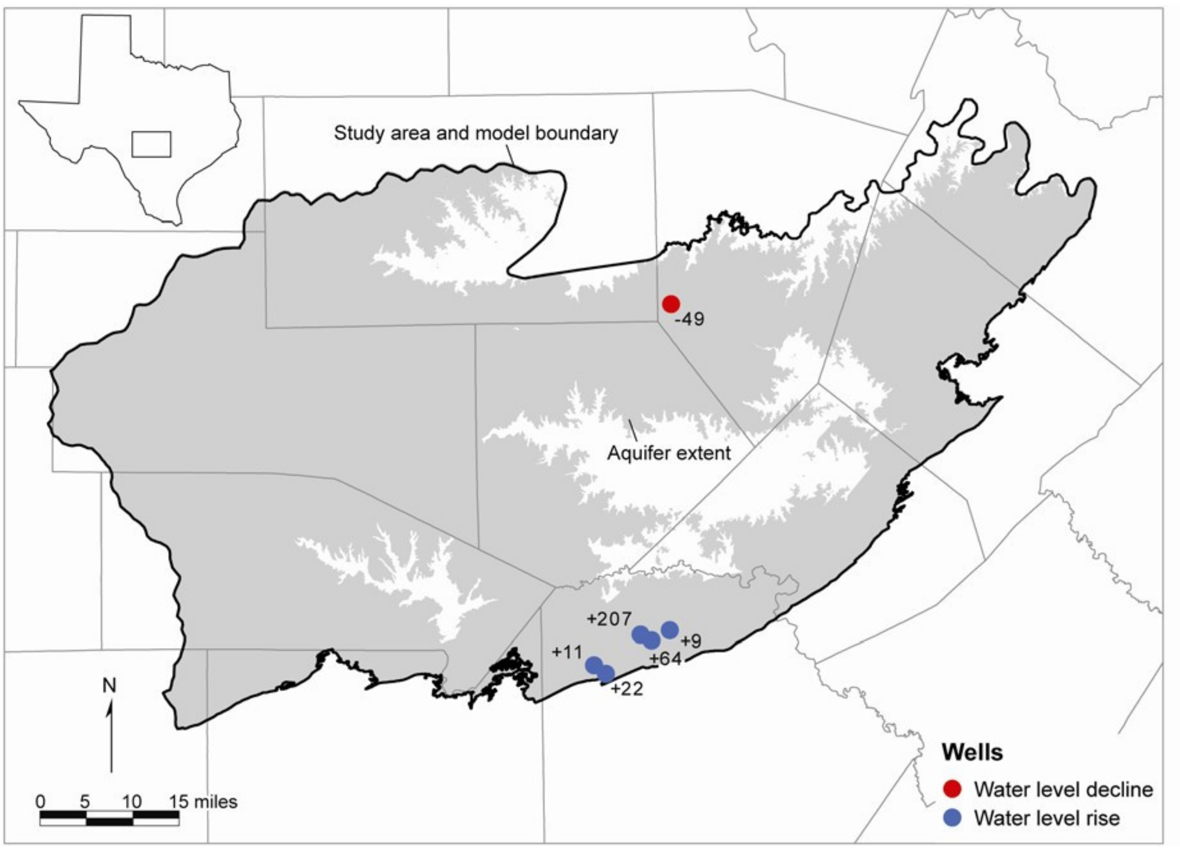
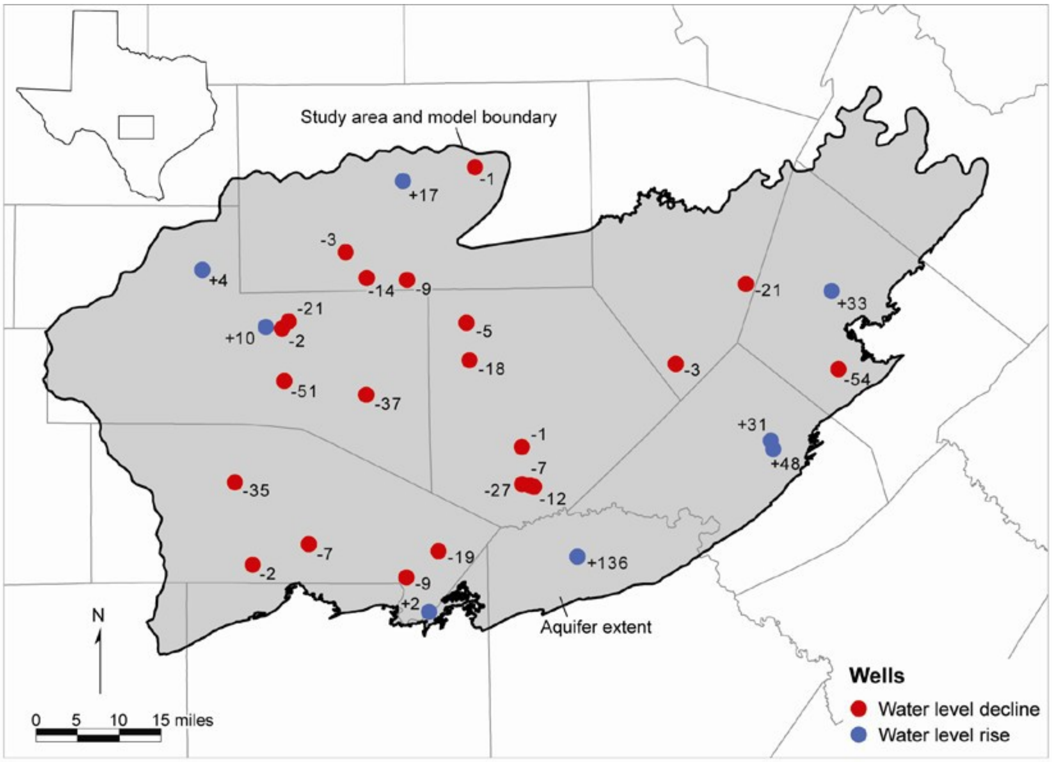
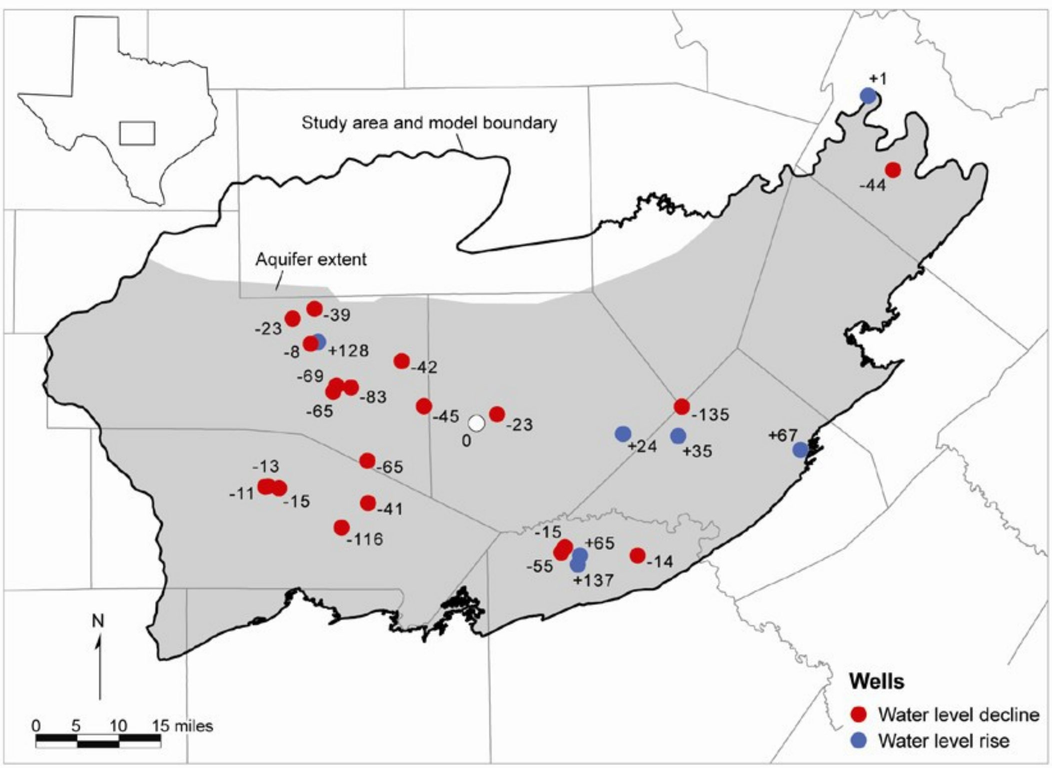


Figure 5-17. Net water level change in the Upper Trinity Aquifer between 1980 and 1997 at selected well locations.



(a)



(b)

Figure 5-18. **Net water level change in (a) the Middle Trinity Aquifer and (b) Lower Trinity Aquifer between 1980 and 1997 at selected well locations. Positive values (blue points) indicate rise in water level, and negative values (red points) indicate decline in water levels.**

5.4 Recharge

The primary sources of inflow to the Hill Country portion of the Trinity Aquifer System are rainfall on the outcrop, seepage losses through headwater creeks, and lakes during high stage levels. The outcrops in the study area are composed of the upper and lower members of the Glen Rose Limestone, Hensell Sand, and Edwards Group and receive all of the direct recharge from rainfall. The Cow Creek Limestone and Lower Trinity Aquifer sediments are not exposed at land surface in the study area and receive water by vertical leakage from overlying strata (Ashworth, 1983). Beds containing relatively low permeability sediments within the upper member of the Glen Rose Limestone impede downward percolation of interstream recharge and facilitate horizontal groundwater flow, resulting in base flow and spring flow to the mostly gaining perennial streams that drain the Hill Country (Ashworth, 1983; Barker and Ardis, 1996). Recharge in the Edwards Group limestones of the northwestern portion of the study area occurs as infiltration of rainfall and losing streams. Much of this water later emerges as springs and seeps along the geologic contact between the Edwards Group and the upper member of the Glen Rose Limestone.

Sinkholes and caverns in the Glen Rose Limestone of southern Kendall, northern Bexar, and western Comal counties may transmit large quantities of water to the Hill Country portion of the Trinity Aquifer System. Karst-enhanced recharge is especially significant along Cibolo Creek between Boerne and Bulverde (Ashworth, 1983; Veni, 1994). However, because much of this recharge is quickly transmitted to the Edwards (Balcones Fault Zone) Aquifer, it has minimal effect on the Hill Country portion of the Trinity Aquifer System (Veni, 1994; Barker and Ardis, 1996).

Several investigators have estimated recharge rates for the Hill Country portion of the Trinity Aquifer System (Table 5-1).

Table 5-1. Estimates of recharge rates to the Hill Country portion of the Trinity Aquifer System as a percentage of average annual precipitation.

Literature source	Recharge rate (inches per year)	Percent value
Muller and Price (1979)	0.5	1.5
Ashworth (1983)	1.3	4.0
Kuniansky (1989)	3.6	11.0
Bluntzer (1992, calculated)	2.2	6.7
Bluntzer (1992, estimated)	1.7	5.0
Kuniansky and Holligan (1994)	2.3	7.0
Mace and others (2000)	1.3	4.0
Mace (2001)	2.2	6.6
Wet Rock Groundwater Services (2008)	3.1	9.5
Anaya and Jones (2009)	1.4	4.7

Most of them used stream base flow to estimate recharge. Muller and Price (1979) assumed a recharge rate of 1.5 percent of average annual precipitation for their rough approximation of groundwater availability. This estimate of recharge was intended to minimize impacts of groundwater production on base flow and groundwater flow to the Edwards (Balcones Fault Zone) Aquifer. On the basis of a study of base-flow gains in the Guadalupe River between the Comfort and Spring Branch gaging stations during a 20-year period between 1940 and 1960, Ashworth (1983) estimated an average annual effective recharge rate of 4 percent of average annual precipitation for the Hill Country. Kuniansky (1989) estimated base flow for 11 drainage basins in our study area for a 28-month period between December 1974 and March 1977 and estimated an annual recharge rate of about 11 percent of average annual rainfall. However, Kuniansky and Holligan (1994) reduced this recharge rate to 7 percent of average annual precipitation to calibrate a groundwater model that included the Hill Country portion of the Trinity Aquifer System. They suggested that the numerical model did not include all the local streams accepting discharge from the aquifer. Bluntzer (1992) calculated long-term average annual base flow from the Blanco, Guadalupe, Medina, Pedernales, and Sabinal rivers and Cibolo and Seco creeks to be 369,100 acre-feet per year. Using a long-term average annual precipitation of 30 inches per year, the recharge estimate by Bluntzer (1992) is equivalent to a recharge rate of 6.7 percent of average annual precipitation (Riggio and others, 1987). However, Bluntzer (1992) suggested that a recharge rate of 5 percent is more appropriate to account for human impacts on base flow such as nearby groundwater pumping, streamflow diversions, municipal and irrigation return flows, and retention structures. Bluntzer (1992) also noted that base flow was highly variable over time. Mace and others (2000) suggested that differences in recharge rates reflect biases in the record of analysis due to variation of precipitation. The higher recharge rate estimated by Kuniansky (1989) is most likely due to the higher-than-normal precipitation between December 1974 and March 1977, her record of analysis. Ashworth's (1983) recharge rate is probably biased toward a lower value because his record of analysis includes the 1950s' drought of record.

Mace and others (2000) developed an automated digital hydrograph-separation technique to estimate base flow for the drainage basin defined by the Guadalupe River gaging stations between Comfort and Spring Branch. Mace and others (2000) based this technique on methods used by Nathan and McMahon (1990) and Arnold and others (1995). Mace and others (2000) used the program to estimate base flow from 1940 to 1990 and adjusted parameters to attain the best fit with Ashworth's (1983) and Kuniansky's (1989) base-flow values for the same stream reach. Using this technique, Mace and others (2000) estimated a recharge rate of 6.6 percent of average annual precipitation. Note that the calibrated recharge rate by Mace and others (2000) is about 4 percent of average annual precipitation. All base-flow-based estimates of recharge underestimate recharge because they do not consider the component of recharge that follows the regional flow paths and bypasses the local streams. Additional error in this methodology is associated with the implied assumption that each watershed is a closed system and thus all water that recharges the aquifer discharges to the adjacent river. Regional groundwater flow between watersheds, however, results in underestimation of recharge in up-gradient watersheds and overestimation in down-gradient watersheds.

In the updated model, we spatially distributed recharge using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) data (Daly and Taylor, 1998; Spatial Climate Analysis Service, 2004). The Parameter-elevation Regressions on Independent Slopes Model is an analytical model that spatially distributes monthly, seasonal, and annual precipitation. We assumed that recharge is a fraction of annual precipitation. This fraction, or recharge coefficient, is determined during model calibration. In addition to precipitation, we assumed that the aquifer receives recharge from streamflow losses in Cibolo Creek. This recharge is estimated on the basis of watershed modeling of the Cibolo Creek watershed by the U.S. Geological Survey (Ockerman, 2007). This watershed modeling indicates average annual recharge of approximately 72,000 acre-feet to the Trinity Aquifer System within the study area. The methodology used in the updated model is an improvement over the recharge estimation method used by Mace and others (2000) that was based on base-flow coefficients and precipitation distribution. In addition to overcoming the weaknesses in base-flow-based recharge estimation methods stated above, the updated model was further improved by using data from a study of the Cibolo Creek watershed (Ockerman, 2007) that was not available for use by Mace and others (2000).

5.5 Rivers, Streams, Springs, and Lakes

Most of the rivers in the study area arise along the eastern margin of the Edwards Plateau and descend with a steep gradient into the Hill Country (Figure 3-6). Many of these streams have upper reaches contained within narrow canyons and broaden into flat-bottomed valleys farther downstream (Barker and Ardis, 1996). Three major drainage basins—the San Antonio, Guadalupe, and Colorado rivers—traverse the study area and funnel flow toward the southeast.

Most of the rivers in the study area gain water from the Hill Country portion of the Trinity Aquifer System (Ashworth, 1983; Slade and others, 2002) (Figure 5-19) and are hydraulically connected to the regional flow system (Kuniansky, 1990). These streams receive groundwater that discharges through seeps and springs that occur along the tops of impermeable units where they appear at land surface (Barker and Ardis, 1996). Much of the groundwater in local flow systems within the Hill Country portion of the Trinity Aquifer System discharges to adjacent deeply entrenched, perennial streams instead of flowing to deeper portions of the aquifer (Ashworth, 1983). Many springs issue from the Edwards Group along the margin of the Edwards Plateau in the western part of the study area (Ashworth, 1983).

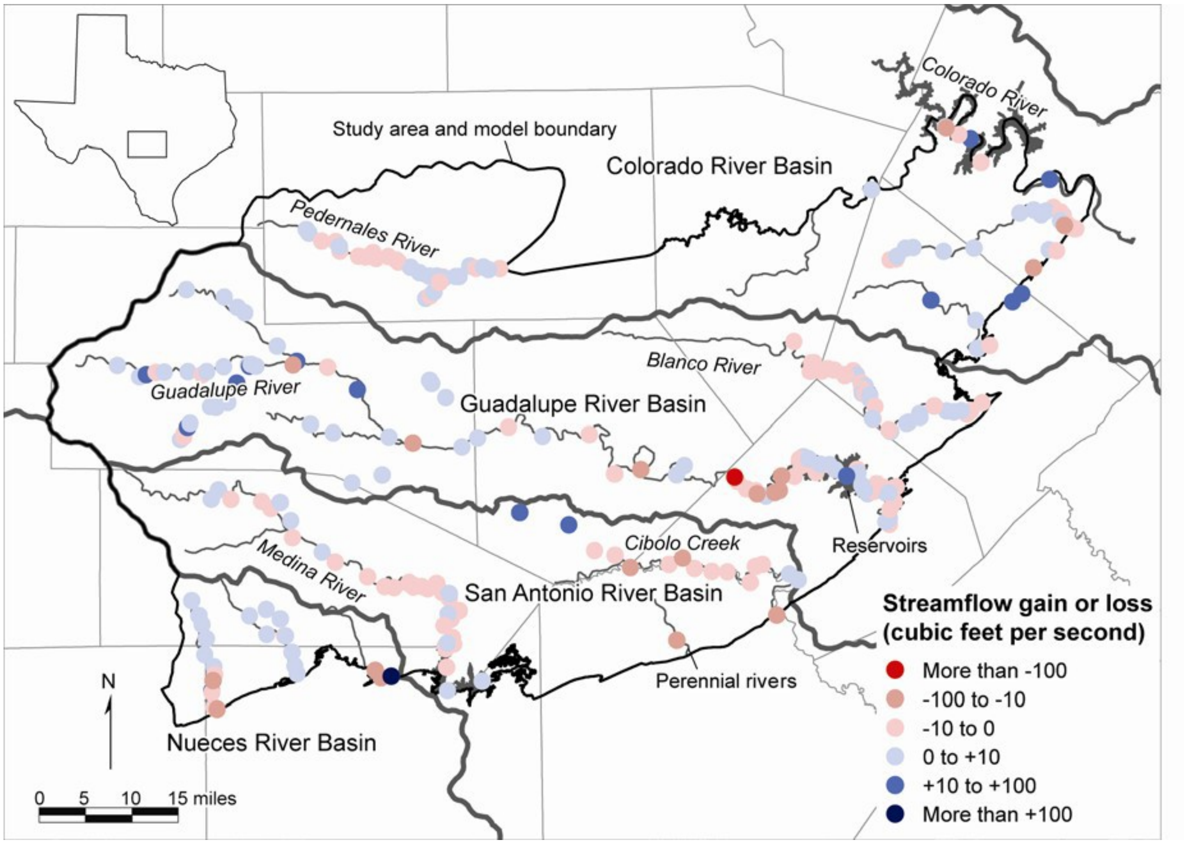


Figure 5-19. Streamflow gain (positive values) and loss (negative values) from Slade and others (2002).

Most of the rivers in the study area are perennial (Figures 5-20 through 5-26). Lower reaches of Cibolo Creek lose flow between Boerne and Bulverde where the creek flows over the lower member of the Glen Rose Limestone (Ashworth, 1983) (Figure 5-26). Upstream of Boerne, Cibolo Creek gains water where it flows over the upper member of the Glen Rose Limestone (Guyton and Associates, 1958, 1970; Espey, Huston and Associates, 1982; LBG-Guyton Associates, 1995; Mace and others, 2000). Lower reaches of most of the streams in the study area lose significant quantities of flow where they cross the recharge zone of the Edwards (Balcones Fault Zone) Aquifer (Barker and others, 1994). Most perennial rivers in the study area have extremely low flow for brief periods during droughts (Figures 5-21 through 5-23).

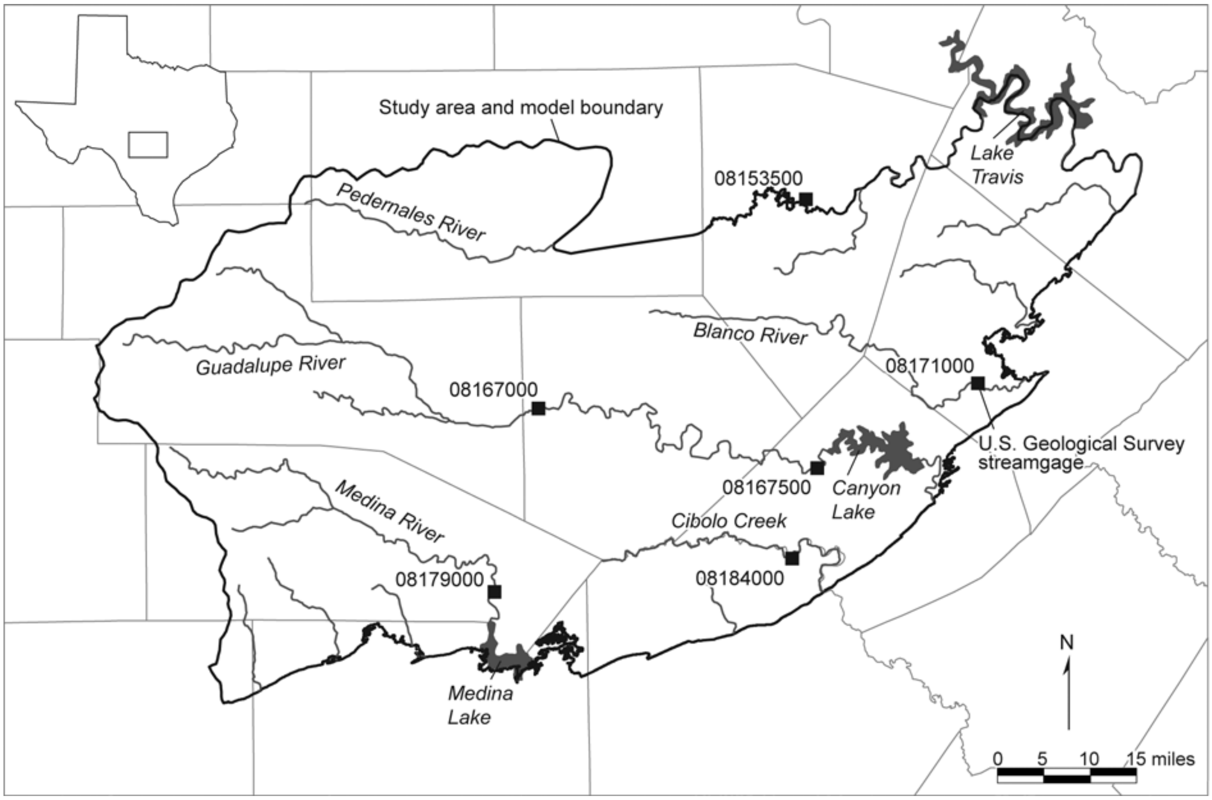


Figure 5-20. **Location of streamgages for the streamflow hydrographs shown in Figures 5-21 through 5-26 (from Mace and others, 2000).**

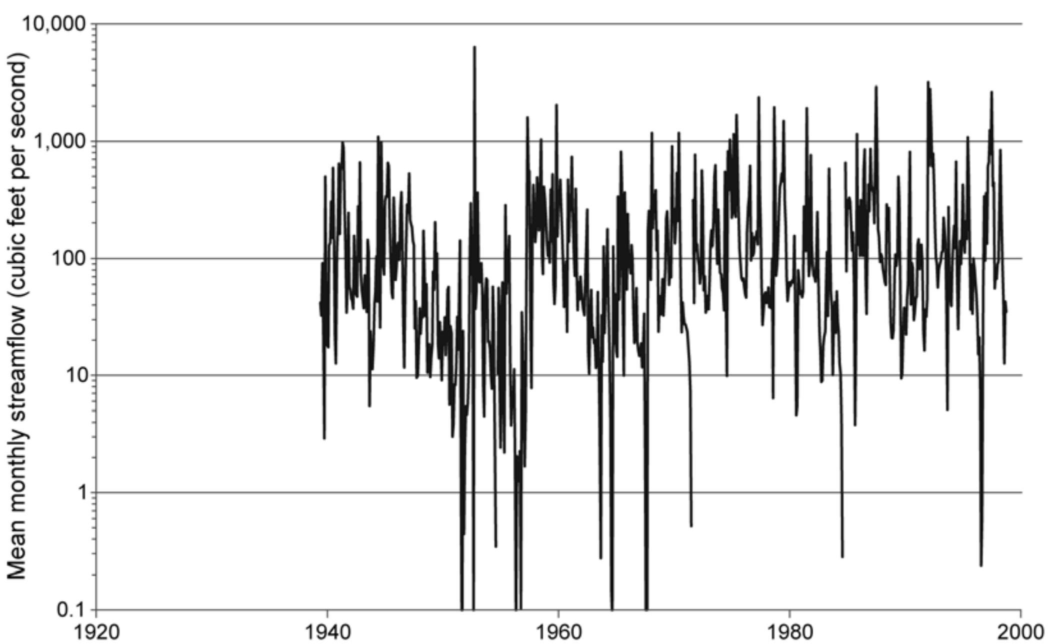


Figure 5-21. **Mean monthly streamflow for the U.S. Geological Survey gaging 08153500 on the Pedernales River near Johnson City. The station location can be found in Figure 5-20 (from Mace and others, 2000).**

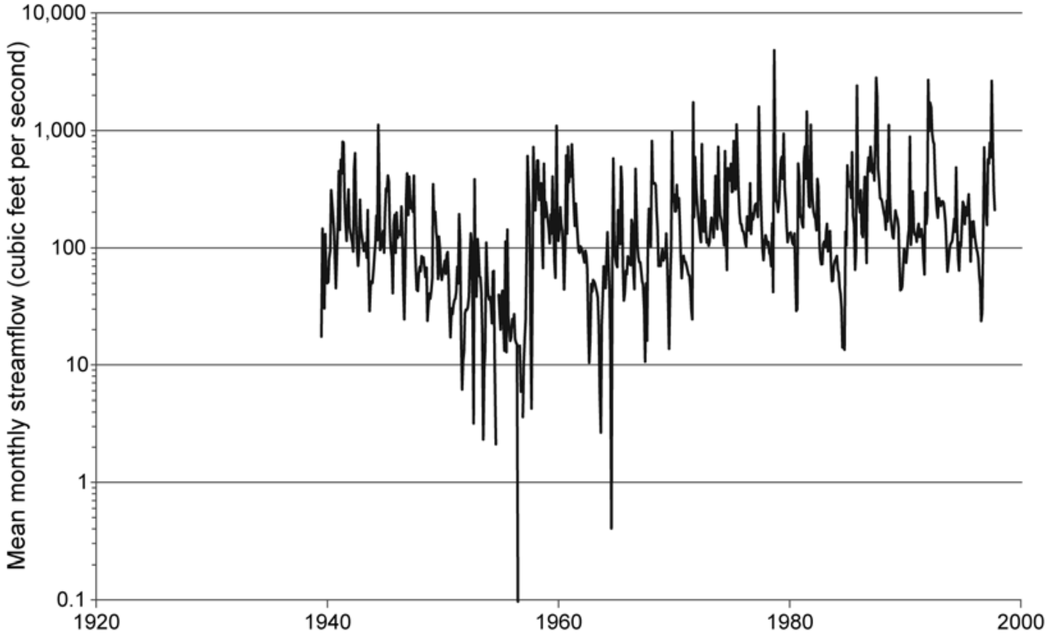


Figure 5-22. **Mean monthly streamflow for the U.S. Geological Survey gaging 08167000 on the Guadalupe River at Comfort. The station location can be found in Figure 5-20 (from Mace and others, 2000).**

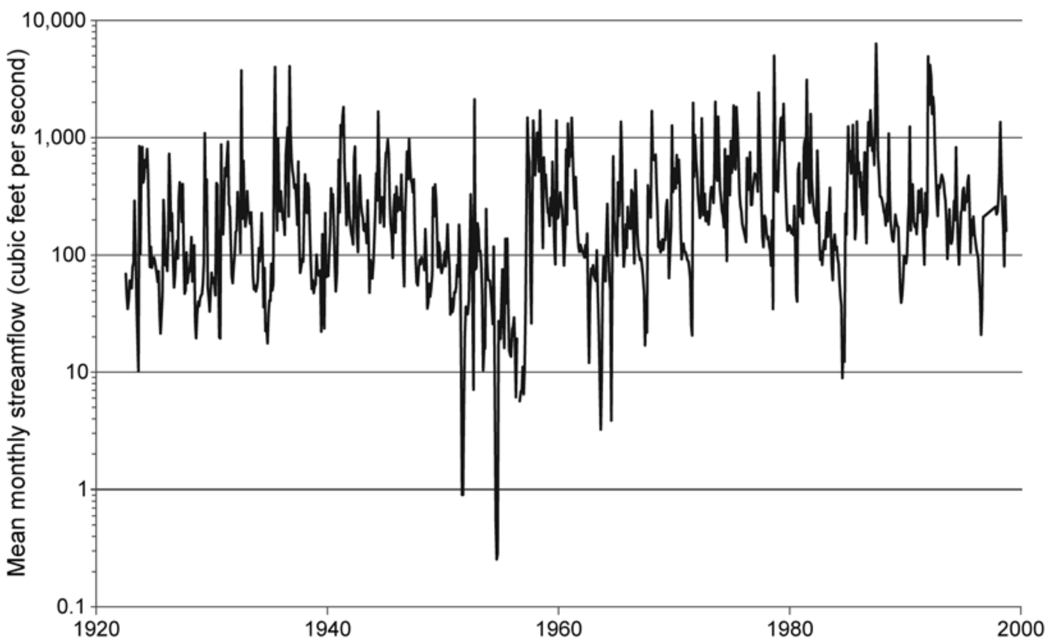


Figure 5-23. **Mean monthly streamflow for the U.S. Geological Survey gaging 08167500 on the Guadalupe River near Spring Branch. The station location can be found in Figure 5-20 (from Mace and others, 2000).**

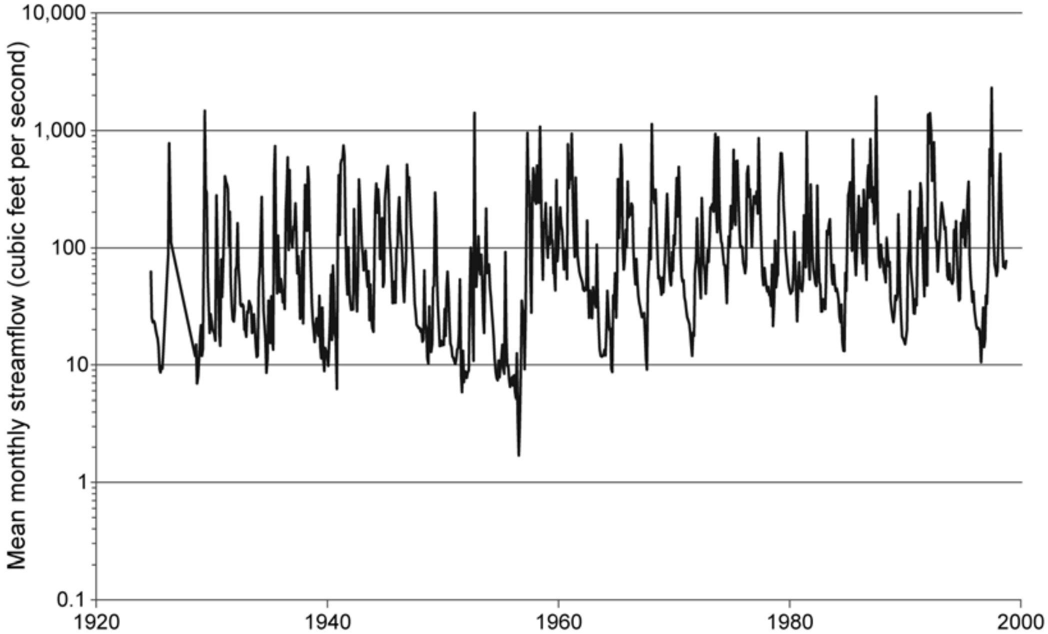


Figure 5-24. **Mean monthly streamflow for the U.S. Geological Survey gaging 08171000 on the Blanco River at Wimberley. The station location can be found in Figure 5-20 (from Mace and others, 2000).**

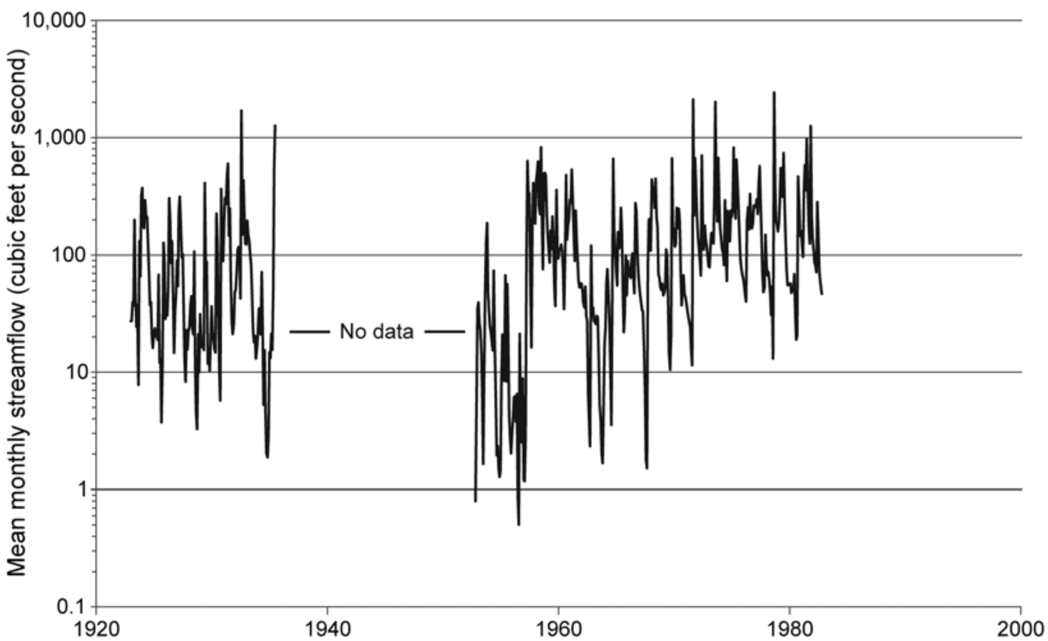


Figure 5-25. **Mean monthly streamflow for the U.S. Geological Survey gaging 08179000 on the Medina River near Pipe Creek. The station location can be found in Figure 5-20 (from Mace and others, 2000).**

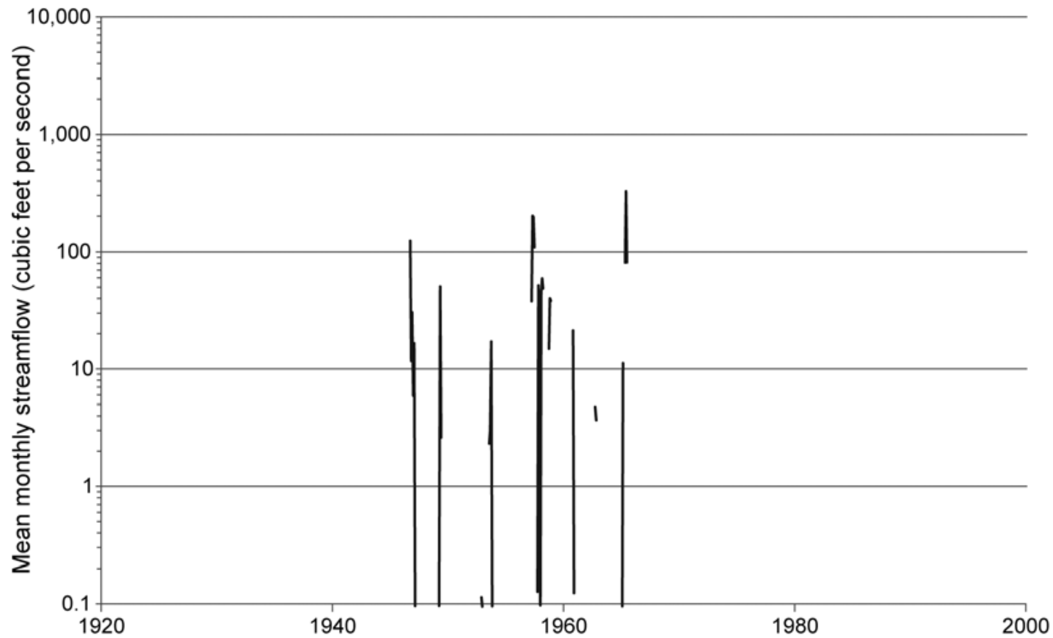


Figure 5-26. **Mean monthly streamflow for the U.S. Geological Survey gaging 08184000 on Cibolo Creek near Bulverde. The station location can be found in Figure 5-20 (from Mace and others, 2000).**

The study area includes four major lakes: Lake Travis, Lake Austin, Canyon Lake, and Medina Lake (Figure 3-1). Canyon Lake and Lake Travis have maintained approximately constant lake levels (± 20 feet), although Lake Travis had large declines during droughts in the 1950s and mid-1960s (Figure 5-27). Lake Medina has much more variation in water levels and was nearly dry on a few occasions during the drought of the 1950s (Espey, Huston and Associates, 1989) (Figure 5-27).

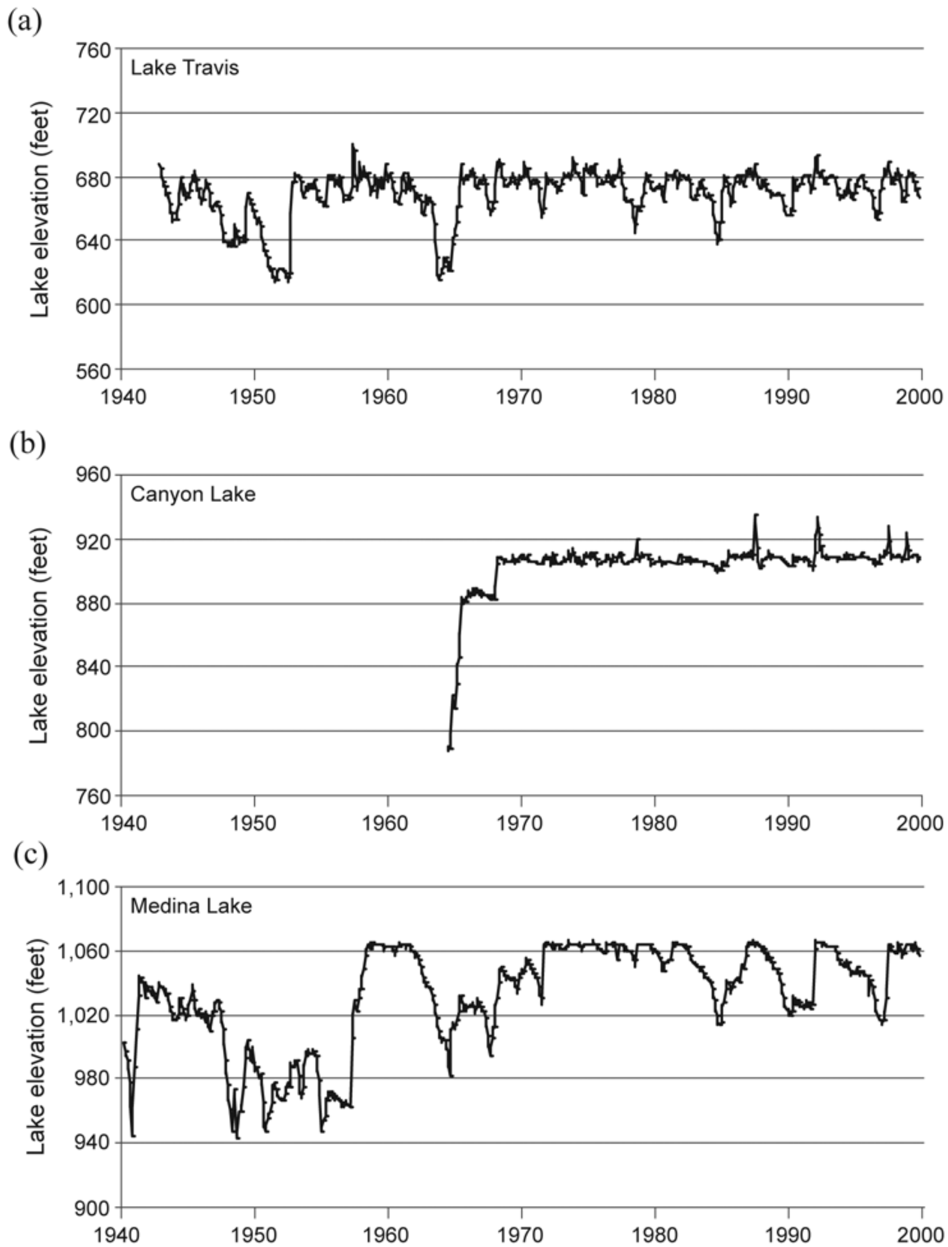


Figure 5-27. **Lake-level elevations in (a) Lake Travis, (b) Canyon Lake, and (c) Medina Lake. Lake Travis water levels are from the Lower Colorado RiverAuthority. Canyon Lake water levels are from the U.S. Army Corps of Engineers. Medina Lake water levels for the period 1940 through 1986 are from Espey, Huston and Associates (1989). Water levels for the periods January 1987 through September 1994 and October 1997 through September 1999 are from the U.S. Geological Survey. Mace and others (2000) calculated lake levels for the period October 1994 through September 1997 by relating lake volumes from a TWDB database to lake level using the rate curve by Espey, Huston and Associates(1989).**

Numerous springs occur in the study area (Figure 5-28). Most of these springs issue from low-lying areas below the base of bluffs along rivers and streams, discharging groundwater that flows laterally along the tops of hard, more resistant Glen Rose Limestone beds. Other springs discharge along the margin of the Edwards Plateau and contribute significant flow to the headwaters of the major rivers in the study area. Many of the spring discharge zones are characterized by phreatic vegetation, such as marsh purslane, cattails, ferns, and cypress trees, indicative of a constant supply of water (Brune, 1981). Springs that occur in the Edwards Group generally have higher discharge rates than those occurring in the lower and upper members of the Glen Rose Limestone and the Cow Creek Limestone (Table 5-2), presumably because of the cavernous nature of the Edwards Group.

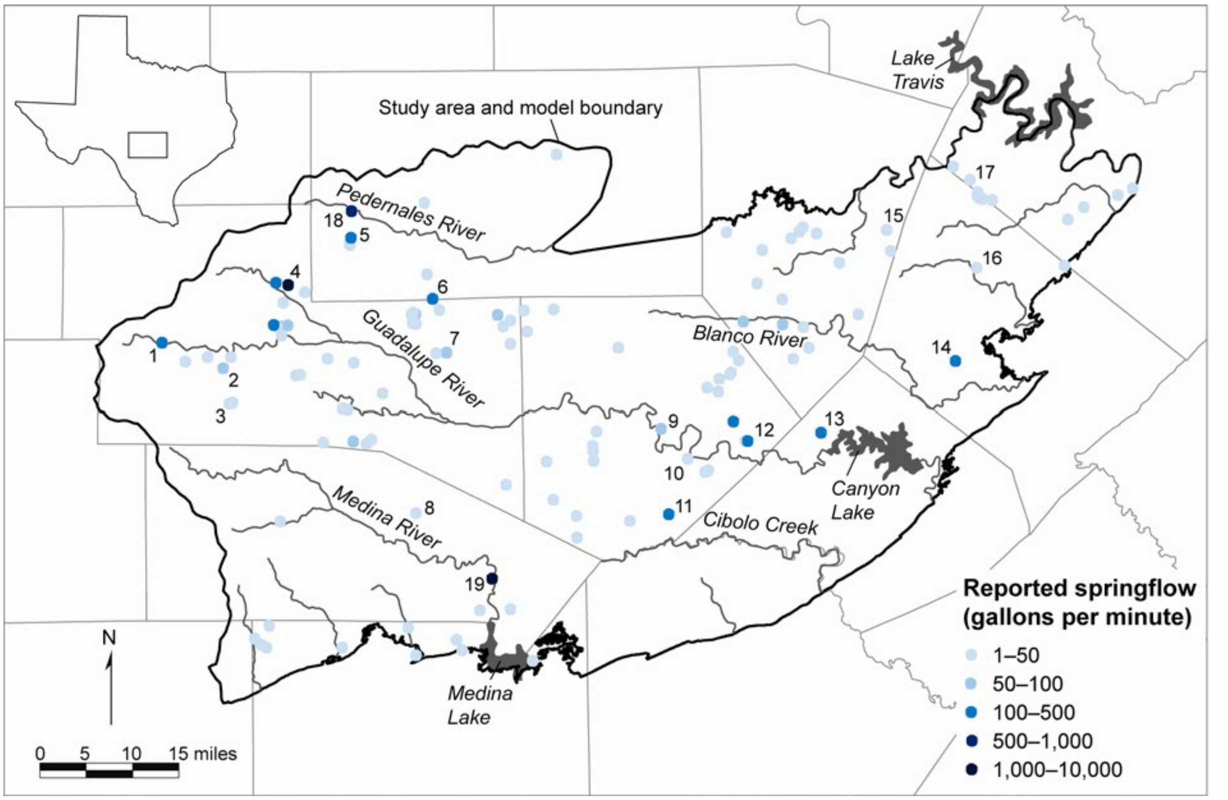


Figure 5-28. Location and estimated spring discharge in the study area. Springflow and geological formations where the numbered springs occur are included in Table 5-2 (from Mace and others, 2000).

Table 5-2. **Estimated flow for selected springs in the study area (see Figure 5-28) (from Mace and others, 2000).**

Spring	Estimated flow (gallons per minute)	Formation	Remarks
1	150	Edwards Group and associated limestone	Measured on 4/13/67
2	100	Edwards Group and associated limestone	Measured on 4/12/67, reported flow never ceased
3	100	Edwards Group and associated limestone	
4	2,500	Edwards Group and associated limestone	Measured on 3/31/66, reported flow never ceased
5	310	Edwards Group and associated limestone	Measured on 3/11/70
6	480	Edwards Group and associated limestone	Measured on 3/11/70, owner's trough spring
7	100	Edwards Group and associated limestone	Measured on 6/15/66, reported flow never ceased
8	20	Upper member of the Glen Rose Limestone	Measured on 7/13/76
9	75	Lower member of the Glen Rose Limestone	Measured on 7/10/75, ceased flowing in 1956
10	50	Lower member of the Glen Rose Limestone	Measured on 1/17/40
11	150	Lower member of the Glen Rose Limestone	Measured on 7/17/75, owner's well 9
12	300	Lower member of the Glen Rose Limestone	
13	300	Cow Creek Limestone	Measured on 7/11/75
14	500	Cow Creek Limestone	Measured on 8/31/76, estimated flow 1,070 gallons per minute, January 1955
15	25	Lower member of the Glen Rose Limestone	Measured on 1/1/66
16	50	Upper member of the Glen Rose Limestone	Measured on 12/30/88, Bassett Springs
17	50	Upper member of the Glen Rose Limestone	Measured on 5/25/73
18	9,000	Edwards Group and associated limestone	Measured on 12/20/60
19	5,000	Lower member of the Glen Rose Limestone	Measured on 8/20/91, springs discharge into Medina River

5.6 Hydraulic Properties

Variations in well yields are generally a result of variation in hydraulic properties of aquifers. Well yields in the Hill Country portion of the Trinity Aquifer System are commonly controlled by the location of fractures and dissolution features and, consequently, may vary considerably over short distances. Although the Hill Country portion of the Trinity Aquifer System as a whole is recognized by the TWDB as a major aquifer (Ashworth and Hopkins, 1995), well yields can be low compared with those of other major aquifers.

Hydraulic conductivity is defined as the rate of movement of water through a porous medium under a unit gradient. For example, very porous limestone may have hydraulic conductivities greater than 1,000 feet per day, and sandy limestone may range from 100 to 1,000 feet per day, whereas aquifers having moderate hydraulic conductivity values may range from 10 to 100 feet per day, and aquifers having low hydraulic conductivity may range from 0.1 to 10 feet per day. Transmissivity is defined as the hydraulic conductivity times the thickness of the aquifer and is thus a measure of the rate of movement through a defined thickness of aquifer under a unit gradient.

Pumping tests in wells are conducted to develop estimates of hydraulic conductivity and transmissivity. On the basis of 15 aquifer tests, Hammond (1984) determined that hydraulic conductivity ranges from 0.1 to 10 feet per day in the lower member of the Glen Rose Limestone. Barker and Ardis (1996) thought that hydraulic conductivity probably averages about 10 feet per day in the Hill Country portion of the Trinity Aquifer System. No one has investigated vertical hydraulic conductivities, although vertical hydraulic conductivities are likely to be much lower than horizontal hydraulic conductivities, especially in the upper member of the Glen Rose Limestone. Barker and Ardis (1996) noted that recharging water moves laterally more easily atop low-permeability beds than vertically through them. Guyton and Associates (1993) estimated that the vertical hydraulic conductivity of the Hammett Shale, the Bexar Shale, and the marls of the upper member of the Glen Rose Limestone was about 0.0001 to 0.003 feet per day. In their model that included the Hill Country portion of the Trinity Aquifer System, Kuniansky and Holligan (1994) considered part of the Hill Country portion of the Trinity Aquifer System along the Edwards (Balcones Fault Zone) Aquifer to have anisotropic properties, with greater hydraulic conductivity in the direction of faulting.

Ashworth (1983) reported average transmissivities of about 230 square feet per day and 1,300 square feet per day for the Middle and Lower Trinity aquifers, respectively, and suggested that substantially lower transmissivities are expected for the Upper Trinity Aquifer. Kuniansky and Holligan (1994) determined that transmissivity for the Hill Country portion of the Trinity Aquifer System ranged from 100 to 58,000 square feet per day. LBG-Guyton Associates (1995) summarized 53 aquifer tests in the Glen Rose Limestone along the Edwards (Balcones Fault Zone) Aquifer and found a median transmissivity of about 220 square feet per day. The Glen Rose Limestone can be unusually permeable in outcrop and shallow subcrop in northern Bexar County and southwestern Comal County near Cibolo Creek (Kastning, 1986; Veni, 1994). Barker and Ardis (1996) developed a map of transmissivity for the Hill Country portion of the Trinity Aquifer System on the basis of aquifer tests, geologic observation, and computer modeling. They determined that transmissivity is generally less than 5,000 square feet per day but increases from 5,000 to 50,000 square feet per day along the boundary between Comal and Bexar counties and through Kendall County and eastern Kerr County. The quartzose clastic facies of the updip Hensell Sand include some of the most permeable sediments in the Hill

Country portion of the Trinity Aquifer System (Barker and Ardis, 1996). Ardis and Barker (1993) and Barker and Ardis (1996) surmised that the variations in transmissivity in the Hill Country are probably due more to variations in aquifer thickness than to tectonism or diagenesis. However, Barker and Ardis (1996) noted that diagenesis of stable minerals has diminished permeability in most down-gradient, subcropping strata and that the leaching of carbonate constituents has enhanced permeability in some of the outcrop.

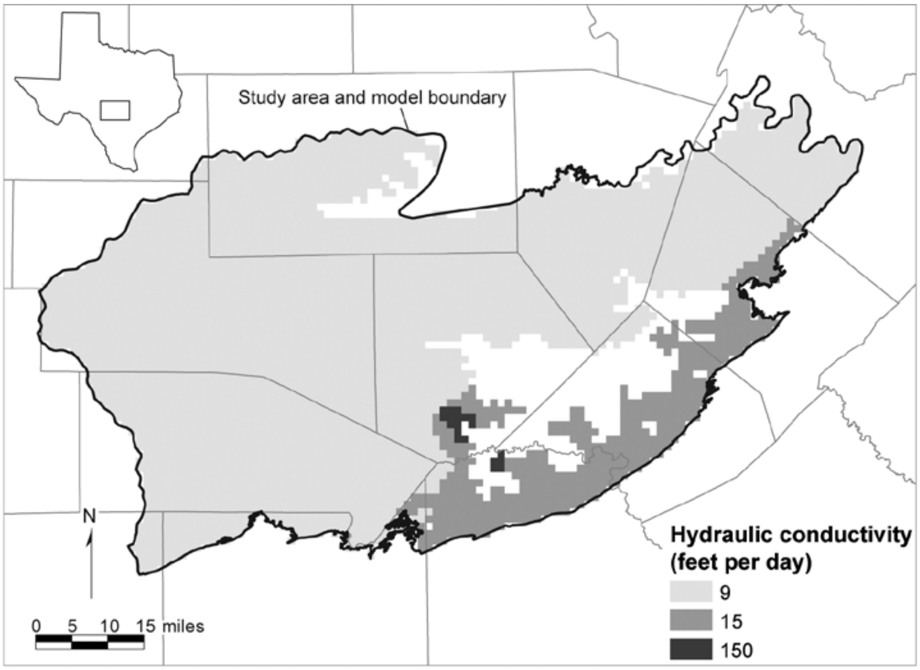
Storativity is the volume of water released from storage per decline of hydraulic head (water pressure) and is typically less than 0.01 for a confined aquifer. Specific storage is defined as the storativity divided by the aquifer thickness. Ashworth (1983) estimated that in the Trinity Group, the confined storativity ranges between 10^{-5} and 10^{-3} (a specific storage of about 10^{-6} per foot) and that the unconfined storativity (specific yield) ranges between 0.1 and 0.3. On the basis of two aquifer tests, Hammond (1984) determined a storativity of 3×10^{-5} for the lower member of the Glen Rose Limestone. Although we could not locate values for the Edwards Group in the plateau area, the specific yield for the Edwards Group in the Edwards (Balcones Fault Zone) Aquifer is 0.03 (Maclay and Small, 1986, p. 68–69). Specific yield is a ratio that describes the fraction of aquifer volume that will “yield,” or be released, when the water is allowed to drain out of the aquifer under gravity.

To estimate hydraulic properties for the study area and expand upon previous studies, Mace and others (2000) (1) compiled available information on aquifer properties or tests from published reports and well records, (2) conducted and analyzed detailed aquifer tests in the study area, (3) used specific-capacity information to estimate transmissivity, and (4) summarized the results using statistics. Mace and others (2000) compiled aquifer property data from (1) available literature (Meyers, 1969; Hammond, 1984; Simpson Company Limited and Guyton and Associates, 1993; LBG-Guyton Associates, 1995; Bradley and others, 1997), (2) aquifer tests that they conducted in the study area, analyzing the results using the methodologies of Theis (1935), Cooper and Jacob (1946), and Kruseman and de Ridder (1994), and (3) specific-capacity (well-performance) tests from the TWDB water-well database. To estimate transmissivity, Mace and others (2000) used an analytical technique (Theis, 1963).

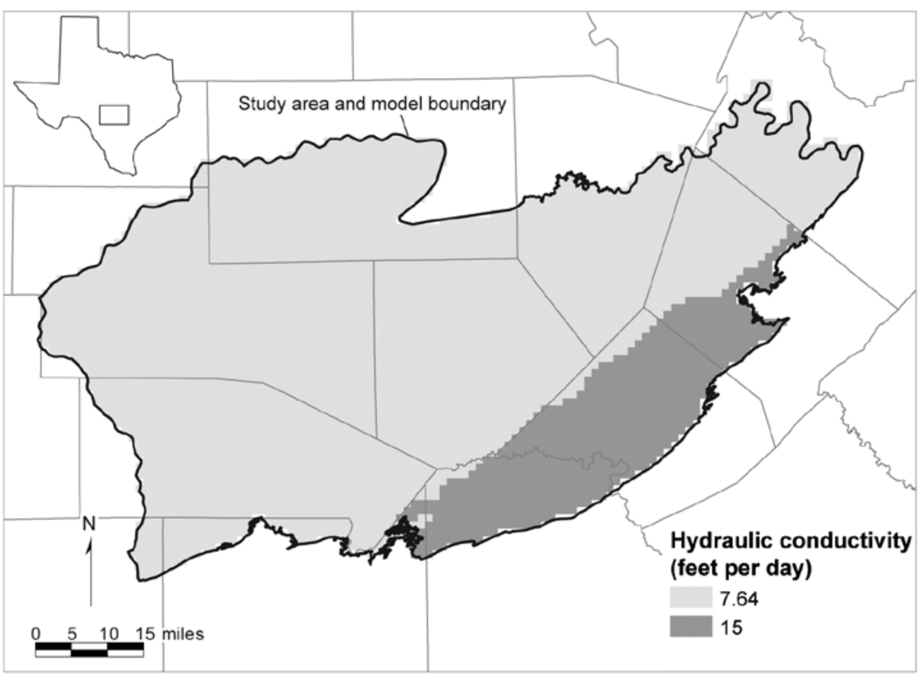
Mace and others (2000) developed a map of hydraulic conductivity for the Middle Trinity Aquifer, using the spatial distribution of hydraulic conductivity in each unit of the Middle Trinity Aquifer (Cow Creek Limestone, Hensell Sand, and lower member of the Glen Rose Limestone) and the relative thickness of each unit. To estimate the hydraulic conductivity of the Middle Trinity Aquifer at any given point, Mace and others (2000) weighted the hydraulic conductivity of each layer by the relative thickness of each respective layer at that point. As a result of the paucity of data from the Edwards Group and Upper Trinity Aquifer, Mace and others (2000) distributed hydraulic conductivity uniformly through the study area. The hydraulic conductivity values used in the Edwards Group and Upper Trinity Aquifer, 7 feet per day and 5 feet per day, respectively, are derived from calibration of the model by Mace and others (2000).

In the updated model, we simplified the distribution of hydraulic conductivity in the model and adjusted it during model calibration. As a result, hydraulic conductivity in the Edwards Group is the uniformly distributed value of 11 feet per day, whereas hydraulic conductivity in the underlying Upper, Middle, and Lower Trinity aquifers is divided into two zones. One zone represents higher hydraulic conductivity values in the Balcones Fault Zone and along Cibolo Creek, and the other zone represents the rest of the aquifer (Figure 5-29). Hydraulic conductivity values for the Lower Trinity Aquifer obtained from the TWDB groundwater database and Hays

Trinity Groundwater Conservation District lie within the range of 0.01 to 4.41 feet per day with a geometric mean of 0.52 feet per day. We calculated the hydraulic conductivity from specific-capacity data from the TWDB well database using methods outlined in Mace (2001).

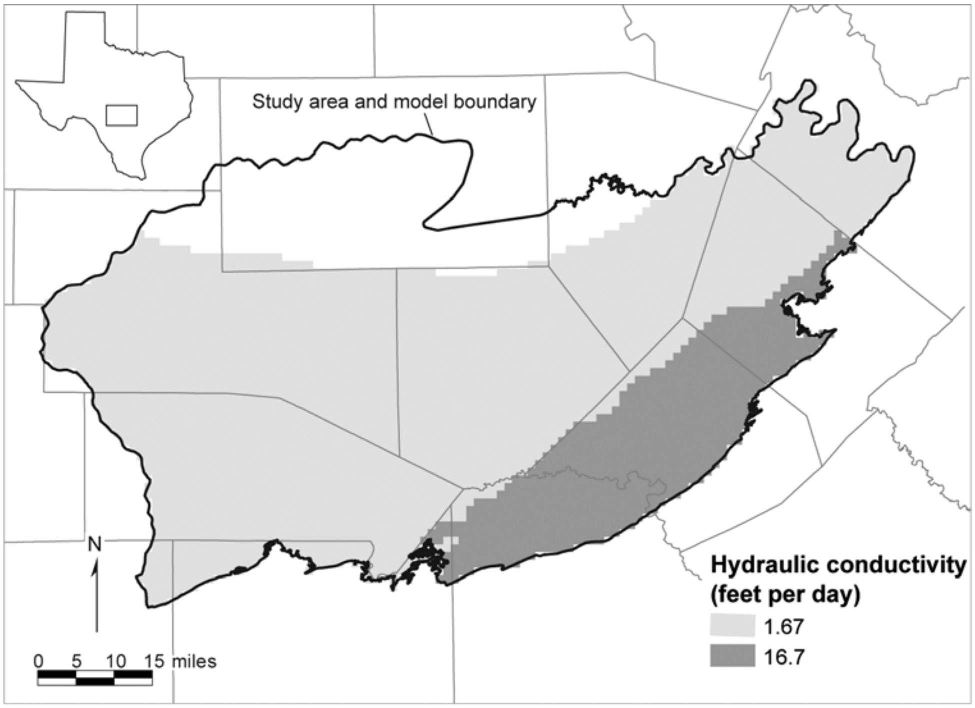


(a) Upper Trinity Aquifer



(b) Middle Trinity Aquifer

Figure 5-29. Distribution of hydraulic conductivity in the (a) Upper, (b) Middle, and (c) Lower Trinity aquifers.



(c) Lower Trinity Aquifer

Figure 5-29. (continued).

5.7 Discharge

Discharge from the Upper and Middle Trinity aquifers in the Hill Country portion of the Trinity Aquifer System is, from greatest to lowest, through (1) discharge to streams and springs (Ashworth, 1983), (2) lateral subsurface flow and diffuse upward leakage to the Edwards (Balcones Fault Zone) Aquifer (Veni, 1994), (3) pumping from the aquifer, and (4) vertical leakage to the Lower Trinity Aquifer. Discharge from the Lower Trinity Aquifer takes the form of pumping and vertical leakage to the overlying Middle Trinity Aquifer. The model by Kuniansky and Holligan (1994) indicates net discharge to streams from the Hill Country portion of the Trinity Aquifer System of 155,000 acre-feet per year. The volume of base flow varies from year to year depending on precipitation.

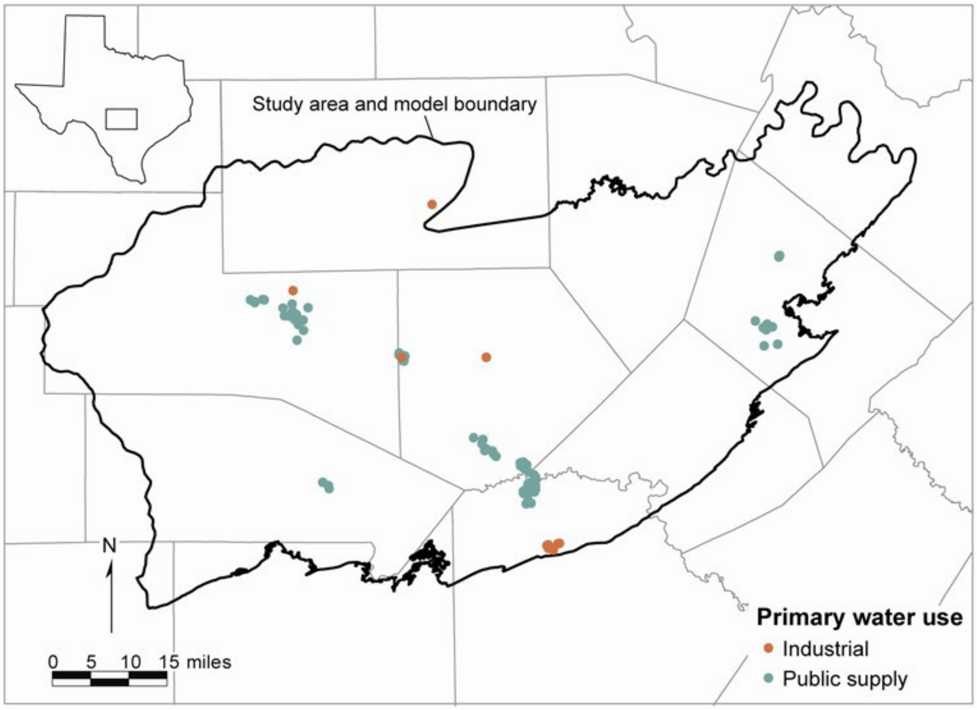
The volume of water that moves laterally from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer is not known, partly because of the difficulty in estimating the amount of flow. A number of studies have indicated, either through hydraulic or chemical analysis, that groundwater most likely flows from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer (Long, 1962; Klemt and others, 1979; Walker, 1979; Senger and Kreitler, 1984; Slade and others, 1985; Maclay and Land, 1988; Waterreus, 1992; Veni, 1994, 1995). Most of these studies focused on the movement of groundwater from the Glen Rose Limestone into the Edwards (Balcones Fault Zone) Aquifer; however, water levels (Figures 5-10 through 5-12) suggest that groundwater from the entire Hill Country portion of the Trinity Aquifer System discharges to the south and east in the direction of the Edwards (Balcones Fault Zone) Aquifer. Some of this groundwater flows directly into the Edwards (Balcones Fault Zone) Aquifer along faults, whereas the rest continues to flow in the Hill Country portion of the Trinity Aquifer System beneath the Edwards (Balcones

Fault Zone) Aquifer. It is possible that groundwater that continues to flow in the Hill Country portion of the Trinity Aquifer System eventually discharges upward into the Edwards (Balcones Fault Zone) Aquifer. However, work by Hovorka and others (1996) suggests that this vertical cross-formational flow is limited. The Glen Rose Limestone in the Cibolo Creek area has been argued to be a part of the Edwards (Balcones Fault Zone) Aquifer owing to the hydraulic response and continuity of the formations (George, 1947; Pearson and others, 1975; Veni 1994, 1995).

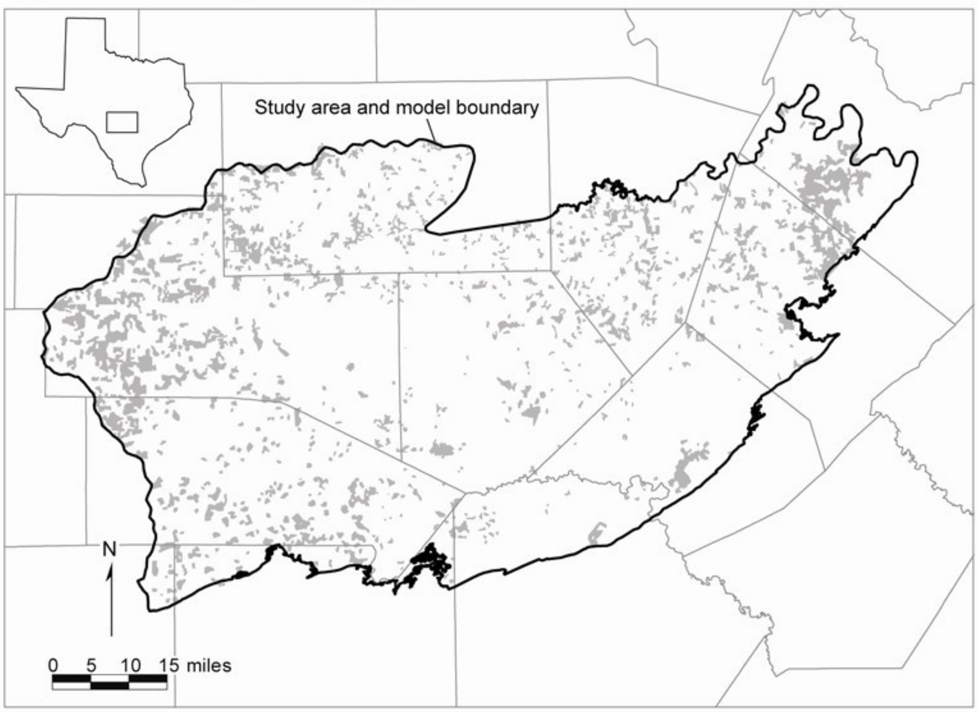
A few studies have estimated the volume of flow from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer. Lowry (1955) attributed a 5 percent error between measured inflows and outflows in the Edwards (Balcones Fault Zone) Aquifer to cross-formational flow from the Glen Rose Limestone. Woodruff and Abbott (1986), citing a personal communication with Bill Klemt, reported that recharge from cross-formational flow accounts for 6 percent of total recharge, or about 41,000 acre-feet per year on average, to the Edwards (Balcones Fault Zone) Aquifer. Kuniansky and Holligan (1994) suggested predevelopment groundwater discharge of 360,000 acre-feet per year from the Hill Country portion of the Trinity Aquifer System to the Edwards (Balcones Fault Zone) Aquifer. This estimate is about 53 percent of average annual recharge to the Edwards (Balcones Fault Zone) Aquifer and is probably too high (Mace and others, 2000). LBG-Guyton Associates (1995) estimated cross-formational flow from the Glen Rose Limestone to the Edwards (Balcones Fault Zone) Aquifer in the San Antonio area, excluding recharge from Cibolo Creek, to be about 2 percent of total recharge to the aquifer. Mace and others (2000) estimated net discharge from the Hill Country portion of the Trinity Aquifer System to the Edwards (Balcones Fault Zone) Aquifer of 64,000 acre-feet per year. Of the numerical groundwater flow models of the Edwards (Balcones Fault Zone) Aquifer by Klemt and others (1979), Slade and others (1985), Maclay and Land (1988), Wanakule and Anaya (1993), Barrett and Charbeneau (1996), and Lindgren and others (2004), only that of Lindgren and others (2004) includes cross-formational flow from the Hill Country portion of the Trinity Aquifer System. Maclay and Land (1988) recognized the occurrence of cross-formational flow between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer, but only as a topic for future study. Kuniansky and Holligan (1994) estimated 1974 to 1975 cross-formational flow from the Hill Country portion of the Trinity Aquifer System to be about 480,000 acre-feet per year, an order of magnitude larger than calculated cross-formational flow by Lindgren and others (2004) of about 40,000 acre-feet per year.

Groundwater also discharges from the aquifer through pumping of water wells. Lurry and Pavlicek (1991), Barker and Ardis (1996), and Kuniansky and Holligan (1994) estimated pumping from the Hill Country portion of the Trinity Aquifer System to be between 10,000 and 15,000 acre-feet per year in the 1970s. On the basis of information in Bluntzer (1992), we estimated that about 14,000 acre-feet per year was produced from the Hill Country portion of the Trinity and Edwards-Trinity (Plateau) aquifer systems in the study area. Guyton and Associates (1993) estimated that about 6,350 acre-feet was pumped from the Hill Country portion of the Trinity Aquifer System in northern Bexar County in 1990, with 85 percent of production coming from the Middle Trinity Aquifer. TWDB pumping data indicate that for the period 1980 through 1997 pumping from the Hill Country portion of the Trinity Aquifer System ranged from 14,000 to 24,000 acre-feet per year.

The primary categories of water use in the Hill Country portion of the Trinity Aquifer System are (1) municipal, (2) manufacturing, (3) livestock, (4) rural domestic, and (5) irrigation. Municipal and manufacturing water uses are based on reported values from the users. We associated these values with known well locations and aquifers by cross-referencing the water use to the municipal and manufacturing wells through the Texas Commission on Environmental Quality municipal water-well database, through the TWDB water-well database, and through telephone interviews with water users (Figure 5-30a). We distributed livestock, rural domestic, and irrigation pumping on the basis of the spatial distribution of range land, nonurban population, and irrigated farm land, respectively (Figures 5-30a through 5-30d). Pumping from the Hill Country portion of the Trinity Aquifer System has been rising over time, from about 15,000 acre-feet per year in 1981 to more than 20,000 acre-feet per year by 1997 (Figure 5-31). About two-thirds of this pumping is for rural domestic and municipal uses, and the rest is used for manufacturing, livestock, and irrigation. The increasing pumping from the aquifer is mostly due to increasing rural domestic pumping that rose from 6,000 acre-feet per year in 1980 to more than 10,000 acre-feet per year by 1997 (Figure 5-32). Municipal pumping rose gradually from 2,500 acre-feet per year in 1981 to about 5,000 acre-feet per year in 1997. Pumping for livestock and irrigation has remained relatively constant over the period 1980 through 1997. Manufacturing pumping rose from about 2,500 acre-feet per year to about 4,400 acre-feet per year in the late 1980s and remained relatively constant after 1988. Pumping from the Hill Country portion of the Trinity Aquifer System has been progressively increasing in most counties within the study area (Figure 5-33; Tables 5-3 to 5-8). However, pumping has remained relatively constant in Comal, Kimble, Travis, and Uvalde counties. Over the period 1980 through 1997, pumping doubled in Blanco, Gillespie, Hays, and Kendall counties.

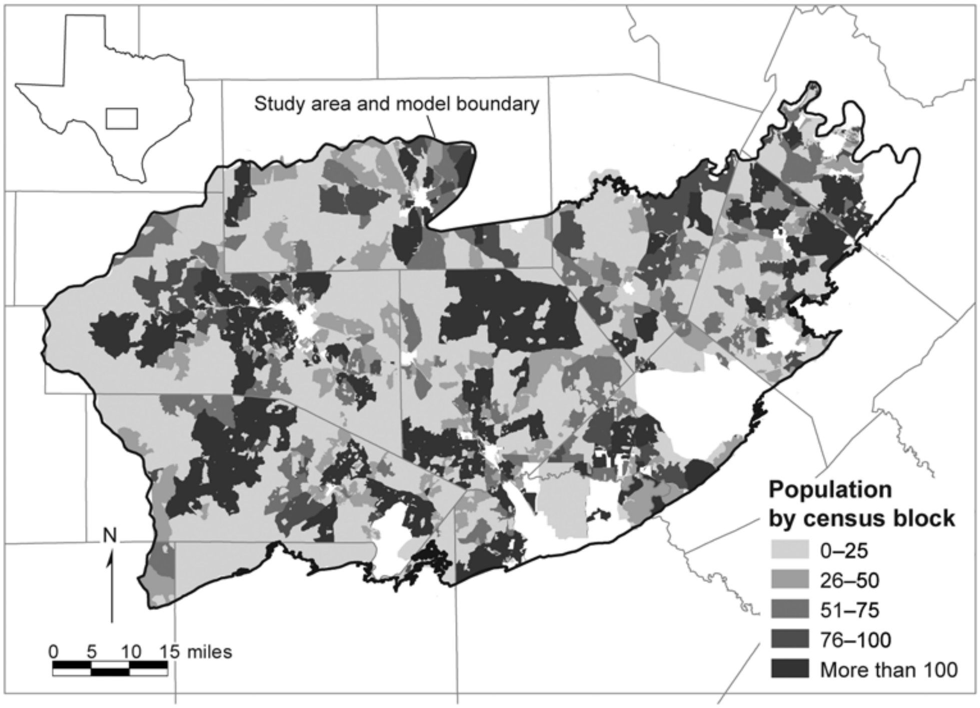


(a) Industrial and public supply wells

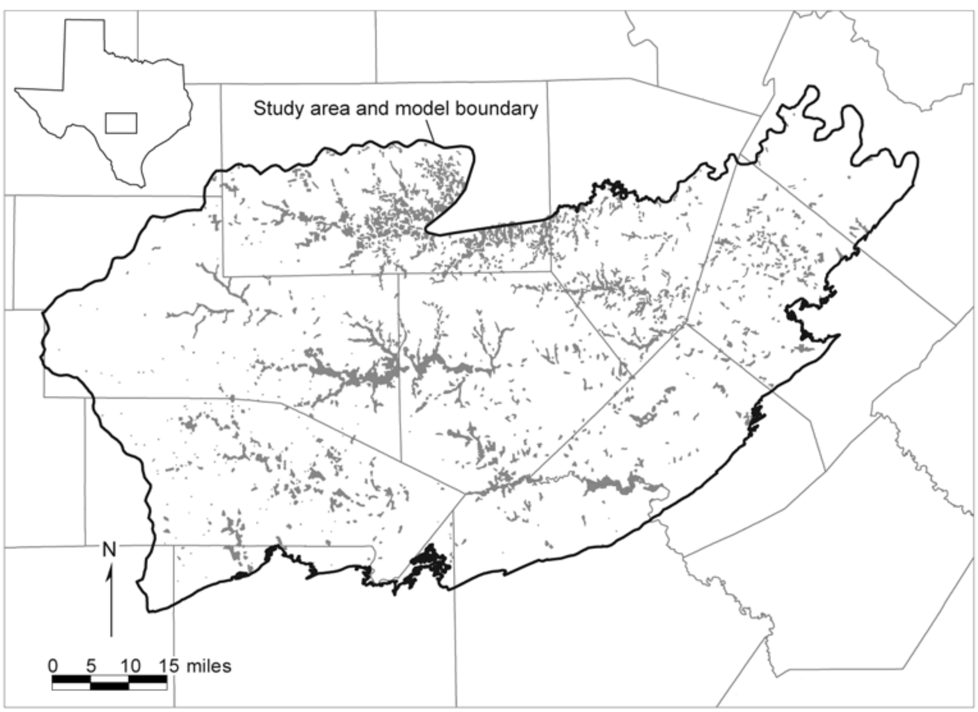


(b) Range land

Figure 5-30. Spatial distribution of pumping throughout the 1980 through 1997 model period for manufacturing, municipal, livestock, rural domestic, and irrigation uses based on the spatial distribution of (a) industrial and public supply wells, (b) range land, (c) rural population, and (d) irrigated farm land, respectively.



(c) Rural population



(d) Irrigated farm land

Figure 5-30. (continued).

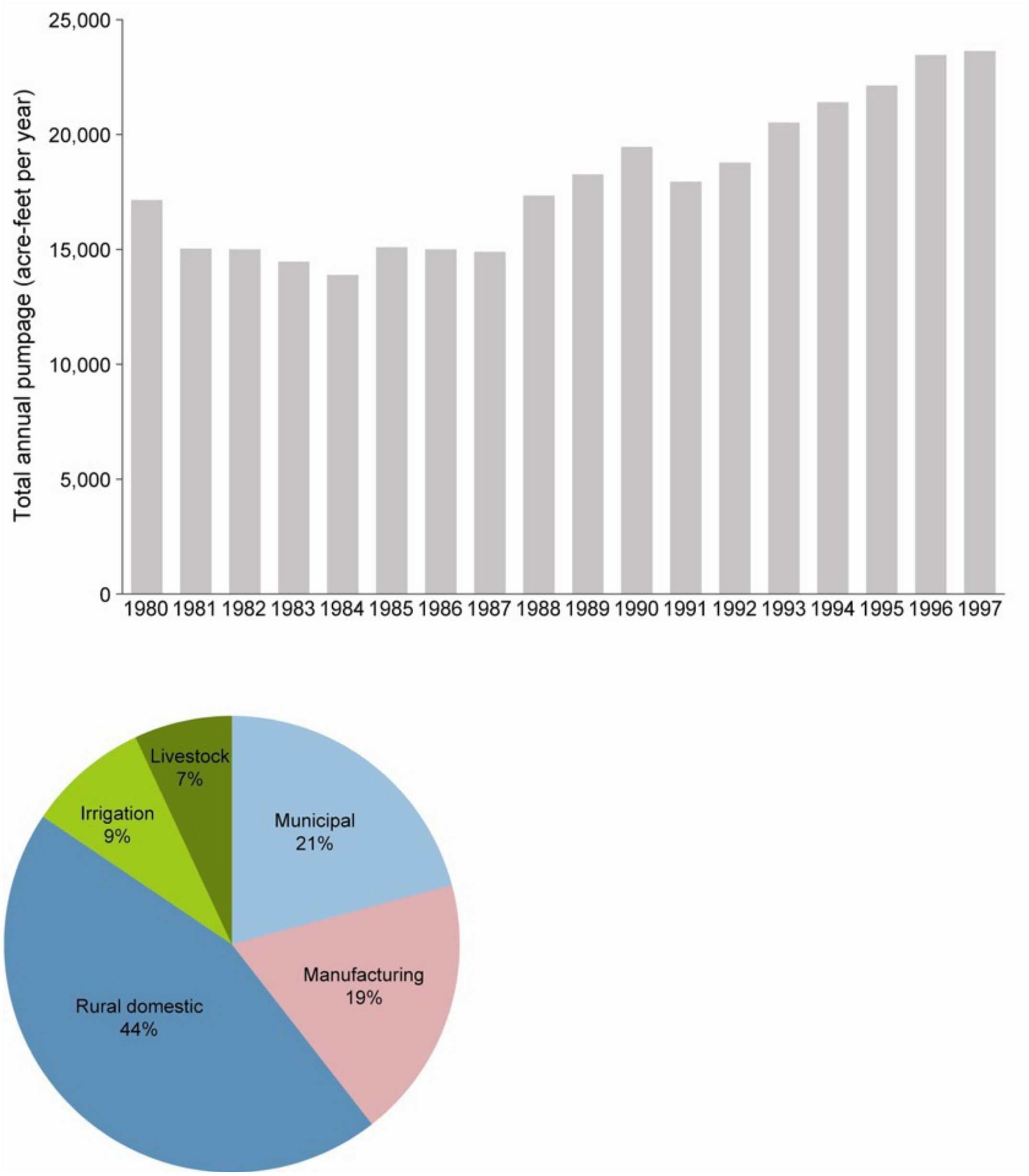


Figure 5-31. Total annual groundwater pumpage from the Hill Country portion of the Trinity Aquifer System, 1980 through 1997.

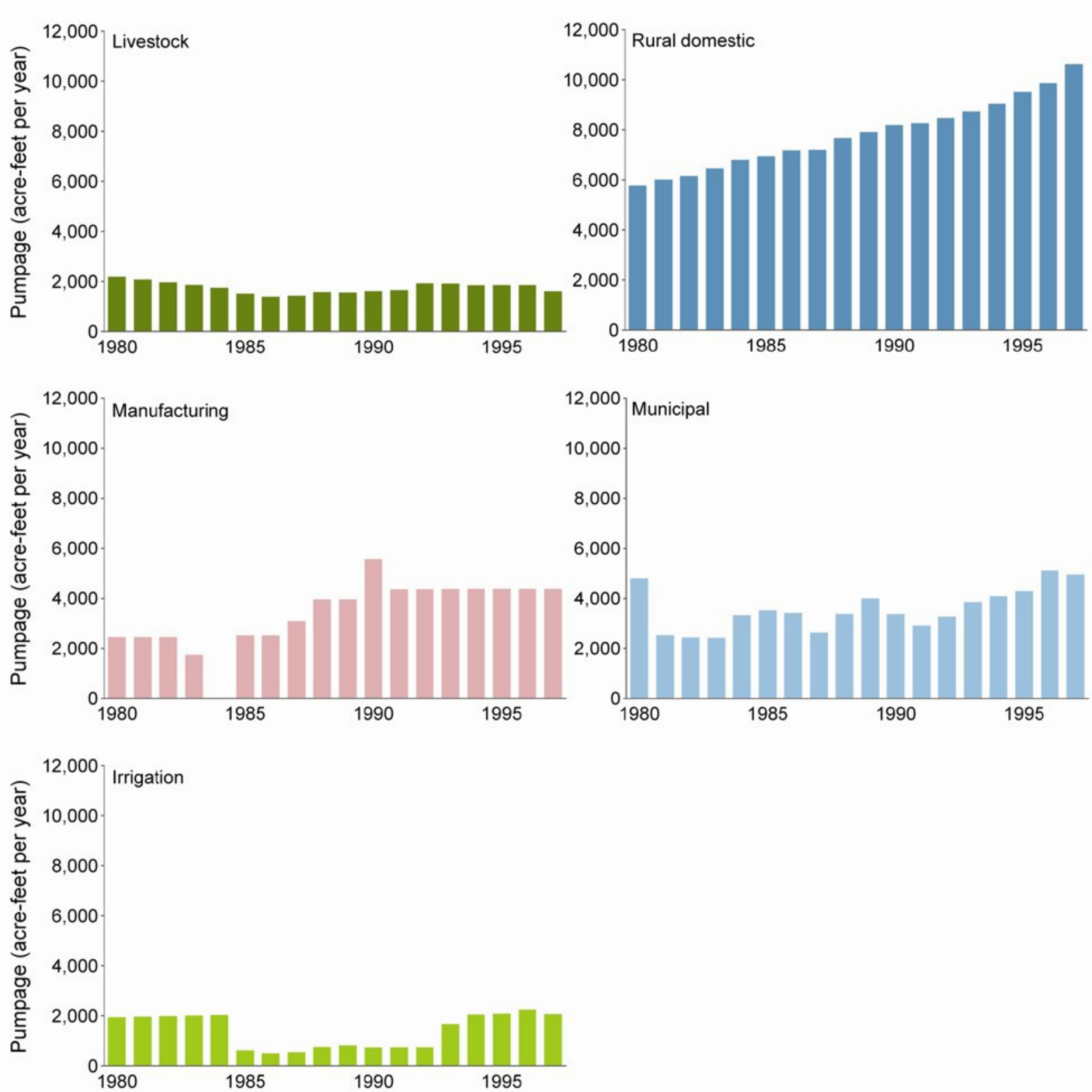


Figure 5-32. **Annual groundwater pumping from the Hill Country portion of the Trinity Aquifer System for livestock, rural domestic, manufacturing, municipal, and irrigation uses, 1980 through 1997.**

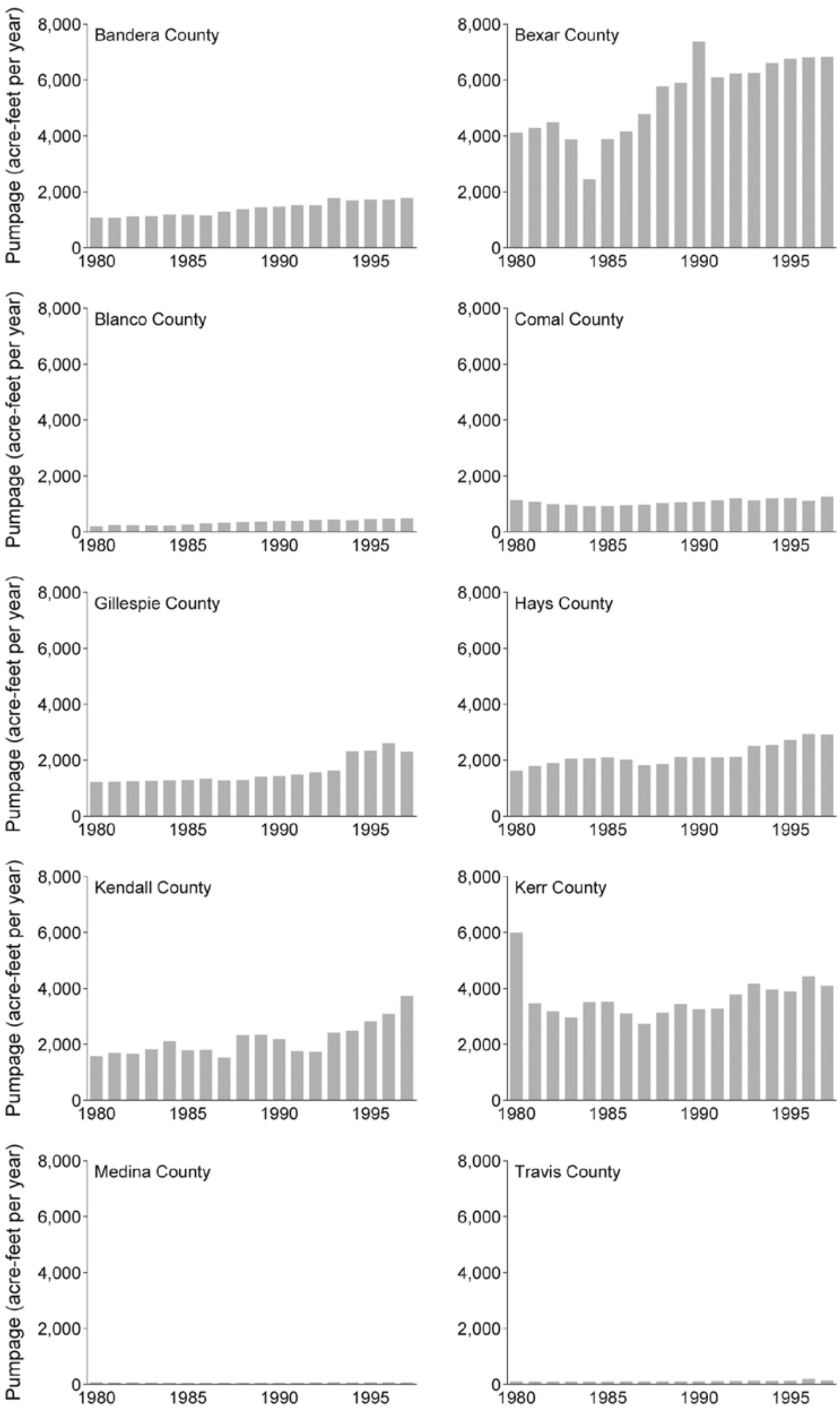


Figure 5-33. **Total annual pumpage from the Hill Country portion of the Trinity Aquifer System for each county in the study area.**

Table 5-3. **Total pumping from the Hill Country portion of the Trinity Aquifer System for each county for the period 1980 through 1997 (all values in acre-feet per year).**

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall
1980	1,084	4,120	195	1,135	1,223	1,621	1,585
1981	1,077	4,280	234	1,076	1,235	1,788	1,690
1982	1,120	4,486	230	998	1,248	1,903	1,663
1983	1,129	3,875	224	978	1,260	2,046	1,829
1984	1,182	4,359	217	916	1,273	2,059	2,115
1985	1,175	3,892	261	918	1,289	2,087	1,781
1986	1,154	4,165	312	949	1,332	2,018	1,793
1987	1,290	4,775	333	987	1,273	1,817	1,518
1988	1,374	5,774	350	1,035	1,289	1,865	2,337
1989	1,441	5,900	367	1,058	1,421	2,116	2,343
1990	1,462	7,372	386	1,080	1,440	2,093	2,185
1991	1,529	6,098	388	1,128	1,484	2,096	1,751
1992	1,528	6,227	422	1,200	1,558	2,125	1,728
1993	1,784	6,249	432	1,125	1,633	2,506	2,414
1994	1,684	6,609	413	1,199	2,308	2,539	2,482
1995	1,723	6,767	453	1,214	2,329	2,719	2,823
1996	1,709	6,814	465	1,112	2,615	2,935	3,092
1997	1,785	6,832	472	1,268	2,297	2,923	3,738

Year	Kerr	Kimble	Medina	Travis	Uvalde	Total
1980	5,994	7	63	111	11	17,148
1981	3,463	7	60	108	11	15,027
1982	3,176	6	57	101	11	15,000
1983	2,954	6	53	100	11	14,466
1984	3,517	5	50	96	11	15,799
1985	3,529	5	45	100	11	15,093
1986	3,104	7	45	110	10	14,999
1987	2,727	6	49	111	10	14,896
1988	3,135	6	49	116	10	17,342
1989	3,433	5	49	116	10	18,259
1990	3,263	5	50	117	10	19,461
1991	3,282	5	51	125	10	17,945
1992	3,787	5	57	127	11	18,775
1993	4,161	5	66	139	11	20,525
1994	3,962	5	60	134	11	21,406
1995	3,886	6	64	138	11	22,133
1996	4,439	6	62	200	12	23,460
1997	4,095	5	59	146	11	23,631

Table 5-4. Total pumping from the Hill Country portion of the Trinity Aquifer System by use category for each county for the period 1980 through 1997 (all values in acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Municipal													
1980	190	157	0	0	0	573	380	3,491	0	0	0	0	4,791
1981	168	177	0	0	0	732	404	1,042	0	0	0	0	2,523
1982	198	245	0	0	0	834	424	735	0	0	0	0	2,436
1983	193	220	0	0	0	965	500	538	0	0	0	0	2,416
1984	232	380	0	0	0	964	700	1,036	0	0	0	0	3,312
1985	199	360	0	0	0	1,150	553	1,248	0	0	0	0	3,510
1986	222	612	0	0	0	1,062	582	925	0	0	0	0	3,403
1987	204	645	0	0	0	825	449	506	0	0	0	0	2,629
1988	227	761	0	0	0	834	712	830	0	0	0	0	3,364
1989	297	869	0	0	0	1,076	737	1,023	0	0	0	0	4,002
1990	269	719	0	0	0	1,019	632	720	0	0	0	0	3,359
1991	275	612	0	0	0	979	378	658	0	0	0	0	2,902
1992	219	719	0	0	0	962	322	1,035	0	0	0	0	3,257
1993	298	719	0	0	0	1,220	412	1,178	0	0	0	0	3,827
1994	340	1,071	0	0	0	1,281	474	924	0	0	0	0	4,090
1995	322	1,213	0	0	0	1,317	566	867	0	0	0	0	4,285
1996	299	1,213	0	0	0	1,485	746	1,363	0	0	0	0	5,106
1997	331	1,213	0	0	0	1,432	999	965	0	0	0	0	4,940
Manufacturing													
1980	0	2,449	0	0	0	0	0	0	0	0	0	0	2,449
1981	0	2,449	0	0	0	0	0	0	0	0	0	0	2,449
1982	0	2,449	0	0	0	0	0	0	0	0	0	0	2,449
1983	0	1,727	0	0	0	0	0	0	0	0	0	0	1,727
1984	0	1,912	0	0	0	0	0	0	0	0	0	0	1,912
1985	0	2,516	0	0	0	0	0	0	0	0	0	0	2,516
1986	0	2,516	0	0	0	0	0	0	0	0	0	0	2,516
1987	0	3,085	0	0	0	0	0	0	0	0	0	0	3,085
1988	0	3,949	0	0	1	0	0	0	0	0	0	0	3,950
1989	0	3,949	0	0	0	0	0	0	0	0	0	0	3,949
1990	0	5,549	0	0	0	0	0	0	0	0	0	0	5,549
1991	0	4,363	0	0	0	0	0	0	0	0	0	0	4,363
1992	0	4,363	0	0	0	0	0	4	0	0	0	0	4,367
1993	0	4,363	0	0	0	0	0	7	0	0	0	0	4,370
1994	0	4,370	0	0	0	0	0	7	0	0	0	0	4,377
1995	0	4,370	0	0	0	0	0	7	0	0	0	0	4,377
1996	0	4,370	0	0	0	0	0	6	0	0	0	0	4,376
1997	0	4,370	0	0	0	0	0	7	0	0	0	0	4,377

Table 5-4. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Rural domestic													
1980	570	878	39	557	832	624	564	1,654	0	21	34	7	5,780
1981	598	897	85	581	854	663	652	1,619	0	21	36	7	6,013
1982	626	915	88	587	877	705	613	1,687	0	22	35	7	6,162
1983	654	930	87	650	899	747	710	1,709	0	22	39	7	6,454
1984	683	948	87	672	922	791	803	1,820	0	22	40	7	6,795
1985	710	966	138	697	945	832	770	1,813	0	23	41	7	6,942
1986	739	984	177	728	967	874	808	1,844	0	23	48	7	7,199
1987	766	1,001	198	755	989	916	643	1,865	0	23	54	7	7,217
1988	794	1,019	210	778	1,012	959	909	1,916	0	24	54	8	7,683
1989	822	1,036	213	803	1,035	997	963	1,969	0	24	55	8	7,925
1990	850	1,054	215	828	1,057	1,031	968	2,108	0	25	54	8	8,198
1991	908	1,073	214	870	1,080	1,073	779	2,179	0	26	61	8	8,271
1992	964	1,091	225	916	1,102	1,132	722	2,222	0	27	67	8	8,476
1993	1,022	1,110	235	843	1,124	1,249	787	2,266	0	28	70	8	8,742
1994	1,078	1,128	245	905	1,146	1,217	904	2,309	0	29	77	8	9,046
1995	1,135	1,147	268	909	1,168	1,361	1,075	2,352	0	30	81	8	9,534
1996	1,193	1,165	304	859	1,190	1,418	1,234	2,396	0	31	82	8	9,880
1997	1,249	1,184	307	1,016	1,213	1,462	1,632	2,439	0	32	91	8	10,633
Irrigation													
1980	62	611	47	368	52	102	200	500	4	0	0	0	1,946
1981	58	734	45	279	70	89	221	469	4	0	0	0	1,969
1982	54	857	43	190	88	76	241	437	4	0	0	0	1,990
1983	50	979	40	101	105	63	262	406	4	0	0	0	2,010
1984	47	1,102	38	12	123	50	282	374	3	0	0	0	2,031
1985	68	0	28	0	111	64	132	204	4	0	0	0	611
1986	10	0	28	0	93	44	176	136	5	0	0	0	492
1987	124	0	28	0	30	35	176	136	5	0	0	0	534
1988	124	0	28	0	8	29	440	136	4	0	0	0	769
1989	95	0	41	0	127	0	369	191	3	0	0	0	826
1990	115	0	47	0	113	0	274	187	3	0	0	0	739
1991	115	0	47	0	127	0	274	187	3	0	0	0	753
1992	115	0	47	0	127	0	274	187	3	0	0	0	753
1993	248	0	51	0	170	0	808	396	3	0	0	0	1,676
1994	15	0	51	10	845	0	718	406	3	0	0	0	2,048
1995	14	0	54	9	841	0	808	355	4	0	0	0	2,085
1996	15	0	54	10	957	0	808	396	4	0	0	0	2,244
1997	15	0	54	9	782	0	808	396	3	0	0	0	2,067

Table 5-4. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Livestock													
1980	262	25	109	210	339	322	441	349	3	42	78	4	2,184
1981	252	23	104	216	311	305	413	333	3	39	72	4	2,075
1982	241	21	100	221	283	288	386	318	3	35	66	4	1,966
1983	231	18	96	227	256	271	358	302	2	32	61	3	1,857
1984	221	16	92	232	228	254	330	286	2	28	55	3	1,747
1985	198	50	96	221	232	41	326	264	2	22	59	3	1,514
1986	184	53	108	221	272	38	228	199	2	22	62	2	1,391
1987	197	44	106	232	254	40	249	219	2	26	58	2	1,429
1988	229	46	112	257	268	43	276	253	2	25	62	2	1,575
1989	227	46	113	255	259	43	274	250	2	25	61	2	1,557
1990	228	50	124	252	269	42	312	248	2	25	62	2	1,616
1991	231	50	126	258	278	44	319	258	2	25	64	2	1,657
1992	231	54	150	284	330	31	410	338	2	30	60	3	1,923
1993	216	57	146	282	339	37	407	314	2	38	69	3	1,910
1994	251	40	118	284	317	41	386	317	2	31	57	3	1,847
1995	251	37	131	296	321	41	374	305	2	34	57	3	1,852
1996	203	66	107	243	468	32	303	278	2	31	118	4	1,855
1997	190	65	111	243	302	28	298	288	2	27	55	3	1,612

Table 5-5. Total pumping from the Edwards Group by use category for each county for the period 1980 through 1997 (all values in acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Municipal													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0
Manufacturing													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5-5. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Rural domestic													
1980	47	0	0	0	262	0	77	448	0	0	0	0	834
1981	49	0	0	0	269	0	89	439	0	0	0	0	846
1982	52	0	0	0	276	0	83	457	0	0	0	0	868
1983	54	0	0	0	283	0	96	463	0	0	0	0	896
1984	56	0	0	0	290	0	109	493	0	0	0	0	948
1985	59	0	0	0	297	0	104	492	0	0	0	0	952
1986	61	0	0	0	304	0	110	500	0	0	0	0	975
1987	63	0	0	0	311	0	87	506	0	0	0	0	967
1988	66	0	0	0	318	0	123	519	0	0	0	0	1,026
1989	68	0	0	0	326	0	131	534	0	0	0	0	1,059
1990	70	0	0	0	333	0	131	572	0	0	0	0	1,106
1991	75	0	0	0	340	0	106	591	0	0	0	0	1,112
1992	80	0	0	0	347	0	98	603	0	0	0	0	1,128
1993	84	0	0	0	354	0	107	614	0	0	0	0	1,159
1994	89	0	0	0	361	0	123	626	0	0	0	0	1,199
1995	94	0	0	0	368	0	146	638	0	0	0	0	1,246
1996	99	0	0	0	375	0	167	650	0	0	0	0	1,291
1997	103	0	0	0	382	0	221	661	0	0	0	0	1,367
Irrigation													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5-5. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Livestock													
1980	16	0	0	0	0	0	0	157	3	0	0	0	176
1981	16	0	0	0	0	0	0	150	3	0	0	0	169
1982	15	0	0	0	0	0	0	143	3	0	0	0	161
1983	15	0	0	0	0	0	0	136	2	0	0	0	153
1984	14	0	0	0	0	0	0	129	2	0	0	0	145
1985	12	0	0	0	0	0	0	119	2	0	0	0	133
1986	11	0	0	0	0	0	0	89	2	0	0	0	102
1987	12	0	0	0	0	0	0	98	2	0	0	0	112
1988	14	0	0	0	0	0	0	113	2	0	0	0	129
1989	14	0	0	0	0	0	0	112	2	0	0	0	128
1990	14	0	0	0	0	0	0	112	2	0	0	0	128
1991	15	0	0	0	0	0	0	116	2	0	0	0	133
1992	15	0	0	0	0	0	0	152	2	0	0	0	169
1993	14	0	0	0	0	0	0	141	2	0	0	0	157
1994	17	0	0	0	0	0	0	143	2	0	0	0	162
1995	17	0	0	0	0	0	0	137	2	0	0	0	156
1996	13	0	0	0	0	0	0	125	2	0	0	0	140
1997	12	0	0	0	0	0	0	130	2	0	0	0	144

Table 5-6. **Total pumping from the Upper Trinity Aquifer by use category for each county for the period 1980 through 1997 (all values in acre-feet per year).**

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Municipal													
1980	0	0	0	0	0	0	33	0	0	0	0	0	33
1981	0	0	0	0	0	0	38	0	0	0	0	0	38
1982	0	0	0	0	0	0	38	0	0	0	0	0	38
1983	0	0	0	0	0	0	43	0	0	0	0	0	43
1984	0	0	0	0	0	0	67	0	0	0	0	0	67
1985	0	0	0	0	0	0	48	0	0	0	0	0	48
1986	0	0	0	0	0	0	46	0	0	0	0	0	46
1987	0	0	0	0	0	0	32	0	0	0	0	0	32
1988	0	0	0	0	0	0	67	0	0	0	0	0	67
1989	0	0	0	0	0	0	69	0	0	0	0	0	69
1990	0	0	0	0	0	0	57	0	0	0	0	0	57
1991	0	0	0	0	0	0	22	0	0	0	0	0	22
1992	0	0	0	0	0	0	10	0	0	0	0	0	10
1993	0	0	0	0	0	0	22	0	0	0	0	0	22
1994	0	0	0	0	0	0	31	0	0	0	0	0	31
1995	0	0	0	0	0	0	38	0	0	0	0	0	38
1996	0	0	0	0	0	0	65	0	0	0	0	0	65
1997	0	0	0	0	0	0	103	0	0	0	0	0	103
Manufacturing													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5-6. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Rural domestic													
1980	409	865	25	345	79	559	375	1,205	0	21	32	7	3,922
1981	429	884	54	360	81	593	434	1,180	0	21	34	7	4,077
1982	449	902	56	363	84	632	407	1,229	0	22	33	7	4,184
1983	469	917	56	402	86	669	472	1,246	0	22	38	7	4,384
1984	490	934	55	416	88	708	534	1,327	0	22	39	7	4,620
1985	509	952	88	431	90	745	512	1,322	0	23	39	7	4,718
1986	530	969	113	450	92	782	537	1,344	0	23	46	7	4,893
1987	549	987	126	467	94	821	428	1,360	0	23	51	7	4,913
1988	570	1,004	134	482	96	859	604	1,396	0	24	52	8	5,229
1989	590	1,021	136	497	99	892	640	1,435	0	24	53	8	5,395
1990	610	1,038	137	512	101	923	643	1,536	0	25	52	8	5,585
1991	651	1,058	136	539	103	961	518	1,588	0	26	58	8	5,646
1992	692	1,075	143	567	105	1,013	480	1,620	0	27	64	8	5,794
1993	733	1,094	149	521	107	1,118	523	1,651	0	28	67	8	5,999
1994	773	1,112	156	560	109	1,089	601	1,683	0	29	73	8	6,193
1995	814	1,130	170	563	111	1,218	714	1,715	0	30	77	8	6,550
1996	855	1,148	193	532	113	1,269	821	1,746	0	31	78	8	6,794
1997	896	1,166	195	629	115	1,309	1,085	1,778	0	32	87	8	7,300
Irrigation													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5-6. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Livestock													
1980	227	25	95	155	257	298	299	192	0	42	74	4	1,668
1981	218	23	91	158	236	281	280	183	0	39	69	4	1,582
1982	209	21	88	161	215	264	261	175	0	35	63	4	1,496
1983	200	18	84	165	194	247	242	166	0	32	58	3	1,409
1984	192	16	80	168	173	230	223	157	0	28	53	3	1,323
1985	172	50	83	155	176	37	221	145	0	22	56	3	1,120
1986	160	53	94	155	206	35	154	109	0	22	60	2	1,050
1987	171	44	93	163	192	36	168	121	0	26	55	2	1,071
1988	199	46	98	181	203	39	187	140	0	25	59	2	1,179
1989	197	46	99	179	196	39	185	138	0	25	58	2	1,164
1990	197	50	108	177	204	38	211	136	0	25	59	2	1,207
1991	200	50	110	181	210	40	216	142	0	25	61	2	1,237
1992	200	54	131	200	250	28	277	186	0	30	57	3	1,416
1993	187	57	128	198	257	34	276	173	0	38	66	3	1,417
1994	217	40	103	200	240	37	261	174	0	31	54	3	1,360
1995	217	37	114	208	243	37	253	168	0	34	54	3	1,368
1996	175	66	94	171	354	29	205	153	0	31	113	4	1,395
1997	164	65	97	171	229	26	202	158	0	27	53	3	1,195

Table 5-7. Total pumping from the Middle Trinity Aquifer by use category for each county for the period 1980 through 1997 (all values in acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Municipal													
1980	0	157	0	0	0	510	346	293	0	0	0	0	1,306
1981	0	177	0	0	0	666	366	200	0	0	0	0	1,409
1982	0	245	0	0	0	756	386	250	0	0	0	0	1,637
1983	0	220	0	0	0	869	457	262	0	0	0	0	1,808
1984	0	355	0	0	0	827	595	372	0	0	0	0	2,149
1985	0	341	0	0	0	1,003	469	355	0	0	0	0	2,168
1986	0	581	0	0	0	988	492	373	0	0	0	0	2,434
1987	0	613	0	0	0	724	353	318	0	0	0	0	2,008
1988	0	723	0	0	0	745	576	370	0	0	0	0	2,414
1989	0	830	0	0	0	981	596	409	0	0	0	0	2,816
1990	0	689	0	0	0	928	508	349	0	0	0	0	2,474
1991	0	587	0	0	0	882	293	347	0	0	0	0	2,109
1992	0	689	0	0	0	875	240	384	0	0	0	0	2,188
1993	0	691	0	0	0	1,098	316	441	0	0	0	0	2,546
1994	0	1,030	0	0	0	1,149	370	400	0	0	0	0	2,949
1995	0	1,166	0	0	0	1,218	442	349	0	0	0	0	3,175
1996	0	1,168	0	0	0	1,368	597	435	0	0	0	0	3,568
1997	0	1,169	0	0	0	1,313	817	356	0	0	0	0	3,655
Manufacturing													
1980	490	0	0	0	0	0	0	0	0	0	0	0	490
1981	490	0	0	0	0	0	0	0	0	0	0	0	490
1982	490	0	0	0	0	0	0	0	0	0	0	0	490
1983	345	0	0	0	0	0	0	0	0	0	0	0	345
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	419	0	0	0	0	0	0	0	0	0	0	0	419
1986	359	0	0	0	0	0	0	0	0	0	0	0	359
1987	441	0	0	0	0	0	0	0	0	0	0	0	441
1988	564	0	0	0	1	0	0	0	0	0	0	0	565
1989	564	0	0	0	0	0	0	0	0	0	0	0	564
1990	793	0	0	0	0	0	0	0	0	0	0	0	793
1991	623	0	0	0	0	0	0	0	0	0	0	0	623
1992	623	0	0	0	0	0	0	4	0	0	0	0	627
1993	623	0	0	0	0	0	0	7	0	0	0	0	630
1994	624	0	0	0	0	0	0	7	0	0	0	0	631
1995	624	0	0	0	0	0	0	7	0	0	0	0	631
1996	624	0	0	0	0	0	0	6	0	0	0	0	630
1997	624	0	0	0	0	0	0	7	0	0	0	0	631

Table 5-7. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Rural domestic													
1980	114	13	14	212	491	65	113	0	0	0	1	0	1,023
1981	120	13	31	222	504	69	130	0	0	0	1	0	1,090
1982	125	13	32	224	517	74	122	0	0	0	1	0	1,108
1983	131	14	32	248	531	78	142	0	0	0	1	0	1,177
1984	137	14	32	256	544	83	160	0	0	0	1	0	1,227
1985	142	14	50	266	557	87	154	0	0	0	1	0	1,271
1986	148	14	64	277	571	91	161	0	0	0	1	0	1,327
1987	153	15	72	288	584	96	128	0	0	0	1	0	1,337
1988	159	15	76	297	597	100	181	0	0	0	1	0	1,426
1989	165	15	77	306	611	104	192	0	0	0	1	0	1,471
1990	170	15	78	316	624	108	193	0	0	0	1	0	1,505
1991	182	16	78	332	637	112	155	0	0	0	2	0	1,514
1992	193	16	82	349	650	119	144	0	0	0	2	0	1,555
1993	204	16	85	321	663	131	157	0	0	0	2	0	1,579
1994	216	17	89	345	676	127	180	0	0	0	2	0	1,652
1995	227	17	97	347	689	142	214	0	0	0	2	0	1,735
1996	239	17	111	328	702	148	246	0	0	0	2	0	1,793
1997	250	17	112	387	715	153	325	0	0	0	2	0	1,961
Irrigation													
1980	16	385	47	257	52	102	200	335	4	0	0	0	1,398
1981	15	462	45	196	70	89	221	314	4	0	0	0	1,416
1982	15	540	43	135	88	76	241	293	4	0	0	0	1,435
1983	14	617	40	73	105	63	262	272	4	0	0	0	1,450
1984	14	694	38	12	123	50	282	251	3	0	0	0	1,467
1985	20	0	28	0	111	64	132	137	4	0	0	0	496
1986	0	0	28	0	93	44	176	91	5	0	0	0	437
1987	36	0	28	0	30	35	176	91	5	0	0	0	401
1988	36	0	28	0	8	29	440	91	4	0	0	0	636
1989	26	0	41	0	127	0	369	128	3	0	0	0	694
1990	33	0	47	0	113	0	274	125	3	0	0	0	595
1991	33	0	47	0	127	0	274	125	3	0	0	0	609
1992	33	0	47	0	127	0	274	125	3	0	0	0	609
1993	77	0	51	0	170	0	808	265	3	0	0	0	1,374
1994	0	0	51	7	845	0	718	272	3	0	0	0	1,896
1995	0	0	54	7	841	0	808	238	4	0	0	0	1,952
1996	0	0	54	8	957	0	808	265	4	0	0	0	2,096
1997	0	0	54	7	782	0	808	265	3	0	0	0	1,919

Table 5-7. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Livestock													
1980	18	0	14	55	82	24	142	0	0	0	3	0	338
1981	18	0	13	58	76	24	133	0	0	0	3	0	325
1982	17	0	13	60	69	24	125	0	0	0	3	0	311
1983	16	0	12	62	62	24	116	0	0	0	3	0	295
1984	15	0	12	64	55	24	107	0	0	0	2	0	279
1985	14	0	12	66	56	4	105	0	0	0	3	0	260
1986	13	0	14	66	66	3	74	0	0	0	3	0	239
1987	14	0	13	69	62	4	81	0	0	0	3	0	246
1988	16	0	14	76	65	4	89	0	0	0	3	0	267
1989	16	0	14	76	63	4	89	0	0	0	3	0	265
1990	16	0	16	75	65	4	101	0	0	0	3	0	280
1991	16	0	16	77	67	4	103	0	0	0	3	0	286
1992	16	0	19	84	80	3	133	0	0	0	3	0	338
1993	15	0	18	84	82	3	131	0	0	0	3	0	336
1994	17	0	15	84	77	4	125	0	0	0	3	0	325
1995	17	0	16	88	78	4	121	0	0	0	3	0	327
1996	14	0	13	72	113	3	98	0	0	0	5	0	318
1997	13	0	14	72	73	2	96	0	0	0	2	0	272

Table 5-8. Total pumping from the Lower Trinity Aquifer by use category for each county for the period 1980 through 1997 (all values in acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Municipal													
1980	190	0	0	0	0	63	0	3,198	0	0	0	0	3,451
1981	168	0	0	0	0	66	0	841	0	0	0	0	1,075
1982	198	0	0	0	0	77	0	485	0	0	0	0	760
1983	193	0	0	0	0	97	0	276	0	0	0	0	566
1984	232	25	0	0	0	137	39	665	0	0	0	0	1,098
1985	199	19	0	0	0	147	36	893	0	0	0	0	1,294
1986	222	31	0	0	0	74	43	551	0	0	0	0	921
1987	204	32	0	0	0	101	64	188	0	0	0	0	589
1988	227	38	0	0	0	89	69	460	0	0	0	0	883
1989	297	40	0	0	0	95	73	614	0	0	0	0	1,119
1990	269	30	0	0	0	91	67	371	0	0	0	0	828
1991	275	26	0	0	0	98	63	311	0	0	0	0	773
1992	219	30	0	0	0	87	71	651	0	0	0	0	1,058
1993	298	28	0	0	0	122	75	737	0	0	0	0	1,260
1994	340	41	0	0	0	132	73	524	0	0	0	0	1,110
1995	322	47	0	0	0	99	87	518	0	0	0	0	1,073
1996	299	45	0	0	0	117	84	927	0	0	0	0	1,472
1997	331	43	0	0	0	119	79	609	0	0	0	0	1,181
Manufacturing													
1980	0	1,959	0	0	0	0	0	0	0	0	0	0	1,959
1981	0	1,959	0	0	0	0	0	0	0	0	0	0	1,959
1982	0	1,959	0	0	0	0	0	0	0	0	0	0	1,959
1983	0	1,382	0	0	0	0	0	0	0	0	0	0	1,382
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	2,097	0	0	0	0	0	0	0	0	0	0	2,097
1986	0	2,157	0	0	0	0	0	0	0	0	0	0	2,157
1987	0	2,644	0	0	0	0	0	0	0	0	0	0	2,644
1988	0	3,385	0	0	0	0	0	0	0	0	0	0	3,385
1989	0	3,385	0	0	0	0	0	0	0	0	0	0	3,385
1990	0	4,756	0	0	0	0	0	0	0	0	0	0	4,756
1991	0	3,739	0	0	0	0	0	0	0	0	0	0	3,739
1992	0	3,739	0	0	0	0	0	0	0	0	0	0	3,739
1993	0	3,739	0	0	0	0	0	0	0	0	0	0	3,739
1994	0	3,746	0	0	0	0	0	0	0	0	0	0	3,746
1995	0	3,746	0	0	0	0	0	0	0	0	0	0	3,746
1996	0	3,746	0	0	0	0	0	0	0	0	0	0	3,746
1997	0	3,746	0	0	0	0	0	0	0	0	0	0	3,746

Table 5-8. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Rural domestic													
1980	0	0	0	0	0	0	0	0	0	0	1	0	1
1981	0	0	0	0	0	0	0	0	0	0	1	0	1
1982	0	0	0	0	0	0	0	0	0	0	1	0	1
1983	0	0	0	0	0	0	0	0	0	0	1	0	1
1984	0	0	0	0	0	0	0	0	0	0	1	0	1
1985	0	0	0	0	0	0	0	0	0	0	1	0	1
1986	0	0	0	0	0	0	0	0	0	0	1	0	1
1987	0	0	0	0	0	0	0	0	0	0	1	0	1
1988	0	0	0	0	0	0	0	0	0	0	1	0	1
1989	0	0	0	0	0	0	0	0	0	0	1	0	1
1990	0	0	0	0	0	0	0	0	0	0	1	0	1
1991	0	0	0	0	0	0	0	0	0	0	1	0	1
1992	0	0	0	0	0	0	0	0	0	0	1	0	1
1993	0	0	0	0	0	0	0	0	0	0	1	0	1
1994	0	0	0	0	0	0	0	0	0	0	2	0	2
1995	0	0	0	0	0	0	0	0	0	0	2	0	2
1996	0	0	0	0	0	0	0	0	0	0	2	0	2
1997	0	0	0	0	0	0	0	0	0	0	2	0	2
Irrigation													
1980	46	226	0	111	0	0	0	165	0	0	0	0	548
1981	43	271	0	83	0	0	0	155	0	0	0	0	552
1982	40	317	0	55	0	0	0	144	0	0	0	0	556
1983	36	362	0	28	0	0	0	134	0	0	0	0	560
1984	33	408	0	0	0	0	0	123	0	0	0	0	564
1985	48	0	0	0	0	0	0	67	0	0	0	0	115
1986	10	0	0	0	0	0	0	45	0	0	0	0	55
1987	88	0	0	0	0	0	0	45	0	0	0	0	133
1988	88	0	0	0	0	0	0	45	0	0	0	0	133
1989	68	0	0	0	0	0	0	63	0	0	0	0	131
1990	81	0	0	0	0	0	0	62	0	0	0	0	143
1991	81	0	0	0	0	0	0	62	0	0	0	0	143
1992	81	0	0	0	0	0	0	62	0	0	0	0	143
1993	171	0	0	0	0	0	0	131	0	0	0	0	302
1994	15	0	0	3	0	0	0	134	0	0	0	0	152
1995	14	0	0	2	0	0	0	117	0	0	0	0	133
1996	15	0	0	2	0	0	0	131	0	0	0	0	148
1997	15	0	0	2	0	0	0	131	0	0	0	0	148

Table 5-8. (continued).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total pumpage
Livestock													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

5.8 Water Quality

Total dissolved solids in groundwater are a measure of water salinity. Fresh, slightly saline, moderately saline, and very saline water have total dissolved solids of less than 1,000, 1,000 to 3,000, 3,000 to 10,000, and 10,000 to 35,000 milligrams per liter, respectively. Most groundwater in the study area is fresh to slightly saline, but in some parts of the Hill Country portion of the Trinity Aquifer System groundwater is moderately saline (Figure 5-34). Although the groundwater in the Edwards Group generally has lower salinity than groundwater in the Upper, Middle, and Lower Trinity aquifers, the median value of total dissolved solids in groundwater is similar in the Edwards Group and Upper and Middle Trinity aquifers (Figure 5-34). The median total dissolved solids are 450, 470, and 410 milligrams per liter in the Edwards Group and Upper and Middle Trinity aquifers, respectively. In the Lower Trinity Aquifer, the median value of total dissolved solids is higher than that of the other aquifers at 760 milligrams per liter. Fresh groundwater occurs throughout the Edwards Group in the study area (Figure 5-35). In the Upper, Middle, and Lower Trinity aquifers, slightly to moderately saline groundwater typically occurs in eastern, downdip parts of the aquifers, especially in Blanco, Comal, Hays, Kendall, and Travis counties (Figures 5-36 through 5-38).

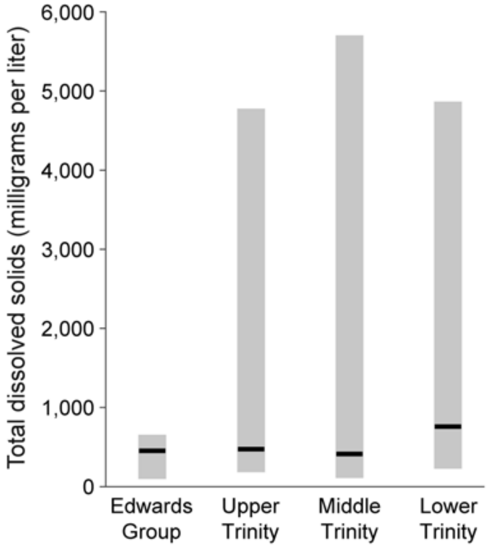


Figure 5-34. Ranges of total dissolved solids found in groundwater in the Edwards Group and the Upper, Middle, and Lower Trinity aquifers. The black line indicates the median value for each aquifer.

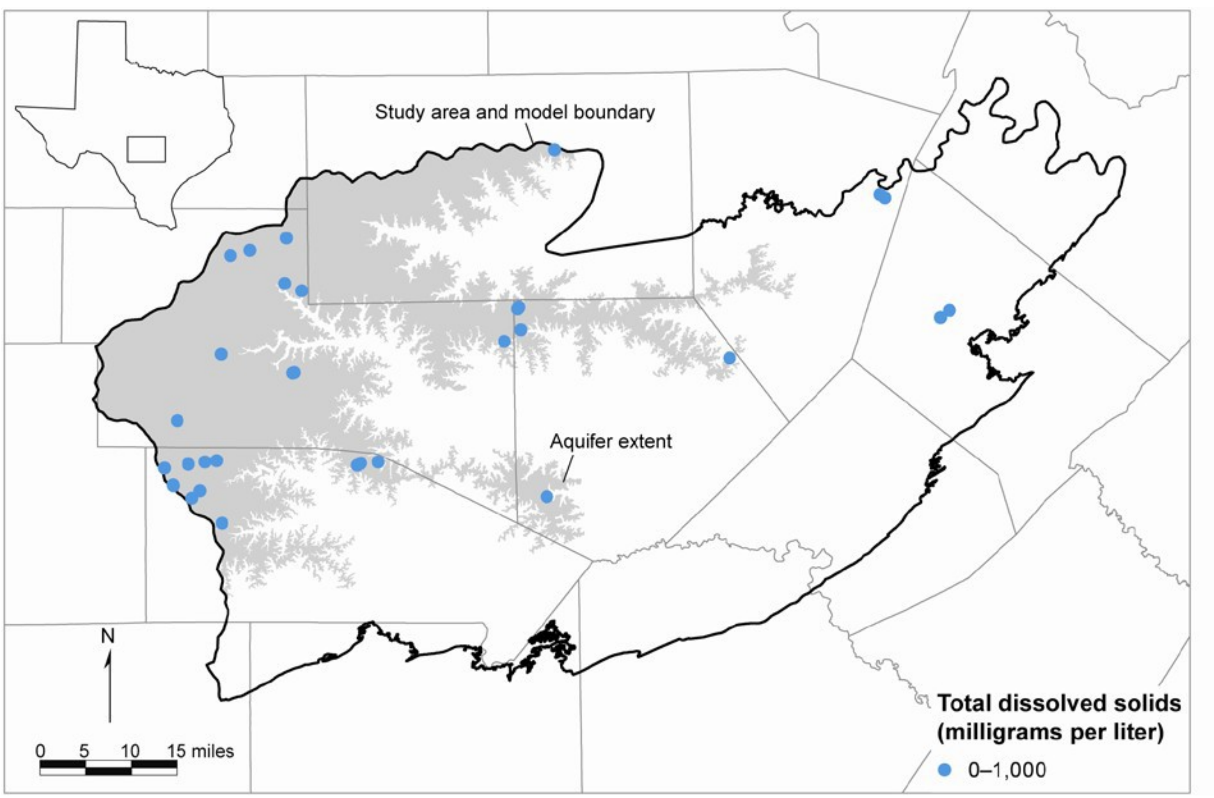


Figure 5-35. Map of total dissolved solids in the Edwards Group.

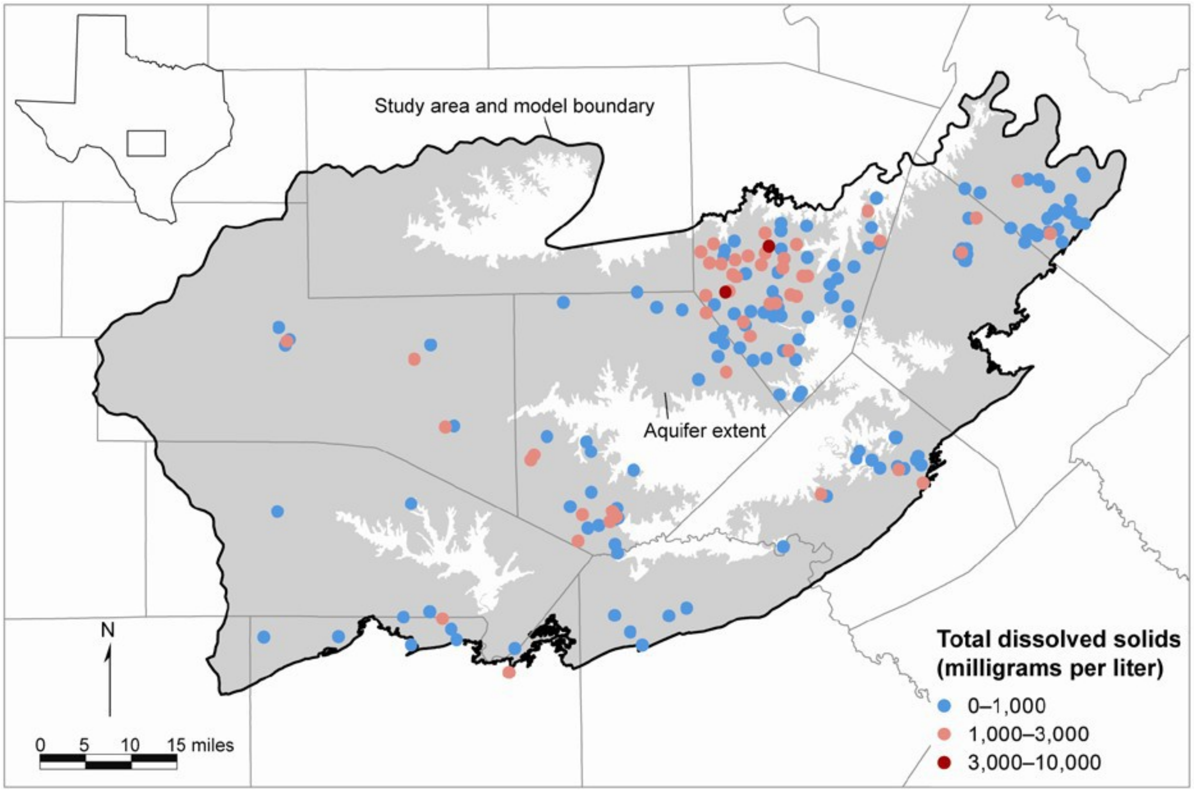


Figure 5-36. Map of total dissolved solids in the Upper Trinity Aquifer.

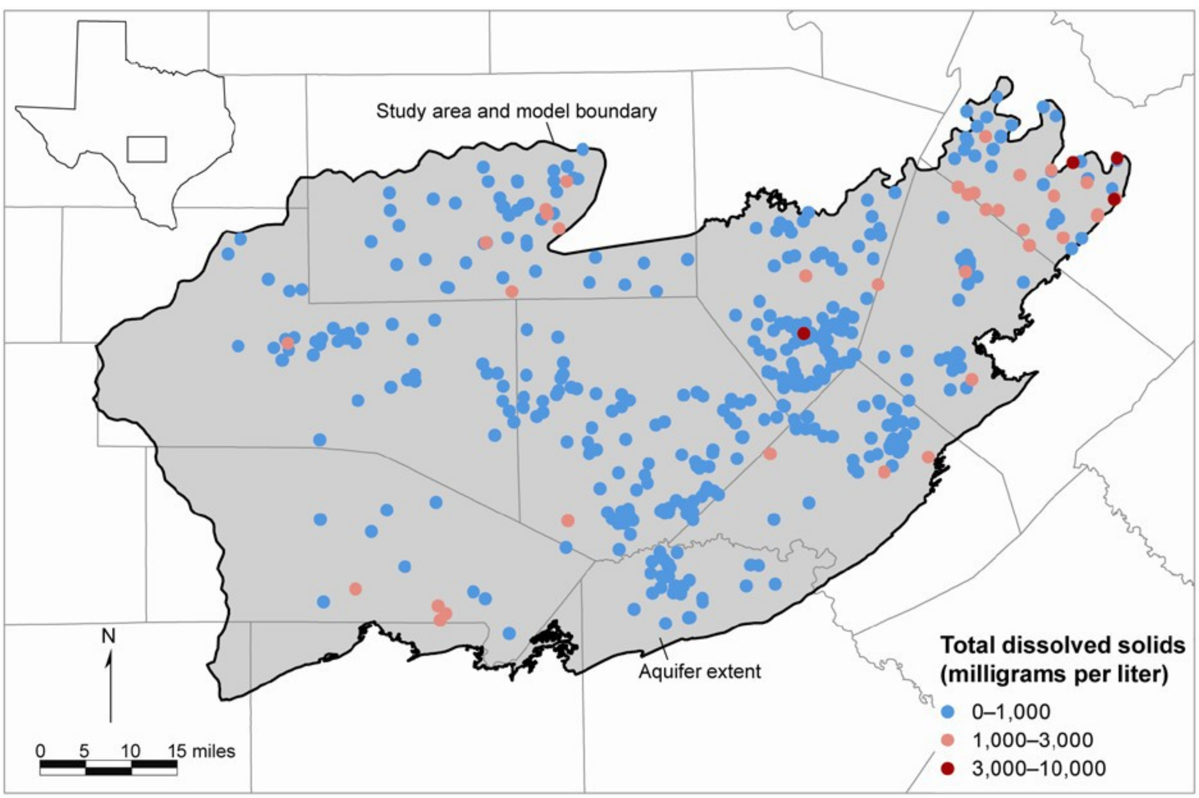


Figure 5-37. Map of total dissolved solids in the Middle Trinity Aquifer.

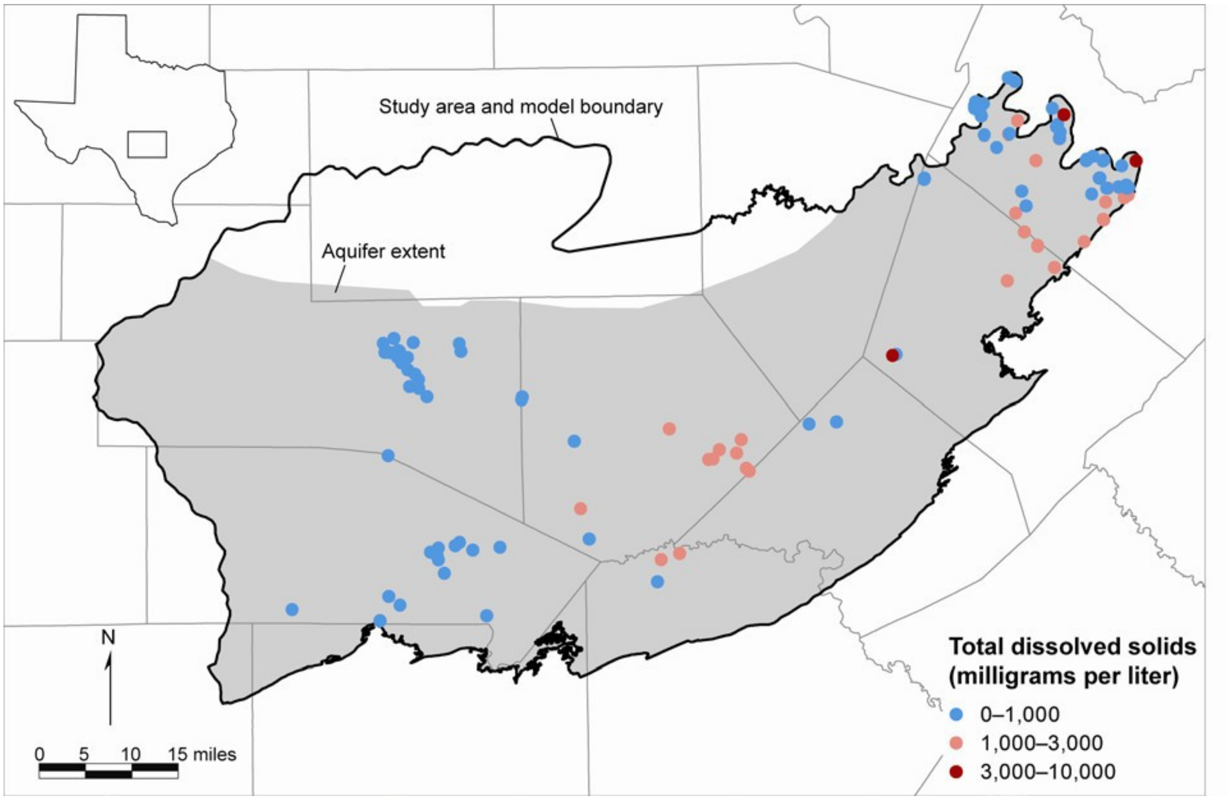


Figure 5-38. Map of total dissolved solids in the Lower Trinity Aquifer.

Groundwater in the Edwards Group is mainly calcium-magnesium-bicarbonate type (Figure 5-39). Groundwater in the Upper Trinity Aquifer is also mainly calcium-magnesium-bicarbonate type but progressively becomes calcium-magnesium-sulfate type in downdip parts of the aquifer (Figure 5-40). Groundwater in the Middle and Lower Trinity aquifers displays similar ranges of geochemical compositions, the former displaying more sulfate-dominated compositions and the latter displaying greater sodium and chloride (Figures 5-41 and 5-42). With increasing depth in the Hill Country portion of the Trinity Aquifer System, groundwater compositions can be categorized into three groups: (1) calcium-magnesium-bicarbonate-type compositions, (2) groundwater compositions characterized by increasing magnesium and sulfate, and (3) groundwater compositions characterized by increasing sodium and chloride (Figure 5-43). Groundwater compositions in the Edwards Group are characteristic of Group 1, groundwater in the Upper Trinity Aquifer displays Groups 1 and 2, and groundwater in the Middle and Lower Trinity aquifers displays compositions reflective of all three groups. These compositional trends can be explained by the following processes: (1) groundwater interaction with the limestone of the Edwards Group and the upper member of the Glen Rose Limestone, producing the calcium-magnesium-bicarbonate-type composition; (2) groundwater interaction with the dolostone and evaporites that occur within the Glen Rose Limestone, resulting in increased magnesium and sulfate in the groundwater; and (3) mixing with sodium-chloride brine migrating from depth.

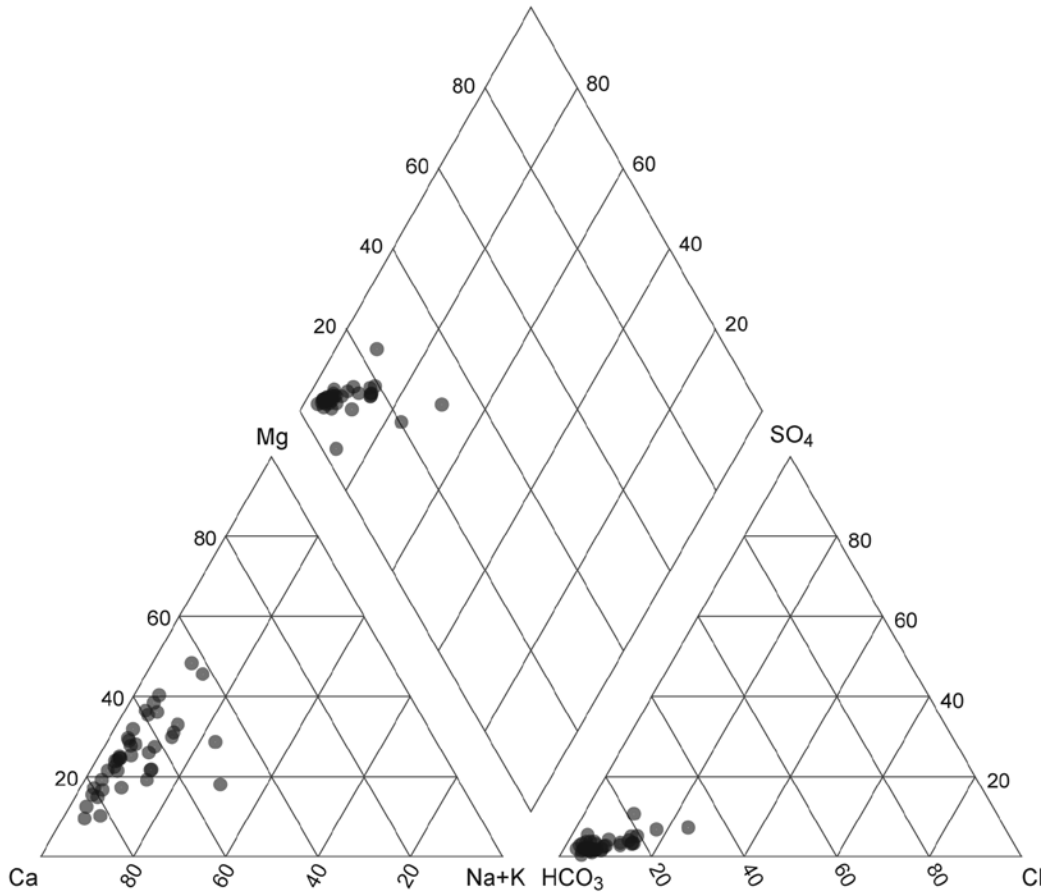


Figure 5-39. Piper diagram of groundwater from the Edwards Group showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

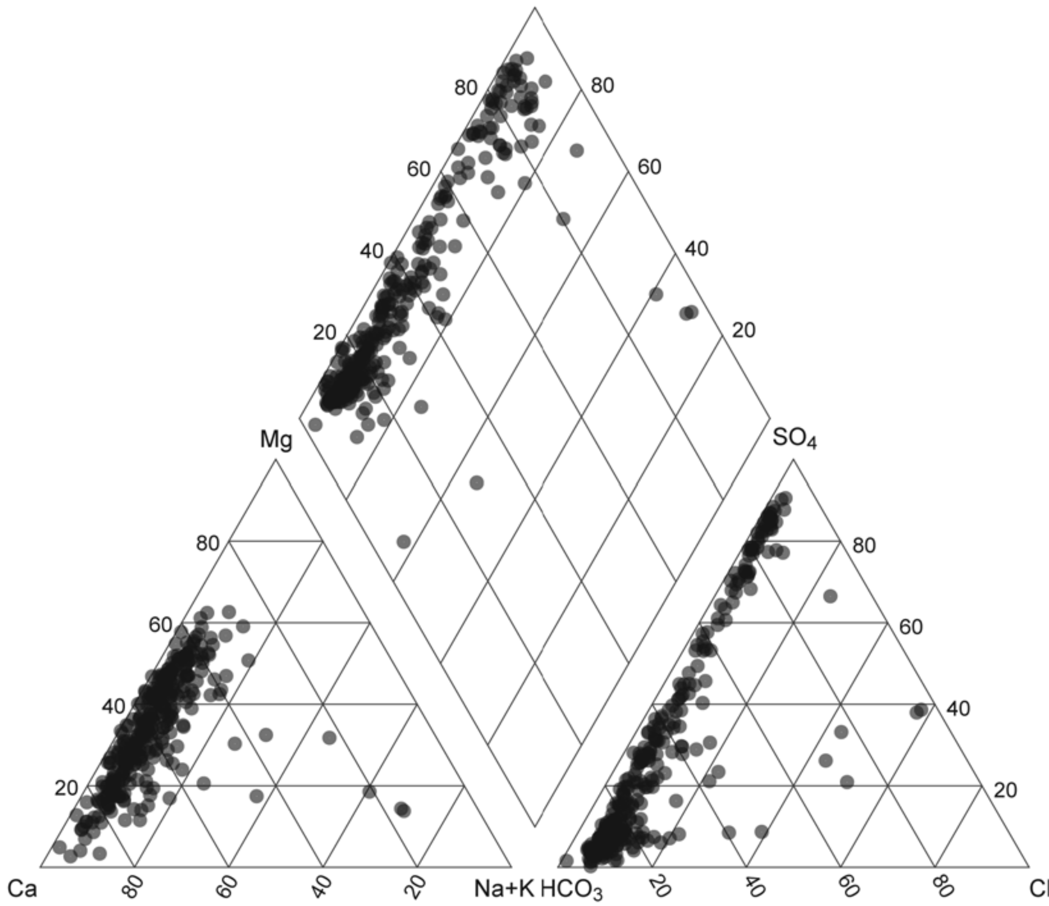


Figure 5-40. **Piper diagram of groundwater from the Upper Trinity Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.**

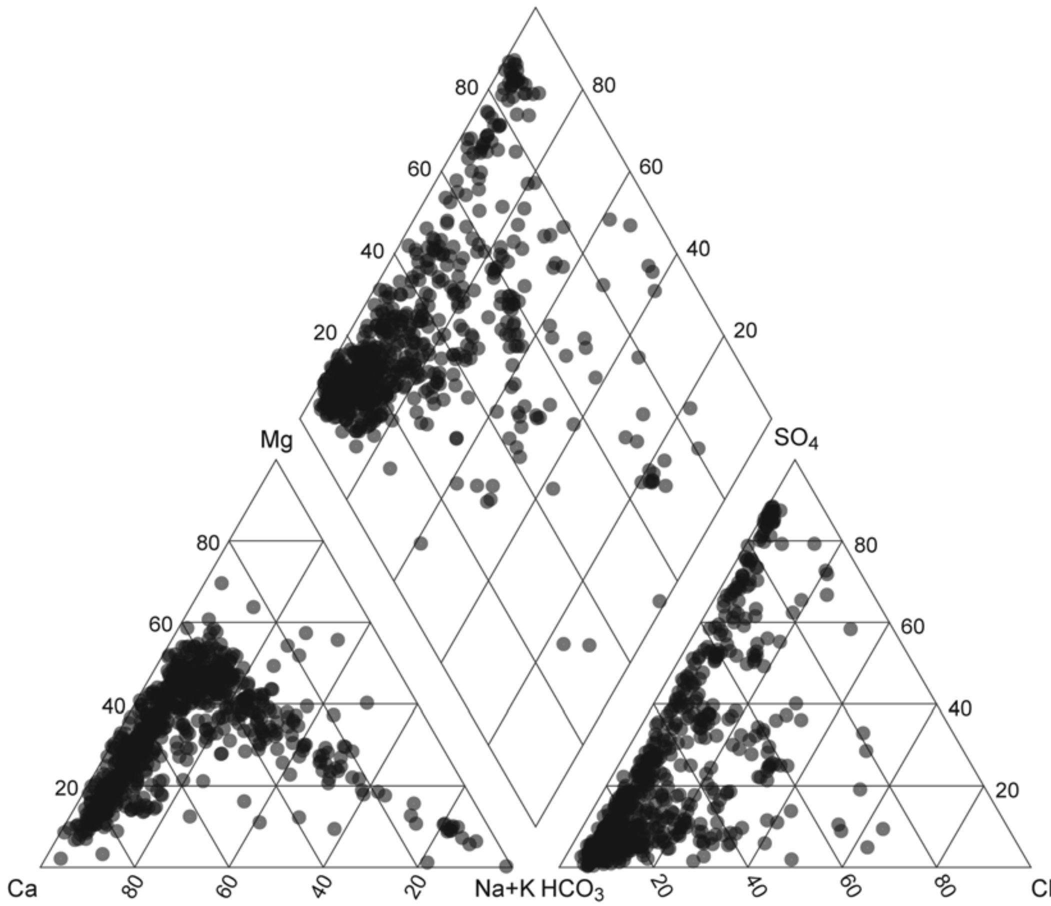


Figure 5-41. **Piper diagram of groundwater from the Middle Trinity Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.**

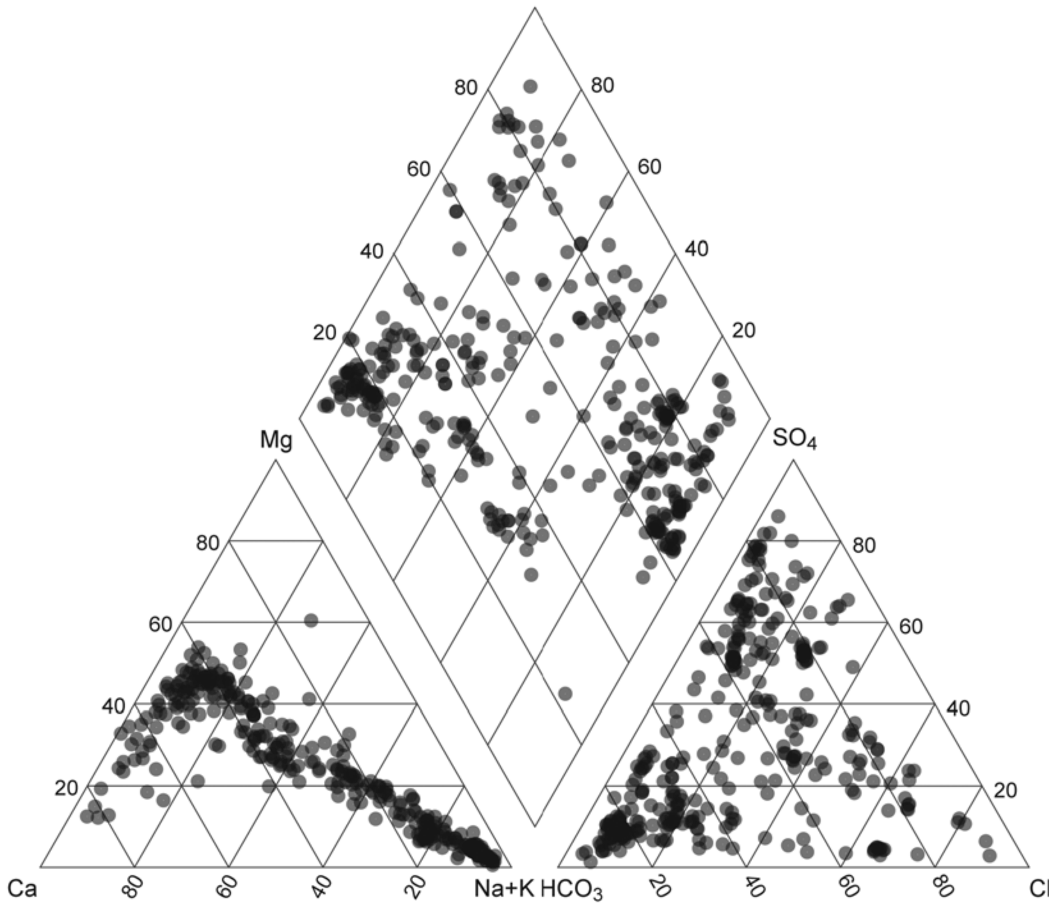


Figure 5-42. **Piper diagram of groundwater from the Lower Trinity Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.**

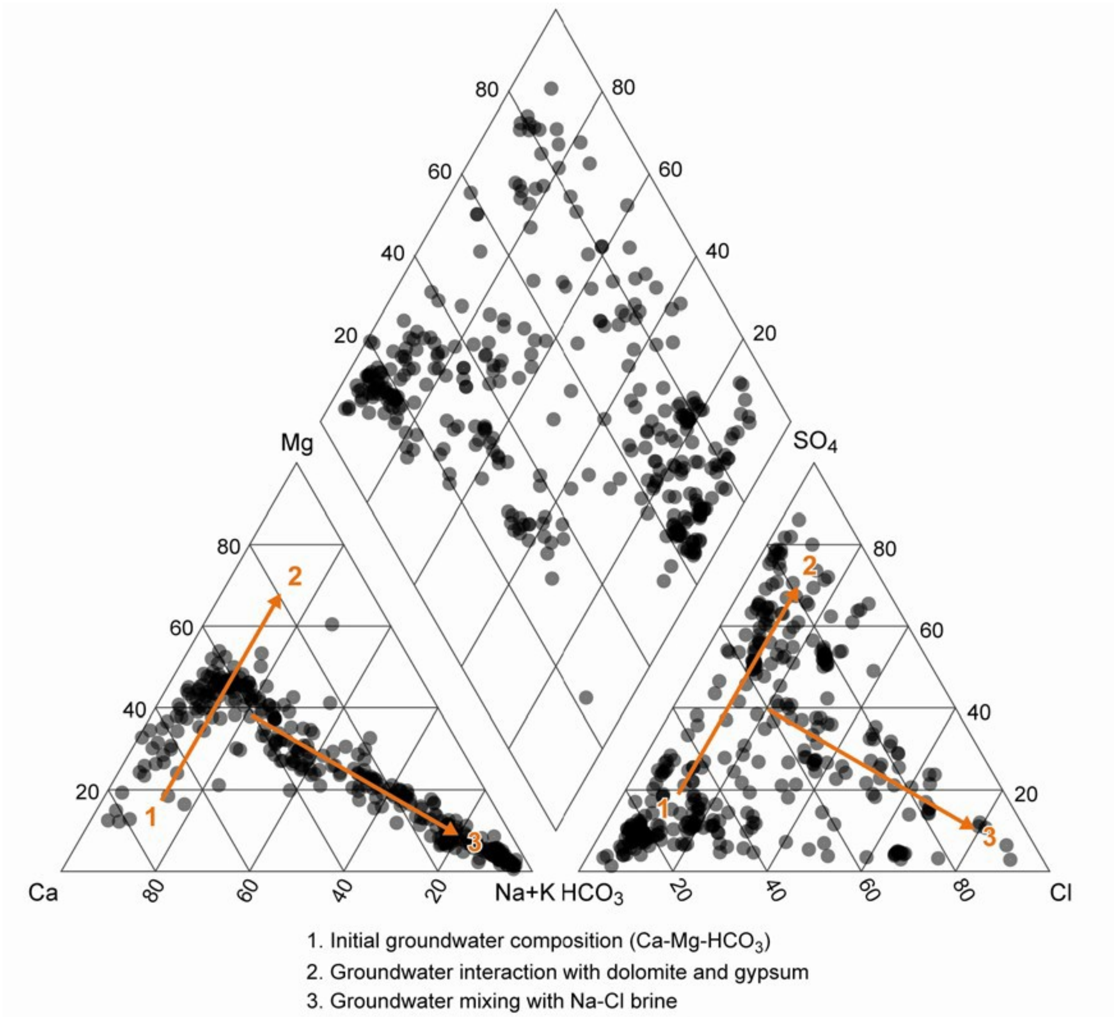


Figure 5-43. Groundwater geochemical trends that are apparent in the Hill Country portion of the Trinity Aquifer System. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

Distribution of total dissolved solids, chloride, and sulfate shows no specific trend with increasing well depth. Most of the samples from the Edwards Group show no significant changes in total dissolved solids, chloride, sulfate, and nitrate from the ground surface to well depths of about 3,500 feet. In the Lower Trinity Aquifer, highest groundwater salinity occurs at depths greater than 500 feet. Nitrate concentrations progressively decrease with increasing well depth in the Edwards Group and Upper, Middle, and Lower Trinity aquifers. Groundwater in the Edwards Group has the least nitrate, and the highest nitrate concentrations occur in the Upper and Middle Trinity aquifers.

6.0 Conceptual Model of Regional Groundwater Flow in the Aquifer

The conceptual model (Figure 6-1) is our best understanding of regional groundwater flow in the Hill Country portion of the Trinity Aquifer System.

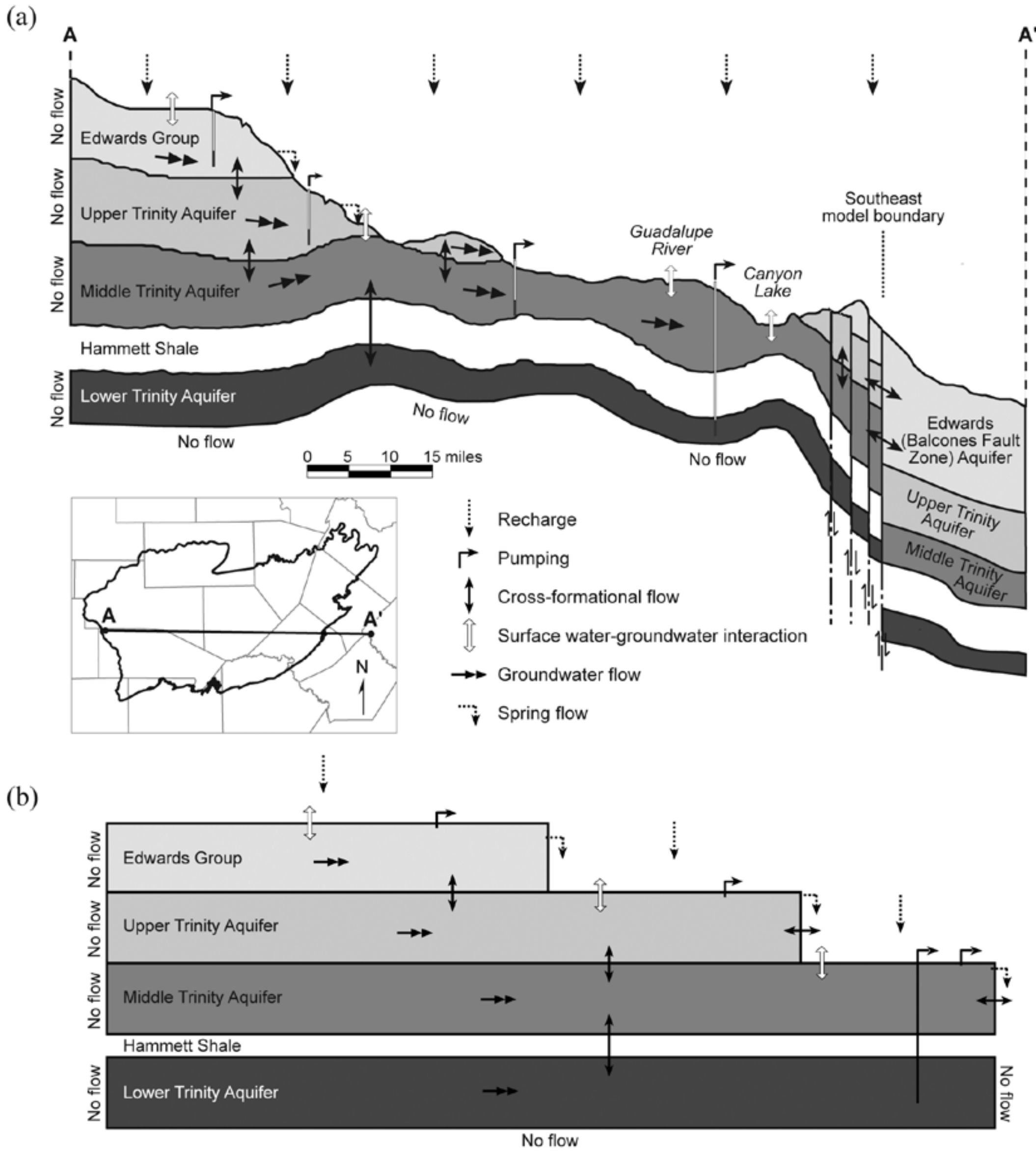


Figure 6-1. Conceptual model of the Hill Country portion of the Trinity Aquifer System. (a) Schematic cross section through the aquifer system. (b) Diagram showing the boundary conditions at the outer edge of the model, flows between the layers, and translation of the conceptual model into the numerical model (modified from Mace and others, 2000).

The conceptual model does not treat the Hammett Shale confining unit that separates the Middle and Lower Trinity aquifers as a distinct layer of flow. Rather, this confining unit is simulated as a zone of restricted vertical leakance between the two aquifers. When precipitation falls on the outcrop of the aquifer, much of the water evaporates, is taken up and transpired by vegetation, or runs off into local streams and eventually discharges through major streams outside of the study area. About 4 to 6 percent of the precipitation infiltrates into and recharges the underlying aquifers over most of the study area. This percentage is higher in the eastern portion of the study area where the fractures of the Balcones Fault Zone facilitate higher recharge rates.

Losing streams contribute recharge to the Edwards Group in the headwater areas of the streams along the western margin of the study area (Figure 3-6a) because the Edwards Group in the plateau area has high permeability. Most of the recharge to the Edwards Group in the study area discharges along the edge of the plateau through springs, seeps, and evapotranspiration. A small amount of the flow from the Edwards Group percolates downward into the underlying Upper, Middle, and Lower Trinity aquifers.

Most of the precipitation that recharges the Upper and Middle Trinity aquifers discharges to local and major streams through base flow to these surface-water features. An exception is Cibolo Creek, where karstification of the lower member of the Glen Rose Limestone changes the creek from a gaining stream to a losing stream between Boerne and Bulverde (Figure 3-1). Most of the remaining recharge in the aquifer either discharges through wells pumping from the aquifer or flows laterally into the Edwards (Balcones Fault Zone) Aquifer.

Several short flow paths probably lie along streams where the water table is shallow. In these areas recharged precipitation most likely flows a short distance and is discharged through evapotranspiration. Because of the localized nature of the flow paths and the limitations of the model grid, this evapotranspiration discharge would most likely be included in discharge to streams.

Groundwater can perch on low-permeability beds within the Upper Trinity Aquifer and flow laterally to springs; however, some water percolates through the Upper Trinity Aquifer into the Middle Trinity Aquifer. The Lower Trinity Aquifer is not exposed at land surface. Consequently, groundwater flow enters the Lower Trinity Aquifer through downward cross-formational flow from the Middle Trinity Aquifer and discharges by cross-formation back to the Middle Trinity Aquifer in downdip portions of the aquifers. In general, groundwater in the Hill Country portion of the Trinity Aquifer System flows from areas of higher topography to areas of lower topography, from the west to the east.

In general, lithology and local fracturing control permeability development and distributions in the Edwards Group and the Upper, Middle, and Lower Trinity aquifers. We think that hydraulic conductivity is higher in the eastern portion of the study area, where the higher hydraulic conductivity coincides with the Balcones Fault Zone, than in the rest of the aquifer system. The Edwards Group in the plateau area has high vertical and horizontal permeability due to karstification. The Upper Trinity Aquifer generally has lower permeability but can locally be very permeable, especially in the outcrop. Owing to the occurrence of shaly beds, the Upper Trinity Aquifer has a much lower ratio of vertical to horizontal permeability than does the overlying Edwards Group. The Middle Trinity Aquifer has moderate permeability and greater ability to transmit water vertically than the Upper Trinity Aquifer. The Middle Trinity Aquifer is most permeable in the sandy outcrop area of Gillespie County. Specific yield in the limestone is primarily controlled by fractures. The Lower Trinity Aquifer is on average less permeable than the overlying aquifers, the highest values occurring in the Kerrville area.

Pumping from the Hill Country portion of the Trinity Aquifer System has been progressively rising over the period 1980 through 1997. This increasing pumping is most apparent in counties adjacent to San Antonio and Austin—the two largest cities in the region—which are Bexar, Hays, Kendall, and Kerr counties. Pumping in some of these counties has doubled over the period of time covered by this study.

7.0 Model Design

Model design includes (1) choice of code and processor, (2) discretization of the aquifer into model layers and cells, and (3) assignment of model parameters into the various model layers. The model design must agree as much as possible with the conceptual model of groundwater flow in the aquifer.

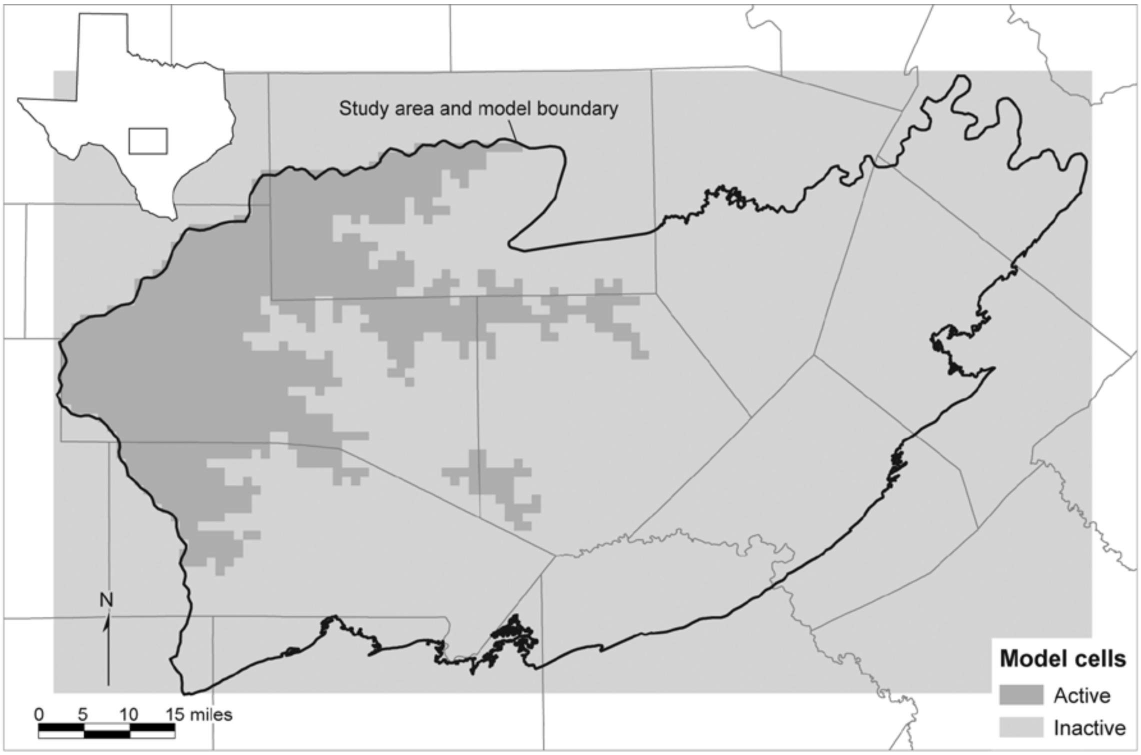
7.1 Code and Processor

Groundwater flow through the Hill Country portion of the Trinity Aquifer System was simulated using MODFLOW-96, a widely used modular finite-difference groundwater flow code written by the U.S. Geological Survey (Harbaugh and McDonald, 1996). This code was selected because of (1) its capabilities of simulating regional-scale groundwater processes in the Hill Country portion of the Trinity Aquifer System, (2) its documentation and wide use (McDonald and Harbaugh, 1988; Anderson and Woessner, 2002), (3) the availability of a number of third-party pre- and post-processors facilitating easy use of the modeling software, and (4) its ready availability as public domain software. Processing MODFLOW Pro version 7.0.18 was used to load input data into the model and view model outputs (Chiang, 2005). Other pre- and post-processors can read source files for MODFLOW-96. This model was developed and run on a Dell Precision™ 490 Workstation with a 3.0 GHz Dual-Core Xeon processor and 2 GB RAM running Microsoft Windows® XP Professional (v. 5).

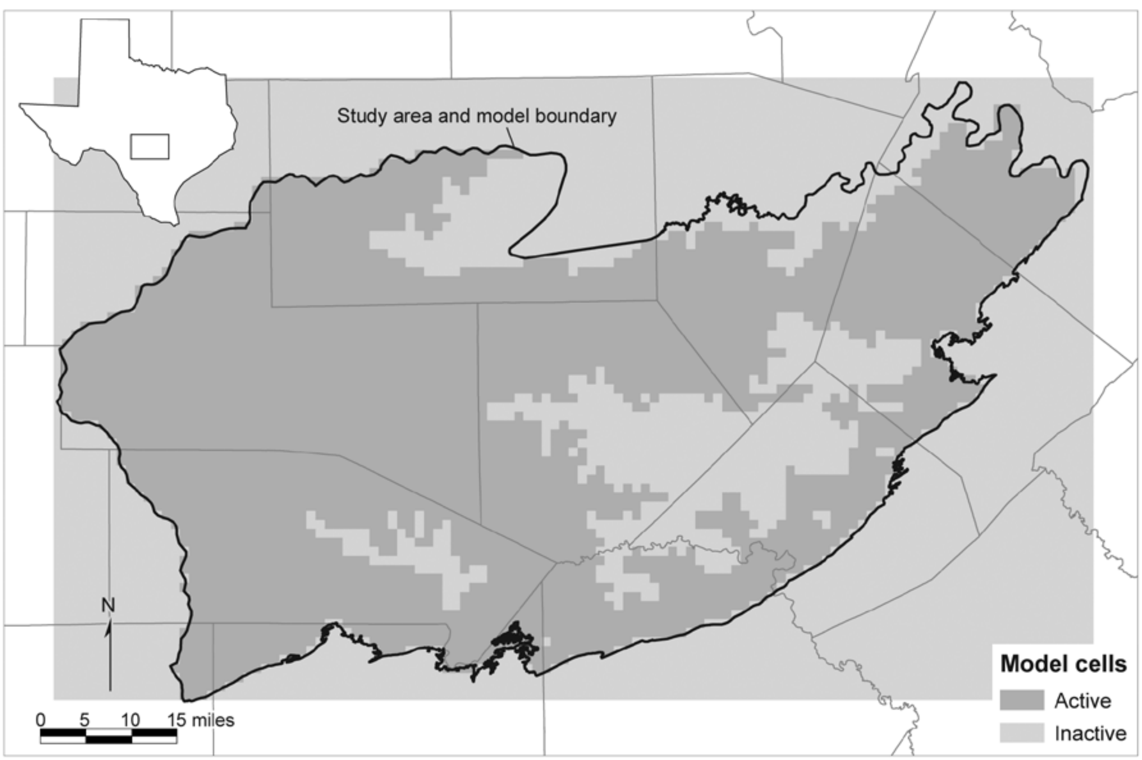
7.2 Layers and Grid

The lateral extent of the model corresponds to natural hydrologic boundaries, such as erosional limits of the aquifers, rivers, and the structural boundary with the Edwards (Balcones Fault Zone) Aquifer, and hydraulic boundaries to the west that coincide with groundwater divides. According to the hydrostratigraphy and conceptual model, we designed the model to have four layers: layer 1—the Edwards Group of the Edwards-Trinity (Plateau) Aquifer System, layer 2—the Upper Trinity Aquifer, layer 3—the Middle Trinity Aquifer, and layer 4—the Lower Trinity Aquifer.

We defined the active and inactive cells by first establishing the lateral extent of the formations in each layer using the geologic map (Figure 3-16). We assigned a cell as active if the formation covered more than 50 percent of the cell area. Please note that the spatial extents of the respective aquifers were revised slightly during model calibration to address dry cell and numerical stability issues. We did not include the thin slivers of the Edwards Group in the eastern part of the study area, for example, in Blanco County, because (1) our structure maps do not accurately represent the complexity of faulting in the area, (2) flow in some of these rocks is associated with the Edwards (Balcones Fault Zone) aquifer, and (3) in many areas these rocks are discontinuous and thus groundwater flow, if any, would be difficult to simulate at the regional scale. It should be noted that we did include a part of the Edwards Group that is not recognized by the TWDB as part of the Edwards-Trinity (Plateau) Aquifer in eastern Kerr County and western Kendall County. Each layer has 69 rows and 115 columns, for a total of 31,740 cells in the model. All the cells have uniform lateral dimensions of 1 mile by 1 mile. We selected this cell size to be small enough to reflect the density of input data and the desired output detail and large enough for the model to be manageable. Cell thickness depended on differences in top and bottom elevations of the model layers. After we made cells outside of the model area and outside the lateral extent of each layer inactive, the model had a total of 12,976 active cells: 1,107 in layer 1; 3,562 in layer 2; 4,517 in layer 3; and 3,790 in layer 4 (Figure 7-1).

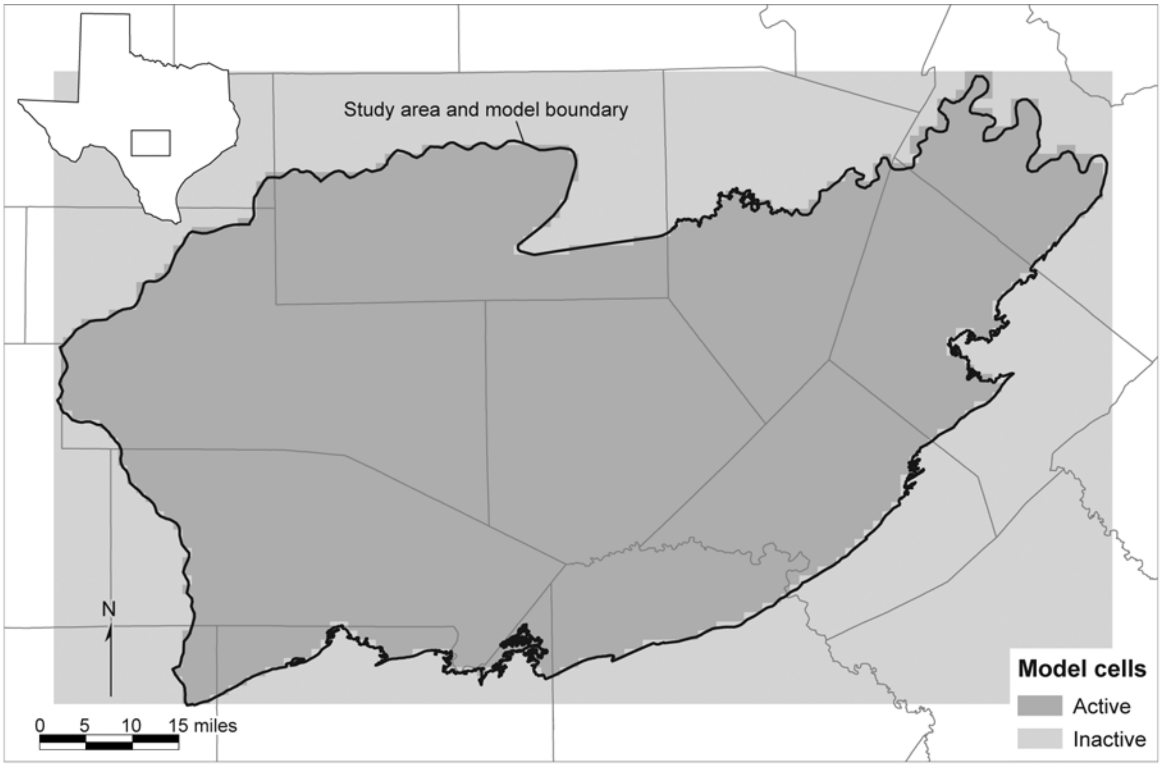


(a)

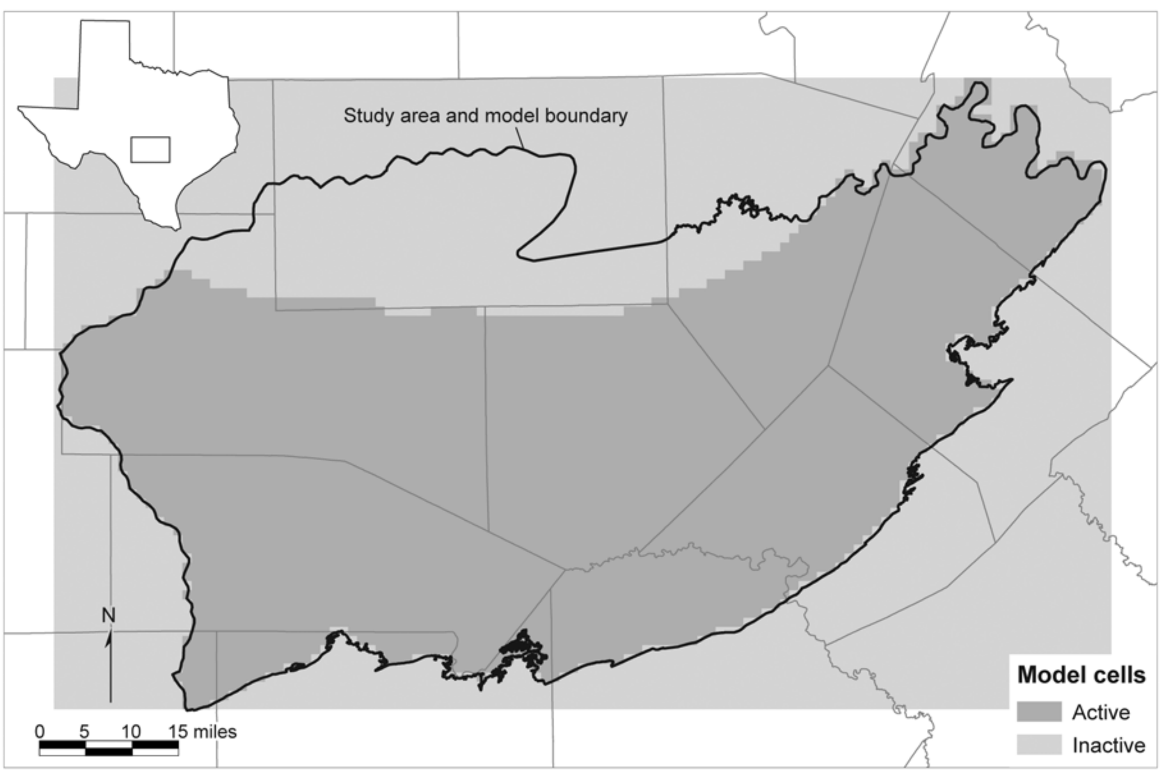


(b)

Figure 7-1. **Active and inactive cells in model grid for (a) layer 1 (Edwards Group), (b) layer 2 (Upper Trinity Aquifer), (c) layer 3 (Middle Trinity Aquifer), and (d) layer 4 (Lower Trinity Aquifer).**



(c)



(d)

Figure 7-1. (continued).

7.3 Model Parameters

We distributed model parameters, including (1) elevations of the top and bottom of each layer, (2) horizontal and vertical hydraulic conductivity, (3) specific storage, and (4) specific yield, using ArcGIS® 9.1. We defined top and bottom elevations for each layer from the structure maps and land surface elevations from digital elevation models downloaded from the U.S. Geological Survey. We used ArcGIS® 9.1 to assign top and bottom elevations. For layer 1 (Edwards Group), we assigned the top as the land surface elevation and the bottom according to the structure map of the base of the Edwards Group (Figure 5-1). The top and base of layer 2 (Upper Trinity Aquifer) were assigned according to the structure map of the Upper Trinity Aquifer (Figure 5-2). Where covered by active cells in layer 1, the top of layer 2 coincides with the base of layer 1; otherwise, it is defined by the land surface elevation. The bottom of layer 2 was defined by the base of the Upper Trinity Aquifer (Figure 5-2). Similarly, the top of layer 3 (Middle Trinity Aquifer) was defined as the bottom of layer 2 and the land surface elevation where exposed (Figure 5-3). The bottom of layer 3 was assigned using the elevation of the base of the Middle Trinity Aquifer (Figure 5-3). The top of layer 4 (Lower Trinity Aquifer) is defined as the base of the Hammett Shale, the confining unit separating the Middle and Lower Trinity aquifers (Figure 5-4). Groundwater flow through the Hammett Shale is not explicitly simulated in the model.

We initially assigned hydraulic conductivity values for layers 1, 2, and 3 previously used in Mace and others (2000) and adjusted these values during calibration. These values were uniform values of 7 and 5 feet per day in layers 1 and 2 based on geometric mean of hydraulic conductivity data, respectively, and a distributed range of values of 0.7 to 64 feet per day inlayer 3. The initial hydraulic conductivity value we assigned to layer 4 was 0.6 feet per day, the geometric mean of the hydraulic conductivity data for the Lower Trinity Aquifer. We initially assigned vertical hydraulic conductivity to be one-tenth the horizontal hydraulic conductivity. We simulated groundwater flow between layers 3 and 4, through the Hammett Shale, using vertical leakance values. These vertical leakance values were initially set to be proportional to the relative thickness of the Hammett Shale in each cell. The purpose for using vertical leakance is to simulate vertical flow through the Hammett Shale confining unit without the need to simulate horizontal flow through the unit, which is assumed to be small. The range of vertical leakance values is 10^{-6} to 0.8 per day (Figure 7-2). We assigned uniform values of specific storage and specific yield in each layer. Initially assigned specific-storage values are 10^{-6}, 10^{-7}, 10^{-8}, and 10^{-8} per foot in layers 1, 2, 3, and 4, respectively. Initially assigned specific-yield values are 8×10^{-4}, 5×10^{-5}, 8×10^{-5}, and 8×10^{-5} in layers 1, 2, 3, and 4, respectively.

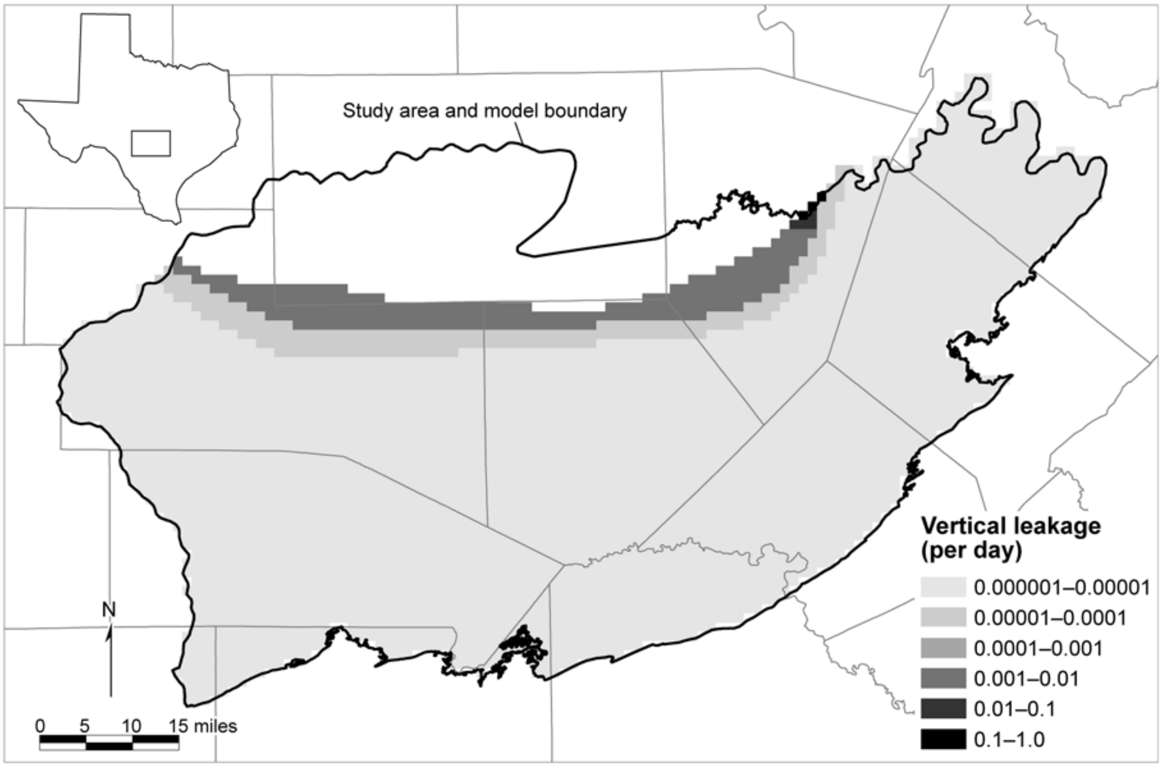


Figure 7-2. Vertical leakance between the Middle and Lower Trinity aquifers.

We assigned layer 1 as unconfined and layers 2 through 4 as confined/unconfined. We allowed the model to calculate transmissivity and storativity according to saturated thickness. We used units of feet for length and days for time for all input data to the model. To solve the groundwater flow equation, we used the Slice Successive Over-Relaxation solver with a convergence criterion of 0.0001 feet.

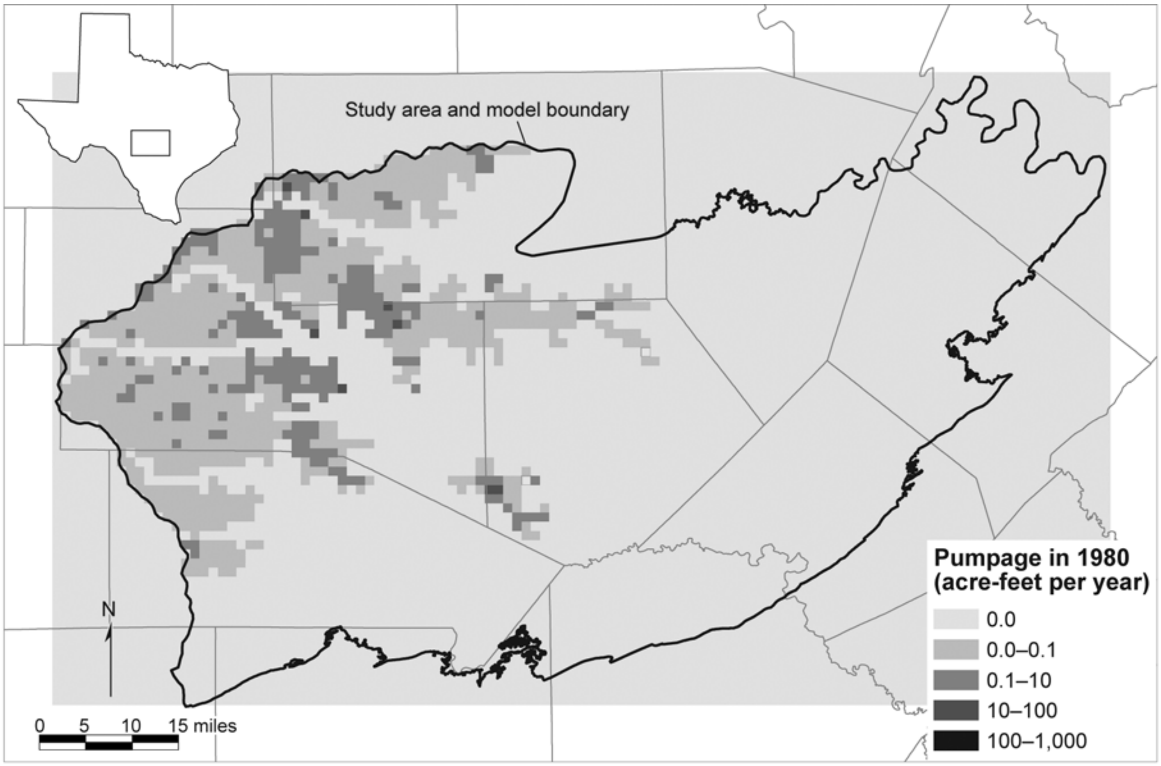
7.4 Model Boundary Conditions

Model boundary conditions are factors that control the inflow and outflow of groundwater in a numerical model. We assigned model boundary conditions for (1) recharge, (2) pumping, (3) rivers and streams, (4) reservoirs, (5) outer model boundaries, and (6) initial head conditions. We used ArcGIS® 9.1 to distribute values for model boundary conditions spatially, such as drains, general-head boundaries, recharge, and pumping.

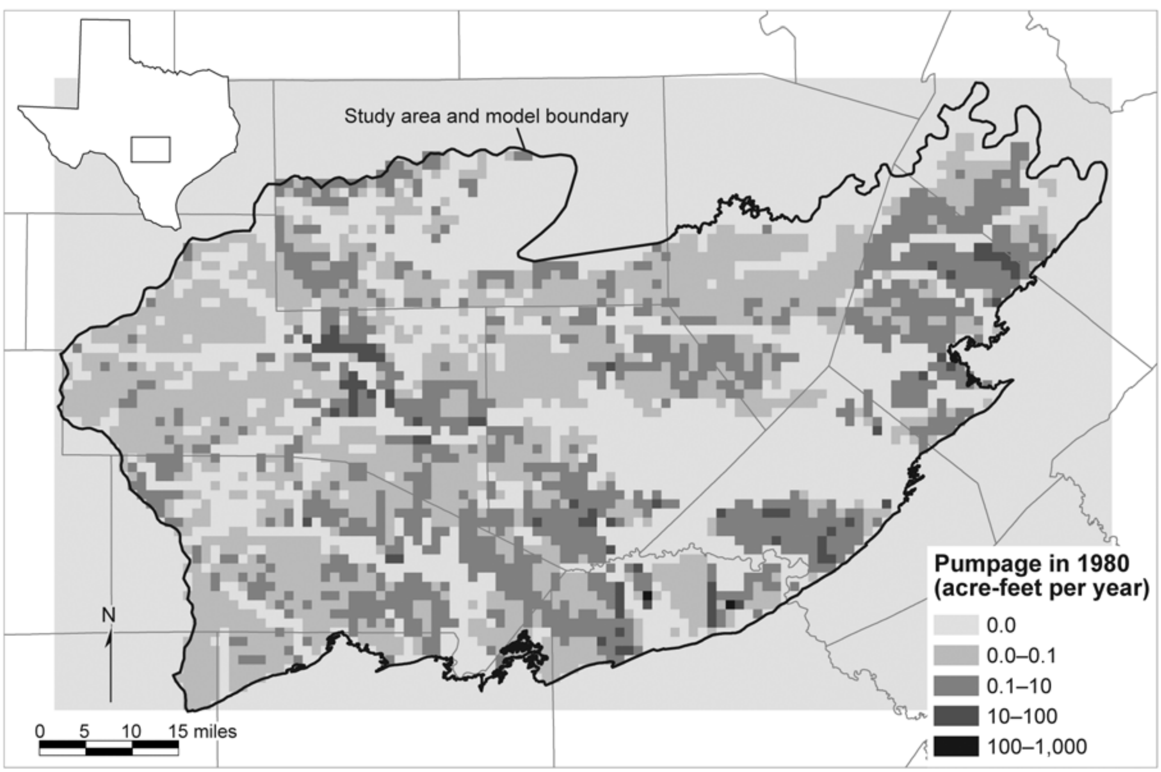
We assigned recharge primarily on the basis of the spatial distribution of annual precipitation over the study area (Figure 3-9). The initial recharge assigned to the model was 4.7 percent of annual precipitation. This value coincides with the value used in the groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009). We also included in the recharge distribution, recharge from streamflow losses in Cibolo Creek.

We assigned pumping values in the model according to our analysis of pumping as discussed in Section 5.7 (Discharge) of this report (Figure 5-30). This model simulates the regional effects of pumping on water levels for rural domestic, municipal, irrigation, industrial, and livestock uses

(Tables 5-3 through 5-8). Municipal and manufacturing pumping was distributed on the basis of known well locations and pumping data from the TWDB Water Use Survey. The other uses (domestic, irrigation, and livestock) were distributed throughout the model grid, reflecting the spatial distribution of associated land use. Rural domestic pumping was distributed on the basis of the spatial distribution of population outside major urban areas that lie within the model grid. Irrigation pumping was distributed on the basis of 1:250,000-scale land use and land cover data from the U.S. Geological Survey. Irrigation was assumed to occur on all land classified as orchards, row crops, or small grains. Livestock pumping was also distributed on the basis of 1:250,000-scale land use and land cover data from the U.S. Geological Survey. Livestock pumping was assumed on all range land. Figure 7-3 shows the spatial distribution of total pumping for the year 1980.

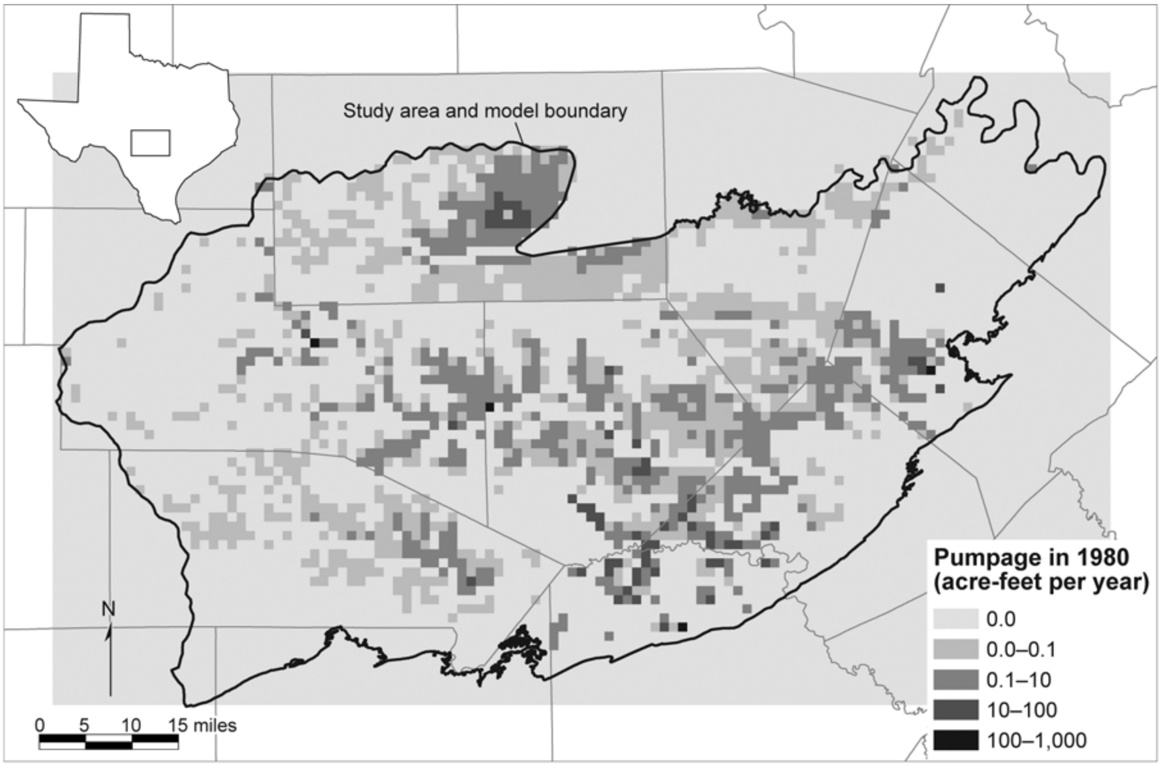


(a)

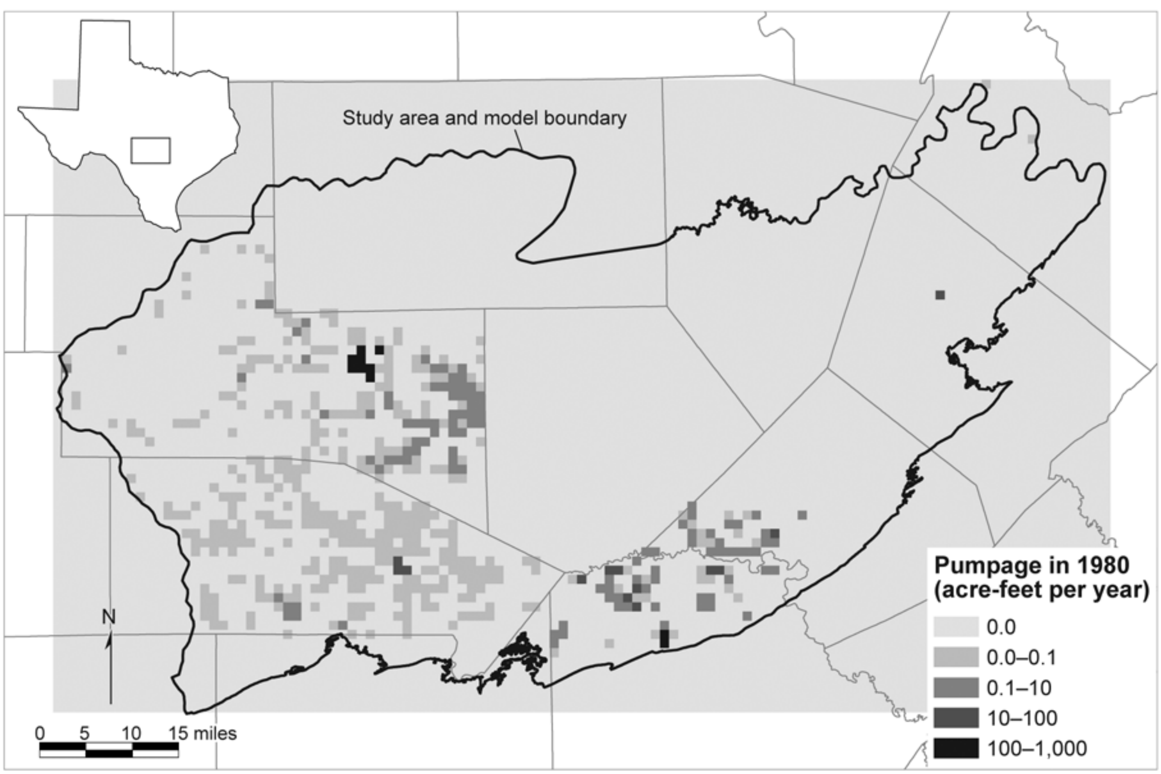


(b)

Figure 7-3. **The spatial distribution of total pumping for 1980 for (a) layer 1, (b) layer 2, (c) layer 3, and (d) layer 4.**



(c)

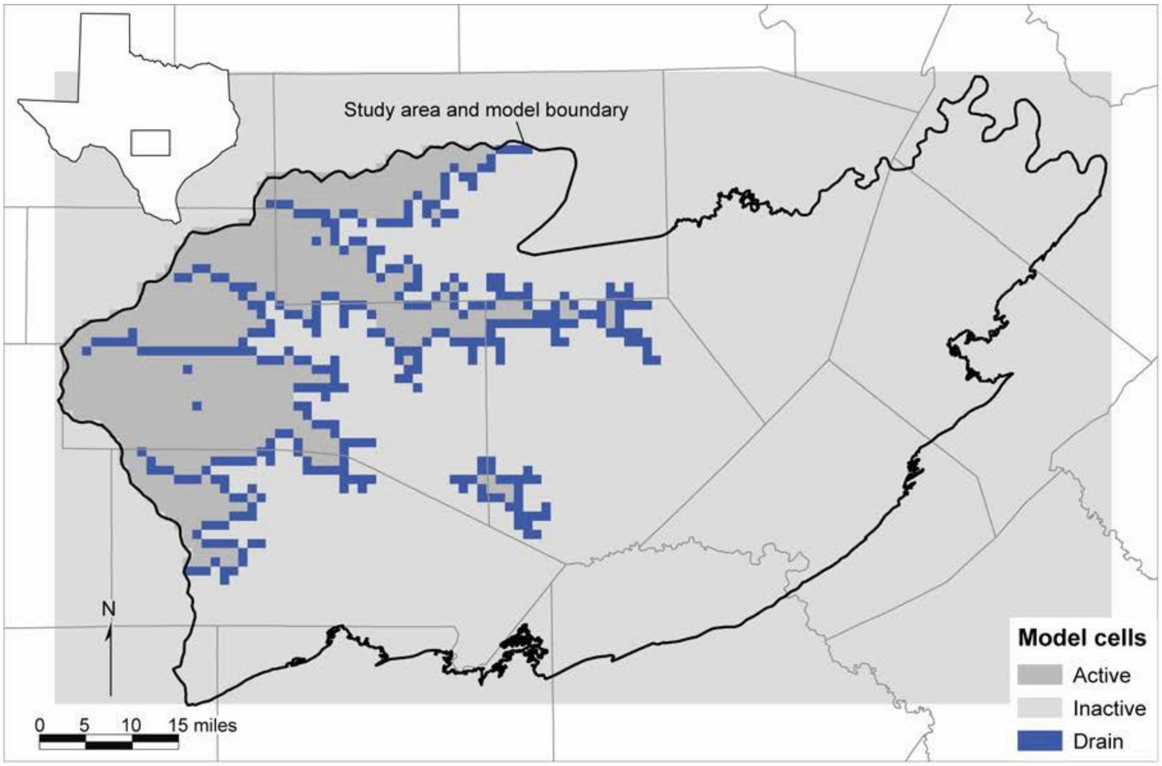


(d)

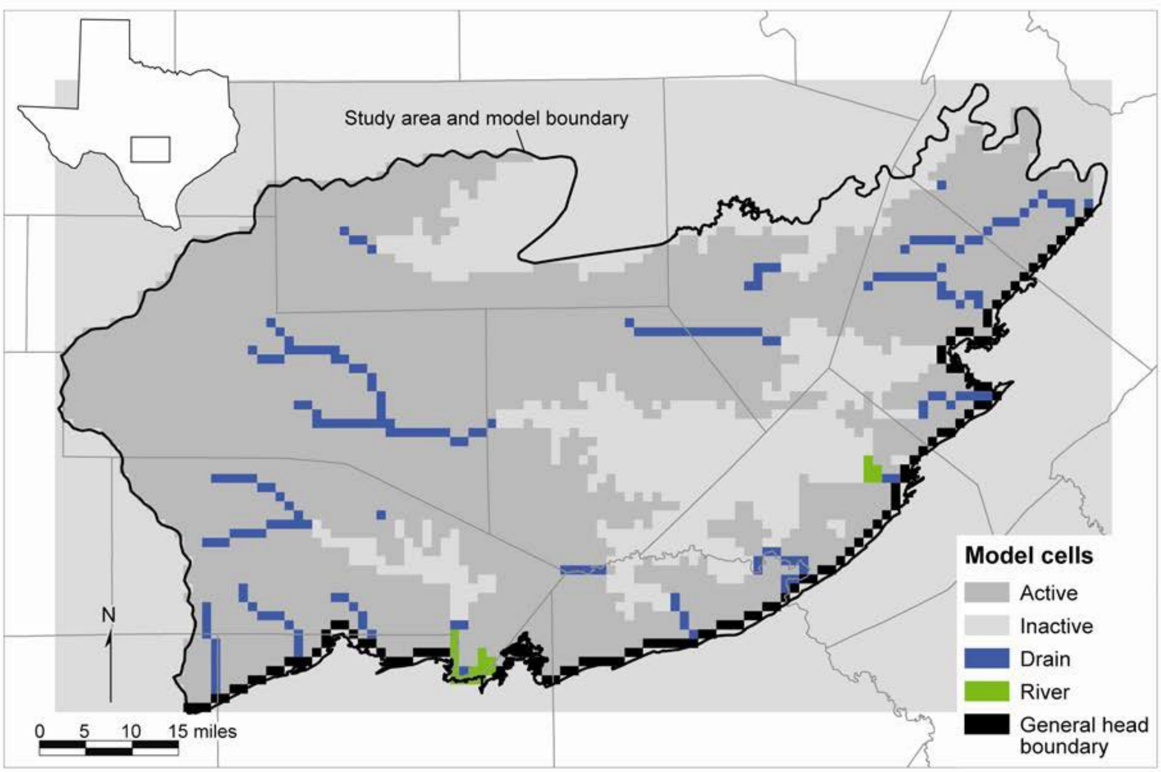
Figure 7-3. (continued).

We used the Drain Package of MODFLOW to represent rivers and streams in the model (Figure 7-4). This package only allows the streams to gain water from the aquifer. The River Package, which is another possible approach for simulating rivers and streams, allows streams to gain and lose water. Mace and others (2000) found that the River Package could allow unrealistic amounts of water to move from the rivers and streams into the aquifer and thus underestimate potential water level declines due to pumping or drought. Observed streamflow losses in Cibolo Creek along the boundary between Bexar and Comal counties are simulated as recharge. The Drain Package requires a drain elevation and conductance. When the head in the aquifer is above the drain elevation, water flows out of the model through the drain. If the head in the aquifer is equal to or below the drain elevation, no flow occurs from the drain to the aquifer. Drain conductance is a measure of hydraulic resistance to flow out of the drain. We defined the drain elevation by intersecting stream-bed location with the digital elevation model in ArcGIS® 9.1. We assigned the drain conductance on the basis of estimated width of the stream, a stream length of 1 mile (equivalent to the model cell size), an assumed riverbed thickness of 1 foot, and an assumed vertical hydraulic conductivity of 0.1 feet per day. After Mace and others (2000) calibrated the model, they investigated the sensitivity of simulated water levels to different values of drain conductance. Except for very low values, the drain conductance generally has little effect on water levels in the model (Mace and others, 2000). We also used drains to represent discharge to major springs, seepage from the erosional edge of the Edwards Group in the plateau area, and flow out of the Middle Trinity Aquifer in Gillespie County (Figure 7-4). For the springs, we assigned the drain elevation as the land surface elevation at the spring location and an initial conductance based on an assumed 1-foot thickness and the geometric mean hydraulic conductivity of the layer. For the erosional edge of the Edwards Group and flow out of the Middle Trinity Aquifer in Gillespie County, we assigned a drain elevation 10 feet above the base of layer 1 and a drain conductance based on a 1-foot thickness and the geometric mean hydraulic conductivity of the layer.

We simulated the influence of Medina Lake, Canyon Lake, Lake Travis, and Lake Austin on the aquifer using MODFLOW's River Package (Figure 7-4). The River Package requires hydraulic conductance of riverbed, river stage, and bottom elevation of the river. We assigned the riverbed conductance according to estimated width of the stream, a stream length of 1 mile (equivalent to the model cell size), riverbed thickness of 1 foot, and vertical hydraulic conductivity of 0.1 feet per day. We assigned the head in the river as the average lake-level elevation for the respective lakes. We defined the elevation of the riverbed by intersecting stream-bed location with the digital elevation model in ArcGIS® 9.1.

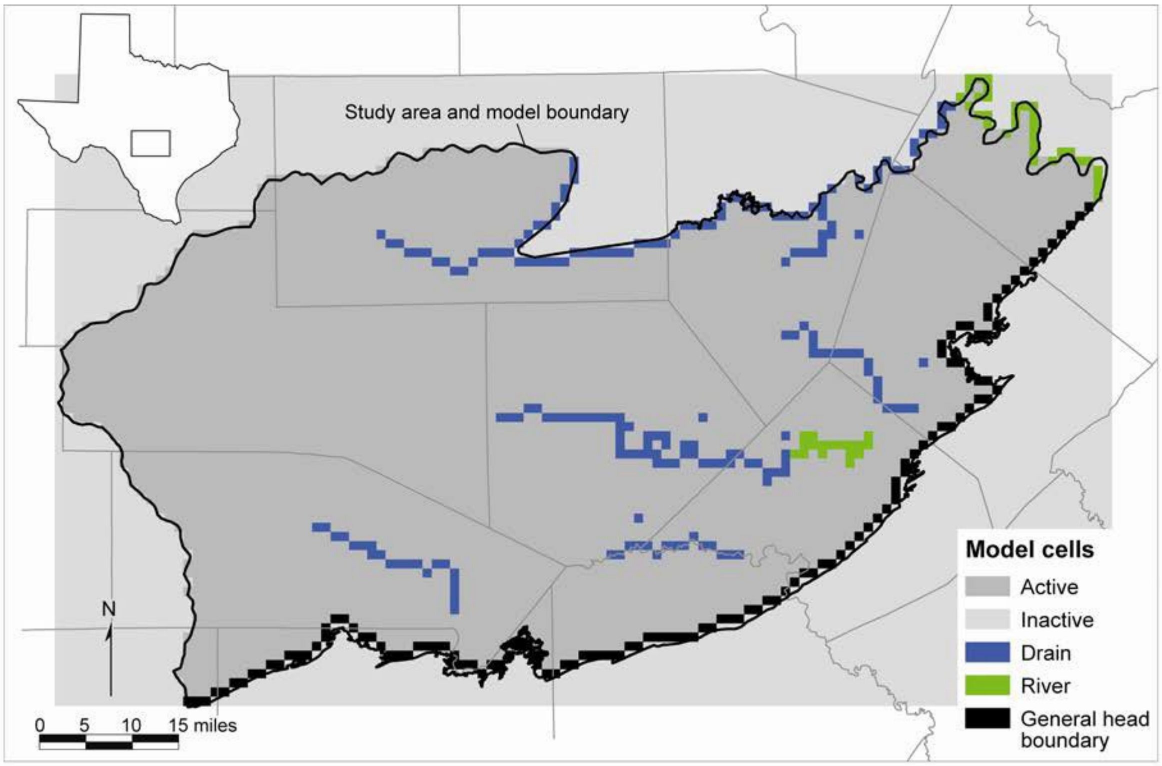


(a)

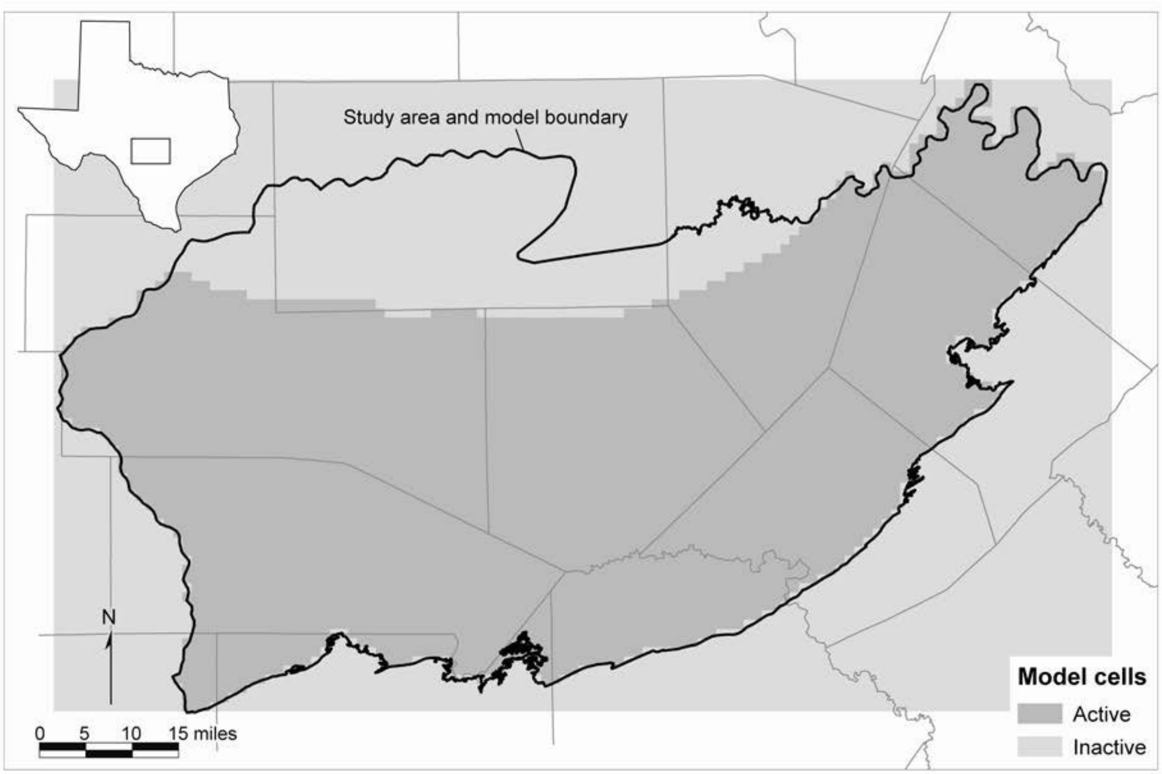


(b)

Figure 7-4. Boundary cells in model grid for (a) layer 1, (b) layer 2, (c) layer 3, and (d) layer 4.



(c)



(d)

Figure 7-4. (continued).

Outer model boundary conditions define the spatial extent of active flow within the respective layers in the model. In this model, the outer boundary conditions are defined by the use of no-flow and general-head boundaries. The model boundaries are generally simulated by no-flow boundaries to the north and west and general-head boundaries in the south and east, where the Hill Country portion of the Trinity Aquifer System bounds the Edwards (Balcones Fault Zone) Aquifer. The no-flow boundary in the north coincides with surface-water divides in the Pedernales and Colorado River basins. The no-flow boundary in the west follows a flow path in the Edwards-Trinity (Plateau) Aquifer. We inferred that layer 4 is also bound by no-flow boundaries in the south and east on the basis of the assumption, in response to work by Hovorka and others (1996), that there is very little groundwater flow between the Hill Country portion of the Trinity Aquifer System and Trinity Group rocks underlying the Edwards (Balcones Fault Zone) Aquifer. A no-flow boundary also exists at the base of the Lower Trinity Aquifer, a conclusion based on the assumption that there is no cross-formational flow between the Lower Trinity Aquifer and underlying Pre-Cretaceous rocks. To model the flow of groundwater between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer, we used the General-Head Boundary Package of MODFLOW. We placed general-head boundary cells along the contact with the Edwards (Balcones Fault Zone) Aquifer in layers 2 and 3 (Figure 7-4). The General-Head Boundary Package requires values for hydraulic head and conductance. We assigned the hydraulic head according to the interpreted water level map (Figure 5-3) in the area of the general-head boundary cells. We assigned the general-head boundary conductance according to the hydraulic conductivity and geometry of the cell and an assumed 1-foot thickness. Conceptually, the general-head boundary conductance represents the resistance to flow between a cell in the model and a constant-head source or sink. In this case, we have used the general-head boundary to represent flow out of the study area either into the Edwards (Balcones Fault Zone) Aquifer across faults or continuing into the downdip parts of the Trinity Aquifer System. For simplicity, we used an arbitrary thickness of unity (1 foot) to define conductance.

The updating of this model included changes to the boundary conditions. Besides adding the Lower Trinity Aquifer as another layer, the model comprised these changes: (1) the constant-head cells that were used by Mace and others (2000) to simulate reservoirs were replaced by river cells, (2) river cells simulating Lake Travis were removed from layer 2 and now only appear in layer 3, (3) the spatial extent of Medina Lake was revised, and (4) the spatial distribution of recharge was revised to account for the effects of the Balcones Fault Zone and recharge from Cibolo Creek. The constant-head cells were converted to river cells because constant head provides an unlimited, unrestricted source of water when impacted by nearby pumping and therefore could produce unrealistically high water levels adjacent to the constant-head cells. On the other hand, the River Package in MODFLOW includes a conductance parameter that can be used to restrict flow and would therefore allow water levels to fall to more realistic values in response to pumping. Although the potential exists to produce unrealistically high flows from the River Package (similar to the use of constant heads), amounts of water to the groundwater flow system under periods of high pumping and proper attention to boundary elevation and conductance can mitigate this effect. During model calibration, we made minor adjustments to the outer model boundary conditions to address dry cell and numerical stability issues.

8.0 Modeling Approach

Model calibration involves the adjustment of parameters until the model results of groundwater elevations and base-flow discharge reasonably match measured field data. Our approach for calibrating the model comprised two major steps: (1) calibrating a steady-state model and (2) calibrating a transient model.

The steady-state model was developed first to facilitate easier calibration because some parameters, such as aquifer storage and water level variations over time, do not need to be taken into consideration. In the steady-state model, calibration only requires consideration of spatial variations of all input parameters within the aquifer. We calibrated the steady-state model to reproduce water levels for 1980, reproducing the 1977 through 1985 water level measurements (Figure 5-9 through 5-12). We used the steady-state model to investigate (1) recharge rates, (2) hydraulic properties, (3) boundary conditions, (4) discharge from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer, (5) groundwater flow budget, and (6) sensitivity of model results to different parameters.

Our approach for calibrating the model was to match water levels and groundwater discharge to rivers (for steady-state conditions) and water level and groundwater discharge fluctuations (for transient conditions) using our conceptual understanding of the flow system. We quantified the calibration, or goodness of fit between the simulated and measured water level values, using the mean absolute error (*MAE*):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|(h_m - h_s)_i\right|, \qquad (1)$$

where *MAE* is the mean absolute error, *n* is the number of calibration points, h_m is the measured hydraulic head at point *i*, and h_s is the simulated hydraulic head at point *i*. The mean absolute error is the mean of the absolute value of the differences in measured and simulated hydraulic head (Anderson and Woessner, 2002). Our standards for calibration were (1) the mean absolute error must be less than 10 percent of the measured hydraulic-head drop across the model area, and (2) the error shall not be biased by areas having considerably more control points than other areas. Once we completed the steady-state model, we used the framework of the model to develop a transient model for the years 1980 through 1997 using annual stress periods. Please note that the first stress period in the transient model is 1,000,000 days long and represents the 1980 steady-state model. The transient model allowed us to test how well the model could reproduce water level fluctuations in the aquifer. We calibrated the transient model by adjusting aquifer storage values to minimize the difference between simulated and measured water level variations.

9.0 Steady-State Model

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

9.1 Calibration

We calibrated the model to measured water levels for 1977 through 1985 used to represent 1980 water levels. We chose the year 1980 for our steady-state model because it fell within a period of relatively stable water levels in the Hill Country portion of the Trinity Aquifer System. We adjusted recharge and spatial distribution of hydraulic conductivity and general-head boundary conductance to calibrate the steady-state model.

We assigned recharge into three zones on the basis of varying aquifer characteristics and recharge pathways: (1) Balcones Fault Zone, (2) areas outside the fault zone, and (3) Cibolo Creek. We varied recharge during the calibration process, resulting in a final recharge rate of 5 percent of average annual precipitation in the Balcones Fault Zone along the eastern margin of the study area and 3.5 percent of average annual precipitation throughout the rest of the model area. Along Cibolo Creek, we set recharge equivalent to measured streamflow loss of about 70,300 acre-feet per year (Figure 9-1).

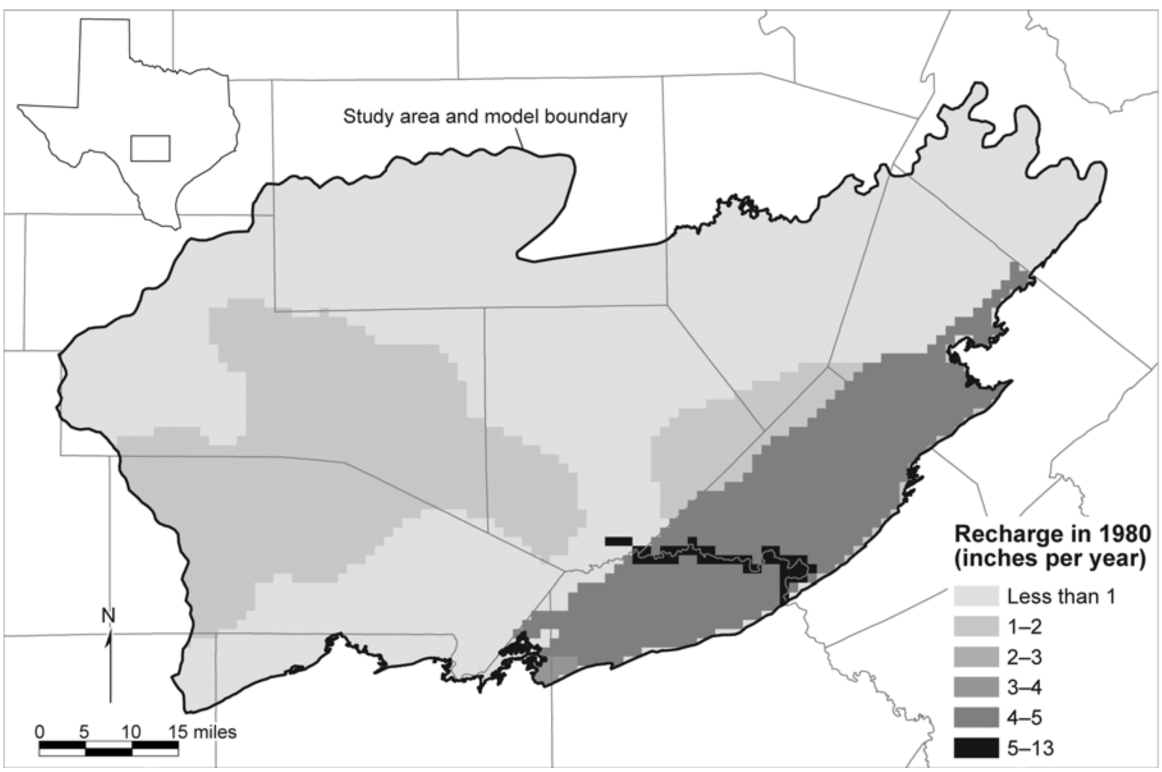


Figure 9-1. **Estimated spatial distribution of recharge for 1980 based on precipitation data for the study area and Cibolo Creek streamflow loss studies.**

We also adjusted hydraulic conductivity during model calibration. In the calibrated model, we assigned a uniform hydraulic conductivity value of 11 feet per day to the Edwards Group. Assigned hydraulic conductivity values in the Upper Trinity Aquifer are 150 feet per day along Cibolo Creek, 15 feet per day within the Balcones Fault Zone, and 9 feet per day in the rest of the aquifer. The two lower hydraulic conductivities, within and outside the Balcones Fault Zone, fall within the range of measured hydraulic conductivity in the Upper Trinity Aquifer. The highest hydraulic conductivities in the Upper Trinity Aquifer, which lie along part of Cibolo Creek, can be justified on the basis of work done by Kastning (1986) and Veni (1994) that indicates very high hydraulic conductivity near the creek. In the Middle Trinity Aquifer, we assigned a uniform hydraulic conductivity of 7.64 feet per day, the geometric mean of the hydraulic conductivity values used by Mace and others (2000), for the portion of the aquifer outside the Balcones Fault Zone. In the Balcones Fault Zone portion of the Middle Trinity Aquifer, we assigned a uniform hydraulic conductivity of 15 feet per day. In the Lower Trinity Aquifer, we assigned hydraulic conductivity values of 16.7 and 1.67 feet per day to the Balcones Fault Zone and the rest of the aquifer, respectively.

The calibration process resulted in only minor changes to drain conductance values in individual cells. We increased general-head boundary conductance values by factors of 5 and 2.5 in layers 2 and 3, respectively, to facilitate increased interaquifer flow between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer owing to the large amounts of recharge flowing from the Cibolo Creek.

Interaquifer flow between the Middle and Lower Trinity aquifers through the Hammett Shale is simulated using vertical leakance. We varied vertical leakance spatially on the basis of the Hammett Shale thickness. Vertical leakance values decrease with increasing Hammett Shale thickness, reaching a maximum value where the Hammett Shale is absent. Vertical leakance values lie in the range of 10^{-6} to 0.8 per day.

Simulated water levels from the calibrated steady-state model are fairly close to measured water levels and display no apparent spatial biases (Figure 9-2). The mean absolute error of the calibrated model is 54 feet, which is approximately 4 percent of the 1,700-foot range of measured water levels (Figure 9-3). This value indicates that the average difference between measured and simulated water levels in the model is 54 feet—acceptable because the result lies within the 10 percent target for model calibration. Water-balance discrepancies are also acceptable, approaching 0 percent.

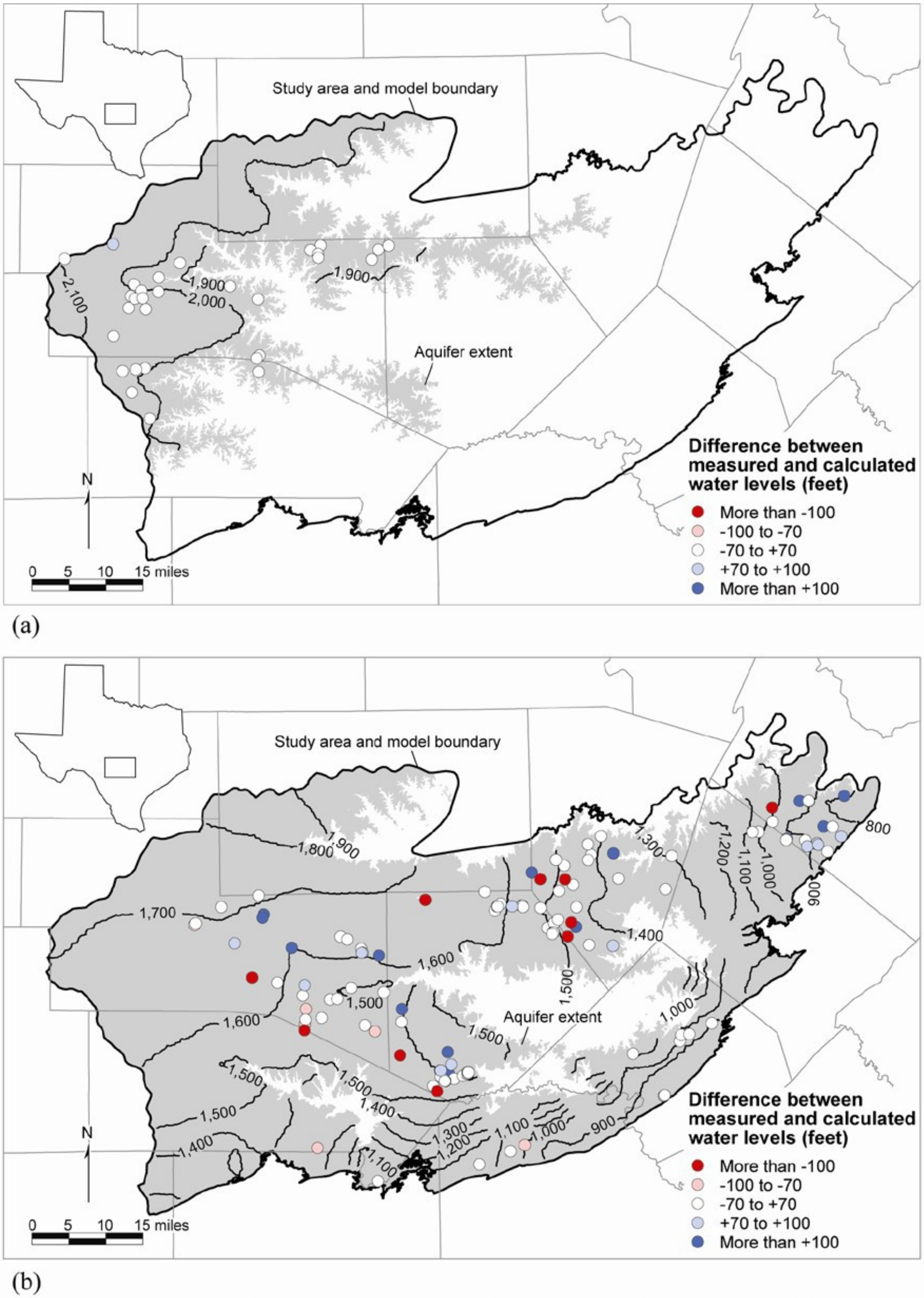
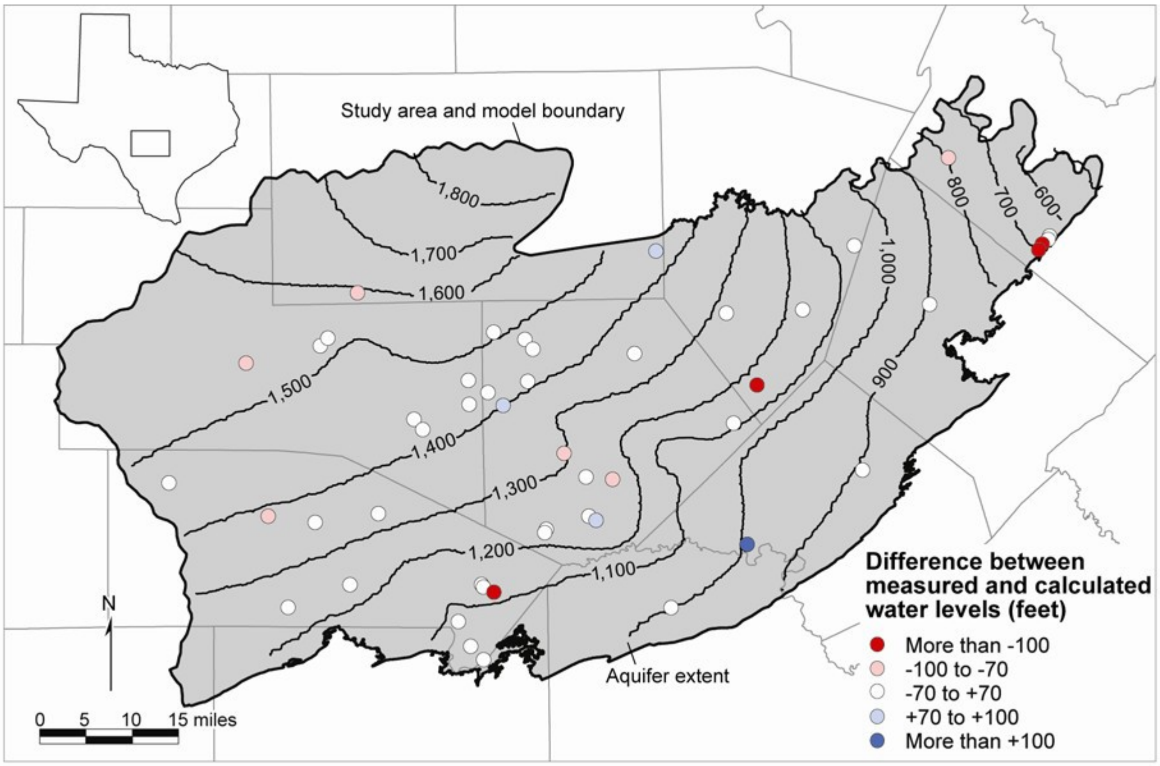
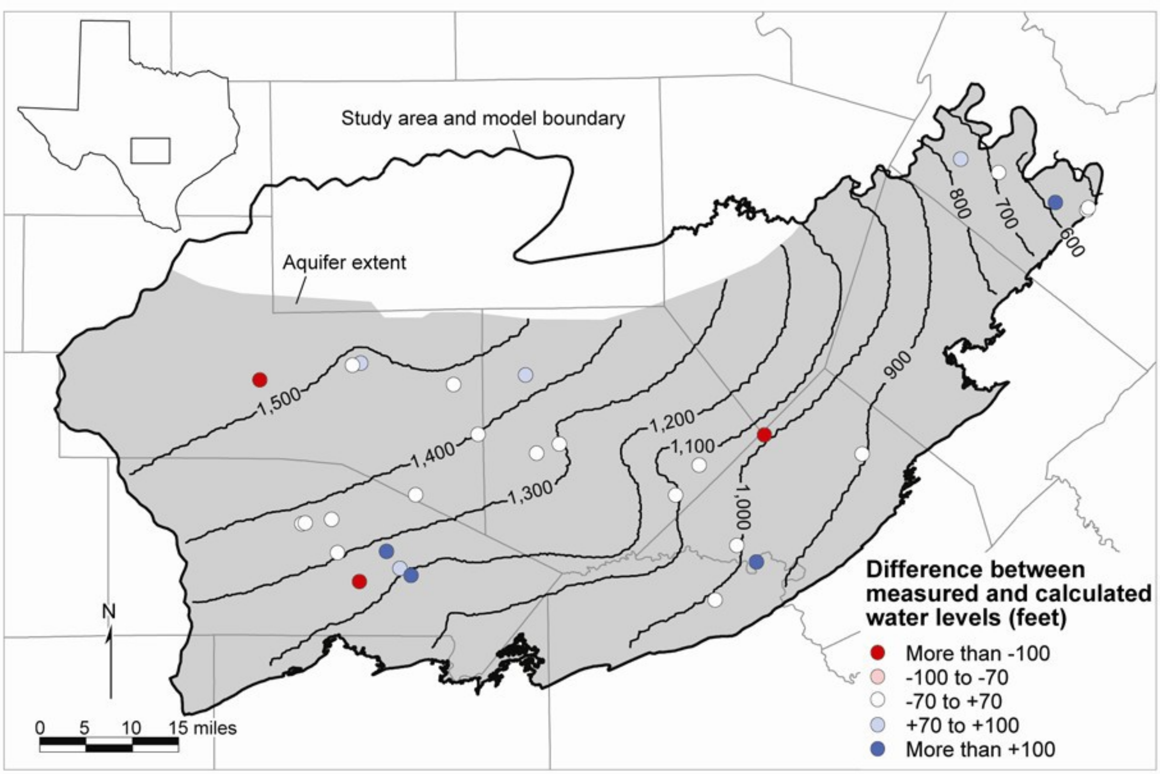


Figure 9-2. **Comparison of measured and calculated water levels from the steady-state model for (a) layer 1, (b) layer 2, (c) layer 3, and (d) layer 4. The contours represent calculated water levels, expressed in feet above sea level, whereas the points indicate the difference between measured and simulated water levels relative to the measured water levels.**



(c)



(d)

Figure 9-2. (continued).

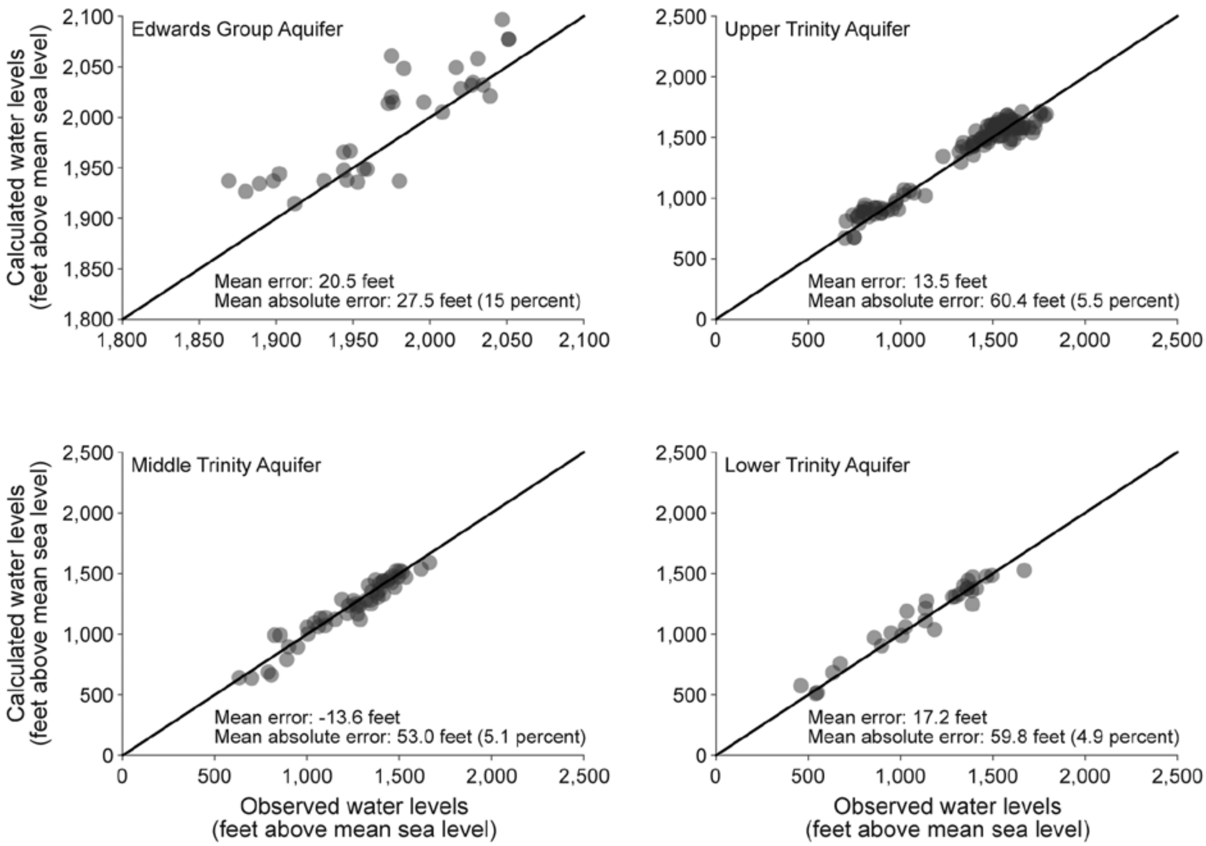


Figure 9-3. Comparison of measured and calculated water levels from the steady-state model.

In addition to comparing measured and simulated water levels, we compared measured streamflow and simulated drain discharge to determine how well the model reproduces groundwater discharge to major streams in the study area (Figures 9-4 and 9-5). General agreement between measured stream discharge of Barton Creek, Blanco River, Guadalupe River, Hondo Creek, Medina River, Onion Creek, and Pedernales River indicates that the steady-state model does a reasonable job of reproducing base flow to streams.

The water budget of the steady-state model indicates that total groundwater flow through the model is approximately 321,000 acre-feet per year (Table 9-1). Of this flow, about 60 percent discharges to streams, springs, and reservoirs, and 35 percent discharges through cross-formational flow to the Edwards (Balcones Fault Zone) Aquifer. About 5 percent of groundwater discharge is due to well pumping, mostly for municipal and rural domestic uses.

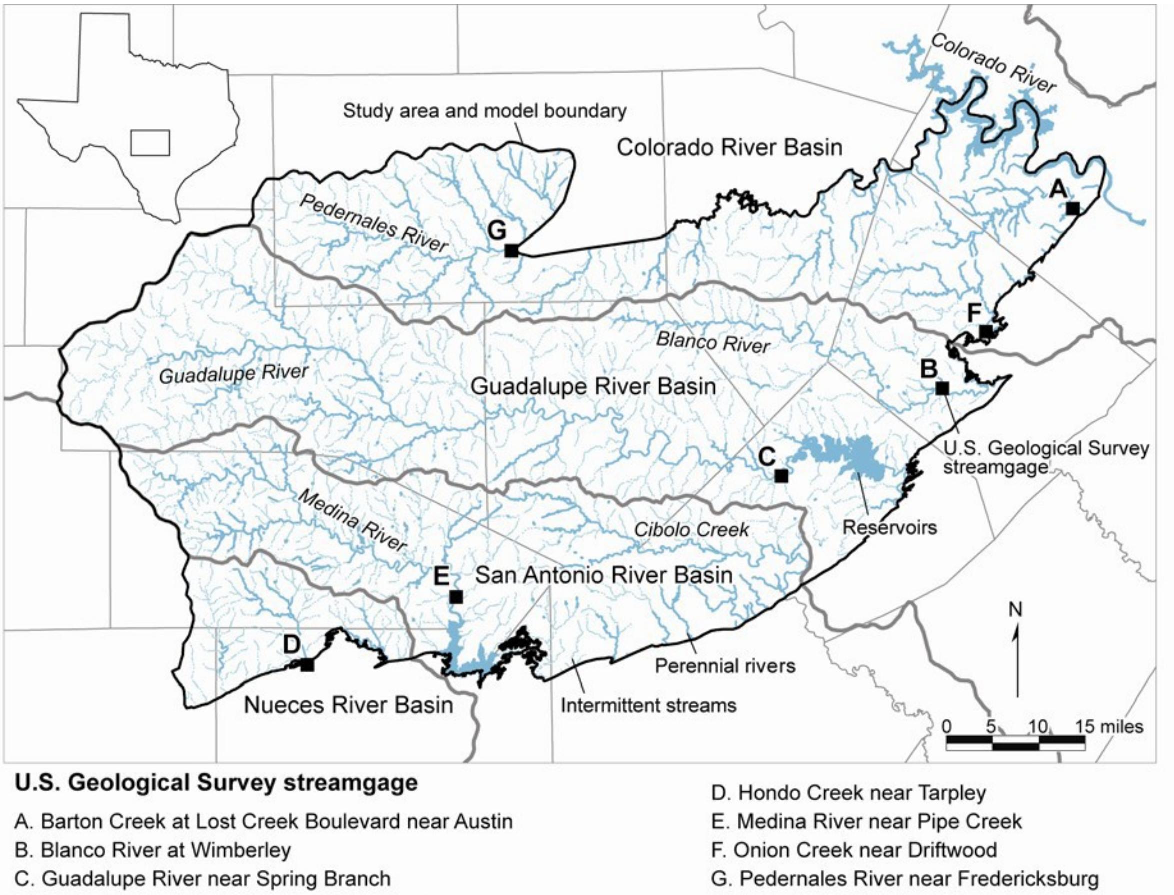


Figure 9-4. **Location of streamgages used to compare measured streamflow and calculated discharge to streams from the model.**

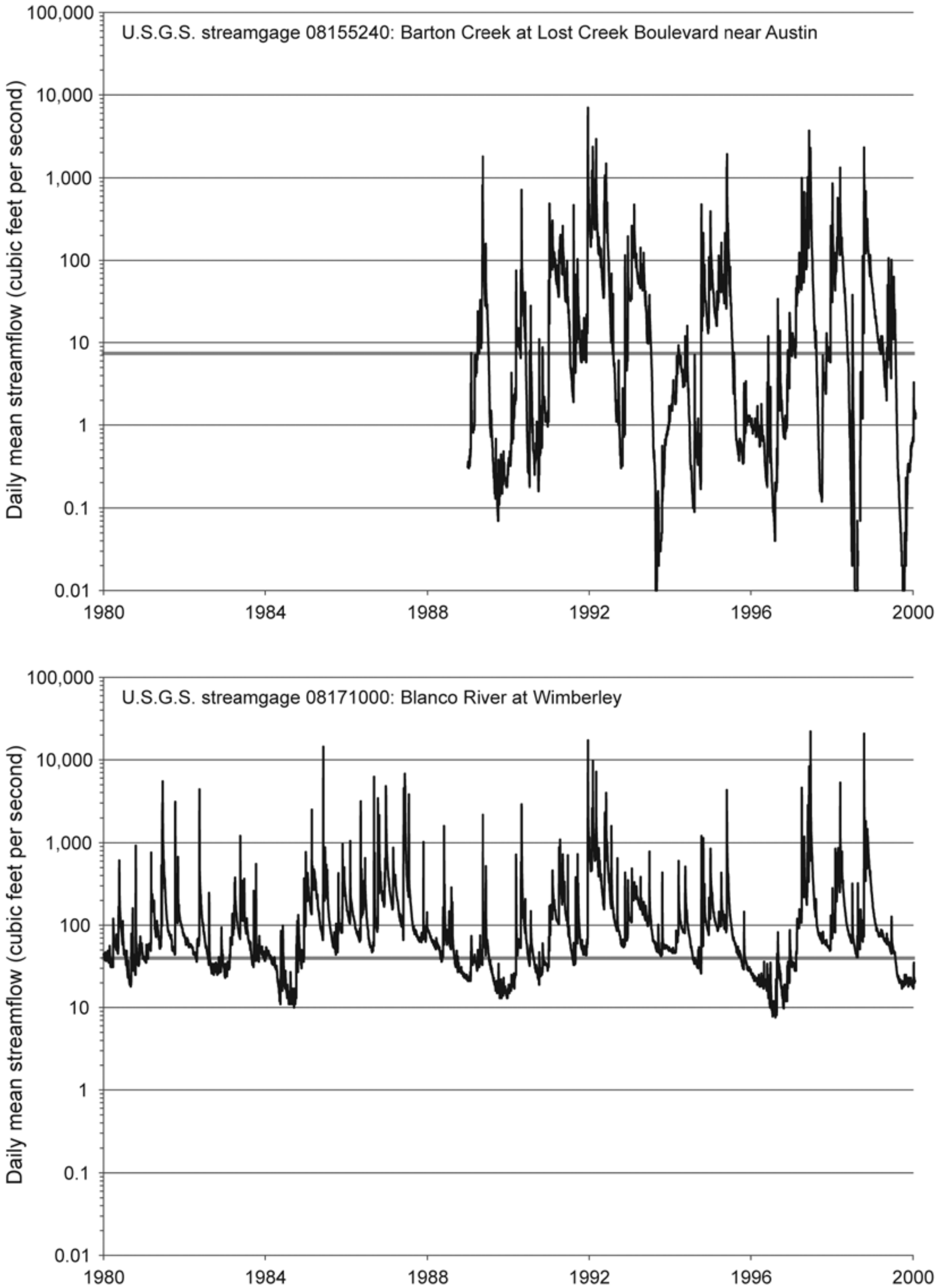
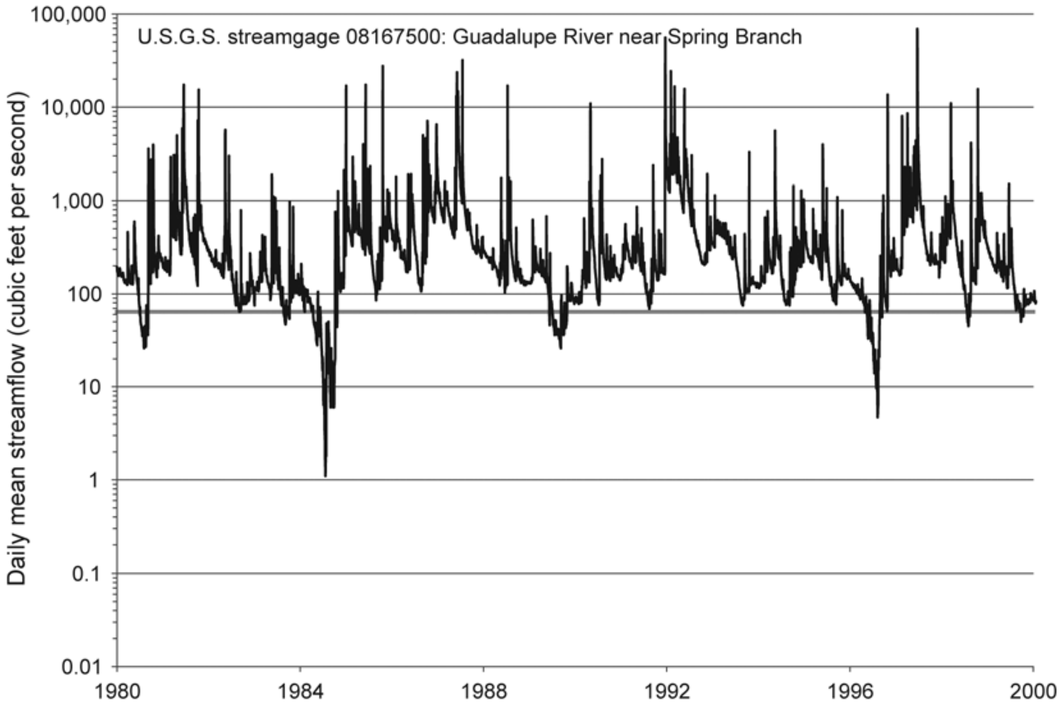


Figure 9-5. **Comparison of the calculated groundwater discharge rate to perennial streams from the 1980 steady-state model (gray line) and measured streamflow data. Streamgage locations are shown in Figure 9-4. U.S.G.S. = U.S. Geological Survey**



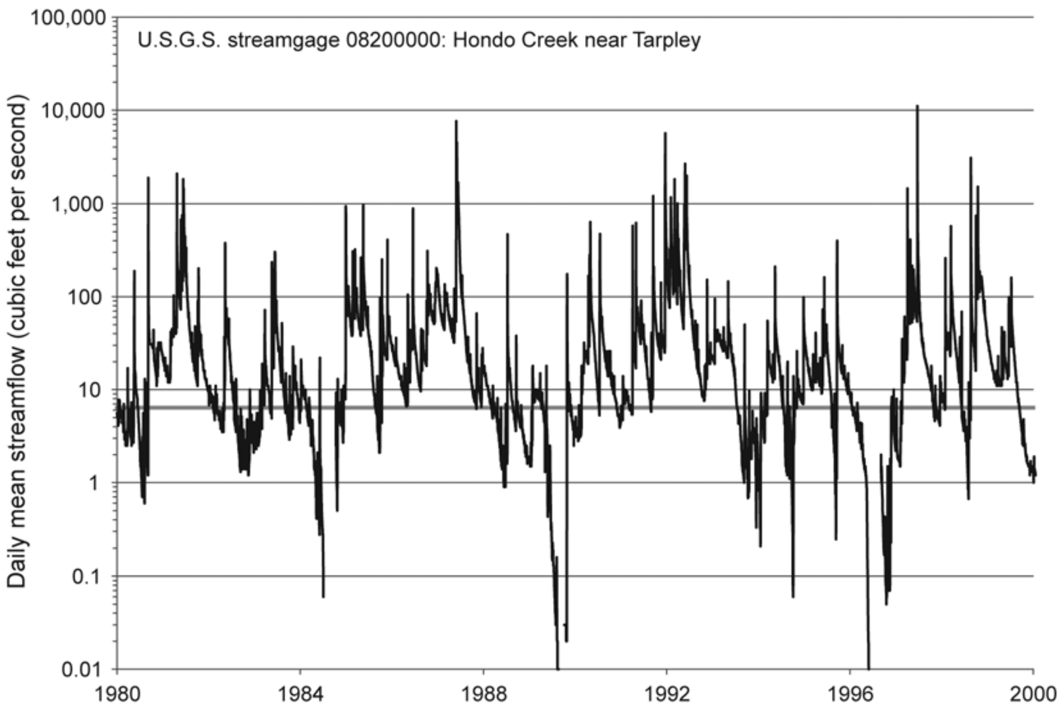
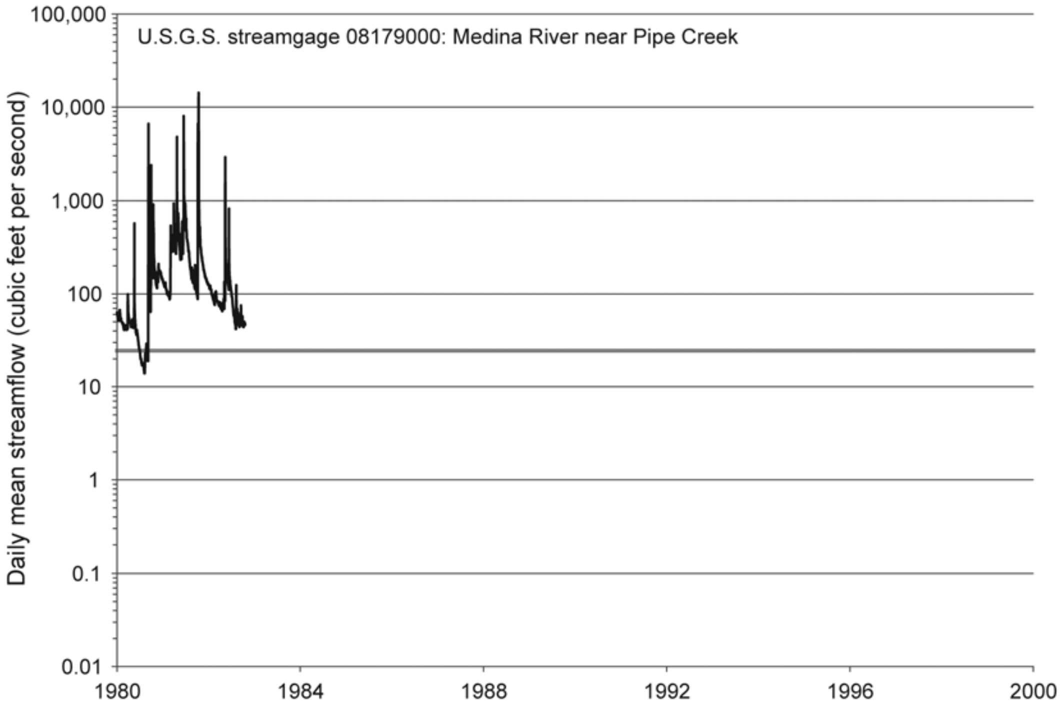


Figure 9-5. (continued).



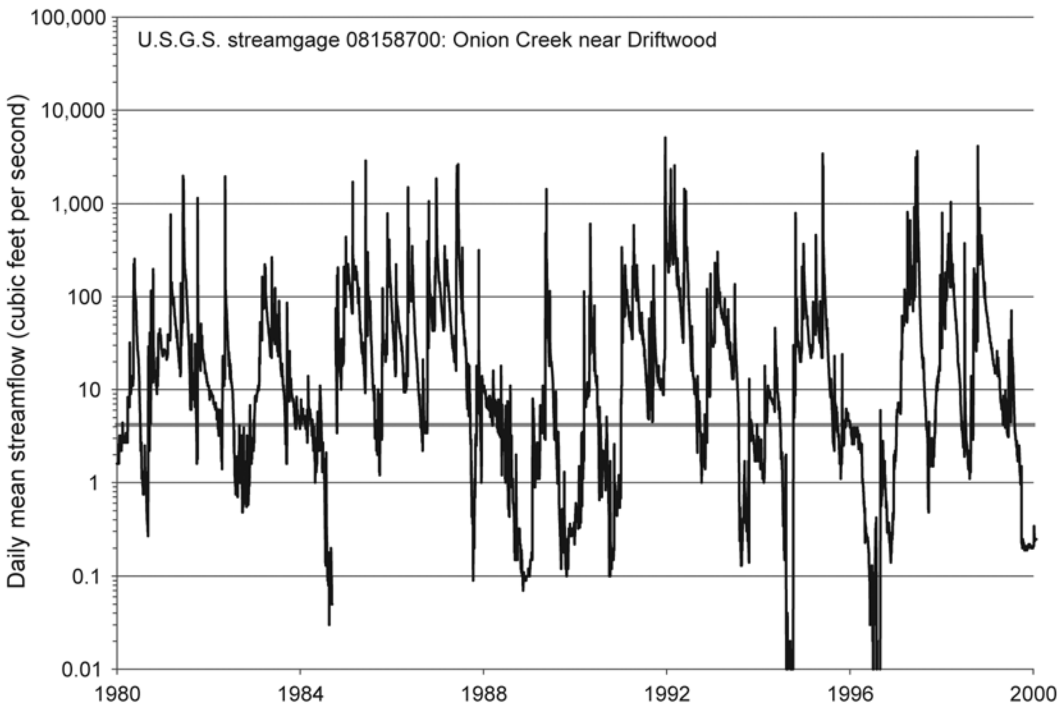


Figure 9-5. **(continued).**

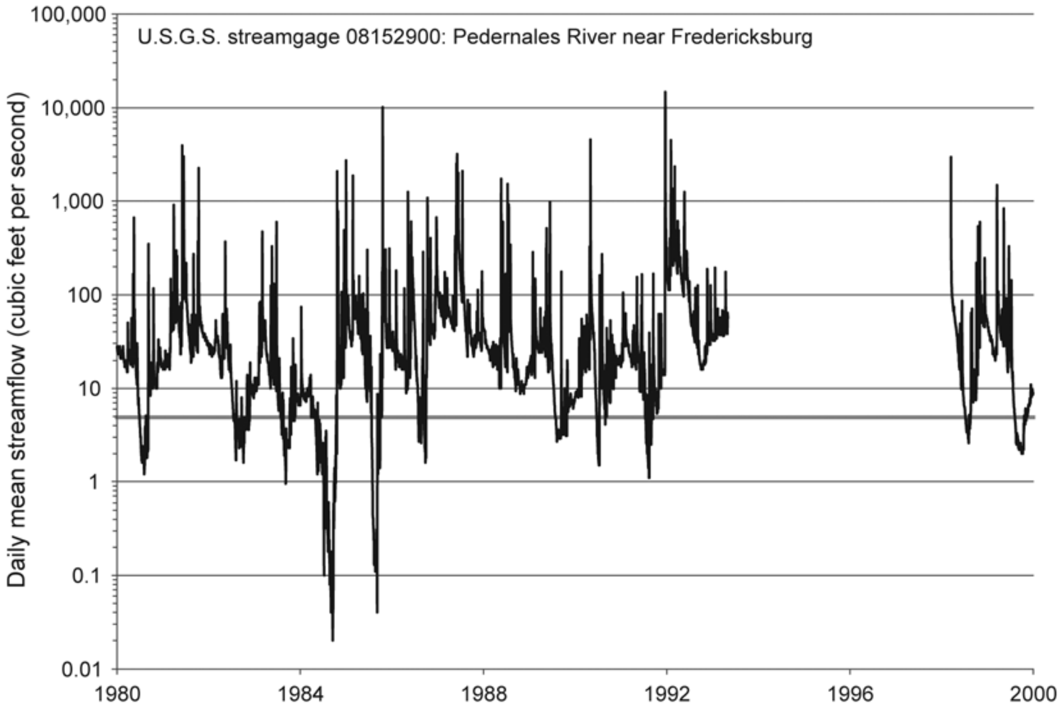


Figure 9-5. **(continued).**

Table 9-1. **Water budget for the calibrated steady-state model for 1980 (all values in acre-feet per year, rounded to hundreds of acre-feet; negative values indicate net discharge from the aquifer).**

	In	Out	Net
Wells	0	16,700	-16,700
Streams and springs	0	164,500	-164,500
Reservoirs	9,000	28,800	-19,800
Edwards (Balcones Fault Zone) Aquifer	8,100	110,600	-102,500
Recharge	303,500	0	303,500
Total	**320,600**	**320,600**	**0**

We used the calibrated model to investigate the volume of recharge to and groundwater moving between the different aquifers (Table 9-2). The total volume of recharge to the aquifer due to precipitation falling on the land surface and streamflow loss from Cibolo Creek is about 304,000 acre-feet per year. About 50 percent of the recharge in the study area occurs in the Upper Trinity Aquifer, whereas 20 and 30 percent of recharge occurs in the Edwards Group and Middle Trinity Aquifer, respectively. Recharge to the Lower Trinity Aquifer is insignificant. In the model, very small amounts of recharge to the Lower Trinity Aquifer occur along the Pedernales River where the overlying Middle Trinity Aquifer is thin and may not be saturated. About 20 percent of the water that recharges the Edwards Group flows into the Upper Trinity Aquifer. The total inflow of water to the Upper Trinity Aquifer, including infiltration of precipitation and cross-formational flow, is about 166,000 acre-feet per year. About 40 percent of the total inflow into the Upper Trinity Aquifer flows into the Middle Trinity Aquifer. Total inflow into the Middle Trinity

Aquifer is about 153,000 acre-feet per year. According to the model, slightly less water enters the Middle Trinity Aquifer through cross-formational flow than through direct infiltration on the outcrop. Our conceptual model indicates total groundwater circulation in the Lower Trinity Aquifer is a relatively minor component of the total groundwater budget of the Hill Country portion of the Trinity Aquifer System. In this steady-state model, net cross-formational flow from the Middle Trinity Aquifer to the Lower Trinity Aquifer is approximately equal to total pumping from the Lower Trinity Aquifer.

Table 9-2. **Water budget for the respective layers in the calibrated steady-state model for 1980 (all values in acre-feet per year, rounded to hundreds of acre-feet; negative values indicate net discharge from the aquifer).**

	Edwards Group	Upper Trinity Aquifer	Middle Trinity Aquifer	Lower Trinity Aquifer	Total
Interaquifer flow (above)	0	9,800	64,100	5,800	79,700
Interaquifer flow (below)	-9,800	-64,100	-5,800	0	79,700
Wells	-1,000	-5,100	-4,600	-6,000	-16,700
Streams and springs	-47,700	-60,900	-55,900	0	-164,500
Reservoirs	0	-2,500	-17,300	0	-19,800
Edwards (Balcones Fault Zone) Aquifer	0	-33,300	-69,200	0	-102,500
Recharge	58,500	156,200	88,700	100	303,500

The model shows that more than 100,000 acre-feet per year of groundwater flows out through the general-head boundary along the eastern and southern margins of the model. This groundwater flows from the Upper and Middle Trinity aquifers into the Edwards (Balcones Fault Zone) Aquifer. Some of this groundwater flows directly from the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer, and some continues to flow in the portion of the Trinity Aquifer System that underlies the Edwards (Balcones Fault Zone) Aquifer (Ashworth and Hopkins, 1995). Presumably, groundwater moves downdip in the Trinity Aquifer System and eventually discharges upward into the Edwards (Balcones Fault Zone) Aquifer.

The model results show that the flow of groundwater across the general-head boundary is much less in the northeastern part of the boundary than in the central and southwestern parts (Table 9-3). The groundwater flow across the general-head boundary is 260 acre-feet per year per mile for the boundary within Travis and Hays counties, reaches a maximum of 1,700 acre-feet per year per mile in Comal and Bexar counties, and is 490 acre-feet per year per mile within Medina, Bandera, and Uvalde counties. This numerical result is qualitatively supported by the measured potentiometric surface, which shows groundwater generally flowing perpendicular to the boundary in Comal, Bexar, and Medina counties and subparallel to the boundary in Travis and Hays counties (Figure 9-2). The spatial distribution of groundwater flow between the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer is most likely influenced by the large amounts of recharge occurring along Cibolo Creek in Bexar and Comal counties. Faults also have greater displacements to the east and may therefore act as more effective barriers to flow.

Table 9-3. **Water budget for the respective counties in the calibrated steady-state model for 1980 (all values in acre-feet per year, rounded to hundreds of acre-feet; negative values indicate net discharge from the aquifer).**

County	Wells	Streams and springs	Recharge	Reservoirs	Edwards (Balcones Fault Zone) Aquifer	Lateral inflow	Lateral outflow
Bandera	-1,100	-34,300	36,900	-1,000	-1,800	25,500	-24,200
Bexar	-3,900	-9,900	39,000	0	-37,200	36,200	-24,300
Blanco	-200	-14,200	19,000	0	0	6,900	-11,500
Comal	-1,000	-3,700	40,300	-5,900	-37,900	37,600	-29,500
Gillespie	-1,200	-14,300	28,300	0	0	900	-13,700
Hays	-1,600	-18,800	21,800	0	-6,700	14,200	-9,000
Kendall	-1,600	-28,500	51,000	0	0	9,600	-30,500
Kerr	-6,000	-32,600	47,100	0	0	10,500	-19,000
Kimble	0	0	400	0	0	200	-500
Medina	0	-2,400	5,800	-2,600	-14,300	20,400	-6,900
Travis	-100	-5,200	11,900	-10,300	-2,100	6,100	-400
Uvalde	0	-500	1,800	0	-2,500	2,000	-800
Total	**-16,700**	**-164,500**	**303,500**	**-19,800**	**-102,500**	**170,200**	**-170,200**

9.2 Sensitivity Analysis

After we completed calibration of the steady-state model, we analyzed the input parameters to assess the sensitivity of model results to respective input parameters: vertical and horizontal hydraulic conductivity, general-head boundary conductance, drain conductance, river conductance, pumping, and recharge. Sensitivity analysis is a method of quantifying uncertainty of the calibrated model related to uncertainty in the estimates of respective aquifer parameters, stresses, and boundary conditions (Anderson and Woessner, 2002). Determining the sensitivity of the model to specific parameters offers insights into the uniqueness of the calibrated model. Sensitivity analysis identifies which parameters have the greatest influence on water levels and groundwater discharge to springs and streams. A model is sensitive to a specified input parameter if relatively small changes in that parameter result in relatively large changes in simulated water levels. In other words, calibration is possible only over a narrow range of values and, consequently, model uncertainties are relatively low. A model is insensitive if relatively large changes of a specific input parameter produce small water level changes. Insensitivity results in higher uncertainties because the model will remain calibrated over a large range of input parameter values. Sensitivity is analyzed by systematically varying parameter values and noting changes in water levels over the calibrated model. The water level changes are quantified by calculating the mean difference (*MD*) as follows:

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_{sen} - h_{cal}\right), \qquad (2)$$

where n is the number of points, h_{sen} is the simulated water level for the sensitivity analysis, and h_{cal} is the calibrated water level. The mean difference is positive if water levels are higher than calibrated values and negative if they are lower than calibrated values.

Water levels in the model are most sensitive to recharge and horizontal hydraulic conductivity and, to a lesser extent, to vertical hydraulic conductivity (Figure 9-6). The model is insensitive to pumping and to general-head boundary, drain, and river conductance. The insensitivity to pumping can be attributed to the fact that pumping is a relatively minor component of the overall aquifer water budget. Insensitivity to drain and general-head boundary conductance can be attributed to high conductance values of as much as 10^9 square feet per day. Consequently, in order to have much of an effect on water levels, drain and general-head boundary conductance would probably have to be lowered by several orders of magnitude. Additionally, the effects of drain and general-head boundary conductance are local. As a result, varying drain and general-head boundary conductance only produces water level changes close to the boundaries and does not have widespread effects throughout the model.

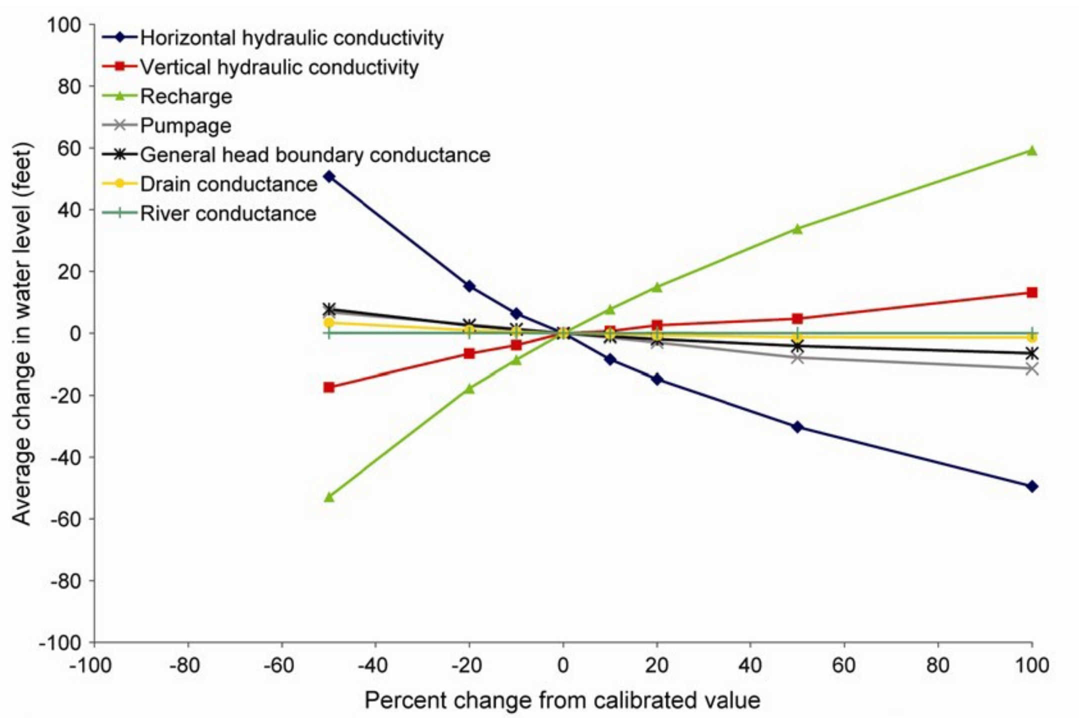


Figure 9-6. **Sensitivity of calculated water levels in the steady-state model to changes in model parameters.**

10.0 Transient Model

Once we calibrated the steady-state model to 1980 conditions, we proceeded to calibrate the model for transient conditions for the period 1980 through 1997 (Table 10-1).

Table 10-1. Stress periods of the transient model.

Stress period	Year	Length (days)
1	Steady-state (1980)	100,000
2	1981	365
3	1982	365
4	1983	365
5	1984	365
6	1985	365
7	1986	365
8	1987	365
9	1988	365
10	1989	365
11	1990	365
12	1991	365
13	1992	365
14	1993	365
15	1994	365
16	1995	365
17	1996	365
18	1997	365

10.1 Calibration

We simulated water level fluctuations during the period 1980 through 1997 using annual stress periods for 1981 through 1997. Calibration was achieved by adjusting storage parameter values, specific storage, and specific yield until the model responses approximated water level fluctuations observed in wells in the model area. Specific yield is applicable to the unconfined parts of the aquifer and is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water level (Domenico and Schwartz, 1990). Specific storage is applicable to the confined parts of the aquifer and is defined as a measure of the volume of water per unit volume of aquifer rock that enters or leaves storage per unit change in water level (Domenico and Schwartz, 1990). Specific storage and specific yield are important factors in transient calibration because they influence water level responses to changes in recharge and discharge. Low specific-storage or specific-yield values result in water level fluctuations that are larger and more rapid than those associated with higher specific-storage or specific-yield values. This difference occurs because less water is required to produce a given water level change.

Using annual stress periods, we simulated water level fluctuations due to recharge and pumping variations during the period 1980 through 1997. We found that specific-storage values of 10^{-5}, 10^{-6}, 10^{-7}, and 10^{-7} per foot for the Edwards Group and the Upper, Middle, and Lower Trinity aquifers, respectively, and specific-yield values of 0.008, 0.0005, 0.0008, and 0.0008 for the Edwards Group and the Upper, Middle, and Lower Trinity aquifers, respectively, worked best for reproducing observed water level fluctuations (Table 10-2).

Table 10-2. Calibrated specific-yield, specific-storage, and hydraulic conductivity data for the respective model layers.

Model layer	Aquifer	Specific yield	Specific storage (per foot)	Hydraulic conductivity (feet per day)	
				Range	Mean
1	Edwards Group	0.008	1.0E-05	11	11.0
2	Upper Trinity Aquifer	0.0005	1.0E-06	9 to 150	10.4
3	Middle Trinity Aquifer	0.0008	1.0E-07	7.6 to 15	8.8
4	Lower Trinity Aquifer	0.0008	1.0E-07	1.67 to 16.7	4.4

The model does a good job of reproducing observed water level fluctuations in some areas but not as well in other areas (Figures 10-1 through 10-5). Note that baseline shifts in water levels in Figure 10-2 are commonly due to the influence of local-scale conditions not represented in the regional model or errors in our parameterization of the aquifer data. Although it has limitations, the model does a good job of reproducing year-to-year water level variations in most wells. Comparison of measured and simulated 1990 and 1997 water levels indicates mean absolute errors of 52 and 57 feet, respectively, or approximately 3.5 and 5.3 percent of the range of measured water levels (Table 10-3; Figure 10-4).

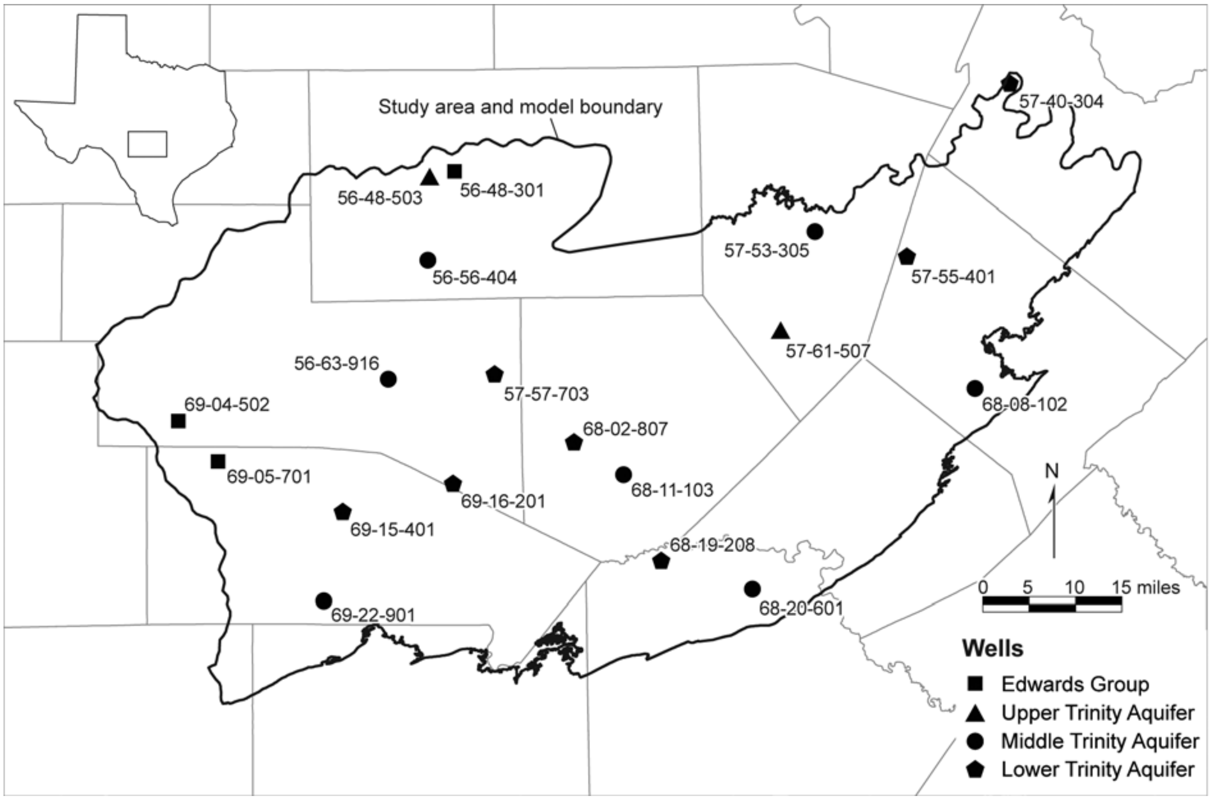


Figure 10-1. **Locations of wells used to compare measured water levels over the transient period (1980 through 1997) and calculated water levels.**

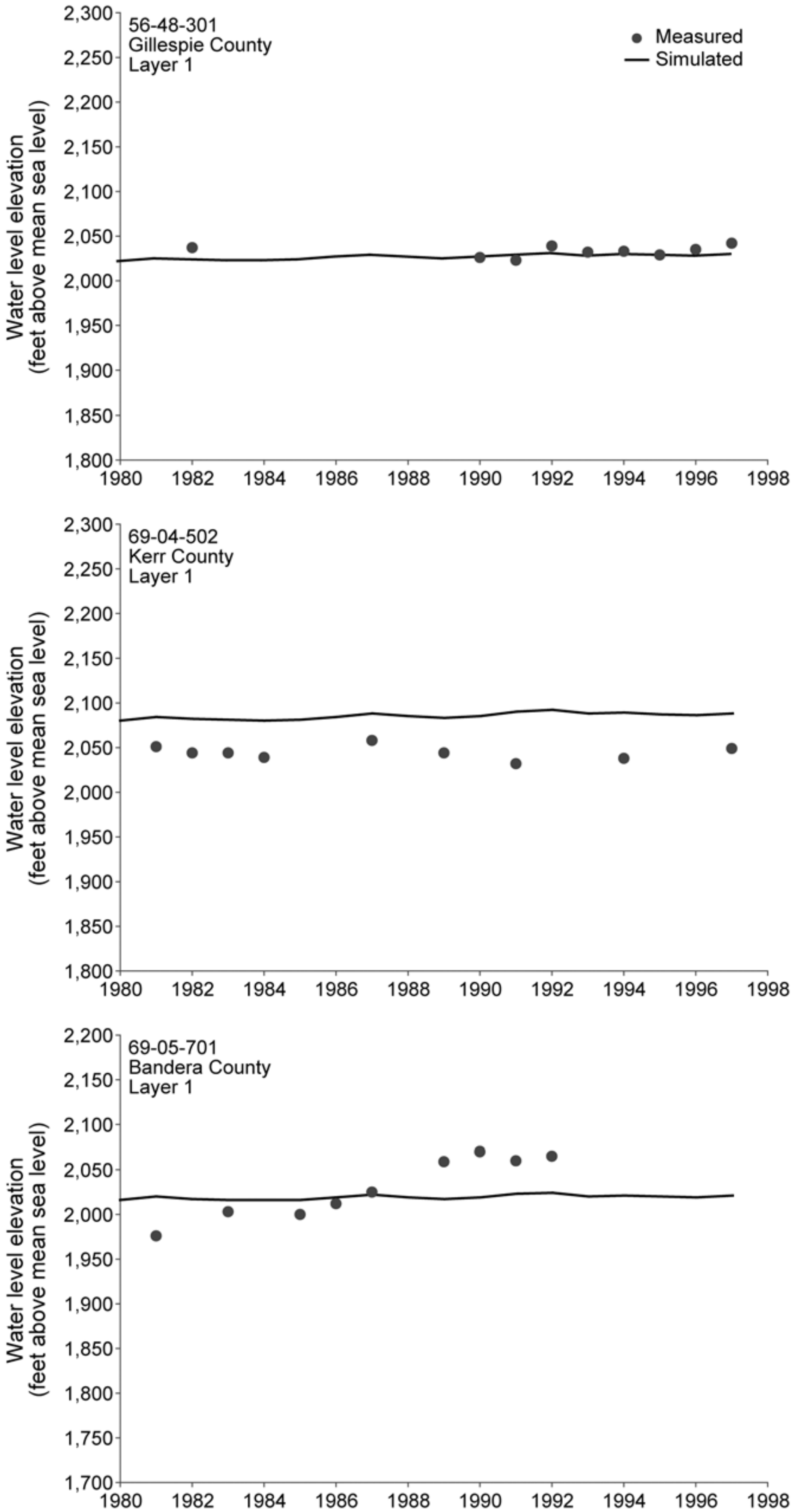
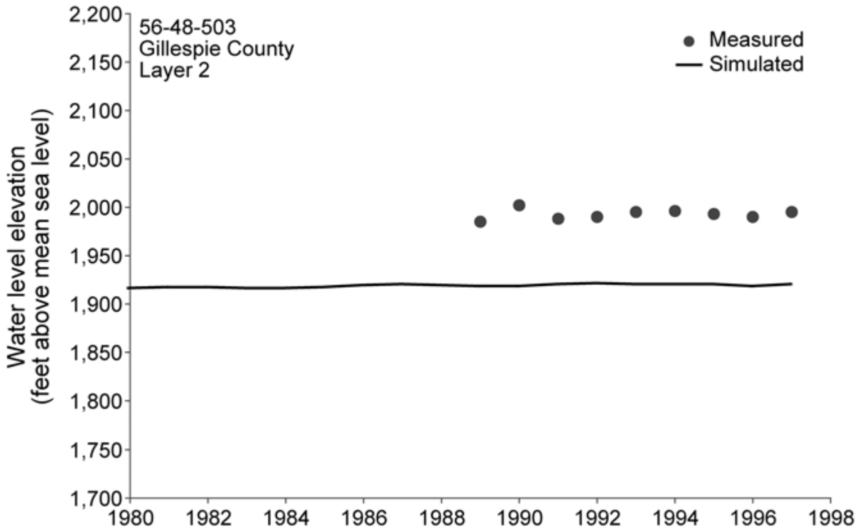
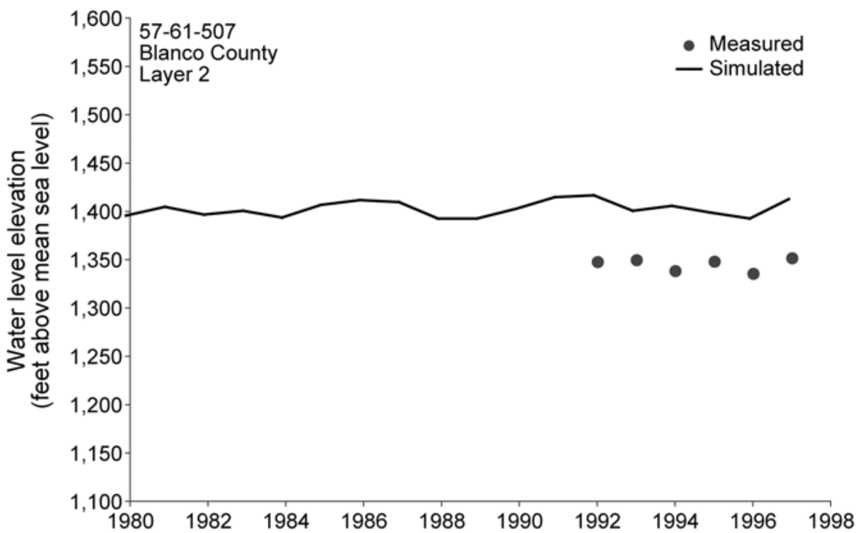


Figure 10-2. **Comparison of simulated water level fluctuations to measured water levels. Well locations are shown in Figure 10-1.**





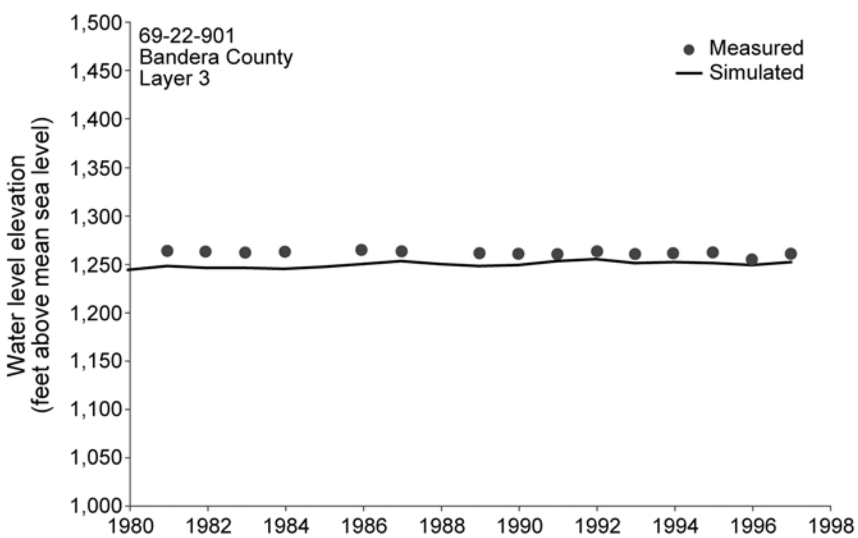


Figure 10-2. (continued).

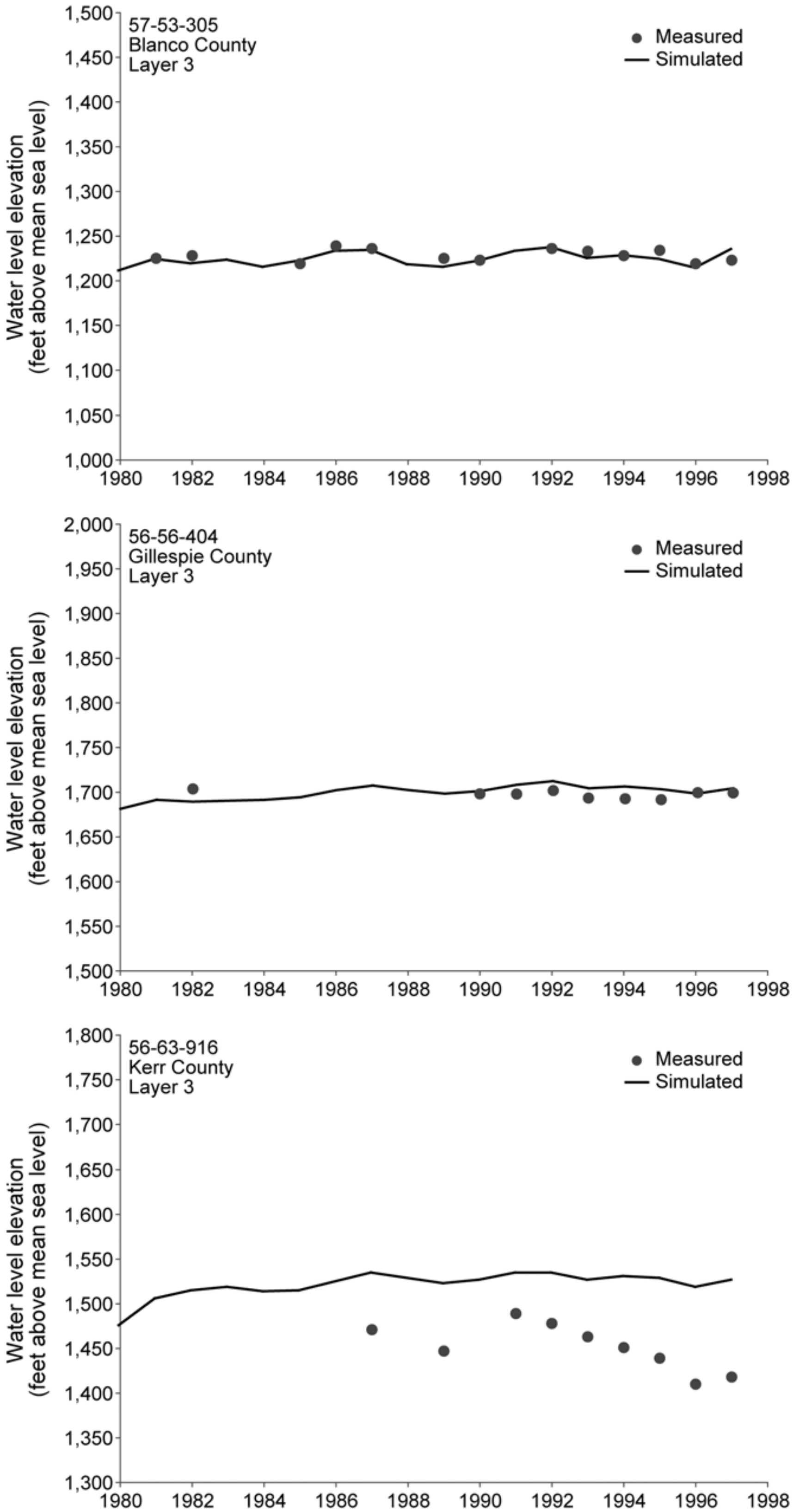


Figure 10-2. (continued).

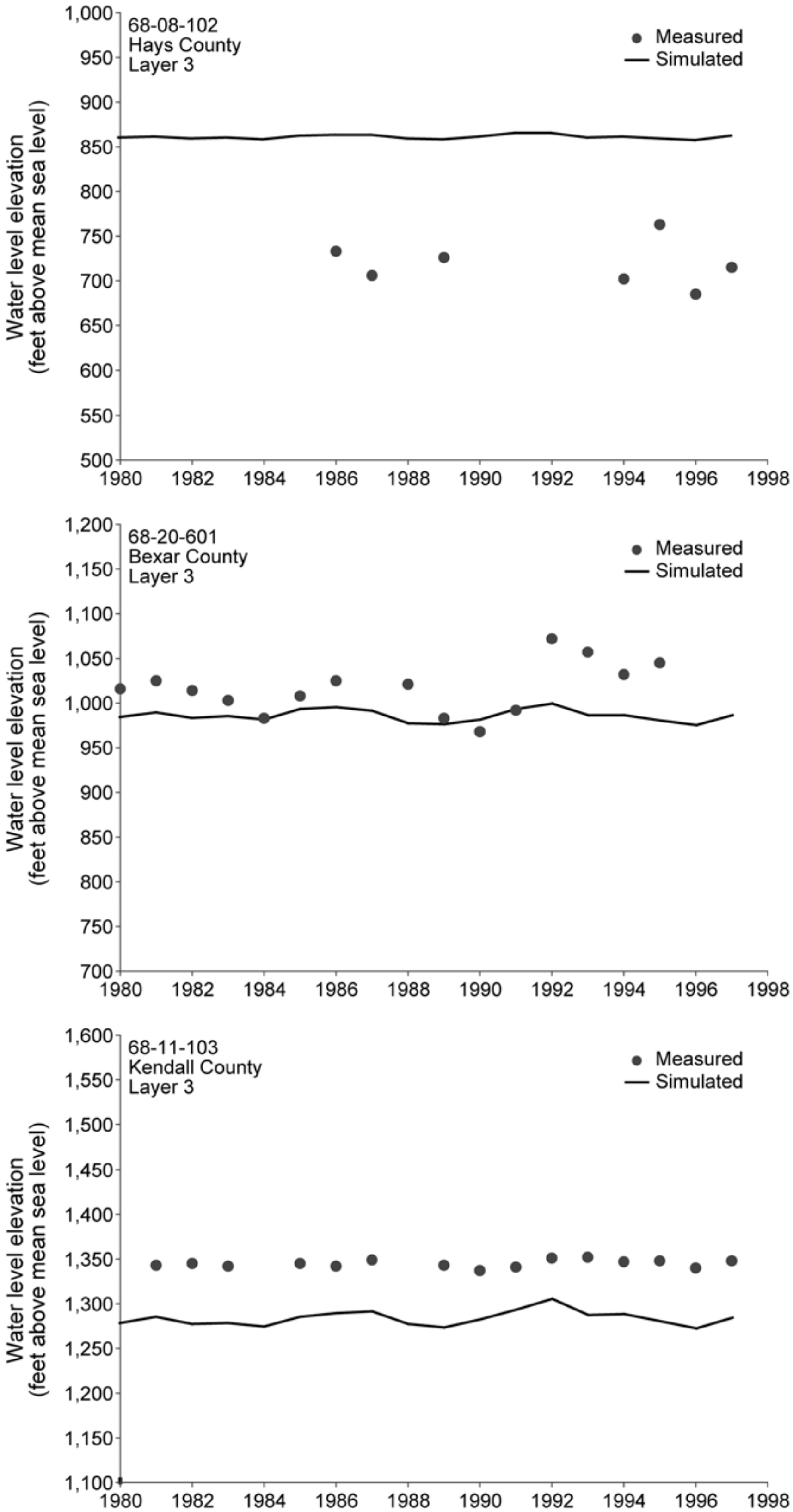


Figure 10-2. (continued).

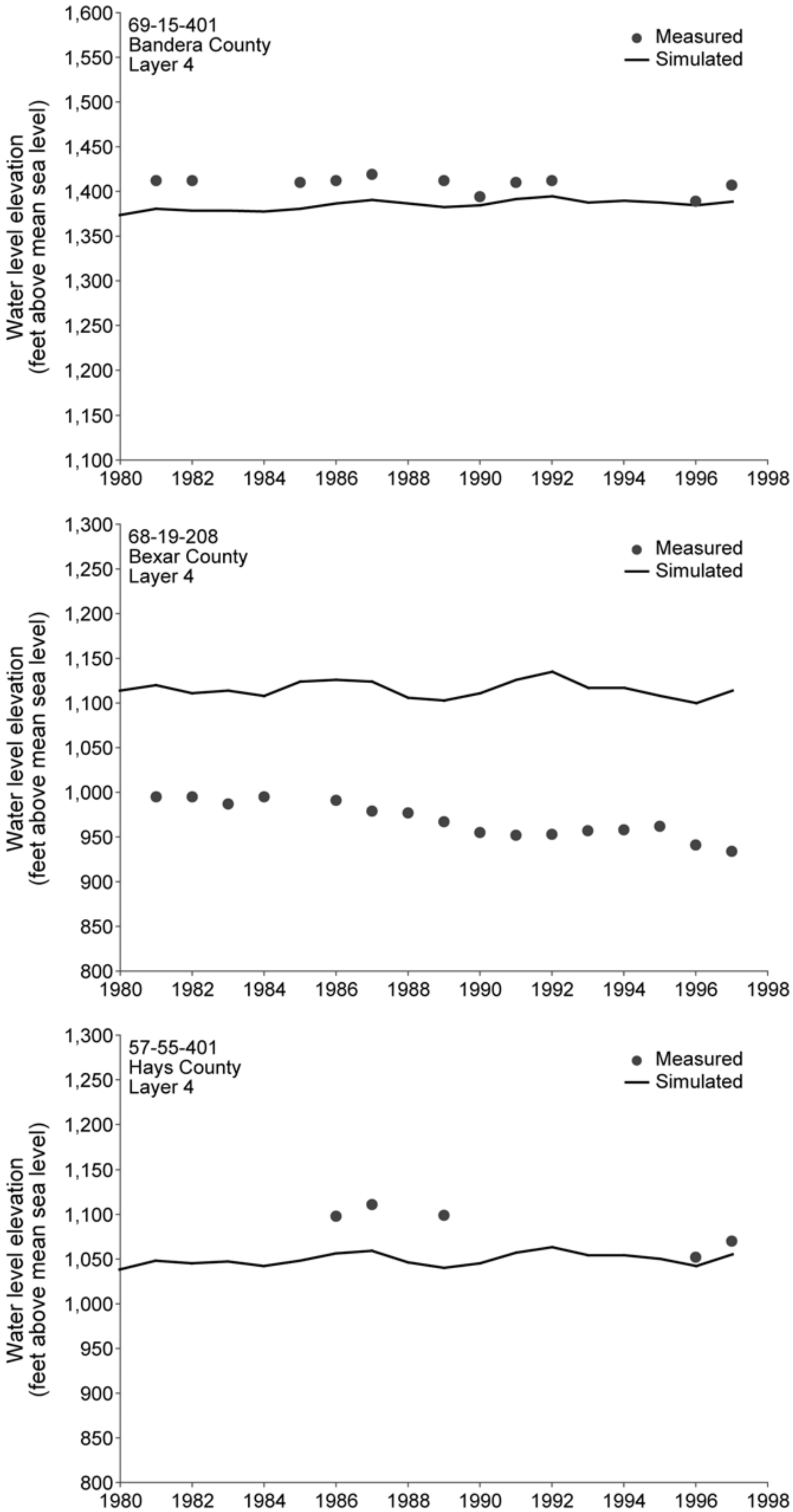


Figure 10-2. (continued).

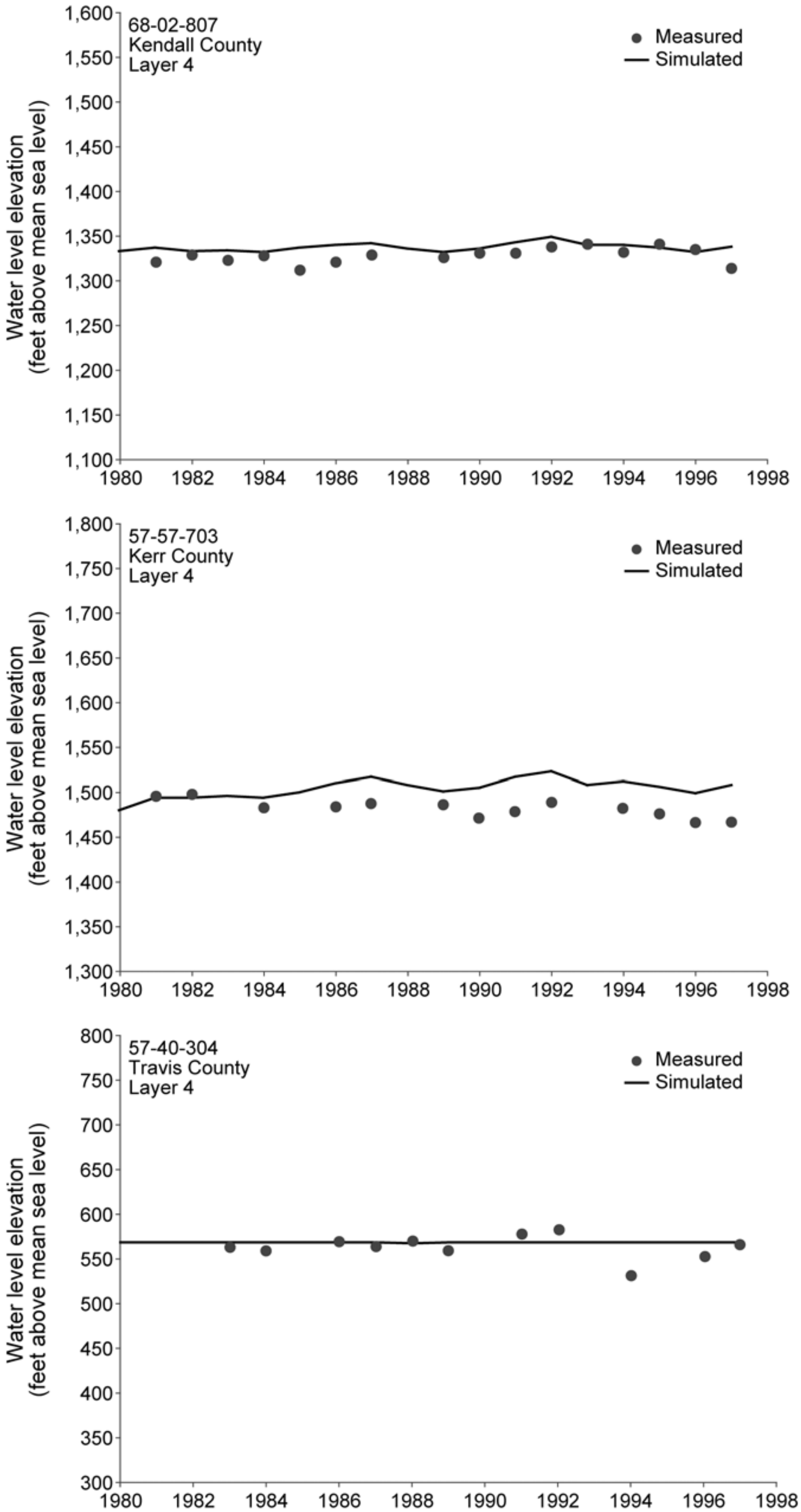


Figure 10-2. (continued).

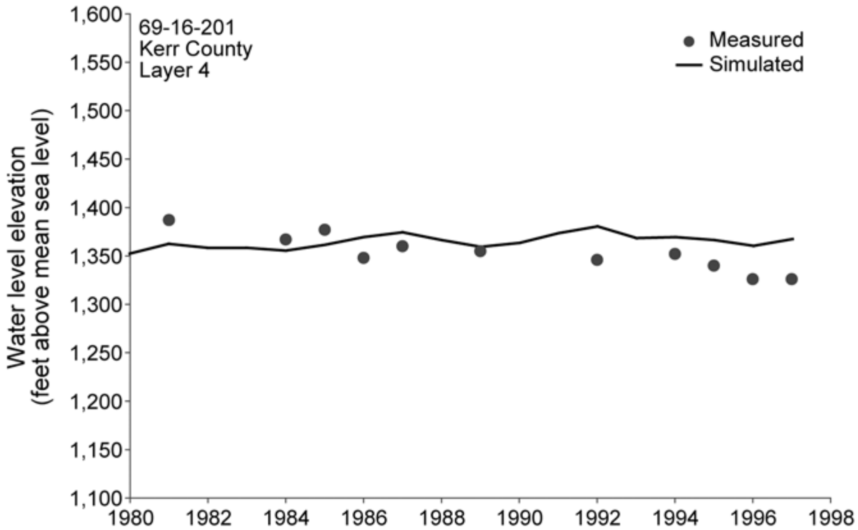


Figure 10-2. (continued).

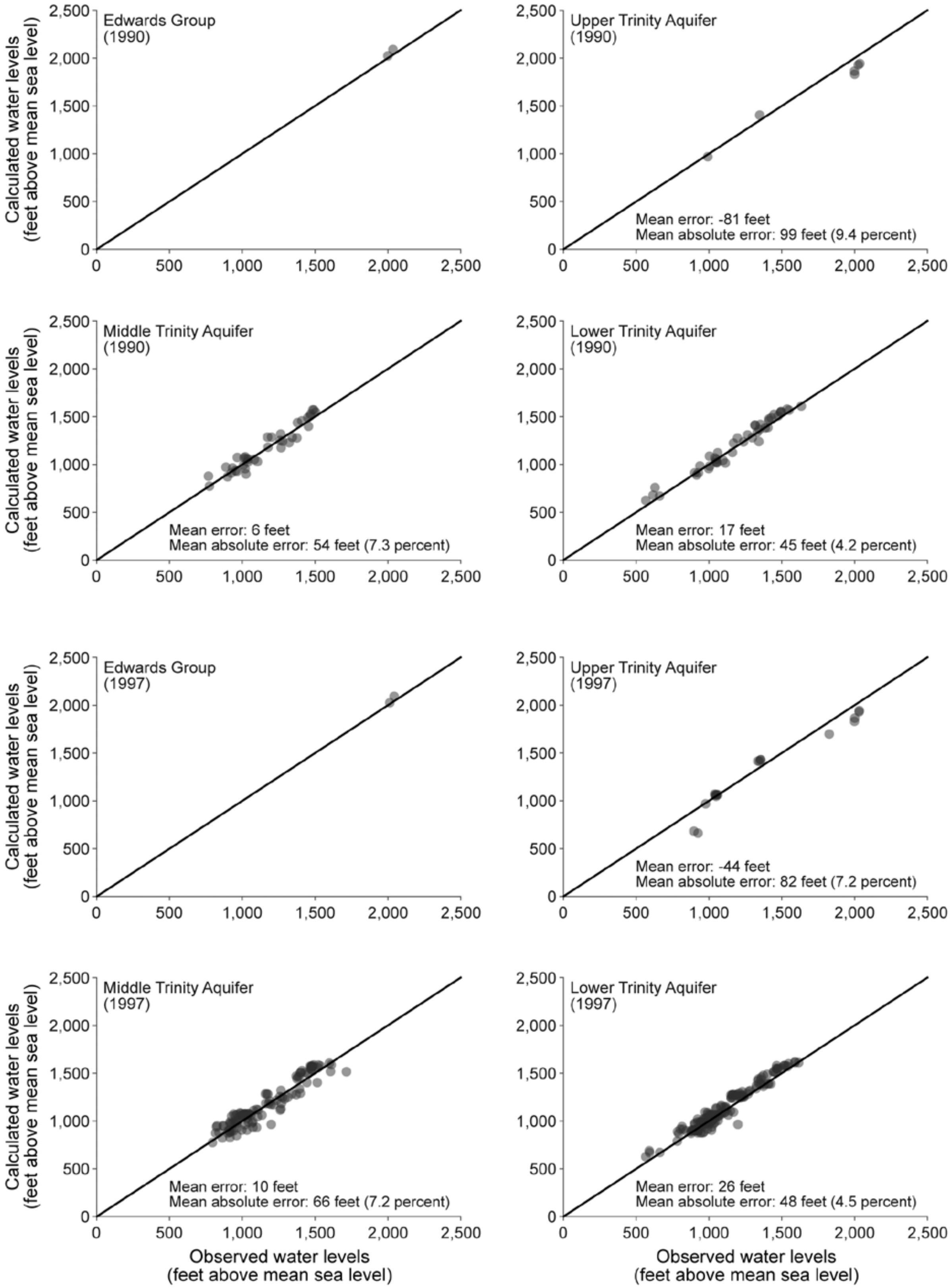


Figure 10-3. **Comparison of measured and calculated water levels for 1990 and 1997 from the transient model.**

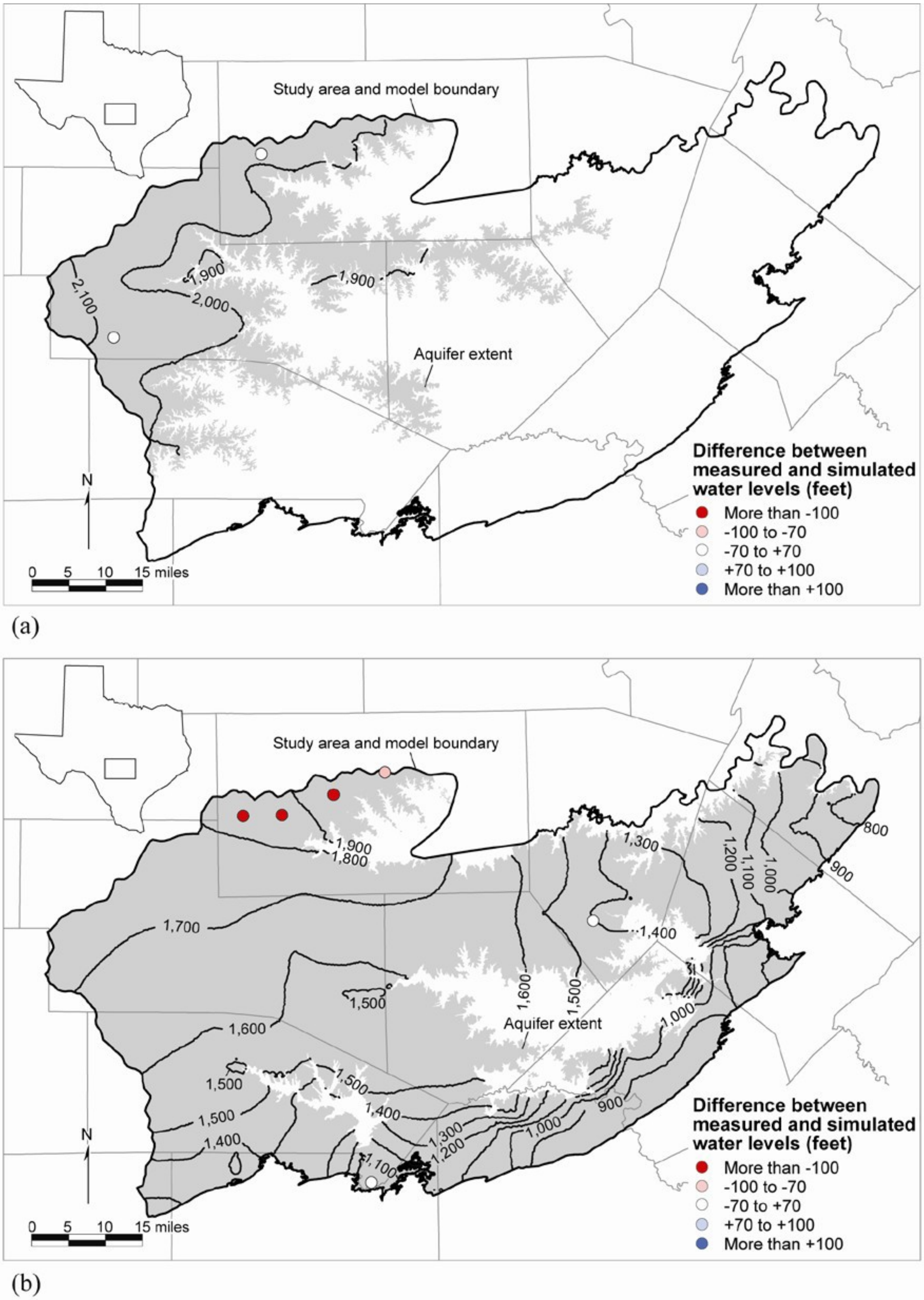
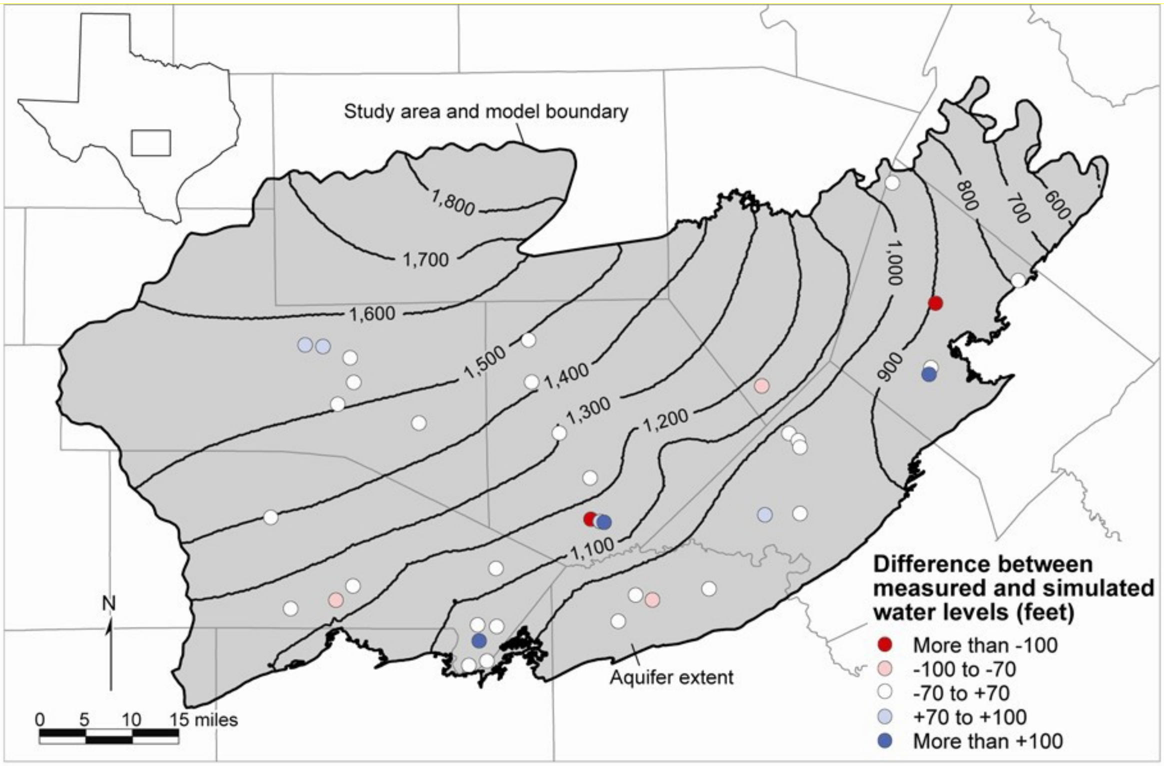
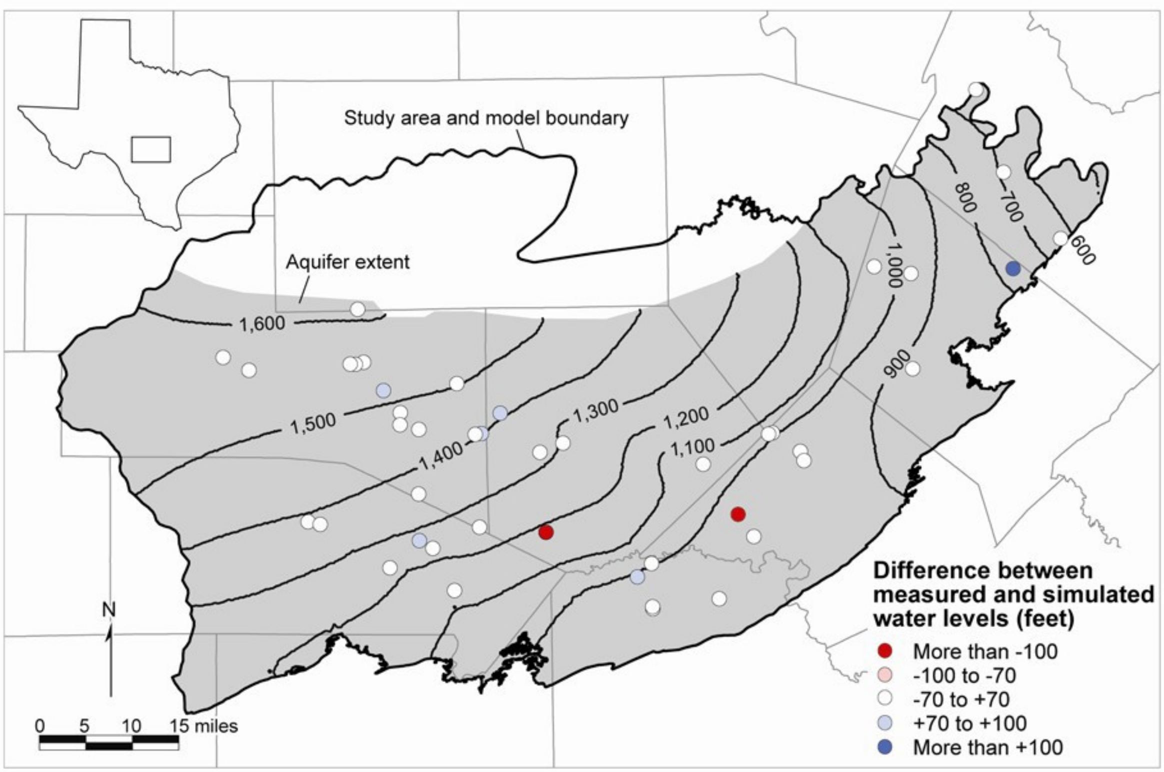


Figure 10-4. Comparison of 1990 measured and calculated water levels from the transient model for (a) layer 1, (b) layer 2, (c) layer 3, and (d) layer 4. The contours represent calculated water levels, expressed in feet above sea level, whereas the points indicate the difference between measured and simulated water levels relative to the measured water levels.

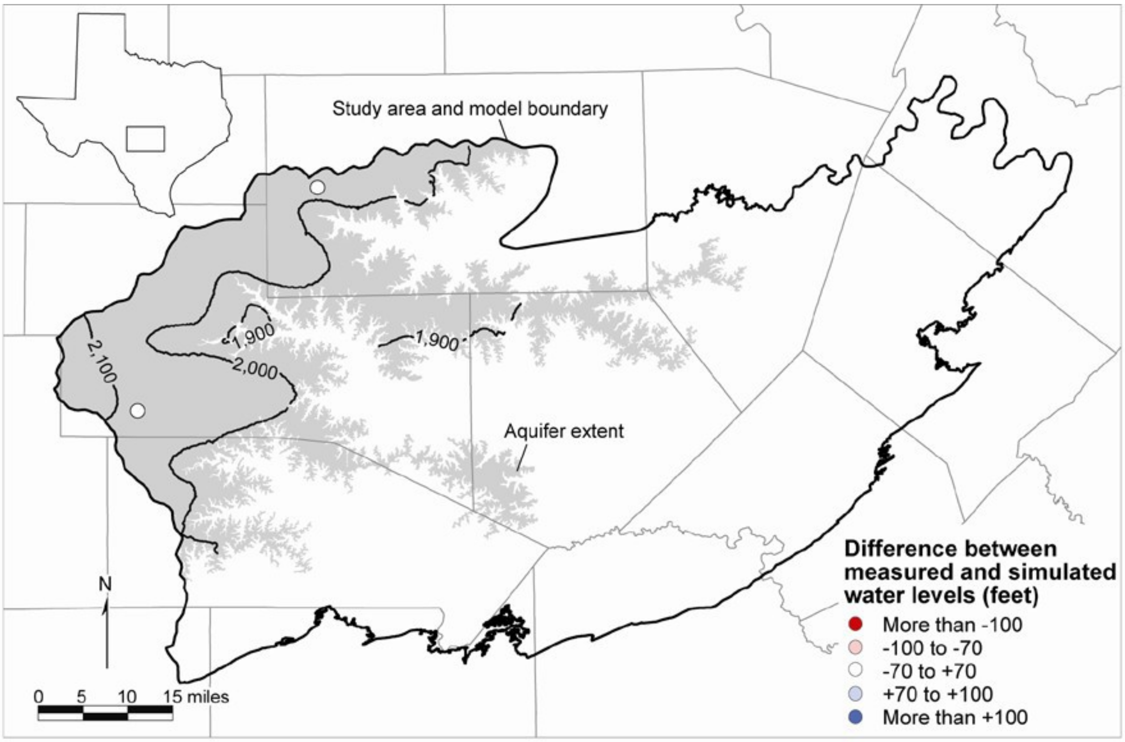


(c)

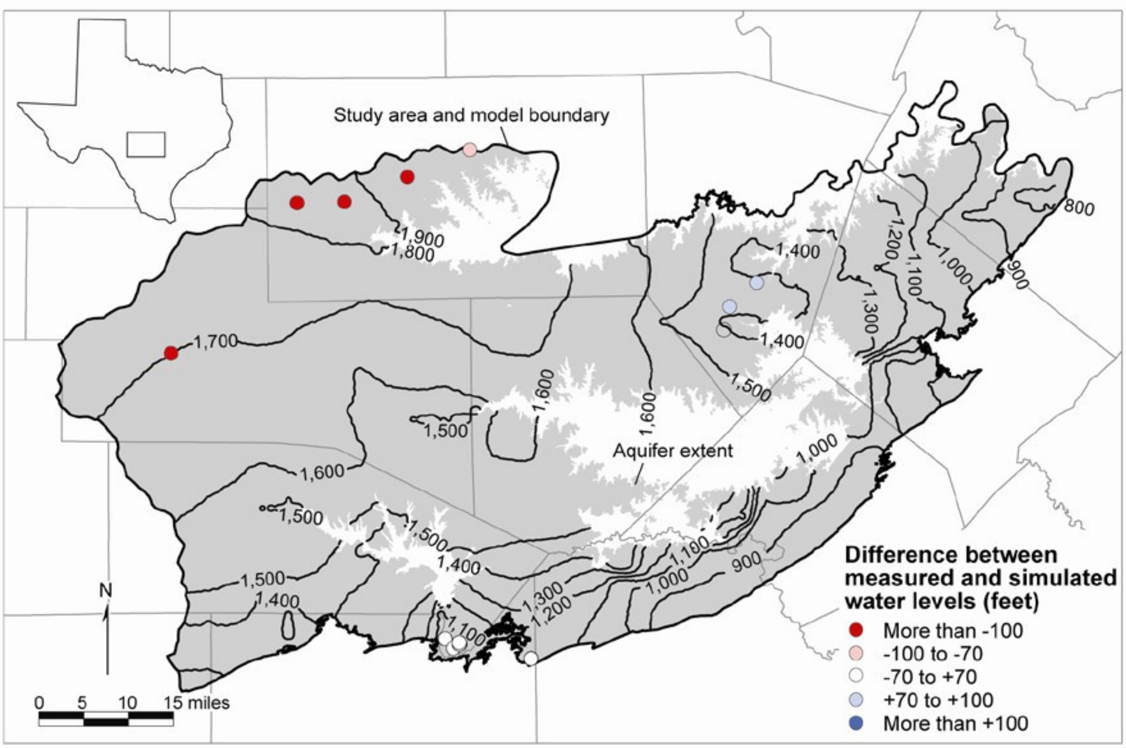


(d)

Figure 10-4. (continued).

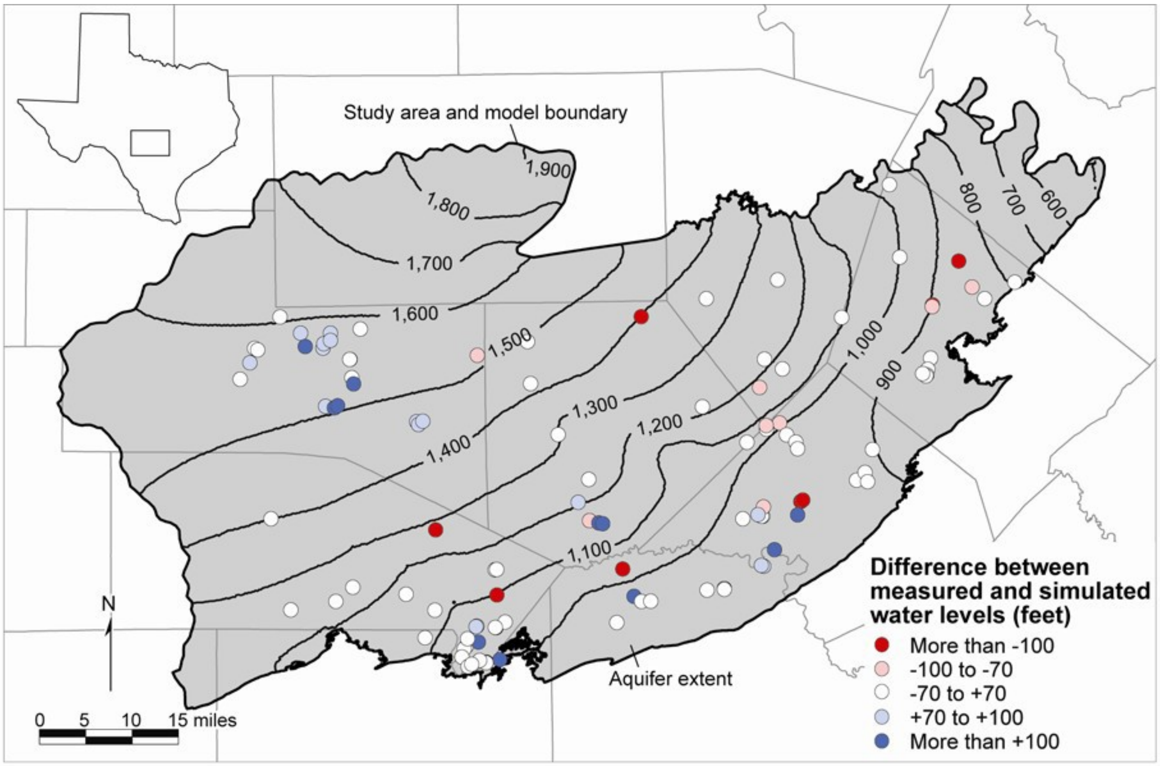


(a)

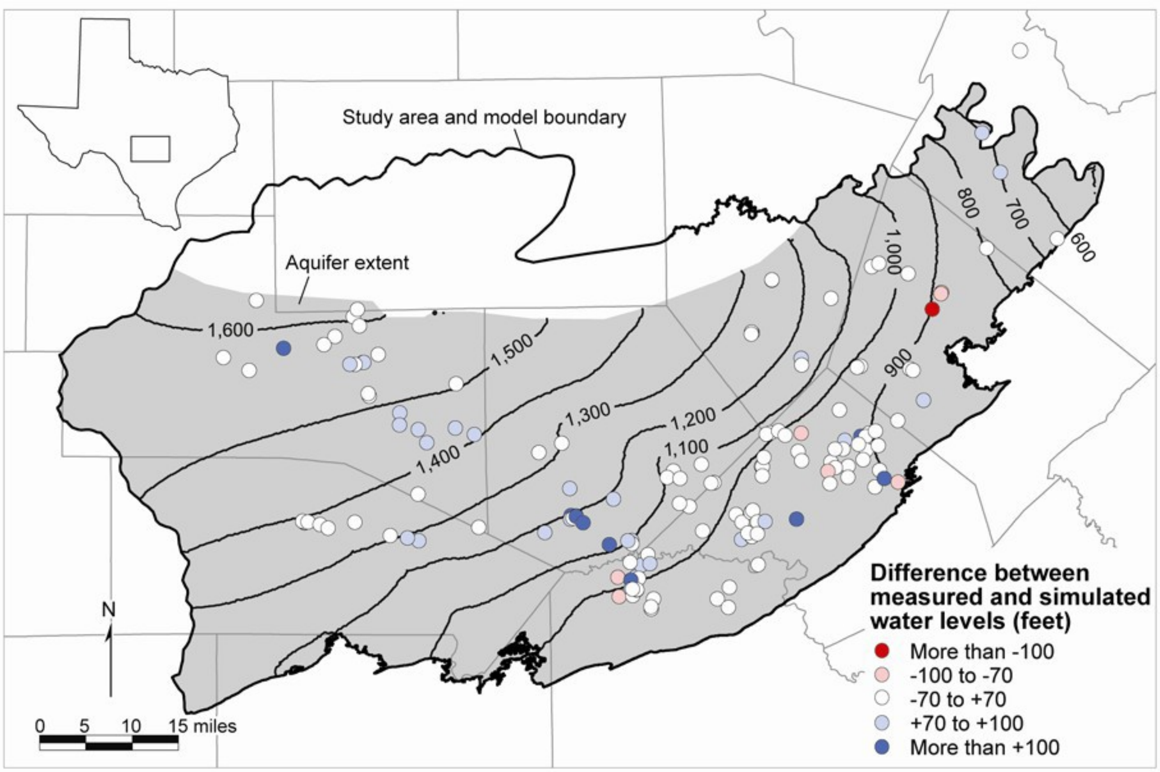


(b)

Figure 10-5. **Comparison of 1997 measured and calculated water levels from the transient model for (a) layer 1, (b) layer 2, (c) layer 3, and (d) layer 4. The contours represent calculated water levels, expressed in feet above sea level, whereas the points indicate the difference between measured and simulated water levels relative to the measured water levels.**



(c)



(d)

Figure 10-5. (continued).

Table 10-3. Calibration statistics for the transient model for the years 1980, 1990, and 1997. The percentage represents the mean absolute error relative to the range of measured water levels.

1980	Mean error	Mean absolute error	Mean absolute error (percent)
Overall	14	59	4
Edwards Group	23	31	17
Upper Trinity Aquifer	23	68	6
Middle Trinity Aquifer	-14	53	5
Lower Trinity Aquifer	17	58	5

1990	Mean error	Mean absolute error	Mean absolute error (percent)
Overall	6	52	4
Edwards Group	34	34	—
Upper Trinity Aquifer	-81	99	9
Middle Trinity Aquifer	6	54	7
Lower Trinity Aquifer	17	45	4

1997	Mean error	Mean absolute error	Mean absolute error (percent)
Overall	15	57	4
Edwards Group	26	26	—
Upper Trinity Aquifer	-44	82	7
Middle Trinity Aquifer	10	66	7
Lower Trinity Aquifer	26	48	5

— = too few water-level measurements to calculate percent mean absolute error.

Table 10-4 shows the water budgets for the respective model layers in 1980, 1990, and 1997. Simulating discharge to springs using a regional-scale model is commonly difficult because of spatial and temporal scale issues. Table 10-5 shows simulated and measured discharge for selected springs in the study area. It should be noted that the measured discharge values represent single snapshots in time that (1) in most cases did not fall within the 1980 through 1997 transient model period and (2) may not be representative of average discharge from the spring during the transient modeling period because spring discharge varies widely over time. Simulated discharge values represent discharge averaged over each annual stress period. Additionally, springs are commonly discharge sites for highly localized flow systems that cannot be simulated in regional models. The result is that the apparent ability of the model to simulate spring discharge varies widely. Of 17 springs, 6 display a good comparison between measured and simulated discharge values. Simulated spring discharge from springs having the highest measured discharge values differs from measured values by about an order of magnitude. Most springs in the study area represent discharge from highly localized flow systems within the aquifer system that are characterized by short flow paths. The localized nature of these flow paths and the limitations of the regional model grid result in much of the spring discharge being included in base-flow discharge to streams. Overall, the model also does a good job of mimicking base-flow fluctuations (Figure 10-6).

Table 10-4. Water budget for the respective layers in the calibrated transient model for 1980,1990, and 1997 (all values in acre-feet per year; negative values indicate net discharge from the aquifer).

1980	**Edwards Group**	**Upper Trinity Aquifer**	**Middle Trinity Aquifer**	**Lower Trinity Aquifer**
Interaquifer flow (above)	0	9,773	64,138	5,825
Interaquifer flow (below)	-9,773	-64,138	-5,825	0
Wells	-1,007	-5,157	-4,556	-5,961
Streams and springs	-47,735	-60,879	-56,013	0
Reservoirs	0	-2,519	-17,329	0
Edwards (Balcones Fault Zone) Aquifer	0	-33,224	-69,293	0
Recharge	58,516	156,135	88,910	155

1990	**Edwards Group**	**Upper Trinity Aquifer**	**Middle Trinity Aquifer**	**Lower Trinity Aquifer**
Storage	-7,960	-9,839	-5,788	-232
Interaquifer flow (above)	0	10,087	68,750	5,793
Interaquifer flow (below)	-10,087	-68,750	-5,793	0
Wells	-1,229	-6,253	-5,650	-5,732
Streams and springs	-51,290	-70,642	-64,676	0
Reservoirs	0	-3,097	-18,990	0
Edwards (Balcones Fault Zone) Aquifer	0	-37,821	-68,783	0
Recharge	70,567	186,292	100,916	180

1997	**Edwards Group**	**Upper Trinity Aquifer**	**Middle Trinity Aquifer**	**Lower Trinity Aquifer**
Storage	-12,380	-16,923	-11,8528	-447
Interaquifer flow (above)	0	10,329	77,150	5,297
Interaquifer flow (below)	-10,329	-77,150	-5,297	0
Wells	-1,504	-7,901	-8,448	-5,079
Streams and springs	-54,343	-85,266	-75,397	0
Reservoirs	0	-4,408	-23,563	0
Edwards (Balcones Fault Zone) Aquifer	0	-45,1623	-70,962	0
Recharge	78,557	226,464	118,348	240

Table 10-5. Estimated spring discharge and simulated average spring discharge rates from the calibrated transient model expressed in gallons per minute. The location of these springs can be found in Figure 5-28 (all values in gallons per minute). Please note that (1) the spring discharge measurements are single measurements collected over a wide range of conditions and time periods, (2) only two of the spring discharge measurements coincide with the calibration period, and (3) owing to scale issues, the model results may not reflect the more localized flow systems that influence discharge at specific springs.

	Spring	**Estimated Flow**	**Date**	**1980**	**1981**	**1982**	**1983**
1		150	4/13/1967	139	142	140	139
2	Bee Caves Spring	100	4/12/1967	75	83	78	75
3	Lynx Haven Springs	100		82	86	84	82
4	Ellebracht Springs	2,500	3/31/1966	225	238	217	213
5		310	3/11/1970	330	358	331	317
8		20	7/13/1976	366	474	350	346
9		75	7/10/1975	33	40	33	36
10	Cave Without A Name	50	1/17/1940	119	127	115	119
11	Kenmore Ranch Spring #9	150	7/17/1975	0	81	0	0
12	Edge Falls Springs	300		0	0	0	0
13	Rebecca Springs	300	7/11/1975	0	0	0	0
14	Jacob's Well Spring	500	8/31/1976	0	0	0	0
15		25	1/1/1966	6	9	8	9
16	Bassett Springs	50	12/30/1988	0	0	0	0
17		50	5/25/1973	0	0	0	0
18		9,000	12/20/1960	407	423	407	400
19	Cold Springs	5,000	8/20/1991	441	516	437	448

Table 10. 5 (continued).

	Spring	1984	1985	1986	1987	1988	1989
1		139	140	142	145	142	140
2	Bee Caves Spring	74	76	84	92	87	81
3	Lynx Haven Springs	82	83	86	90	88	85
4	Ellebracht Springs	218	226	241	255	228	222
5		321	332	360	393	358	338
8		322	388	466	500	368	308
9		32	42	46	46	32	32
10	Cave Without A Name	113	132	134	132	111	110
11	Kenmore Ranch Spring #9	0	113	152	140	0	0
12	Edge Falls Springs	0	0	0	0	0	0
13	Rebecca Springs	0	0	0	0	0	0
14	Jacob's Well Spring	0	0	0	0	0	0
15		7	9	11	12	7	6
16	Bassett Springs	0	0	0	0	0	0
17		0	0	0	0	0	0
18		408	413	429	446	416	410
19	Cold Springs	419	489	542	558	442	414

Table 10. 5 (continued).

	Spring	1990	1991	1992	1993	1994	1995
1		142	145	146	142	144	142
2	Bee Caves Spring	85	93	98	88	92	88
3	Lynx Haven Springs	87	91	94	89	91	89
4	Ellebracht Springs	236	244	250	219	242	227
5		359	382	404	355	378	363
8		392	508	528	359	426	386
9		40	50	56	40	44	37
10	Cave Without A Name	125	139	150	124	129	118
11	Kenmore Ranch Spring #9	1	195	351	59	70	0
12	Edge Falls Springs	0	0	83	0	0	0
13	Rebecca Springs	0	0	0	0	0	0
14	Jacob's Well Spring	0	0	0	0	0	0
15		8	12	13	10	10	9
16	Bassett Springs	0	0	0	0	0	0
17		0	0	0	0	0	0
18		428	436	447	415	432	425
19	Cold Springs	474	568	626	473	518	471

	Spring	1996	1997
1		142	144
2	Bee Caves Spring	86	90
3	Lynx Haven Springs	88	90
4	Ellebracht Springs	224	247
5		350	388
8		335	446
9		31	47
10	Cave Without A Name	110	132
11	Kenmore Ranch Spring #9	0	35
12	Edge Falls Springs	0	0
13	Rebecca Springs	0	0
14	Jacob's Well Spring	0	0
15		7	11
16	Bassett Springs	0	0
17		0	0
18		420	446
19	Cold Springs	419	522

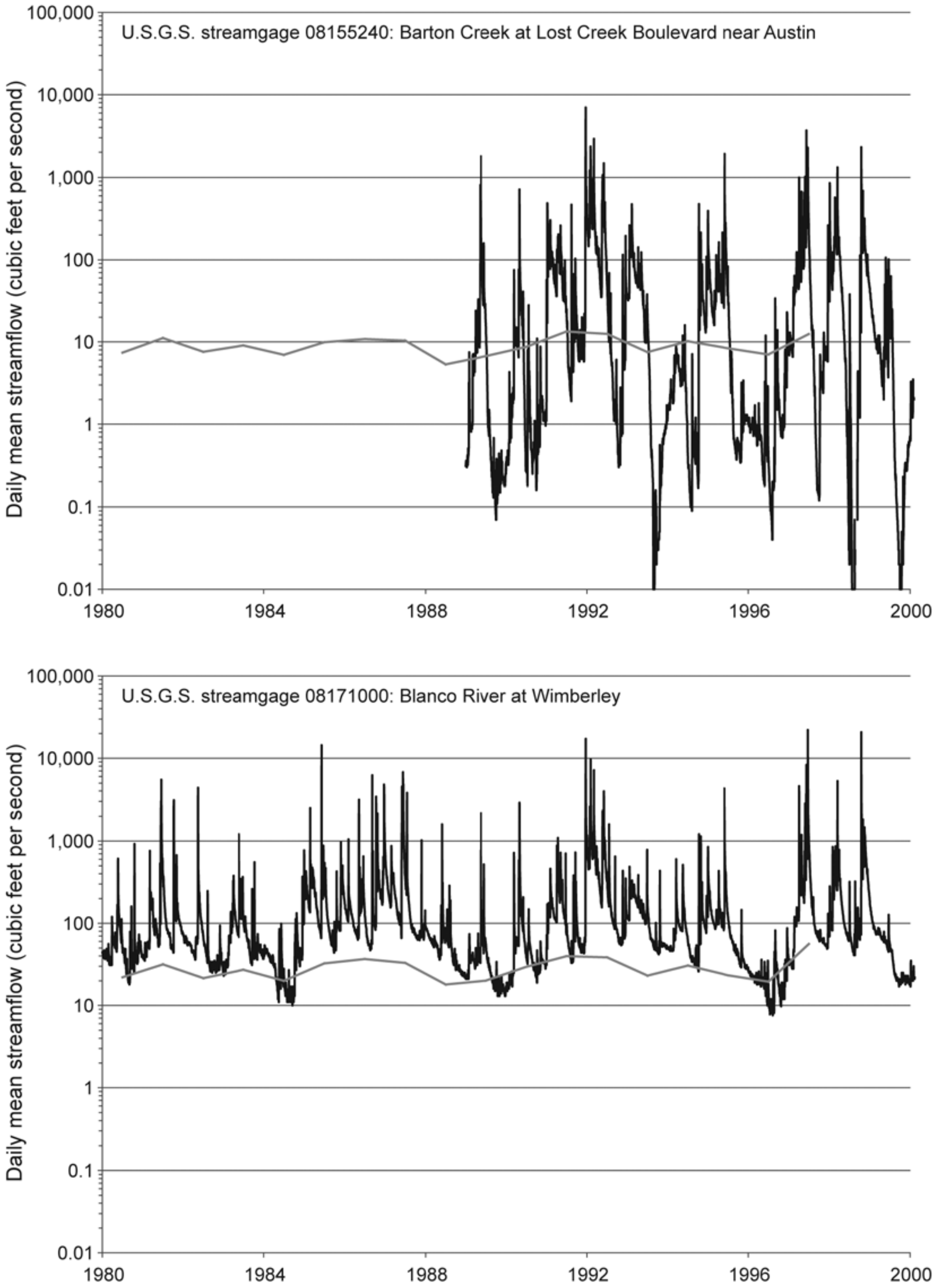
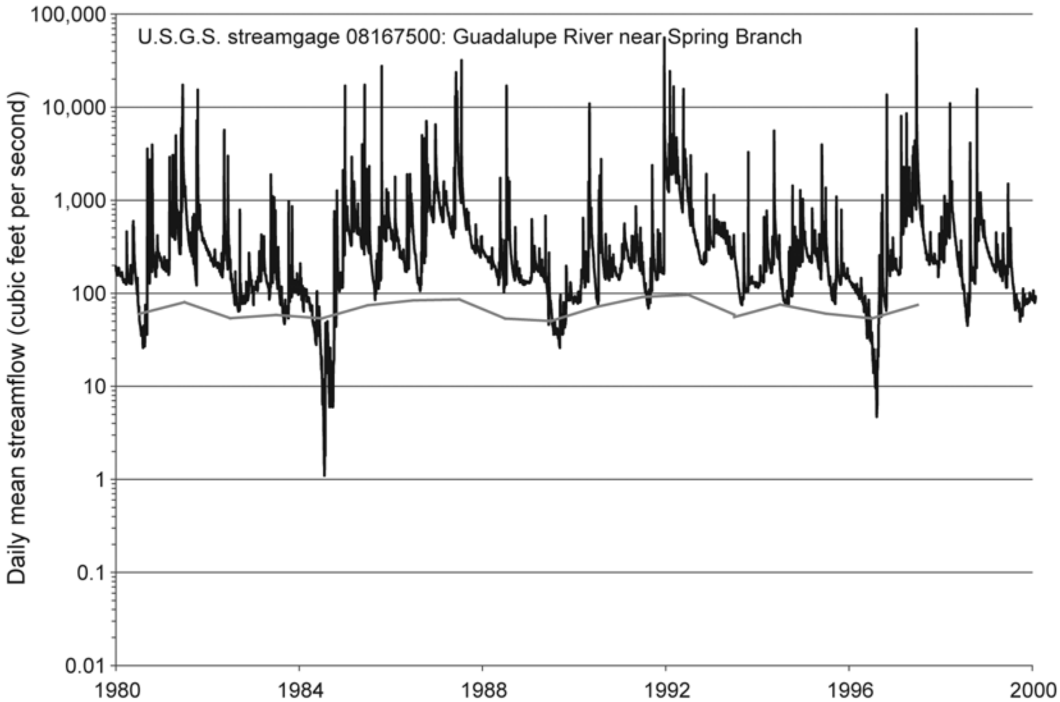


Figure 10-6. Comparison of calculated annual groundwater discharge rates to perennial streams from the transient model (gray line) and measured streamflow data. Streamgage locations are shown in Figure 9-4.



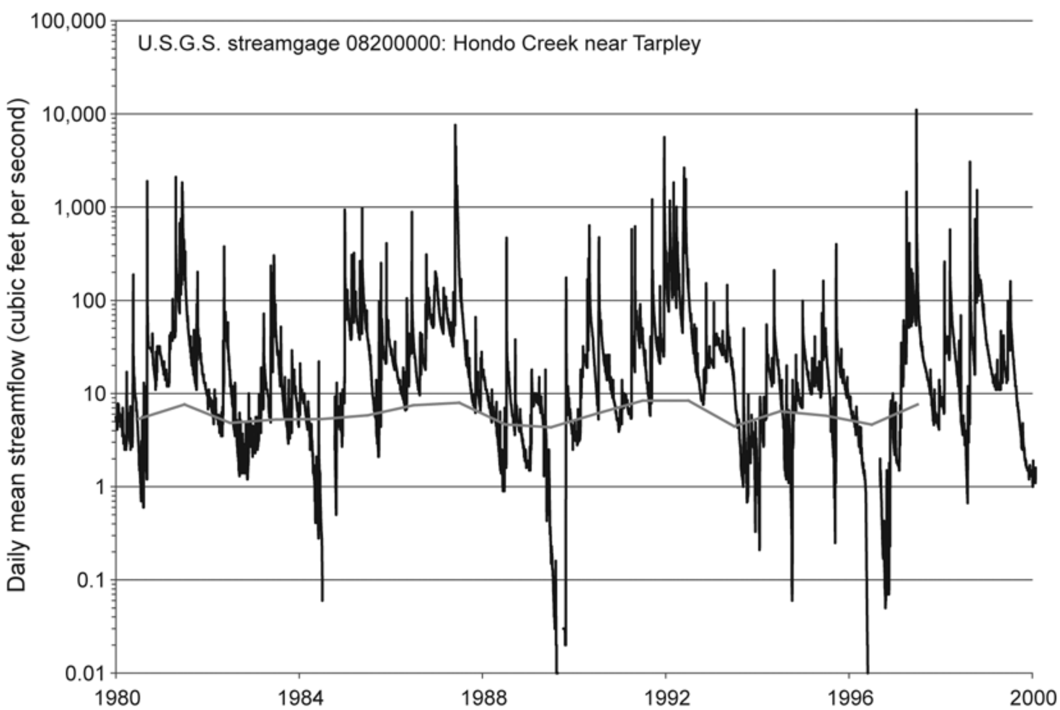


Figure 10-6. (continued).

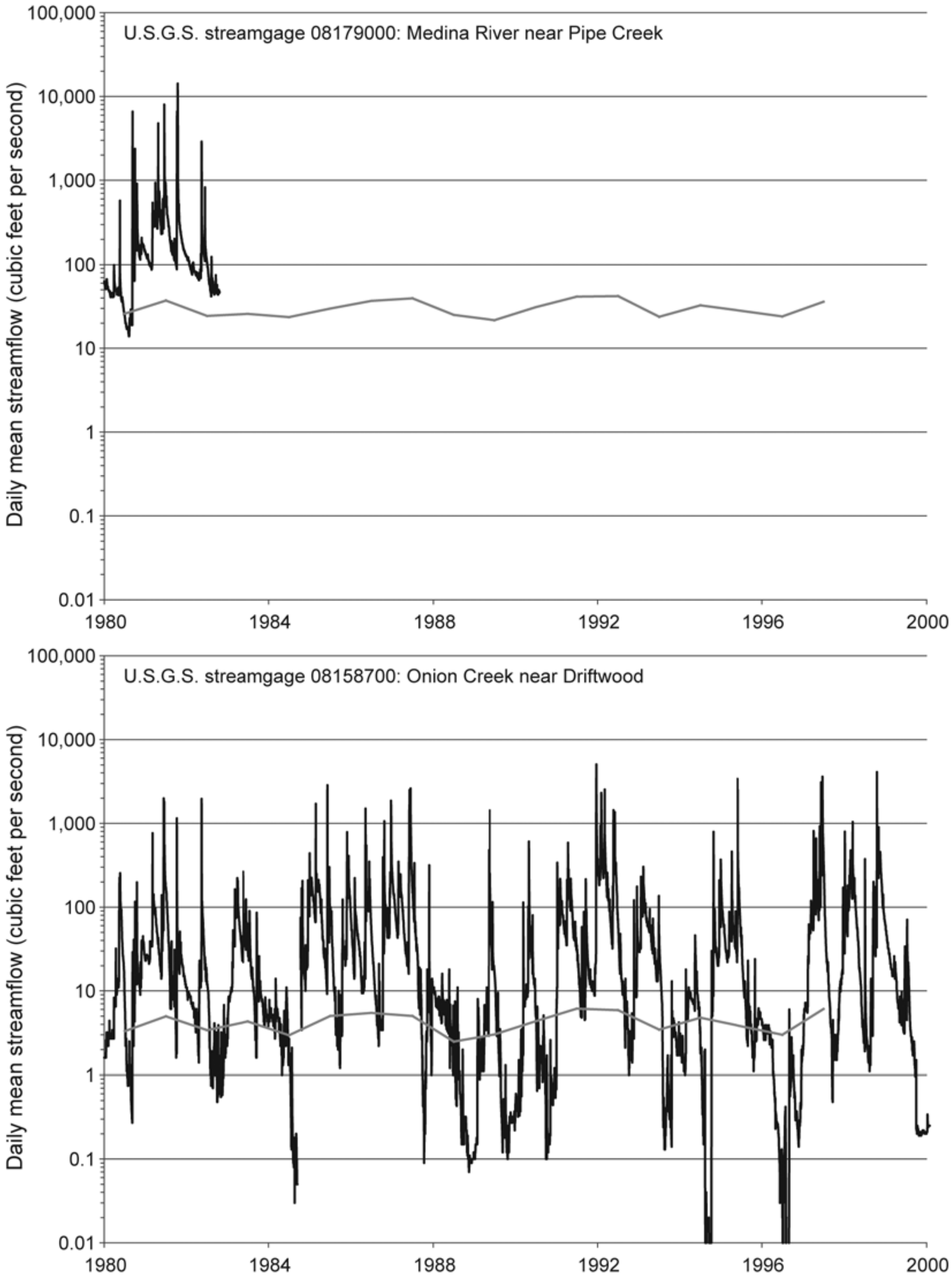


Figure 10-6. **(continued).**

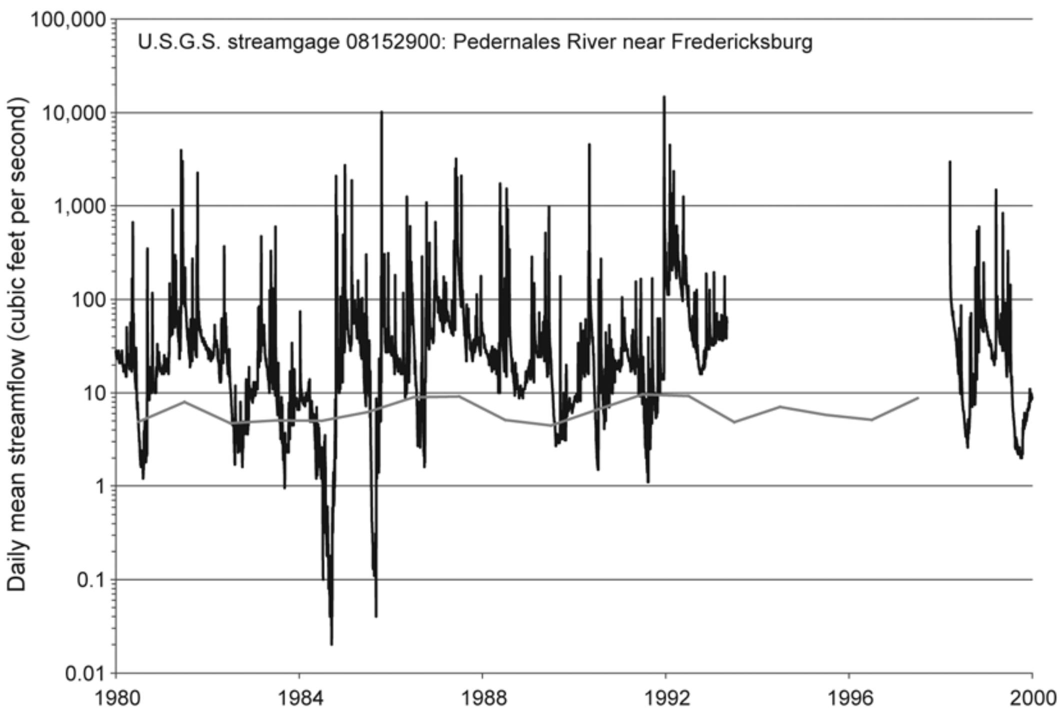


Figure 10-6. (continued).

10.2 Sensitivity Analysis

Upon completion of transient model calibration, we assessed the storage parameters to determine the sensitivity of the model to variation of specific-yield and specific-storage values. Sensitivity analysis involves systematically varying specific yield and specific storage to determine associated changes in aquifer response over the transient model run. We ran the model multiple times, lowering and then raising the calibrated specific-yield and specific-storage values by an order of magnitude.

Sensitivity analysis indicates that the unconfined Edwards Group (layer 1) is sensitive to increasing specific-yield input values and insensitive to specific-storage input values (Figures 10-7 and 10-8). This result is not surprising because MODFLOW only utilizes specific-yield input values when simulating groundwater flow through an unconfined aquifer. Overall, the model is much more sensitive to specific yield than to specific storage.

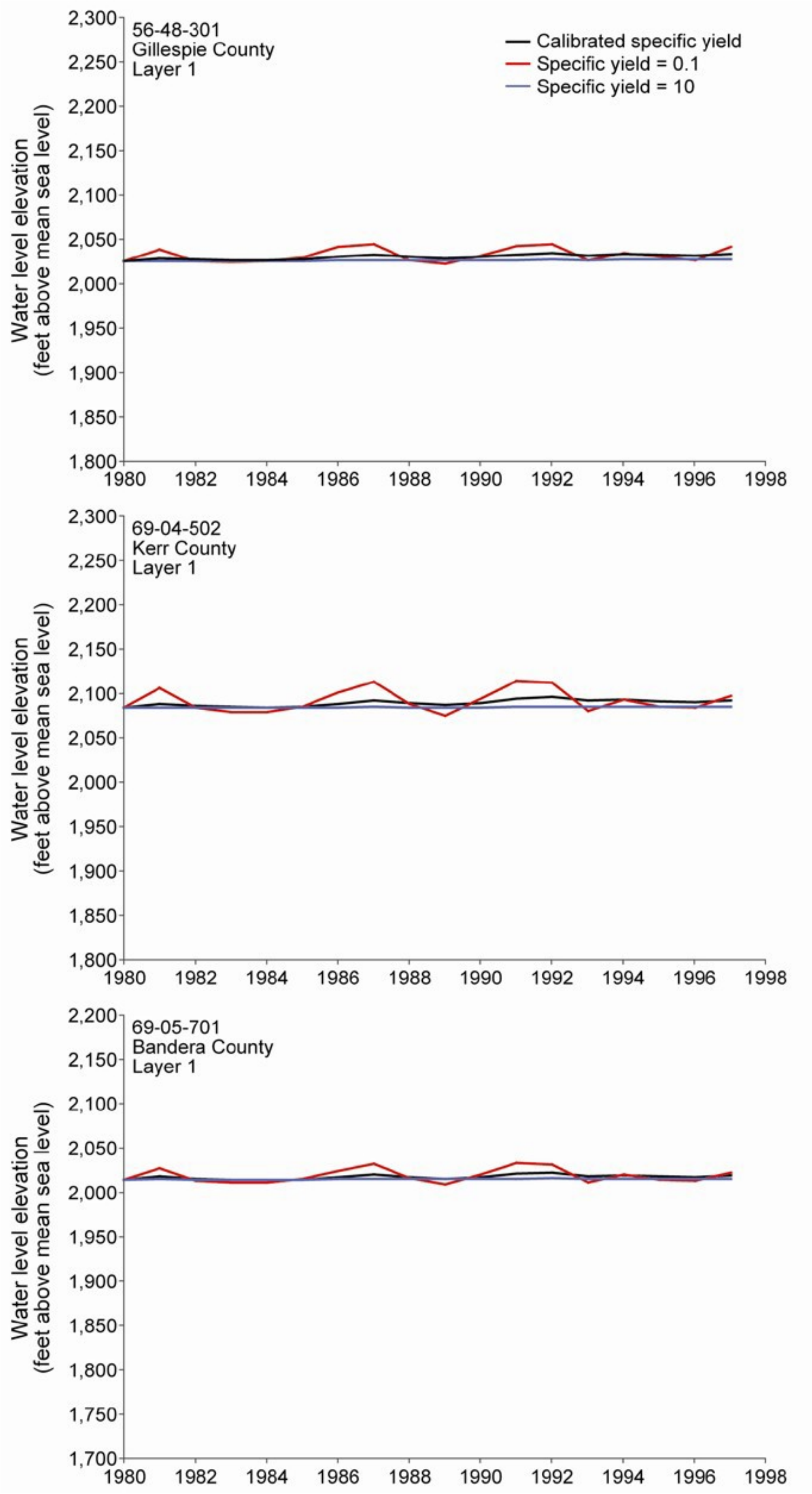


Figure 10-7. **Sensitivity of the transient calibration to specific yield. The red and blue lines represent one order of magnitude lower and higher than the calibrated values, respectively, relative to calibrated specific-yield values (black line).**

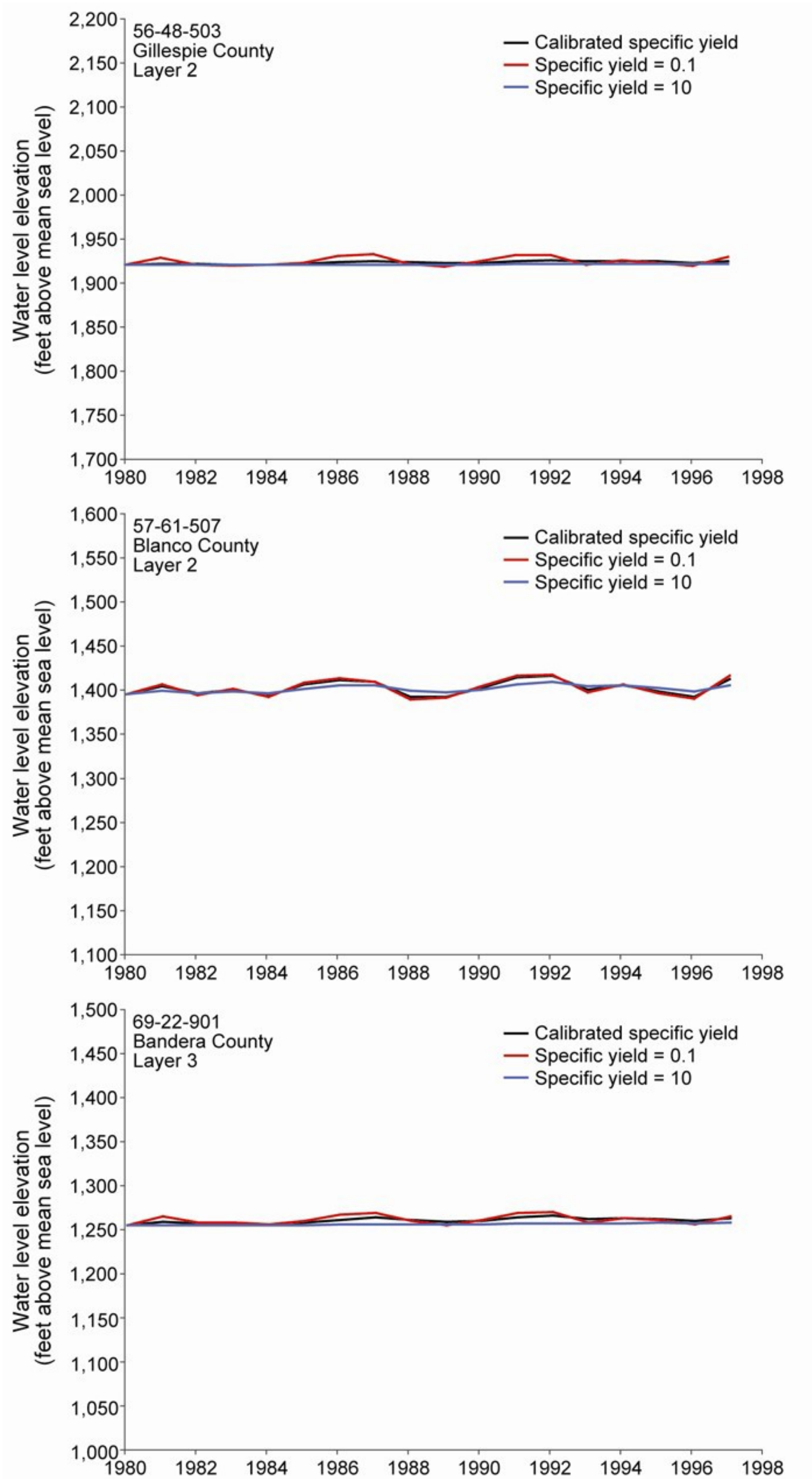


Figure 10-7. (continued).

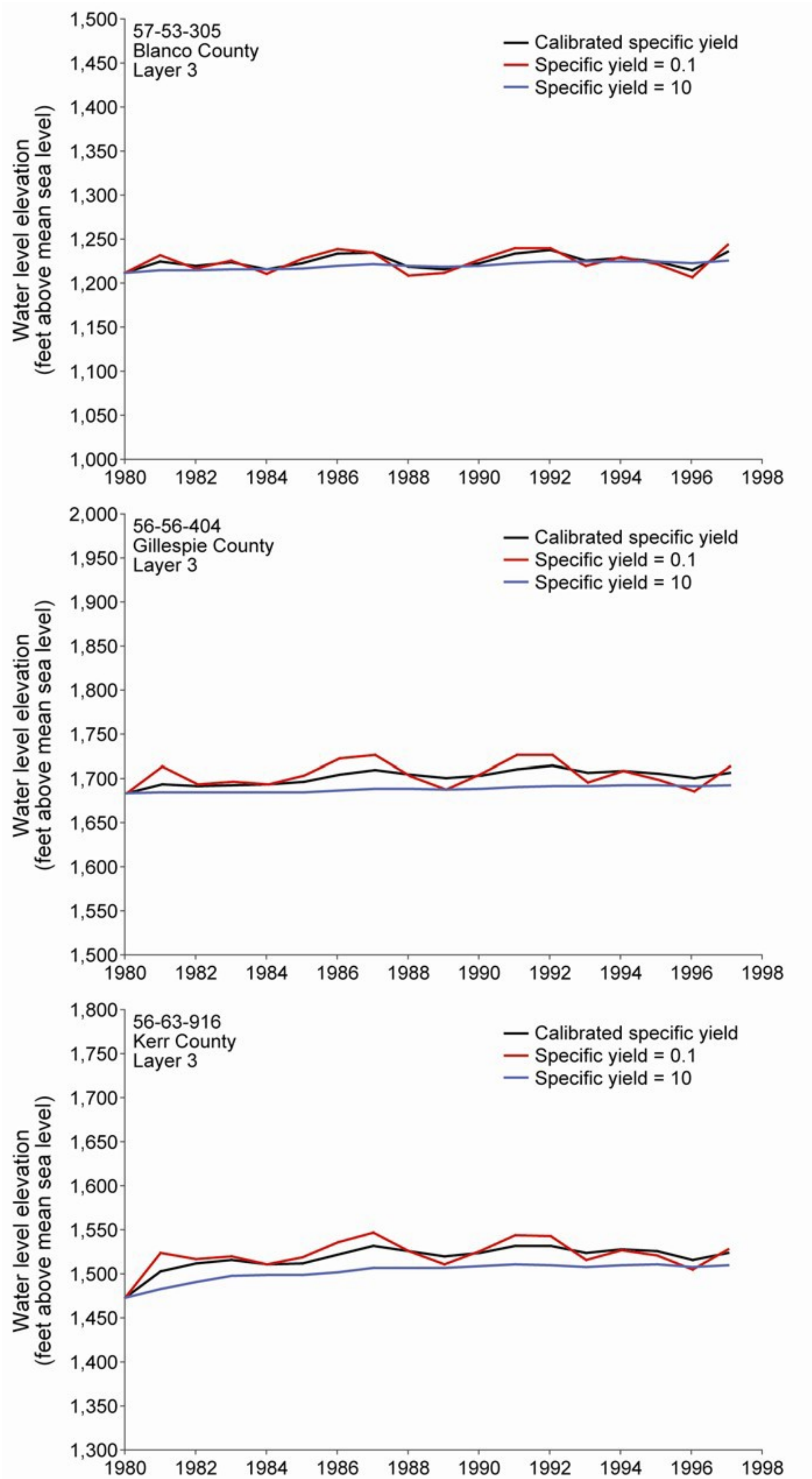


Figure 10-7. (continued).

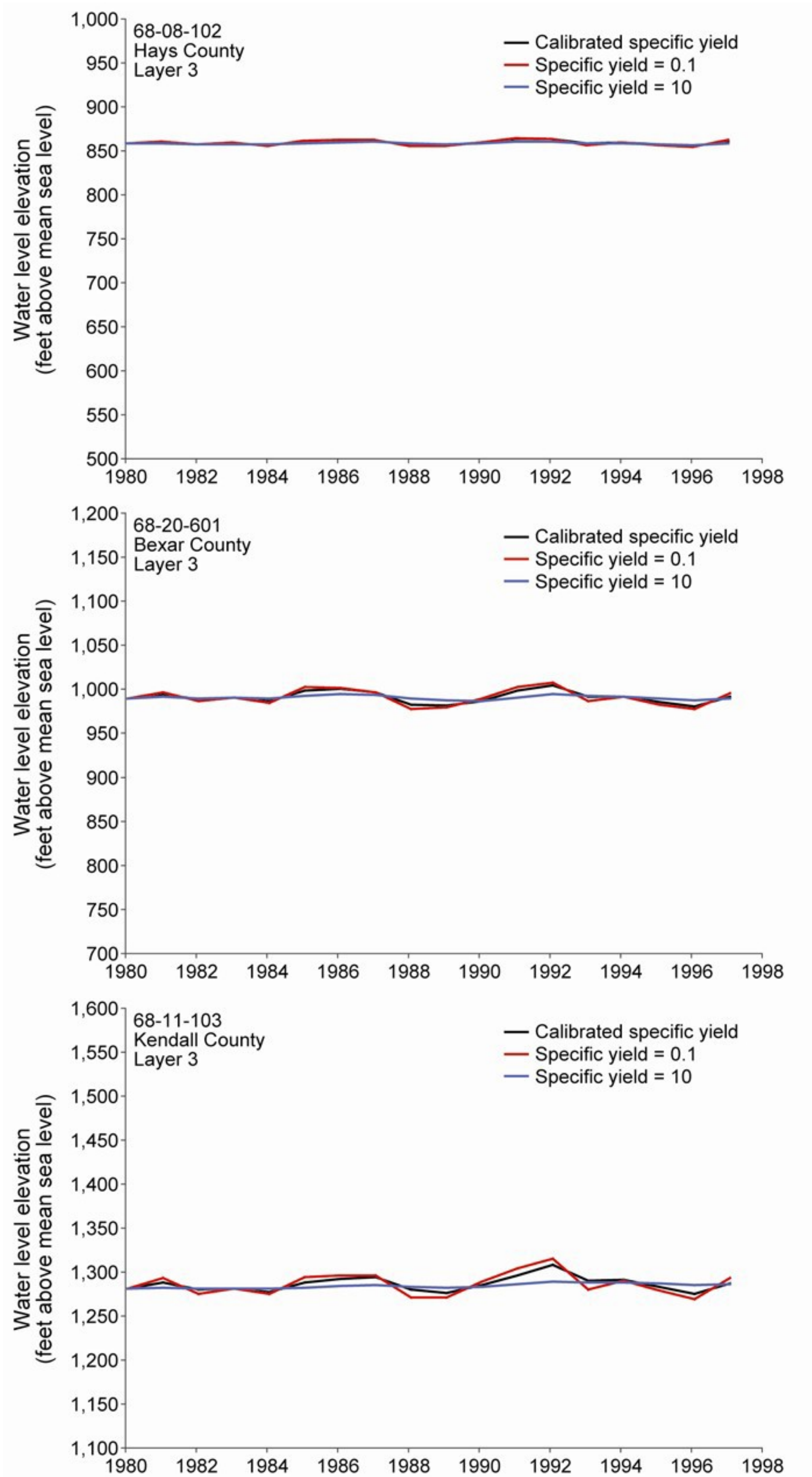


Figure 10-7. (continued).

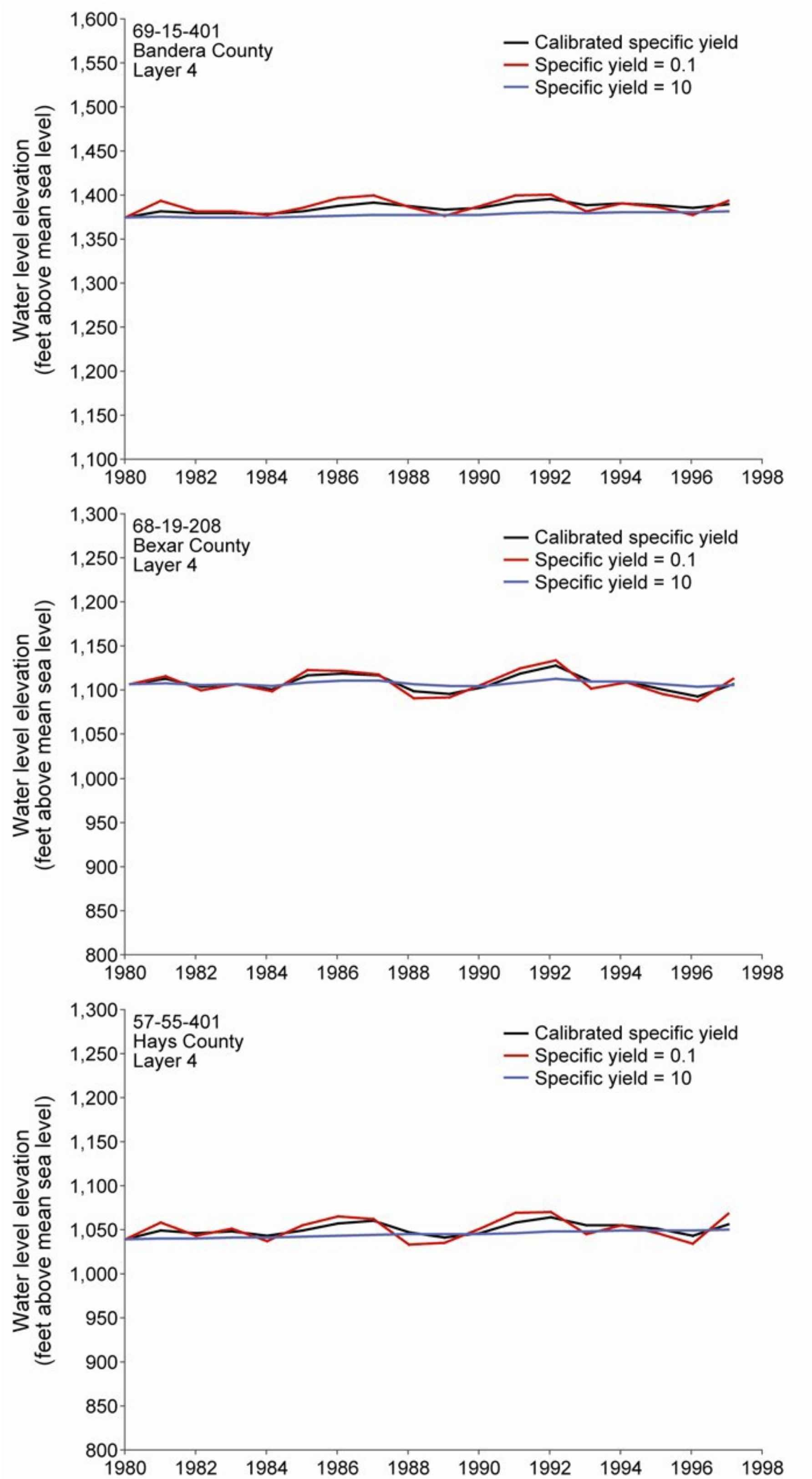


Figure 10-7. **(continued).**

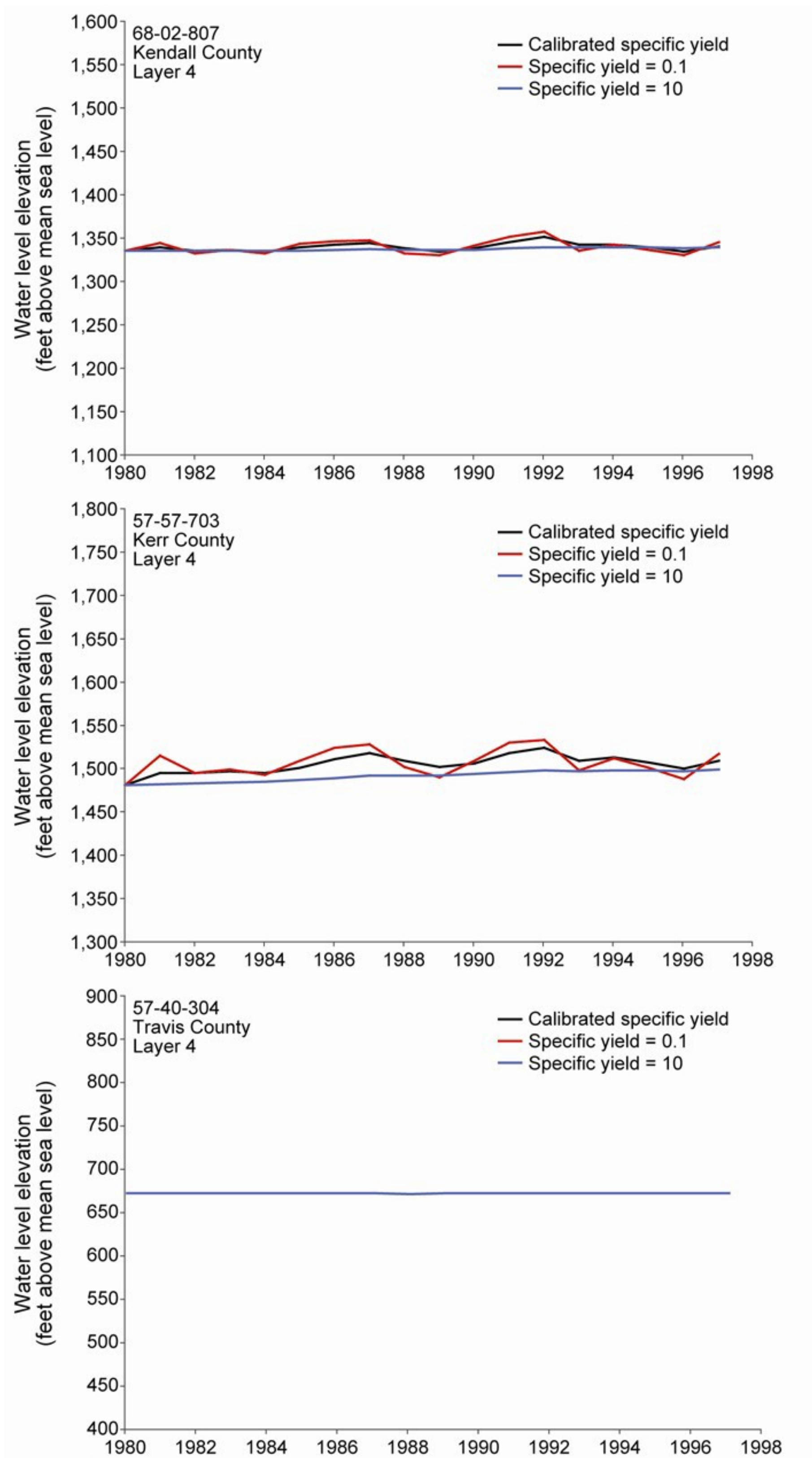


Figure 10-7. (continued).

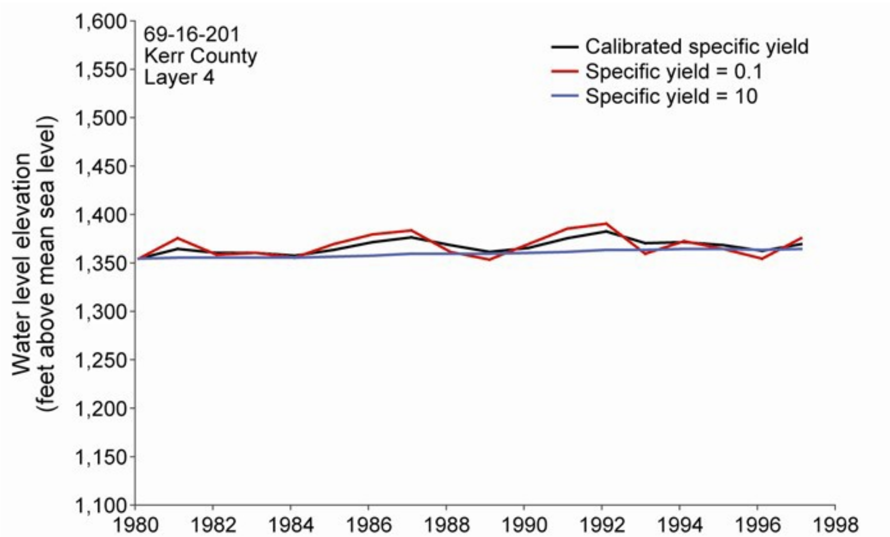


Figure 10-7. (continued).

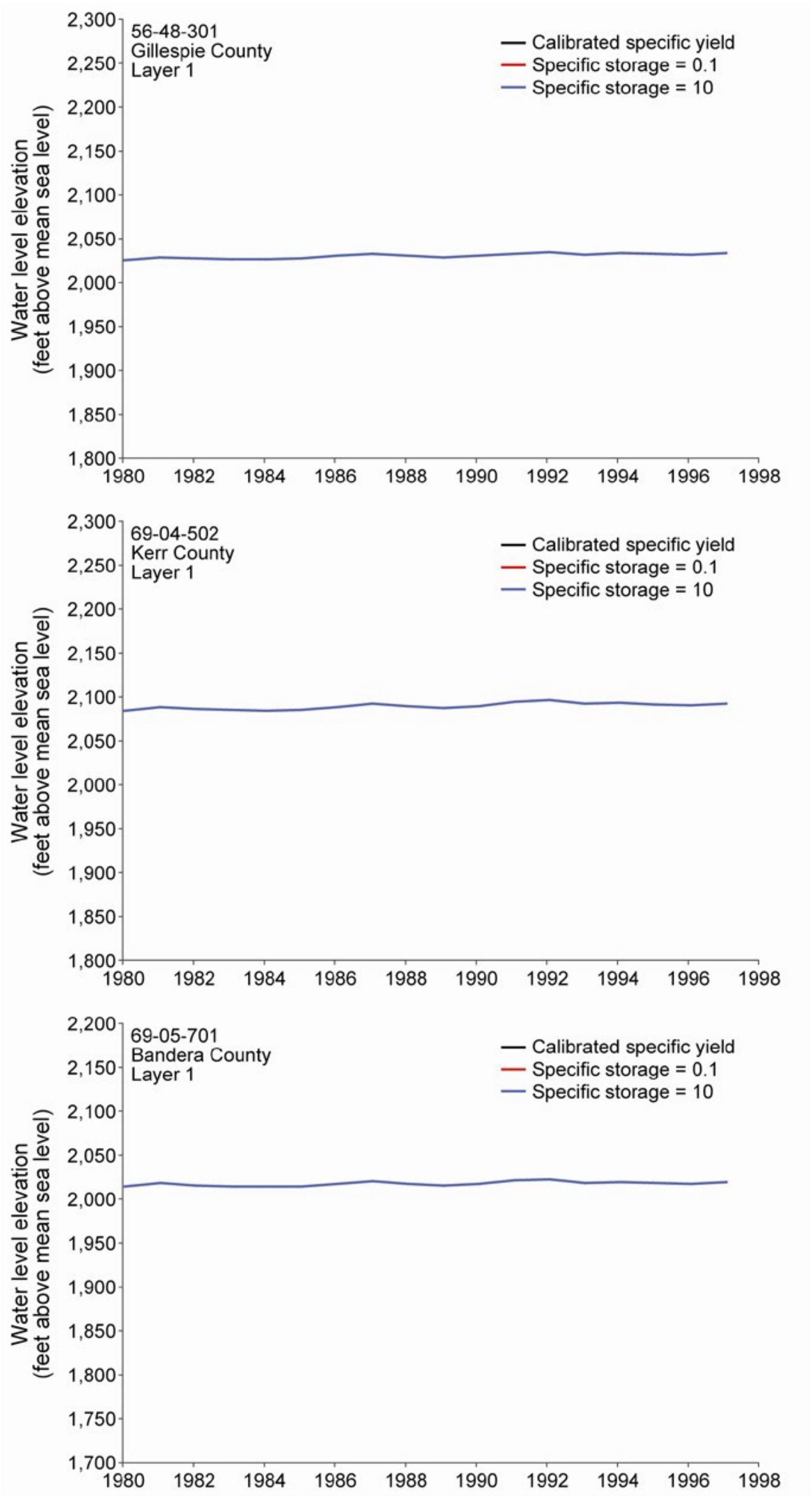
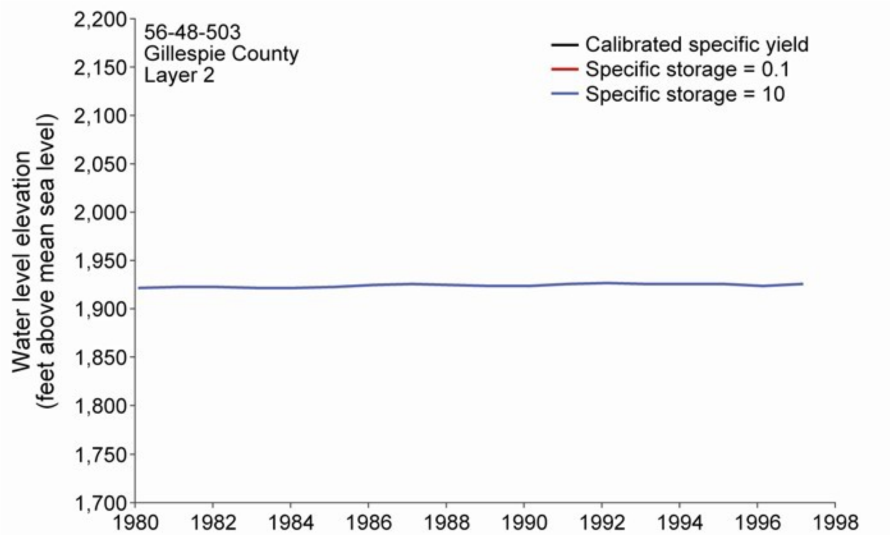
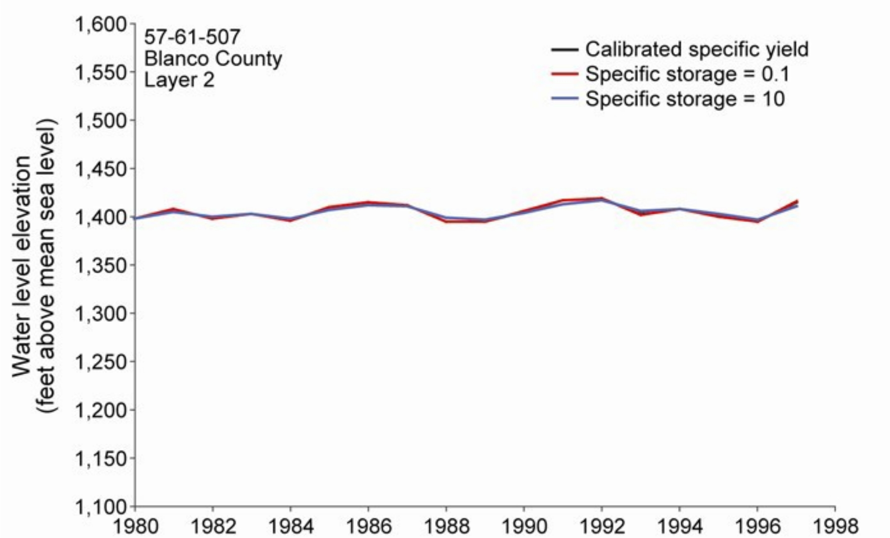


Figure 10-8. **Sensitivity of the transient calibration to specific storage. The red and blue lines represent one order of magnitude lower and higher than the calibrated values, respectively, relative to calibrated specific-storage values (black line).**





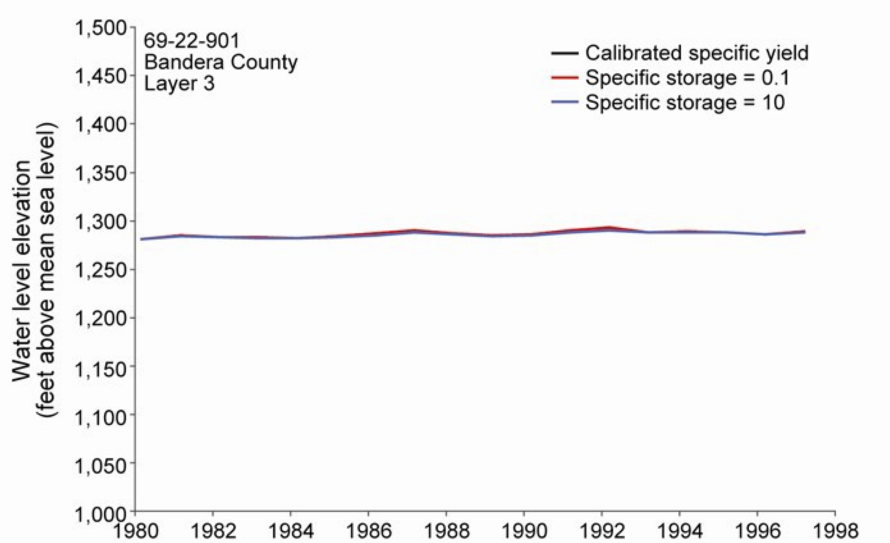


Figure 10-8. (continued).

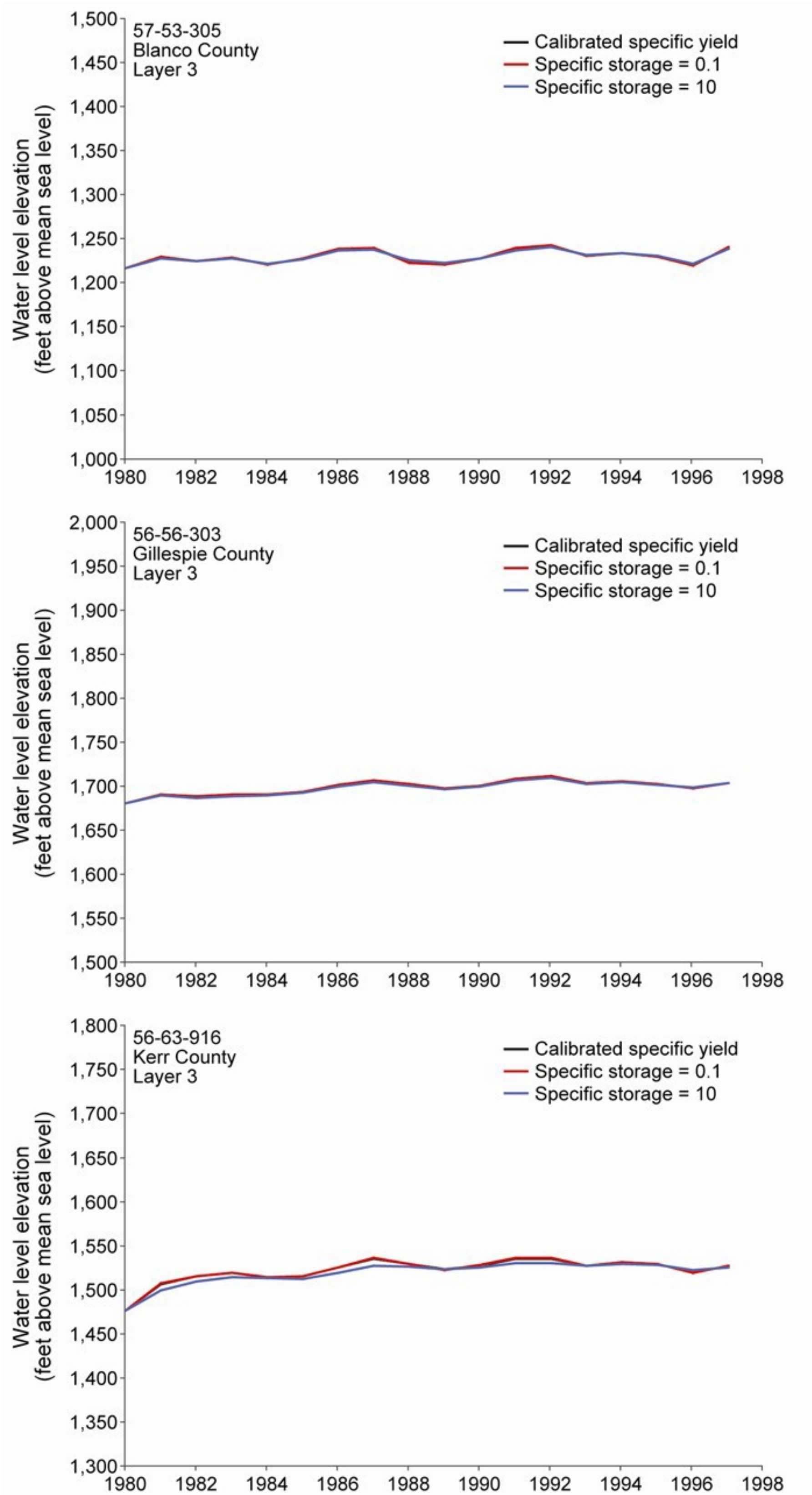
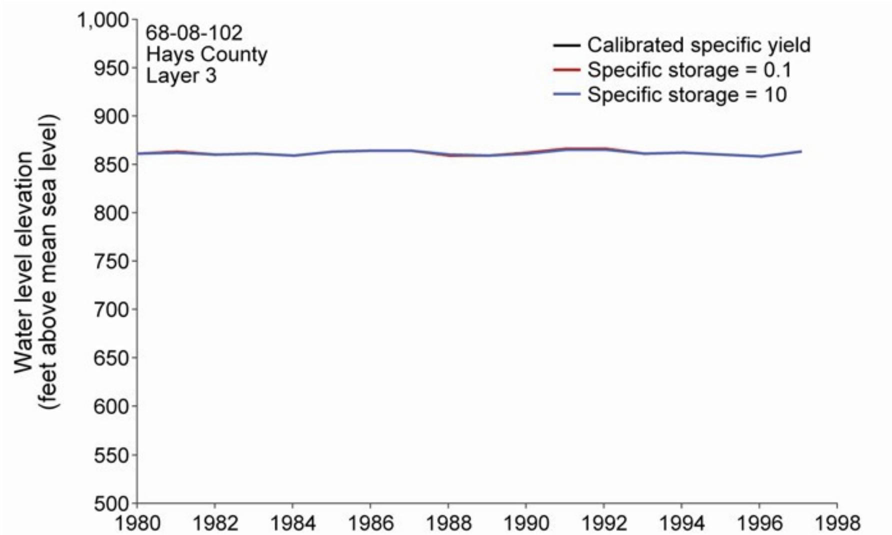
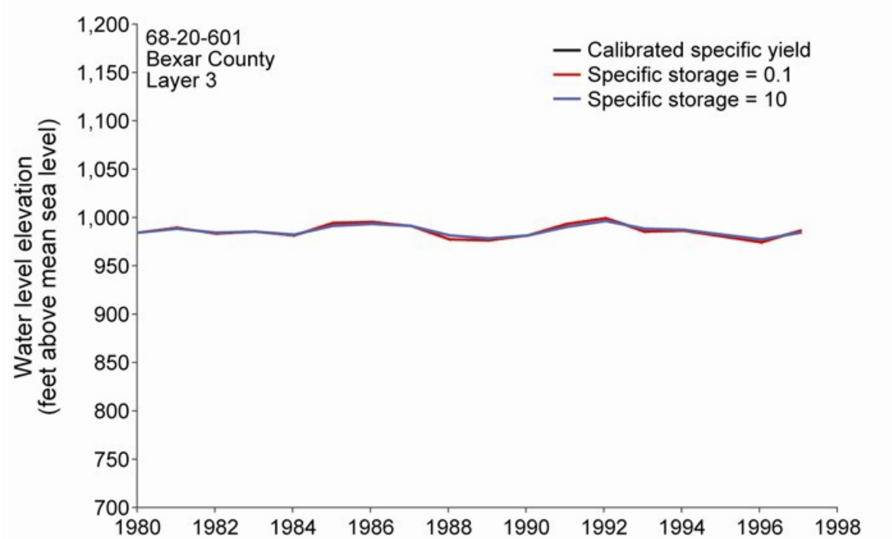


Figure 10-8. (continued).





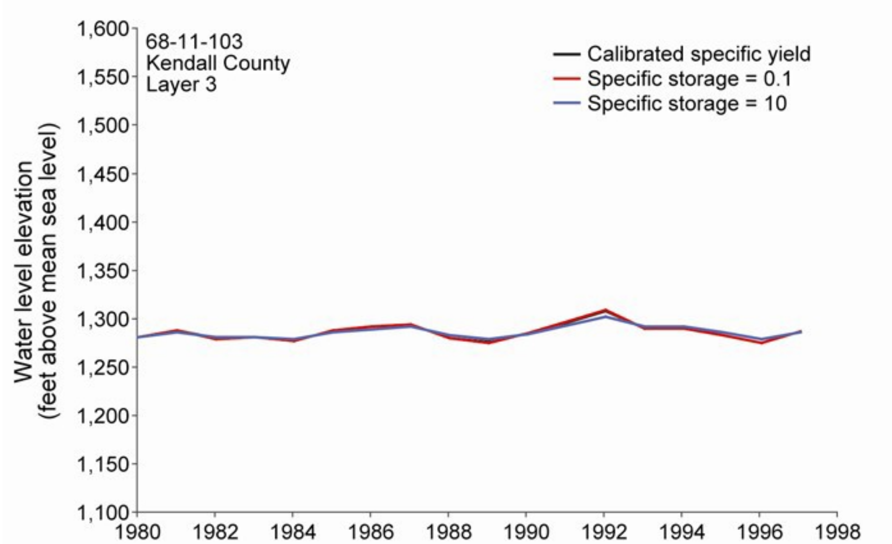


Figure 10-8. (continued).

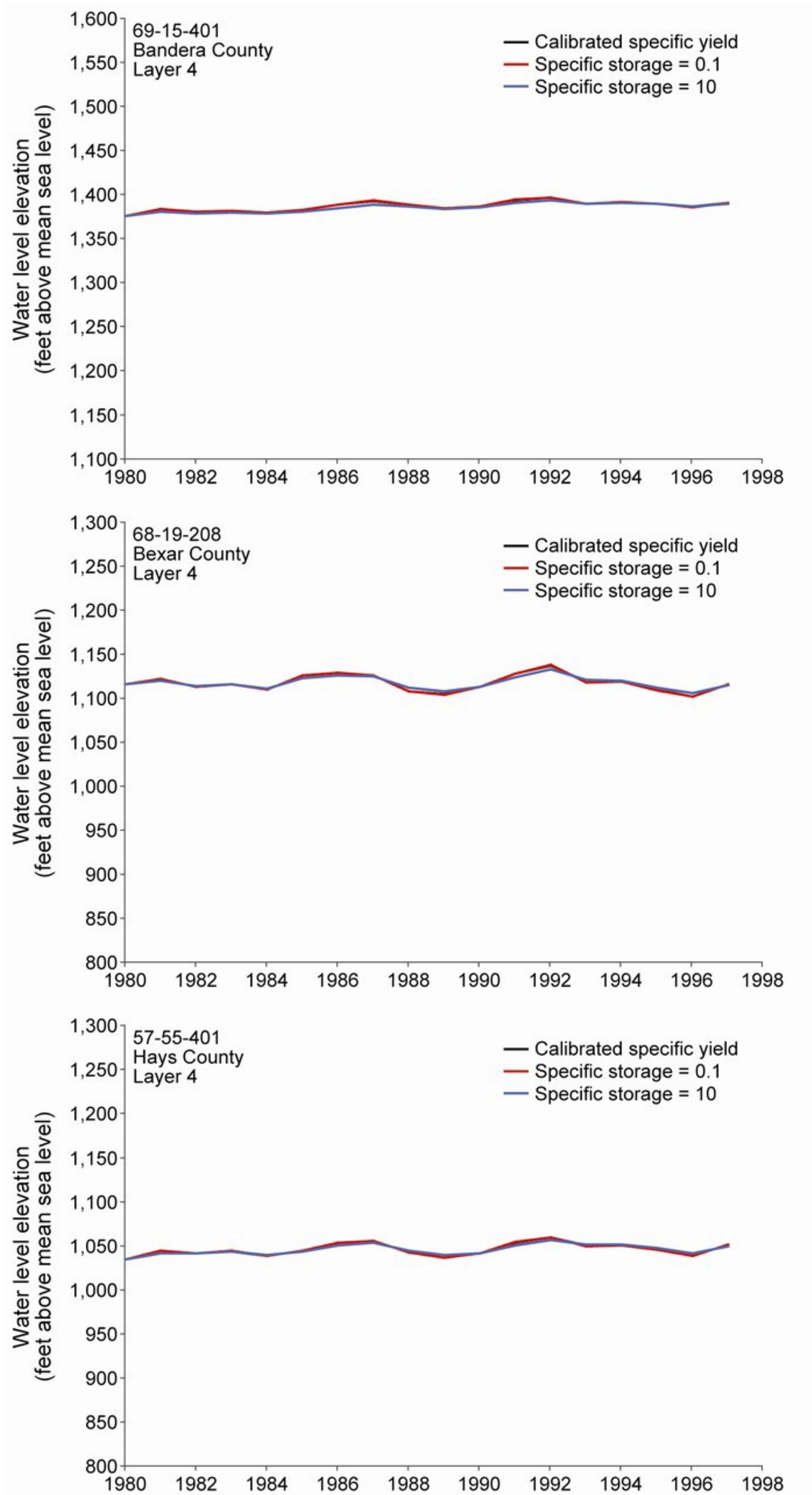


Figure 10-8. (continued).

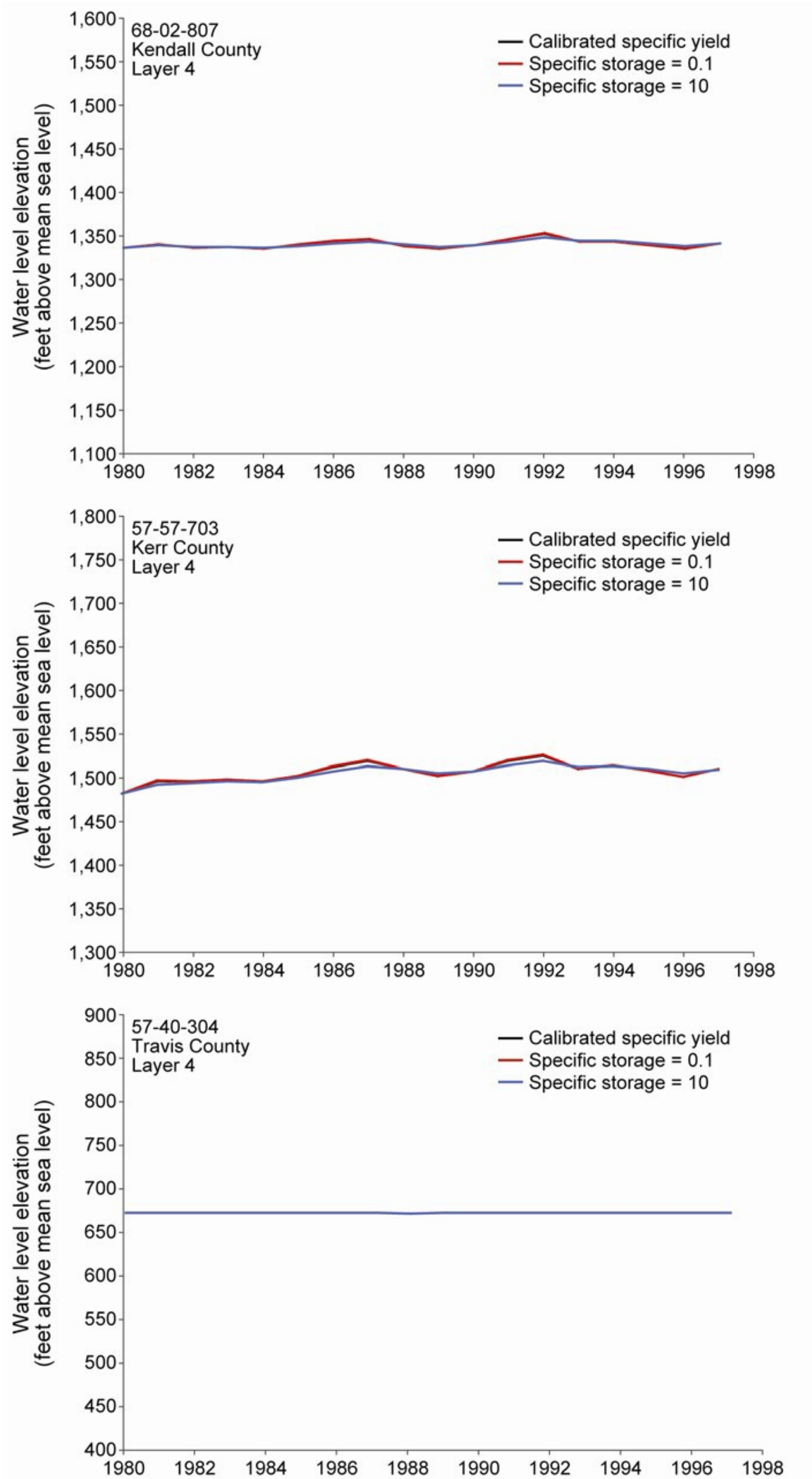


Figure 10-8. **(continued).**

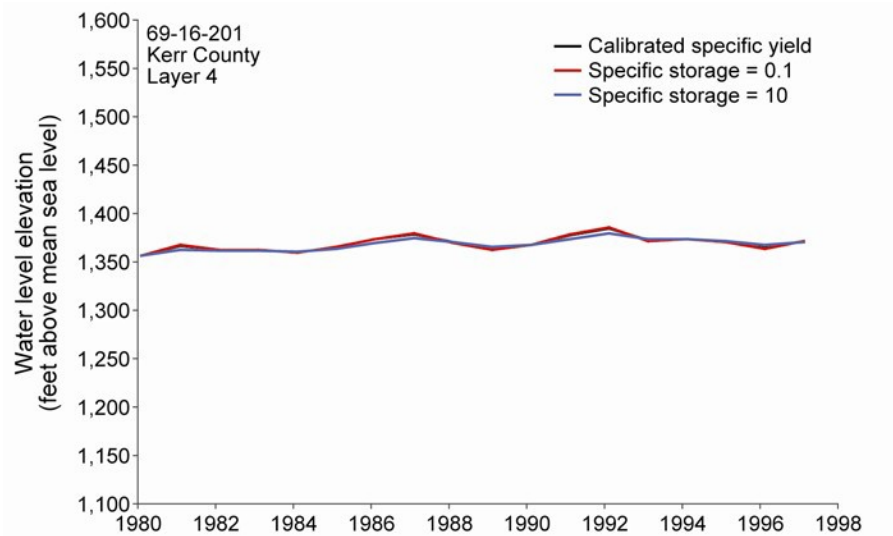


Figure 10-8. (continued).

11.0 Limitations of the Model

All numerical groundwater flow models have limitations. These limitations are usually associated with (1) the extent of current understanding of the workings of the aquifer, (2) the availability and accuracy of input data, (3) the assumptions and simplifications used in developing the conceptual and numerical models, and (4) the scale of application of the model. The limitations determine the spatial and temporal variation of uncertainties in the model because calibration uncertainty decreases with increased availability of input data. Additionally, many of the assumptions, degree of simplification, and spatial resolution of groundwater flow models are influenced by availability of input data.

11.1 Input Data

Several of the input data sets for the model are based on limited information. These include structural geology, recharge, water level data, hydraulic conductivity, specific storage, and specific yield.

Although this model's representation of aquifer hydraulic properties may be adequate for the regional model, it may not be appropriate for local-scale conditions. The same problem occurs in the assigning of specific-storage and specific-yield values in the model. The paucity of measured specific-storage and specific-yield values is partly overcome by calibrating the model on the basis of observed water level responses in the wells in the model area having the most water level measurements over the model period.

There is no published information on the spatial distribution of recharge throughout the Hill Country portion of the Trinity Aquifer System. Calibration of recharge rates is obtained by trial and error during construction of the steady-state model. Application of these recharge rates to the transient model assumes that (1) a linear relationship exists between precipitation and recharge and (2) there is no threshold that must be exceeded before recharge occurs. This assumption suggests the possibility of overestimating recharge during dry periods, when all precipitation may be taken up by evapotranspiration or absorbed by dry soils. The relatively good correlation between observed and simulated water levels and stream discharge suggests that, despite uncertainties, the model water budget reasonably represents the regional groundwater budget.

Our structural maps simplify faulting along the southeastern margin of the model and smooth out the base of the Middle Trinity Aquifer in the northern part of the model. This simplification causes the model to represent the regional structural controls and regional groundwater flow but limits the ability to simulate local groundwater flow in these areas. Greater structural control may be attained with more detailed maps and a finer model grid in this area. However, this increased complexity would come at the cost of the requirement of a finer model grid and consequently much longer run times and increased computational complexity, resulting in increased instability of the model with no guarantee of increased model accuracy.

Water level maps, and therefore the calibration of the model, are affected by limited information, especially in layer 1 where there are few measurements. Limited availability of wells having multiple water level measurements affects calibration of the transient model. Limited water level measurements bias model calibration to areas where water levels have been measured. The difference between measured and simulated water levels can be accounted for by factors such as unavoidable simplifications incorporated into the model and water level measurements not representative of the average water level for a specific period of time simulated by the model.

11.2 Assumptions

We used several assumptions to simplify construction of the model. The most important assumptions are (1) there is no flow between the Lower Trinity Aquifer and underlying Paleozoic units, (2) the Drain Package of MODFLOW can be used to simulate discharge to streams and rivers, (3) the General-Head Boundary Package of MODFLOW can be used to simulate cross-formational flow between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer, and (4) recharge from Cibolo Creek is constant over time.

We assumed that the vertical leakance between the Middle and Lower Trinity aquifers is a function of the thickness of the Hammett Shale. Most of the base of the Middle Trinity Aquifer is underlain by the Hammett Shale (Amsbury, 1974; Barker and Ardis, 1996), which restricts flow between the Middle and Lower Trinity aquifers (Ashworth, 1983).

We used the Drain Package of MODFLOW to simulate streams and rivers in the study area. The Drain Package only allows water to move from the aquifer to the streams and rivers, thus implying that the streams and rivers in the study area are gaining streams and will remain so in the future.

We used the General-Head Boundary Package to simulate cross-formational flow between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer. The spatial distribution of general-head boundary cells in the model is based on the assumption that cross-formational flow occurs where the two aquifers juxtapose along the

Balcones Fault Zone. We also assumed that there is no groundwater flow from the Lower Trinity Aquifer to the Trinity rocks underlying the Edwards (Balcones Fault Zone) Aquifer.

Annual fluctuations in recharge from Cibolo Creek are small enough during the transient model period not to affect calibration, thus allowing the use of constant recharge. However, during periods of extreme drought, it is likely that recharge from Cibolo Creek will decline and eventually cease. Consequently, predictive model runs that include periods of lower precipitation and streamflow (for example, drought of record) should include reduced recharge in this area.

11.3 Scale of Application

The limitations described earlier and the nature of regional groundwater flow models affect the scale of application of the model. As calibrated, this model is most accurate in assessing regional-scale groundwater issues, such as predicting aquifer-wide water level changes and trends in the groundwater budget that may result from different proposed water management strategies, on an annual timescale. Accuracy and applicability of the model decrease when moving from addressing regional- to local-scale issues because of limitations of the information used in model construction and the model cell size that determines spatial resolution of the model. Consequently, this model is not likely to accurately predict water level declines associated with a single well or spring because (1) these water level declines depend on site-specific hydrologic properties not included in detail in regional-scale models and (2) the cell size used in the model is too large to resolve changes in water levels that occur over relatively short distances. Addressing local-scale issues requires a more detailed model, with local estimates of hydrologic properties, or an analytical model. This model is more useful in determining the impacts of groups of wells or well fields distributed over a few square miles. The model can be used to predict changes in ambient water levels rather than actual water level changes at specific locations, such as an individual well.

12.0 Future Improvements

The TWDB plans periodically to update, and thus improve, its groundwater availability models. This model may be improved by incorporating greater complexity or hydrologic information that was not available when it was updated. Model uncertainty may be reduced with additional information on streamflow, hydraulic properties, water level elevations, and recharge.

Additional hydraulic head measurements and aquifer-test data are required for the Hill Country portion of the Trinity Aquifer System. This information can be used to improve calibration of the model by increasing the number and spatial distribution of sites and the frequency of measurements for comparing measured and simulated water levels. Aquifer tests will facilitate determination of whether improving the model by more complex spatial distribution of hydraulic conductivity, specific storage, and specific yield can be justified.

Future updates of this model might include using the Stream-flow Routing Package (Prudic, 1989) to simulate streams. Using the Stream-flow Routing Package would simulate two-way interaction between the aquifer and rivers or streams. This approach is a potentially superior alternative to the Drain Package and may allow better simulation of recharge from Cibolo Creek.

13.0 Conclusions

We updated a finite-difference groundwater flow model that can be used to predict water level changes in response to specified pumping and drought scenarios. The updated model has four layers—the Edwards Group and the Upper, Middle, and Lower Trinity aquifers—and 12,976 active cells, each with a uniform grid size of 1 mile by 1 mile. We developed the conceptual model of groundwater flow and defined aquifer properties on the basis of a review of previous work and studies we conducted on water levels, structure, recharge, and hydraulic properties. The process of updating the model included (1) adding the Lower Trinity Aquifer as another layer to the model, (2) revising the structure and spatial distribution of parameters, such as recharge and pumping, and (3) calibrating to steady-state conditions for 1980 and historical transient conditions for the period 1980 through 1997.

The calibrated model does a reasonable job of matching the water level distribution and water level fluctuations in the aquifer. The steady-state model has an overall mean absolute error of 54 feet, about 3.5 percent of the hydraulic-head drop across the study area. Calibration of the steady-state model indicates an average recharge rate of about 5 percent of average annual precipitation in the Balcones Fault Zone portion of the aquifer and 3.5 percent in the rest of the aquifer. Estimated recharge from Cibolo Creek averages about 70,000 acre-feet per year. Calibrated hydraulic conductivity is 11 feet per day in the Edwards Group, 9 to 150 feet per day in the Upper Trinity Aquifer, 7.6 to 15 feet per day in the Middle Trinity Aquifer, and 1.7 to 17 feet per day in the Lower Trinity Aquifer. Water levels in the model are most sensitive to changes in (1) recharge, (2) horizontal hydraulic conductivity, and (3) vertical hydraulic conductivity. We also calibrated values of vertical hydraulic conductivity, specific storage, and specific yield for the aquifer.

We found that more than 300,000 acre-feet per year of water flows through the aquifer, mostly in the Upper and Middle Trinity aquifers. Of the total flow, almost all is derived from infiltration of precipitation, with minor amounts from inflow from reservoirs and the adjacent Edwards (Balcones Fault Zone) Aquifer. The model estimates that about 100,000 acre-feet per year of groundwater flows from the Upper and Middle Trinity aquifers to the Edwards (Balcones Fault Zone) Aquifer.

14.0 Acknowledgments

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