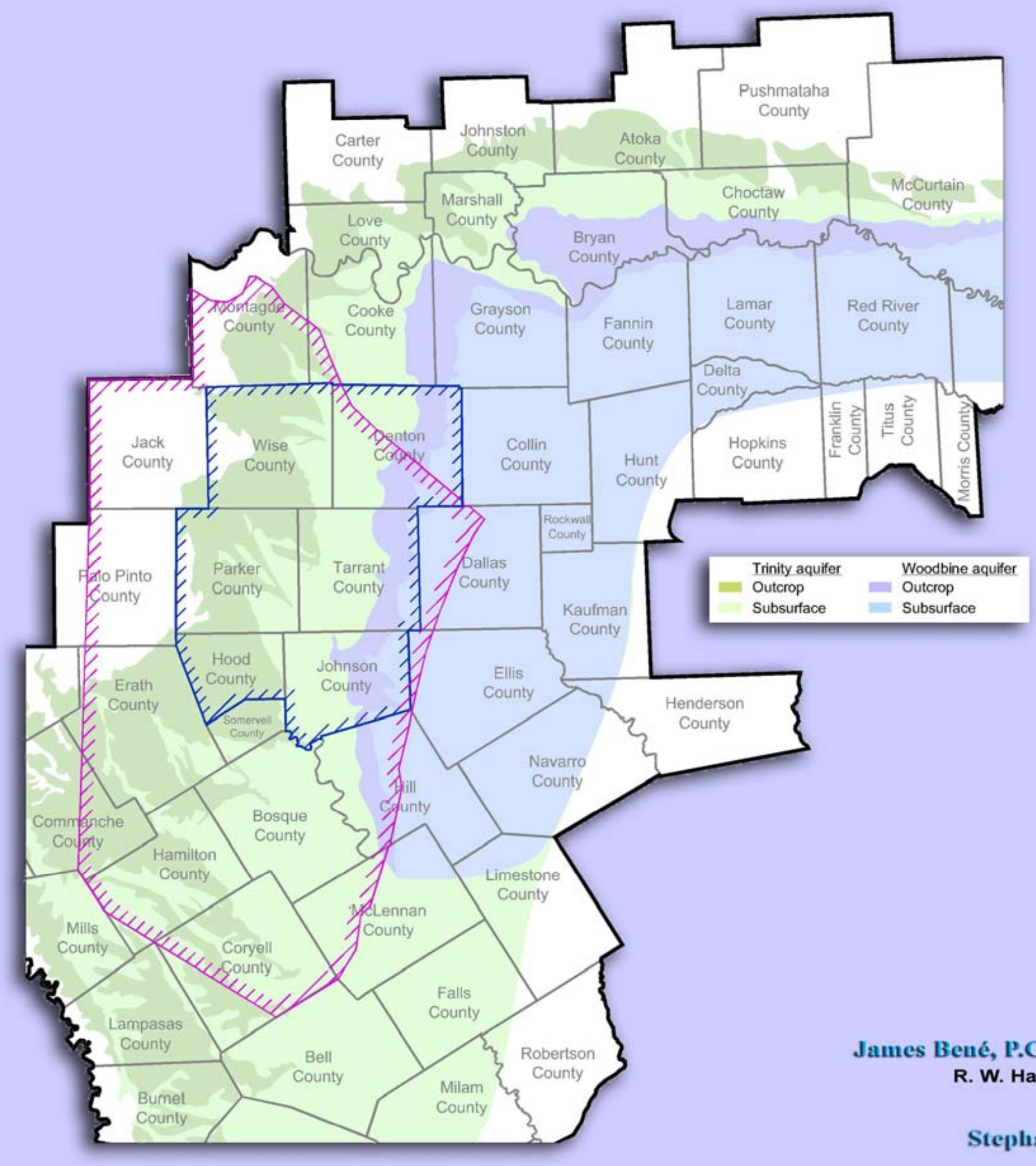
Northern Trinity / Woodbine Aquifer

Groundwater Availability Model

Assessment of Groundwater Use in the Northern Trinity Aquifer Due To Urban Growth and Barnett Shale Development

TWDB Contract Number: 0604830613



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Northern Trinity/Woodbine GAM Assessment of Groundwater Use in the Northern Trinity Aquifer Due To Urban Growth and Barnett Shale Development

Prepared for

Texas Water Development Board
Austin, Texas

TWDB Contract Number: 0604830613

Prepared by

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January 2007

The seals appearing on this document were authorized by James E. Bené, P.G. 2089 and Robert Harden, P.E. 79290 on January 11, 2007.

Changes to the Report Date

The following edits have been made to the original report published on January 11, 2007.

(1) Appendix 3, page 3-1: Additional narratives are provided to better explain the pumpage data sets and histograms presented in this appendix. The pumpage data presented includes county use estimates and may include pumpage from all aquifers within a county, and not necessarily correspond to the Trinity/Woodbine GAM pumpage inputs ……………………………………………………………07-24-2007

(2) Appendix 2, page 2-45: Changed reported units for recycled water from 2,500 gal/day/unit (~2 gpm) to 2,500 bbl/day/unit (~73 gpm)………………………04-09-2007

(3) Executive Summary, page 1, paragraph 1: We have now included Denton County to the description of the study area. The study area included Denton County but we did not list Denton County in the original Executive Summary…………………………...02-12-2007

(4) Appendix 2, page 2-21, Table 1: Changed the caption from “2000-2005 Historical Groundwater Use in the Barnett Shale(all sources, AF/yr)” to “2000-2005 Historical Water Use in the Barnett Shale (all sources, AF/yr)”………………………….02-12-2007

(5) Appendix 3, page 3-82, Table 3-3: This table shows predictive groundwater use under a high use scenario. In the original report, Table 3-3 had the same numbers as Table 3-2, groundwater use under a low use scenario. We have changed the numbers in table 3-3 to include the correct values……………………………………………….......02-07-2007

Table of Contents

Table of Tables

Table of Figures

Table of Appendices

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EXECUTIVE SUMMARY

Increasing water use due to growing population, drought, and natural gas production have heightened concerns in North-Central Texas about the viability of local groundwater resources. Recognizing these concerns, the Texas Water Development Board selected the team of R.W. Harden and Associates, Inc., Freese and Nichols, Inc., and the University of Texas at Austin Bureau of Economic Geology to: (1) estimate current and future pumping of groundwater due to urban growth, (2) estimate current and future pumping of groundwater for fracture enhancement to improve gas well production in the Barnett Shale, and (3) simulate how this pumping may affect the Trinity and Woodbine aquifers. The team worked closely with the Barnett Shale Water Management and Conservation Committee to estimate current and projected water use related to gas well development. The study area includes Bosque, Comanche, Cooke, Coryell, Dallas, Denton, Ellis, Erath, Hamilton, Hill, Hood, Jack, Johnson, McLennan, Montague, Palo Pinto, Parker, Somervell, Tarrant, and Wise Counties, which overlie both the Trinity and Woodbine aquifers, the Barnett Shale, and include urbanized areas near Fort Worth.

The Trinity (Paluxy, Hensell, and Hosston Formations) and Woodbine aquifers have provided water supplies to North-Central Texas for over a century. Initially, water levels in many parts of these aquifers were above land surface, and groundwater naturally flowed from wells. As groundwater use increased, water levels declined in the aquifers and wells stopped flowing in many areas by the 1920s. Pumps were installed in wells and groundwater use continued to increase until the near present. Water level declines have been relatively minor in recharge zones where water seeps into the ground to replenish the aquifers, but water level declines increase to more than 800 feet towards the east in the Dallas-Fort Worth Metroplex area and near Waco, Texas. Water level declines in western recharge zones represent an actual draining of the aquifer, whereas water level declines eastward away from the recharge zones represent a decrease in artesian water pressure, not a draining of the aquifer. To support the increased use levels, artesian pressure must be reduced.

Throughout the study area, water is used for a variety of purposes, including municipal, industrial, electric power generation, agricultural, and mining demands. Municipal use is the greatest current use, representing 77 percent of the total 1.3 million acre-feet of water used in the area in 2000 (an acre-foot is equal to 325,851 gallons of water). Most of the water supply for the region, 89 percent, is provided by surface water sources, while groundwater is utilized for the remainder of the total demand (about 140,000 acre-feet per year). The relative amount of

groundwater use compared to the total water use varies across the study area. Groundwater provides as much as 85 percent of the total water supply in Cooke County, but furnishes only 1 percent in Dallas County. Historically, the Trinity aquifer was a primary source of water for many users in the Dallas-Fort Worth Metroplex area. As population increased, withdrawals from the Trinity and Woodbine aquifers increased and surface water resources were developed and brought online in regional water supply systems. Today, while use of the Trinity and Woodbine is near historically high levels, groundwater comprises only a small fraction of the total water supply in the Dallas-Fort Worth area. Alternatively, the Trinity and Woodbine often provide sole-source supplies in rural areas. As a result, groundwater provides a greater percent of total supply in rural counties and a smaller proportion of total use in more urban counties.

A relatively new use of water in the study area is for the development of natural gas wells in the Barnett Shale. Water is used in the drilling process and to hydraulically fracture the formation around the gas well. The Barnett Shale formation is so tight and dense that development of these natural gas reserves is not economic if the wells cannot be hydraulically fractured. Depending on the well type, about 1.2 to 3.5 million gallons (4 to 11 acre-feet) of water is required to hydraulically fracture, or frac, a gas well. This is a temporary water demand, usually spanning an interval of about one month per gas well. Total water demand for gas well development in the Barnett Shale is estimated at about 7,200 acre-feet in 2005. About 60 percent of this total use (4,300 acre-feet) is estimated to be supplied by groundwater from the Trinity and Woodbine aquifers. Assuming that total groundwater use in 2005 is similar to total groundwater use in 2000, the amount of groundwater use associated with gas well development in the Barnett Shale accounts for about 3 percent of the total groundwater use in the study area.

Projections of future water demands depend on estimates of population growth and various economic factors. Estimates of future municipal and rural domestic water demands are primarily contingent upon population projections, while steam electric power, mining (including Barnett Shale gas well development), and agricultural uses depend chiefly on economic assumptions. Based on the current regional water plans and analysis conducted for this report, it is estimated that total water use in the study area will increase from about 1.3 million acre-feet per year in 2000 to about 2.1 million acre-feet per year in 2025, with most of this escalation due to increases in municipal use.

This study calculates both low and high groundwater demand estimates based on a number of technical and economic factors including: projected population growth, rates of conversion to alternative supplies, and other factors, including natural gas price, that control Barnett Shale drilling activities and associated groundwater production. The low groundwater demand estimate suggests total groundwater use from the study area may decrease from about 142,000 acre-feet in 2000 to about 140,000 acre-feet in 2025. The high groundwater demand estimate suggests about a 30 percent increase in total groundwater use from about 142,000 acre-feet in 2000 to about 190,000 acre-feet in 2025. Total water demand for the development of natural gas wells in the Barnett Shale may rise to about 10,000 to 25,000 acre-feet per year by 2025, depending on the technical and economic development factors including sufficiently high natural gas prices to support additional development. This represents a potential growth from about 3 percent of total groundwater use today, to perhaps 7 percent to 13 percent of total groundwater use through 2025. Long-term, groundwater use for new Barnett Shale wells will likely decline as fewer new wells are completed, and any continued use will be primarily dependent upon the amount of refracing that occurs (if any) of existing wells. Over a much longer time frame, no significant amounts of water would be used for Barnett Shale operations, while municipal and rural domestic uses will likely continue indefinitely.

The low and high groundwater demand estimates developed during this study were input into the Texas Water Development Board's Groundwater Availability Model (GAM) of the Trinity and Woodbine aquifers. The GAM is a computer-based model that can be used to predict how pumping affects water levels and water movement in the aquifer. For the low groundwater demand estimate, the model suggests that water levels will rise in the lower portions of the Trinity aquifer in the Tarrant County area, while declines in water levels will occur in the shallower parts of the aquifer and in areas as far south as McLennan County. Again, these changes in water levels are artesian pressure changes, and do not represent an actual draining of the aquifer. Net change in artesian pressure (either a rise or decline in water level) was generally less than 100 feet, although a rise of up to 200 feet is projected in the lower parts of the Trinity aquifer in Tarrant County.

Groundwater modeling results of the high water demand estimate suggest that water levels will decline regionally in all parts of the Trinity aquifer. Artesian pressure declines of up to 150 feet are projected in Dallas, Tarrant, Johnson, Hill, and McLennan Counties, with smaller declines in adjoining counties. Further to the west, slight draining of the aquifers (regional water table declines of up to a few feet) will occur primarily in central Parker County, northward into Wise County, and southward into Hood and Erath Counties.

Water level changes in the Trinity aquifer are proportional to pumping. In general, the more water produced, the lower the water levels; the less water produced, the higher the water levels. From a regional perspective, historical water level declines do not represent overuse or unsustainability of the aquifer; the aquifer generally supports historical pumping rates. Similarly, both the low and high groundwater use projections are supportable in the regional sense. The low demand estimate will produce a slightly higher water level, while the high demand estimate will result in a lower water level. For the high demand estimate, it may not be practical at the local level for all water users, especially municipalities, to obtain their supply from the aquifer. This is likely a case-by-case issue, and is also dependent upon the availability of alternate sources and associated development costs. For either the low or high demand scenario, if new areas of the Trinity aquifer are developed, water levels will decline in and near the newly developed areas. Locally, some existing wells may have to be re-drilled or have their pumps lowered to accommodate the lower water levels.

During drought conditions, water levels are primarily controlled by the amount of pumping, not the lack of replenishment from rainfall. Groundwater use tends to increase during drought conditions, and water levels will decline in response to increased use. Subsequently, if groundwater use returns to more typical levels during normal rainfall conditions, then water levels will respond in direct relation to the new amount of pumping.

In general, well yields in the Trinity aquifer decrease as you move westward and specifically in the area west of the Dallas-Fort Worth area and across a north-south line extending through Montague, Wise, Parker, Hood, and Erath Counties. Throughout this area, the Trinity aquifer provides reliable supplies through the common use of numerous smaller-capacity wells distributed over greater areas. This is the type of well development pattern that occurs with both rural domestic and Barnett Shale development uses, but is less common for municipal supplies. As population increases westward from the Dallas-Fort Worth area, or perhaps around other communities, the Trinity aquifer will likely not be reliable as a long-term, sole-source supply for all users, and development of additional water supply sources and regional distribution systems will likely become a necessity.

ACKNOWLEDGEMENTS

Numerous organizations were involved in the analysis, modeling, and authoring of this report. R. W. Harden & Associates, Inc. first thanks the immediate project team consisting of Stephanie Griffith and other members of Freese and Nichols, Inc., and J.P. Nicot and other associates at the Bureau of Economic Geology. Next, the project oversight, data assimilation, and report review efforts of Ali Chowdury, Cindy Ridgeway, and Robert Mace of the Texas Water Development Board are greatly appreciated. We thank Peter Galusky from Texerra, and the Barnett Shale Water Conservation and Management Committee for sharing data directly applicable to Barnett Shale development, and for providing review comments of draft reports. Similarly, the efforts of members of the Railroad Commission of Texas, the Texas Commission on Environmental Quality, and the Texas Oil and Gas Association are appreciated.

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INTRODUCTION

Recent urban and rural growth in and near the Dallas/Fort Worth metroplex and increased development of the Barnett Shale for natural gas production have increased the demand on the Trinity/Woodbine aquifer system in northern Central Texas. In response to these trends, the Texas Water Development Board (TWDB) commissioned an updated groundwater demand assessment and aquifer study. This report addresses estimates of this increased groundwater use. Predictions of future aquifer water levels and water budgets are also presented as simulated by the TWDB Groundwater Availability Model (GAM).

Participating in the study was R.W. Harden & Associates, Inc., Freese & Nichols, Inc (FNI), and the Bureau of Economic Geology (BEG). FNI prepared updated demand projections for rural domestic and municipal uses in Denton, Hood, Johnson, Parker, Tarrant, and Wise Counties. The BEG provided projections of potential groundwater use associated with Barnett Shale development in Bosque, Comanche, Cooke, Coryell, Dallas, Denton, Ellis, Erath, Hamilton, Hill, Hood, Jack, Johnson, McLennan, Montague, Parker, Palo Pinto, Somervell, Tarrant, and Wise Counties.

Updated demand estimates were input into the TWDB's Groundwater Availability Model (GAM) of the Northern Trinity/Woodbine aquifers. The Northern Trinity is the sole source for many rural and municipal supplies, and extensive use of the Trinity has occurred since the late 1800's. GAM results were used to project changes in aquifer water levels and water budgets. These projected changes are compared to historical trends to provide the reader with some perspective of the projected effects.

STUDY AREA

The study area includes parts of the Regional Water Planning Group Areas C and G. The area is covered by the Trinity and Brazos River Basins and smaller parts of the Red, Sulfur, and Sabine river basins. The Dallas-Fort Worth area and the adjoining counties are the fastest growing areas in the state, where about 27 percent of Texas population is projected to live in the year 2010 (Water for Texas 2007, 2006). As a result, future demand for water in the area will rise significantly, which will be mainly addressed through the development of alternative supply sources, conservation, and reuse strategies (Water for Texas 2007, 2006).

Within the study area, there is a potential for increased groundwater use associated with rural development in and near the Dallas-Fort Worth metroplex and mining use associated with development of the Barnett Shale. Based on more recent rural development trends, Denton, Hood, Johnson, Parker, Tarrant, and Wise Counties are identified for investigation of updated rural domestic and municipal use. The potential development area for the Barnett Shale includes these six counties as well as additional counties where development of the Barnett Shale formation could occur over the next 20 years. See Appendix 2 for a more detailed discussion of the BEG work efforts. In order to properly simulate these potential new uses, the pumpage input into the GAM was also reviewed in other surrounding counties. The study area for this report is depicted in Figure 1.

Projections of future water demand depend on estimates of population growth and various economic factors. Estimates of future municipal and rural domestic water uses depend primarily on population projections, while steam electric power, mining (including the development of natural gas wells in the Barnett Shale), and agricultural uses depend primarily on economic assumptions. Based on the current regional water plans and analysis conducted for this report, it is estimated that total water use in the study area will increase from about 1.3 million acre-feet per year in 2000 to about 2.1 million acre-feet per year in 2025, with most of this escalation due to increases in municipal use. Table 1 provides the estimated total water use by county and source for 2000, and Table 2 lists the projected water uses in future decades.

Throughout the study area, water is used for a variety of purposes, including municipal, industrial, electric power generation, agricultural, and mining uses. Municipal use is the greatest current use, representing 77 percent of the total 1.3 million acre-feet of water used in 2000 (an acre-foot is equal to 325,851 gallons of water). Most of the water supply for the region, 89 percent, comes from surface water, with the remaining water supply provided by groundwater (about 140,000 acre-feet per year) (Table 1). The relative amount of groundwater used compared to the total water use varies across the study area. Groundwater provides as much as 85 percent of the total water supply in Cooke County, but supplies only 1 percent in Dallas County (Table 1). Historically, the Trinity aquifer was a primary source of water for many users in the Dallas-Fort Worth Metroplex area. As population increased, use of the Trinity aquifer increased, and surface water resources were developed and brought online in regional water supply systems. Today, while use of the Trinity aquifer is near historically high levels, groundwater comprises only a small portion of the total water supply in the Dallas-Fort Worth area. In more rural areas, the Trinity and Woodbine are often sole-source supplies. Therefore, groundwater provides a greater percent of the total supply in more rural counties, and a smaller proportion of total supply in more urban counties.

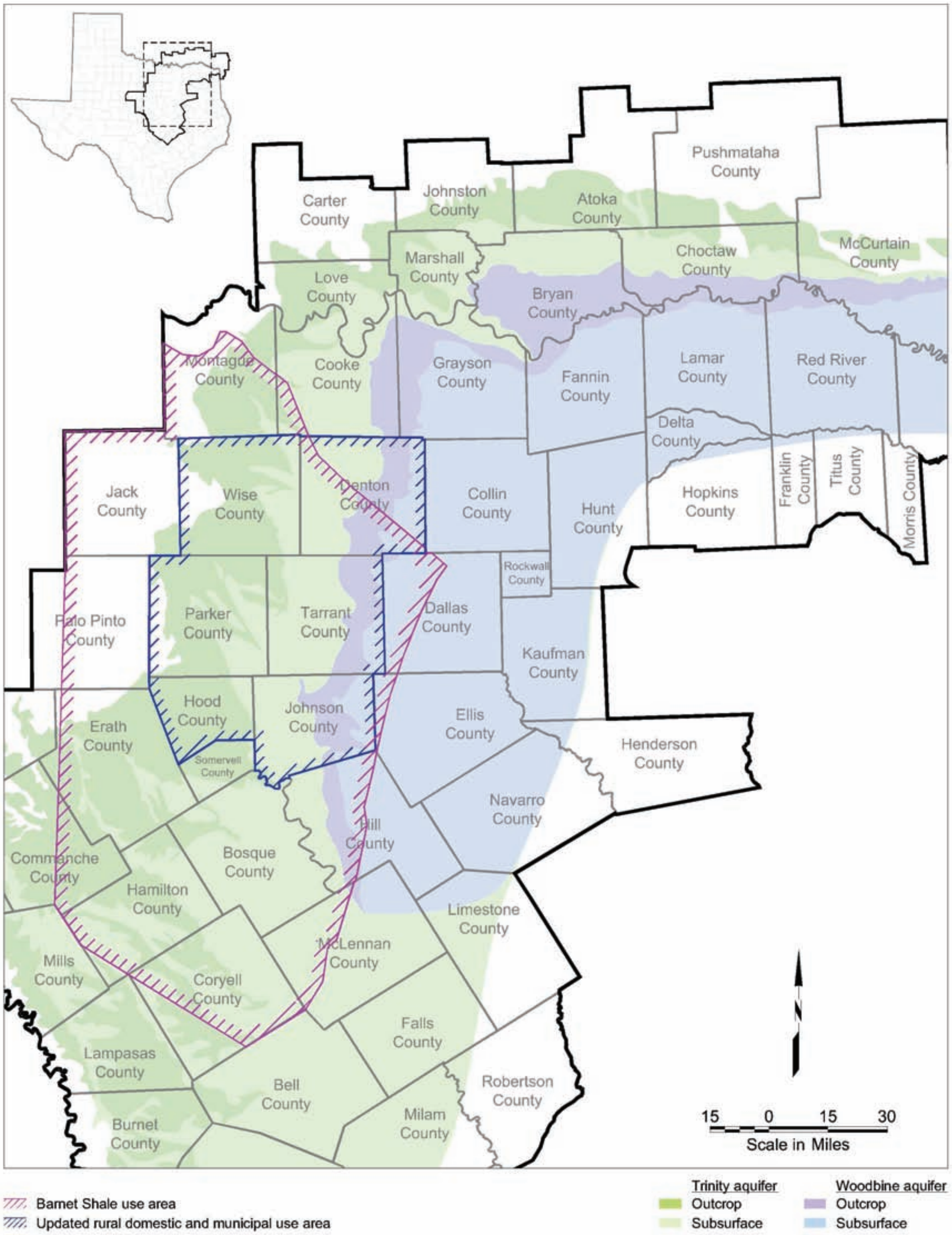


Figure 1. Study Area

Table 1. Estimates of Total Water Use in 2000*

County	Groundwater	Surface water	County Total	Municipal Total	Percent Use by Source	
					Groundwater	Surface Water
Bosque	4,811	2,997	7,808	2,626	61.62	38.38
Comanche	15,349	26,764	42,113	1,784	36.45	63.55
Cooke	6,441	1,118	7,559	5,287	85.21	14.79
Coryell	978	17,066	18,044	16,597	5.42	94.58
Dallas	6,777	541,180	547,957	487,155	1.24	98.76
Denton	15,751	80,573	96,324	92,149	16.35	83.65
Ellis	7,240	19,378	26,618	22,116	27.20	72.80
Erath	19,182	5,809	24,991	4,798	76.76	23.24
Hamilton	950	2,868	3,818	1,371	24.88	75.12
Hill	2,121	4,432	6,553	4,924	32.37	67.63
Hood	4,364	8,500	12,864	6,242	33.92	66.08
Jack	586	2,017	2,603	1,142	22.51	77.49
Johnson	10,107	15,918	26,025	21,591	38.84	61.16
McLennan	15,760	59,090	74,850	44,097	21.06	78.94
Montague	1,526	3,181	4,707	2,513	32.42	67.58
Palo Pinto	438	7,864	8,302	5,043	5.28	94.72
Parker	6,716	4,890	11,606	8,611	57.87	42.13
Somervell	1,535	77,032	78,567	1,024	1.95	98.05
Tarrant	16,529	310,118	326,647	299,695	5.06	94.94
Wise	4,856	8,684	13,540	6,623	35.86	64.14
All	142,017	1,199,479	1,341,496	1,035,388		

*Note: All units are in acre-feet. Includes all counties of estimated Barnett Shale use area. Data from Craig Caldwell, Water Uses Section, Texas Water Development Board, December 22, 2006.

Table 2. Predicted Total Water Use*

County	2000	2010	2020	2025*	2030
Bosque	7,808	12,011	14,379	15,089	15,799
Comanche	42,113	41,824	41,515	41,344	41,173
Cooke	7,559	10,014	11,011	11,508	12,004
Coryell	18,044	17,631	20,272	21,558	22,843
Dallas	547,957	727,506	809,759	838,924	868,089
Denton	96,324	166,191	220,661	248,409	276,156
Ellis	26,618	47,325	61,130	67,107	73,083
Erath	24,991	25,142	25,501	25,656	25,811
Hamilton	3,818	3,743	3,721	3,714	3,707
Hill	6,553	6,613	6,877	7,028	7,178
Hood	12,864	19,912	23,119	24,594	26,068
Jack	2,603	2,824	6,595	6,949	7,302
Johnson	26,025	33,098	38,935	42,048	45,160
McLennan	74,850	93,096	93,440	96,771	100,101
Montague	4,707	5,787	5,781	5,770	5,759
Palo Pinto	8,302	8,294	8,561	8,826	9,091
Parker	11,606	22,246	39,436	44,668	49,900
Somervell	78,567	25,251	25,336	25,373	25,409
Tarrant	326,647	407,958	468,357	497,181	526,004
Wise	13,540	42,906	53,663	61,325	69,071
All	1,341,496	1,719,372	1,978,049	2,093,879	2,209,708

*Note: All units are in acre-feet. Source of data is the 2007 State Water Plan. 2025 is estimated from reported 2020 and 2030 use. Includes all counties of estimated Barnett Shale use area.

UPDATED GROUNDWATER USE ESTIMATES

Rural Domestic and Municipal Demand Projections

The original Trinity/Woodbine GAM included decreases in demand in many counties beginning in the year 2000, which were consistent with the 2001 water plan available at the time of the GAM development. Since then, another round of regional water planning has been conducted, and increased rural development has occurred especially in Parker County. Based on this new information, updated estimates of municipal, manufacturing, irrigation, and livestock groundwater use trends were developed by FNI for Denton, Hood, Johnson, Parker, Tarrant, and Wise Counties.

Driller's reports of recently competed wells submitted to the Texas Department of Licensing and Regulation were tabulated to help assess groundwater use trends (Ridgeway, 2006). A summary of the results by county and reported type of well are included in Appendix 1. The majority of the wells recently drilled are for rural domestic supplies. For the six counties, about 1,300 new wells were reportedly drilled each year. However, it is unknown how many of these wells represent new demands, or how many are replacement wells.

Water use surveys were sent to a selected group of 123 water users to assist in estimates of current and future use. The survey requested information pertaining to current and projected production rates and well location, depth, and construction details. About one-half of the mailed surveys were completed and returned for inclusion in the analysis. Estimations of current populations and projected growth were obtained from the Texas State Data Center, the U.S. Census, The North Texas Council of Governments, and the TWDB. Regional water plan demands, population estimates, and water use plans from entities answering the surveys were used to create an estimate of use trends for inclusion in the update to the GAM. Because of uncertainty in the implementation of alternative sources, two demand estimates were developed. A high demand estimate assumes Trinity aquifer use would increase in the future. The low demand estimate assumes use would remain near 2000 use levels (or decline slightly) as alternative water supply sources are developed.

A summary of the results of this work are included in Tables 3 and 4. A more complete listing of the methodologies used and results of the study conducted by FNI is included in Appendix 1.

Table 3. Non-Barnett Shale Demands on the Trinity Aquifer by County*

County	Low Demand (ac-ft/yr)					High Demand (ac-ft/yr)				
	2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
Denton	10,320	9,870	9,870	9,830	9,880	12,030	14,750	17,040	19,560	22,750
Hood	7,410	6,830	6,820	6,800	6,790	8,560	8,110	8,340	8,560	8,770
Johnson	4,680	4,510	4,470	4,430	4,130	11,700	12,960	13,650	14,360	15,060
Parker	6,950	7,030	6,910	6,910	6,910	7,060	8,680	10,600	12,960	13,230
Tarrant	11,190	10,520	10,040	9,650	9,650	13,690	15,730	16,040	16,370	16,970
Wise	4,110	4,150	4,120	4,090	4,090	4,730	5,750	6,940	7,850	8,220

*Note: Does not include any potential Barnett Shale groundwater use.

Table 4. Non-Barnett Shale Demands on the Woodbine Aquifer by County*

County	Low Demand (ac-ft/yr)					High Demand (ac-ft/yr)				
	2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
Denton	1,830	1,840	1,850	1,860	1,880	4,770	7,430	8,960	10,460	11,490
Johnson	170	170	170	170	170	280	280	280	280	280

*Note: Does not include any potential Barnett Shale groundwater use.

Barnett Shale Water Use

Gas production in the Barnett Shale has rapidly increased in the past decade due in large part to improvements in hydraulic fracture stimulation (frac) technologies. The frac process uses water to generate and improve fracturing within the shale matrix. The fracturing greatly improves the gas production from a well, but the use of fresh water is an added cost to the development of a well so there is incentive to use only the amount of water necessary for satisfactory completion of the process. Within the Barnett Shale formation, there are currently more than 5,600 producing wells (Appendix 2, pg. 2-27), and it is likely many thousands more will be constructed within the next couple of decades.

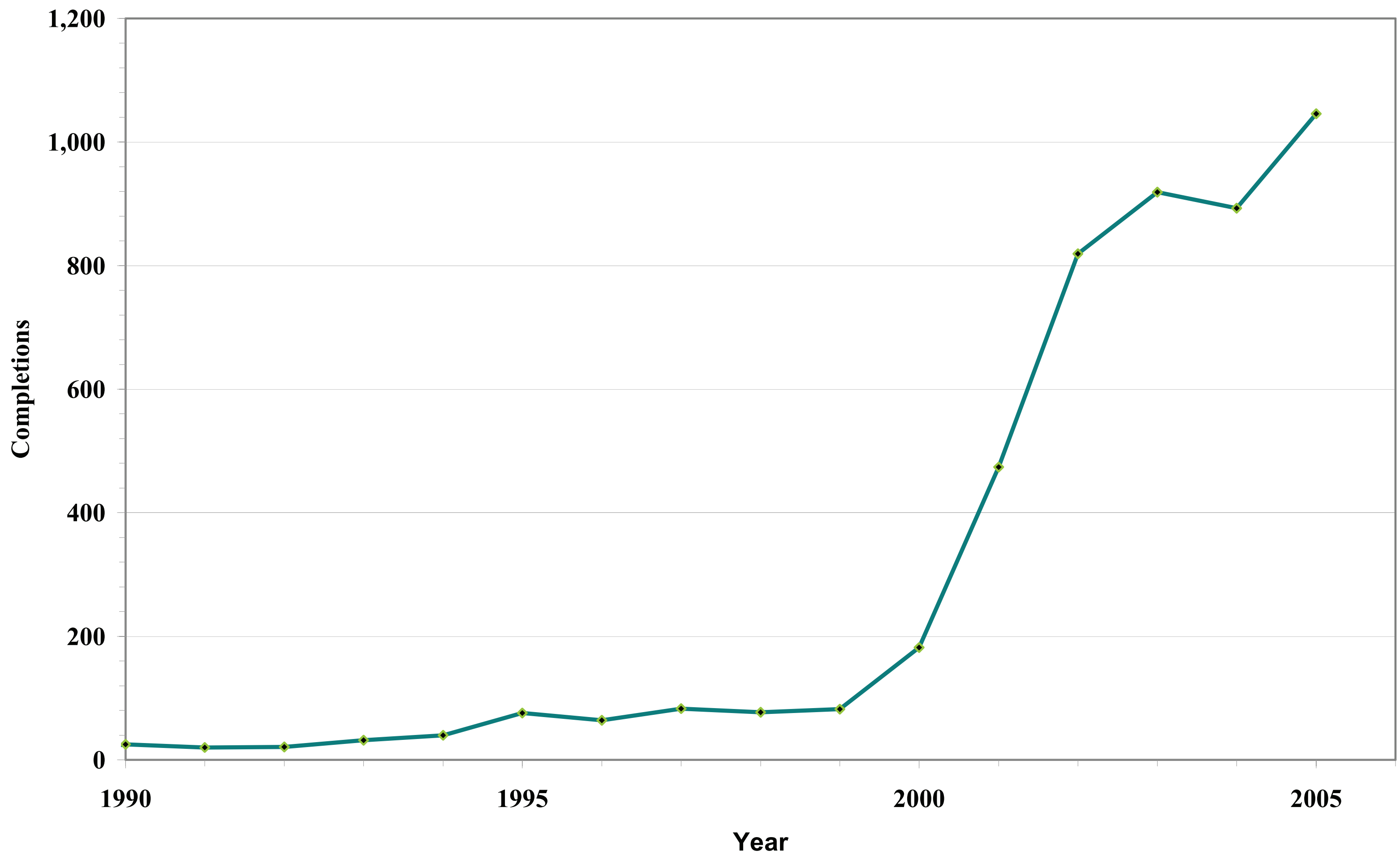
Fracture stimulation techniques have been around since the 1940's, but within the last 10 years the methods used have made the process simpler and cheaper, which has led to a rapid expansion of well completions in the Barnett Shale (Figure 2). The current frac process is often accomplished through what is called "Slick Water" or "Light Sand" frac, and utilizes larger volumes of water than historically used to complete the process. Reports on fracturing practices estimate the water use to be anywhere from 2,000 to 3,200 gallons per foot (gal/ft) of fractured formation (Appendix 2, pg. 2-23). The petroleum industry is also researching ways to recycle water used in frac operations. Estimations of the numbers of Barnett Shale completions were derived from DrillingInfo.com, IHS Energy databases, and completion forms submitted to the Texas Railroad Commission. Locations of the completions and their proximity to urban centers, the extents and geology of the Barnett Shale, estimations of potential technological changes in frac techniques, and an understanding of gas development practices and limitations were all used by the BEG during development of estimates of potential groundwater use.

When frac technology is used to improve production from a well, vertical and horizontal completions typically require about 1.2 and 3.5 million gallons (MG) respectively. Well frac operations use surface water and/or groundwater as a source water. Currently, it is estimated that groundwater is used about 60% of the time, with county-wide averages ranging from about 45% to 90% (Appendix 2, pg. 68). The total amounts of Trinity and Woodbine groundwater currently used for fracture enhancement are estimated from available oil and gas completion records, discussions with well operators, and an understanding of current and past practices. Projections of water use are highly speculative due to the volatility of gas prices and other important factors including geologic risk factors in the Barnett (maturity of the shale, thickness of the formation, presence of features limiting or hampering well completion), technological factors (horizontal vs.

vertical wells, water recycling), operational factors (number of well completions that can be completed in a year, proximity of a fresh-water source), and regulatory factors. To account for these uncertainties, low, medium, and high groundwater use projections were prepared by the BEG. During this process, the BEG created polygons that reflect the potential for groundwater use (Appendix 2, Figure 20, pg 2-48.) In each of these polygons, an annual estimate of potential groundwater use was developed using the methodology described in Appendix 2. A more detailed description of the Barnett Shale and its potential impacts to water demands on the Trinity/Woodbine is included in Appendix 2 – Barnett Shale Groundwater Use Estimates.

The potential groundwater use estimates were further refined by the BEG as follows. The Trinity/Woodbine aquifers only partially overlie the eastern sections of the Barnett Shale; no defined major or minor aquifers exist beneath the western portions of the Barnett Shale. Furthermore, it is assumed that groundwater use for Barnett Shale frac operations would occur only where it is estimated that the Trinity or Woodbine is capable of producing 50 gallons per minute (gpm) or more. This is the assumed minimum supply well acceptable to an operator developing a Barnett well (Appendix 2, pg 2-72), however, it is possible that some operators may choose to drill numerous rig supply wells (of less than 50 gpm per well) to provide for their supply. In addition, trucking of groundwater from more productive Trinity areas to less productive regions (or even further west where the Trinity does not exist) may also occur. Therefore, it is recognized that the approach adopted herein of assuming that a rig supply well must be capable of producing a minimum of 50 gpm may slightly underestimate the total future Trinity groundwater used in the most western extents of the Trinity. Any increased use is likely small compared to total use, and the effects of this use would be restricted to the far western extents of the aquifer and only near the individual producing wells.

Barnett Shale well completions are highly dependent upon natural gas prices. The BEG developed three demand estimates – a low, medium, and high estimate. Figure 3 presents the total annual use for the three demand estimates following the completion of all spatial and technical analyses.



*Note: Incomplete reporting of 2006 completions was omitted from the graph

Figure 2. Annual Gas Well Completions in Barnett Shale

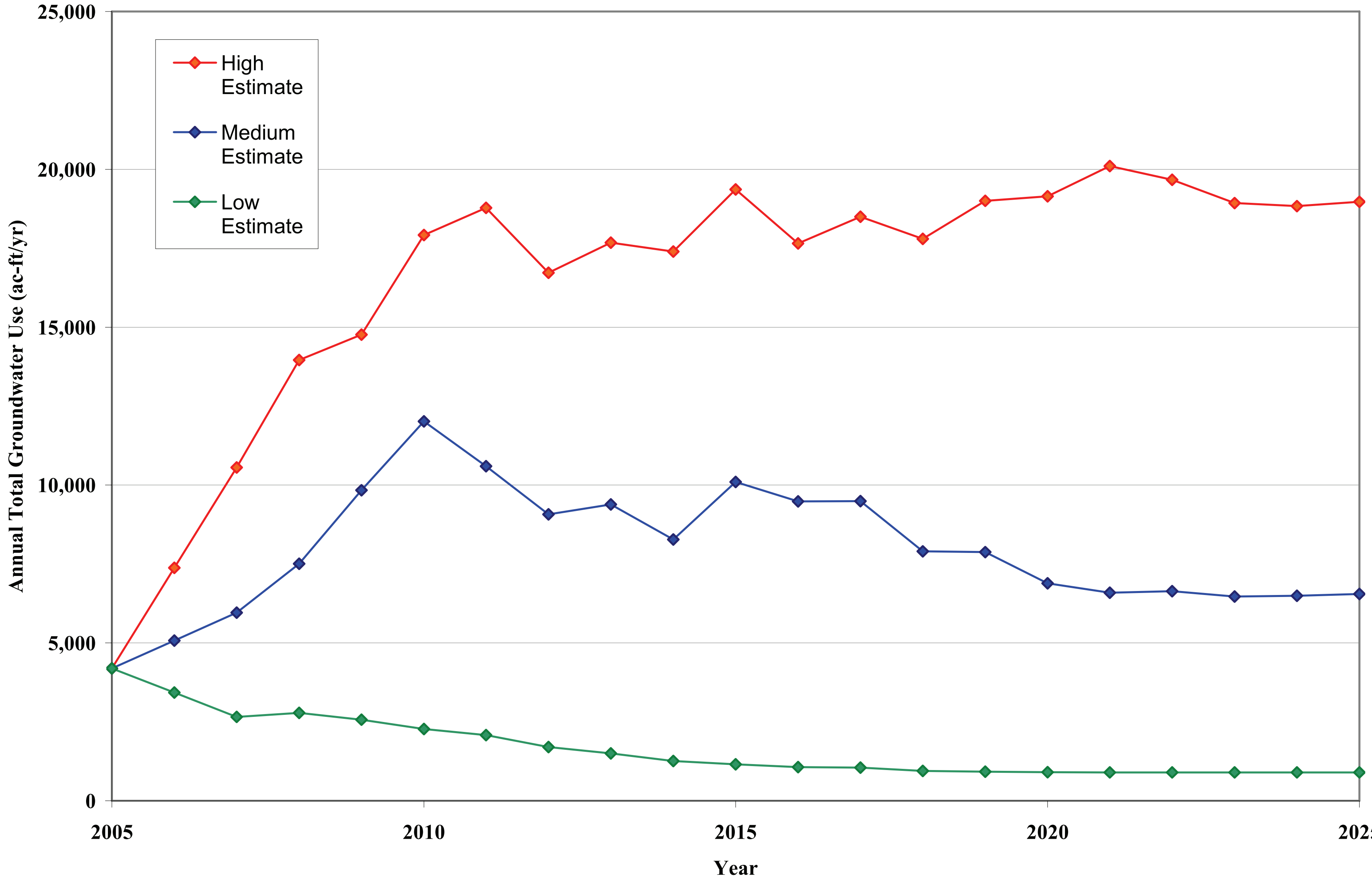


Figure 3. Total Annual Barnett Shale Groundwater Demand Projections

Total Groundwater Use

As indicated earlier, the predictive pumpage dataset contained in the original Trinity/Woodbine GAM was based on 2001 regional water plan projected demands. These projected demands were oftentimes less than groundwater use experienced during the late 1990's. As part of this study, predictive pumpage in the GAM was first reviewed on a county basis, and, if the county experienced a significant drop in demand, a new "base" demand was estimated using the average of the 1995 through 1999 reported use. Demands in Denton, Hood, Johnson, Parker, Tarrant, and Wise Counties were based on the FNI projections discussed previously. The estimated Barnett Shale groundwater use was then added to the base (non Barnett-related) groundwater use amounts to obtain the estimated total use for this study. It is assumed that future natural gas prices will be sufficient to support either the BEG's medium or high demand estimate. Two future projected demand estimates were prepared to account for the uncertainty of: 1) municipal users shifting to alternative sources and 2) the rate of Barnett Shale development. Therefore, to provide a potential "worst-case" evaluation, a low demand estimate was developed by combining the low demand estimates for rural domestic/municipal uses with the medium demand estimates for the Barnett Shale. Similarly, a high demand estimate was developed by combining the high demand estimate for the rural domestic/municipal uses with the high demand estimate for the Barnett Shale.

Percent of total use by Barnett Shale development, point source, rural domestic, livestock, and irrigation uses are shown in Tables 5a and 5b for the low and high demand estimates, respectively. Point sources include total use from municipal, manufacturing, mining (other than Barnett Shale) and/or power generation. Figure 4 presents the total groundwater demand estimate for the low demand estimate by category of use for the study area counties, and, similarly, Figure 5 presents the high demand estimate total groundwater use for the study area counties. Appendix 3 provides charts of total use volume by year and category for both the low and high use estimates for all counties whose pumpage input was modified from the original GAM input.

Table 5a. Percent Use by Category – Low Groundwater Demand Estimate

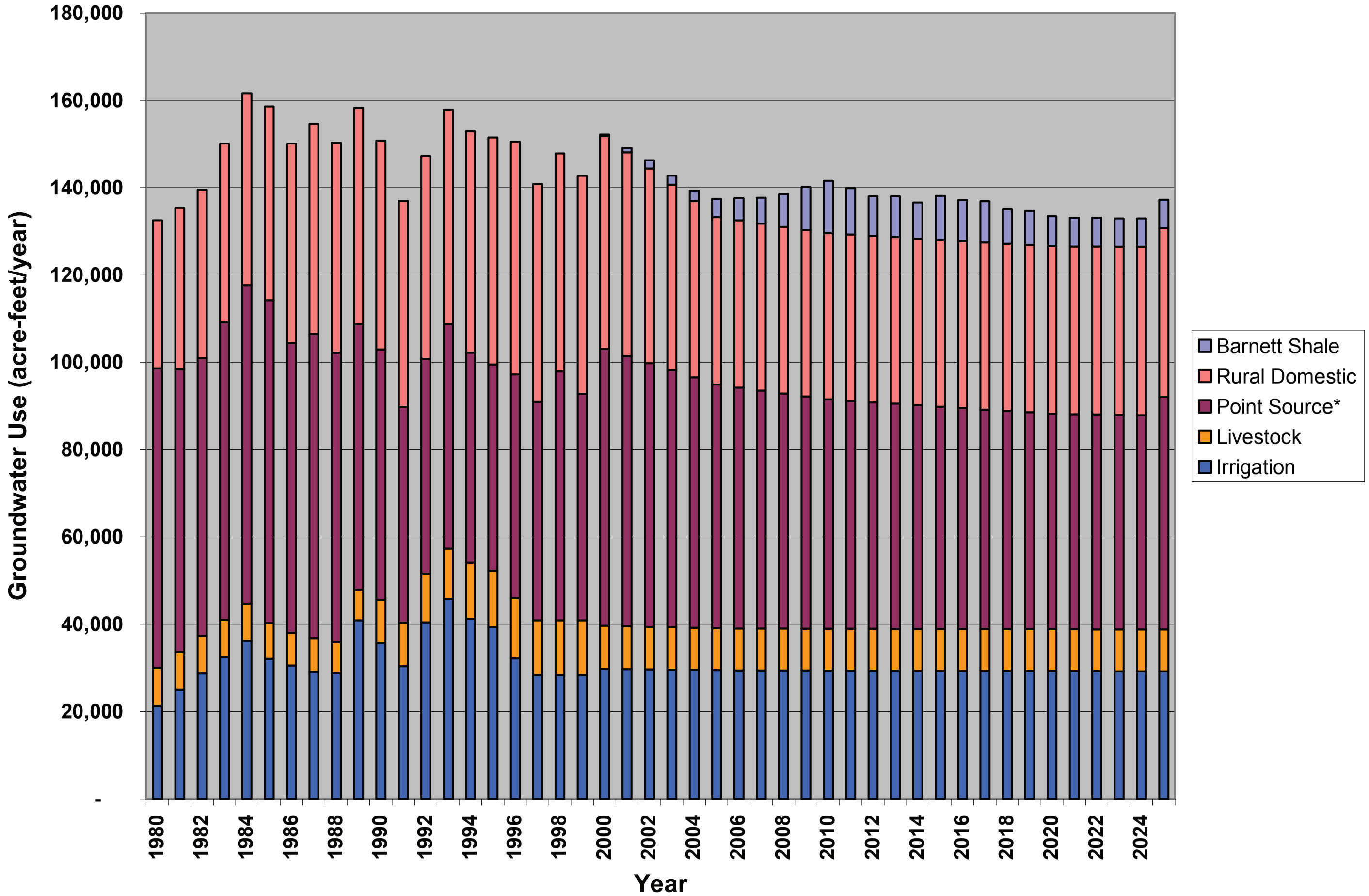
County	Year				
	2000-2005	2006-2010	2011-2015	2016-2020	2021-2025
Bosque	0 / 35 / 42 / 23 / 0	3 / 34 / 41 / 22 / 0	30 / 25 / 30 / 16 / 0	45 / 19 / 23 / 12 / 0	27 / 26 / 31 / 17 / 0
Comanche	0 / 0 / 2 / 3 / 94	0 / 0 / 2 / 3 / 95	0 / 0 / 1 / 3 / 95	0 / 0 / 1 / 3 / 95	0 / 0 / 1 / 3 / 95
Cooke	0 / 51 / 30 / 15 / 4	0 / 51 / 30 / 15 / 4	1 / 50 / 30 / 15 / 4	2 / 50 / 29 / 15 / 4	1 / 50 / 30 / 15 / 4
Coryell	0 / 7 / 60 / 34 / 0	0 / 7 / 60 / 33 / 0	0 / 7 / 60 / 33 / 0	0 / 7 / 60 / 33 / 0	0 / 7 / 60 / 33 / 0
Dallas	0 / 96 / 3 / 1 / 0	0 / 94 / 5 / 1 / 0	3 / 90 / 6 / 1 / 0	2 / 89 / 7 / 1 / 0	2 / 89 / 8 / 1 / 0
Denton	7 / 64 / 27 / 2 / 0	10 / 59 / 29 / 2 / 0	3 / 62 / 33 / 2 / 0	3 / 61 / 35 / 2 / 0	3 / 58 / 37 / 2 / 0
Ellis	0 / 45 / 53 / 2 / 0	0 / 45 / 53 / 2 / 0	1 / 44 / 53 / 2 / 0	1 / 45 / 53 / 2 / 0	0 / 45 / 53 / 2 / 0
Erath	0 / 18 / 12 / 23 / 47	0 / 15 / 13 / 24 / 48	0 / 14 / 13 / 24 / 49	0 / 15 / 13 / 24 / 48	0 / 15 / 13 / 24 / 48
Hamilton	0 / 15 / 25 / 19 / 40	0 / 15 / 25 / 19 / 41	0 / 15 / 24 / 20 / 41	0 / 15 / 24 / 20 / 42	0 / 14 / 23 / 21 / 43
Hill	0 / 16 / 78 / 5 / 0	5 / 16 / 74 / 5 / 0	34 / 11 / 52 / 4 / 0	23 / 13 / 60 / 4 / 0	18 / 13 / 64 / 4 / 0
Hood	0 / 37 / 41 / 4 / 18	8 / 32 / 40 / 4 / 16	15 / 27 / 38 / 4 / 15	7 / 30 / 42 / 4 / 17	8 / 30 / 42 / 4 / 17
Jack	0 / 0 / 100 / 0 / 0	2 / 0 / 98 / 0 / 0	11 / 0 / 89 / 0 / 0	6 / 0 / 94 / 0 / 0	5 / 0 / 95 / 0 / 0
Johnson	3 / 30 / 60 / 6 / 0	29 / 30 / 34 / 7 / 0	20 / 34 / 38 / 8 / 0	16 / 35 / 41 / 8 / 0	17 / 32 / 42 / 9 / 0
McLennan	0 / 68 / 31 / 1 / 0	0 / 68 / 31 / 1 / 0	0 / 67 / 31 / 1 / 0	2 / 66 / 30 / 1 / 0	1 / 67 / 30 / 1 / 0
Montague	1 / 0 / 81 / 5 / 14	0 / 0 / 81 / 5 / 14	3 / 0 / 79 / 5 / 13	20 / 0 / 65 / 4 / 11	14 / 0 / 70 / 4 / 12
Palo Pinto	0 / 0 / 100 / 0 / 0	0 / 0 / 100 / 0 / 0	0 / 0 / 100 / 0 / 0	1 / 0 / 99 / 0 / 0	0 / 0 / 99 / 0 / 0
Parker	1 / 21 / 74 / 2 / 1	20 / 17 / 59 / 2 / 1	21 / 17 / 59 / 2 / 1	13 / 19 / 64 / 2 / 1	13 / 19 / 64 / 2 / 1
Somervell	0 / 44 / 39 / 7 / 10	19 / 35 / 32 / 6 / 8	32 / 30 / 27 / 5 / 7	17 / 36 / 32 / 6 / 8	18 / 36 / 32 / 6 / 8
Tarrant	2 / 83 / 13 / 3 / 0	6 / 90 / 0 / 3 / 0	3 / 93 / 0 / 4 / 0	3 / 93 / 0 / 4 / 0	3 / 93 / 0 / 4 / 0
Wise	8 / 23 / 50 / 14 / 5	23 / 21 / 39 / 13 / 4	18 / 22 / 42 / 14 / 4	14 / 23 / 44 / 15 / 5	15 / 23 / 44 / 14 / 4

*Note: Values are percent of total groundwater use for Barnett Shale/Point Source/Rural Domestic /Livestock /Irrigation. Point source represents municipal, industrial, mining other than Barnett Shale, and power generation uses. Due to rounding, individual values may not always total 100%.

Table 5b. Percent Use by Category – High Groundwater Demand Estimate

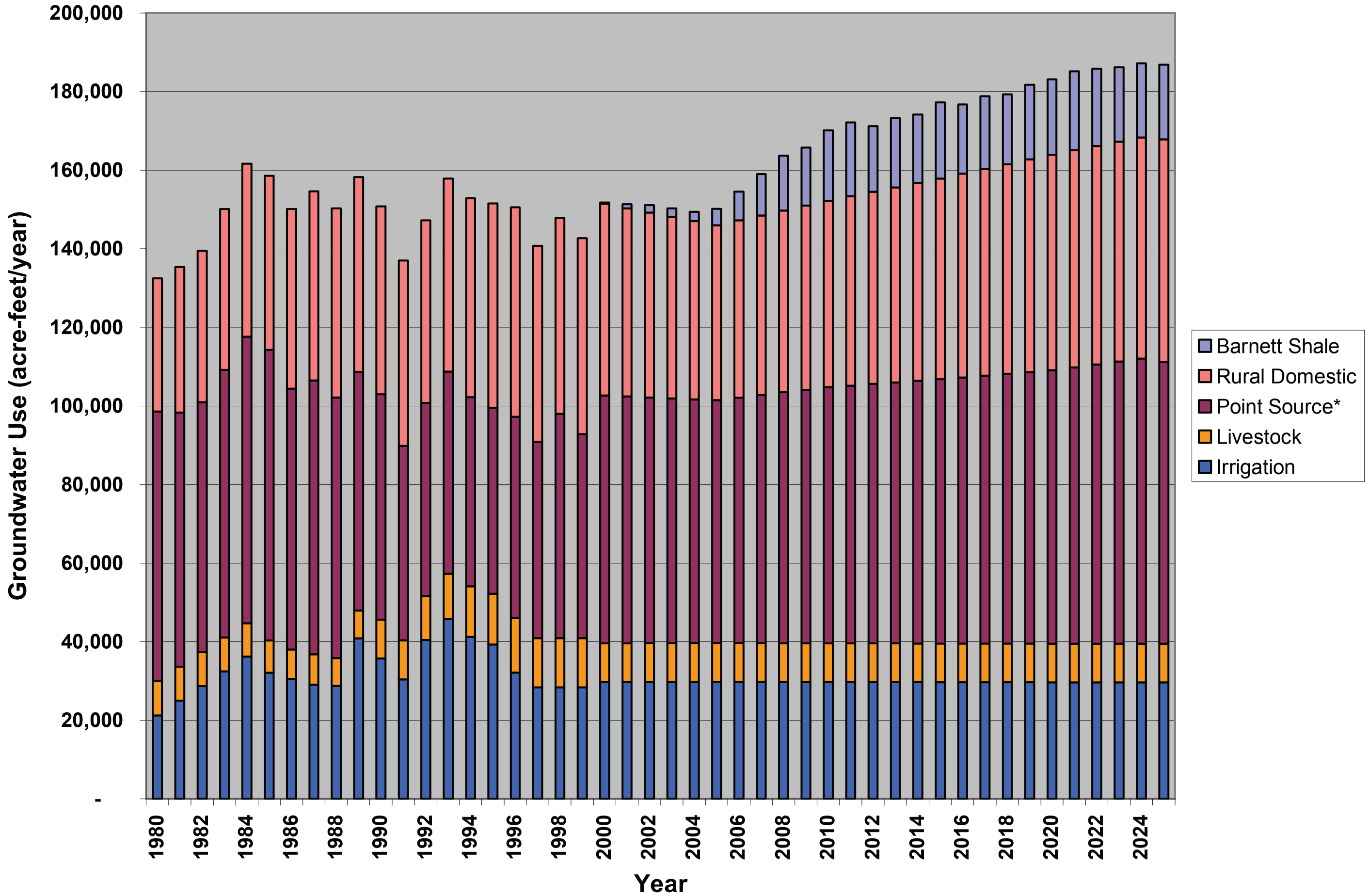
County	Year				
	2000-2005	2006-2010	2011-2015	2016-2020	2021-2025
Bosque	0 / 35 / 42 / 23 / 0	4 / 34 / 40 / 22 / 0	36 / 23 / 27 / 14 / 0	51 / 17 / 21 / 11 / 0	41 / 21 / 25 / 13 / 0
Comanche	0 / 0 / 2 / 3 / 94	0 / 0 / 2 / 3 / 94	1 / 0 / 1 / 3 / 94	3 / 0 / 1 / 3 / 91	2 / 0 / 1 / 3 / 93
Cooke	0 / 51 / 30 / 15 / 4	0 / 51 / 30 / 15 / 4	1 / 50 / 30 / 15 / 4	3 / 49 / 29 / 15 / 4	2 / 50 / 29 / 15 / 4
Coryell	0 / 7 / 60 / 34 / 0	0 / 7 / 60 / 33 / 0	4 / 7 / 57 / 32 / 0	38 / 4 / 37 / 21 / 0	60 / 3 / 24 / 13 / 0
Dallas	0 / 96 / 3 / 1 / 0	0 / 93 / 5 / 1 / 0	4 / 89 / 6 / 1 / 0	3 / 89 / 7 / 1 / 0	3 / 88 / 8 / 1 / 0
Denton	6 / 66 / 26 / 2 / 0	10 / 66 / 23 / 2 / 0	3 / 73 / 22 / 1 / 0	2 / 74 / 23 / 1 / 0	3 / 72 / 24 / 1 / 0
Ellis	0 / 45 / 53 / 2 / 0	0 / 45 / 53 / 2 / 0	2 / 44 / 53 / 2 / 0	1 / 44 / 53 / 2 / 0	1 / 44 / 53 / 2 / 0
Erath	0 / 18 / 12 / 23 / 47	3 / 14 / 12 / 23 / 47	19 / 11 / 11 / 20 / 40	11 / 13 / 12 / 22 / 43	12 / 13 / 12 / 21 / 42
Hamilton	0 / 15 / 25 / 19 / 40	3 / 14 / 24 / 19 / 40	29 / 11 / 17 / 14 / 29	66 / 5 / 8 / 7 / 14	52 / 7 / 11 / 10 / 21
Hill	0 / 16 / 78 / 5 / 0	8 / 15 / 72 / 5 / 0	40 / 10 / 47 / 3 / 0	27 / 12 / 57 / 4 / 0	29 / 12 / 55 / 4 / 0
Hood	0 / 37 / 40 / 4 / 18	11 / 33 / 35 / 3 / 17	18 / 30 / 32 / 3 / 16	8 / 36 / 35 / 3 / 18	11 / 36 / 33 / 3 / 17
Jack	0 / 0 / 100 / 0 / 0	6 / 0 / 94 / 0 / 0	27 / 0 / 73 / 0 / 0	14 / 0 / 86 / 0 / 0	17 / 0 / 83 / 0 / 0
Johnson	2 / 26 / 67 / 4 / 0	20 / 21 / 56 / 3 / 0	12 / 22 / 63 / 3 / 0	8 / 23 / 66 / 3 / 0	10 / 22 / 65 / 3 / 0
McLennan	0 / 68 / 31 / 1 / 0	0 / 68 / 31 / 1 / 0	1 / 67 / 31 / 1 / 0	6 / 64 / 29 / 1 / 0	5 / 65 / 30 / 1 / 0
Montague	1 / 0 / 81 / 5 / 14	1 / 0 / 81 / 5 / 14	7 / 0 / 76 / 4 / 13	34 / 0 / 54 / 3 / 9	35 / 0 / 53 / 3 / 9
Palo Pinto	0 / 0 / 100 / 0 / 0	0 / 0 / 100 / 0 / 0	1 / 0 / 99 / 0 / 0	4 / 0 / 96 / 0 / 0	2 / 0 / 98 / 0 / 0
Parker	1 / 21 / 74 / 2 / 1	26 / 16 / 56 / 2 / 1	21 / 16 / 61 / 2 / 1	10 / 16 / 72 / 2 / 1	13 / 15 / 70 / 1 / 1
Somervell	0 / 44 / 39 / 7 / 10	26 / 32 / 29 / 5 / 7	40 / 26 / 23 / 4 / 6	21 / 34 / 31 / 6 / 8	28 / 31 / 28 / 5 / 7
Tarrant	1 / 84 / 12 / 2 / 0	7 / 89 / 1 / 2 / 0	3 / 94 / 1 / 2 / 0	3 / 94 / 1 / 2 / 0	4 / 93 / 1 / 2 / 0
Wise	8 / 27 / 47 / 14 / 4	25 / 26 / 34 / 12 / 3	18 / 29 / 39 / 11 / 3	12 / 32 / 44 / 10 / 3	15 / 32 / 41 / 9 / 3

*Note: Values are percent of total groundwater use for Barnett Shale/Point Source/Rural Domestic /Livestock /Irrigation. Point source represents municipal, industrial, mining other than Barnett Shale, and power generation uses. Due to rounding, individual values may not always total 100%.



*Note: Includes total groundwater use for Bosque, Comanche, Cooke, Coryell, Dallas, Denton, Ellis, Erath, Hamilton, Hill, Hood, Jack, Johnson, McLennan, Montague, Palo Pinto, Parker, Somervell, Tarrant, and Wise Counties. Point source represents municipal, industrial, mining other than Barnett Shale, and power generation uses.

Figure 4. Total Groundwater Use by Category - Low Demand Estimate



*Note: Includes total groundwater use for Bosque, Comanche, Cooke, Coryell, Dallas, Denton, Ellis, Erath, Hamilton, Hill, Hood, Jack, Johnson, McLennan, Montague, Palo Pinto, Parker, Somervell, Tarrant, and Wise Counties. Point source represents municipal, industrial, mining other than Barnett Shale, and power generation uses.

Figure 5. Total Groundwater Use by Category - High Demand Estimate

Distribution of Pumpage

As described in previous sections, additional investigations into the likely future Trinity/Woodbine groundwater demands were conducted during this study, and were subsequently integrated into the model pumpage inputs. Specifically, the predictive pumpage datasets were modified in two ways:

- Model pumpage in Denton, Hood, Johnson, Parker, Tarrant, and Wise Counties was replaced with the "high" or "low" estimates generated during this study.
- Constant pumpage rates (appropriately distributed to model cells within county boundaries) were input for Bell, Bosque, Brown, Burnet, Collin, Cooke, Delta, Ellis, Falls, Fannin, Grayson, Hill, Hunt, Kaufman, Lamar, Lampasas, Limestone, McLennan, Milam, Montague, Navarro, Palo Pinto, Red River, Somervell, Travis, and Williamson Counties. The values were found by averaging the 1995 to 1999 historical pumpage values for each county, and were then applied throughout the 25-year predictive simulations.

For the remaining counties within the model (such as counties in Oklahoma), the future pumpage assigned to the original GAM datasets was used during this study.

Barnett Shale Production

Because the locations of future gas well sites and their accompanying Trinity/Woodbine groundwater supply wells is only generally known, a variety of methods and assumptions were employed when assigning potential pumpage associated with Barnett Shale development to aquifer layers. A description of the processes used to assign pumpage vertically within the model is included below, while a detailed discussion of the methods employed to determine the aerial distribution of Barnett-related Trinity/Woodbine groundwater use is included in Appendix 2.

To assign the Barnett Shale use into the GAM, it was first determined which area of the aquifer (and model layers) would support a minimum well capacity of 50 gpm. This is the assumed minimum well capacity suitable for a Barnett supply (Appendix 2, pg. 69). To determine this production minimum, maps of the estimated transmissivity, available artesian pressure, saturated thickness, specific yield, and storativity were prepared. Using this information, the Theis method of drawdown prediction (Theis, 1935) was used to find the maximum rate of withdrawal that could be sustained by a well within the area of the aquifer overlain by a model cell. These maximum values were then used during subsequent aerial and vertical pumpage distribution procedures to restrict the cells where Barnett Shale use was assigned.

Vertical Distribution of Pumpage

The amount of pumpage assigned to each aquifer layer (Layer 1 – Woodbine, Layer 3 – Paluxy, Layer 5 – Hensell, Layer 7 – Hosston) was determined by employing a variety of techniques that utilize the Theis method of drawdown calculation, and available well completion records within the model footprint.

Aquifer completion data associated with wells in the TWDB's water well information database and well completion records for rig supply wells from the TDLR database (Ridgeway, 2006) were tabulated. For larger capacity wells (municipal, irrigation, and industrial) listed in the TWDB database, the aquifer code assigned to each site was used to derive aerial distributions of aquifer completion. For wells with unknown completions, the casing/screen information (when available) listed in the database was compared to model layer structure to identify probable completion zones for each well. The reported aquifer completions of (generally) smaller capacity wells such as those used for domestic and livestock purposes were not included in the vertical distribution analysis.

The total depth data associated with each rig supply well was used in conjunction with model layer elevations to determine which aquifer represents the most likely production zone. These data were merged with the completion data compiled describing the TWDB registered wells.

Once the aerial distribution of wells and associated aquifers was found, the percentage of wells completed in specific aquifer zones within a ten mile radius of each model cell was calculated and used to assign the percentage of Barnett pumpage withdrawn from each model layer. Consider the hypothetical situation where 100 wells exist within a ten mile radius of a model cell centroid and, of these wells,

- 10 wells reportedly produce from the Woodbine,
- 15 wells reportedly produce from the Paluxy,
- 25 wells reportedly produce from the Hensell, and
- 50 wells reportedly produce from the Hosston.

Given this distribution, then 10, 15, 25, and 50 percent of the total Barnett pumpage applied to that cell is assigned to the Woodbine, Paluxy, Hensell, and Hosston, respectively. For cells where one or more aquifer layers are not present, the wells within the 10-mile radius that withdraw from the nonexistent layers are not included in the percentage calculation. In addition, model layers beneath the target model cell that are not capable of supporting at least 50 gallons per minute of pumpage were assigned a distribution percentage of zero.

Distribution of Other Use Categories

Model assignment for municipal, rural domestic, livestock, irrigation, and other use categories strictly followed the methodology utilized in the preparation of the original GAM. For a more detailed description of this methodology see the GAM report (Bené, etal, 2004, pg 4-115 through 4-118 of TWDB Groundwater Availability Model report).

RESULTS OF GAM SIMULATIONS

Future water level response in the outcrop, and artesian pressure declines/recovery in the downdip portions of the Trinity/Woodbine aquifers are evaluated using the two demand scenarios for the period 2000 through 2025. The simulations are conducted using average rainfall; the drought of record was not simulated for this work effort. Because the GAM is comprised of 1 mile square grid cells, the results of the simulations should be viewed from a regional perspective.

Regional Changes in Water Levels

Changes in Piezometric Head

The simulated change in piezometric head from 2000 to 2025 for the low groundwater use estimates are presented in Figures 6 through 9. Decline in head is water level drawdown, while a rise in head is recovery of water levels. The low demand estimate scenario results in some recovery of the piezometric head in the Hensell and Hosston in and near Tarrant and Dallas Counties, while other areas are projected to experience additional declines. The simulation results also suggest that additional declines will occur in the Paluxy over the next 20 years. The reason for the differences in the responses of these aquifer layers is the amount of groundwater use projected to occur in each aquifer zone on the low demand estimate. In the Hensell and Hosston layers of the Trinity, numerous groundwater users are projected to reduce their use, while it is predicted that withdrawals from the Paluxy will not decrease through time.

The simulation results for the high demand estimate are presented in Figures 10 through 13. This is for the period from 2000 to 2025. In the high use scenario, model results suggest that water level declines will take place throughout the study area in the Paluxy, Hensell, and Hosston zones. One exception occurs in eastern Tarrant County. In this area, the City of Hurst is projected to reduce their total demand from the Trinity (from 1999 use levels), and a resultant recovery of about 50 feet is projected in the Hosston.

Piezometric head drawdown is comprised of both artesian pressure change and changes in the level of the water table. Most of the projected change in Figures 6 through 13 represents variations in artesian pressure. Generally, changes in artesian pressure do not affect well yields to the same extent changes in water table levels can. Historically, the Trinity has experienced artesian pressure declines of up to 800 feet or more. To put the projected declines into some perspective, Figures 14 through 17 show the historical simulated drawdown in the Trinity and

Woodbine that occurred in the time period between 1880 (predevelopment) and 2000. Specific to the high demand scenario, the projected changes in artesian pressure in the deeper portions of the aquifers represent less than 10% to about 25% of the historically experienced change. At current aquifer water levels, reductions in artesian pressure can be linearly applied to reductions in future well rates. Accordingly, current peak well rates would decline proportionally to the percent decline the deeper sections of the aquifer. In order to maintain current rates of withdrawal, wells would need to run a little longer, or additional wells drilled to obtain the same peak capacity of current supply systems.

Effect of Drought

During a drought, there is increased pressure on water supplies to support increased irrigation and other demands. While conservation measures can eventually reduce overall consumption, increased groundwater use can initially occur during dry weather conditions. This increased demand will cause water levels in the Trinity and/or Woodbine to decline.

Within the outcrop areas of these aquifers, large amounts of water are stored. The Trinity/Woodbine underlies thousands of square miles in North-Central Texas. Assuming a 5-mile wide line that extends 200 miles across the outcrop extents, one foot of decline in the water table would provide 64,000 acre-feet of water (assuming a 0.1 specific yield). This simple calculation assumes no recharge and does not account for any interformational leakage. Compared to the hundreds of feet of artesian pressure change that have historically occurred, or the tens of feet that can happen during summer months in a drought, the lack of recharge for a relatively short period of time is not what causes water levels to decline in the Trinity. Changes in artesian pressure occur in direct response to pumping rates, and these pressure changes are essentially instantaneous when viewed over a multi-year, variable rainfall period. Therefore, unlike karst aquifers which can be very drought prone, it is more appropriate to classify the Trinity and other regional sand and sandstone-based aquifers as more drought proof rather than drought prone. Quick changes in water levels that occur during a particular summer of a drought period are mostly changes in artesian pressure, which are reflective of the level of use, not the rate of recharge.

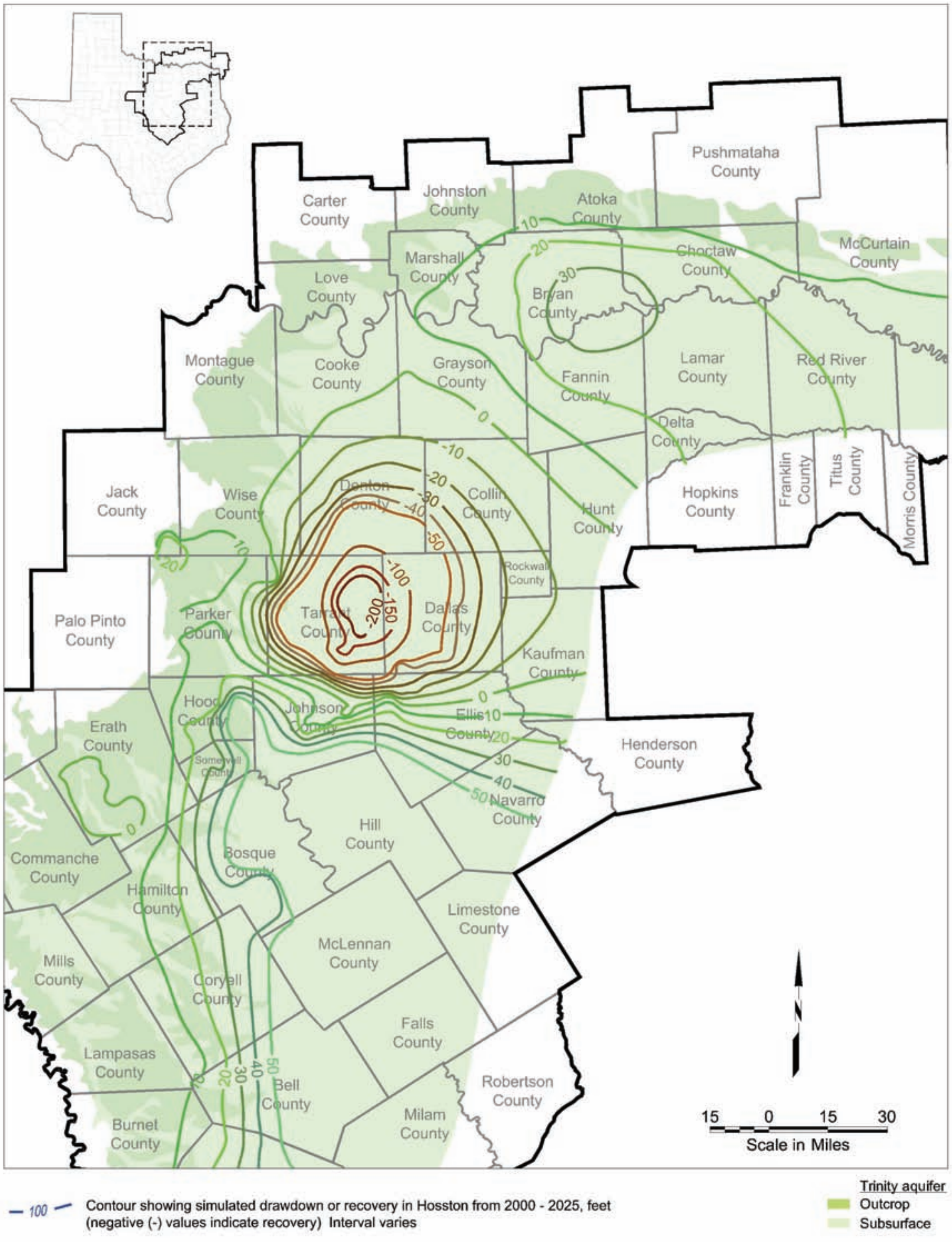


Figure 6. Projected Water Level Change in Hosston (2000 through 2025) – Low Demand Estimate

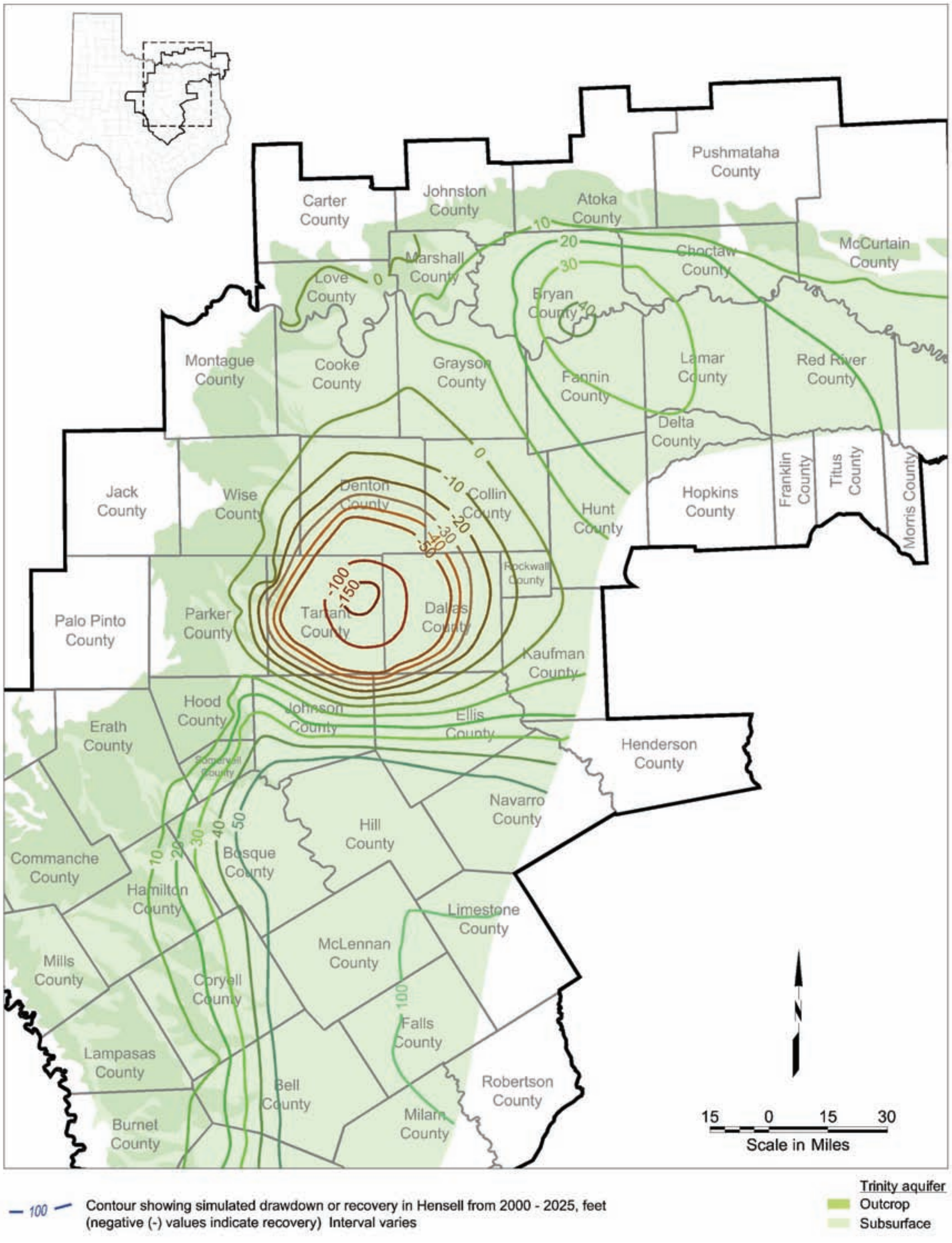


Figure 7. Projected Water Level Change in Hensell (2000 through 2025) – Low Demand Estimate

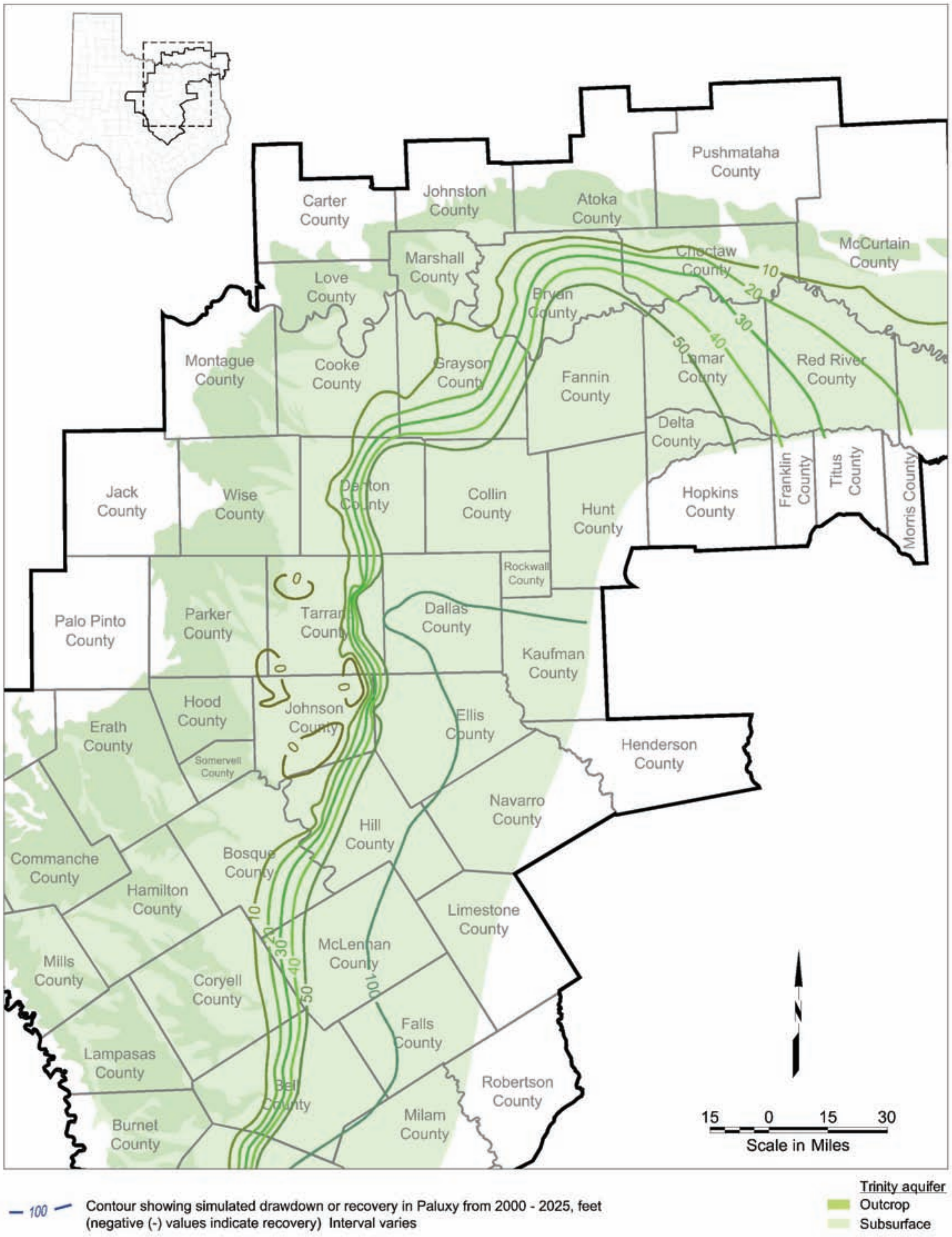


Figure 8. Projected Water Level Change in Paluxy (2000 through 2025) – Low Demand Estimate

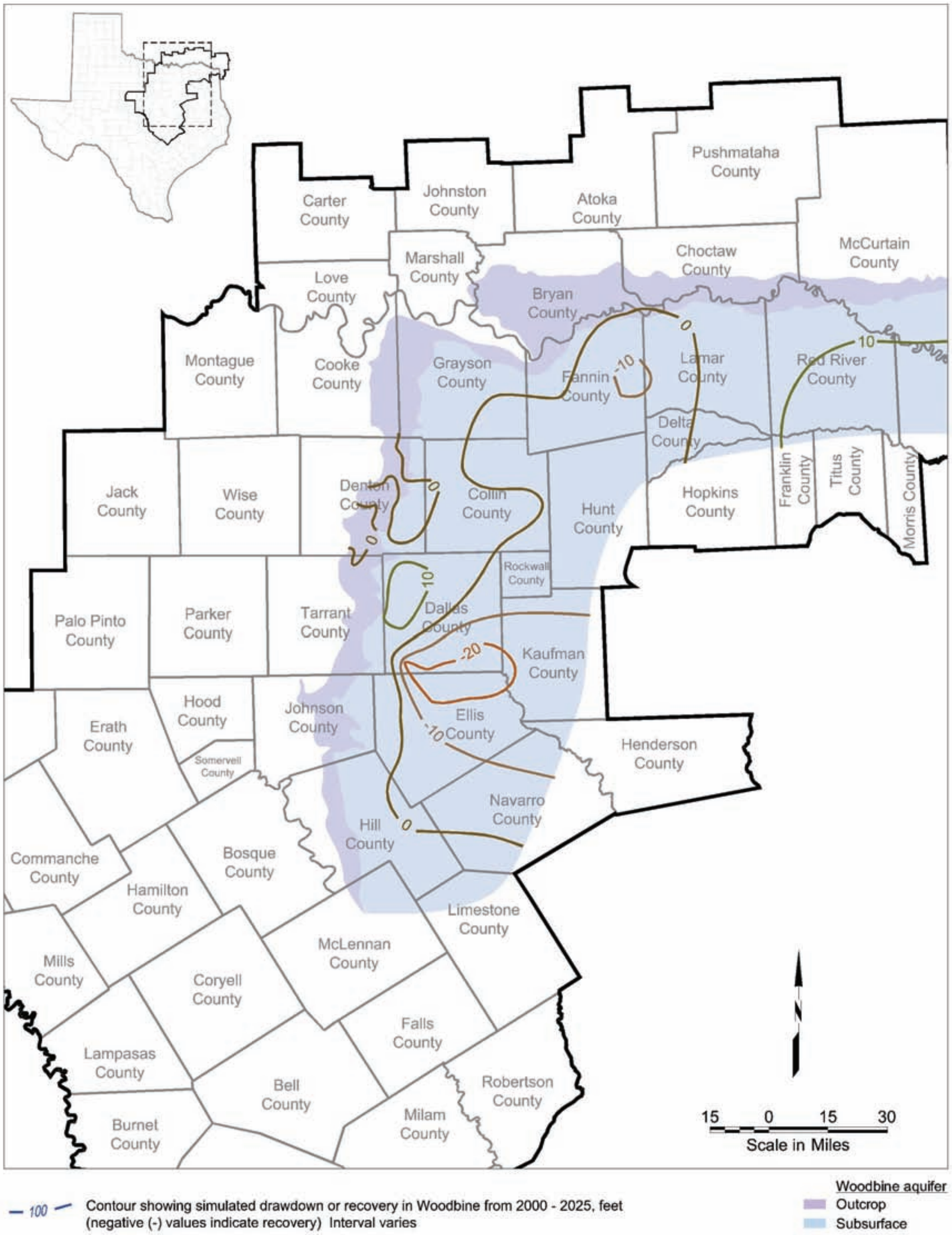


Figure 9. Projected Water Level Change in Woodbine (2000 through 2025) – Low Demand Estimate

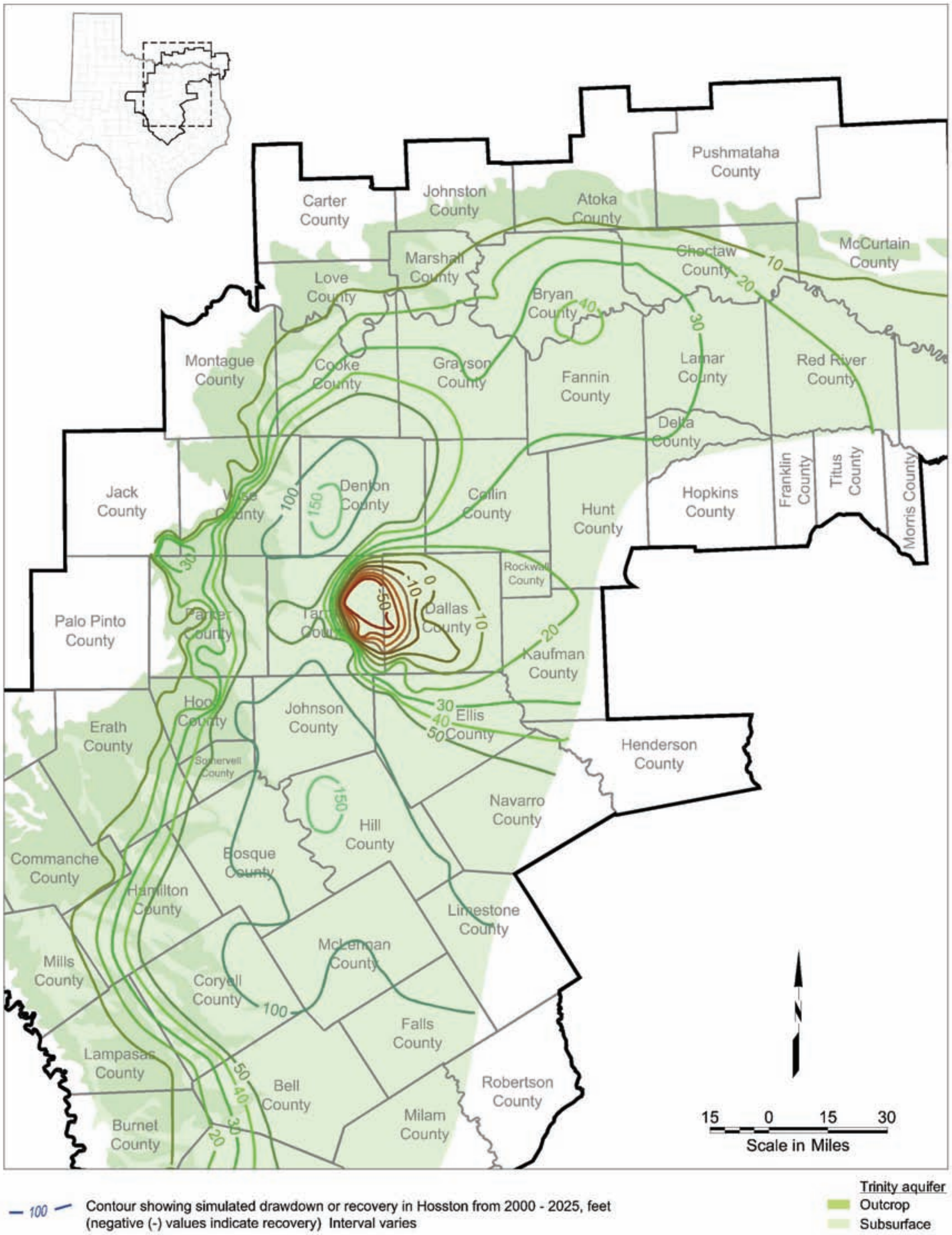


Figure 10. Projected Water Level Change in Hosston (2000 through 2025) – High Demand Estimate

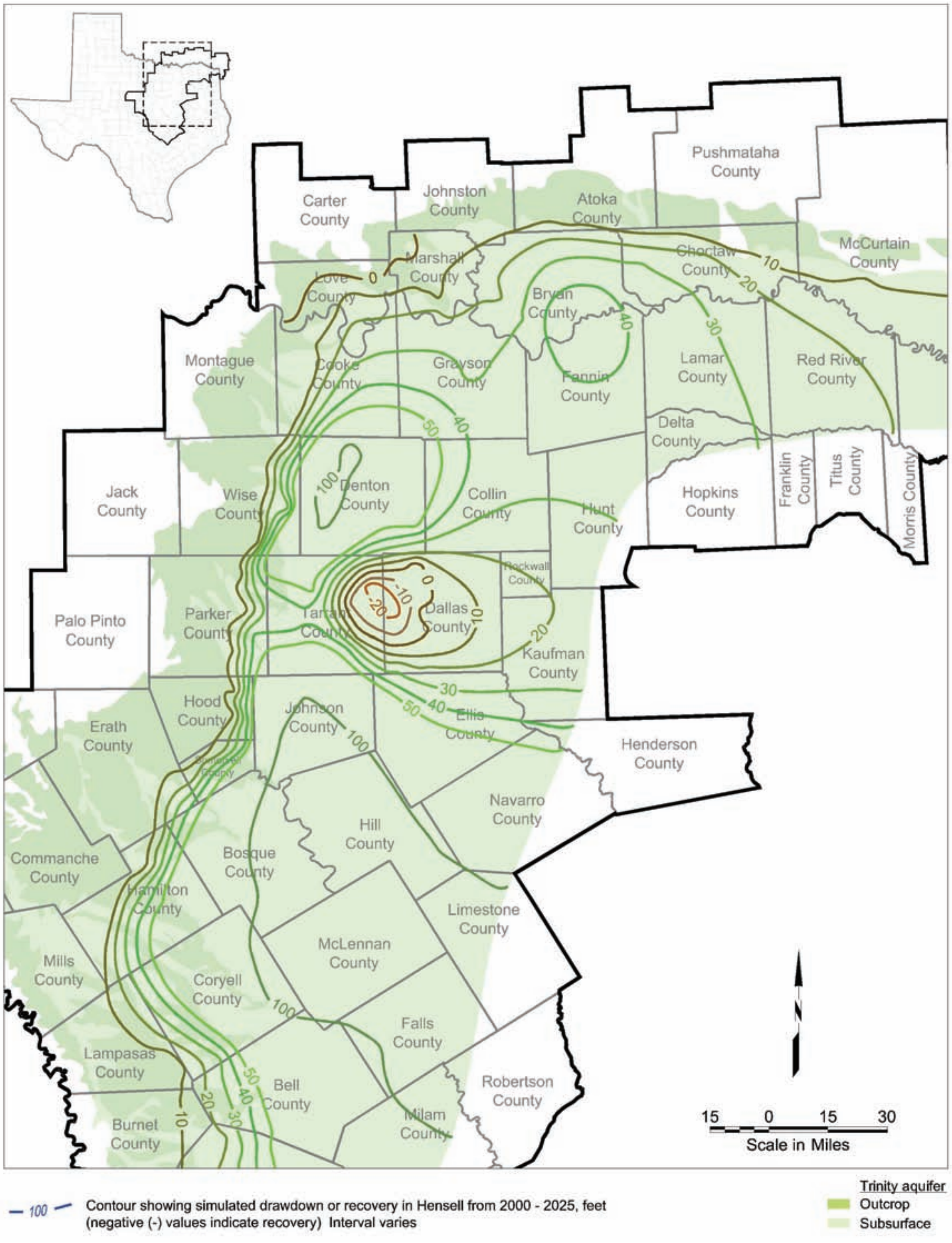


Figure 11. Projected Water Level Change in Hensell (2000 through 2025) – High Demand Estimate

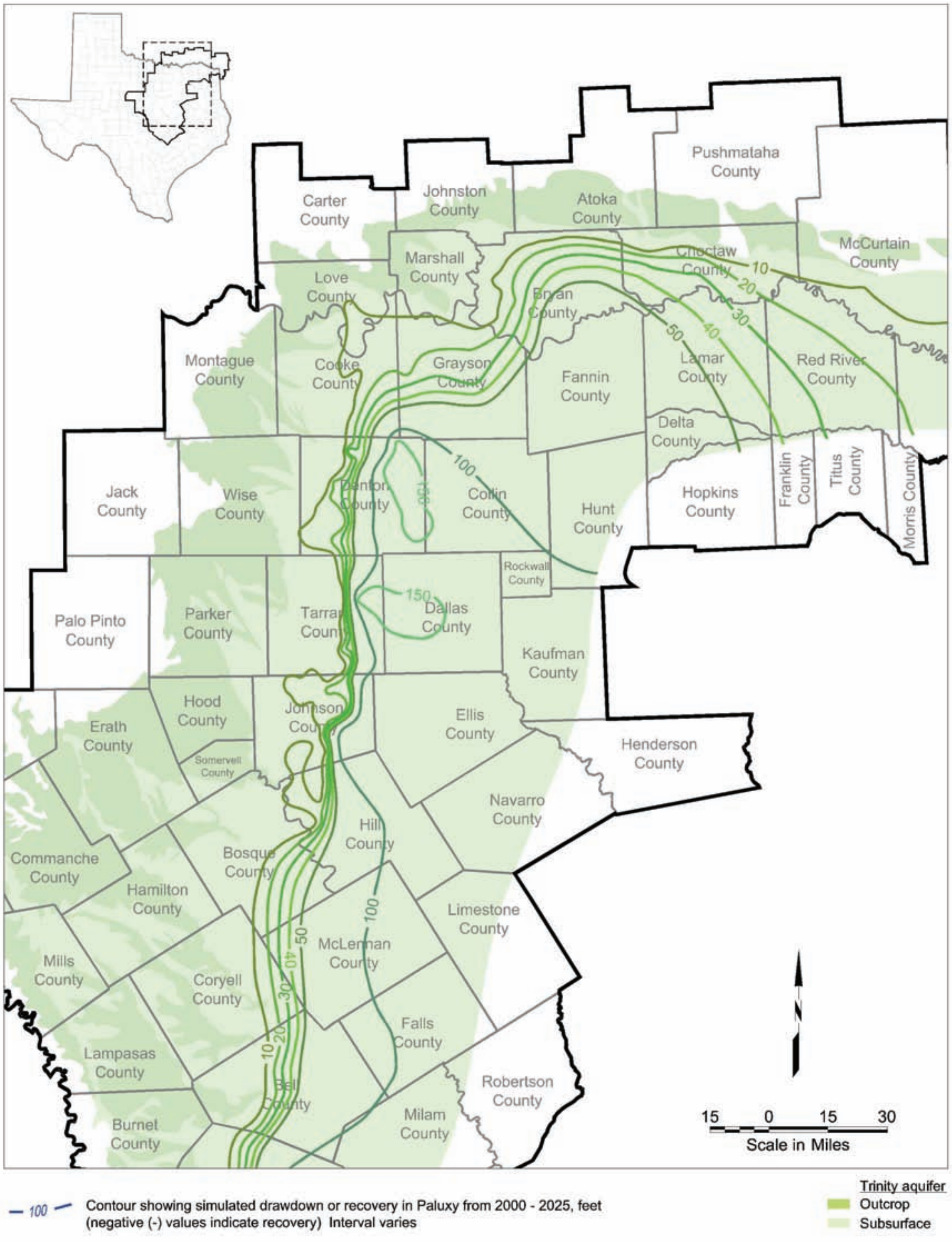


Figure 12. Projected Water Level Change in Paluxy (2000 through 2025) – High Demand Estimate

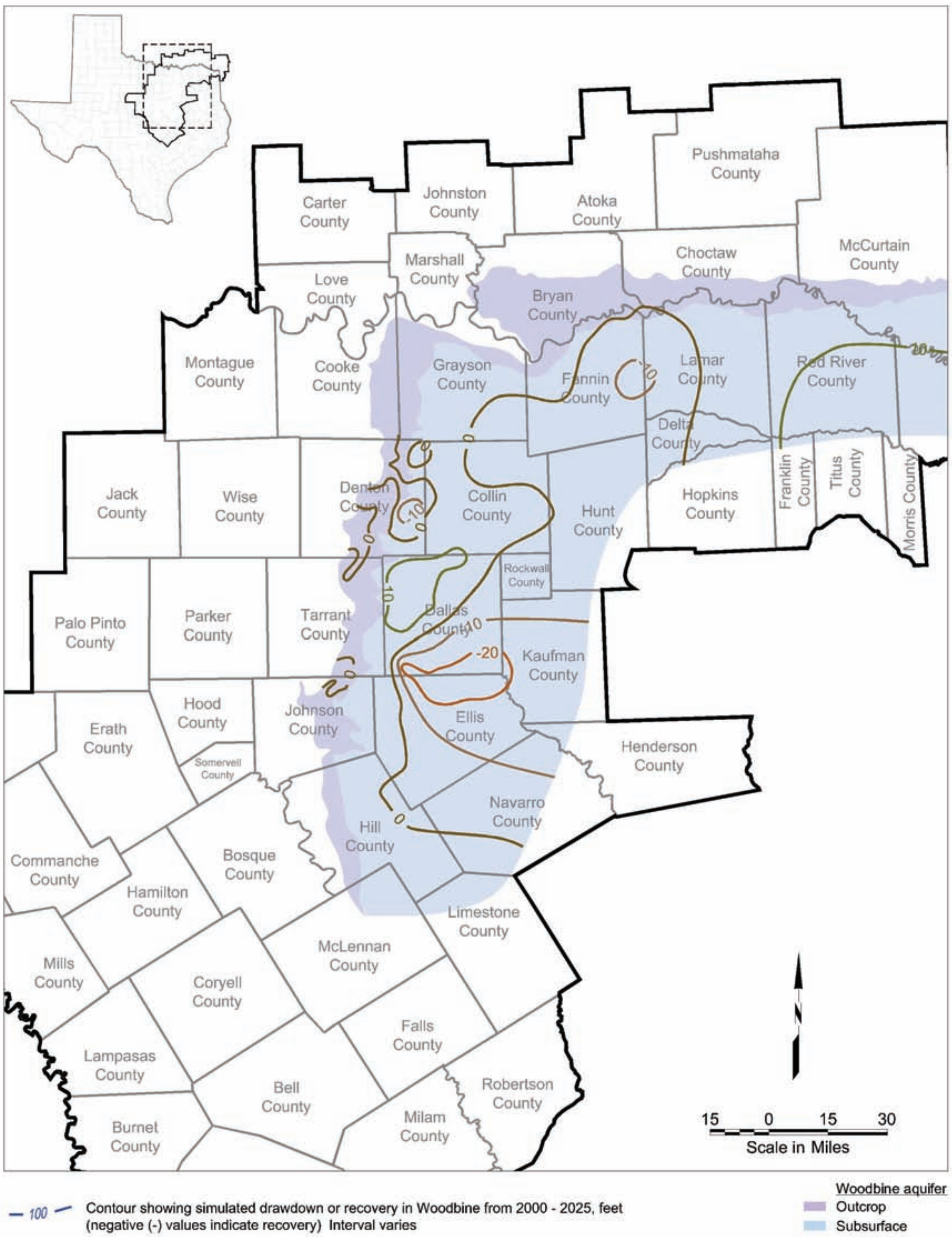


Figure 13. Projected Water Level Change in Woodbine (2000 through 2025) – High Demand Estimate

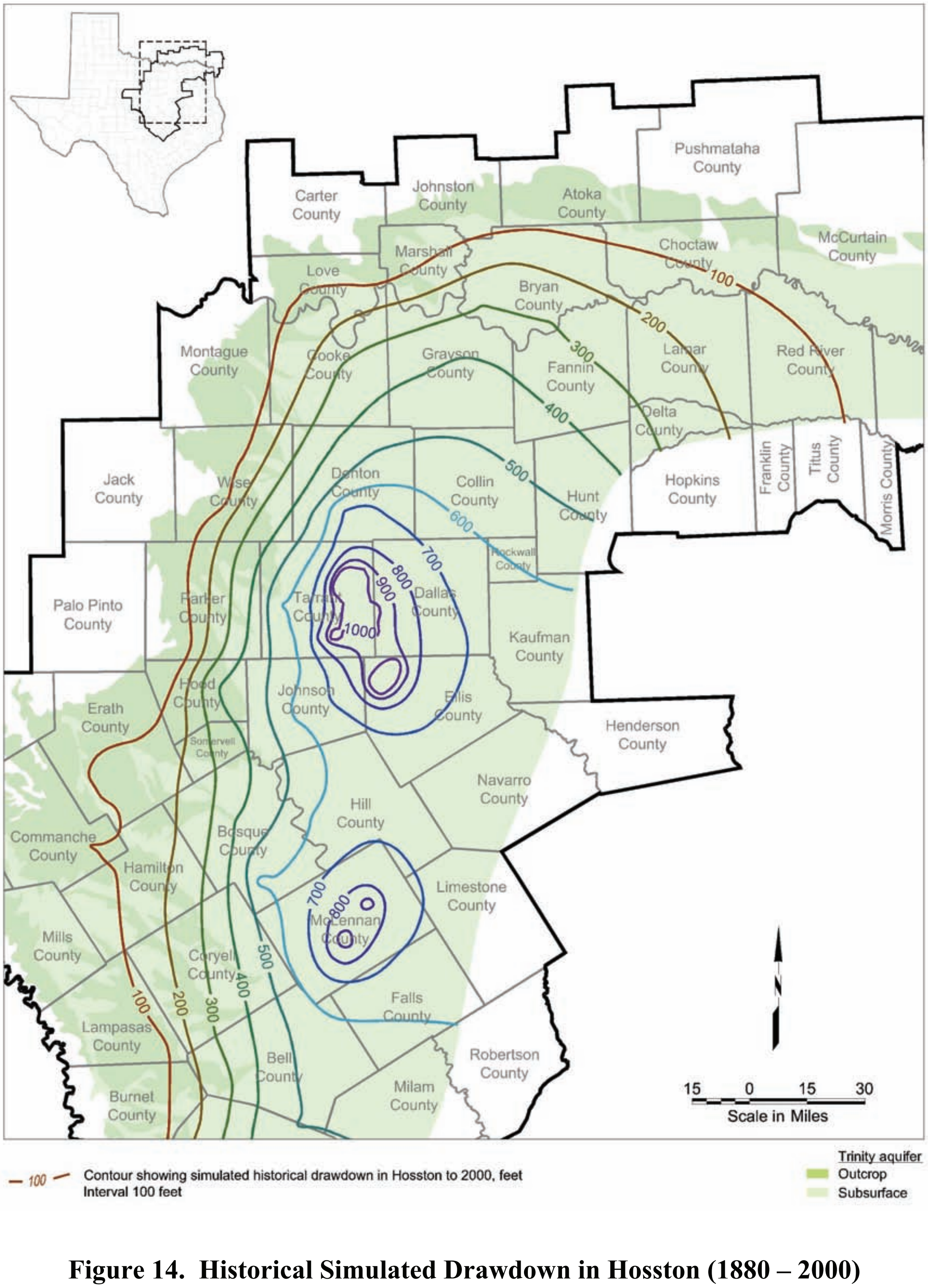


Figure 14. Historical Simulated Drawdown in Hosston (1880 – 2000)

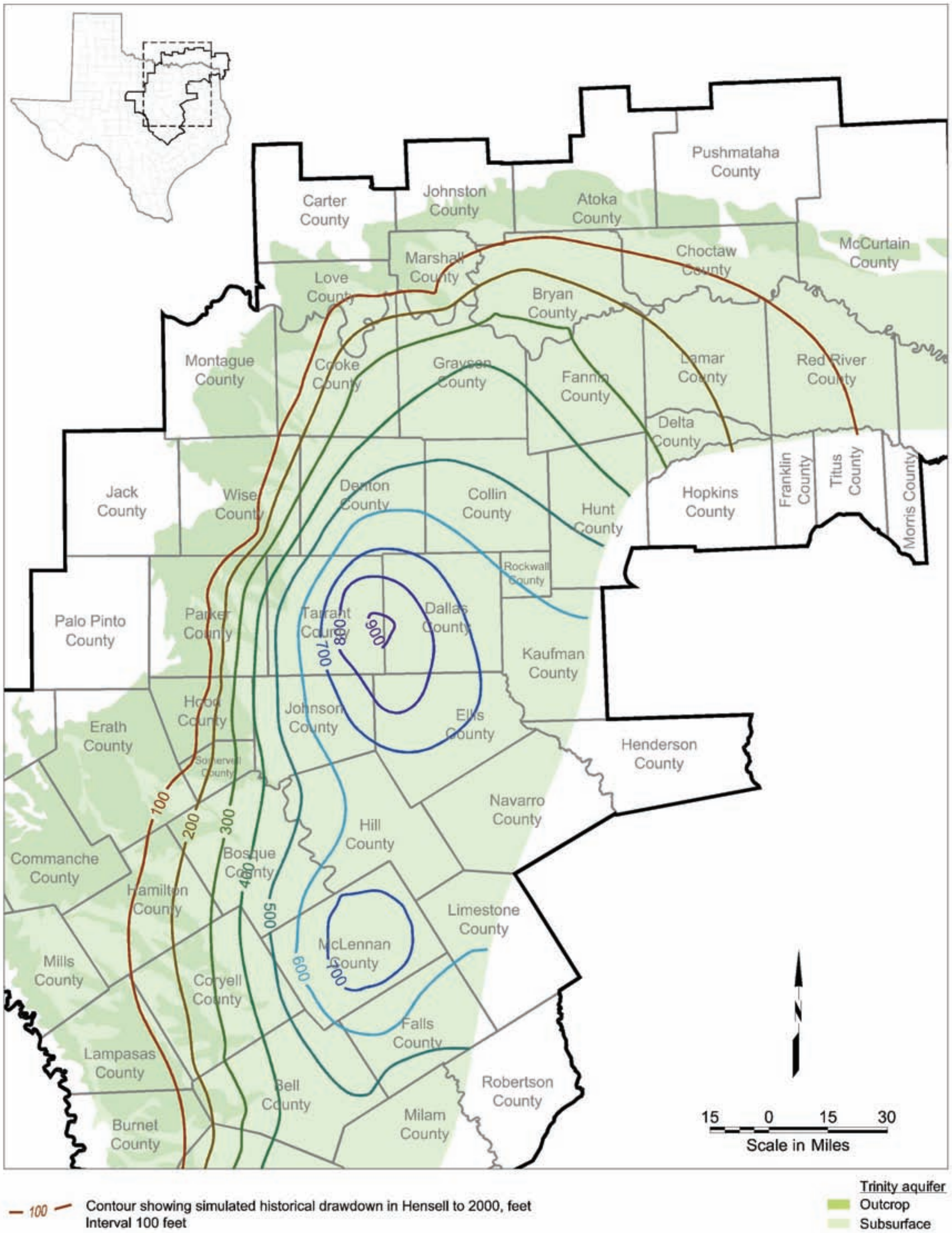


Figure 15. Historical Simulated Drawdown in Hensell (1880 – 2000)

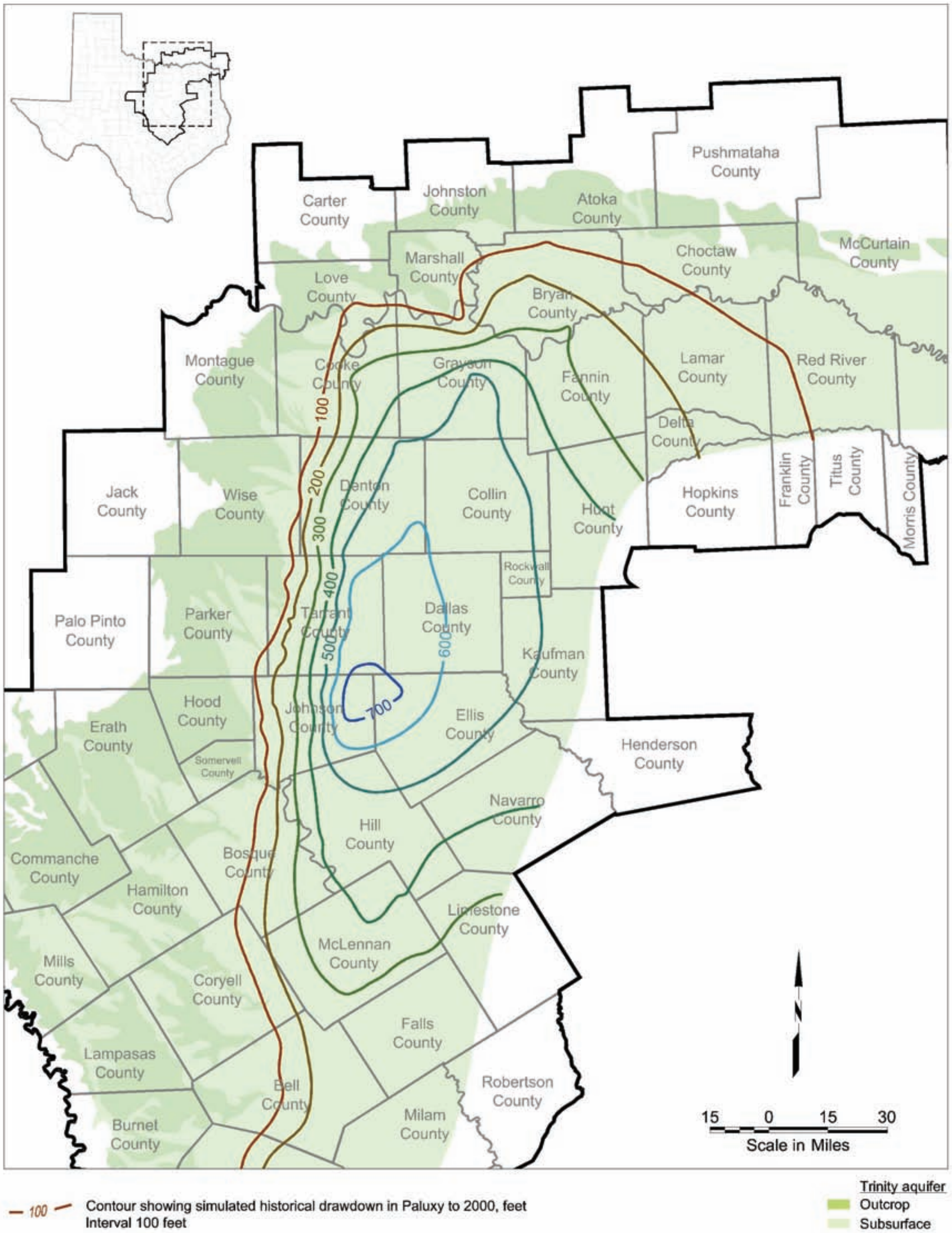


Figure 16. Historical Simulated Drawdown in Paluxy (1880 – 2000)

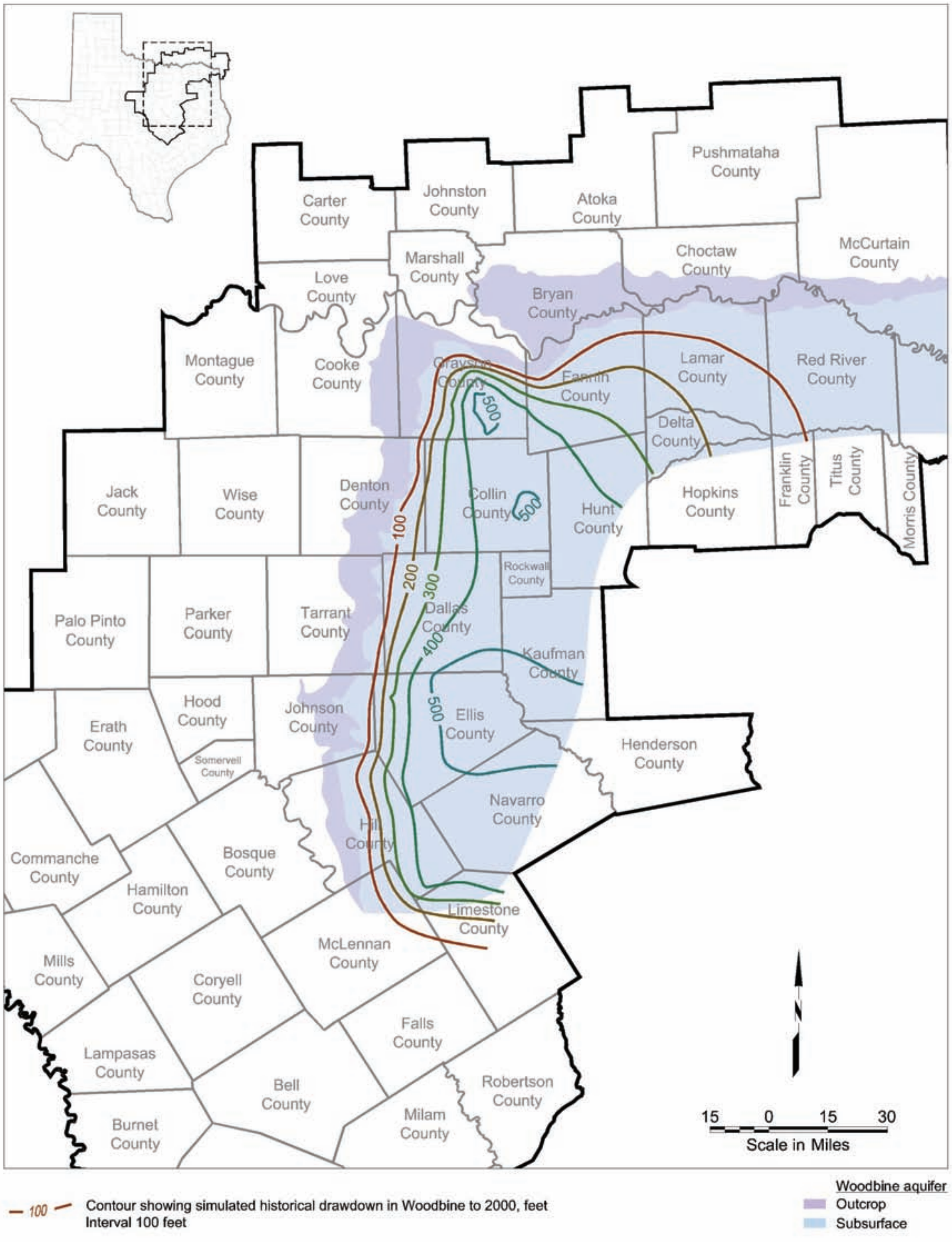


Figure 17. Historical Simulated Drawdown in Woodbine (1880 – 2000)

Water Table Depletion

Further analysis of the high demand scenario indicates the presence of some areas where the water level of the aquifer is lowered below the top of the producing formation during the 25-year simulation interval. Figure 18 shows general areas where the GAM projects that some transition from artesian to water table conditions will occur in the high demand scenario. These areas are primarily in Parker County and in areas directly to the north and south in Wise, Montague, Hood, Erath, and Johnson Counties. Within these areas and directly towards the west, small amounts of dewatering of the aquifer are projected to occur in the high demand scenario pumpage. This dewatering is a reduction in saturated thickness of the aquifer.

Maximum well yield generally declines as you move towards the west in the Trinity. Reductions in saturated thickness will typically cause the potential maximum pumping rate of a well to decline proportionally to the percent reduction in saturated thickness squared. Actual reductions in well pumping rates are dependent upon site-specific aquifer characteristics, well spacing, and the size of the well. A smaller well, such as a domestic well, may not decline in yield at all when saturated thickness is not the controlling factor in the yield of the well.

Reduction of water table levels can decrease natural discharge if seeps, springs, or evapotranspiration areas exist in the zones of water table decline. This is the natural response of all aquifers to pumpage by wells. In the areas identified on Figure 18 and directly westward into outcrop areas, known springflow is quite limited, with only small springs documented historically (Bené, et al., 2004, pg. 4-119, Figure 4.70, TWDB Northern Trinity GAM Report). Evapotranspiration discharge could also be reduced in these areas, but the amounts of reduction are difficult to estimate with the GAM due to the coarseness of the model. To the extent dewatering does occur, it provides a temporary source of supply. Also, if a decrease in natural discharge occurs, then this increases the amount of water that can be pumped by wells on a sustainable basis (Theis, 1940).

Regional Changes in Aquifer Water Budgets

For the four aquifer layers, Tables 4 through 7 show a comparison of the aquifer water budgets in 2000 and 2050 for the low and high demand scenarios. For both the low and high demand scenarios, the total estimated use by wells is less than the potential capturable recharge and induced leakage. From a regional perspective, this means that even the high estimated demand level could be sustained indefinitely, but locally this may not always be true. Small reductions in natural discharge are projected for both the low and high demand estimates. Total change in the stream package is less than 10% for both the low and high demand estimate. The greatest change is projected in the amount of modeled evapotranspiration. As used in the GAM, the evapotranspiration package accounts for natural discharge through evaporation, transpiration, and seeps and spring flow not specifically accounted for by the streams package.

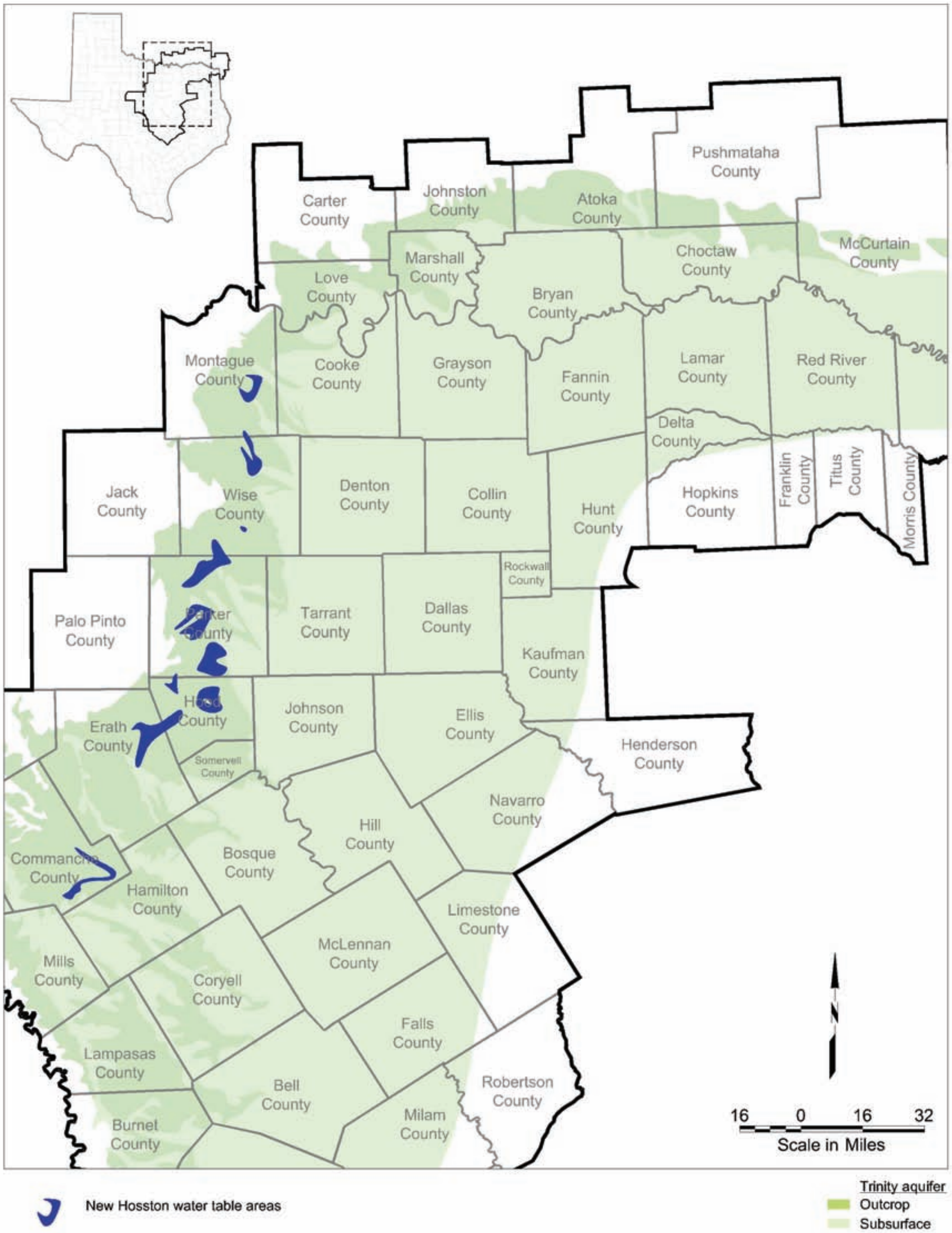


Figure 18. Location of New Water Table Depletion Areas in High Demand Estimate – Hosston (2000 – 2025)

Table 6. Model Water Budget – Year 2000*

Layer	Storage	Top	Bottom	Wells	Recharge	ET	Lakes	GHB	Streams
1 – (Woodbine)	42,414	0	408	-28,212	197,468	-201,933	148	782	-11,081
2	46,466	-408	-4,453	-7,562	424,839	-444,582	1,504	0	-15,804
3 – (Paluxy)	64,781	4,453	-10,505	-39,803	217,911	-230,634	38	-11	-6,253
4	33,904	10,505	-22,756	-6,647	116,405	-121,100	114	-330	-10,092
5 – (Hensell)	55,618	22,756	-43,794	-29,032	140,076	-141,970	2	0	-3,675
6	3,637	43,794	-47,342	-89	0	0	0	0	0
7 – (Hosston)	37,712	47,342	0	-84,033	171,329	-170,866	34	-291	-1,240
All	284,532	NA	NA	-195,378	1,268,028	-1,311,086	1,839	150	-48,145

Table 7. Model Water Budget – Year 2025 – Low Demand Scenario*

Layer	Storage	Top	Bottom	Wells	Recharge	ET	Lakes	GHB	Streams
1 – (Woodbine)	15,109	0	206	-25,529	197,468	-178,730	155	912	-9,601
2	8,843	-206	-4,967	-7,954	424,737	-406,725	1,507	0	-15,238
3 – (Paluxy)	27,011	4,967	-9,053	-37,097	218,013	-197,923	38	-10	-5,970
4	15,120	9,053	-21,136	-6,774	116,405	-103,922	115	-318	-8,542
5 – (Hensell)	37,863	21,136	-42,552	-28,271	140,076	-125,136	2	0	-3,138
6	2,874	42,552	-45,340	-86	0	0	0	0	0
7 – (Hosston)	19,879	45,340	0	-85,933	171,278	-149,317	34	-212	-1,083
All	126,698	NA	NA	-191,644	1,267,977	-1,161,753	1,851	372	-43,572

*Note: Values are in acre-feet per year. For the "Storage" field, positive values indicate water lost from storage. For all other fields positive numbers indicate water entering the aquifer system or layer while negative numbers indicate water leaving the aquifer system or layer. The "Top" and "Bottom" fields indicate interformational leakage into (+) or out of (-) the top and bottom of each layer, respectively. The "ET" field denotes water removed from the model due to near-surface processes (evaporation, transpiration, springs/seeps, and surface/groundwater interaction not specifically modeled in the GAM), while the "GHB" field indicates water entering or leaving the system through interaction with sediments overlying the Woodbine. N/A is not applicable.

Table 8. Model Water Budget – Year 2000*

Layer	Storage	Top	Bottom	Wells	Recharge	ET	Lakes	GHB	Streams
1 – (Woodbine)	42,414	0	408	-28,212	197,468	-201,933	148	782	-11,081
2	46,466	-408	-4,453	-7,562	424,839	-444,582	1,504	0	-15,804
3 – (Paluxy)	64,781	4,453	-10,505	-39,803	217,911	-230,634	38	-11	-6,253
4	33,904	10,505	-22,756	-6,647	116,405	-121,100	114	-330	-10,092
5 – (Hensell)	55,618	22,756	-43,794	-29,032	140,076	-141,970	2	0	-3,675
6	3,637	43,794	-47,342	-89	0	0	0	0	0
7 – (Hosston)	37,712	47,342	0	-84,033	171,329	-170,866	34	-291	-1,240
All	284,532	NA	NA	-195,378	1,268,028	-1,311,086	1,839	150	-48,145

Table 9. Model Water Budget – Year 2025 – High Demand Scenario*

Layer	Storage	Top	Bottom	Wells	Recharge	ET	Lakes	GHB	Streams
1 – (Woodbine)	13,923	0	-35	-23,318	197,468	-179,223	155	828	-9,808
2	8,786	35	-5,145	-7,954	424,737	-406,730	1,507	0	-15,239
3 – (Paluxy)	49,960	5,145	-10,338	-61,107	218,013	-195,797	38	-10	-5,929
4	17,303	10,338	-24,713	-6,869	116,405	-103,753	115	-318	-8,507
5 – (Hensell)	49,722	24,713	-49,800	-36,887	140,076	-124,771	2	0	-3,077
6	5,644	49,800	-55,358	-86	0	0	0	0	0
7 – (Hosston)	28,356	55,358	0	-106,095	171,278	-147,686	34	-212	-1,048
All	173,694	NA	NA	-242,317	1,267,977	-1,157,961	1,851	289	-43,608

*Note: Values are in acre-feet per year. For the "Storage" field, positive values indicate water lost from storage. For all other fields positive numbers indicate water entering the aquifer system or layer while negative numbers indicate water leaving the aquifer system or layer. The "Top" and "Bottom" fields indicate interformational leakage into (+) or out of (-) the top and bottom of each layer, respectively. The "ET" field denotes water removed from the model due to near-surface processes (evaporation, transpiration, springs/seeps, and surface/groundwater interaction not specifically modeled in the GAM), while the "GHB" field indicates water entering or leaving the system through interaction with sediments overlying the Woodbine. N/A is not applicable.

Site Specific Well Drawdown Issues

The model simulations conducted during this study suggest that the Trinity/Woodbine system will likely provide sufficient groundwater to meet both the low and high demand estimates over the next two decades. In addition, model water budget calculations indicate that total groundwater use is much less than the total available recharge and induced leakage. However, it cannot be directly concluded from these findings that the estimated groundwater demand estimates are "available".

While the GAM water budget predicts pumpage by wells is less than total aquifer recharge, capture of groundwater by wells is independent of recharge (Bredehoeft, etal. 1982). Spatial well patterns (location and production rates) affect the long-term ability to capture recharge and the sustainability of the supply. Limiting total production to below a recharge amount does not ensure sustainability, because well locations usually do not conform to the capturable recharge field. Within the Trinity, only slow changes in the effective capture rate will ever occur due to the relatively low transmissivity and large spatial extent of the aquifer. As such, the capability of the groundwater production locations to effectively capture recharge over the short time period of this study is insignificant.

More importantly, GAM models have inherent limitations for simulating production of groundwater by actual wells. Finite-difference groundwater flow models (which all GAM models are) simulate groundwater flow based on the interactions between discrete aquifer volumes, which are represented by individual model cells. In GAM models, a relatively coarse, one square mile grid cell is used because of the practical limitations of computer memory, software, realistic data availability, and other constraints. Therefore, production from a well(s) is simulated over the entire area and volume of the grid cell (one square mile), as opposed to a typical well diameter (4 to 16 inches). In addition, the well's total annual production is input as a continuous average rate in the model, not the instantaneous rate. Because of these two issues, GAM models do not accurately predict water levels within or near a producing well. Therefore, in thin saturated thickness aquifers, or aquifers with low inherent transmissivity like the Trinity, GAM models can successfully simulate production that cannot be practically produced by wells.

To provide a perspective of local drawdown around a producing well, analytical calculations were conducted assuming a typical well production rate and aquifer characteristics of the Trinity aquifer (2,000 gpd/ft transmissivity and 0.0001 storativity). Figure 19 shows the projected decline in artesian pressure around a well producing 100 gallons per minute, and after 10 days, 30 days, six months, and one year of continuous production. These drawdown cones assume a new well is drilled, or a well that has been turned off for a significant period is turned back on. The important point of this figure is that any neighboring wells within the cone of depression would experience these declines. If the pumping water level of a well has adequate available drawdown above the pump, then this well can withstand the onset of the induced drawdown. Alternatively, if the new pumping well causes a decline that results in an adjoining well's pumping level to drop below the pump setting, then the adjoining well will cease to produce water. This is commonly referred to as "drying" the well. In this situation, the current water level of the aquifer is below the depth of the pump. The remedies include setting the pump to a deeper depth, or, alternatively, reduce local and/or regional pumpage such that artesian pressures return to previous levels above the original pump setting. Figure 19 shows an example of this local drawdown situation.

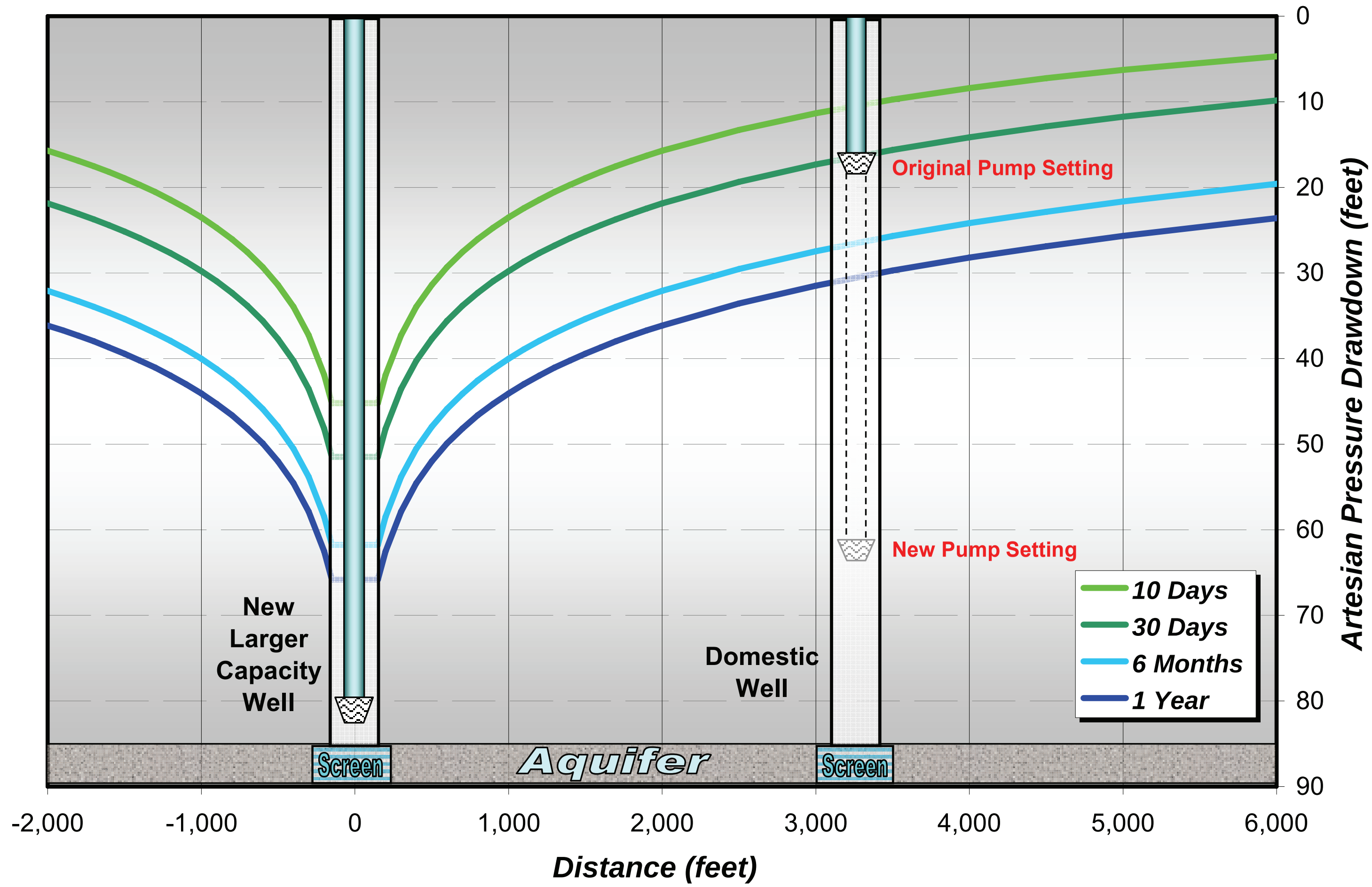


Figure 19. Well Drawdown Diagram

LIMITATIONS OF MODEL RESULTS

The GAM is effective tool for simulating the groundwater use described in this report and evaluating the regional response of the Trinity/Woodbine aquifers. The relatively coarse cell size (one square mile) necessitates the averaging of spatial data and requires the introduction of many assumptions when constructing parameter datasets. This includes spatial averaging of ground levels, aquifer hydraulic properties, evapotranspiration, pumpage from individual wells, and other hydrogeologic controls. The stress periods in the Northern Trinity GAM are one year in length. In many cases, the spatial averaging of these model inputs coupled with the temporally "averaged" model results severely limits the use of the GAM to ascertain site-specific or detailed impacts of pumpage on individual well fields or changes in natural discharge in local areas. For instance, it is quite possible to conclude groundwater is available in an area based on GAM results, yet site specific investigations conclude otherwise because the number of wells required to obtain a supply becomes impractical. This does not mean GAM models do not provide meaningful results, it illustrates that more specific study is generally required to determine the local availability of groundwater.

CONCLUSIONS

The GAM successfully simulates both the low and high demand scenarios generated during this study. For the low demand scenario, a recovery of artesian pressure of up to 100 to 200 feet is simulated in the Hensell and Hosston, while declines of up to 50 feet or more are projected along, and east of, the IH-35 corridor. The high demand scenario projections indicate an average pressure decline ranging from less than 10 feet in the westernmost areas, to up to 150 feet in all Trinity aquifer zones. Within the Woodbine aquifer, up to 20 feet of decline is projected along the IH-35 corridor for both the high and low demand estimates. The majority of the simulated reduction in aquifer water levels can be attributed to increased municipal and rural domestic use and to increased mining use for Barnett Shale frac operations. The contributing proportion of decline caused by each demand category is proportional to the individual use compared to the total use (see Figure 4 and Figure 5, and Appendix 3), as well as the assumptions of spatial and vertical placement of the demands.

Historically, the Trinity and Woodbine aquifers have supported widespread groundwater production for over a century. As use has increased, aquifer water levels declined in direct response to the pumpage. Historical reductions in artesian pressure of up to 800 feet or more have been experienced in the Dallas-Ft. Worth Metroplex area and near Waco. However, GAM water budget calculations suggest that, regionally, the historical and present use levels can be sustained. Similarly, both the low and high demand estimates compiled during this study are supported by the regional aquifer water budget.

Locally, greater uncertainty exists as to whether all supplies can be practically obtained. This is likely a case-by-case situation, which depends upon site-specific aquifer conditions, alternative source availability, and cost. If lower aquifer water levels are acceptable, then increased use of the Trinity or Woodbine is possible in many areas of the aquifer. Increases in use in any areas of the aquifer will cause a lowering of water levels, while decreased use will cause water levels to rise. If increased use occurs, some areas will require a greater number of smaller capacity wells to obtain the supplies. In some cases, and especially in the high demand scenario, the number of wells required to obtain a supply may be impractical. If this is the case, then realized demands on the aquifer will not be as high as projected. If increased use occurs in an area, some wells (especially older domestic wells) will undoubtedly need to have their pumps lowered, or be drilled to deeper depths to accommodate reduced aquifer water levels. The most significant effects are projected to occur in central Parker County and in regions to the north and south (in the high demand estimate). Additional site specific studies for this area are recommended to gain a better understanding of the potential groundwater availability in this and the immediately surrounding areas. History and experience have shown that, as population increases, the Trinity/Woodbine aquifers will not provide a sole-source supply for all users. Similarly, if population increases in areas now solely served by Trinity/Woodbine supplies, then development of supplemental water supply sources and regional distribution systems will likely become a necessity.

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Appendix 1
Updated Rural Domestic and Municipal Supplies for Denton, Hood, Johnson, Parker, Tarrant and Wise Counties

Prepared for:

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Table of Contents

List of Tables

List of Figures

Freese and Nichols

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Introduction

The original groundwater availability model (GAM) developed for the northern Trinity Aquifer was calibrated to water levels from 1980 to 1999 based on groundwater pumping estimates for the same period. The projected demands included in the original GAM decreased significantly in the years 2000 through 2050. The GAM is being updated with more recent demands in the Trinity aquifer in Denton, Hood, Johnson, Parker, Tarrant, and Wise Counties (study area).

Freese and Nichols, Inc. (FNI) analyzed municipal, manufacturing, irrigation, and livestock demands on the Trinity aquifer in the study area. The water use associated with oil and gas exploration is being developed by the Bureau of Economic Geology as a separate task.

Survey

Freese and Nichols, Inc. mailed surveys to 123 entities in the study area. The survey inquired about water use since 2000, particularly focusing on water use in the Trinity aquifer. Forty-seven percent of the recipients participated in the survey. A follow-up phone call was made to each entity whose survey had not been received by FNI.

In some cases, the entities did not use any groundwater. Others used a combination of surface water and groundwater. The information provided by these entities helped establish the historical water use in the Trinity aquifer. Questions were also asked regarding the location, depth, and capacity of each well.

Future water plans were also requested. Some entities have made agreements to purchase surface water and plan to decrease their dependence on the Trinity aquifer. Others plan to continue using the Trinity aquifer as their sole water supply. All of the information provided was considered when developing the projected demands that are recommended to be used in this study.

Population

Available historical and projected population data was collected for each entity. FNI gathered historical population data from the Texas State Data Center, the U.S. Census, and the North Central Texas Council of Governments.

The projected population estimates developed by the North Central Texas Council of Governments and those approved by the Texas Water Development Board for regional water planning were collected.

The population data was used to review growth in the cities. The population projections used in the regional water planning effort appear to be reasonable considering the more recent population information in all but one county. The population in Parker County area is growing faster than what was projected in the regional water plans. This information was considered when establishing the recommended demands in this analysis.

Demands

The historical and projected demands were reviewed. The historical water use data that cities provide to the Texas Water Development Board were used in this study. The water use records extend through 2003.

The demand projections for each city and county group that were developed in the regional water planning process for the TWDB were collected in this study. FNI reviewed the demand projections for municipal water user groups, as well as manufacturing, livestock, and irrigation collective county group users.

Recent water usage data provided by cities indicated the demand placed on each source of water supply. This information was used to establish the likely demands that might be placed on the Trinity aquifer in the future. If cities provided information regarding their future water supply plans, FNI took that into account in establishing the current and projected demands on the Trinity aquifer. If a city provided water use in the Trinity aquifer for the year 2005, the city's water usage information was recommended as the demand for that year.

In the event that an entity did not provide any additional water use data, the demand data included in the regional water plans was used as the basis for making decisions regarding demands on the Trinity aquifer.

Drill Logs for Wells

The Texas Department of Licensing and Regulation (TDLR) collects the well completion reports and driller's logs provided by groundwater drillers. Both paper records and a new online registration system exist. From this information well records were tabulated. Table 1 shows the number of wells drilled by county and purpose from January 2003 through August 2006.

Most of the wells logged in this TDLR database are for domestic and irrigation purposes. "Rig Supply" is the category that accounts for wells drilled for oil and gas exploration/production. Wells drilled for rig supply began increasing in most of the study area in 2005. These records do not indicate the number of new wells that have been drilled as compared to the number of existing wells that were redrilled to deeper levels in the aquifer. These logs do indicate an increased interest and likely an increased use of the Trinity aquifer in the study area.

Recommended Demands by Entity

A range of demands that is likely to be placed on the Trinity aquifer is recommended for each entity listed in the tables below. The range is low to high. The values are shown in acre-feet per year in five year increments beginning in 2005 and ending in 2025. The recommended demands are primarily based on one of the following rationale:

- Demands in the regional water plans
- Data provided by the entity
- Maintaining the current percentage of demand met by the Trinity aquifer into the future
- Historical water use

The lowest demands from these resources were used as the low estimate. The highest demands presented by these resources resulted in the high estimate. Typically, historical lows were used as the low estimates and one of the other three rationale were used as the high estimates. Data provided by cities were given special consideration.

FNI took steps to avoid double counting the county-other and manufacturing demands. The demands for county rural domestic are based on the TWDB county-other category less the entities called out in the GAM that are currently included in the TWDB county-other category. Several municipal users are recommended to be added as individual water users in the GAM. In a few cases, the manufacturing demands listed individually in the GAM were equal to the TWDB demand projections. In these cases, the county manufacturing number was set to zero while the individual manufacturer was assigned a water demand.

Tables 2 through 7 show the recommended demands for the water user groups in each county in the study area. Each table shows the current and projected demands in the particular county.

In Denton County, four entities are recommended to be listed individually in the GAM: City of Denton, City of Hackberry, City of Lincoln Park, and City of Ponder.

Acton MUD and Oak Trail Shores should be included as individual entries in the GAM in Hood County. The City of Burleson should be added as an individual entity in Johnson County. Parker County does not need any additional entities to be listed individually.

The City of Haslet and the City of Blue Mound should be added as individual entities in the GAM in Tarrant County. The Cities of New Fairview and Newark should be added as an individual demand in the GAM in Wise County. Table 8 summarizes the low and high recommended demands in the Trinity aquifer by county.

Figures 1 through 6 show the recommended demands for each county in the study area.

Several entities in the GAM rely on the Woodbine aquifer. This study focused on the impacts of current water use on the Trinity aquifer. For completeness, the Woodbine aquifer demands should be updated as shown in Table 9. The entities with an asterisk following the name should be included in the GAM as individual line entries.

Conclusion

The municipal, manufacturing, irrigation, and livestock demands in the six county study area presented in this memo report, represent FNI's recommended demands for the specified water users in the update to the Northern Trinity-Woodbine GAM. The low and high ranges included represent a realistic range for demands for the study area through the year 2025.

Table 1 Groundwater Wells Recorded and Submitted by Well Drillers to the TDLR

County	Purpose	2003	2004	2005	2006*
Denton	Domestic	90	107	50	17
Denton	Industrial	3	2	5	0
Denton	Irrigation	55	31	32	23
Denton	Geothermal	1	5	7	1
Denton	Public	4	5	1	0
Denton	Rig Supply	11	1	5	12
Denton	Stock	0	0	2	8
Denton Total		**164**	**151**	**102**	**61**
Hood	Domestic	73	98	90	40
Hood	Industrial	0	1	0	0
Hood	Irrigation	0	6	0	1
Hood	Geothermal	0	1	0	0
Hood	Public	4	3	1	2
Hood	Rig Supply	0	2	10	18
Hood	Stock	0	0	0	1
Hood Total		**77**	**111**	**101**	**62**
Johnson	Domestic	58	60	62	33
Johnson	Industrial	0	4	10	2
Johnson	Irrigation	12	9	7	5
Johnson	Geothermal	0	0	0	1
Johnson	Public	2	3	2	0
Johnson	Rig Supply	0	1	34	64
Johnson	Stock	3	1	2	0
Johnson Total		**75**	**78**	**117**	**105**
Parker	Domestic	399	458	417	286
Parker	Industrial	3	9	3	3
Parker	Irrigation	13	15	3	11
Parker	Geothermal	0	0	0	0
Parker	Public	4	3	6	2
Parker	Rig Supply	0	8	15	25
Parker	Stock	0	1	16	8
Parker Total		**419**	**494**	**460**	**335**
Tarrant	Domestic	281	268	213	135
Tarrant	Industrial	6	2	1	2
Tarrant	Irrigation	89	80	49	62
Tarrant	Geothermal	3	5	8	5
Tarrant	Public	3	2	4	0
Tarrant	Rig Supply	2	0	10	25
Tarrant	Stock	2	2	1	2
Tarrant Total		**386**	**359**	**286**	**231**
Wise	Domestic	214	143	151	76
Wise	Industrial	3	1	0	0
Wise	Irrigation	11	8	4	11
Wise	Geothermal	1	1	1	0
Wise	Public	3	1	1	0
Wise	Rig Supply	3	4	3	7
Wise	Stock	1	0	2	10
Wise Total		**236**	**158**	**162**	**104**
Study Area Total		**1357**	**1351**	**1228**	**898**

*Note: The data for year 2006 are for a partial year. They include January through August.

Table 2 Recommended Denton County Demands on the Trinity Aquifer

Entity	Low Demand (Acre-Feet per Year)					High Demand (Acre-Feet per Year)				
	2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
Argyle WSC	660	360	360	340	320	660	760	760	760	760
Bartonville WSC	600	600	600	600	600	600	600	600	750	850
Bolo Point WSC	10	10	10	10	10	10	10	10	10	10
City of Aubrey	240	180	170	170	160	240	460	660	860	1,110
City of Corinth	10	10	10	10	10	20	20	20	20	20
City of Denton	380	0	0	0	0	380	400	300	300	200
City of Hackberry	70	70	70	70	70	110	140	180	210	240
City of Highland Village	800	1,270	1,260	1,240	1,150	800	1,270	1,290	1,300	1,330
City of Justin	320	320	300	270	240	410	500	680	860	1,120
City of Krum	300	300	300	300	300	370	470	570	660	730
City of Lincoln Park	50	50	50	50	50	90	110	140	170	190
City of Little Elm	0	0	0	0	0	0	0	0	0	0
City of Pilot Point	790	790	690	590	530	870	1,210	1,440	1,670	1,780
City of Ponder	200	200	200	200	180	400	620	1,170	1,710	2,570
City of Roanoke	60	60	60	60	60	200	200	200	200	200
City of Sanger	490	490	450	410	370	1,350	2,210	2,490	2,770	3,020
City of The Colony	930	930	930	930	930	930	1,300	1,470	1,650	1,730
Harbor Grove Water System	30	30	30	30	30	30	30	30	30	30
Hebron WSC	0	0	0	0	0	0	0	0	0	0
Inca Metal Products Corp.	10	10	10	10	10	10	20	20	20	20
Kruger Water Works	0	0	0	0	0	0	0	0	0	0
Lake Cities MUA	0	0	0	0	0	0	0	0	0	0
Northlake Highlands W.S. # 2	10	10	10	10	10	10	10	10	10	10
Red Rock Water Co.	10	10	10	10	10	20	20	20	20	20
Texas Industries, Inc.	40	40	40	40	40	40	50	50	60	60
Trophy Club MUD #1	550	550	550	550	550	550	590	630	660	690
Twin Cove WSC	0	0	0	0	0	0	0	0	0	0
Denton Co. Rural Domestic	3,550	3,370	3,550	3,720	4,040	3,680	3,500	4,050	4,610	5,810
Denton Co. Irrigation	0	0	0	0	0	0	0	0	0	0
Denton Co. Livestock	210	210	210	210	210	250	250	250	250	250
Denton County Total	10,320	9,870	9,870	9,830	9,880	12,030	14,750	17,040	19,560	22,750

Table 3 Recommended Hood County Demands on the Trinity Aquifer

Entity	Low Demand (Acre-Feet per Year)					High Demand (Acre-Feet per Year)				
	2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
Acton MUD	1,880	1,310	1,310	1,310	1,310	1,880	1,350	1,480	1,620	1,740
City of Granbury	540	540	540	540	540	880	950	1,040	1,120	1,210
City of Tolar	100	100	100	90	90	150	150	150	150	150
Ingram Enterprises, L.P.	20	20	20	20	20	20	30	30	30	30
Oak Trail Shores	130	130	130	130	130	380	380	380	380	380
Texas Utilities Electric Co.	30	30	30	30	30	40	40	50	50	50
Hood Co. Rural Domestic	3,120	3,120	3,120	3,120	3,120	3,280	3,280	3,280	3,280	3,280
Hood Co. Irrigation	1,280	1,270	1,260	1,250	1,240	1,620	1,620	1,620	1,620	1,620
Hood Co. Livestock	310	310	310	310	310	310	310	310	310	310
Hood County Total	7,410	6,830	6,820	6,800	6,790	8,560	8,110	8,340	8,560	8,770

Table 4 Recommended Johnson County Demands on the Trinity Aquifer

Entity	Low Demand (Acre-Feet per Year)					High Demand (Acre-Feet per Year)				
	2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
City of Alvarado	410	480	500	520	300	410	490	500	520	540
City of Burlseon	40	20	20	20	20	40	40	40	40	40
City of Cleburne	800	800	700	600	500	800	800	800	800	800
City of Godley	30	30	30	30	30	150	170	190	210	230
City of Grandview	190	210	210	220	220	190	210	210	220	220
City of Keene	100	100	100	100	100	590	620	660	710	750
City of Rio Vista	20	20	20	20	20	70	70	70	80	80
Johnson Co. FWSD 1	140	140	150	150	150	750	780	820	850	890
Johnson Co.Rural Domestic	2,480	2,240	2,270	2,300	2,320	8,230	9,310	9,890	10,460	11,040
Johnson Co. Livestock	470	470	470	470	470	470	470	470	470	470
Johnson County Total	4,680	4,510	4,470	4,430	4,130	11,700	12,960	13,650	14,360	15,060

Table 5 Recommended Parker County Demands on the Trinity Aquifer

Entity	Low Demand (Acre-Feet per Year)					High Demand (Acre-Feet per Year)				
	2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
City of Aledo	290	290	290	290	290	360	440	520	590	670
City of Reno	170	170	170	170	170	190	220	220	220	220
City of Springtown	160	240	240	240	240	160	330	380	430	480
City of Weatherford	20	20	20	20	20	20	30	30	30	30
City of Willow Park	640	640	640	640	640	640	640	700	760	840
David's Patio Inc	10	10	10	10	10	10	10	10	10	10
Lake Shore Hills Estates	40	40	40	40	40	40	40	40	40	40
Texas Industries, Inc	10	10	10	10	10	10	10	10	10	10
U.S. Brick	10	10	10	10	10	10	10	10	10	10
Parker Co. Rural Domestic	5,320	5,320	5,200	5,200	5,200	5,320	6,650	8,380	10,560	10,620
Parker Co. Irrigation	90	90	90	90	90	90	90	90	90	90
Parker Co. Livestock	190	190	190	190	190	210	210	210	210	210
Parker County Total	6,950	7,030	6,910	6,910	6,910	7,060	8,680	10,600	12,960	13,230

Table 6 Recommended Tarrant County Demands on the Trinity Aquifer

Entity	Low Demand (Acre-Feet per Year)					High Demand (Acre-Feet per Year)				
	2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
Benbrook Water-Sewer Authority	1,260	960	960	960	960	1,260	1,400	1,400	1,400	1,400
Best Maid Products, Inc	60	60	60	60	60	70	80	80	90	100
Chemlime	20	20	20	20	20	30	30	30	30	40
City of Bedford	300	430	430	430	430	300	1,000	1,000	1,000	1,000
City of Blue Mound	180	180	180	180	180	280	300	300	300	300
City of Colleyville	560	560	560	560	560	920	920	920	920	920
City of Crowley	150	150	150	150	150	720	720	720	720	720
City of Dalworthington Garden	190	190	190	190	190	270	270	270	270	270
City of Euless	930	930	930	930	930	1,500	1,500	1,500	1,500	1,500
City of Everman	530	410	410	410	410	530	690	710	730	770
City of Grand Prairie	260	160	160	160	160	260	260	260	260	260
City of Haslet	40	150	150	150	150	40	150	160	160	220
City of Hurst	500	500	500	500	500	500	1,080	1,080	1,080	1,080
City of Kennedale	1,290	1,290	1,050	810	810	1,290	1,350	1,470	1,590	1,680
City of Lake Worth	350	350	350	350	350	450	470	490	510	530
City of Lakeside	400	430	350	270	270	410	450	480	510	550
City of North Richland Hills	220	240	240	240	240	220	240	240	240	240
City of Richland Hills	480	150	150	150	150	480	450	450	450	630
City of Sansom Park	580	420	420	420	420	580	600	600	620	620
City of White Settlement	830	830	830	830	830	1,240	1,270	1,300	1,320	1,370
Doskocil Manufacturing	10	10	10	10	10	10	10	10	10	10
Fort Worth Laundry & Dry Clean	10	10	10	10	10	10	10	10	10	10
Fort Worth Star-Telegram	30	30	30	30	30	30	40	40	40	50
Glen Garden Country Club	40	40	40	40	40	40	40	40	40	40
Hanson Concrete Central	10	10	10	10	10	10	10	10	10	10
International Home Foods	130	130	130	130	130	150	170	180	200	210
Johnson & Johnson Medical, Inc.	240	240	240	240	240	280	310	340	370	390
Martin Sprocket & Gear, Inc.	20	20	20	20	20	20	30	30	30	30
Monticello Spring Water Co	0	0	0	0	0	0	0	0	0	0
Pelican Bay Utility Co., Inc.	110	160	80	80	80	110	160	180	200	230
Spring Creek Circle WSC	10	10	10	10	10	10	10	10	10	10
Styrochem	250	250	250	250	250	280	320	340	370	400
Tarrant County FWSD No. 1	170	170	170	170	170	170	170	170	170	170
Texas Mobile Homes	10	10	10	10	10	10	10	10	10	10
Texas Utilities Electric Co.	10	10	10	10	10	10	10	10	10	10
Town of Pantego-Water Util.	620	620	540	470	470	650	650	650	640	640
Woodvale Water Co.	10	10	10	10	10	10	10	10	10	10
Tarrant Co. Rural Domestic	0	0	0	0	0	120	120	120	120	120
Tarrant Co. Irrigation	20	20	20	20	20	20	20	20	20	20
Tarrant Co. Livestock	360	360	360	360	360	400	400	400	400	400
Tarrant County Total	11,190	10,520	10,040	9,650	9,650	13,690	15,730	16,040	16,370	16,970

Table 7 Recommended Wise County Demands on the Trinity Aquifer

Entity	Low Demand (Acre-Feet per Year)					High Demand (Acre-Feet per Year)				
	2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
City of Alvord	140	170	140	110	110	140	170	180	190	190
City of Boyd	150	150	150	150	150	190	220	250	280	290
City of Chico	110	120	120	120	120	110	200	210	230	250
City of New Fairview	100	100	100	100	100	200	200	240	270	310
City of Newark	90	90	90	90	90	130	150	190	230	270
City of Rhome	220	220	220	220	220	460	680	960	1,240	1,480
Dynegy Midstream Inc	210	210	210	210	210	230	260	280	300	320
Hanson Aggregates Central Inc	0	0	0	0	0	0	0	0	0	0
Wise Co. Rural Domestic	2,160	2,160	2,160	2,160	2,160	2,160	2,760	3,520	4,000	4,000
Wise Co. Irrigation	220	220	220	220	220	250	250	250	250	250
Wise Co. Livestock	710	710	710	710	710	860	860	860	860	860
Wise County Total	4,110	4,150	4,120	4,090	4,090	4,730	5,750	6,940	7,850	8,220

Table 8 Recommended Demands on the Trinity Aquifer by County

County	Low Demand (Acre-Feet per Year)					High Demand (Acre-Feet per Year)				
	2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
Denton	10,320	9,870	9,870	9,830	9,880	12,030	14,750	17,040	19,560	22,750
Hood	7,410	6,830	6,820	6,800	6,790	8,560	8,110	8,340	8,560	8,770
Johnson	4,680	4,510	4,470	4,430	4,130	11,700	12,960	13,650	14,360	15,060
Parker	6,950	7,030	6,910	6,910	6,910	7,060	8,680	10,600	12,960	13,230
Tarrant	11,190	10,520	10,040	9,650	9,650	13,690	15,730	16,040	16,370	16,970
Wise	4,110	4,150	4,120	4,090	4,090	4,730	5,750	6,940	7,850	8,220
Total Study Area	44,660	42,910	42,230	41,710	41,450	57,770	65,980	72,610	79,660	85,000

Table 9 Recommended Demands on the Woodbine Aquifer

County	Entity	Low Demand (Acre-Feet per Year)					High Demand (Acre-Feet per Year)				
		2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
Denton	**City of Little Elm**	700	700	700	700	700	3000	5440	6870	8290	9040
Denton	**City of Northlake***	10	10	10	10	10	220	390	430	470	680
Denton	**Twin Cove WSC**	30	40	50	60	80	40	50	70	80	110
Denton	**Denton Co. Irrigation***	590	590	590	590	590	670	670	670	670	670
Denton	**Denton Co. Livestock***	250	250	250	250	250	530	530	530	530	530
Denton	**Denton Co. Manufacturing**	50	50	50	50	50	60	60	60	60	60
Denton	**Denton Co. Rural**	200	200	200	200	200	250	290	330	360	400
Johnson	**City of Venus***	170	170	170	170	170	280	280	280	280	280

*Note: Demand should be included as an individual entity in the Woodbine layer in the model

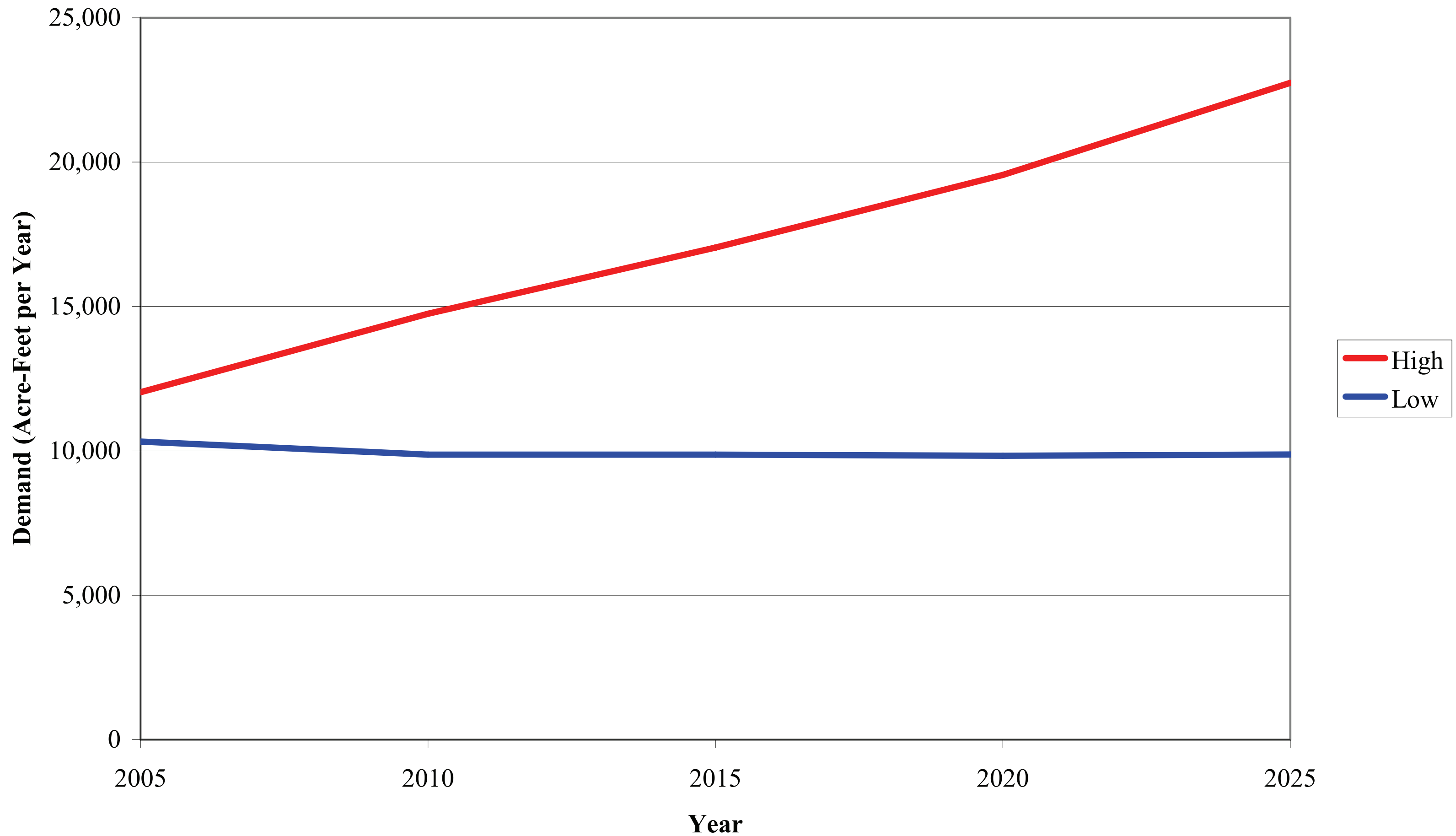

Figure 1 Recommended Demands on the Trinity Aquifer for Denton County

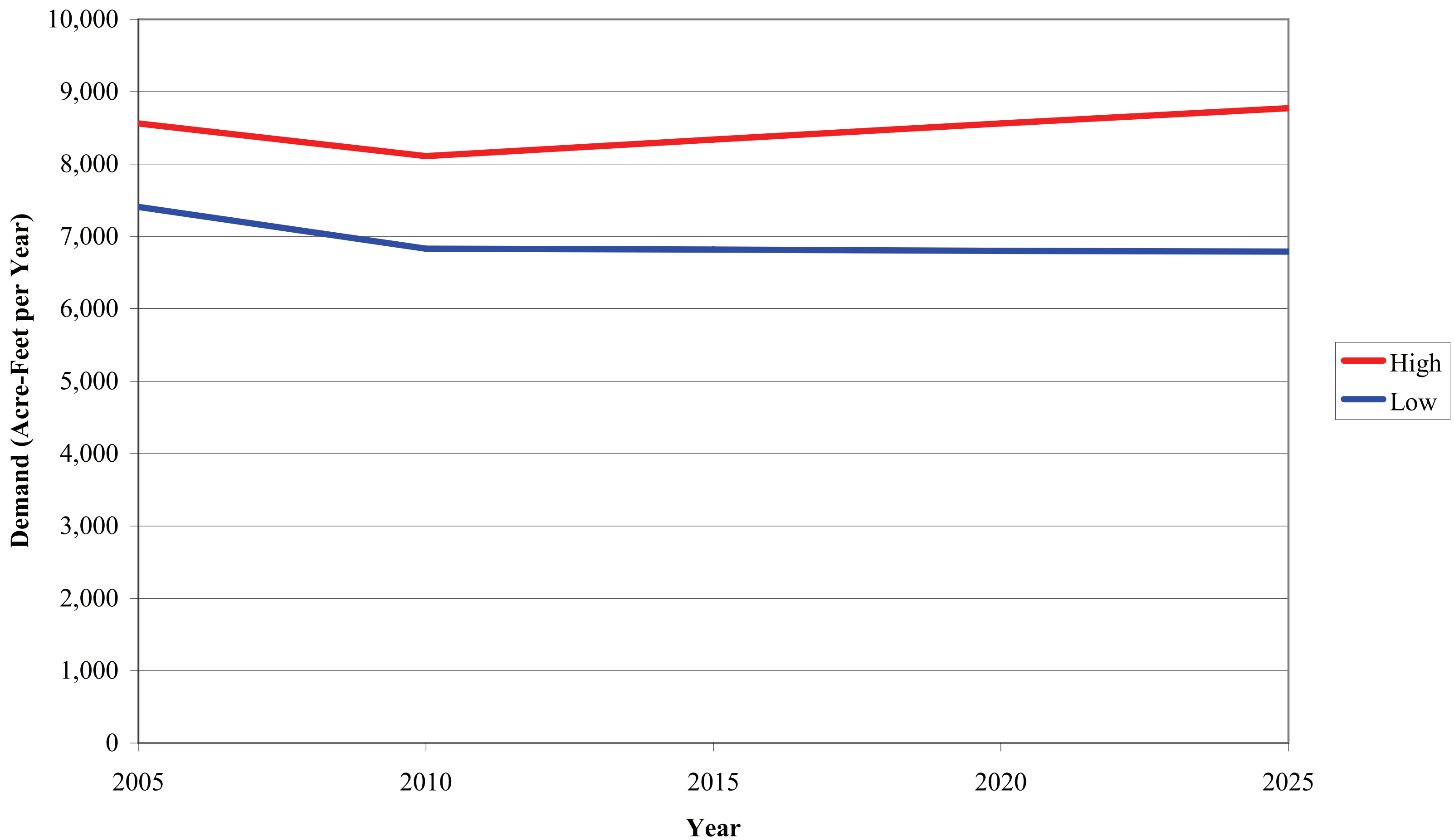

Figure 2 Recommended Demands on the Trinity Aquifer for Hood County

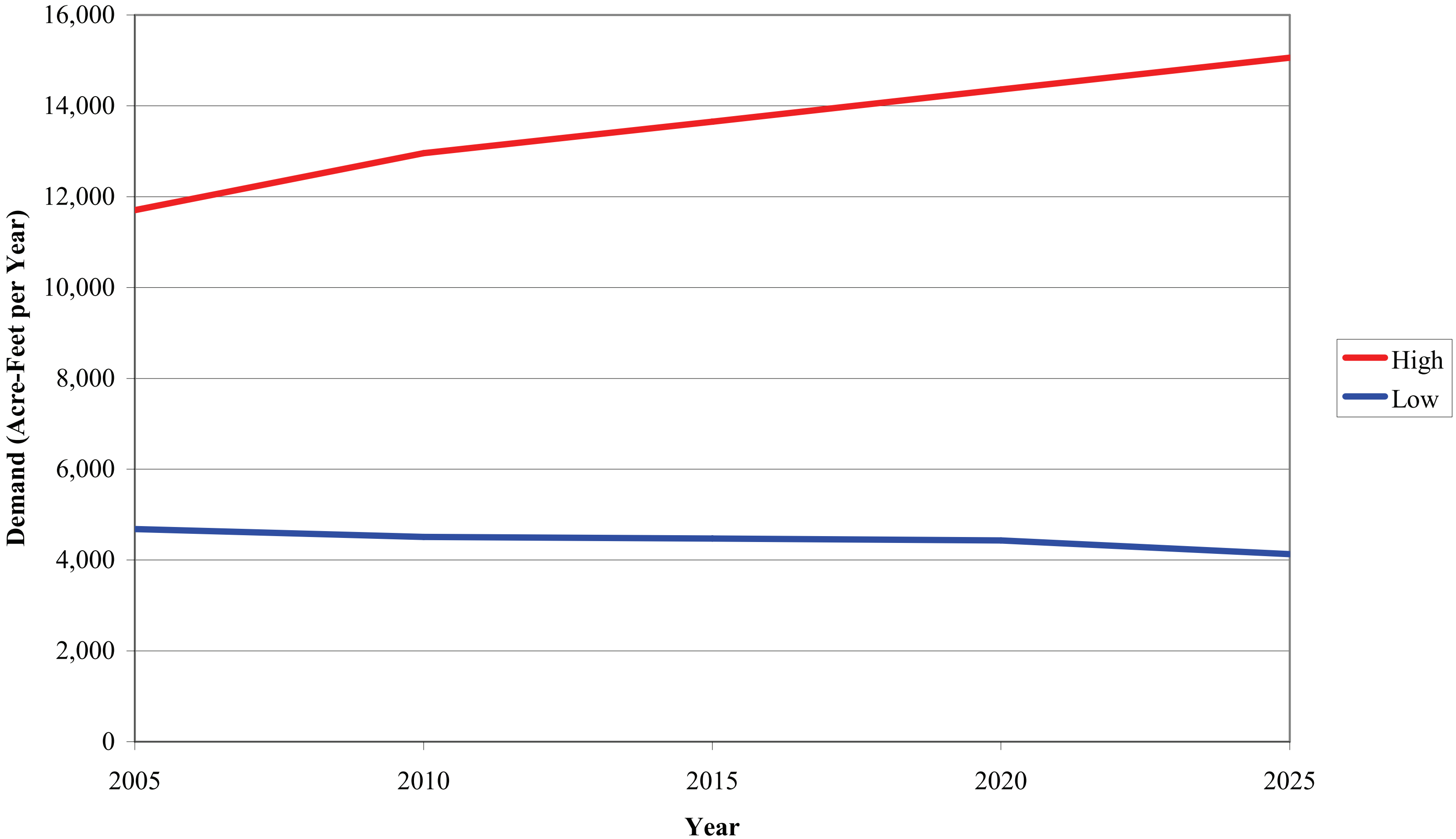

Figure 3 Recommended Demands on the Trinity Aquifer for Johnson County

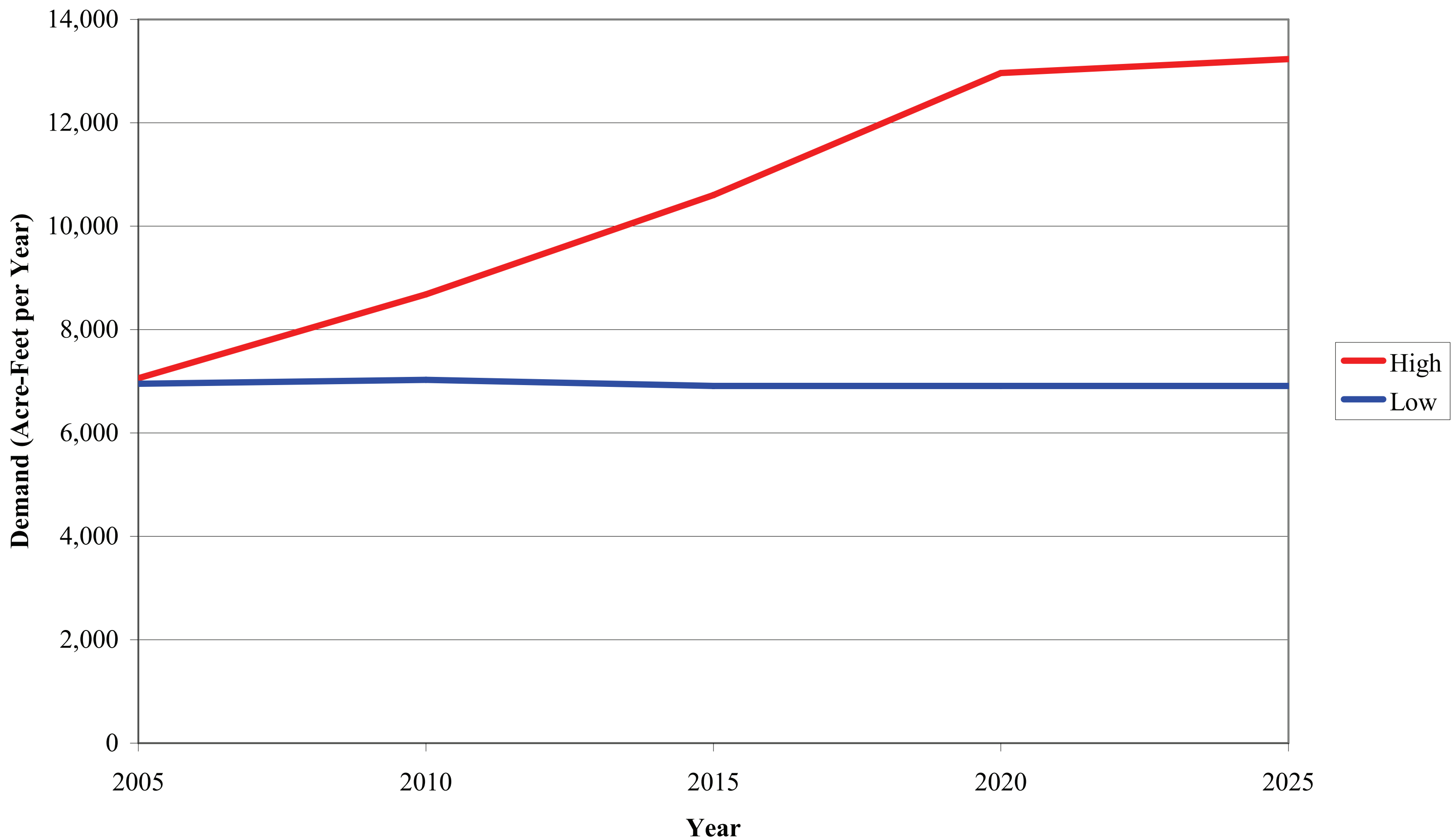

Figure 4 Recommended Demands on the Trinity Aquifer for Parker County

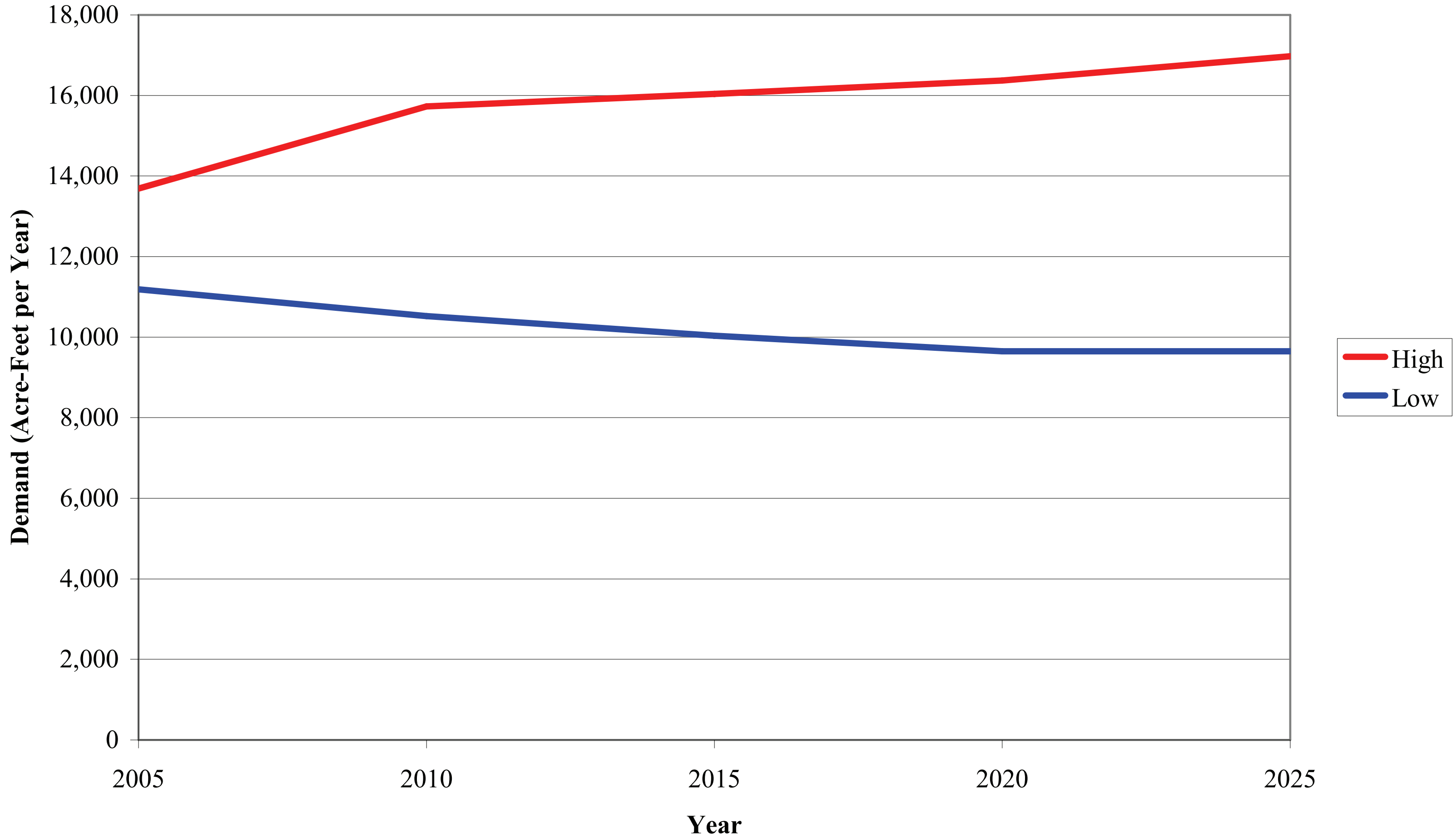

Figure 5 Recommended Demands on the Trinity Aquifer for Tarrant County

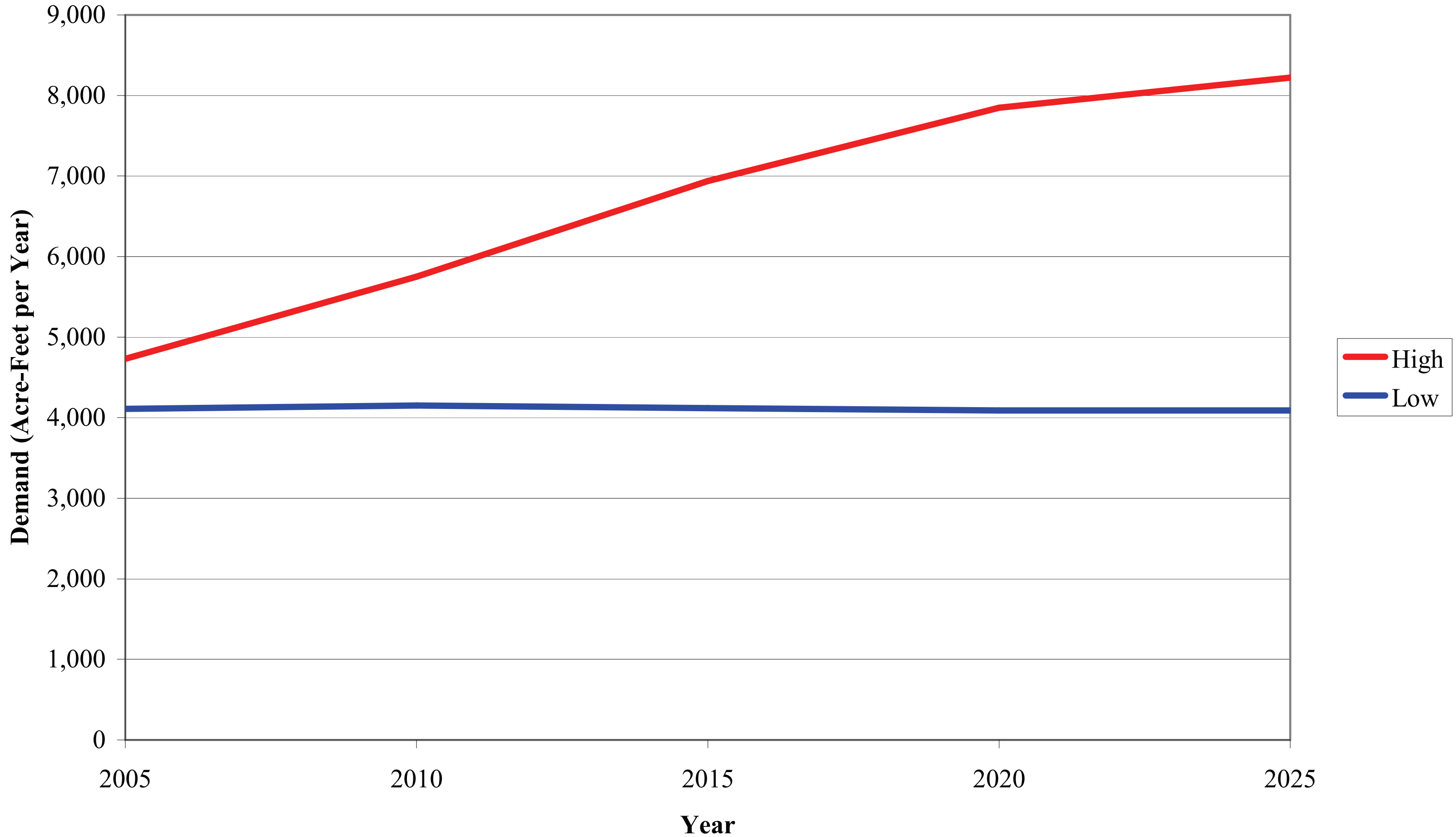

Figure 6 Recommended Demands on the Trinity Aquifer for Wise Count

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Appendix 2:
Barnett Shale Groundwater Use Estimates

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Table of Contents

Table of Tables

Table of Figures

SUMMARY

The Barnett Shale play, currently the most prolific onshore gas play in the country, has seen a quick growth in the past decade with the development of new "frac" (a.k.a. fracture stimulation) technologies needed to create pathways to produce gas in the very low permeability mudstones. This technology uses large amounts of water in a short period of time to develop a gas well. There are currently over 5,600 wells producing gas from the Barnett Shale, with thousands more likely to be drilled in the next couple of decades as the play expands out of its core area. A typical vertical completion consumes approximately 1.2 million gallons, and a typical horizontal well completion 3.0 to 3.5 million gallons of fresh water. Almost 8,000 acre-feet of water (from all sources) was used in 2005, mostly in an area equivalent to a Texas county. This usage has raised some concerns among local communities and other groundwater stakeholders, especially in the footprint of the Trinity aquifer.

In this study, we present projections of groundwater use by the oil and gas industry through 2025. Total water use is highly uncertain, being dependent on the price of gas above all. We approach this uncertainty by developing high, medium, and low scenarios that can be somewhat understood as cases with decreasing gas prices. Other important factors include geologic risk factors in the Barnett (maturity of the shale, thickness of the formation, presence of features limiting or hampering well completion), technological factors (horizontal vs. vertical wells, water recycling), operational factors (number of well completions that can be done in a year, proximity of a fresh-water source), and regulatory factors. The high scenario cumulates most of the high-end water use of the previous parameters, whereas the low scenario uses the low values of their range.

The low scenario utilizes 29,000 AF of groundwater to the 2025 horizon (1,500 AF/yr on average), a clear retreat from current annual rate of water use by the industry, corresponding to a large drop in gas price. The high scenario calls for a total water use between 2007 and 2025 of 417,000 AF of groundwater (~22,000 AF/yr on average). It corresponds to sustained high gas prices allowing operators to expand to all economically viable areas and produce most of the accessible resource but also includes the assumption that water use is not limiting. All scenarios assume that operators continue using water at a per-well rate similar to that of today and that no technological breakthrough will bring it down. The medium scenario assumes a groundwater use of 183,000 AF (~10,000 AF/yr on average). In the high scenario, groundwater use steadily climbs from ~5,000 AF/yr in 2005 to 20,000 AF/yr in 2010 and then slowly increases to a maximum of ~25,000 AF/yr in 2025. The medium scenario follows a similar path, climbing to a maximum of ~13,000 AF/yr in 2010 and then slowly decreasing to ~7,500 AF/yr in 2025. The medium case is not necessarily the most likely. Because the Barnett Shale play is dependent on gas prices, a more accurate statement would be to formulate that the medium case is the most likely under the condition that gas prices stay at their current level.

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Many people/organizations were involved in the production of this document. We acknowledge the help of Bob Harden at R.W. Harden & Associates and Cindy Ridgeway, Robert Mace, Ali Chowdhury, project manager, at the TWDB in helping collect data, contacting numerous individuals, and funneling the information to us.

We thank Peter Galusky from Texerra and the Barnett Shale Water Conservation and Management Committee for sharing with us data directly collected from operators. Several Bureau of Economic Geology (BEG) researchers helped by sharing their Barnett Shale knowledge. Romulo Briceno and Ramón Treviño, also from BEG, helped in processing of the data and in providing useful comments on the report, respectively. Lana Dieterich edited the report.

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INTRODUCTION

The Barnett Shale play, located in North Texas and currently the most prolific onshore gas play in the country, has seen a quick growth in the past decade with the development of new "frac" (a.k.a. fracture stimulation) technologies needed to create pathways to produce gas in the very low permeability shales. Approximately 150 operators are active in the play. Devon Energy, a Barnett Shale pioneer, is still by far the most important player in terms of production. This technology uses a large amount of water in a short period of time (up to 5 million gallons of water within a day, followed by a few days of flowback) to develop a gas well. There are currently more than 5,000 wells tapping the Barnett Shale, with thousands more likely to be drilled in the next few years and possibly decades. The so-called core area, also officially described as Newark East field and which has seen the initial production in the 1990's, includes part of Denton, Wise, and Tarrant Counties (Figure 1). The production area is now expanding to the southwest, into Parker and Johnson Counties, and may eventually include more than 20 of the 44 counties of the Fort Worth Basin covered in all or partly by the Barnett Shale footprint. This growth concerns local communities and other stakeholders because this part of the state does not have any Groundwater Conservation District (GCD) (it generally relies mainly on surface water), except in Erath and Comanche Counties (Middle Trinity GCD). Contrary to the surface water case, where usage rights are well appropriated and water use is tracked, no state or local rule governs the legitimate use of groundwater outside of a GCD, potentially leading to overdraft.

This work was performed to provide input to an updated version of the Trinity Groundwater Availability

(GAM) model (R.W. Harden & Associates, 2004). Although the Trinity Aquifer GAM and Barnett Shale extents only partly overlap (Figure 1), it was felt that the whole Barnett play should be studied because experience shows that water sources can be located far from their point of use. A compounding factor is that the TWDB has not defined any major or minor aquifer on the western half of the Barnett Shale extent, suggesting low yield in the local aquifers and that water could still come from the Trinity and be transported to these areas.

One may wonder why operators would need to use fresh water instead of the abundant saline water produced in the basin. Produced saline water has been the bane of oil operators since hydrocarbon production started, and any reuse option would certainly be welcome. Unfortunately, Barnett Shale operators prefer using fresh water (Margaret Allen, RRC, written communication, April 2006) for technological and operational reasons. Saltwater significantly increases the potential for scale deposition in the formation, tubing, casing, and surface equipment, therefore inhibiting gas production. Saltwater also significantly increases the potential for corrosion on the tubing, casing, and surface equipment, potentially shortening the life of a well. In addition, chemicals needed to carry out a good frac job do not perform as well with saltwater. Friction reducers are not as effective and are more costly when used in saltwater. Depending on the composition of the saltwater, it can be altogether incompatible with friction reducers. Saltwater is not compatible with x-linked gels that were commonly used in fracs (see later section). Economic factors may be important as well. Produced water of acceptable quality may not be available in close proximity.

The Barnett Shale play is rapidly expanding, and new information is released at a fast pace. However, this report will try to capture our understanding of the play as it relates to water resources as of summer 2006. This document presents historical information about the play, as well as tentative projections. It will expand on the following points.

(1) Understanding spatial and temporal trends: the exploration boom started in Wise and Denton Counties but is expanding mainly southward and westward. Using geologic insight, our knowledge of the play, and discussions with operators, we forecast the likely geographic evolution of the play. Operators may also turn their interest to parts of the overlying Bend Conglomerate, increasing the number of frac jobs in a given area.

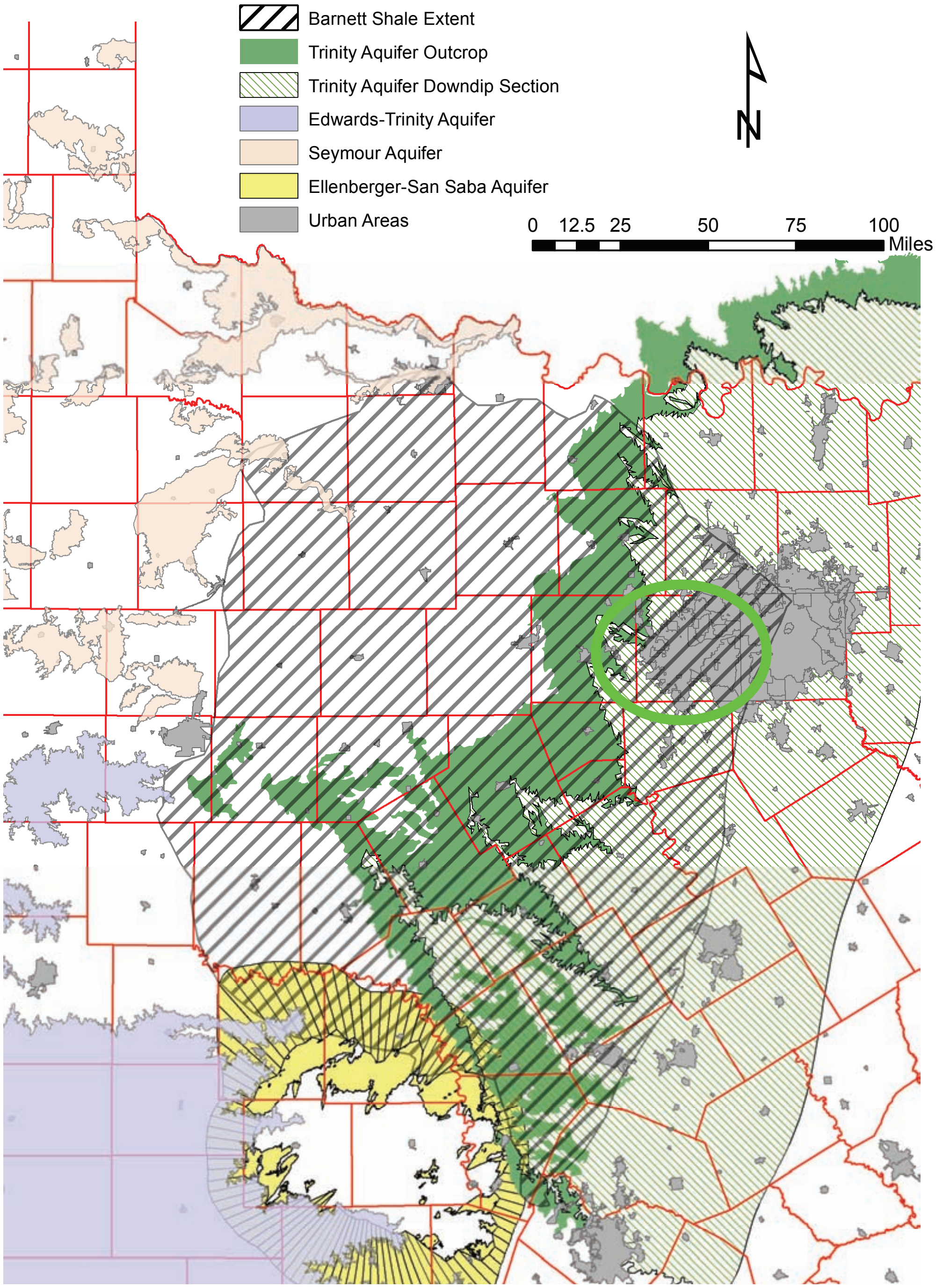
(2) Understanding the future of the technology: a few questions need to be answered. Will the water consumption per frac job decrease? How often can a given well be frac'ed? What percentage of the wells would be directional horizontal wells. Will multiple frac jobs in horizontal wells result in the same number of forecast fracs, compared with development by vertical wells?

(3) Understanding the impact of recycling: there is currently some recycling of the frac water and

strong incentives to increase the recycled fraction because the used frac water ("flowback") has to be hauled away and disposed of generally in commercial disposal wells not necessarily located in close proximity to the drilling area.

We tried to keep the model simple. There might be arguments to make a supposedly more accurate and/or more complicated model, but there are currently no data to build additional or more sophisticated parameter distributions.

A word of caution on terminology: in the oil and gas industry m or M means thousands (as in Mcf—thousand cubic feet), whereas in the water resources field M means million (as in MGD—million gallons a day); in the oil and gas field, million is denoted by MM. Because this report is geared mainly toward water-resources issues, we have adopted "M" to mean millions when water is involved. We also use acre-feet (AF), the standard water resources unit: 1 AF is equivalent to 325,851 gallons, or 7,758 barrels



Barnett extent is approximate and will change with new studies. Llano uplift is outlined by the Ellenburger Aquifer. The lower downdip limit of the aquifers is set when salinity reaches 3,000 ppm. Green circle represents the core area.

Figure 1 Barnett Shale extent and TWDB major aquifers

What is the Barnett Shale?

The Barnett Shale can be defined as an unconventional play. A significant part of US gas production (over 30%) comes from unconventional plays. They are characterized by marginal-quality reservoirs requiring artificial stimulation, usually fracture treatments (“frac jobs”). They are also “continuous” (similar to coalbed methane), that is, the resource is distributed across large geographic areas and there may be few dry wells. It follows that the play is currently more driven by technology than by geology. The U.S. Geological Survey (USGS) estimated the mean of the gas resources at 26.7 Tcf of gas (USGS, 2004), whereas Montgomery et al. (2005) put proven reserves (in the core area) at 2.7 Tcf, at the time the paper was written, and ultimate producible resources between 3 and 40 Tcf. The Railroad Commission of Texas (RCC) puts forward a value of 250 Tcf for total gas in place (not all of it recoverable). Montgomery et al. (2005) cited >200 Tcf. In a quickly evolving play, reserve values are also varying (in general increasing) as geologic understanding and technology progress. The play is currently producing gas at a rate ~0.5 Tcf/year (Figure 2). Per-well reserves are relatively low, compared to conventional gas plays. Reserves are often discussed on a unit surface area basis, although this is an oversimplified approach. Because of stimulation and drilling cost, play success is sensitive to gas price. A large drop in gas price will stop the viability of the play. There seems to be some agreement that the gas price needs to stay above $4/Mcf for the play to stay viable in the long term (e.g., Rach, 2005).

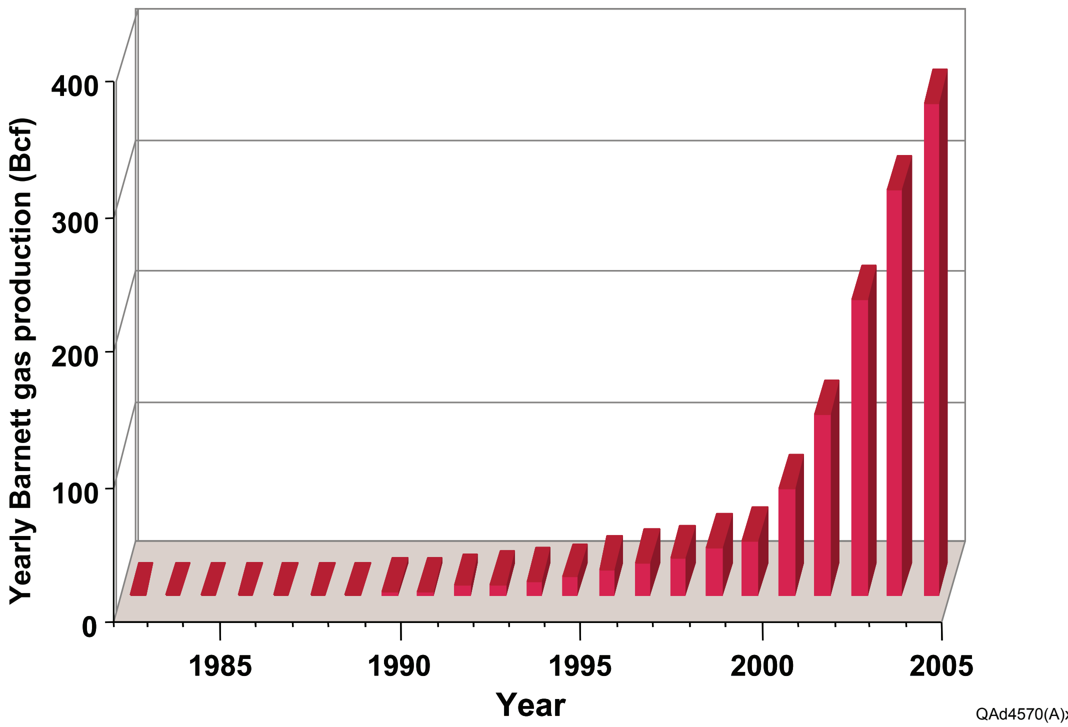


Figure 2 Yearly Barnett gas production

The Barnett Shale has been described as a black organic shale and is a fine-grained rock formation. It is considered the source rock for numerous oil and/or gas conventional reservoirs in the Fort Worth Basin (Pollastro et al., 2003), including the Pennsylvanian-age Bend Conglomerate Formation, that have produced gas starting in the 1950's. However, the Barnett Shale is at the same time, source, reservoir, and trap, with a natural permeability in the microdarcy to nanodarcy range and porosity in the 0.5 to 6% range. Water saturation is below 50% (25% in places, Montgomery et al., 2005). In reality, in geologic parlance, the word shale is a misnomer, or at least misleading by some definitions. The Barnett strata, although very fine grained, are not composed of shales, but of siliceous mudstones, argillaceous lime mudstones (marls), and phosphatic argillaceous skeletal packstones (R. Loucks, BEG, oral communication, 2006). Mineralogically, clays (mainly non-swelling illite) account volumetrically for about 25% of the formation, the remainder being dolomite, calcite, feldspars, and quartz, as well as metal oxides and pyrite (Montgomery et al., 2005, p.162).

The Barnett Shale formation exists under wide areas in Texas and crops out on the flanks of the Llano Uplift 150 miles to the south of the core area (Figure 3). Most current boundaries of the formation are due to erosion. The Fort Worth Basin is bounded by tectonic features to the east by the Ouachita thrust foldbelt (old, eroded, and buried mountain range) and to the north by the uplifted Muenster and Red River Arches. The Barnett Shale is also limited by erosional limits on its western boundaries. A depositional equivalent is present farther west in the Delaware Basin. Equivalents are also present in the Texas

Panhandle in the Hardeman and Palo Duro Basins (Pollastro et al., 2003).

The Barnett Shale dips gently toward the core area and the Muenster Arch from the south where it crops out and west where it thins considerably and its base reaches a maximum depth of ~8,500 ft (subsea) in the NE confines of its extent. The depth to the top of the Barnett ranges from about ~4,500 ft in northwestern Jack County to about ~2,500 ft in southwest Palo Pinto County to about ~3,500 ft in northern Hamilton County to about ~6,000 ft in western McLennan County to about 7,000 to 8,000 ft in the Dallas-Fort Worth area (Figure 4). Further west in Throckmorton, Shackelford, and Callahan Counties the depth to the Barnett varies between ~4,000 to 2,000 ft.

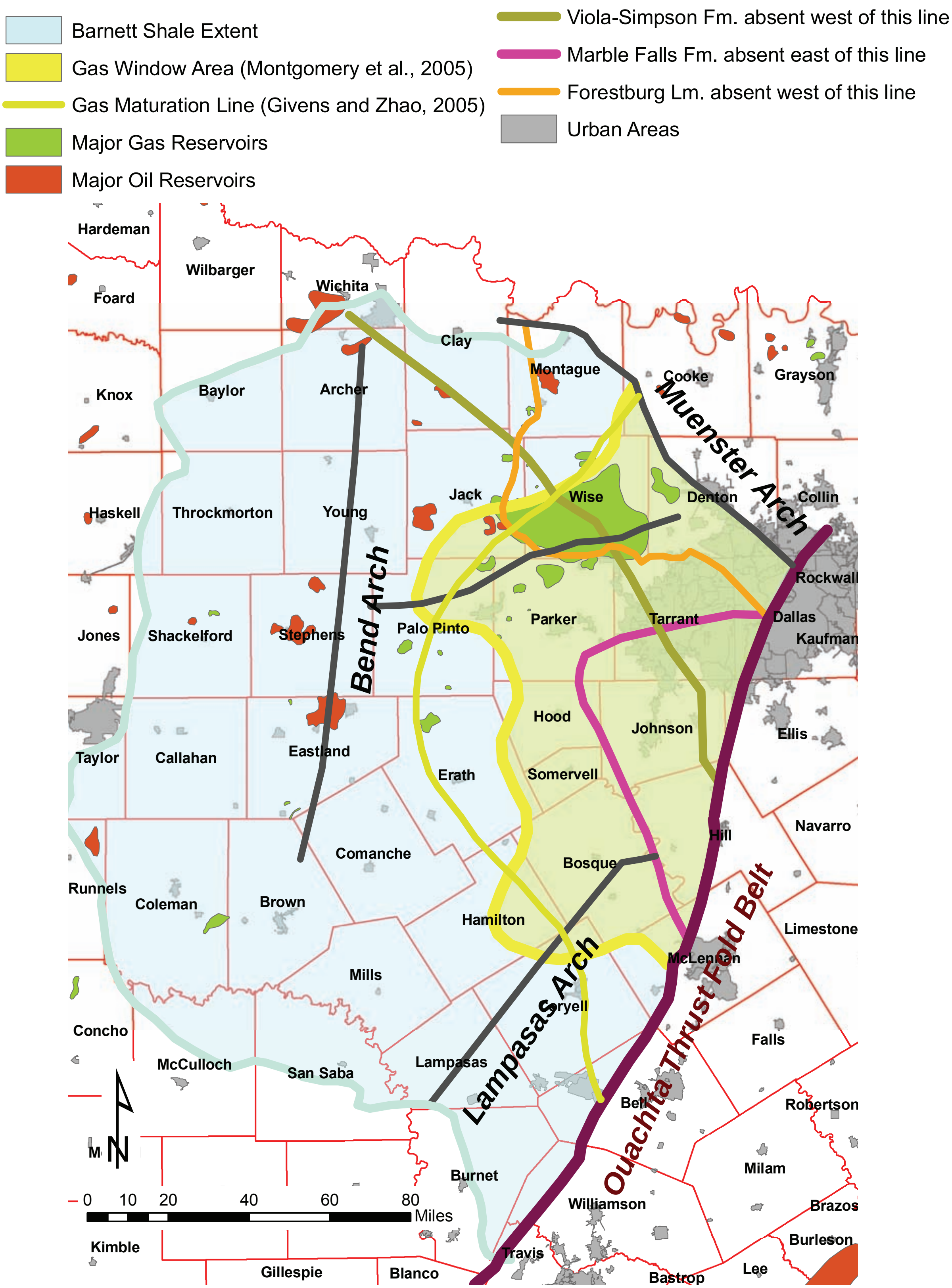
Formation thickness is in the 30-to 50-ft range on the Llano Uplift and increases to almost 1,000 ft farther north in the core area, when the whole Barnett section, including interspersed limestones, is counted. Toward the west, Barnett Shale thickness is impacted by the presence of the Chapel Limestone and decreases to almost zero in southwestern Jack County (Figure 5). In the northeasternmost part of the Barnett extent, in eastern Jack County and continuing in Young, Throckmorton, and Baylor Counties, the Barnett thickness decreases to ~50 ft because of the presence of the Chappel carbonate shelf, which contains paleo reefs with oil accumulations (Montgomery et al., 2005).

The Barnett Shale is a marine basinal deposit of Mississippian age, deposited under mostly anoxic conditions in a calm back-arc basin just before the formation of the Ouachita thrust foldbelt. It lies unconformably on the Ordovician limestones of the Viola-Simpson formations and dolomites of the Ellenburger Group and is overlain by the carbonates and shales of the Pennsylvanian-age Marble Falls Group. In the core area, the Barnett Shale is divided by a middle muddy limestone (Forestburg Limestone) into lower and upper intervals. The thickest and most productive section is the Lower Barnett. The so-called Forestburg Limestone, not a single individual unit, contains shale intervals (W. Wright, BEG, personal communication, 2006). The Forestburg Limestone and other limestone formations are better developed in Montague County (Figure 3). The marked gross Barnett increase in thickness close to the Muenster Arch is due mostly to limestones. Lower and upper Barnett sections vary from ~260 to 715 ft and ~20 to 210 ft in thickness, respectively. The Marble Falls Formation is also absent locally, in the west half of Hill County, the south half of Tarrant County, and all of Johnson County (Figure 3). Important to the history and technological evolution of the play, the Viola-Simpson Formation, present in the core area, pinches out toward the SW (Figure 3). Where it is present, the Viola-Simpson Formation acts as a buffer between the Ellenburger Formation and the Barnett Shale. It is important to keep the frac job within the Barnett Shale and the dense Viola Limestone is able to achieve this purpose. According to the current operational model, frac jobs penetrating into the Ellenburger generally mean trouble for the operator because of the excess water drawn from the Ellenburger owing to its high permeability. The Viola Limestone covers eastern Wise County, the southwest half of Denton County, and most of Tarrant County, as well as Montague and most of Clay Counties. To a lesser extent, the Marble Falls Limestone plays a similar role helping to confine frac jobs within the upper Barnett.

As most formations, the Barnett Shale is naturally fractured. In Newark East field, the core area, fractures trend NW-SE. They are generally closed by calcite but it is speculated that they can be reactivated during a frac job. Induced fractures have a NE-SW strike (mean of 60 o) (Schmoker et al., 1996, p. 3).

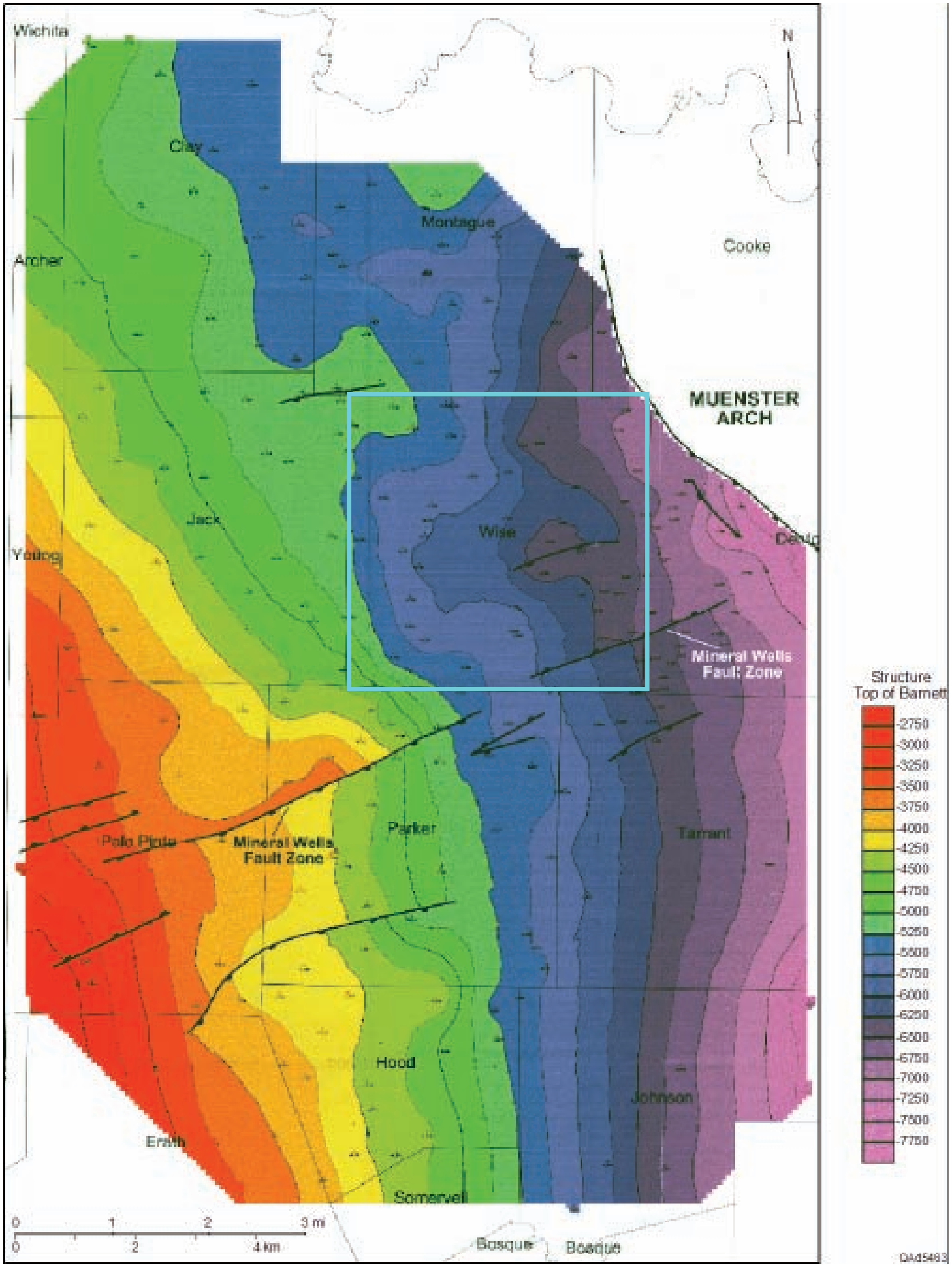
The gas maturity area is another important geologic feature presented in Figure 3 Organic matter and/or oil needs to be subjected to a specific range of temperature for a long enough period of time to produce gas. That threshold occurred in the Mesozoic period for the Barnett Shale (Montgomery et al., 2005, Fig. 7). It is generally thought that some gas subsequently migrated upward to accumulate in stratigraphic traps of the Bend Conglomerate / Atoka Formation, where it has been produced since the 1950's (Figure 3) West and north of the area where the Barnett is in the gas window, the Barnett has been producing both gas and oil (Figure 3). Oil also accumulated in conventional traps above or below the Barnett Figure 3displays a few of the major oil and gas reservoirs and is not comprehensive in that matter. The map boundaries of the gas maturation area are open to geologic interpretation and, as demonstrated In Figure 3, different authors have come up with slightly different boundaries (e.g., Givens and Zhao, 2005; Montgomery et al., 2005; note that Givens and Zhao had less confidence in the southern half of their gas-maturation line). Gas-oil ratio decreases systematically toward the west. The gas maturation area as defined is more of a commercial fairway boundary. It is best defined in Wise County, but there is considerable scope for redefinition in other areas. Gas operators undoubtedly have a better handle on it, as compared with what is available in the open literature, but for understandable reasons, they do not advertise their findings. This is one example of the uncertain and evolving, or "soft" data used in this report.

The impact of these geologic features is clearly visible on the map showing all wells drilled in the Barnett (Figure 6). The core area is constrained (1) on its northeast boundary by the Muenster Arch, immediately beyond which no Barnett has been found; (2) on its southwest boundary by the Viola Limestone pinch-out; (3) on its northwest boundary by the northern limit of the dry gas window; and (4) on its southeast boundary by the presence of the urbanized areas of Fort Worth and its suburbs, and ultimately by the Ouachita fold and thrust system, east of which there is little chance of Barnett presence.. Within the core area, the impact of NE-SW-trending faults is also visible through the lack of wells drilled close to them.



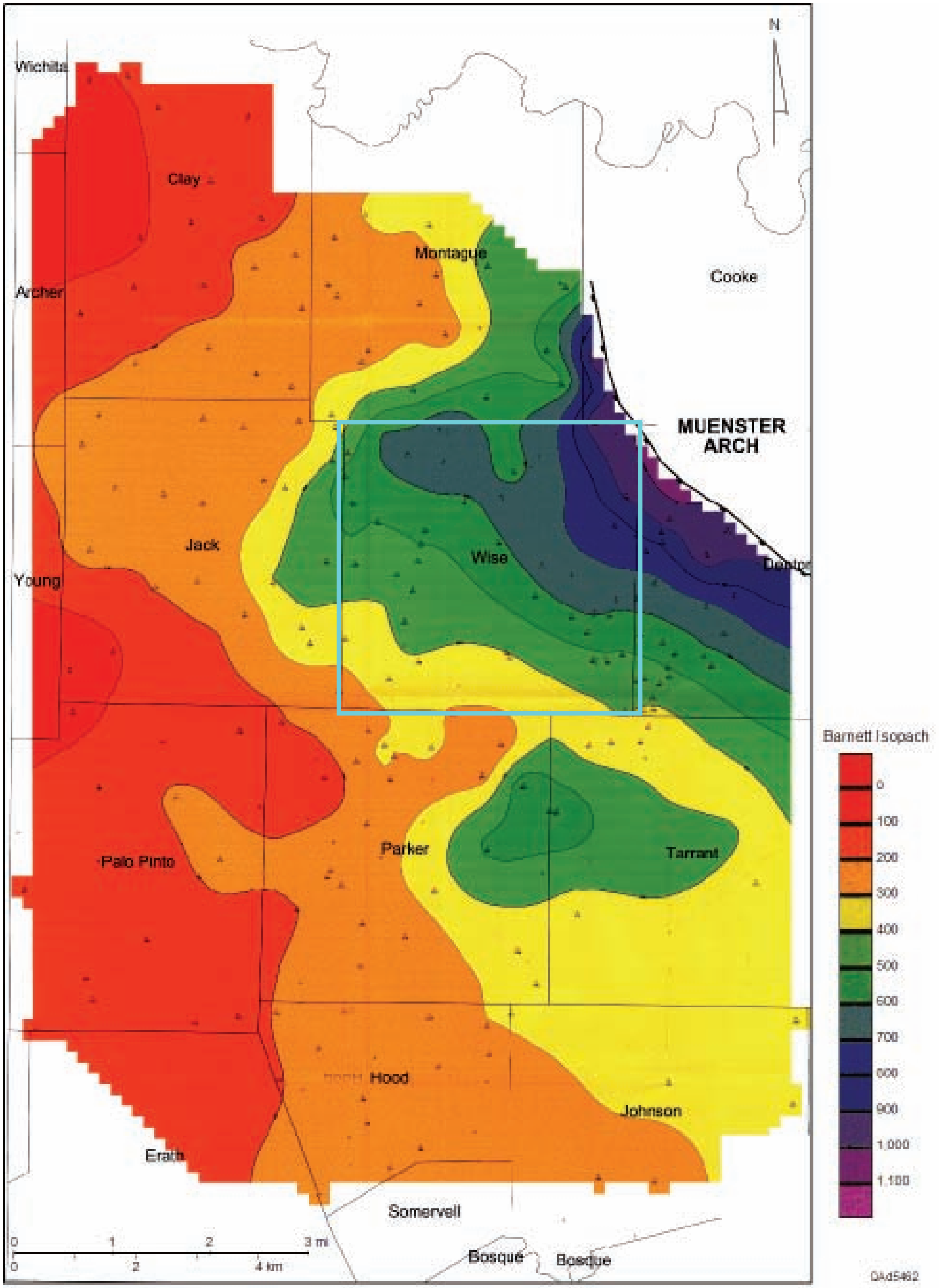
*Note: Forestburg limit modified from Givens and Zhao (2005); all others modified from Montgomery et al. (2005); major oil and gas reservoirs from Galloway et al. (1983) and Kosters et al. (1989). The Major Gas and Oil Reservoirs refer to non-Barnett production

Figure 3 Relevant geologic features associated with the Barnett Shale



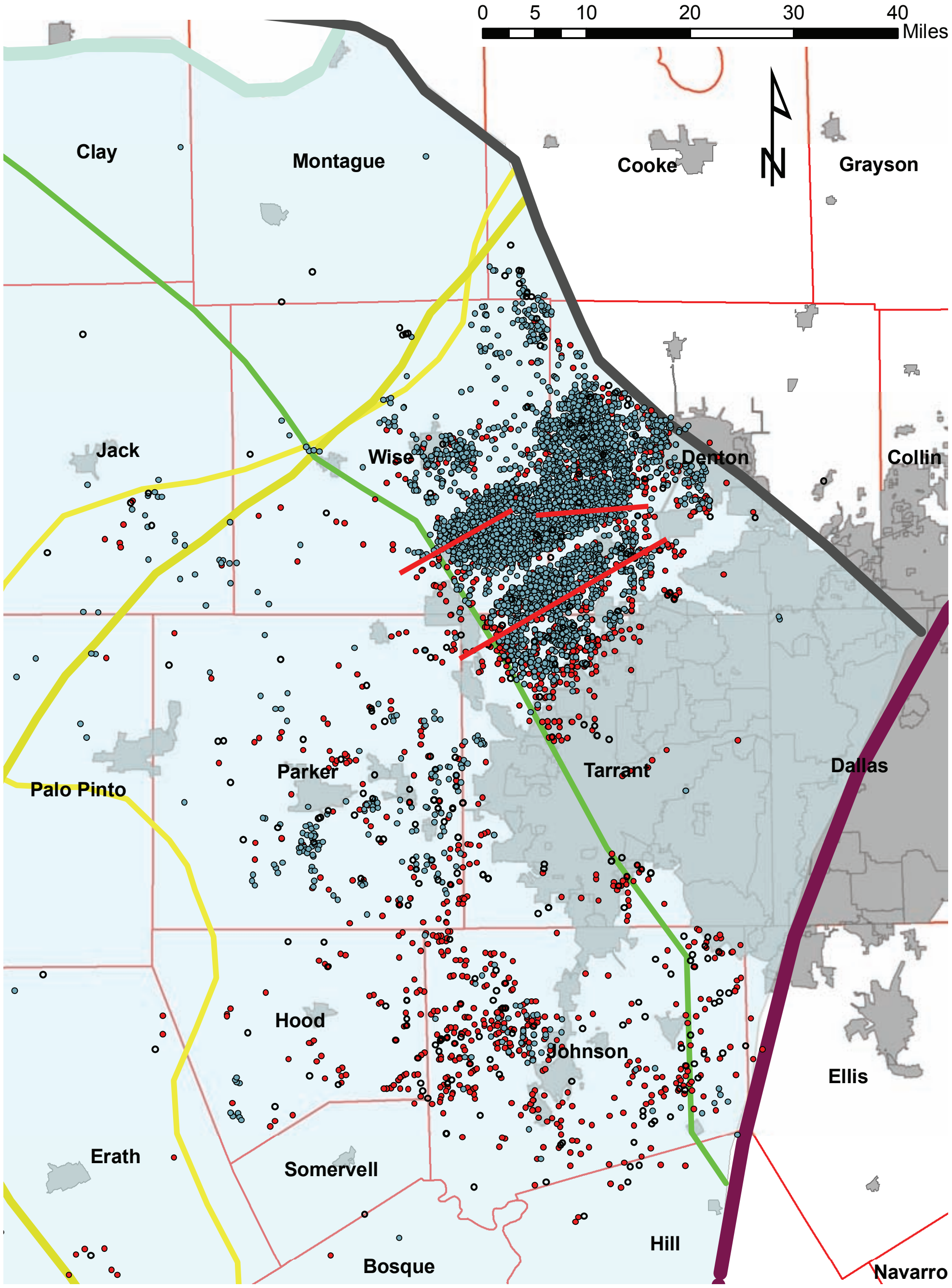
Courtesy of T. Hentz, BEG; Units are subsea feet; blue square represents Wise County

Figure 4 Top of the Barnett Shale (northeastern area of full Barnett Shale extent)



Courtesy of T. Hentz, BEG; Units are feet; blue square represents Wise County

Figure 5 Barnett Shale isopachs (northeastern area of full Barnett Shale extent)



Core area is clearly delimited between the Muenster Arch and the Viola Simpson pinch-out (green line). The vast majority of the wells drilled to date are within the gas window (2 versions shown with yellow lines) and in rural areas. Blue dots represent vertical wells whereas red dots represent horizontal wells. Non-colored dots represent those wells where directional information is not available. Known faults are shown by red lines. Well locations courtesy of drillinginfo.com.

Figure 6 Barnett Shale well location

DATA SOURCES AND PROCESSING

Well Completion and Water Use

Hard data on oil and gas production wells ultimately come from the RRC W2 and G1 (completion) forms. Vendors may handle raw data faster than the RRC and have it processed in a searchable and user-friendly fashion. We turned to both drillinginfo.com and IHS Energy to obtain completion information on all Barnett Shale wells present in their respective databases. We obtained well-location information from drillinginfo.com, as well as a data dump on completion data on all Barnett wells. We were not successful in finding location information for a small percentage of wells. Our lack of success has, however, a negligible impact on the water-use projections. We also obtained full completion information by using Enerdeq IHS software. In both databases, we searched for all Texas wells that included “Barnett” in their profile.

We also gained useful insight by talking to operators in meetings and conferences, including those held by the Barnett Shale Water Conservation and Management Committee (BSWCMC). The BSWCMC was conducting a thorough operator survey, headed by Peter Galusky, at the same time that our work was performed. Although not finalized at the time of submission of this report, those preliminary results from a non-RRC source were consistent with our findings and were integrated into this report.

Fresh-Water Consumption

Even perfect knowledge of water use for frac jobs is not sufficient for the task at hand. There is no legal requirement to declare the source of frac makeup water to the RRC. However, input to a groundwater numerical model in order to understand the impact of water retrieval for frac jobs requires being able to recognize the source of the water (surface-water bodies or subsurface) and its original location. In Texas, water flowing in Texas creeks, rivers, and bays is owned and managed by the State. Therefore, a person who withdraws surface waters for mining, construction, and oil or gas activities must obtain a water rights permit from the Texas Commission on Environmental Quality (TCEQ).

The most useful source of information on groundwater-surface water split in water use was provided by the BSWCMC survey (Galusky, 2006). Galusky (2006) provided groundwater use estimates by operators of historical data for year 2005 and projections for 2006 and 2007. TWDB efforts to get information on Trinity aquifer water wells did not come to fruition except for workers gaining an understanding that groundwater usage for frac jobs is widespread. All water well drillers must complete a Texas Department of Licensing and Regulation (TDLR)’s State of Texas Well Report for any and all groundwater wells. TWDB has maintained the online report database since 2003 and also had access to hard copies for the past 2 years (Ridgeway, 2006). However, water supply wells used for frac jobs can fall into many categories, including, for instance, domestic wells that might be drilled by an operator but later used by the landowner.

Another avenue pursued by R.W. Harden and Associates (R. Harden, 2006, written communication) was to contact river authorities. Brazos River Authority (BRA) has been selling water to Barnett operators. However, that water belongs to the "mining category," which includes quarries, road construction, oil and gas activities, and other activities. BRA provided its mining water use values from ~2000, but we were not able to discriminate between the different mining usages. Although it was not done, a visit to the "Central Records" of the TCEQ, where permits are filed, might not have helped because a specification of "oil and gas" is not required.

Current and Past Practices

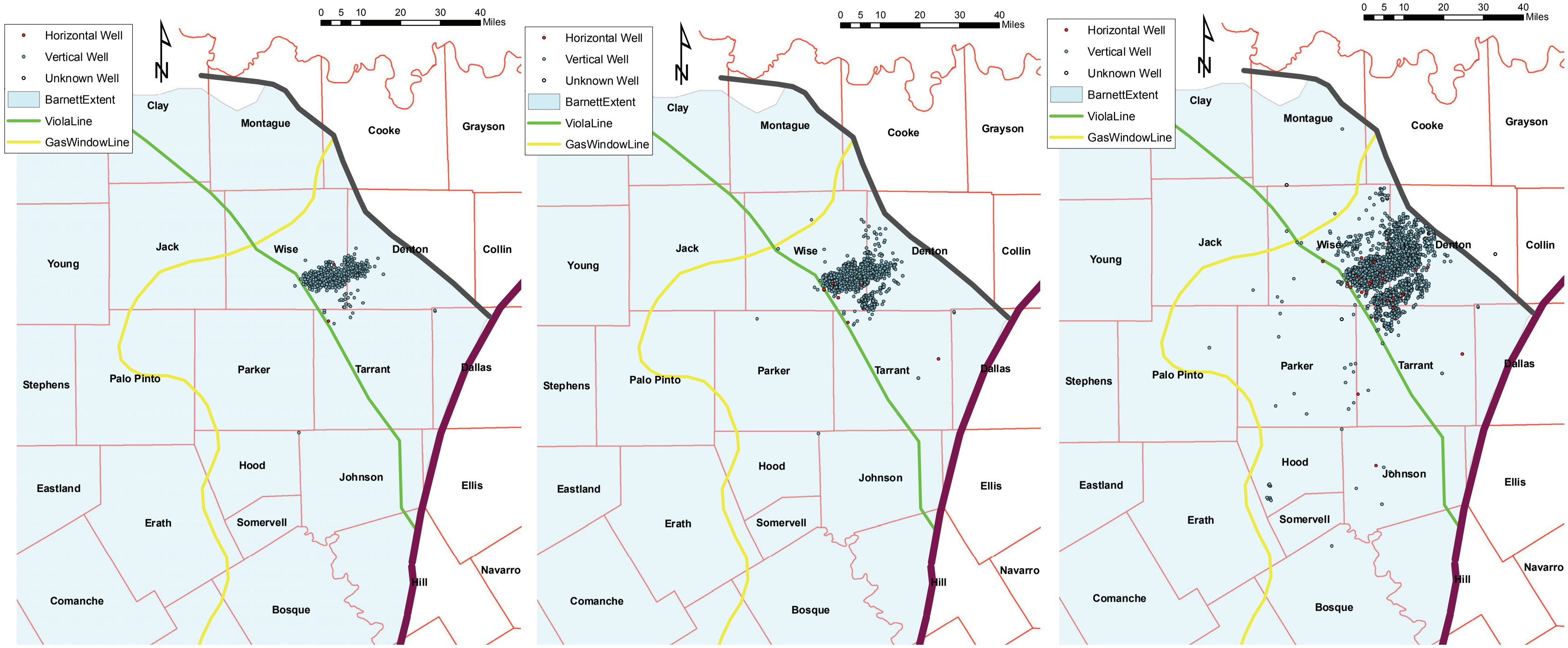
History of Production Technology in the Barnett Shale

Given the extremely low permeability of the Barnett Shale (even naturally fractured), hydraulic fracturing seemed a logical solution. Hydraulic fracturing, initially developed by Halliburton in the 1940's, has been practiced and improved on since then (e.g., Martinez et al., 1987). Early treatments injected only a few thousand gallons of fluids into a few select wells. The technique was expanded to treat many more wells, not necessarily at initial completion, and to use a much larger volume of fluid. The initial impetus was to remove formation damage (scaling, oily deposits, porethroat occlusion by drilling fluids) in the vicinity of the well to renew the good communication between the reservoir and the well bore. Hydraulic fracturing quickly included treatment of low-permeability formations to improve production and is now also applied to medium-permeability formations. The concept is to prop natural or induced fractures open by injecting fluids in order to raise the pressure beyond the point at which it can be sustained by the rock, creating artificial fractures. Addition of a proppant to the fluid is needed to keep the induced fracture open once the fluid has been removed and the pressure has subsided. Sand is usually used as a propping agent, but many more sophisticated materials are also available from vendors and service companies. In the past, oil-based fluids were used as carrying fluids, but nowadays frac jobs use water-based fluids or, more rarely, mix-based fluids (oil-water emulsions). Hydraulic fracturing technology has evolved essentially by changing the nature and amount of the chemicals added to the water and by the accumulated knowledge of what works and what does not.

Starting in the early1980's to just before 1997, operators tried several design approaches to produce gas economically from the Barnett Shale. Initially, massive hydraulic fracture treatments with high-polymer crosslinked gel fluids and large amounts of proppant at moderate concentration were used (e.g., Ketter et al., 2006; Moore and Ramakrishnan, 2006), as it was generally done in the U.S. at the time. Polymer concentrations were progressively reduced to zero and, subsequently, trials with nitrogen foam to improve flowback were used. Those practices were discontinued for the most part by the mid-1990's. The breakthrough came in 1997, when Mitchell Energy (subsequently bought out by Devon Energy in early 2002) realized that much less expensive slickwater completions with small amounts of sand proppant would produce as much gas as the extremely expensive gel frac jobs. These frac jobs are called "slick water frac" or "light sand frac." Very large amounts of fresh water are injected in a short time period (~1 day). Water is injected at a high rate of 60 to 80 bbl/min (2,520–3,360 gpm) (e.g., Ketter et al., 2006) in a 5.5-inch casing, or possibly even higher 140 bbl/min (5,880 gpm) (Lohoefer et al., 2006) in a larger casing (7 inches). In essence, a high flow rate of fresh water has replaced the higher viscosity of previous fluids to keep proppant particles moving with the fluid. Slickwater completion does not generate gel damage (such damage limits gas diffusion from the fracture walls) or limit proppant banking (leaving unopened some sections of the fractures). Fresh water could also generate formation damage if water-sensitive clays were present (e.g., Mace et al., 2006), which is not the case in the Barnett Shale.

Since 2002, when the play started to expand out of the core area, horizontal well technology has become more widespread. Horizontal wells are more expensive to drill and develop but have better performance and larger production. The need for horizontal wells derives from the local geology. Operators' interest is to frac as much of a vertical section of the Barnett Shale as possible because production is clearly related the length of the frac'ed material. A frac job in the Lower Barnett section of the core area can be highly successful, even if it cracks into the underlying Viola-Simpson Formation. However, this formation acts as a barrier between the Ellenburger and the Barnett but pinches out SW of the core area. A frac job with a too-large rate or volume will frac into the Ellenburger Formation where the Viola buffer is absent. The permeability of the Ellenburger is relatively high and the less-than-successful frac job will put in direct communication the well bore and the Ellenburger water, leading to gas production problems and an unacceptable water cut. The solution put forward by operators is to use horizontal wells and multiple carefully sized frac stages. Those consequences also explain the general reluctance of operators to drill next to a fault. The frac job could access the fault and potentially connect the water-rich Ellenburger Formation to the newly drilled well bore through the intersected fault and the induced fracture. Such is apparently the case of the NE-SW-trending Mineral Wells Fault across the core area, where few wells have been drilled (Figure 7). Another geologic feature has also emerged of interest (details in Section V-1-2). Dolomites of the Ellenburger Formation are, at least in large areas underneath the Barnett Shale, paleokarsts—that is, cave-collapse cavities are common. Many of the resulting sags do impact the Barnett Shale, as well as other overlying formations (e.g., Hardage et al., 1996). Barnett Shale horizontal wells drilled through the faults of these collapse features could again encounter weakness zones prone to water flow and directly link the Ellenburger to the borehole. These features are common, and many early well failures could possibly be explained by them. Vertical wells are less likely to encounter a fault, even when they are drilled in the middle of a collapse structure, and are not as affected as horizontal wells.

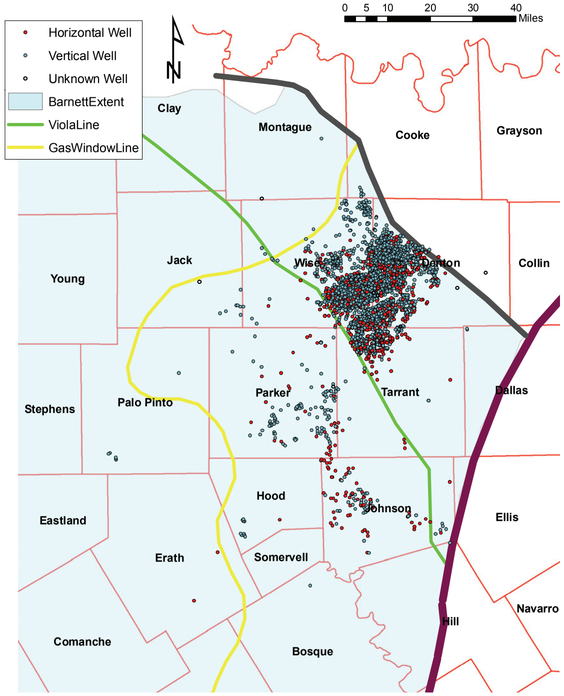
Figure 7a displays well spatial distribution at the onset of the slickwater frac technology in 1997. Following years (Figure 7b) do not show much spatial expansion because operators were busy refrac'ing wells completed using gel technology in the Lower Barnett, frac'ing the Upper Barnett, and doing some infill drilling. In 2001 and 2002 (Figure 7c), the play started to expand as horizontal well technology in the Barnett developed, but it was still confined mostly within the Viola Limestone footprint. Starting in 2002, but most obvious in 2003 and following years (Figure 7d and e), horizontal well technology allowed operators to jump over the Viola pinch-out and start producing from other areas in the gas window, mainly toward the south in Parker and Johnson Counties. On the other hand, the urbanized areas of Fort Worth in Tarrant County, although now technologically accessible by either vertical (because of the Viola footprint) or horizontal wells have been much slower to develop because of administrative issues (local ordinances limiting drilling, mineral rights more time-consuming to determine, access difficulties owing to buildings, resistance of local residents, etc.).



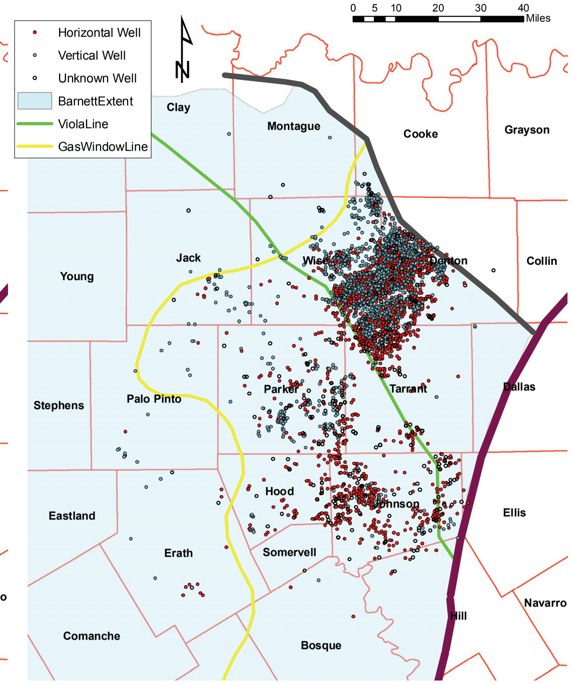
(a) (b) (c)

Data from drilling info.com

Figure 7 Wells drilled (a) up to 1997 (included), (b) up to 2000 (included), and (c) up to 2002 (included)



(d)



(e)

Data from drillinginfo.com

Figure 7 (continued). Wells drilled (d) up to 2004 (included) and (e) up to summer 2006

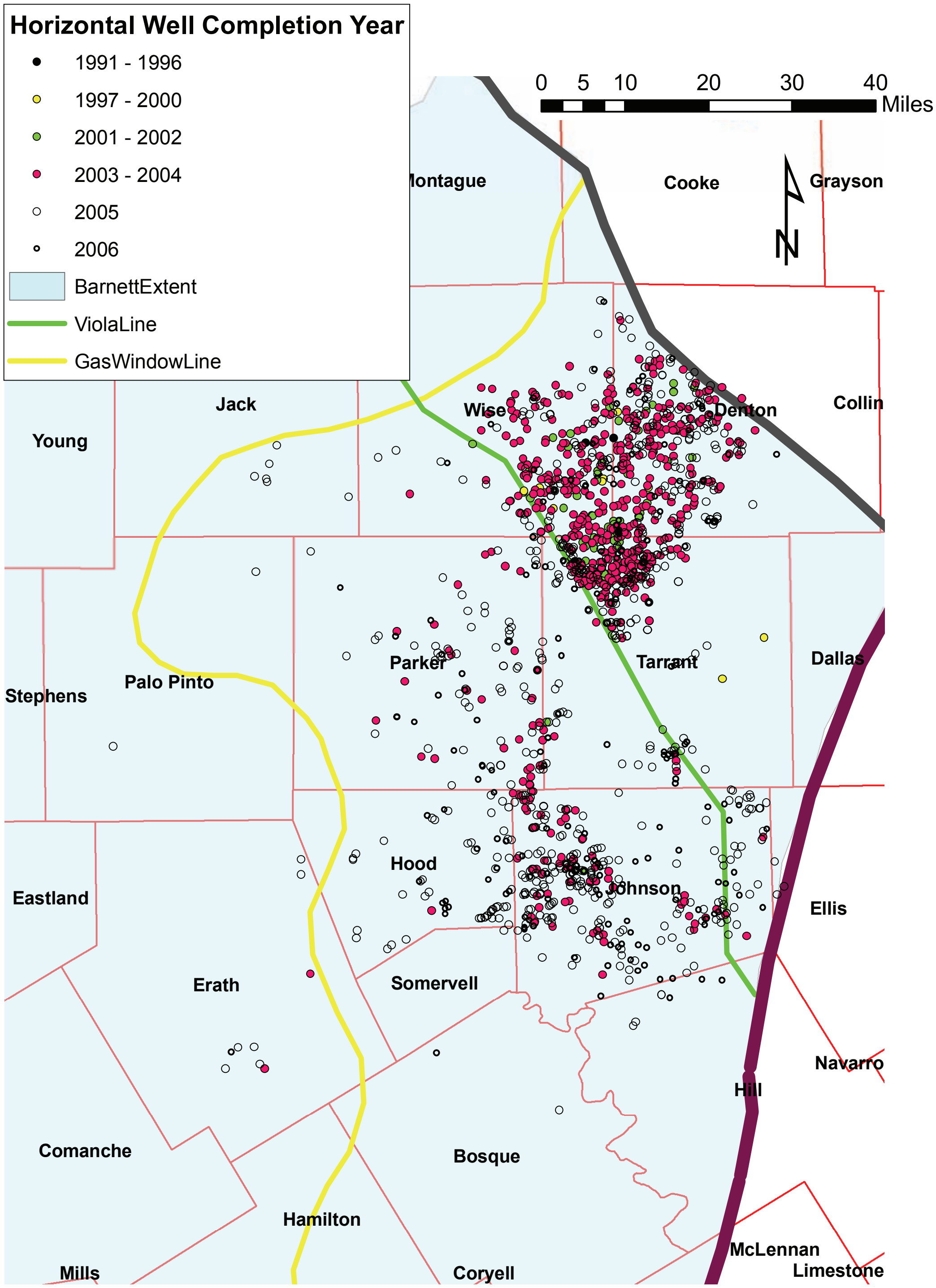


Figure 8 Spatial and temporal distribution of horizontal wells

Historical Water Use

Water use information is derived from drillinginfo.com and IHS Energy (Table 1) from which ground water use can be estimated (Table 2). Water use has quickly increased from ~700 AF in 2000 to more than 7,000 AF in 2005. The trend and partial numbers suggest an even higher water use in 2006.

Table 1 2000-2005 Historical Water Use in the Barnett Shale (all sources, AF/yr)

County Polygon	2000	2001	2002	2003	2004	2005
Bosque	0.0	0.0	0.0	0.0	0.0	3.3
ClayH	0.0	0.0	0.0	0.0	0.0	0
ClayV	0.0	10.7	0.7	0.0	0.0	0
Comanche	0.0	0.0	0.0	0.0	0.0	0
Cooke	0.0	0.0	0.0	9.6	22.9	47.5
Coryell	0.0	0.0	0.0	0.0	0.0	0
Dallas	0.0	0.0	0.0	0.0	0.0	0
DentonR	371.8	1,191.5	1,837.2	1,966.2	1,700.6	1,784.0
DentonU	0.0	0.0	4.4	3.2	6.8	210.2
Ellis	0.0	0.0	0.0	0.0	0.0	18.3
Erath	0.0	0.0	0.0	0.0	1.6	22.7
Hamilton	0.0	0.0	0.0	0.0	0.0	0
Hill	0.0	0.0	0.0	0.0	0.0	0
Hood	0.0	2.3	4.3	0.0	11.4	316.6
Jack	0.0	6.0	2.6	8.7	15.9	38.1
JohnsonH	0.0	0.0	109.0	57.9	508.9	1,626.8
JohnsonV	0.0	0.0	0.0	4.4	0.0	189.0
McLennan	0.0	0.0	0.0	0.0	0.0	0
Montague	0.0	5.5	7.3	33.4	3.2	59.5
Palo Pinto	0.0	0.0	0.7	0.4	0.9	8.8
Parker	0.0	7.5	14.3	37.4	212.6	695.4
Somervell	0.0	0.0	0.0	0.0	0.0	10.6
TarrantH	0.0	0.0	2.7	10.6	61.7	257.1
TarrantVR	3.1	41.1	371.2	318.5	435.8	423.8
TarrantVU	0.0	0.0	27.5	167.5	335.6	565.2
WiseH	0.0	23.9	8.9	24.0	43.6	84.2
WiseV	327.5	517.9	935.3	1,146.0	906.2	843.1
Total	**702.4**	**1,806.5**	**3,325.8**	**3,787.8**	**4,267.6**	**7,214.3**

*Note: County polygons are defined in Section V. H=Horizontal, V=Viola, R=Rural, U=Urban; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting)

Table 2 2000-2005 Estimated Historical Groundwater Use in the Barnett Shale (AF/yr)

County Polygon	2000	2001	2002	2003	2004	2005
Bosque	0.0	0.0	0.0	0.0	0.0	2.0
ClayH	0.0	0.0	0.0	0.0	0.0	0.0
ClayV	0.0	6.4	0.4	0.0	0.0	0.0
Comanche	0.0	0.0	0.0	0.0	0.0	0.0
Cooke	0.0	0.0	0.0	5.7	13.8	28.5
Coryell	0.0	0.0	0.0	0.0	0.0	0.0
Dallas	0.0	0.0	0.0	0.0	0.0	0.0
DentonR	214.5	687.5	1,062.2	1,139.7	988.1	1,070.4
DentonU	0.0	0.0	4.7	3.7	3.9	126.1
Ellis	0.0	0.0	0.0	0.0	0.0	11.0
Erath	0.0	0.0	0.0	0.0	1.0	13.6
Hamilton	0.0	0.0	0.0	0.0	0.0	0.0
Hill	0.0	0.0	0.0	0.0	0.0	0.0
Hood	0.0	1.2	2.2	0.0	5.8	190.0
Jack	0.0	3.6	1.5	5.2	9.5	22.9
JohnsonH	0.0	0.0	58.6	31.2	282.4	976.1
JohnsonV	0.0	0.0	0.0	2.3	0.0	113.4
McLennan	0.0	0.0	0.0	0.0	0.0	0.0
Montague	0.0	5.0	6.5	30.0	2.9	35.7
Palo Pinto	0.0	0.0	0.4	0.2	1.1	5.3
Parker	0.0	5.5	10.4	27.3	155.4	417.3
Somervell	0.0	0.0	0.0	0.0	0.0	6.4
TarrantH	0.0	0.0	1.2	4.8	27.7	154.3
TarrantVR	1.4	18.5	167.0	143.3	196.1	254.3
TarrantVU	0.0	0.0	12.4	75.4	151.0	339.1
WiseH	0.0	14.2	5.3	14.2	25.8	50.5
WiseV	193.9	306.6	555.8	678.4	536.4	505.9
Total	**409.8**	**1,048.4**	**1,888.6**	**2,161.6**	**2,401.0**	**4,322.6**

*Note: County polygons are defined in Section V. H=Horizontal, V=Viola, R=Rural, U=Urban; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting). Ground water use was estimated from total water use (Table 1) to which county ground water use coefficient from Table 11 is applied, except for year 2005 where a blanket 60% coefficient is used

A Few Relevant Numbers: Amount of Water Used per Well

The technology is fast progressing, with numerous operators still seeking out the best approach. Papers sometimes publish contradictory statements, but a few general rules can be derived. This section first cites water-use data from a few selected papers. We then derive our own numbers from drillinginfo.com and IHS Energy databases and contrast them with information provided by Galusky (2006). We conclude that data from all sources are consistent.

Literature Review

Early in the development of horizontal wells, short laterals were uncemented. Longer horizontal sections that required multiple frac stages were cemented. Cemented horizontal wells are now the most common type of well (Ketter et al., 2006; Lohoefer et al., 2006). Large (>4 MGal) single water fracs have been performed on uncemented wells (Fisher et al., 2004), whereas the current trend is to do multistage frac jobs on several perforation clusters at once (in the 1–2.5 MGal range) instead of numerous smaller frac jobs on each cluster (~0.5 MGal) (Fisher et al., 2004). Ketter et al. (2006) suggested that the number of frac stages for horizontal wells is, on average, around three and that each stage is 400 to 600 ft long. In the vertical wells of the core area, two main stages, one in the Upper Barnett and one in the Lower Barnett, can be implemented when the Forestburg Limestone exists (Figure 3). Depending on the number of other limestone intervals, more stages may be needed.

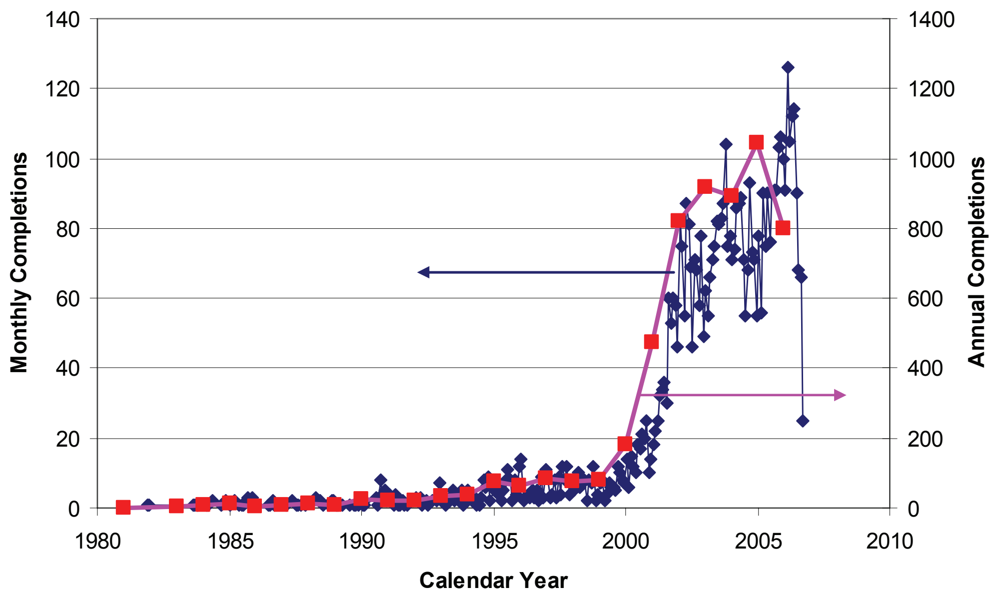
Lohoefer et al. (2006) mentioned a seven-stage completion over 3,300 ft, (that is, ~470 ft/stage) for the API#42-121-32350 well in Denton County using up 111,314 bbl (1,417 gal/ft). Montgomery et al. (2005, p.171) also cited stage lengths varying from 500 to more than 3,500 ft, as well as treatment volume varying from 0.5 MGal to more than 2 MGal. It is clear that the amount of water used in a multistage stimulation varies widely. It follows that it is not the best metric to use for water use projections. Water use per unit length of lateral is an intensive metric that speaks more to the user and that is more easily scalable to future wells. Grieser et al. (2006) presented statistics from ~400 wells, half using a crosslinked gel approach and half using the newer slickwater approach. Their data-set slickwater volumes range from 564,000 to 1,575,000 gallons, with an average of 929,139 gallons and 3,282 gal/ft of lateral. Schein et al. (2004) put forward a water-use value of 2,000 to 2,400 gal/ft for water fracs.

Statistical Analysis of the RRC Database

We analyzed the RRC database as communicated by drillinginfo.com and IHS Energy. The first well intended to test the Barnett Shale was drilled in 1981, and the number of total completions stayed below 100 until 1991. The number of annual completions then rose steadily, to reach more than 1,000 for the first time in

2005 (Figure 9). Projections for 2006 suggest that this number will be exceeded in 2006. The first-order sorting of the completion job involves vertical wells (mainly in the core area) vs. horizontal wells. A second level of classification involving mainly the vertical wells is the 1997 date. Before that date, most wells were treated using a technology that is currently considered inappropriate for the Barnett Shale play. Consequently, data on these wells was not used to develop predictions.

The total number of wells (Table 3) completed in the Barnett Shale is over 5,000 (~5,600 wells as of November 3, 2006, according to IHS Energy, including ~10 completed in the Delaware Basin). Numbers may vary depending on the inclusion of only dry gas wells and/or wells with condensate. The vast majority of these wells were drilled in Denton and Wise Counties (~1,600 and ~1,800, respectively), followed by Tarrant County (~700 wells) and Johnson and Parker Counties (Table 4).



Drop in 2006 is due to incomplete reporting

Figure 9 Historical annual and monthly completions in the Barnett Shale

Table 3 Annual completion statistics in the Barnett Shale

Year	DrillingInfo / IHS Energy			
	H	V	U	Total
≤2000	14	703	42	759
2001	22	424	27	473
2002	50	745	23	818
2003	195	685	38	918
2004	359	430	100	889
2005	679	242	122	1043
Total	1319	3229	352	4900

H = horizontal wells; V = vertical wells; U = unknown

Table 4 Barnett Shale well statistics by county

	Bosque	Cooke	Dallas	Denton	Ellis	Erath	Hamilton	Hill	Hood	Jack	Johnson	Montague	Palo Pinto	Parker	Somervell	Tarrant	Wise
1981																	1
1982																	
1983																	2
1984																	6
1985																	13
1986				1													5
1987																	6
1988				1												1	10
1989				3													4
1990				6													19
1991				5													15
1992				2							1						16
1993				11								2				3	16
1994				16													23
1995				24													50
1996				31													32
1997			2	8							1					1	68
1998				22							2					4	49
1999				21												1	59
2000				93												1	87
2001		2		269			1		2	6		7		5		15	159
2002				427					7	3	6	8	1	7		110	248
2003		4		398						7	18	13	2	16		153	306
2004		8		267		1			1	16	78	4	6	87		202	218
2005	1	14		216	3	9			44	30	217	15	10	108	1	213	162
2006	2	11		136		21		19	49	13	215	20	4		1	108	90
Sum to '05	1	28	2	1821	3	10	1	0	54	62	323	49	19	223	1	704	1574

A compilation of data on these wells, in which water use and location information are available, shows that a sizable percentage of frac jobs performed on vertical wells range from 1 to 1.5 MGal/well (Figure 10). The numbers represent the sum of water use in all stages performed on a given well at a given date. The distribution was computed on the basis of the 5 previous years, to which results available from 2006 were added. It is thought that vertical-well frac technology is mature enough to have (at least temporarily) stabilized in its water use. On the other hand, horizontal well technology, as applied to the Barnett play, is still evolving, and only those frac jobs performed in 2005 and 2006 were included in the histogram (Figure 11). If vertical well water use was clearly unimodal, the distribution of water use for horizontal wells appears much noisier and has a much larger spread with multiple peaks. One of the reasons could be that, contrary to vertical wells, whose length is constrained by the thickness of the formation, horizontal-well laterals can be made as long as technology allows. It follows that a better metric for water use in horizontal wells is water-use "intensity," or water volume per unit length (gal/ft) (Figure 12). The transformation filtered out some noise from the raw number distribution and appears now to be unimodal. Although using the mode as a representative value is tempting, it probably underestimates the true average because of the long tail on the high values clearly visible on the histograms. On the other hand, taking a simple average of the results is not a robust solution because instances where water use had extra zeros or units were reported as barrels instead of gallons have been observed. This practice will tend to overestimate the true average. Undoubtedly, a similar difficulty can happen on the low side when a digit is not entered or when the unit is entered as a gallon instead of a barrel. The solution was to use the average of those frac jobs composing between the 10^{th} and 90^{th} percentiles.

The raw average and average of the values between the 10^{th} and 90^{th} percentiles for vertical wells is 1.25 and 1.19 MGal, respectively. A value of 1.2 MGal is retained. The raw average for horizontal wells (2005–2006) is 3.07 MGal/well, whereas the truncated average is 2.65 MGal/well. Water-use intensity raw average is ~10,000 gal/ft, obviously biased by inaccurate entries, either in water use or in lateral-length columns. The averages of values truncated beyond two complementary percentiles vary somewhat because of the additional uncertainty due to the lateral length, although a value of 2,400 gal/ft seems conservatively reasonable for the medium scenario. Values of 2,000 and 2,800 gal/ft are retained for low and high scenarios, respectively.

These numbers agree well with data provided by Galusky (2006). Average water use for vertical wells is given as 1.25 MGal/well, with no change in the 3 years considered (2005–2007) and no variations across counties. Average water use for horizontal wells varies from 3.30 MGal/well in 2005 to 3.23 MGal/well in 2006 and is projected to be 3.25 MGal/well in 2007, with an overall approximate average of 3.25 MGal/well. The survey seems to suggest an increase in water use in horizontal wells, although it is unclear whether it is due to a true increase or to longer laterals. Galusky (2006, personal communication) proposed an average lateral length of 1,800 to 2,000 ft/well. Using year 2007 projections as representative of current technologies, this datum translates into 1,625 to 1,805 gal/ft of lateral. This number is consistent with the mode of the distribution, as displayed in Figure 12. It is likely that operators have to use more water in some locations, as illustrated by the long tail of Figure 12, yielding an average higher than that reported by Galusky (2006).

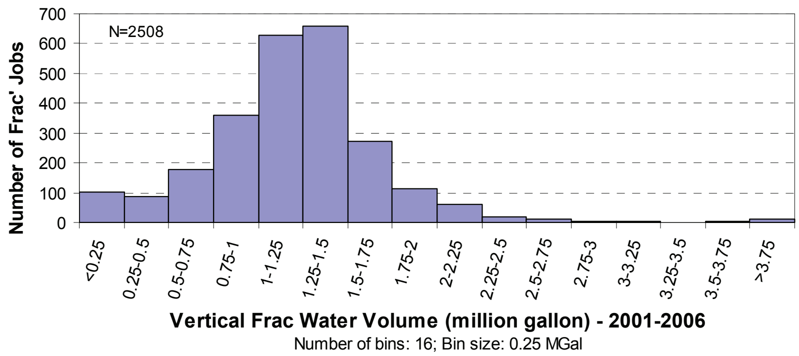


Figure 10 Distribution of water use for vertical-well frac jobs (all water sources)

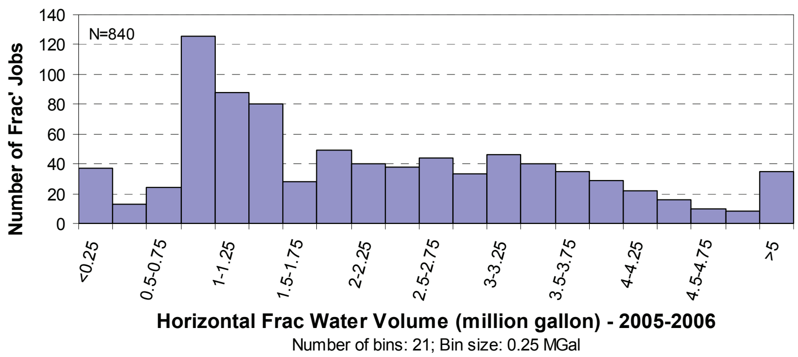


Figure 11 Distribution of water use for horizontal-well frac jobs (all water sources)

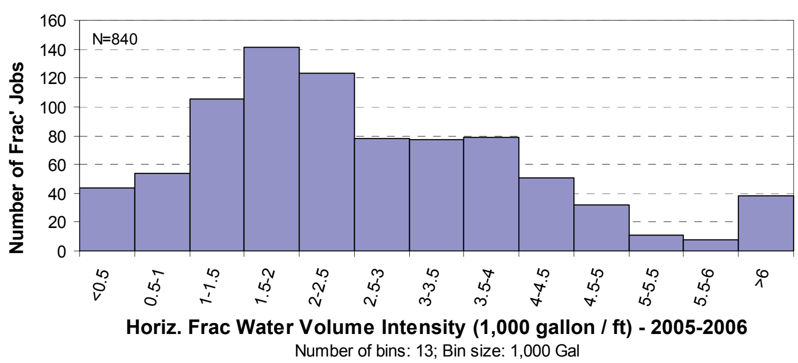


Figure 12 Distribution of water use intensity for horizontal-well frac jobs (all water sources)

Water-Use Projections

Projections of water use hinge on an understanding of both geology and technological controls and advances. Regional features, regional faulting, formation thickness, thermal maturity, and cave-collapse features fall into the former category, whereas water restimulation, recycling, water-use intensity, and well spacing drive the latter. One can add regulatory control. RRC regulations prohibit pollution of surface and subsurface water during drilling, treating, producing, and plugging of oil and gas wells. In McCulloch, San Saba, and parts of Lampasas and Burnet Counties, the Cambrian Hickory and Ellenburger aquifers are a potential source (with or without treatment) of drinkable water (see 3,000-ppm concentration contour in Figure 1).

For all parameters, we defined high, medium, and low scenarios at the county polygon level, mostly on the basis of geologic and cultural constraints. We then add time-dependent constraints: availability of drilling rigs, growth of recycling techniques, and recompletion frequency. Projections are done on an annual basis, the final product of this report being annual water use by county polygons (defined in the next section). The reader should not focus on projections for a given year but, rather, on cumulative water use within a few years' range. In any case, a regional groundwater model, such as the GAM model, is not too sensitive to temporal pumping details, but more to their cumulative impact.

Given a much larger data set, projections would be done by developing parameter distribution and their correlations. Correlations appear when parameters are interdependent. For example, if gas price is high, the play could be drilled out at a small spacing that will generate competition for water and, consequently, a strong incentive to develop technologies frugal in terms of water use, as well as to recycle used water. Unfortunately, the short history of drilling in gas-rich-shale unconventional resources precludes the development of statistics that could be safely applied to the next 20 years. On the contrary, we made a lot of judgment calls that we think are reasonable and defensible but that do not necessarily include all plausible scenarios.

IMPACT OF GEOLOGIC FEATURES

Regional Features

In addition to gas prices, extension of gas production in the Barnett Shale is ultimately controlled by geology. Assuming adequate thickness and total organic carbon content, the single most important parameter is thermal maturity. Oil and gas formation requires that the source organic matter be exposed to elevated temperatures long enough for the kerogen to mature. It could occur by simple deepening of the basin. The core area of the Barnett Shale was indeed buried to a depth >10,000 ft (Montgomery et al., 2005) and subsequently uplifted. However, it seems that the burial depth is not the only control on Barnett organic matter maturity. The story is more complex, involving in particular hot fluid circulation. It follows that the rock potential for hydrocarbon generation is spatially complicated in the details and not yet well known and that a lot will be learned during exploration/production.

An indirect way to assess rock potential is to examine vitrinite-reflectance values (measured by a parameter called R0) of the rock. Gas-prone areas producing mostly dry gas are present toward the east in the basin, along the Ouachita thrust fold belt, with a R0>1.4%. Maturity levels are more favorable for gas generation along an NNE-SSW axis parallel to the Ouachita structural belt from Denton to Tarrant to Somervell to Hamilton to San Saba Counties (Pollastro et al., 2003, Fig.3), and it is reasonable to assume that the play will preferentially grow in that direction. This observation is also consistent with the vitrinite-reflectance map presented in Montgomery et al. (2005, Fig. 6). Moving toward the west, still within the gas window, R0 is in the 1.1 to 1.4% range and the Barnett Shale can produce both gas and condensate (wet gas). More oil-prone production is less economically attractive because of the complexities of multiphase flow in extremely low permeability porous media and in particular the oil's ability to plug pores and block gas flow. Farther west still, in the western Forth Worth Basin, over the Bend Arch and beyond, the Barnett Shale has generated oil which has been commercially produced from traps in different formations (Jarvie et al., 2001), and it is not conducive to gas generation but to oil generation. Givens and Zhao (2005) stated that Tarrant, Johnson, Hood, Somervell, Bosque, most of Wise and Parker and parts of Dallas, Denton, and Ellis Counties are interpreted to be in the gas window, whereas Clay, Montague, Cooke, and most of Jack Counties are in the oil window. Counties between oil-prone and gas-prone areas are expected to produce a mix of oil and gas. Examining maps of Montgomery et al. (2005), we can add parts of Palo Pinto, Erath, Hamilton, Coryell, McLennan, and Hill Counties as belonging to the transition between oil and gas. On the west and south edges of the play, the Barnett Shale may be too thin. However, the minimum productive thickness of the Barnett has not yet been established but is possibly less than 100 feet.

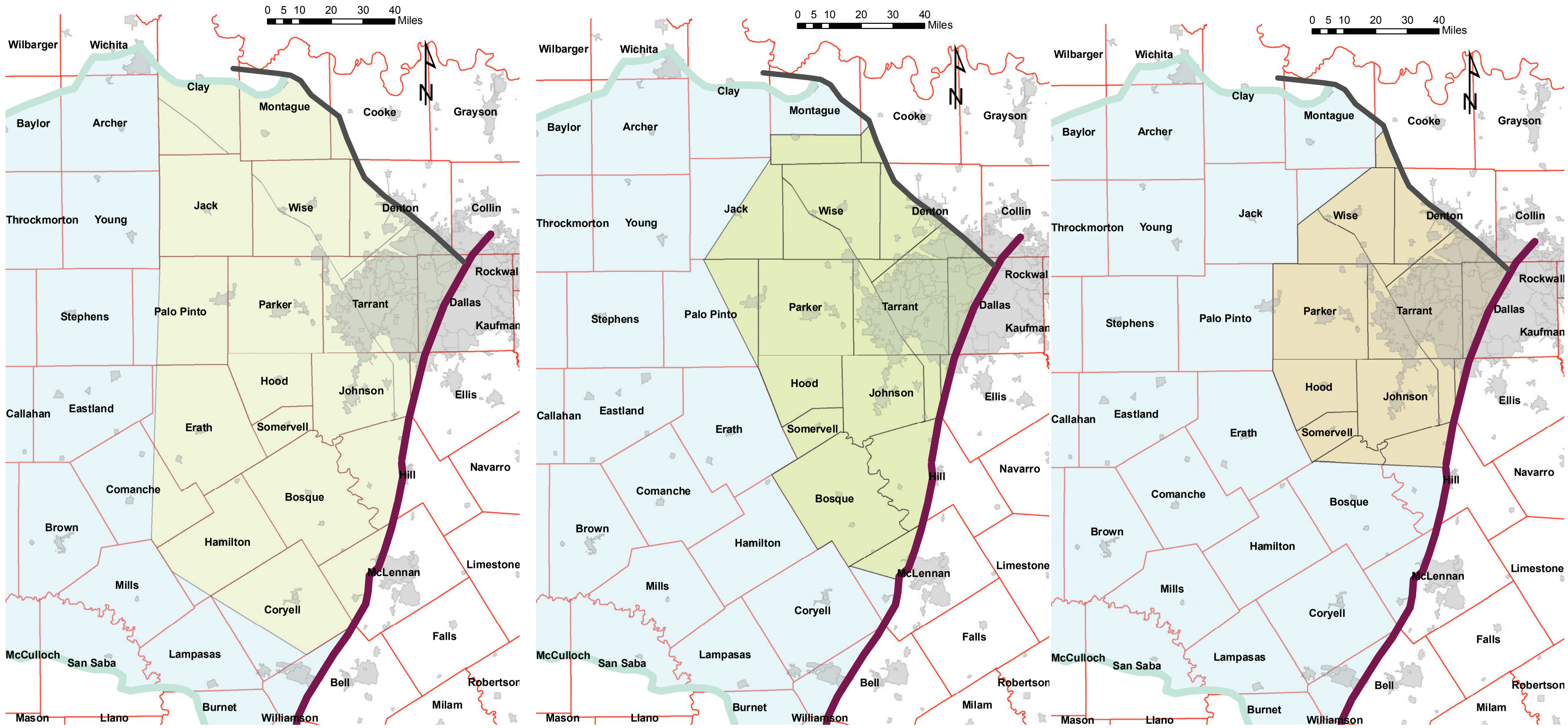
High, medium, and low scenarios for the ultimate extent of the play (Figure 13 and Figure 14) were drawn by integrating knowledge (and uncertainty) about the boundary of the gas window, thickness of the formation, current exploration trends, and economic yield of wells. Histograms in Figure 15 illustrate the differences in surface area of the various counties that will translate later in the report into water use differences even at similar well density. The high scenario represents the maximum extent of the play if gas prices stay acceptable. The low scenario corresponds to a case where gas prices are low and operators retreat to an area of the Barnett in which they know that the Barnett responds well and where they could carry out infill drilling and recompletions. The medium scenario is intermediate. Because the Barnett Shale play is dependent on gas prices, it is not appropriate to say that the medium case is the most likely. A more accurate statement would be to formulate that the medium case is the most likely under the condition that gas prices stay at their current level.

Table 5 presents a summary of ranges of all parameters to be developed in the following sections and relevant to computing projections.

Table 5 Summary description of parameters used in the water-use projections

Category	Comment	High Water Use	Medium Water Use	Low Water Use
County Polygon	There are three binary variable couples: rural/urban—horizontal/vertical wells—within Viola footprint or not, resulting in four main categories: Viola/urban (only horizontal wells) Viola/rural (both horizontal and vertical wells) No Viola/urban (only horizontal wells) No Viola/rural (only horizontal wells)			
Footprint Fraction	A county polygon cannot be covered by more than 90% (vertical wells) or 80% (horizontal wells) of the maximum possible well coverage.			
Vertical Well Spacing		1 well/40 acres	0.5 well/40 acres	0.25 well/40 acres
Horizontal Well Lateral Spacing	No Viola and/or urban	800 feet	1,000 feet	2,000 feet
	Viola rural	800 × 4 feet	1,000x4 feet	2,000 ×4 feet
Sag Feature Avoidance (“Karst”)	Vertical well	100%		
	Horizontal well	100%	75%	40%
Average Water Use	Vertical well	1.2 million gallons		
	Horizontal well (spread reflects uncertainty)	3,000 gal/ft	2,100 gal/ft	1,500 gal/ft
Water-Use Progress Factor[A]	(variations reflect technological progress)	1%	0%	0%
		Water-use annual incremental improvement as a fraction of total water use, e.g., 100% of current use in 2005 with a 1% increment translates into 80% of water use in 2025 compared with the same frac job executed in 2005.		
Recompletion	Vertical well	100%	50%	0%
		of initial completions executed 5 years before		
	Horizontal well	0%	0%	0%
Recycling[A]		1%	0.33%	0%
		Recycling annual increment as a fraction of total water use (e.g., 0% in 2005 with a 1% increment translates into 20% recycling in 2025).		
Maximum Number of Sustained Annual Completions		3,000 completions/year	2,100 completions/year	1,500 completions/year
Additional Water Use in Overlying Formations		0%	0%	0%
Barnett Groundwater Use Expressed as % of Total Barnett Water Use	In year 2005–2006	60%	60%	60%
	Annual increment in following years	2%	1%	0%
	In year 2025	100%	80%	60%

*Note: A These parameters do not maximize water use, but the likely competition for water in the high scenario case suggests that recycling and water-use intensity will get better through time.



(a) (b) (c)

Figure 13 Spatial definition of high (a), medium (b), and low (c) Barnett play development scenarios

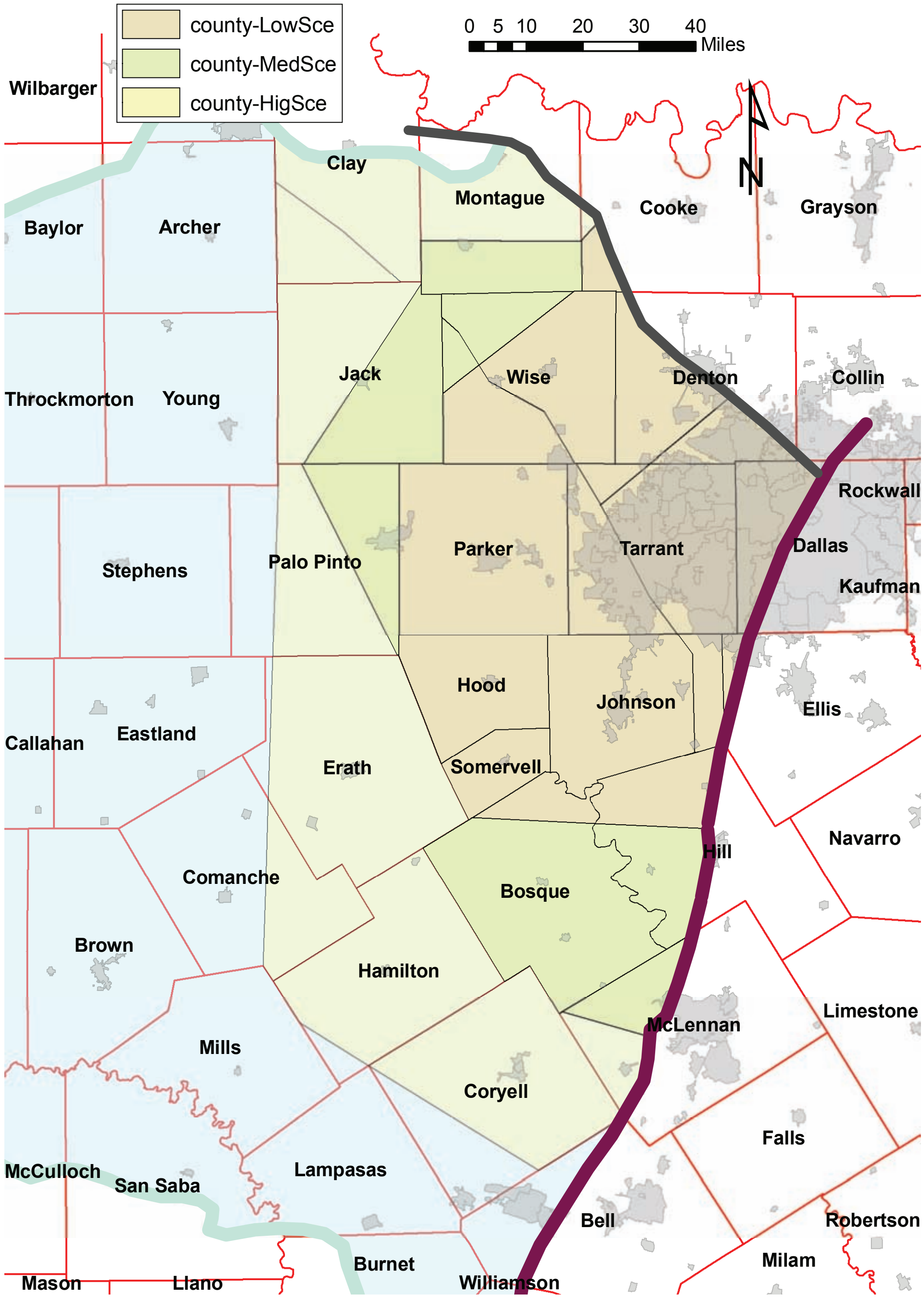
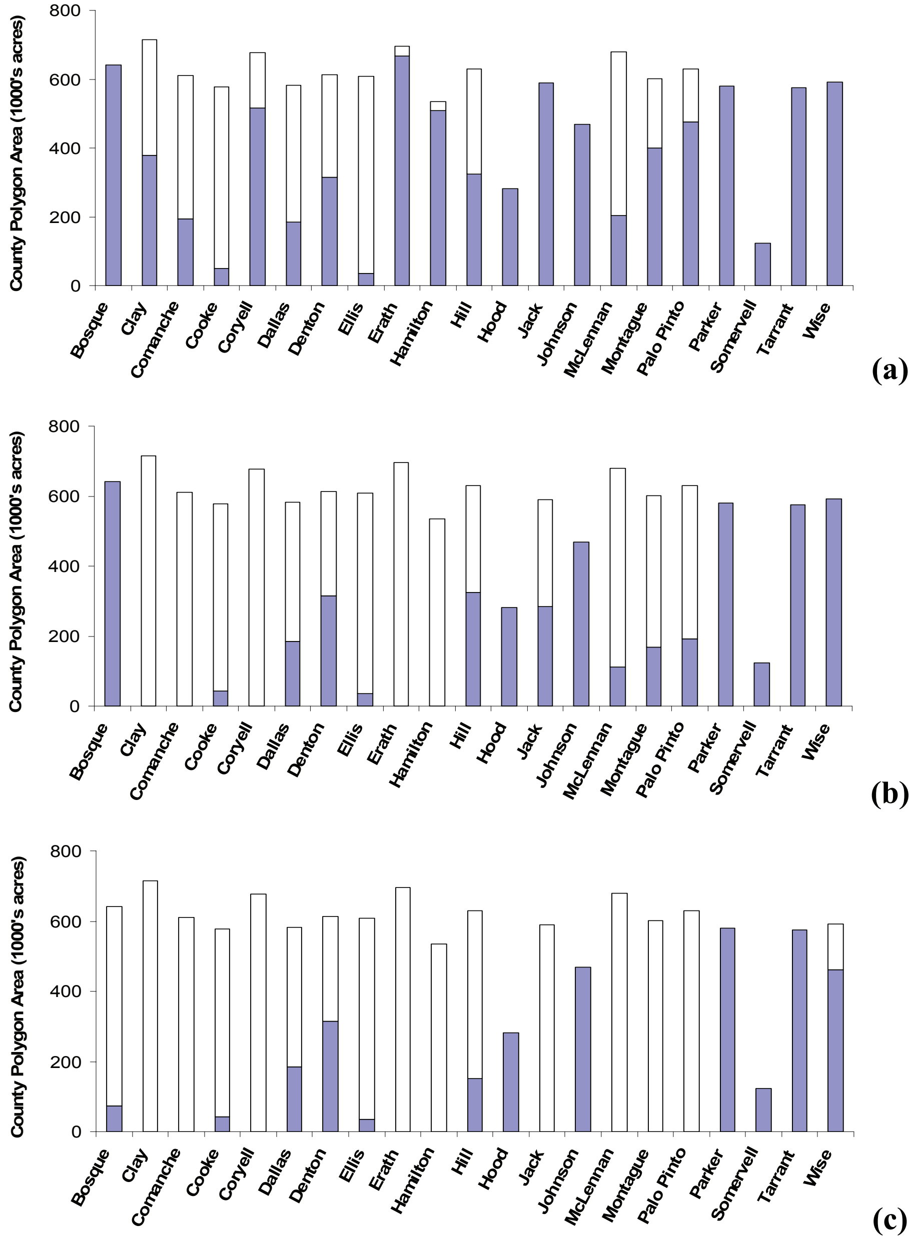


Figure 14 Spatial definition of high, medium, and low scenarios (combined)



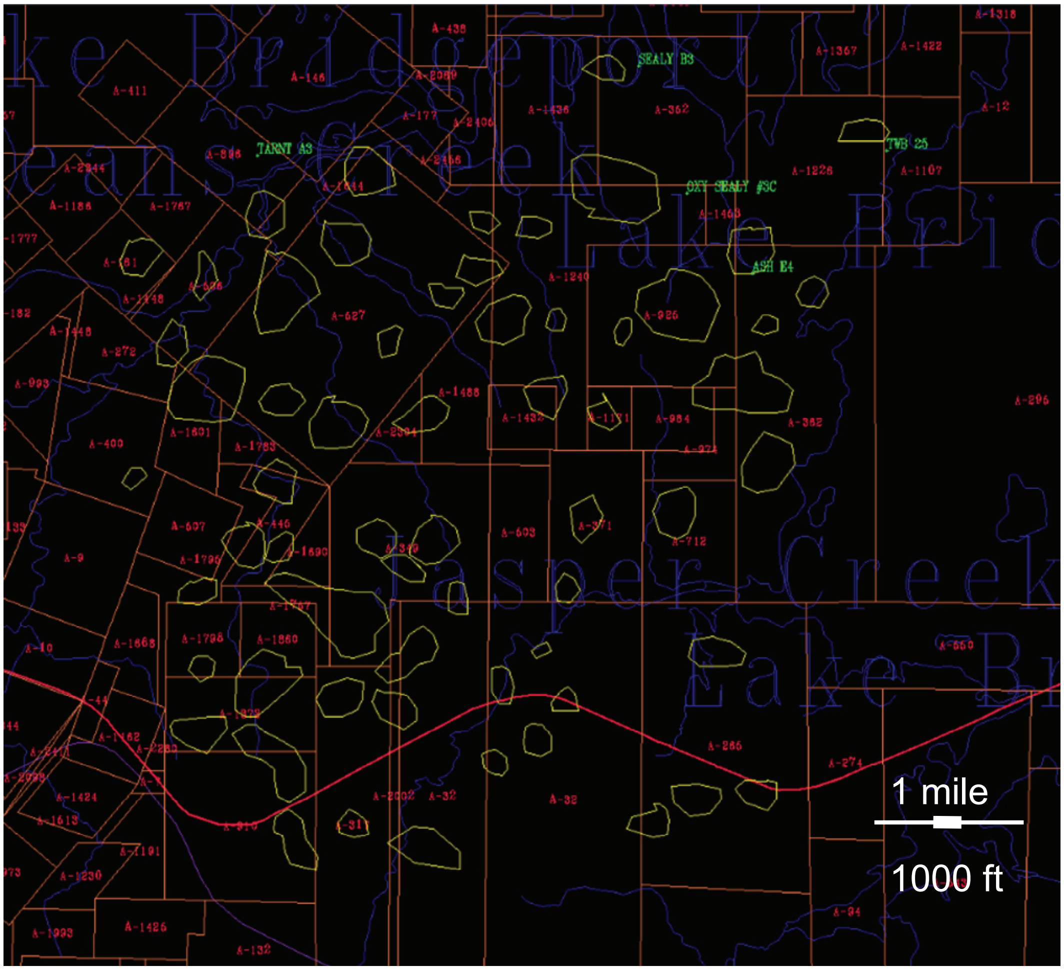
*Note: Projected gas-producing fraction of county is filled

Figure 15 Bar plot of counties in the high (a), medium (b), and low (c) Barnet Play development scenarios

Sags Over Cave-Collapse “Karst” Features

Operators switched to horizontal drilling west of the Viola pinch-out because of the negative impact of the water-rich wet Ellenburger on gas productivity. This behavior of the Ellenburger Formation is due to its collapsed caverns. It has been observed, mostly through seismic, that the caverns, although initially devoid of rock, have subsequently collapsed (Figure 16). The collapse-related features propagated into the overlying formations and occurred along newly created small faults at the periphery of the collapse. The small faults, intercepted by horizontal drilling, would then put in communication the formation water in the Ellenburger and the horizontal borehole. Hardage et al. (1996), in a study of Ellenburger karstic features on a 26-mi2 area straddling the Jack-Wise County limits, just west of the Barnett Shale core area, found that they tend to be circular (sometimes improperly called breccia pipes), with a diameter varying between 500 and up to 3,000 ft in some cases. The features were spaced at a high spatial density, between 2,000 and 6,000 ft apart, on average, and sometimes aligned on a NW-SE trend. Observation of the same structures cropping out near El Paso, Texas, suggests that the feature is widespread in the Ellenburger and thus may impact the Barnett Shale throughout its extent. Loucks et al. (2004) conducted a recent study on Ellenburger subcrops in Central Texas showing similar results. Recent work by A. McDonnell (BEG, personal communication, 2006) and McDonnell (2006a and b) confirms both the size of the structures (1,500–4,500 ft in diameter) and their alignment along NW-SE and NE-SW structural trends by looking at their impact on the Bend Conglomerate. Givens and Zhao (2005) provided a map of areas more karsted than elsewhere. However, there is little public information to support it. Consequently, we make no assumption about the geographic distribution of collapse features but rather assume that they are evenly distributed throughout the Barnett. The assumption is reasonable because the basis for the projections is a county, or at least large fractions of counties, which averages spatial variations. Figure 16 illustrates the shapes of the sags related to collapse features in one location. The current understanding of the Ellenburger karst does not allow concluding whether the picture, created from the study by McDonnell (2006a and b), is representative of the Ellenburger as a whole or where it sits relative to the collapse-structure density spectrum.

Cavern/collapse features are considered a hazard that must be avoided, although apparently a few operators are considering drilling horizontal wells through them to learn how to deal with them. We applied a sag avoidance factor (only to horizontal wells), measuring the fraction of the area left undrilled because of the collapse features. In the high scenario case, we assumed that technology overcame the problem (100% of the area is drilled). The medium and low scenarios were given a factor of 75% and 40%, respectively. The choice of 75% is guided by the observation that on an areal basis about 25% of the Ellenburger is somehow impacted by these collapse features. The low scenario of 40% is based on a principle of precaution that operators would follow by staying farther away from the sag/collapse structures.



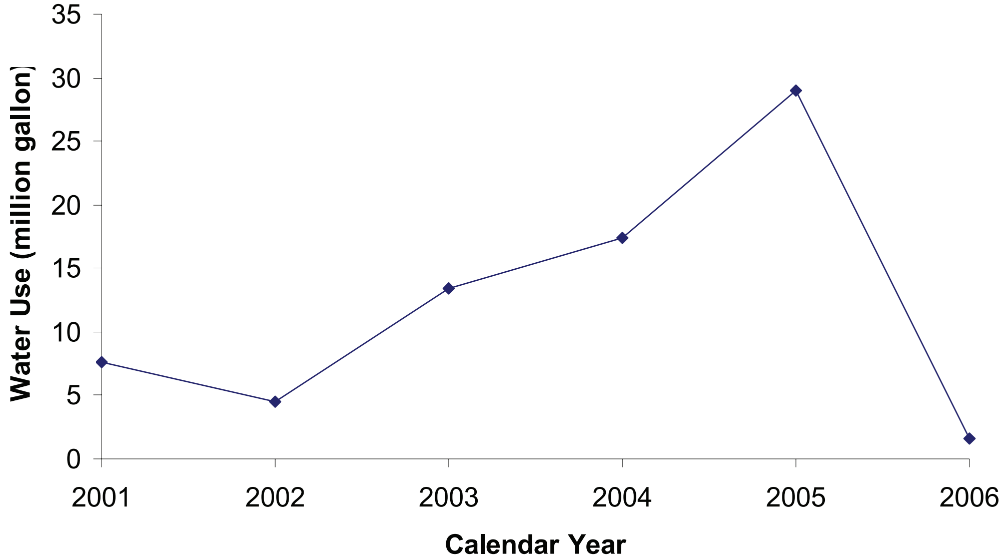
*Note: Example taken from the Wise/Jack County line. The picture may or may not be representative of the Ellenburger as a whole

Figure 16 Collapse features in the Ellenburger Formation from seismic survey

Development in Overlying Formations

A possible additional need for water is the development of the overlying Bend/Atoka Formation. These formations trapped gas migrating from the Barnett Shale. Water use in a six-county area (Denton, Tarrant, Wise, Jack, Palo Pinto, Erath), including those formations (Figure 19) in the 2001 to 2005 period, is only 74 MGal (221 AF), although increasing (Figure 17) probably by taking advantage of the infrastructure for frac jobs in the Barnett. Most of the frac jobs are typically small frac jobs (Figure 18). Only about 25 of them are comparable in size to those performed in the Barnett, with individual water use >0.5 MGal, making up about 85% of the 74 MGal.

These volumes are very small, compared with those used in the Barnett. Even a 10-fold increase of water use in the overlying formations (~300 MGal/yr, or 90 AF/yr using 2005 numbers) is much smaller than the noise in the Barnett data and the uncertainty in the Barnett projections. There is no need to include them in the calculations.



*Note: Incomplete data for 2006

Figure 17 Water use in a six-county area in the Atoka/Bend Formations (2001–2006)

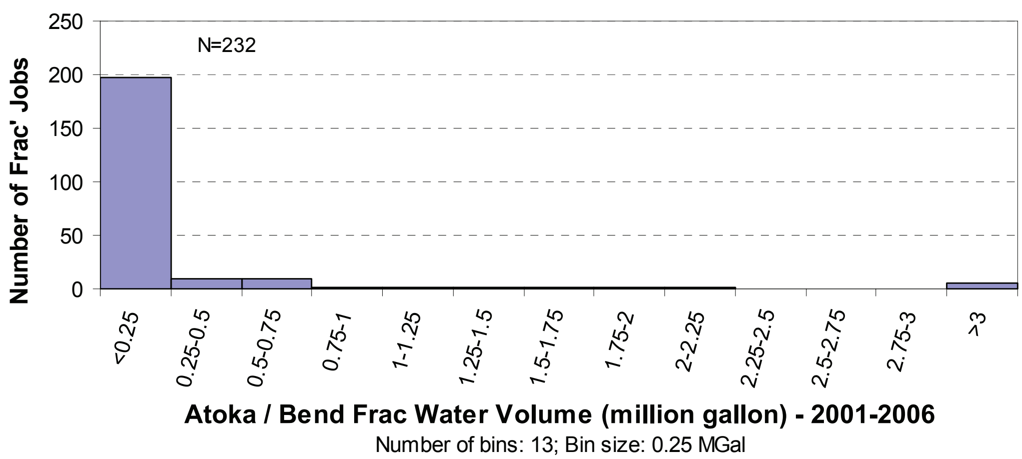


Figure 18 Distribution of water use in the six-county area in the Atoka /Bend Formation (2001–2006)

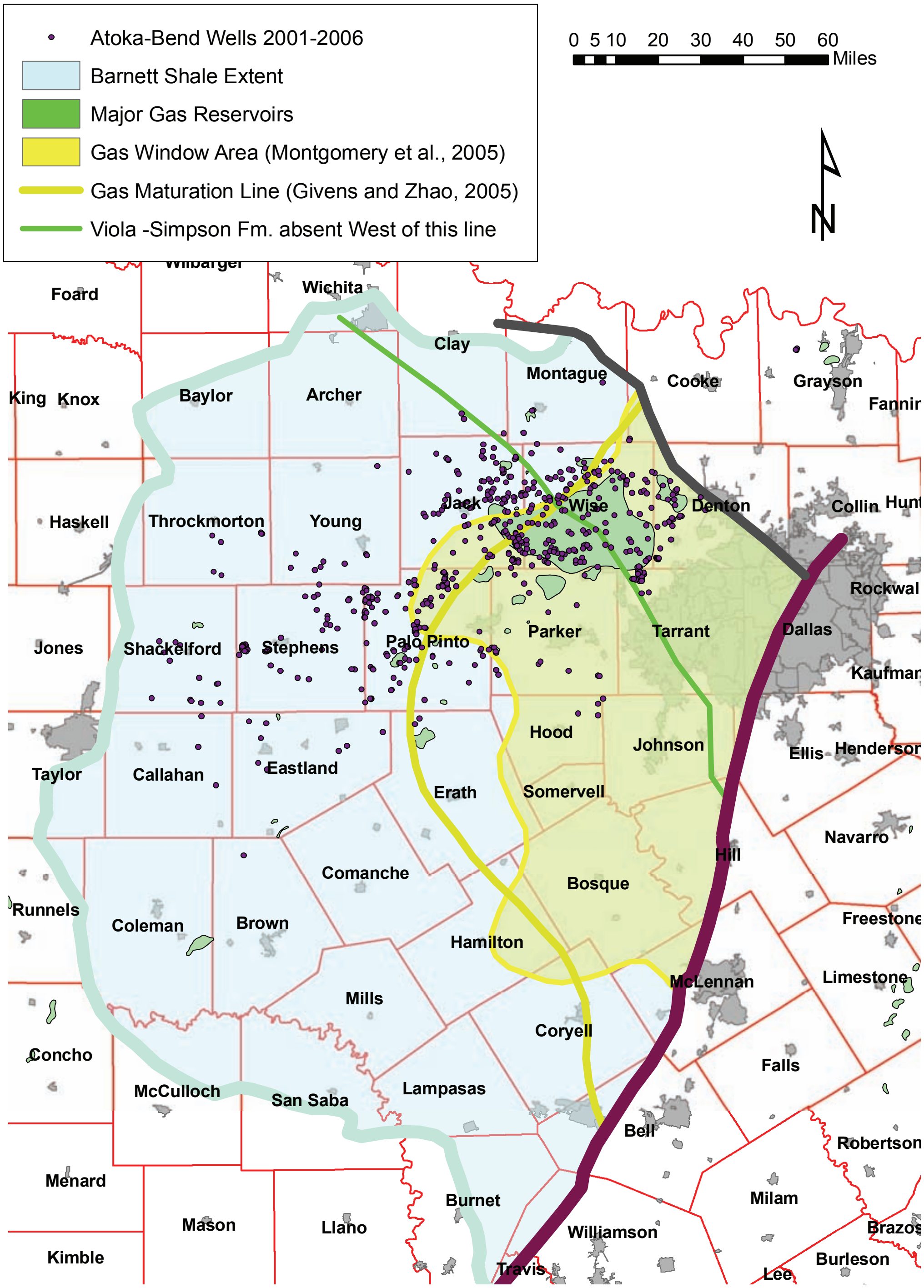
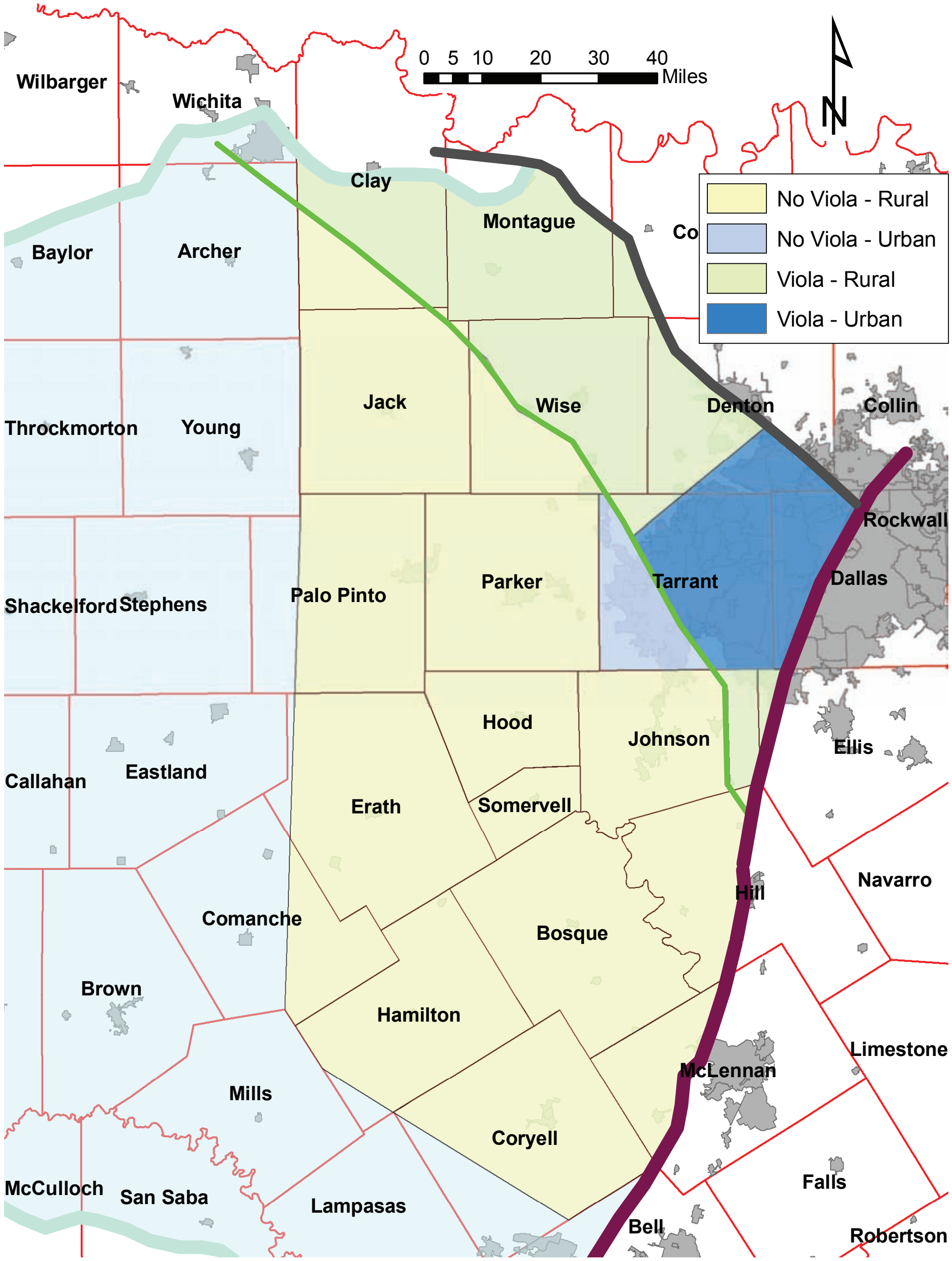


Figure 19 Recent (2001–2006) well completion in the Atoka/Bend Conglomerate of the Fort Worth Basin

TECHNOLOGICAL AND CULTURAL CONTROLS

Horizontal/Vertical Technology and Rural/Urban Environment

In the late 1990's. – early 2000's, the core area contained only vertical wells. When technology and operator technical abilities made horizontal well drilling successful, play prospects increased considerably. As explained earlier, the county unit is the basis for prediction work. However, because their boundaries do not match geology very well, we created multiple polygons in some counties using ArcView GIS software by superimposing geology and urban area limits.



*Note: Viola or no Viola denote the presence or absence of the Viola Limestone.

Figure 20 County polygons for water-use projections

The following categories resulted (Figure 20):

(1) No Viola—Rural: this category includes a large fraction of the high scenario area, most of it in early production stages or relatively unknown potential. All wells are horizontal because the absence of the Viola-Simpson Limestone generally precludes successful vertical frac job completions.

(2) No Viola—Urban: this category includes only the underdeveloped southwest third of Tarrant County. Lack of the Viola-Simpson Limestone, as well as urban environment, requires use of horizontal wells as in the previous category, but development will be slower.

(3) Viola—Rural: this category initially represented the core area (Wise and Denton Counties), that is, numerous vertical wells because of the presence of the Viola-Simpson Limestone and unimpeded by urban environment constraints. This category contains a combination of horizontal and vertical wells, as shown by the current infilling of the core area with horizontal wells. In addition to the core area, this category contains parts of two counties of limited potential, Clay and Montague, as well as a small sliver of Cooke County.

(4) Viola—Urban: this category encompasses the west half of the Dallas-Fort Worth metroplex. The current lack of development of this area illustrates the difficulties and challenges of urban drilling. The area will be developed with horizontal wells only but at a slower pace than that of the No Viola—Rural category.

Overall, development in urban areas is likely to be much slower because of cultural controls such as acquiring mineral rights, respect of local ordinances, and access issues.

Restimulation

Gas production is initially high after a frac job, but a steady decline quickly follows, relayed by a long sloping plateau in the decline curve. Operators have long noticed that a new frac job can lead to production level similar to or higher than that of the initial completion. Empirical evidence shows that refrac'ing wells every few years does improve the total production. It is thought that restimulation works because new fractures are created (e.g., Wright and Weijers, 1991) with a different orientation than the previous ones because the stress field, to which induced fractures respond, has changed. There are many examples of successful recompletions. Moore and Ramakrishnan (2006) showed an example of successful restimulation after 2.5 years of initial production. However, most of these cases deal with vertical wells.

As of the end of 2006, few if any horizontal well recompletions have occurred. Only some of those vertical wells initially not frac'ed with slickwater have been restimulated. It is uncertain whether any recompletion will occur in the future and if so, how often. Shirley (2002) suggested that re-fracing a well after approximately 5 years of production can be very beneficial. In the high water use scenario (Table 5), we assume very conservatively that all vertical wells are refrac'ed 5 years after their initial completion but only once: All wells completed before 2005 will have been refrac'ed by 2010. In the medium and low water use scenarios, we assume that 50% and 0% of the vertical wil be restimulated. We assume that horizontal wells will not be restimulated.

Recycling

Most used (flowback) water is currently hauled away to be injected into disposal wells with little recycling. It is estimated that approximately 30% of the frac water stays in the subsurface and that 70% flows back to the surface. About 30% of the injected water returns without too much of a quality decrease, whereas the remaining 40% is more degraded. It would seem less costly to treat the used water than to transport it to off-site disposal. In Wise County, it costs operators more than $40 per 1,000 gallons of water (~<$2/bbl) to transport and inject produced brine in saltwater-disposal facilities (Dave Burnet, Texas A&M, oral communication, 2004).

As of October 2006, three pilot tests for recycling flowback water have been attempted (DOE, 2004; Texas Drilling Observer, 2006). The first was initiated in Wise County, south of Decatur, by Fountain Quail Water Management in 2005. The treatment method was evaporation based and consisted of a series of heat exchangers. Fresh-water recovery was 85% (RRC Website). The company Website reports a feed capacity of 2,500 bbl/day/unit (~73 gpm). The Website states that three mobile units are already running in Wise County and that six more will be delivered in less than a year ($2.5 million a piece). There is no indication of how the 15% solid-rich concentrate was disposed of in the pilot test, but there is a suggestion in the vendor material that the concentrate can be used as kill fluid. The second pilot was granted to DTE Gas Resources, also in 2005, to test simple filtration methods. The third pilot has been undertaken by Devon and also predicts 85% water recovery. The chosen method is based on membrane technology. Other groups (e.g., GeoPure Water Technologies) are also active in this field.

To conclude, it seems that the technology is available and tested but not likely to make a significant dent in water use in the near future. In the projections (Table 5), we assume that, in the high scenario, recycling will slowly increase in annual increments of 1% to reach a value of 20% of total water use from recycling. In the medium scenario, a smaller increment of 0.3% yields a total water use of 6% due to recycling. The low scenario assumes no significant recycling.

Water Use Intensity

Although there is no hard data and only anecdotal evidence to support it, we assumed that operators will become more water efficient in the future (maybe through use of better additives). For the low and medium water-use scenario, no change in water-use intensity is assumed. However, in the high water scenario, because of likely competition for water, it is anticipated that water use per well (vertical wells) or per unit length of lateral (horizontal well) will decrease by a 1% increment every year from 2005 through 2025 (that is, in 2025, 80% of the current water amount will be used compared with that of the same frac job that would have been performed in 2005).

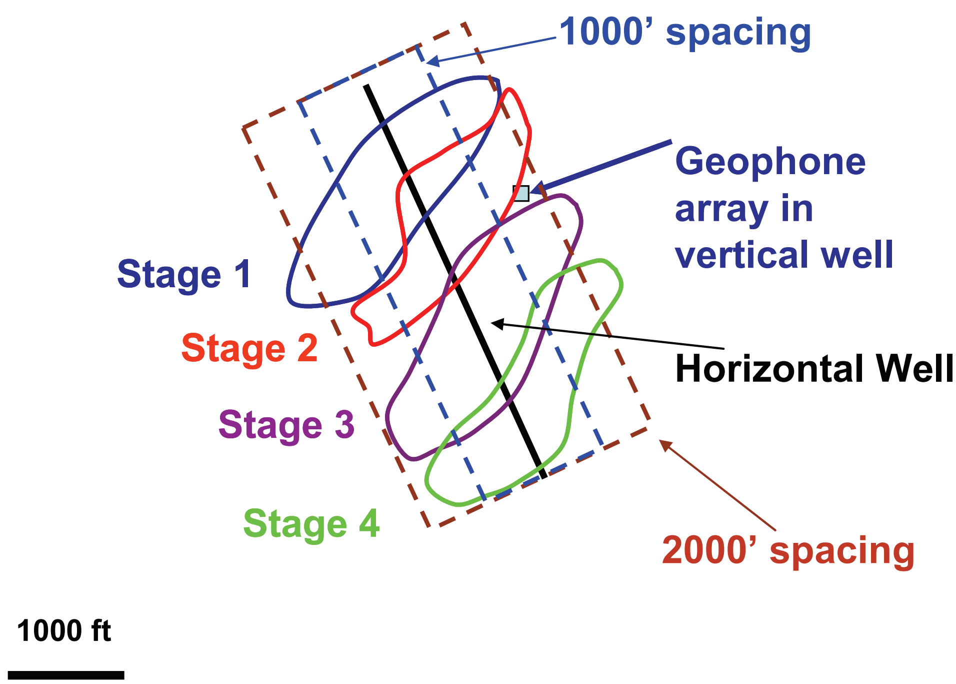
Well Spacing—Infilling

The usual well spacing for vertical wells is 1 well per 40 acres, although Devon Energy recently tested a 20-acre spacing array (Devon Energy website). For the purpose of this work a 1 well/40 acres density is assumed in the high scenario. It is half this number in the medium scenario, and another decrease by a factor of 2 in the low scenario (Table 5).

If vertical well density is suggested by the RRC regulations, currently no consistent one is enforced relative to multilateral horizontal wells. A dense network of multiple laterals could potentially originate from one single well head. The industry as a whole is still investigating the optimal lateral density. Hydraulic fracturing ideally produces two wings of equal size in symmetrical position relative to the well bore. Spacing between horizontal wells is a function of the shape of the induced fractures. Ketter et al. (2006) suggested that spacing between laterals should be at least 1.5 times the fracture height, which they estimate typically in the 300- to 400-ft range (that is, spacing of at least 450 to 600 ft). On the other hand, Givens and Zhao (2005, p. 6) suggested a minimum distance of 1,500 to 2,000 ft. Passive microseismic mapping has become a standard tool for understanding propagation of induced fractures or opening of natural closed fractures (e.g., Fisher et al., 2004). These studies have shown that induced fractures are organized in a complex network along fairways and could open sealed natural fractures. Fisher et al. (2004) calculated that a vertical well frac job created such a fairway with a half-length of 2,000 ft, width of 1,000 ft, and total fracture network length of 30,000 ft.

Several recent field studies have tried to identify the distance from the well to the fracture zone ends (e.g., Figure 21). The figure shows that a fracture can propagate up to 1,000 ft from one side of the well (2,000 ft total). However, some have suggested that microseismic results also include matrix adjustments with no actual opening. The operator EOG Resources tried 500-ft spacing pilots with some success in Johnson County (EOG Website). In this report, it is assumed (Table 5) that horizontal well spacing is 800 ft in the high scenario and 1,000 and 2,000 ft in the medium and low scenarios, respectively. In the case of horizontal drilling in rural areas of the Viola footprint (core area and its numerous vertical wells), horizontal infill spacing is assumed to be four times less dense than that of areas with no vertical wells. This number derives from a crude calibration of the annual completion distribution as described later (see Section V-4-3).

Operators have learned that it is better to wait some time before executing a frac job next to an already stimulated well. This is one of the reasons that there is no clear front to the advance of Barnett production in a map sense, but multiple advances followed by infilling.



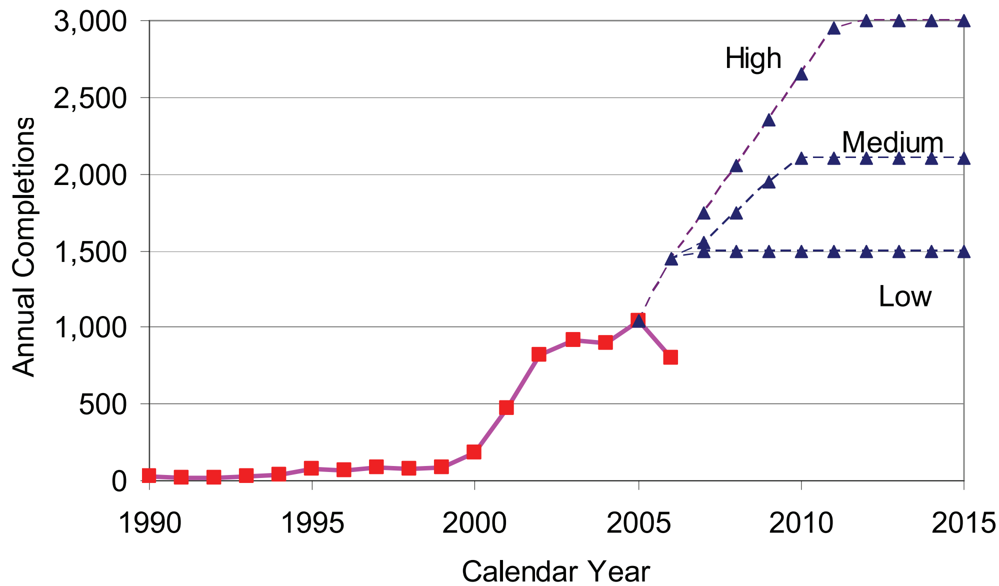
*Note: modified from www.eogresources.com/media/slides/analystconf_barnett.pdf

Figure 21 Schematics of pilot test results of lateral spacing in Johnson County (map view)

Operational Controls

The number of wells drilled is obviously limited by the number of drilling rigs and/or trained workers available. The number of completions for 2005 is ~1,050 (Table 4). If the current trend continues, the total number of completions for 2006 will be ~1,500. This value is retained as a constant annual rate of completions (up to 2025) in the low scenario (Figure 22). In the high scenario case (Table 5), it is assumed that the completion rate will grow to twice the 2006 value (that is, 3,000 completions/year) at a maximum annual incremental rate of 300 completions/year. The medium case is intermediate, with a maximum of 2,100 completions a year and an increment of 200 completions/year.

These numbers compared well with the data provided by Galusky (2006). He collected information from operators totaling about 600 completions done in 2005, which is about 60% of all completions in that year. Operator projections for 2006 and 2007 are 1,000 and 1,341, respectively, translating into a total number of completions for the play of 1,650 and 2,200.



*Note: red squares = actual data (incomplete for 2006) – blue triangles = projected completions

Figure 22 Annual completion projections up to 2015 (constant rate from 2012 to 2025)

Numerical Projections

The starting point for numerical projections is 2005, using historical data, as shown in Table 6. Numerical projections for water use follow a defensible series of steps as outlined below:

(1) Calculate the hypothetical maximum water use in a county polygon, accounting for surface area, footprint fraction, number of vertical wells, footage of lateral, sag feature avoidance factor, and average water use per well type (Table 5),

(2) Derive an activity-weighting curve similar to a production curve, with initial ramp-up, peak, and long tail that is assumed valid for all county polygons,

(3) Assign year of peak activity to each county polygon,

(4) Assess quality of resource in county polygons, and apply a prospectivity/risk factor,

(5) Compute an uncorrected water use per year and per county polygon,

(6) Throw in the maximum number of annual completions (Mca) to correct the uncorrected water use, if an uncorrected water use is not realistic. Corrected water use is simply scaled for all

county polygons from the uncorrected water use by applying a scaling factor equal to the ratio of Mca to the number of wells needed to use up the uncorrected amount of water,

(7) Add water use for recompletion by simply adding on a county polygon basis the water used for vertical-well frac jobs 5 years before in the proportion given in Table 5,

(8) Add water-use savings thanks to recycling in the proportion given in Table 5,

(9) Include the groundwater/surface water split and other issues related to fresh-water sources

(10) Follow the previous steps for high, medium, and low scenarios.

Table 6 Historical water use (all sources combined) in 2005 per county polygon

County Polygon	Area (1000's acres)			Water Use (Gal)	Water Use (AF)
	High	Medium	Low		
Bosque	641	641	73	1,088,094	3.3
ClayH	133			0	0
ClayV	245			0	0
Comanche	194			0	0
Cooke	50	42	42	15,491,922	47.5
Coryell	516			0	0
Dallas	183	183	183	0	0
DentonR	215	215	215	581,308,388	1,784.0
DentonU	100	100	100	68,498,548	210.2
Ellis	36	36	36	5,962,516	18.3
Erath	669			7,409,467	22.7
Hamilton	509			0	0
Hill	325	325	151	0	0
Hood	282	282	282	103,162,534	316.6
Jack	589	284		12,423,365	38.1
JohnsonH	398	398	398	530,096,095	1,626.8
JohnsonV	71	71	71	61,600,697	189.0
McLennan	202	111		0	0
Montague	401	168		19,380,502	59.5
Palo Pinto	476	191		2,859,662	8.8
Parker	581	581	581	226,611,136	695.4
Somervell	122	122	122	3,454,836	10.6
TarrantH	195	195	195	83,773,449	257.1
TarrantVR	30	30	30	138,105,099	423.8
TarrantVU	350	350	350	184,155,872	565.2
WiseH	199	199	169	27,440,474	84.2
WiseV	392	392	292	274,730,880	843.1
Sum				2,350,775,286	7,214.3

H=Horizontal, V=Viola, R=Rural, U=Urban;; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting)

Hypothetical Maximum Water Use

The hypothetical maximum water use in a county polygon accounts for polygon surface area, footprint fraction, number of vertical wells, lateral footage of horizontal wells, sag feature avoidance factor, and average water use per well type (Table 7).

Table 7 Derivation of hypothetical maximum water use by county polygon.

County Polygon	Area (acres)			Linear Length of Lateral (1000's ft)[A]			Number of Vertical Wells[B]			Maximum Hypothetical Water Use (1000's AF)[C]		
	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low
Bosque	641,457	641,457	73,266	27,942	22,354	1,277				240	123	3
ClayH	133,197			5,802						50		
ClayV1	245,103						5,515			20		
ClayV2 [D]				2,669						23		
Comanche	194,448			8,470						73		
Cooke1	49,697	41,992	41,992				1,118	472	236	4	2	1
Cooke2 [D]				541	433	216				5	3	1
Coryell	516,395			22,494						193		
Dallas	183,473	183,473	183,473	7,992	6,394	3,197				69	35	8
DentonR1	215,385	215,385	215,385				4,846	2,423	1,212	18	9	4
DentonR2 [D]				2,346	1,876	938				20	10	2
DentonU	99,786	99,786	99,786	4,347	3,477	1,739				37	19	4
Ellis1	35,975	35,975	35,975				809	405	202	3	1	1
Ellis2 [D]				392	313	157				3	2	0
Erath	668,543			29,122						250		
Hamilton	509,458			22,192						191		
Hill	324,851	324,851	150,946	14,150	11,320	2,630				122	63	6
Hood	282,000	282,000	282,000	12,284	9,827	4,914				106	54	12
Jack	589,126	283,836		25,662	9,891					221	55	
JohnsonH	398,436	398,436	398,436	17,356	13,885	6,942				149	77	17
JohnsonV1	71,376	71,376	71,376				1,606	803	401	6	3	1
JohnsonV2 [D]				777	622	311				7	3	1
McLennan	202,373	111,094		8,815	3,871					76	21	
Montague1	400,537	167,879					9,012	1,889		33	7	
Montague2				4,362	3,489					37	19	
Palo Pinto	476,187	191,216		20,743	6,664					178	37	
Parker	580,919	580,919	580,919	25,305	20,244	10,122				217	112	25
Somervell	122,145	122,145	122,145	5,321	4,257	2,128				46	24	5
TarrantH	194,799	194,799	194,799	8,485	6,788	3,394				73	37	8
TarrantVR1	30,261	30,261	30,261				681	340	170	3	1	1

County Polygon	Area (acres)			Linear Length of Lateral (1000's ft)[A]			Number of Vertical Wells[B]			Maximum Hypothetical Water Use (1000's AF)[C]		
	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low
TarrantVR2 [D]				330	264	132				3	1	0
TarrantVU	350,133	350,133	350,133	15,252	12,201	6,101				131	67	15
WiseH	198,724	198,724	168,629	8,656	6,925	2,938	24,238	16,620	5,876	74	38	7
WiseV1	392,155	392,155	291,735							32	16	6
WiseV2 [D]				4,271	3,416	1,708	11,958	8,199	3,416	37	19	4
Total	8,106,937	4,917,891	3,291,254	306,077	148,512	48,844	59,783	31,152	11,515	2,749	860	134

*Note: H=Horizontal, V=Viola, R=Rural, U=Urban; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting); in addition some counties polygons contains mostly vertical wells but also include horizontal wells (names in italics)

A Applies lateral spacing and footprint fraction

B Applies vertical spacing and footprint fraction

C Applies sag feature avoidance factor and average water use

D Treats horizontal wells in areas with a combination of vertical and horizontal wells

The value of this parameter varies from 2.75 million AF of water that could eventually be used on the play in the high scenario, to 0.860 and 0.134 million AF in the medium and low scenarios, respectively. There is a factor 20 difference between the high and low scenarios explained by the difference in total surface area and the systematic choice of high water use and low water use for the high and low scenarios, respectively. Those high and low scenarios probably are unrealistic extremes of the large range provided.

Derivation of Activity-Weighting Curve

Time distribution of initial well completion in a somewhat large area goes through several steps: initial ramp, peak, decrease, and long tail (Figure 23 and Figure 24). Three county polygons (Denton Rural, Wise Viola, and Tarrant Viola/Rural) have already passed their peak. They are all located in vertical-well-dominated areas, although it is assumed that the model can be applied to all areas as a first approximation. If the number of wells already drilled is compared with the maximum number of wells, assuming a well spacing of 40 acres, the simplified time distribution displayed in Figure 25 can be derived. An exploratory period ("Year 0") of numerically negligible water use, followed by a 6-year period of sustained development and a 3-year peak is assumed. The tail extends to n years after the first year of sustained drilling until total extraction of the resource. If the annual extraction rate stays at 1.5% of the total resource, n is equal to 50. At the end of 2005, the three county polygons used to build the model completed Year 10 of the model. The tail period starts in Year 11, and the first 10 years account for 27% of the maximum number of completions/maximum water use of the scenario considered. This basic model should be adapted to areas where slower drilling is expected, such as in urban areas. We assume a rate four times slower in urban areas than in rural areas. The values described above were obtained after a crude calibration of the model using the years 2000 through 2005 in Denton, Tarrant, and Wise Counties.

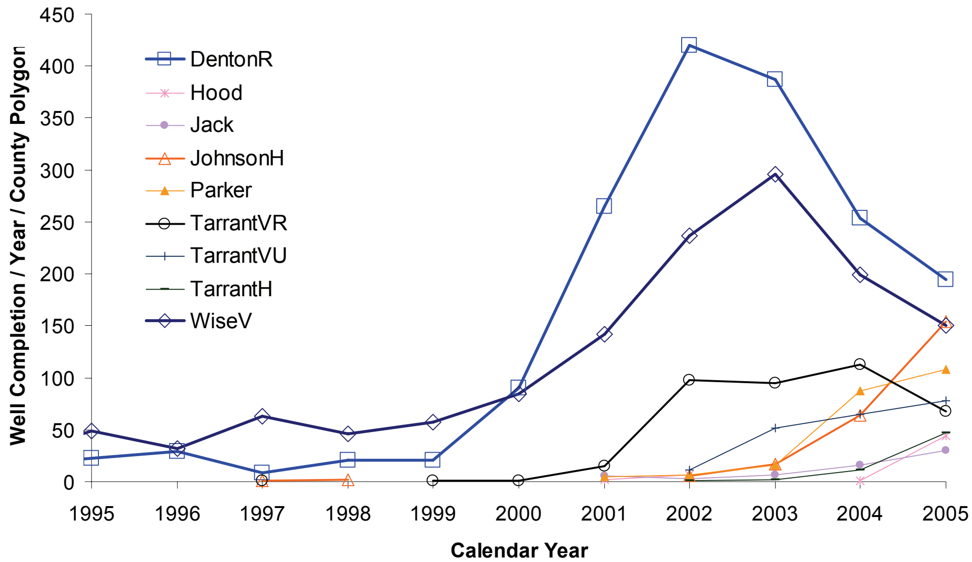
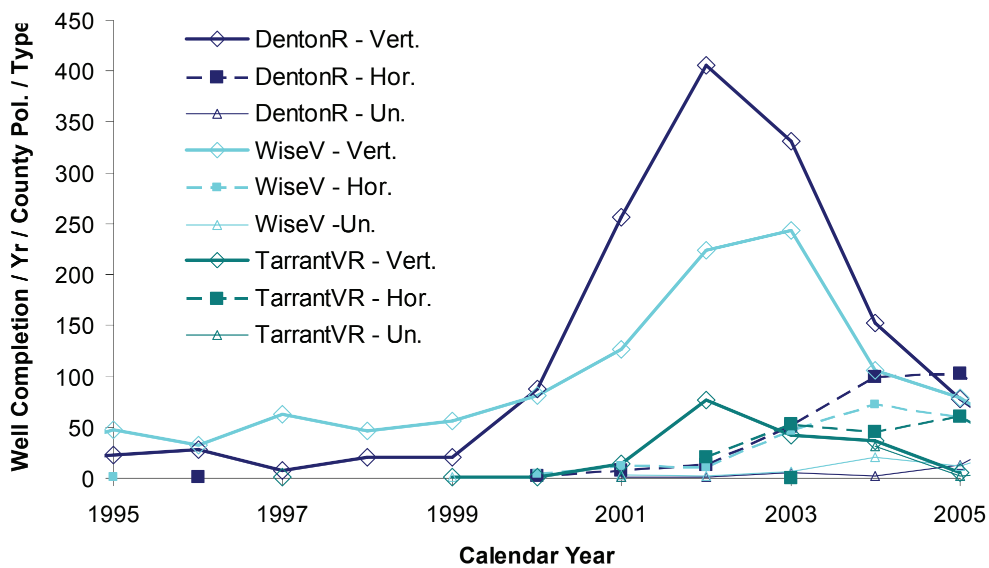


Figure 23 Annual well completion in selected county polygons



Vert. = vertical; Hor. = horizontal; Un. = unknown

Figure 24 Annual well completion in selected county polygons per well type

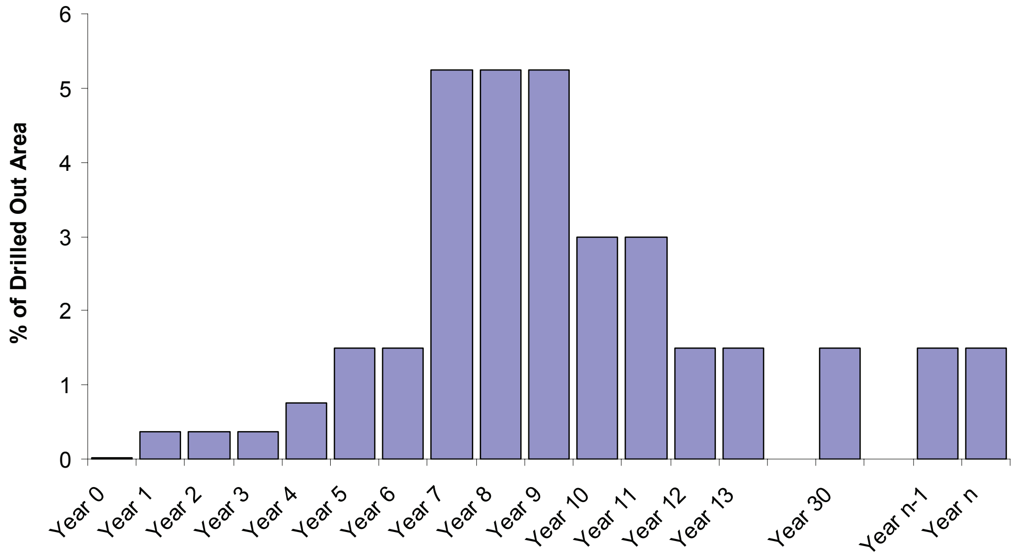


Figure 25 Basic model of time distribution of number of completions/water use

Year of Peak Activity and Quality of the Resource in County Polygons

In the previous sections of this report, we derived a maximum water use and an activity-weighting curve. However, all counties will obviously not be developed in parallel. Rather, they will be developed in a somewhat staggered pattern. We derive the calendar year for “Year 1” or start year (Table 8), using a combination of geology, distance to the core area, necessity of having a relatively smooth overall development curve as opposed to a jagged one, and some crude calibration of the model using the years 2001 through 2005 in Denton, Tarrant, and Wise Counties.

Prospectivity/risk factor can be understood either as a fraction of the area that will be developed or, more adequately, as the mean of the probability distribution describing the likelihood of having the county polygon developed (already given the high, medium, or low scenario condition). This factor is used simply as a multiplier of the hypothetical maximum water use.

Rough calibration of these two parameters is shown in Figure 26 as it translates to the three counties with enough data. Water use in these counties of the core area is matched roughly by derived high and medium scenario results. The final values were obtained by varying year of peak activity and prospectivity/risk factor.

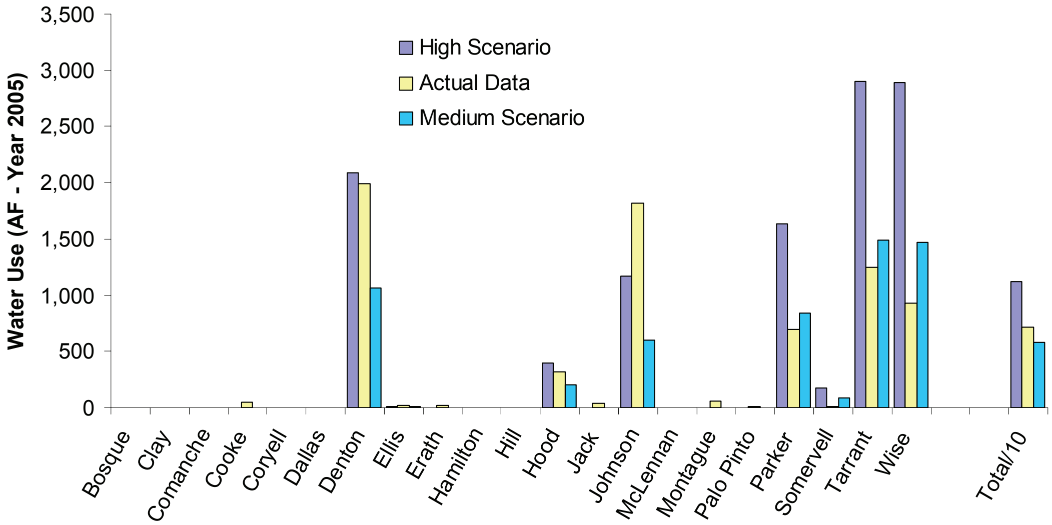
Table 8 Start year and prospectivity/risk factor for county polygons

County Polygon	Start Year	Prospectivity Factor *A*	Comments
Bosque	2009	0.8	No good wells yet, but expect that NE part (at least) will be good
ClayH	2017	0.5	Likely to be oil prone
ClayV1	2016	0.5	
ClayV2 [B]	2018	0.5	
Comanche	2010	0.5	Likely to be fairly thin and oil prone
Cooke1	2008	1	Not much area in the play
Cooke2 [B]	2010	1	
Coryell	2014	0.5	Thin, may take time to solve frac-height problem
Dallas	2007	1	NW part looks highly prospective; will take time to solve urban drilling issues
DentonR1	1996	1	Mostly developed already
DentonR2 [B]	1998	1	
DentonU	1999	1	Very prospective, but will take time to solve urban drilling issues
Ellis1	2004	1	Small area in NW appears very prospective
Ellis2 [B]	2006	1	
Erath	2007	0.8	Fair results with horizontals so far, especially east and central
Hamilton	2010	0.8	No valid horizontal well results yet; probably more prospective in east half
Hill	2007	0.9	Northwest part already economic; SW not really tested yet
Hood	2004	1	Early horizontals very encouraging
Jack	2006	0.7	Only marginal horizontals so far; SE part seems best
JohnsonH	2002	1	Clearly economic; may be mixed vertical and horizontal development
JohnsonV1	2003	1	
JohnsonV2 [B]	2003	1	
McLennan	2012	0.6	Fairly speculative; small part of county only
Montague1	2010	0.7	Known production of both oil and gas; controls on distribution not well understood
Montague2 [B]	2012	0.7	
Palo Pinto	2010	0.8	Nothing clearly economic yet
Parker	2002	1	In core producing area
Somervell	2004	1	One excellent horizontal so far; promising county
TarrantH	1999	1	Very prospective; urban drilling will require plenty of time to develop
TarrantVR1	1996	1	Very prospective; should be relatively quickly developed
TarrantVR2 [B]	1998	1	
TarrantVU	1999	1	Probably mostly done already where possible
WiseH	2003	1	Clearly prospective in current price environment
WiseV1	1996	0.9	Already reasonably well developed; economics marginal in some areas owing to gas/oil ratio; NW seems least prospective.
WiseV2 [B]	1998	0.9	

*Note: H=Horizontal – V=Viola – R=Rural – U=Urban; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting); in addition some counties polygons contains mostly vertical wells but also include horizontal wells (names in italics)

A Prosp. Factor = prospectivity/risk factor

B Treat horizontal wells in areas with a combination of vertical and horizontal wells



*Note: Values showed for overall total is 1/10th of actual total ("Total/10")

Figure 26 Column chart illustrating calibration of county activity

Uncorrected Annual Water Use

By introducing the time variable through the activity-weighting curve and applying it to the hypothetical maximum water use modified by the prospectivity/risk factor, an uncorrected annual water use per county polygon is obtained (Table 9). In the high scenario, overall water use increases until 2016, as more and more counties come into production, and then slowly decreases (Figure 27) as production tapers off. The high scenario yields large water use, for example >50,000 AF in 2016. This large water use is not sustainable because it corresponds to more than 5,000 annual well completions. In a previous section, we mentioned and assumed that more than 3,000 completions a year is unlikely. The medium and especially the low scenarios have much lower uncorrected water use (Figure 28). The low uncorrected water use of the low scenario conveys the assumptions used in developing it: no major expansion of the play and low gas price, giving little incentive for operators to expand.

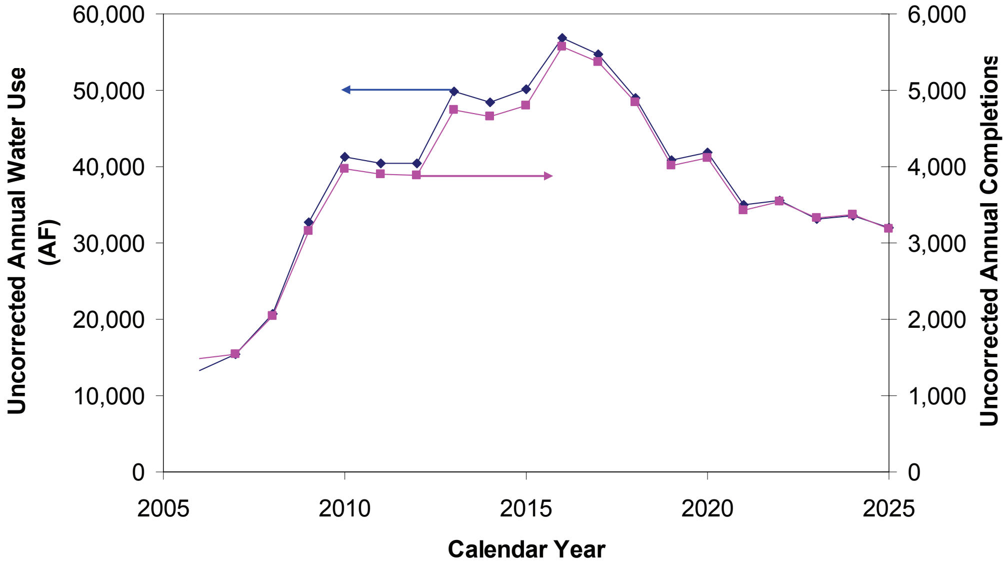


Figure 27 Uncorrected annual water use and completion (high scenario)

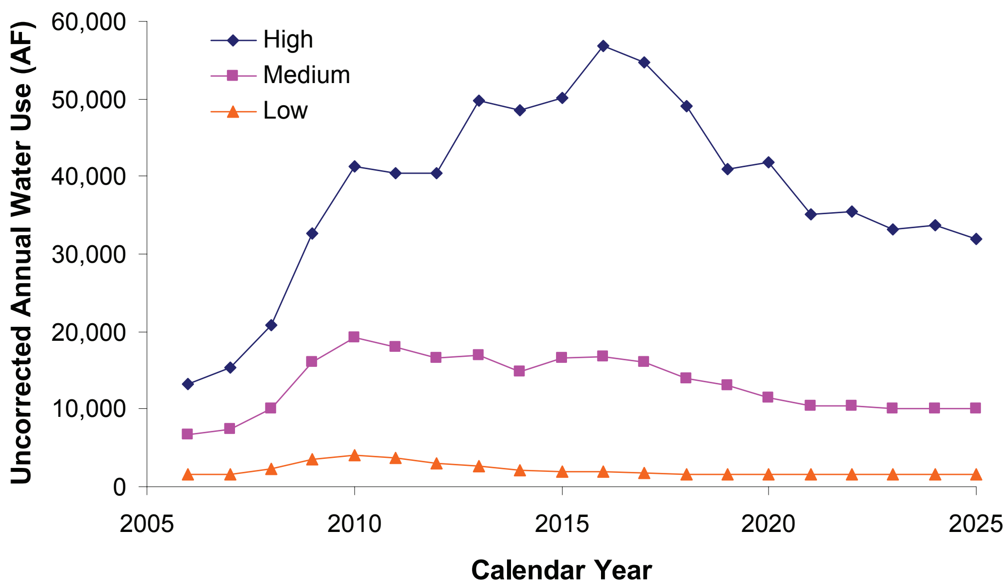


Figure 28 Uncorrected annual water use for high, medium, and low scenarios

Table 9 Uncorrected annual water use per county polygon - high scenario (all water sources, 1000's AF)

County Polygon	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Bosque				0.37	0.37	0.37	0.74	1.48	1.48	5.19	5.19	5.19	2.96	2.96	1.48	1.48	1.48	1.48	1.48	1.48
ClayH												0.09	0.09	0.09	0.19	0.37	0.37	1.31	1.31	1.31
ClayV1											0.04	0.04	0.04	0.08	0.15	0.15	0.53	0.53	0.53	0.30
ClayV2													0.04	0.04	0.04	0.09	0.17	0.17	0.60	0.60
Comanche					0.14	0.14	0.14	0.27	0.55	0.55	1.91	1.91	1.91	1.09	1.09	0.55	0.55	0.55	0.55	0.55
Cooke1			0.02	0.02	0.02	0.03	0.06	0.06	0.22	0.22	0.22	0.12	0.12	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Cooke2					0.02	0.02	0.02	0.03	0.07	0.07	0.24	0.24	0.24	0.14	0.14	0.07	0.07	0.07	0.07	0.07
Coryell									0.36	0.36	0.36	0.72	1.45	1.45	5.07	5.07	5.07	2.90	2.90	1.45
Dallas		0.06	0.06	0.06	0.13	0.26	0.26	0.90	0.90	0.90	0.52	0.52	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
DentonR1	0.54	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
DentonR2	1.06	0.60	0.60	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
DentonU	0.49	0.49	0.28	0.28	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Ellis1	0.01	0.02	0.04	0.04	0.16	0.16	0.16	0.09	0.09	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ellis2	0.01	0.01	0.01	0.03	0.05	0.05	0.18	0.18	0.18	0.10	0.10	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Erath		0.75	0.75	0.75	1.50	3.00	3.00	10.51	10.51	10.51	6.01	6.01	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Hamilton					0.57	0.57	0.57	1.14	2.29	2.29	8.01	8.01	8.01	4.58	4.58	2.29	2.29	2.29	2.29	2.29
Hill		0.41	0.41	0.41	0.82	1.64	1.64	5.75	5.75	5.75	3.28	3.28	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64
Hood	0.40	0.79	1.58	1.58	5.54	5.54	5.54	3.17	3.17	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58
Jack	0.58	0.58	0.58	1.16	2.32	2.32	8.10	8.10	8.10	4.63	4.63	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32
JohnsonH	2.24	2.24	7.83	7.83	7.83	4.47	4.47	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24
JohnsonV1	0.04	0.09	0.09	0.31	0.31	0.31	0.18	0.18	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
JohnsonV2	0.05	0.10	0.10	0.35	0.35	0.35	0.20	0.20	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
McLennan							0.17	0.17	0.17	0.34	0.68	0.68	2.39	2.39	2.39	1.36	1.36	0.68	0.68	0.68
Montague1					0.09	0.09	0.09	0.17	0.35	0.35	1.22	1.22	1.22	0.70	0.70	0.35	0.35	0.35	0.35	0.35
Montague2							0.10	0.10	0.10	0.20	0.39	0.39	1.38	1.38	1.38	0.79	0.79	0.39	0.39	0.39
Palo Pinto					0.53	0.53	0.53	1.07	2.14	2.14	7.49	7.49	7.49	4.28	4.28	2.14	2.14	2.14	2.14	2.14
Parker	1.63	3.26	3.26	11.42	11.42	11.42	6.52	6.52	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26
Somervell	0.17	0.34	0.69	0.69	2.40	2.40	2.40	1.37	1.37	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
TarrantH	0.96	0.96	0.55	0.55	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

County Polygon	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
TarrantVR1	0.08	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
TarrantVR2	0.15	0.08	0.08	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
TarrantVU	1.72	1.72	0.98	0.98	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
WiseH	0.56	1.12	1.12	3.91	3.91	3.91	2.23	2.23	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
WiseV1	0.88	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
WiseV2	1.73	0.99	0.99	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Total	13.29	15.37	20.78	32.31	40.95	40.06	39.80	48.43	47.08	45.19	51.89	49.89	46.22	38.11	40.42	33.65	34.11	31.80	32.23	30.55

*Note: H=Horizontal, V=Viola, R=Rural, U=Urban; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting); in addition some counties polygons contains mostly vertical wells but also include horizontal wells (names in italics)

Correction due to Maximum Number of Completions Constraint

Adding the drilling rig constraint to uncorrected water use generates a table closer to the final estimations. An average water use of 1.2 MGal/vertical well and 3.6 MGal/horizontal well is assumed to compute the total number of wells needed to reach the uncorrected water-use goal. Corrected water use is then simply obtained by linearly scaling uncorrected water use by the ratio of the maximum number of wells to the computed total number of wells. Only the high scenario needs such a scaling, the medium and low scenarios always being below but sometimes close to their maximum attributed annual completions.

Correction due to Recompletions and Recycling and Final

Correction for recompletion is in general small because it applies only to vertical, whose overall percentage within total number of wells completed on that year decreases through time. It is higher in early years (<2010) because, according to our model, vertical wells drilled 2000 through 2005 will then have been recompleted.

The effect of some recycling is also beneficial to total water use, but the general decrease through time depicted in Figure 29 is due mainly to the diminution of the resource. In the high scenario, total water use climbs from ~8,000 AF in 2005 to a peak of ~30,000 AF in 2011, followed by a slow decease to ~25,000 AF in 2025. The medium scenario follows a similar path, climbing to ~20,000 AF in 2010 and decreasing to ~10,000 AF in 2025. The low scenario shows a constant decrease from the 2006 value to 1,600 AF in 2025. Table 10 tabulates annual projections by county polygons.

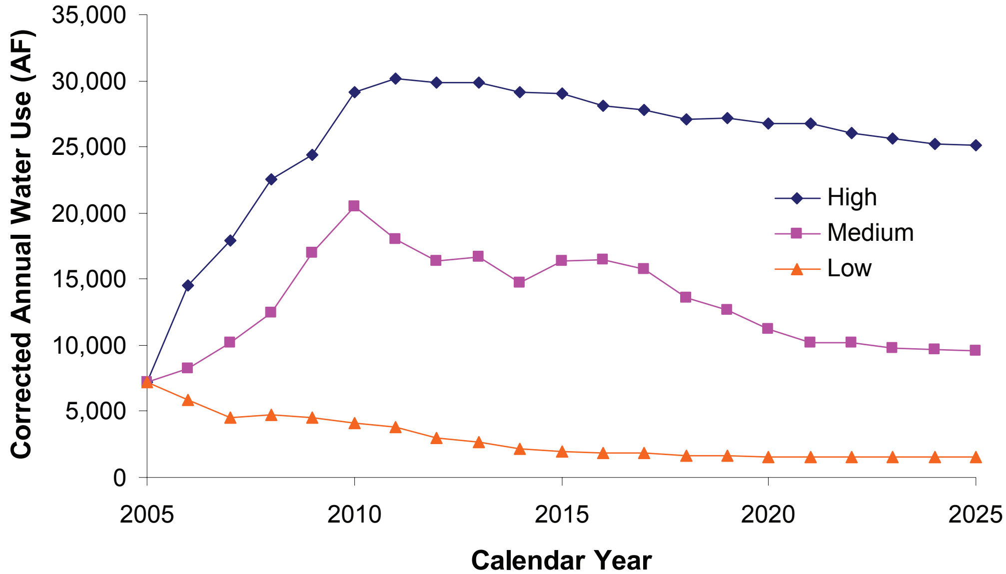


Figure 29 Corrected annual water use for high, medium, and low scenarios (all sources)

Table 10 Corrected annual water use per county polygon - high scenario (all water sources, 1000's AF)

County Polygon	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Bosque				0.51	0.46	0.51	1.03	1.68	1.69	5.68	4.84	4.96	3.10	3.71	1.79	2.12	2.02	2.13	2.08	2.17
ClayH												0.05	0.05	0.06	0.12	0.27	0.26	0.97	0.94	0.99
ClayV1											0.02	0.02	0.02	0.05	0.09	0.13	0.39	0.41	0.43	0.32
ClayV2													0.02	0.03	0.03	0.06	0.12	0.13	0.43	0.45
Comanche					0.09	0.10	0.10	0.16	0.32	0.31	0.92	0.94	1.03	0.70	0.68	0.40	0.38	0.40	0.39	0.41
Cooke1			0.01	0.01	0.05	0.02	0.04	0.05	0.14	0.13	0.12	0.10	0.10	0.16	0.15	0.14	0.10	0.11	0.08	0.08
Cooke2					0.01	0.01	0.01	0.02	0.04	0.04	0.12	0.12	0.13	0.09	0.09	0.05	0.05	0.05	0.05	0.05
Coryell									0.21	0.20	0.17	0.36	0.78	0.93	3.15	3.72	3.56	2.14	2.09	1.09
Dallas		0.06	0.06	0.05	0.08	0.18	0.18	0.53	0.53	0.51	0.25	0.25	0.14	0.17	0.16	0.19	0.18	0.19	0.19	0.19
DentonR1	1.66	2.01	1.73	0.79	1.86	0.68	0.44	0.40	0.34	0.31	0.31	0.31	0.29	0.32	0.31	0.32	0.31	0.33	0.35	0.36
DentonR2	1.02	0.59	0.59	0.22	0.19	0.22	0.22	0.18	0.18	0.17	0.15	0.15	0.16	0.19	0.19	0.22	0.21	0.22	0.22	0.23
DentonU	0.47	0.48	0.27	0.20	0.09	0.10	0.10	0.08	0.08	0.08	0.07	0.07	0.08	0.09	0.09	0.10	0.10	0.10	0.10	0.11
Ellis1	0.01	0.02	0.04	0.03	0.12	0.12	0.13	0.09	0.08	0.12	0.13	0.13	0.07	0.08	0.05	0.05	0.05	0.06	0.06	0.06
Ellis2	0.01	0.01	0.01	0.02	0.03	0.04	0.13	0.10	0.10	0.06	0.05	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Erath		0.74	0.73	0.54	0.95	2.14	2.16	6.12	6.16	5.92	2.88	2.95	1.62	1.93	1.86	2.20	2.11	2.22	2.16	2.27
Hamilton					0.36	0.41	0.41	0.67	1.34	1.29	3.84	3.94	4.31	2.94	2.84	1.68	1.61	1.69	1.65	1.73
Hill		0.40	0.40	0.29	0.52	1.17	1.18	3.35	3.37	3.24	1.57	1.61	0.88	1.06	1.02	1.21	1.15	1.21	1.18	1.24
Hood	0.38	0.78	1.54	1.13	3.51	3.94	3.98	1.85	1.86	0.89	0.76	0.78	0.85	1.02	0.98	1.16	1.11	1.17	1.14	1.19
Jack	0.56	0.57	0.56	0.83	1.47	1.65	5.82	4.72	4.75	2.61	2.22	1.14	1.25	1.49	1.44	1.70	1.63	1.71	1.67	1.75
JohnsonH	2.17	2.19	7.59	5.59	4.96	3.18	3.21	1.30	1.31	1.26	1.07	1.10	1.20	1.44	1.39	1.64	1.57	1.65	1.61	1.69
JohnsonV1	0.04	0.09	0.09	0.22	0.20	0.26	0.21	0.19	0.26	0.24	0.25	0.16	0.15	0.11	0.10	0.11	0.10	0.11	0.12	0.12
JohnsonV2	0.05	0.10	0.10	0.25	0.22	0.25	0.14	0.12	0.06	0.06	0.05	0.05	0.05	0.06	0.06	0.07	0.07	0.07	0.07	0.08
McLennan							0.12	0.10	0.10	0.19	0.33	0.34	1.29	1.53	1.48	1.00	0.96	0.50	0.49	0.51
Montague1					0.11	0.06	0.06	0.10	0.20	0.25	0.64	0.66	0.75	0.64	0.62	0.81	0.81	0.88	0.67	0.67
Montague2							0.07	0.06	0.06	0.11	0.19	0.19	0.74	0.89	0.85	0.58	0.55	0.29	0.28	0.30
Palo Pinto					0.34	0.38	0.38	0.62	1.25	1.20	3.59	3.68	4.03	2.75	2.65	1.57	1.50	1.58	1.54	1.61
Parker	1.58	3.20	3.16	8.15	7.23	8.12	4.68	3.80	1.91	1.84	1.56	1.60	1.76	2.10	2.02	2.39	2.29	2.41	2.35	2.46
Somervell	0.17	0.34	0.67	0.49	1.52	1.71	1.72	0.80	0.80	0.39	0.33	0.34	0.37	0.44	0.43	0.50	0.48	0.51	0.49	0.52
TarrantH	0.93	0.94	0.53	0.39	0.17	0.19	0.20	0.16	0.16	0.15	0.13	0.13	0.15	0.18	0.17	0.20	0.19	0.20	0.20	0.21

County Polygon	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
TarrantVR1	0.11	0.26	0.15	0.14	0.43	0.10	0.06	0.06	0.05	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.05	0.05	0.05
TarrantVR2	0.14	0.08	0.08	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
TarrantVU	1.67	1.69	0.95	0.70	0.31	0.35	0.35	0.29	0.29	0.28	0.24	0.24	0.26	0.32	0.30	0.36	0.35	0.36	0.35	0.37
WiseH	0.54	1.09	1.08	2.79	2.47	2.78	1.60	1.30	0.65	0.63	0.54	0.55	0.60	0.72	0.69	0.82	0.78	0.82	0.80	0.84
WiseV1	1.30	1.29	1.25	0.66	1.08	1.12	0.72	0.66	0.55	0.51	0.51	0.51	0.48	0.53	0.51	0.52	0.51	0.55	0.58	0.59
WiseV2	1.68	0.97	0.96	0.35	0.31	0.35	0.36	0.29	0.29	0.28	0.24	0.24	0.27	0.32	0.31	0.36	0.35	0.37	0.36	0.37
Total	14.50	17.90	22.56	24.39	29.17	30.16	29.86	29.86	29.17	28.99	28.14	27.78	27.09	27.13	26.72	26.79	26.00	25.64	25.26	25.16

*Note: H=Horizontal, V=Viola, R=Rural, U=Urban; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting); in addition some counties polygons contains mostly vertical wells but also include horizontal wells (names in italics)

GROUNDWATER PUMPAGE FOR GAM INPUT

Groundwater/Surface Water Split

Water-use projections are not sufficient to determine the impact of Barnett Shale production on groundwater resources in general or on the Trinity aquifer in particular. External sources of frac job water, excluding recycling, can be (1) groundwater (2) surface water (river, lake, private pond) or (3) municipal water or treated (municipal) waste water whose primary source is either surface or groundwater but is already accounted for in the current GAM pumping file. Trucking water from miles away to its point of use is expensive, and operators are reluctant to do it when groundwater is available nearby. Figure 30 illustrates that all counties but three (Clay, Jack, and Palo Pinto) are on the Trinity aquifer footprint. This fact, however, does not necessarily mean that frac jobs in those three counties will not use groundwater from the Trinity aquifer. In Texas, as a general rule, amount of surface water decreases toward the south and west (combination of a decrease in precipitation and increase in evaporation). As the play expands southward and westward, the fraction of groundwater use will most likely increase through time.

Records from the TWDB show that groundwater is extracted for frac jobs in all areas where gas wells are drilled. Ridgeway (2006) stated that, using records from 2004 and 2005, a total of 3,731 new water wells were drilled in the study area (including 285 whose drilling reports were submitted online; Figure 31). During these 2 years, water wells drilled for rural domestic use (3,101 wells) account for 83% of the total water wells drilled in the study area. The county that had the most new domestic water wells was Parker County (875 wells), followed by Tarrant County (481 wells). The next-highest use of new water wells drilled is irrigation (9%, or 319 wells), with Tarrant County reporting the highest number of new water wells for this use (129). The third-highest use of new water wells drilled was rig supply (3%, or 103 wells), with Johnson County reporting the highest number of new water wells for this use (35). However, these data capture only wells whose reports include an oil operator name and do not include wells drilled by landowners to provide water to operators (Ridgeway, 2006).

Water wells must meet some minimum yield. Operators start storing water needed for the frac job the day drilling starts or shortly before, and the 3.5 million gallons of water must be ready to be injected a month later, when the well has been drilled. This figure translates into a flow rate of 81 gpm, with no downtime. Assuming that two wells provide the water, a minimum yield of 50 gpm is needed.

Galusky (2006) provided an estimate of groundwater/surface water split per county, including both historical and projected use (Table 11). Galusky (2006) does not specify if the groundwater origin is from municipal sources, in which case it would have already been accounted for as municipal use. It is assumed that the latter never occurs. We assumed that 60% of total water use is from groundwater in 2005 increasing to 100% in 2025 in the high scenario to account for overall movement to the west and south of the play, areas with globally less surface water available (Table 5). Similarly, increase is assumed from 60% to 80% in the medium scenario but fraction of groundwater use stays constant at 60% for the low case.

Table 11 Groundwater use as a percentage of total water use (county level)

County	Number of Wells	2005	2006	2007	Weighted Average
Bosque	26		60.0	60.0	60.0
Dallas	8	100.0	100.0	100.0	100.0
Denton	321	62.5	63.6	51.0	57.7
Ellis	27	50.0	50.0	45.0	47.5
Erath	65	60.0	61.7	71.3	66.3
Hill	54		62.5	62.5	62.5
Hood	307	45.0	36.7	62.0	50.5
Johnson	608	50.0	51.9	57.6	53.8
Montague	10			90.0	90.0
Parker	423	75.0	71.3	73.1	73.1
Somervell	65		50.0	50.0	50.0
Tarrant	791	43.8	45.0	45.6	45.0
Wise	240	75.0	75.0	51.3	59.2
Total	2945	58.5	57.0	60.4	59.0

Data from Galusky (2006)

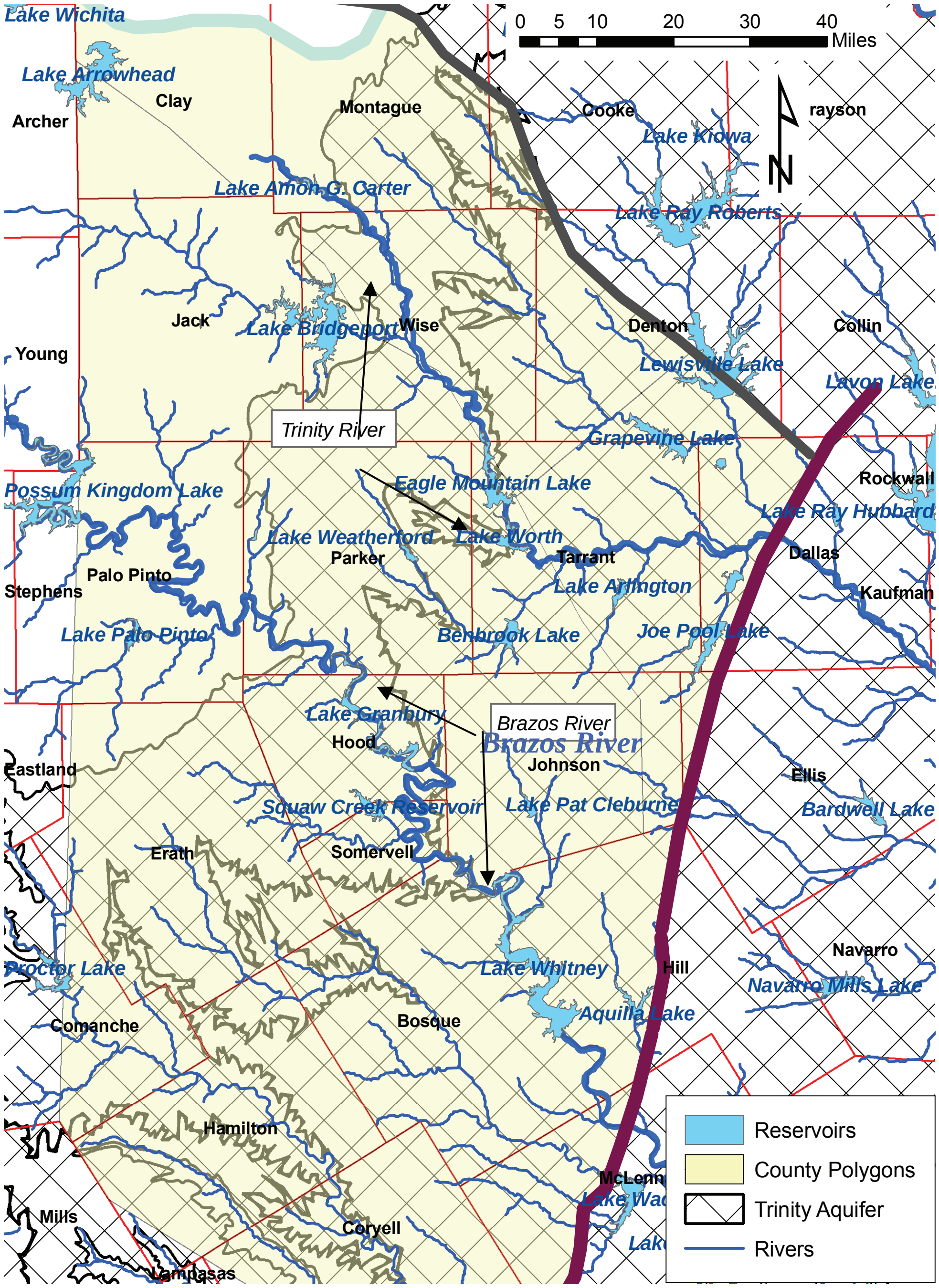
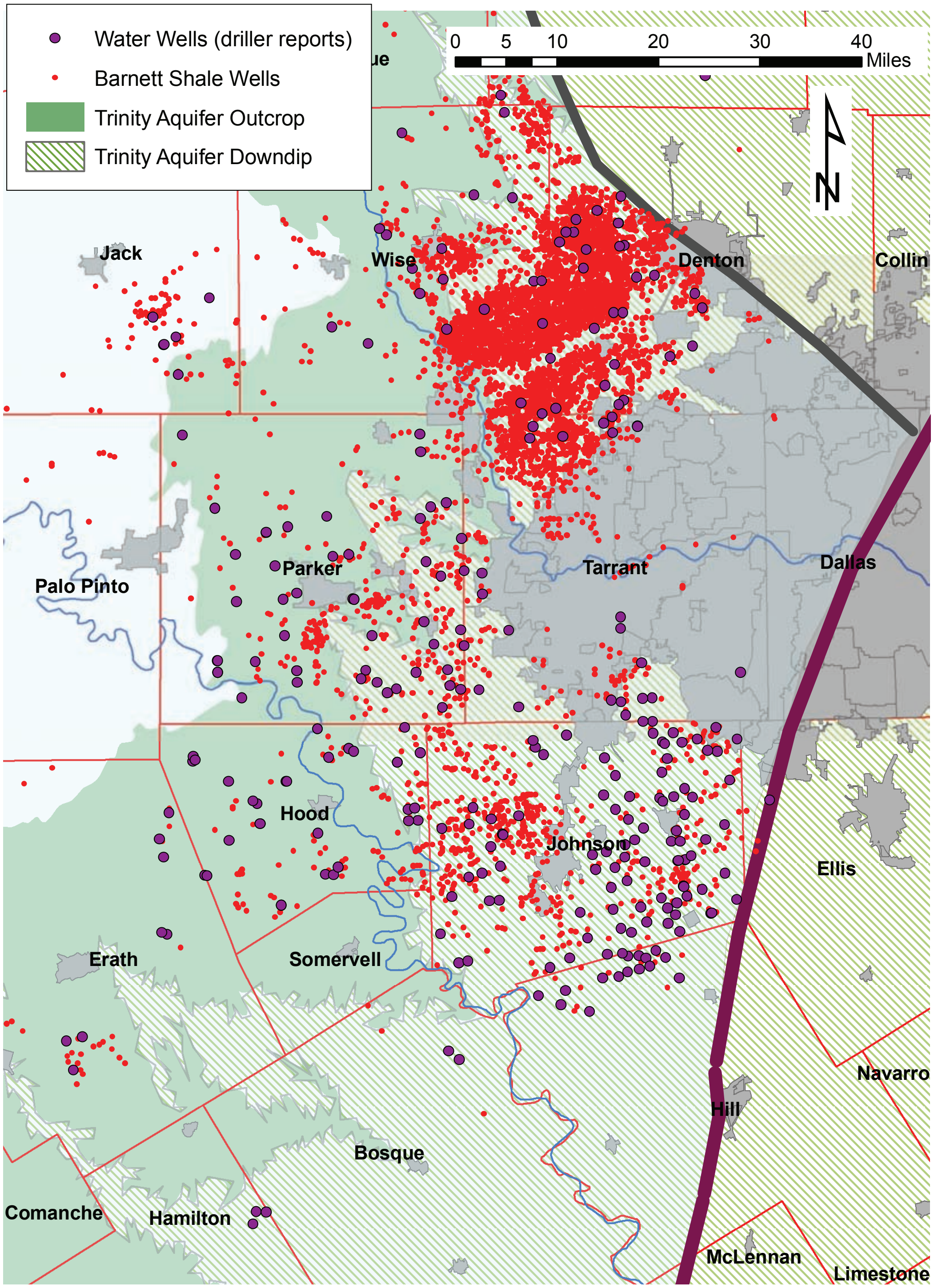


Figure 30 Rivers and reservoirs in the study area



Only those water wells from applications submitted online are plotted

Figure 31 Selected water-supply wells in the study area

Final Projections for Groundwater Use

This section provides final groundwater use by county polygons after all corrections have been done. The low scenario utilizes 29,000 AF of groundwater to the 2025 horizon, a clear retreat from current annual rate of water use by the industry, corresponding to a large drop in gas price or the development of sources of cheaper gas elsewhere (Figure 32). The high scenario calls for a total water use between 2007 and 2025 of 417,000 AF of groundwater. It corresponds to sustained gas prices, allowing operators to expand to all economically viable areas and produce most of the accessible resource, but also includes the assumption that water use is not limited. All scenarios assume that operators continue using water at a per-well rate similar to that of today and that no technological breakthrough will bring it down. The medium scenario, not necessarily the most likely, assumes a groundwater use of 183,000 AF. In the high scenario, groundwater use steadily climbs from ~5,000 AF/yr in 2005 to 20,000 AF/yr in 2010 and then slowly increases to a maximum of ~25,000 AF/yr in 2025. The medium scenario follows a similar path, climbing to a maximum of ~13,000 AF/yr in 2010, and then slowly decreases to ~7,500 AF/yr in 2025. Projections for the low scenario are approximately 29,000 AF.

Distributions by county polygons (Figure 33, Figure 34, Figure 35, Table 12,Table 13, and Table 14) follow a similar trend. Plots illustrate the staggered nature of the location of gas production because of the limit on the number of annual completions. The lack of smoothness of some individual county curves, especially in the high scenario, is due to the scaling process (Section V-4-5). It points out the actual competition for rigs in the play. Some rigs may leave a county, depicted by a slump in the curve, to more profitable areas and come back the next year in the same county. Some counties stand out in part because they have a large surface area.

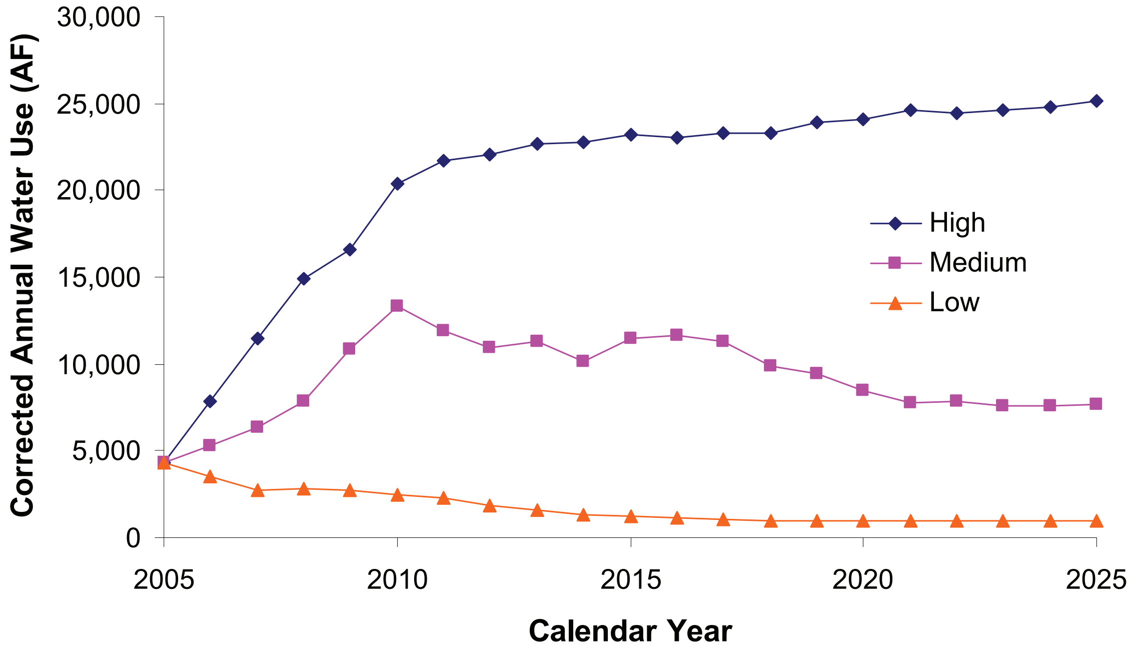


Figure 32 Groundwater annual water use for high, medium, and low scenarios

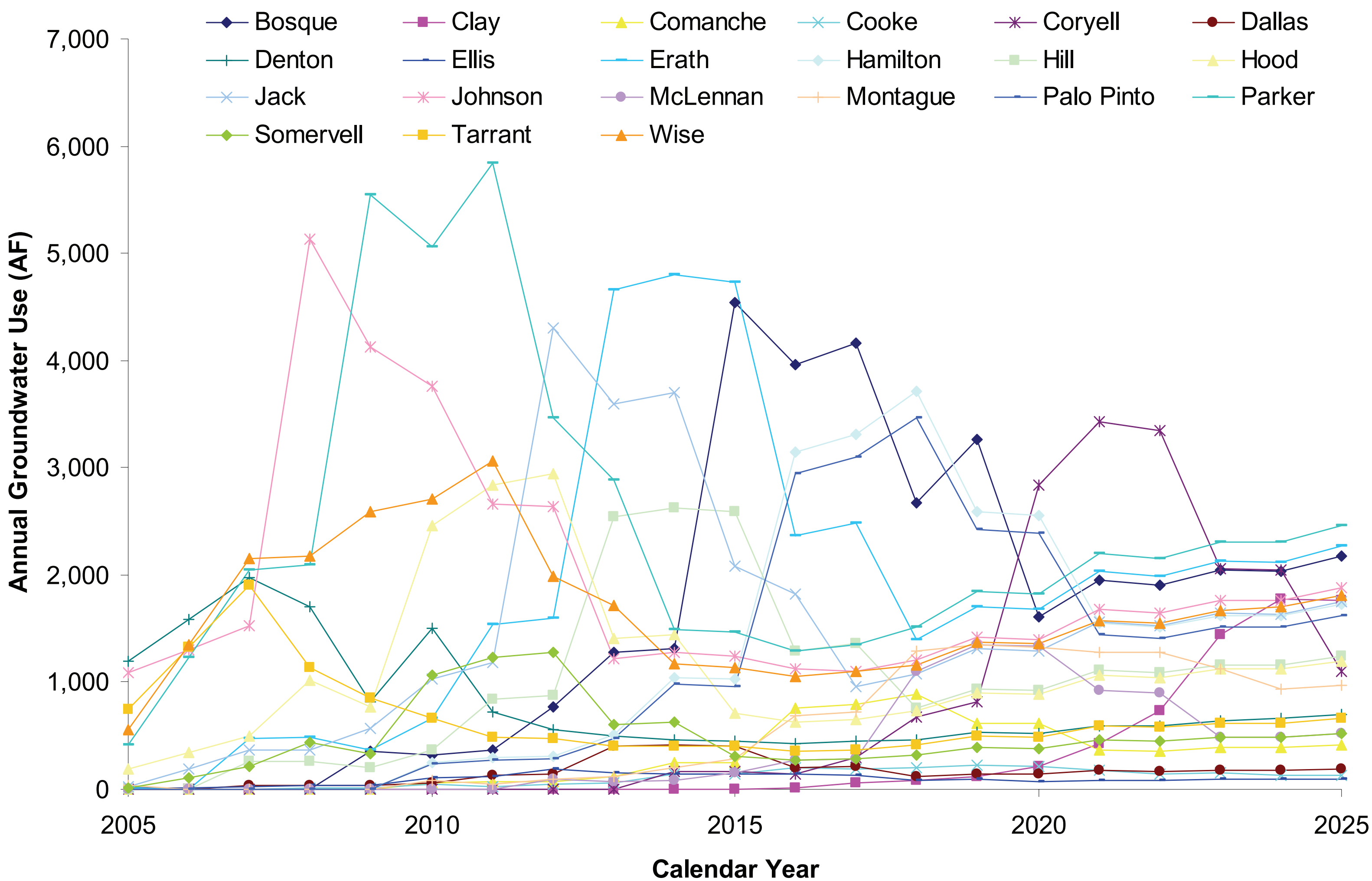


Figure 33 Groundwater annual water use per county polygon for the high scenario

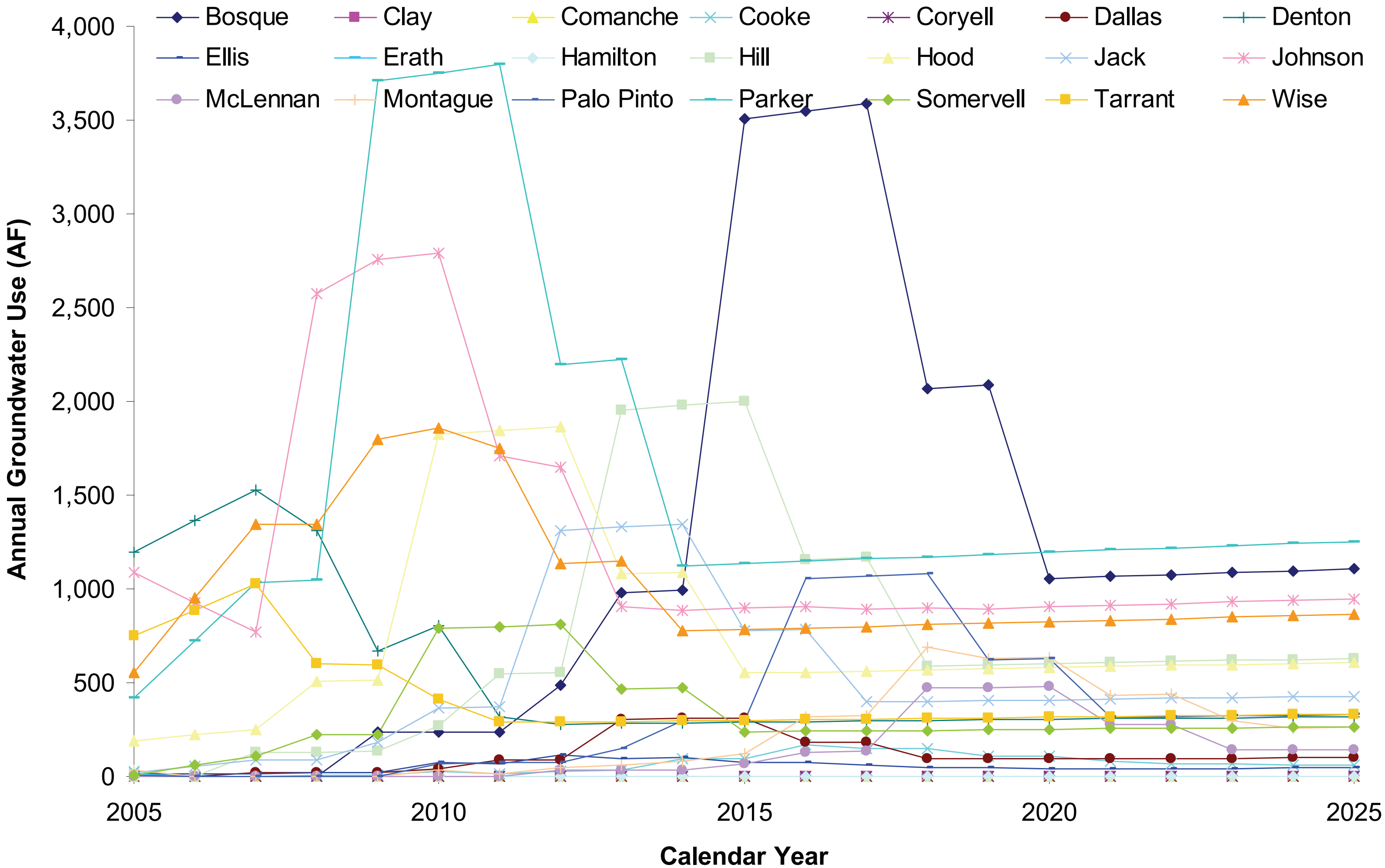


Figure 34 Groundwater annual water use per county polygon for the medium scenario

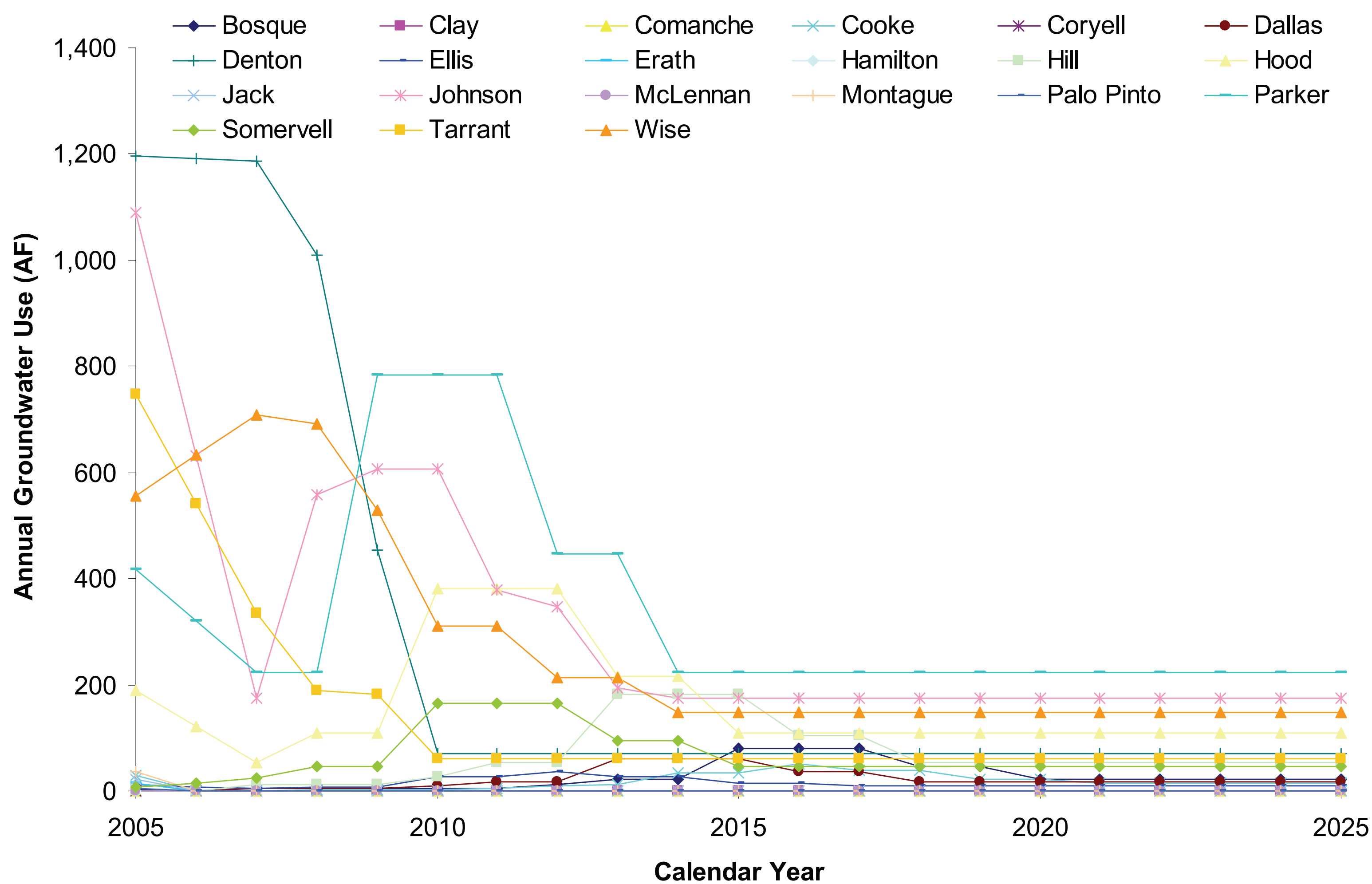


Figure 35 Groundwater annual water use per county polygon for the low scenario

Table 12 Groundwater annual water use per county polygon - high scenario (1000's AF)

County Polygon	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Bosque	0.00	0.00	0.00	0.00	0.35	0.32	0.37	0.77	1.28	1.32	4.54	3.97	4.17	2.67	3.26	1.61	1.95	1.90	2.04	2.03	2.17
ClayH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.05	0.10	0.25	0.25	0.93	0.92	0.99
ClayV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.07	0.11	0.18	0.48	0.52	0.85	0.77
Comanche	0.00	0.00	0.00	0.00	0.00	0.06	0.07	0.07	0.12	0.25	0.25	0.75	0.79	0.89	0.62	0.61	0.37	0.36	0.39	0.39	0.41
Cooke	0.03	0.01	0.00	0.01	0.01	0.05	0.02	0.04	0.05	0.14	0.14	0.20	0.19	0.20	0.22	0.22	0.18	0.14	0.15	0.13	0.14
Coryell	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.16	0.14	0.30	0.67	0.82	2.83	3.43	3.35	2.05	2.05	1.09
Dallas	0.00	0.02	0.04	0.04	0.03	0.06	0.13	0.14	0.40	0.41	0.41	0.20	0.21	0.12	0.15	0.14	0.17	0.17	0.18	0.18	0.19
DentonR	1.07	1.37	1.67	1.53	0.68	1.44	0.65	0.49	0.44	0.40	0.39	0.37	0.39	0.39	0.45	0.45	0.50	0.49	0.53	0.56	0.59
DentonU	0.13	0.22	0.31	0.18	0.14	0.06	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.08	0.08	0.09	0.09	0.10	0.10	0.11
Ellis	0.01	0.02	0.02	0.04	0.03	0.10	0.11	0.19	0.15	0.15	0.14	0.14	0.13	0.09	0.10	0.07	0.08	0.08	0.09	0.09	0.10
Erath	0.01	0.24	0.47	0.48	0.36	0.67	1.54	1.59	4.65	4.81	4.73	2.36	2.48	1.39	1.70	1.68	2.03	1.98	2.13	2.12	2.27
Hamilton	0.00	0.00	0.00	0.00	0.00	0.25	0.29	0.30	0.51	1.05	1.03	3.15	3.31	3.71	2.59	2.56	1.55	1.51	1.62	1.62	1.73
Hill	0.00	0.13	0.26	0.26	0.20	0.36	0.84	0.87	2.54	2.63	2.59	1.29	1.36	0.76	0.93	0.92	1.11	1.08	1.16	1.16	1.24
Hood	0.19	0.34	0.50	1.01	0.77	2.46	2.84	2.94	1.40	1.45	0.71	0.62	0.65	0.73	0.90	0.88	1.07	1.05	1.12	1.12	1.19
Jack	0.02	0.19	0.36	0.37	0.56	1.03	1.19	4.30	3.59	3.71	2.09	1.82	0.96	1.07	1.31	1.29	1.56	1.53	1.64	1.63	1.75
JohnsonH	0.98	1.19	1.40	5.01	3.80	3.47	2.29	2.38	0.99	1.02	1.01	0.88	0.92	1.04	1.27	1.25	1.51	1.48	1.58	1.58	1.69
JohnsonV	0.11	0.12	0.12	0.12	0.32	0.29	0.37	0.26	0.23	0.25	0.23	0.25	0.18	0.17	0.15	0.15	0.16	0.16	0.18	0.19	0.19
McLennan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.08	0.08	0.15	0.27	0.28	1.11	1.35	1.33	0.92	0.90	0.48	0.48	0.51
Montague	0.04	0.02	0.00	0.00	0.00	0.08	0.04	0.10	0.12	0.20	0.29	0.68	0.72	1.29	1.34	1.33	1.27	1.28	1.12	0.94	0.97
Palo Pinto	0.01	0.00	0.00	0.00	0.00	0.24	0.27	0.28	0.47	0.98	0.96	2.94	3.09	3.47	2.42	2.39	1.44	1.41	1.51	1.51	1.61
Parker	0.42	1.23	2.05	2.09	5.54	5.06	5.85	3.46	2.89	1.49	1.47	1.28	1.35	1.51	1.85	1.82	2.20	2.15	2.31	2.30	2.46
Somervell	0.01	0.11	0.22	0.44	0.33	1.06	1.23	1.27	0.61	0.63	0.31	0.27	0.28	0.32	0.39	0.38	0.46	0.45	0.49	0.48	0.52
TarrantH	0.15	0.38	0.60	0.35	0.27	0.12	0.14	0.15	0.12	0.13	0.12	0.11	0.11	0.13	0.15	0.15	0.18	0.18	0.19	0.19	0.21
TarrantVR	0.25	0.24	0.22	0.16	0.11	0.32	0.09	0.07	0.06	0.06	0.05	0.05	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.08	0.08
TarrantVU	0.34	0.71	1.08	0.63	0.48	0.22	0.25	0.26	0.22	0.22	0.22	0.19	0.20	0.23	0.28	0.27	0.33	0.32	0.35	0.35	0.37
WiseH	0.05	0.38	0.70	0.71	1.90	1.73	2.00	1.19	0.99	0.51	0.50	0.44	0.46	0.52	0.63	0.62	0.75	0.74	0.79	0.79	0.84
WiseV	0.51	0.98	1.45	1.46	0.69	0.97	1.06	0.80	0.72	0.66	0.63	0.61	0.64	0.64	0.74	0.73	0.81	0.81	0.88	0.92	0.96
Total	4.32	7.89	11.46	14.89	16.58	20.42	21.72	22.10	22.69	22.75	23.19	23.07	23.33	23.30	23.87	24.05	24.65	24.44	24.61	24.76	25.16

Note: H=Horizontal, V=Viola, R=Rural, U=Urban; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting).

Table 13 Groundwater annual water use per county polygon - medium scenario (1000's AF)

County Polygon	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Bosque	0.00	0.00	0.00	0.00	0.23	0.24	0.24	0.48	0.98	0.99	3.51	3.55	3.58	2.07	2.09	1.06	1.07	1.08	1.09	1.10	1.11
ClayH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ClayV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Comanche	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cooke	0.03	0.01	0.00	0.00	0.00	0.03	0.02	0.02	0.03	0.09	0.09	0.17	0.15	0.15	0.11	0.11	0.08	0.07	0.07	0.06	0.06
Coryell	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dallas	0.00	0.01	0.02	0.02	0.02	0.04	0.09	0.09	0.31	0.31	0.31	0.18	0.18	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.10
DentonR	1.07	1.22	1.37	1.22	0.58	0.76	0.27	0.23	0.24	0.24	0.24	0.24	0.25	0.25	0.25	0.25	0.26	0.26	0.26	0.26	0.27
DentonU	0.13	0.14	0.16	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Ellis	0.01	0.01	0.01	0.02	0.02	0.07	0.07	0.11	0.10	0.10	0.08	0.08	0.06	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04
Erath	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hamilton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hill	0.00	0.06	0.13	0.13	0.13	0.27	0.55	0.55	1.96	1.98	2.00	1.15	1.17	0.59	0.60	0.60	0.61	0.61	0.62	0.62	0.63
Hood	0.19	0.22	0.25	0.51	0.51	1.82	1.84	1.86	1.08	1.09	0.55	0.56	0.56	0.57	0.57	0.58	0.59	0.59	0.60	0.60	0.61
Jack	0.02	0.06	0.09	0.09	0.18	0.37	0.37	1.31	1.33	1.34	0.78	0.78	0.40	0.40	0.40	0.41	0.41	0.42	0.42	0.42	0.43
JohnsonH	0.98	0.84	0.71	2.51	2.54	2.57	1.49	1.51	0.76	0.77	0.78	0.79	0.80	0.80	0.81	0.82	0.83	0.84	0.84	0.85	0.86
JohnsonV	0.11	0.09	0.06	0.06	0.21	0.21	0.22	0.14	0.14	0.12	0.12	0.12	0.10	0.10	0.08	0.08	0.08	0.09	0.09	0.09	0.09
McLennan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.07	0.13	0.13	0.47	0.48	0.48	0.28	0.28	0.14	0.14	0.14
Montague	0.04	0.02	0.00	0.00	0.00	0.03	0.01	0.05	0.06	0.08	0.12	0.32	0.32	0.69	0.63	0.63	0.44	0.44	0.30	0.26	0.26
Palo Pinto	0.01	0.00	0.00	0.00	0.00	0.07	0.07	0.07	0.15	0.30	0.30	1.06	1.07	1.08	0.62	0.63	0.32	0.32	0.32	0.33	0.33
Parker	0.42	0.73	1.03	1.05	3.71	3.75	3.80	2.20	2.22	1.12	1.14	1.15	1.16	1.17	1.18	1.20	1.21	1.22	1.23	1.24	1.25
Somervell	0.01	0.06	0.11	0.22	0.22	0.79	0.80	0.81	0.47	0.47	0.24	0.24	0.24	0.25	0.25	0.25	0.25	0.26	0.26	0.26	0.26
TarrantH	0.15	0.23	0.30	0.18	0.18	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
TarrantVR	0.25	0.22	0.18	0.11	0.10	0.16	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04
TarrantVU	0.34	0.44	0.54	0.32	0.32	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.19	0.19	0.19
WiseH	0.05	0.20	0.35	0.36	1.27	1.28	1.30	0.75	0.76	0.38	0.39	0.39	0.40	0.40	0.40	0.41	0.41	0.42	0.42	0.42	0.43
WiseV	0.51	0.75	0.99	0.98	0.53	0.57	0.45	0.38	0.39	0.39	0.40	0.40	0.40	0.41	0.41	0.42	0.42	0.42	0.43	0.43	0.44
Total	4.32	5.32	6.31	7.87	10.85	13.34	11.92	10.94	11.33	10.15	11.45	11.66	11.32	9.89	9.40	8.43	7.76	7.82	7.60	7.62	7.69

Note: H=Horizontal, V=Viola, R=Rural, U=Urban; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting)

Table 14 Groundwater annual water use per county polygon - low scenario (1000's AF)

County Polygon	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Bosque	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.08	0.08	0.08	0.05	0.05	0.02	0.02	0.02	0.02	0.02	0.02
ClayH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ClayV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Comanche	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cooke	0.03	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.03	0.03	0.05	0.04	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Coryell	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dallas	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.06	0.06	0.06	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
DentonR	1.07	1.11	1.15	0.99	0.43	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
DentonU	0.13	0.08	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ellis	0.01	0.01	0.00	0.01	0.01	0.03	0.03	0.04	0.03	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Erath	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hamilton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hill	0.00	0.01	0.01	0.01	0.01	0.03	0.05	0.05	0.18	0.18	0.18	0.10	0.10	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Hood	0.19	0.12	0.05	0.11	0.11	0.38	0.38	0.38	0.22	0.22	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Jack	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
JohnsonH	0.98	0.56	0.15	0.54	0.54	0.54	0.31	0.31	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
JohnsonV	0.11	0.07	0.02	0.02	0.07	0.07	0.07	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
McLennan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Montague	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Palo Pinto	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Parker	0.42	0.32	0.22	0.22	0.78	0.78	0.78	0.45	0.45	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Somervell	0.01	0.01	0.02	0.05	0.05	0.16	0.16	0.16	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
TarrantH	0.15	0.11	0.07	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
TarrantVR	0.25	0.20	0.15	0.08	0.08	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
TarrantVU	0.34	0.23	0.12	0.07	0.07	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
WiseH	0.05	0.06	0.06	0.06	0.23	0.23	0.23	0.13	0.13	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
WiseV	0.51	0.57	0.64	0.63	0.30	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Total	4.32	3.52	2.73	2.85	2.74	2.45	2.25	1.81	1.60	1.31	1.20	1.12	1.10	1.00	0.98	0.96	0.95	0.95	0.95	0.95	0.95

Note: H=Horizontal, V=Viola, R=Rural, U=Urban; some counties are divided into polygons corresponding to the main completion type (presence or not of Viola Limestone, urban or rural setting).

CONCLUSIONS

In this work, we carried out an estimation of water use by the oil and gas industry in North Texas as a result of gas production from the Barnett Shale. We presented historical information showing the sharp increase in well completions, as well as in water use, in the past few years. The exploration boom started in Wise and Denton Counties but is currently expanding southward and westward in the core area. Using geological public knowledge and cues from operators, we defined three scenarios that vary in their spatial coverage and water-use attributes. There are still major uncertainties related to evolution of the play: will the price of natural gas stay at its current level or increase or decrease? Is water use by the average frac job going to decrease significantly because of technological progress? Is water recycling going to make up for a possible larger number of annual completions? The numbers provided are reasonable. The high scenario yields a total groundwater use of 417,000 AF, an annual average groundwater use of 22,000 AF over the 2007-2015 period, and a cumulative areal groundwater use of 0.05 AF/acre. The medium and low scenarios utilize a total 183,000 and 29,000 AF of groundwater for an annual average of ~10,000 and 1,500 AF, and a cumulative areal groundwater use of ~0.04 and 0.009 AF/acre, respectively. As evidenced by the large range in the results, much uncertainty remains, including in the spatial distribution of those regional averages.

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Appendix 3
County Groundwater
Use Estimates

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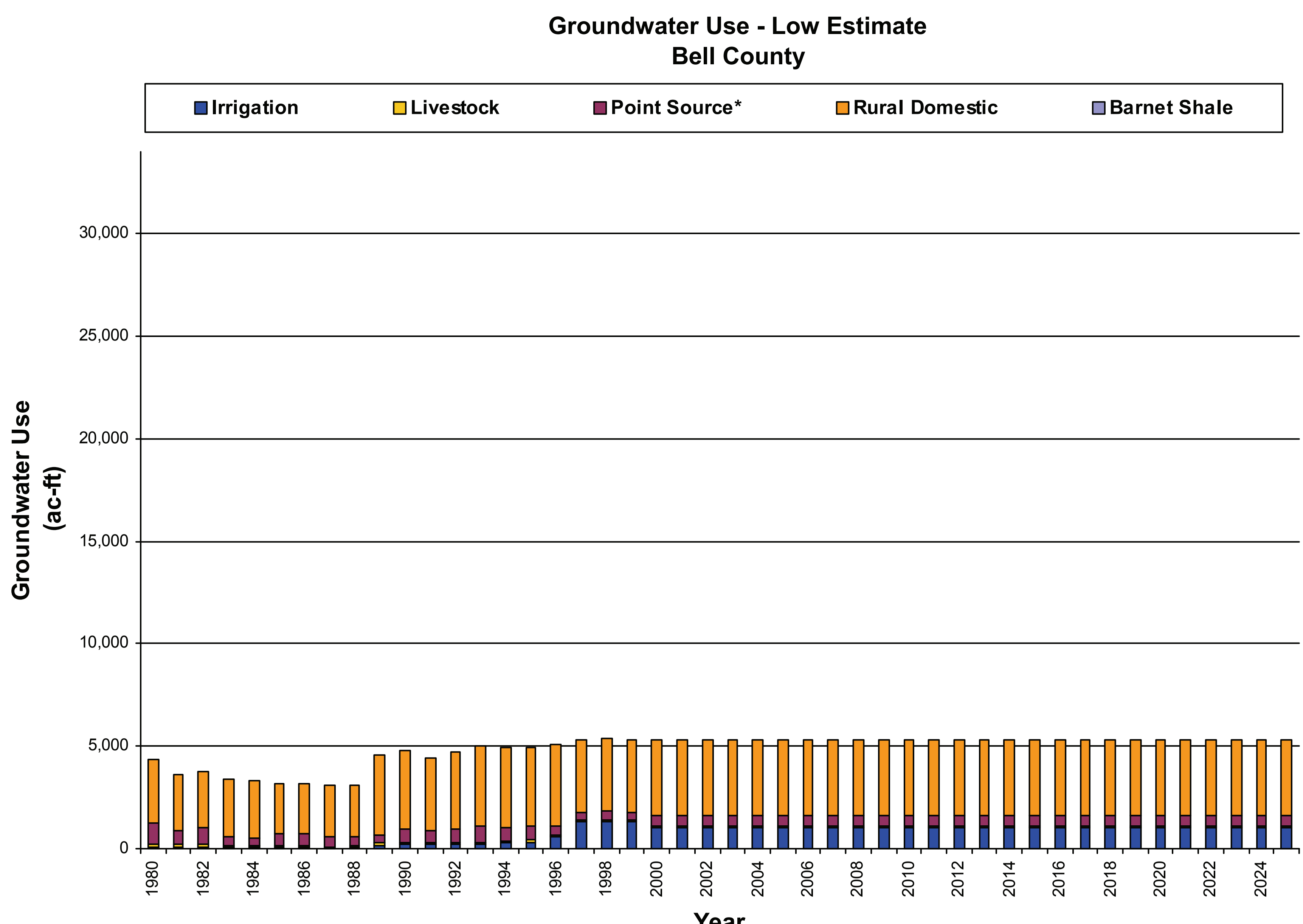
APPENDIX CONTENT

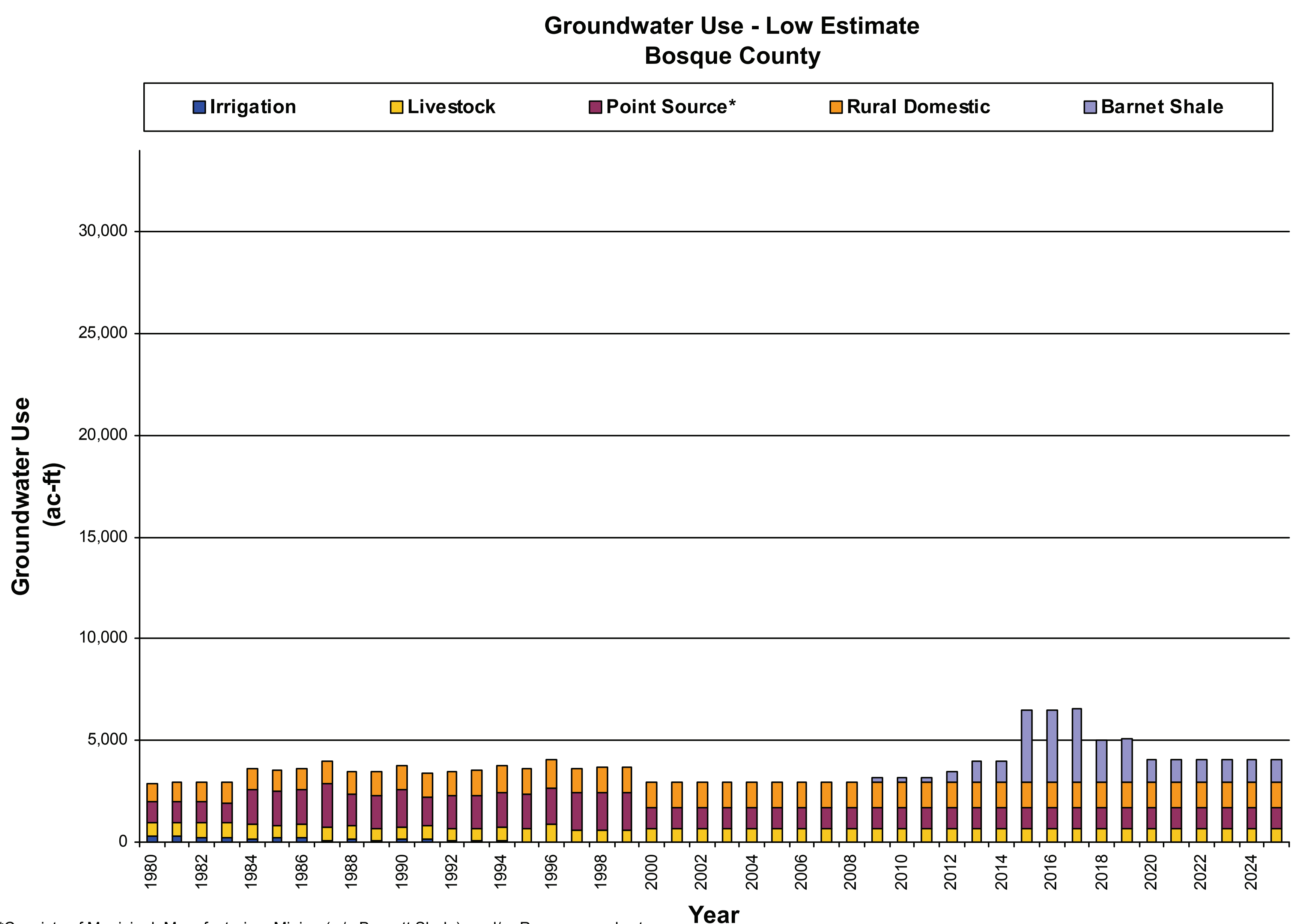
The following charts and tables summarize total estimated groundwater use for all counties in the GAM area where the predicted use was adjusted from the original GAM due to any of the following conditions:

- Addition of Barnet Shale development use as described in Appendix 2.
- Updated projected use as described in Appendix 1.
- Noticeable decreases in future demand (average of the use recorded during the interval 1995 through 1999 was applied throughout the simulations).
- Abnormal increases in future demand (Fannin and Lamar Counties only - average of the use recorded during the interval 1995 through 1999 was applied throughout the simulations).

It should be noted that the county use estimates provided herein represent: 1) the total reported historical groundwater pumpage by county through 1999, and 2) the total projected groundwater production through 2025. These estimates typically include pumpage from all the aquifers within a county, and do not directly correspond to the Trinity/Woodbine GAM pumpage inputs. During creation of the model input files, use estimates were reduced where appropriate to account for pumpage from aquifers other than those simulated in the GAM. The amount of estimated use that was not included in the GAM pumpage inputs varies by county, use category (municipal, county-other, etc.), and year, and is detailed in the model pumpage databases included with the GAM.



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



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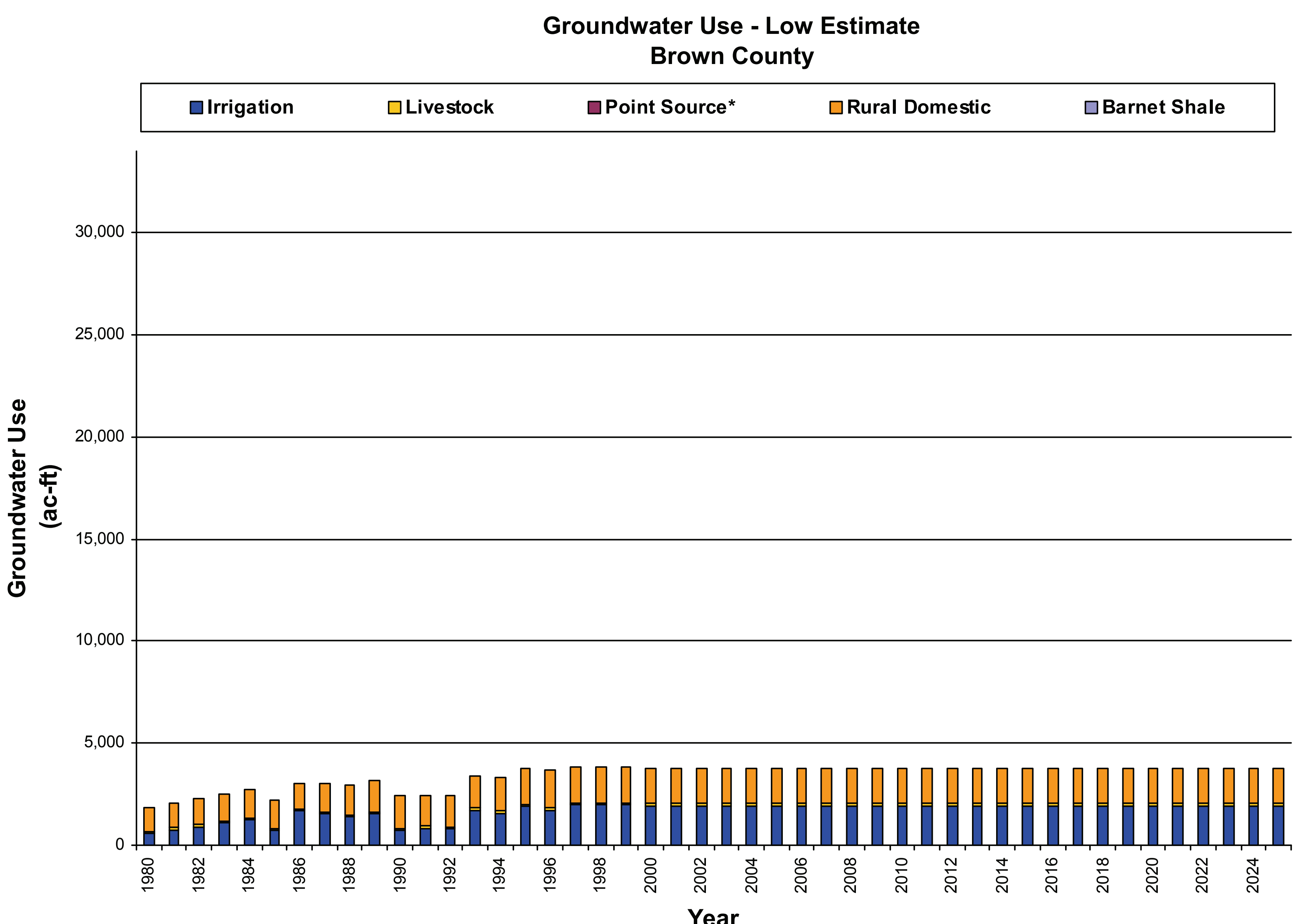
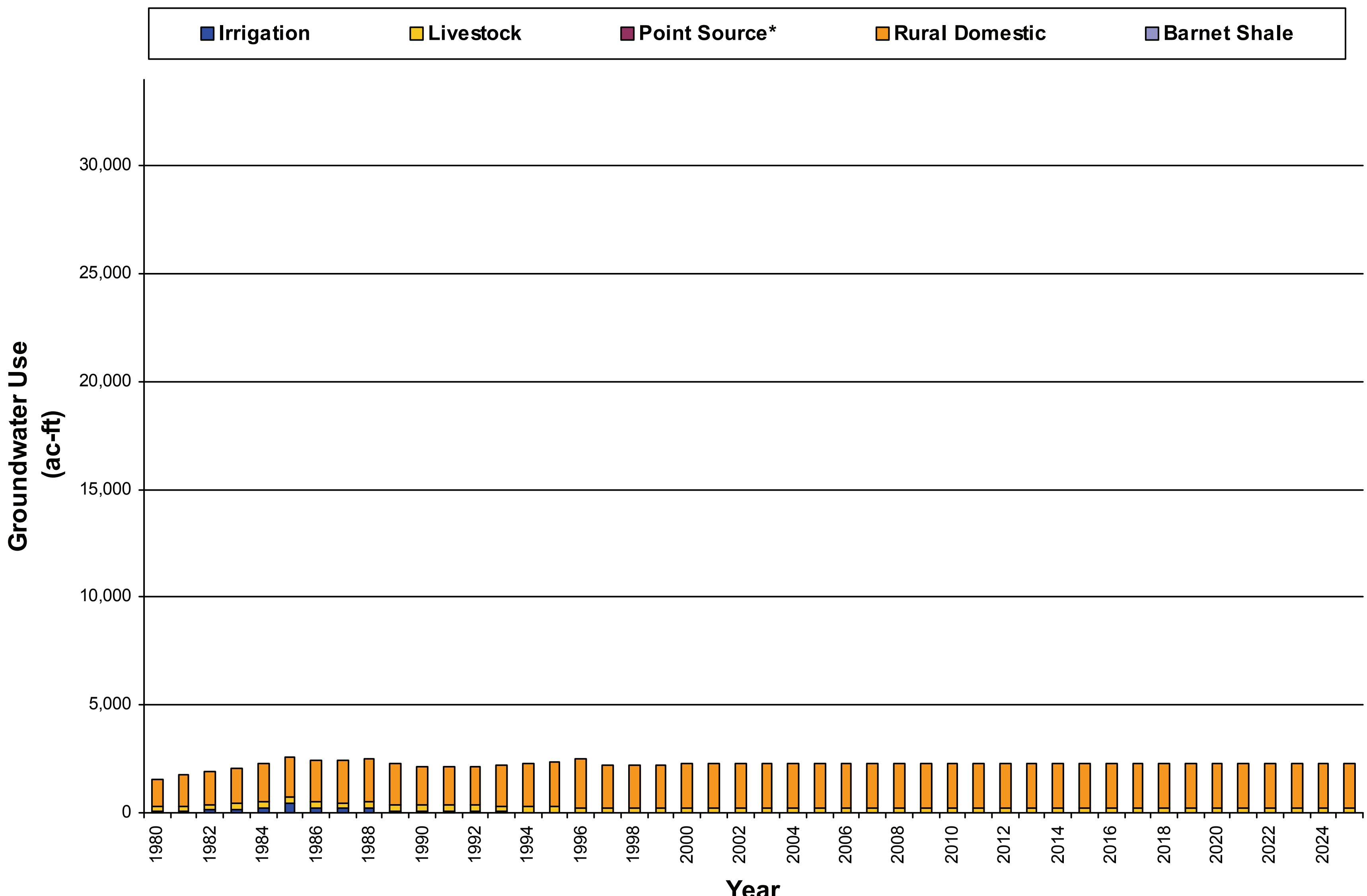
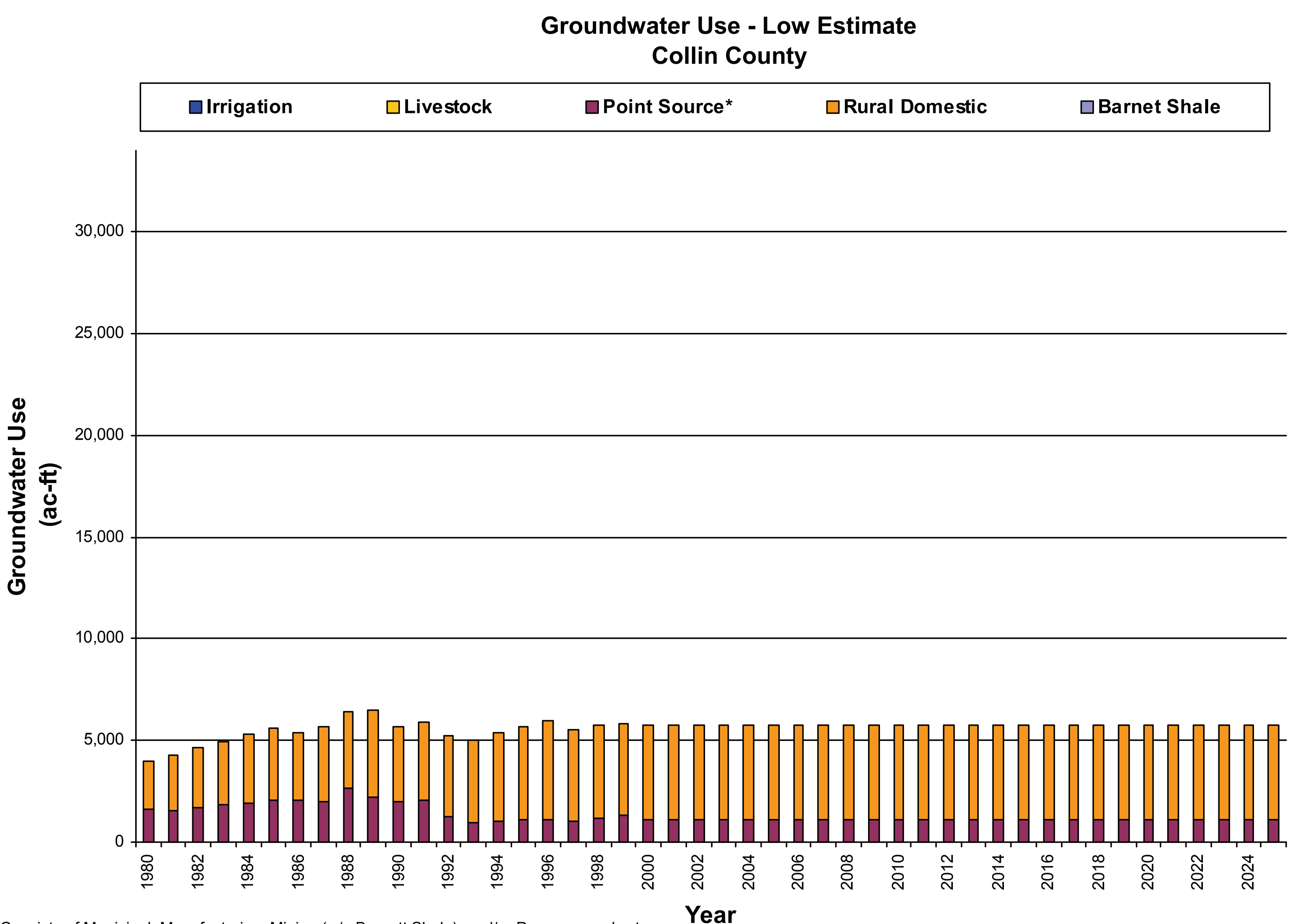


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - Low Estimate
Burnet County

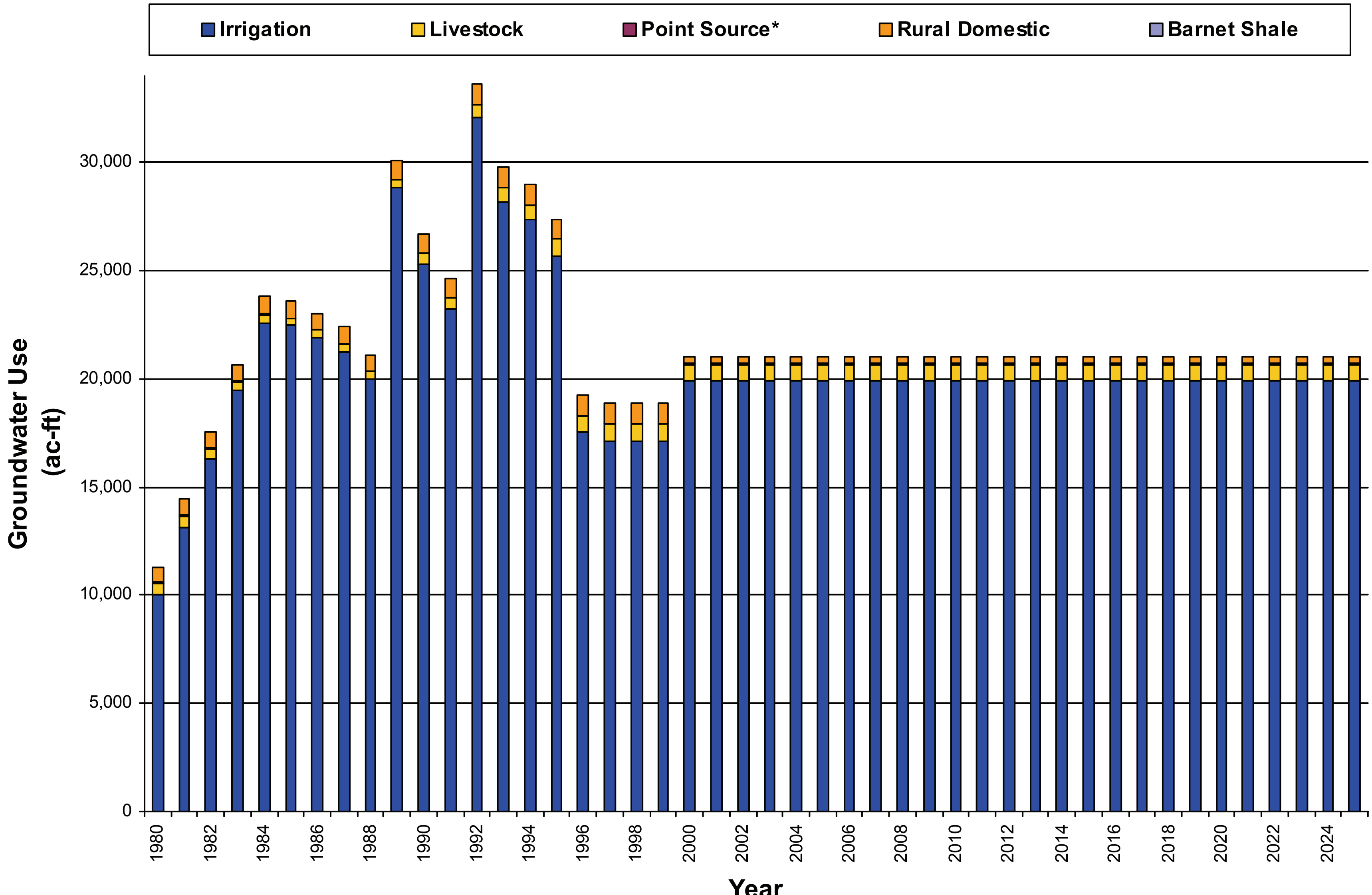


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - Low Estimate
Comanche County



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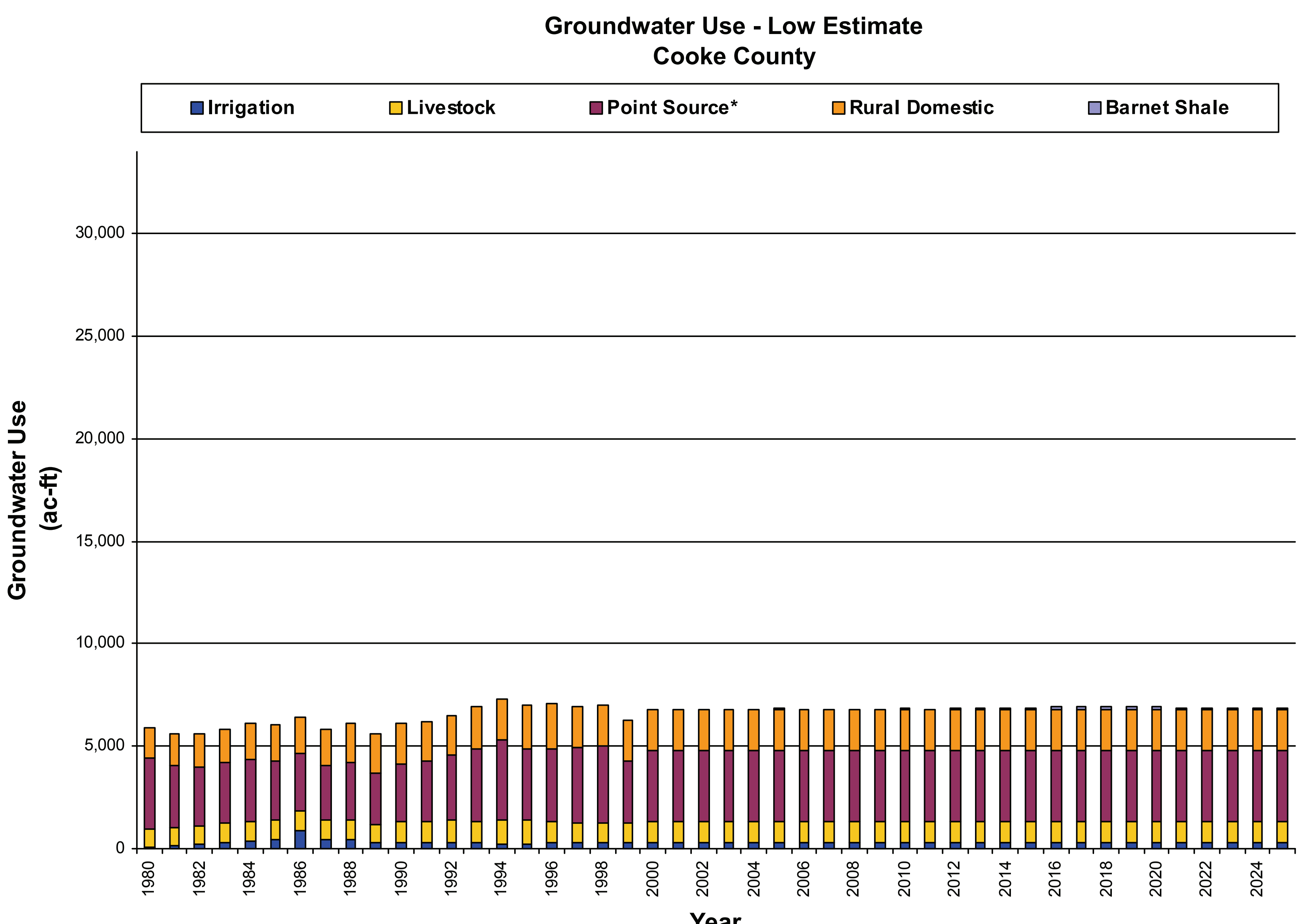

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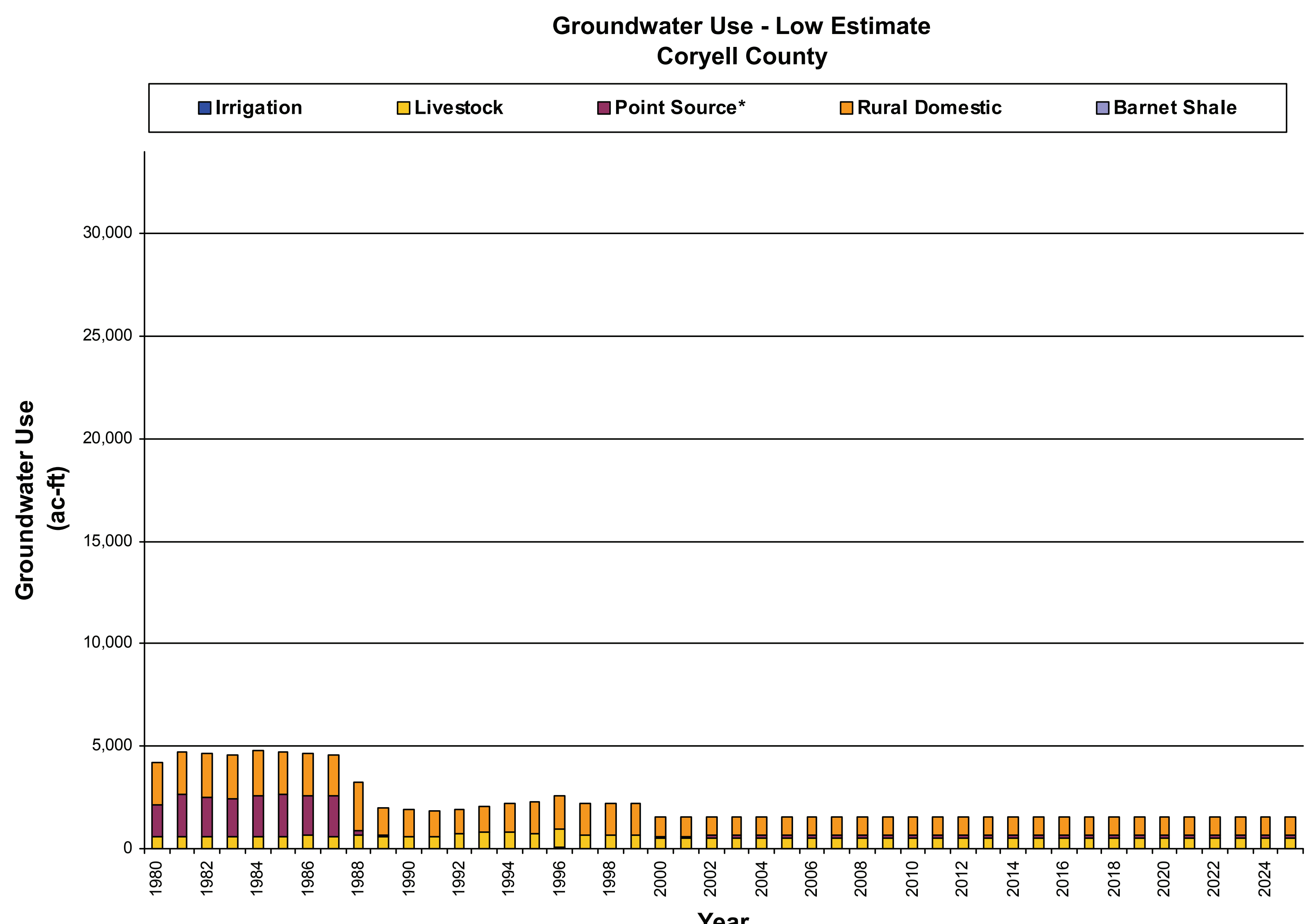

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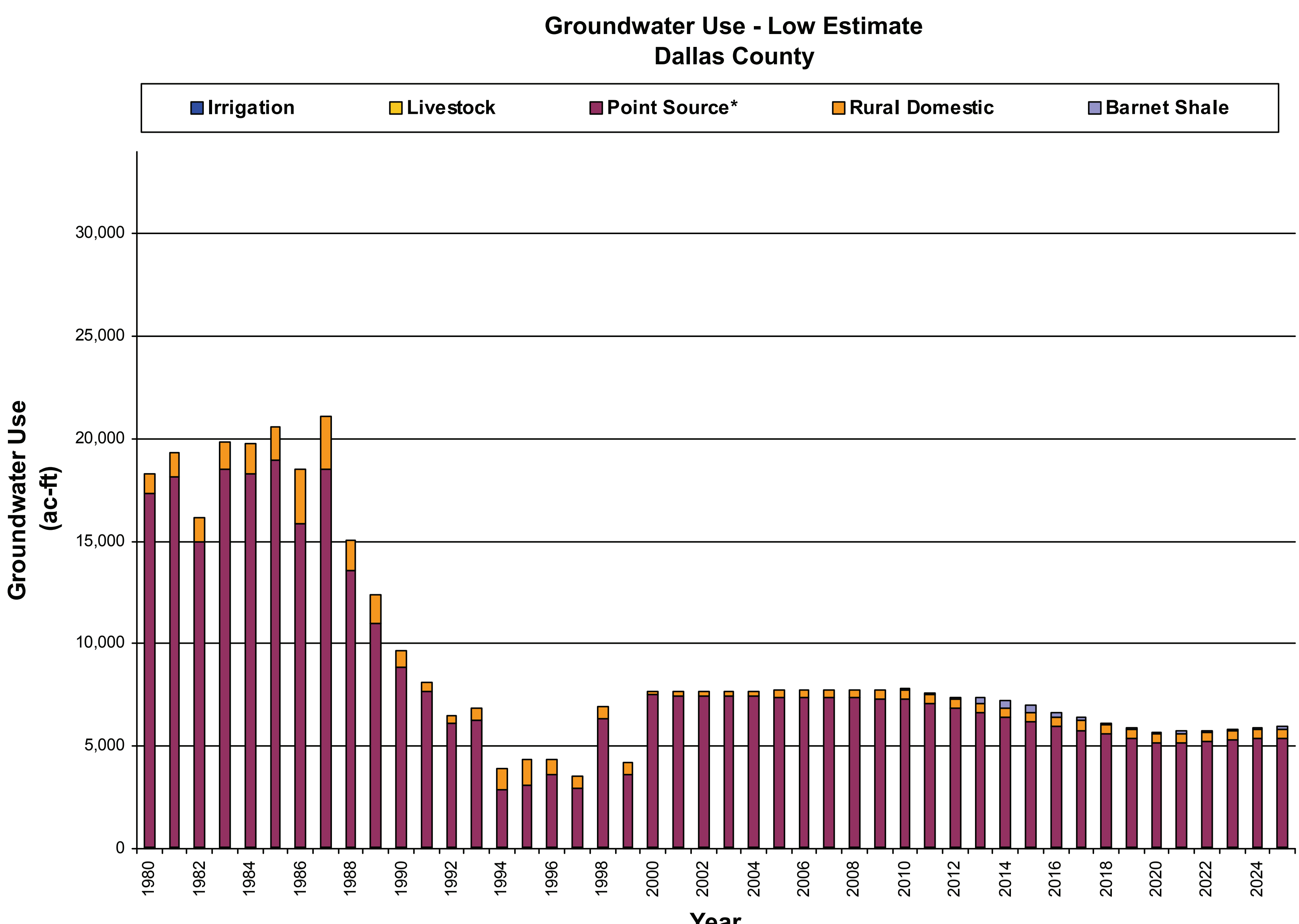

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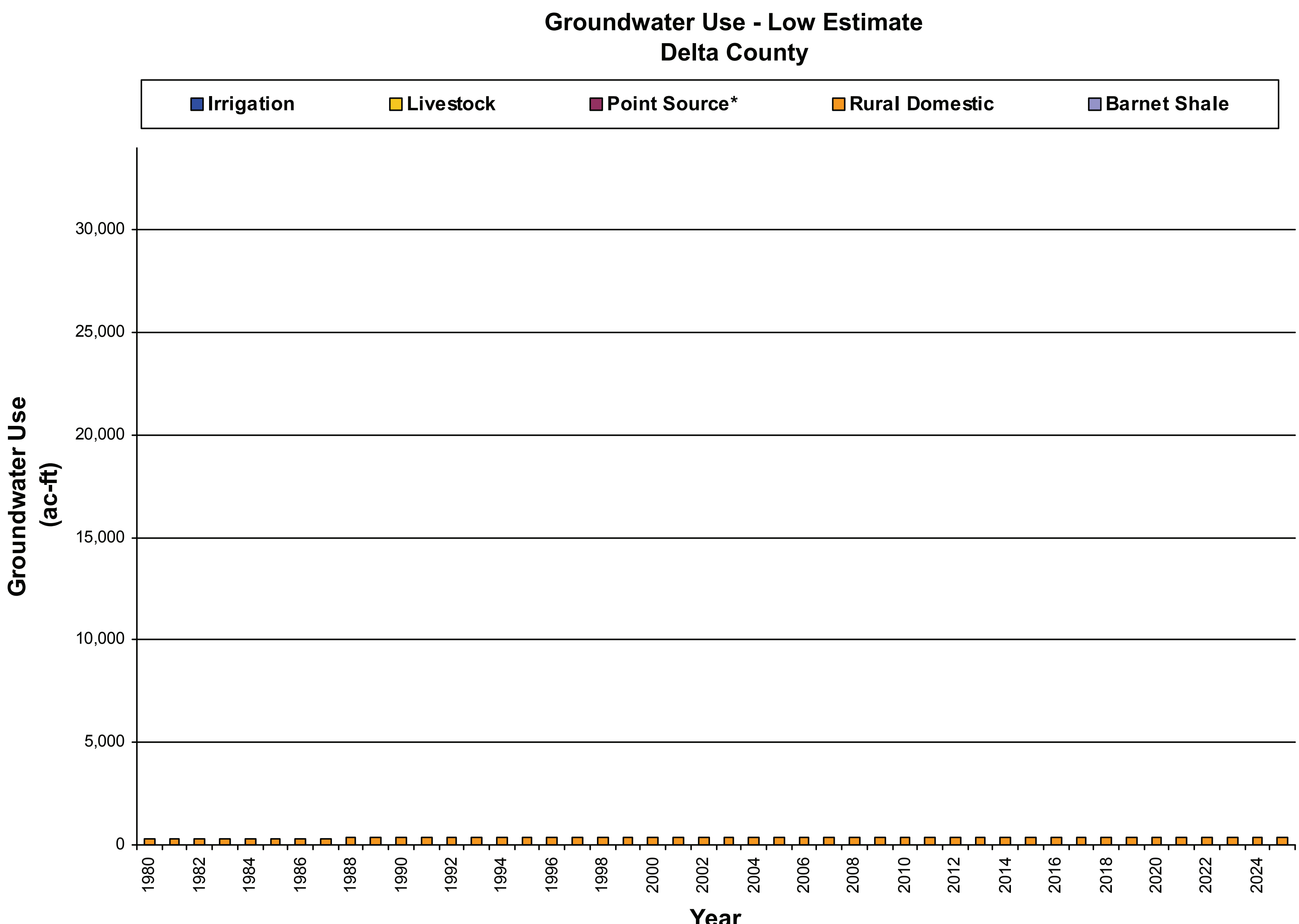

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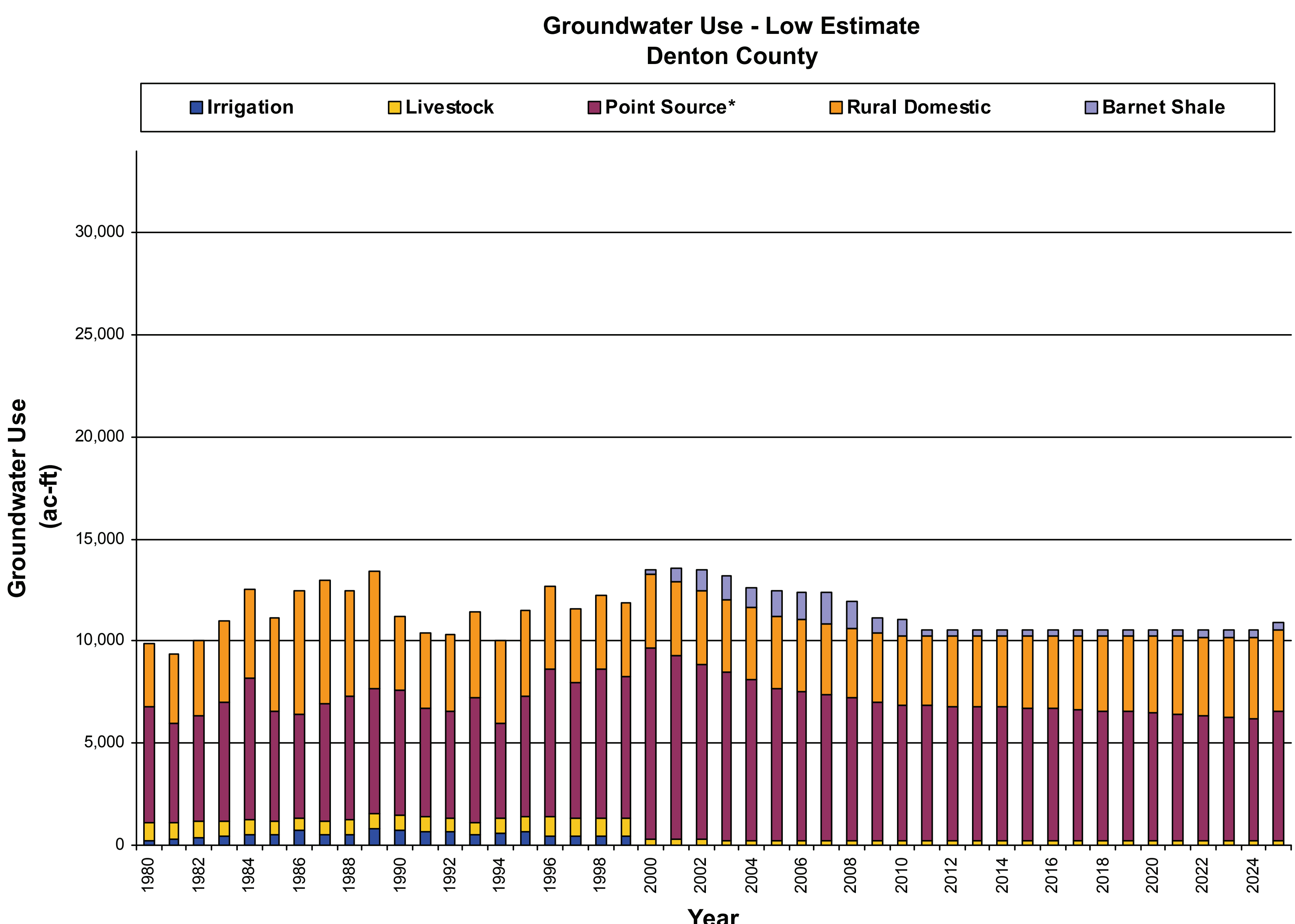
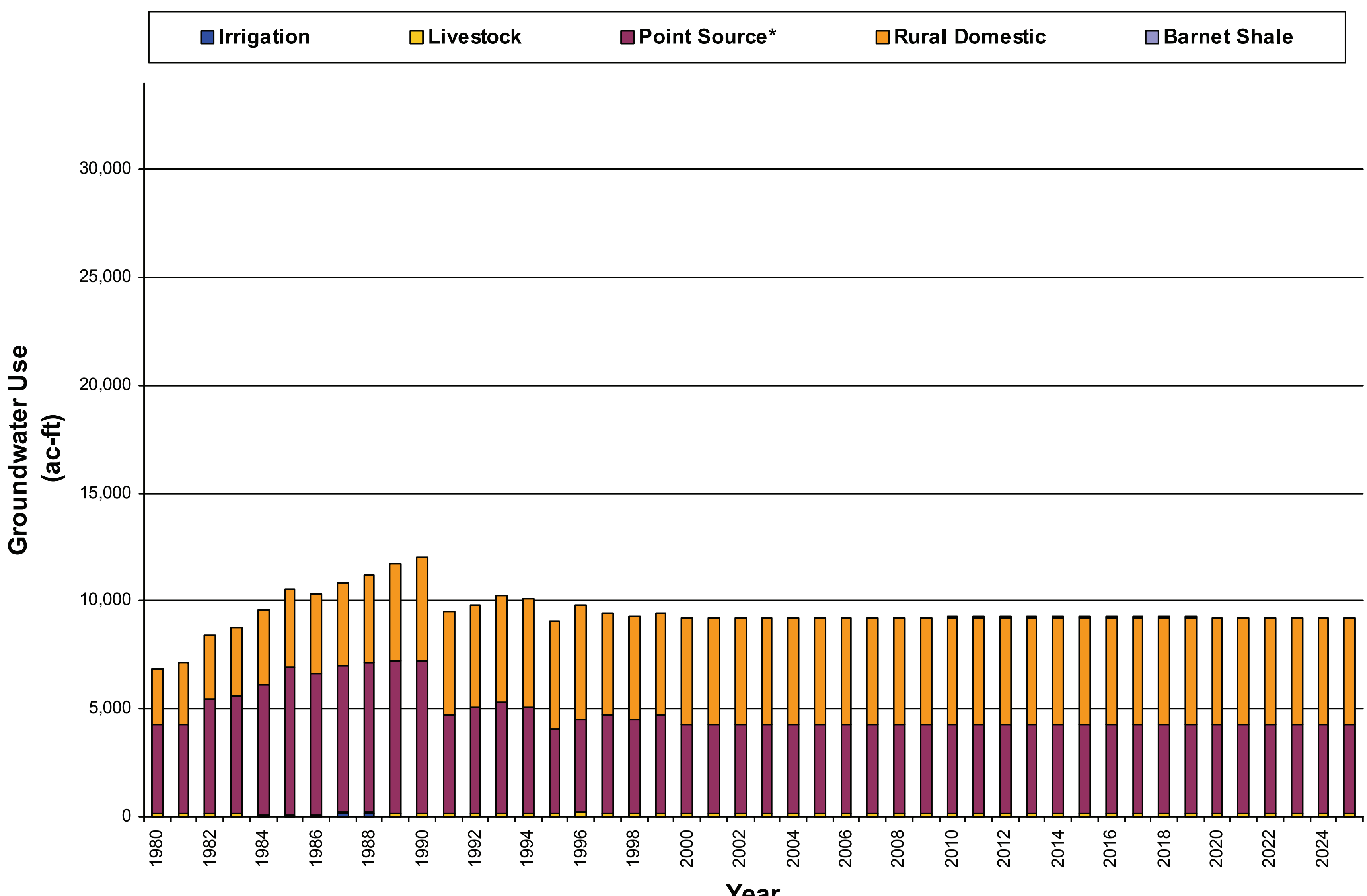


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - Low Estimate
Ellis County



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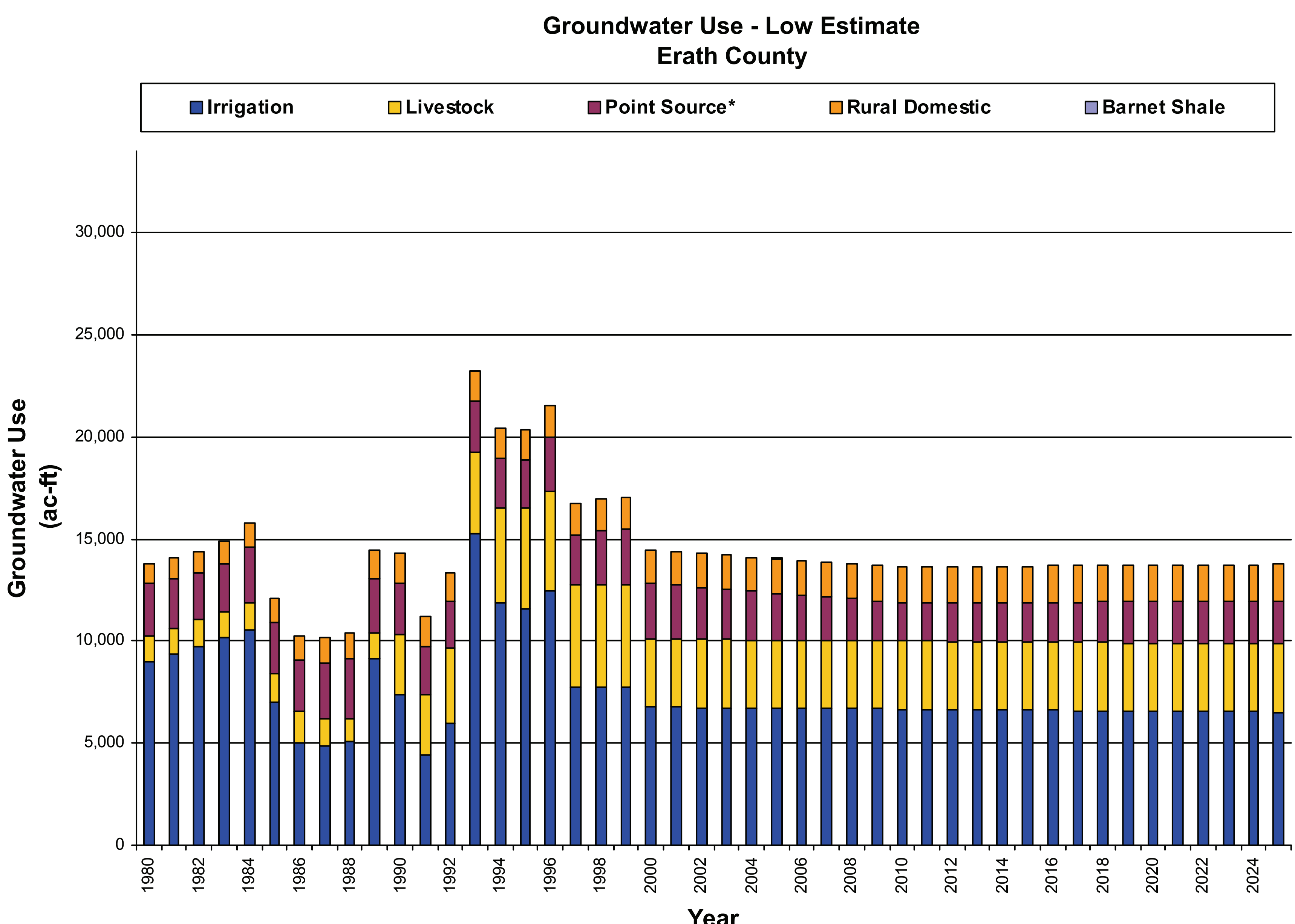
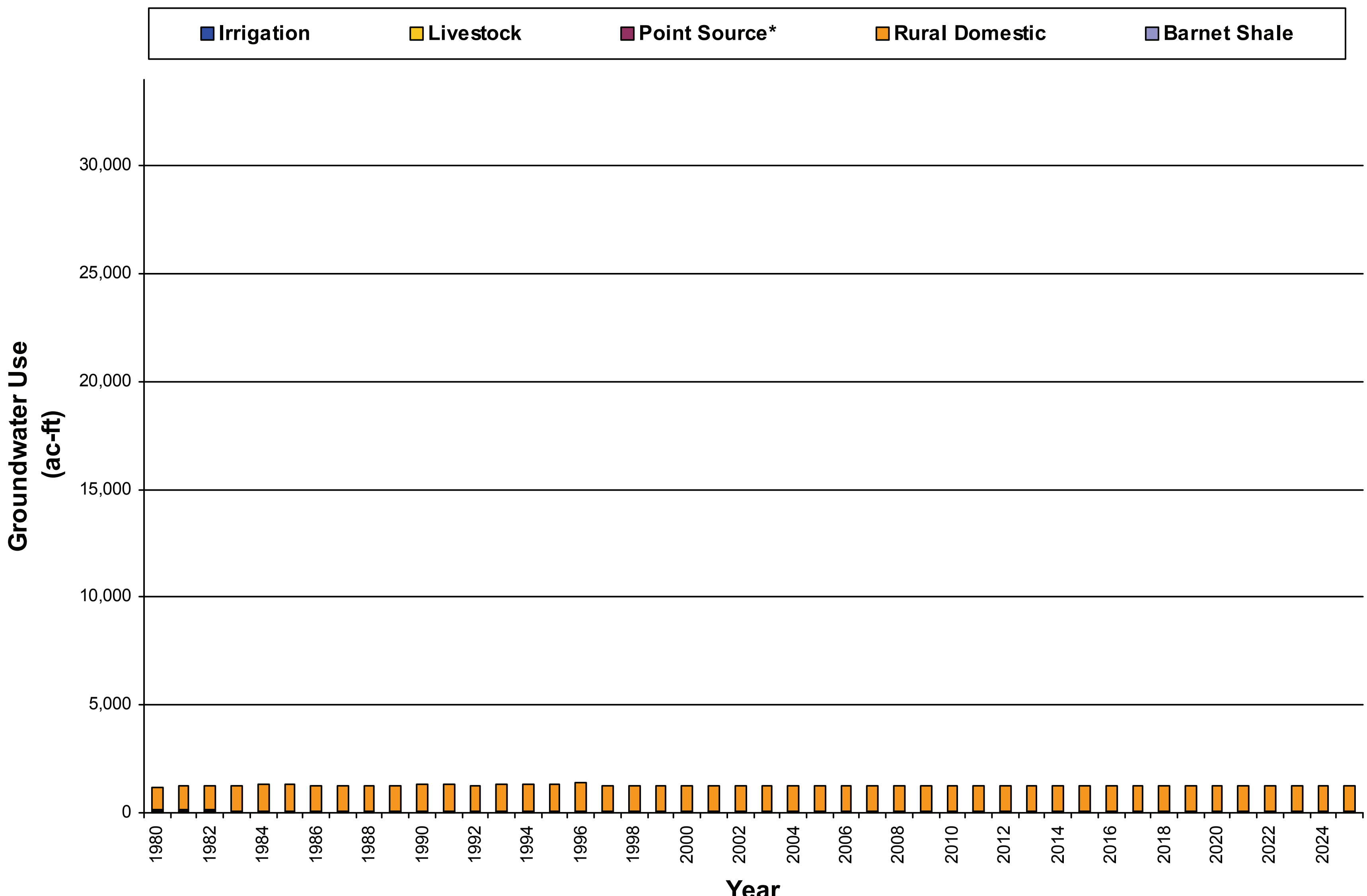


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - Low Estimate
Falls County



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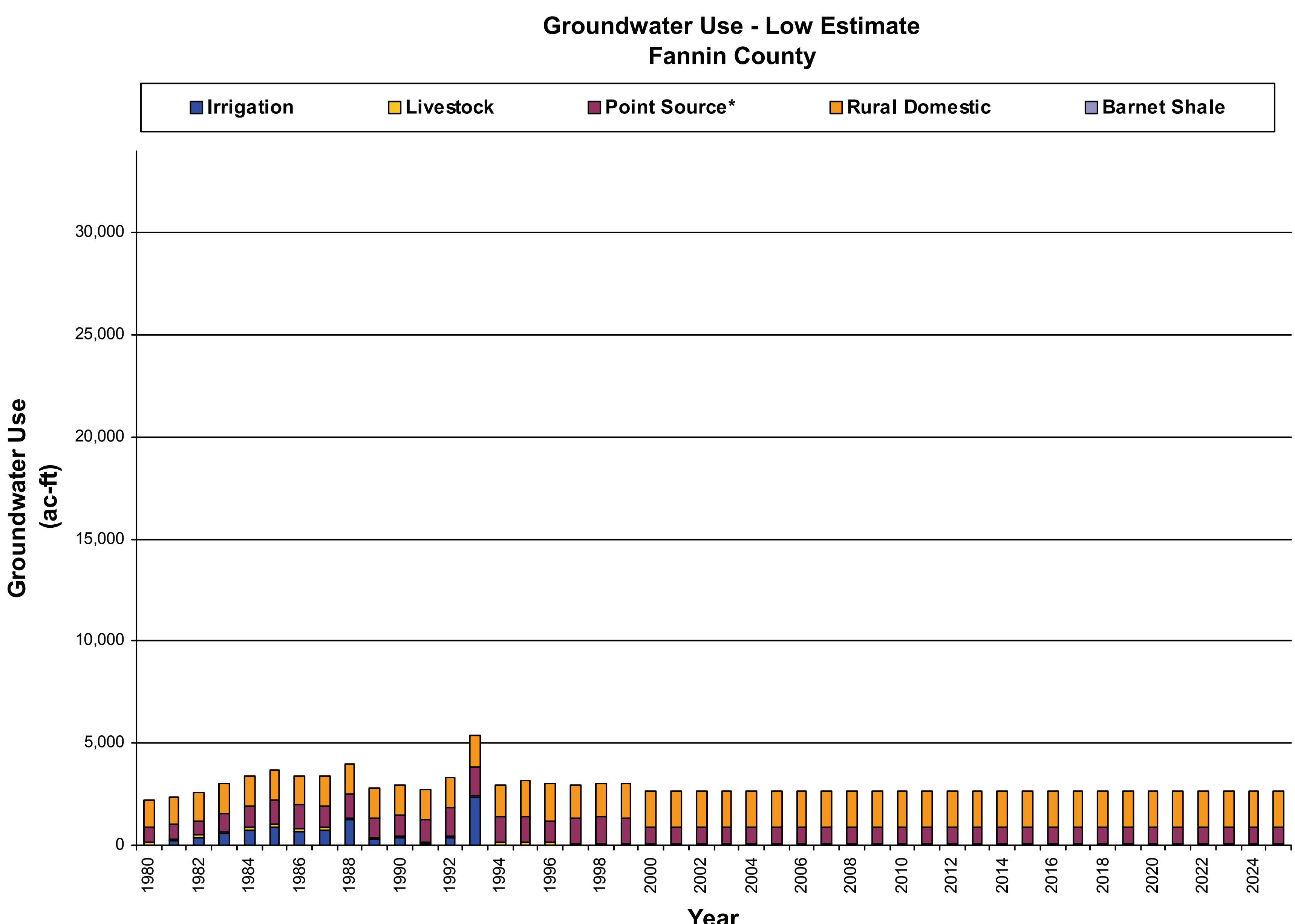

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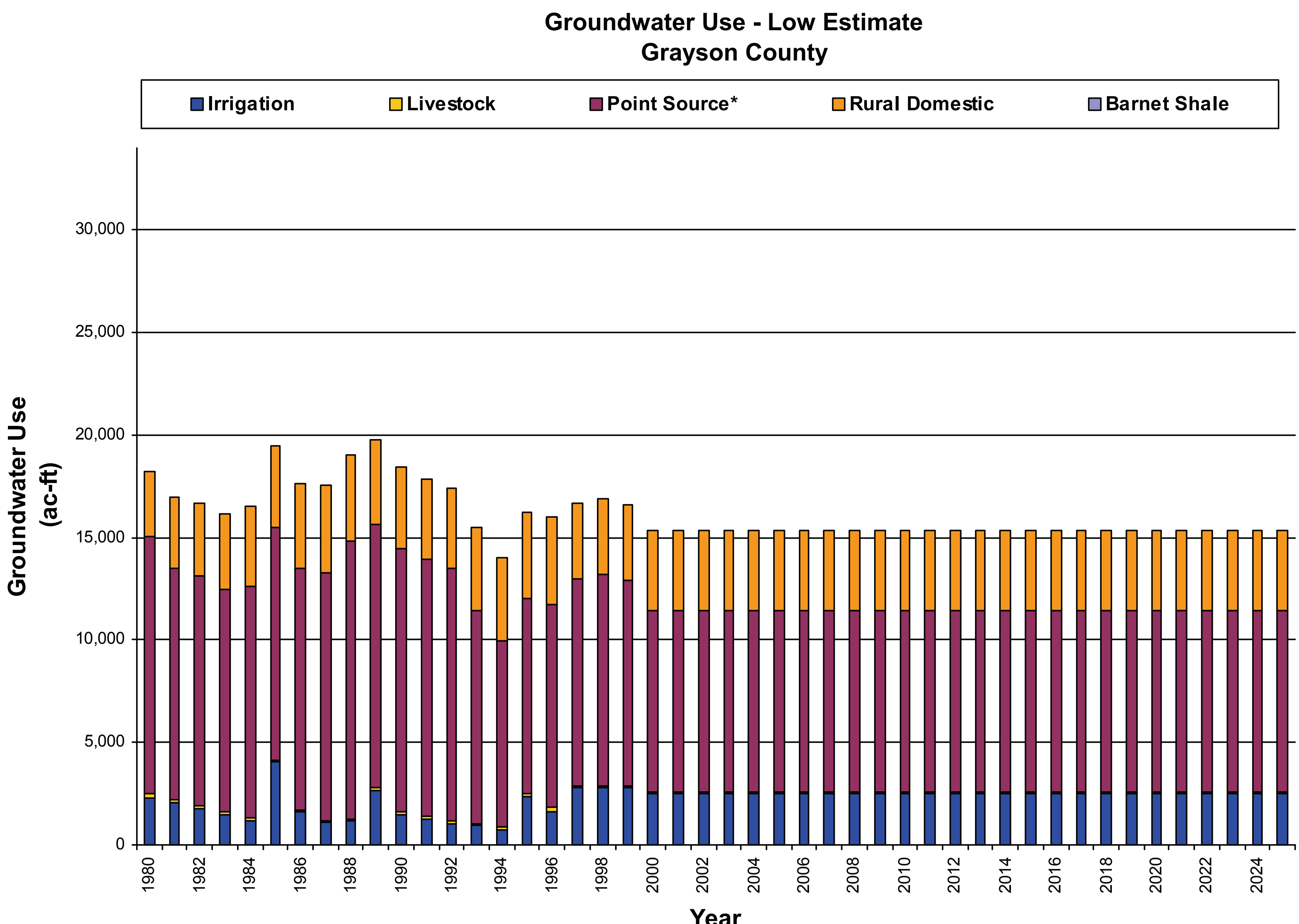
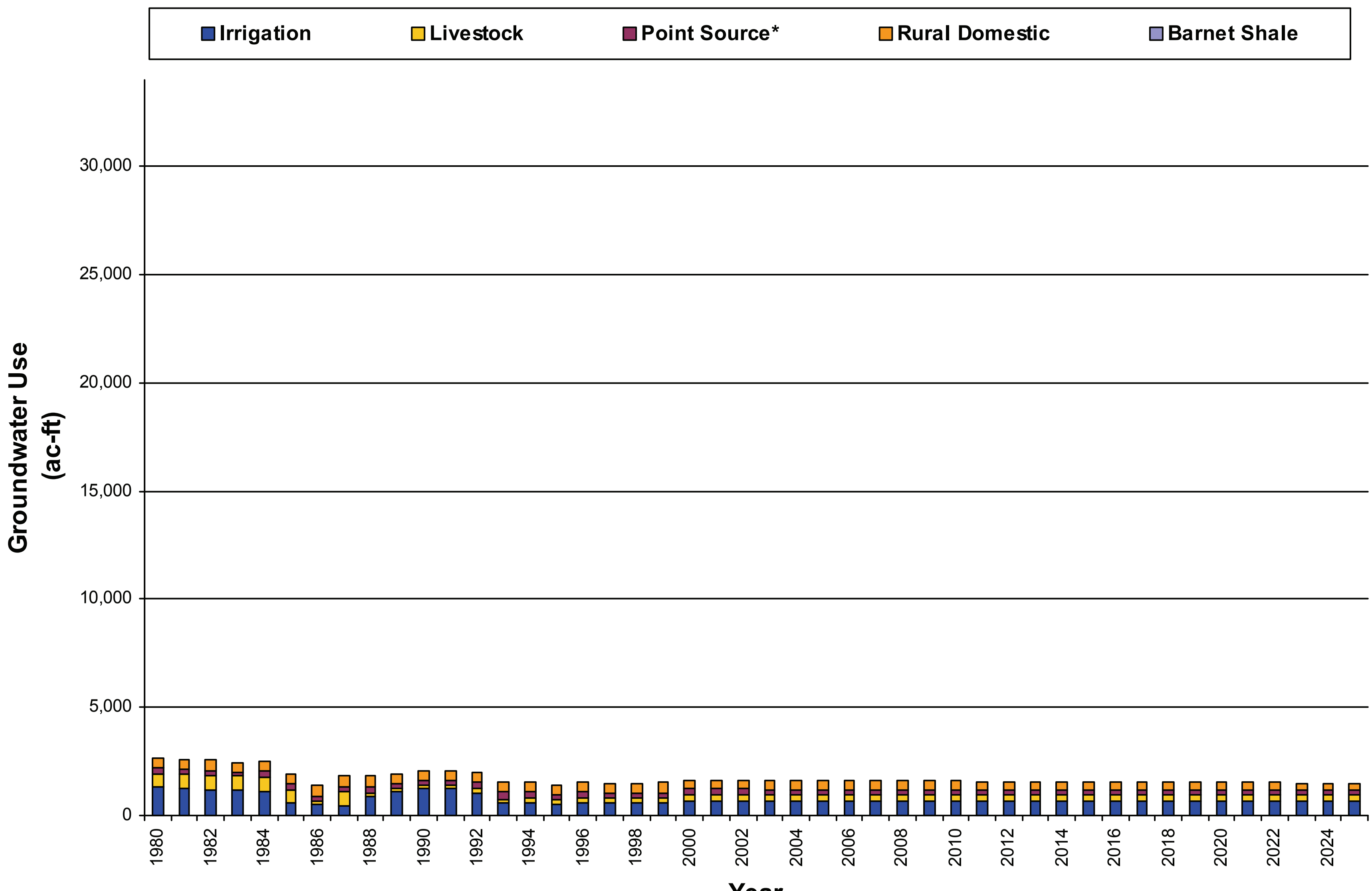
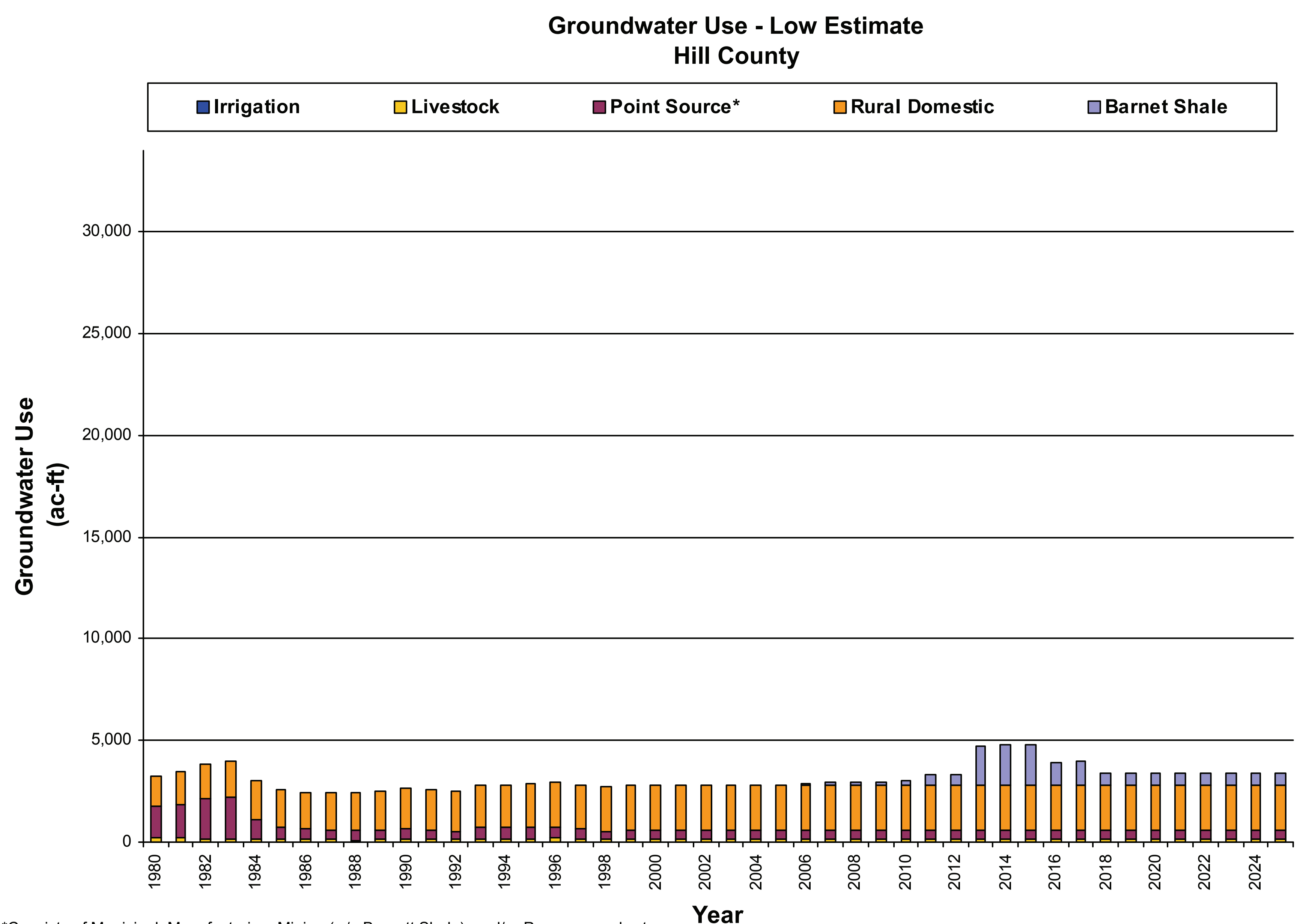


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - Low Estimate
Hamilton County



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



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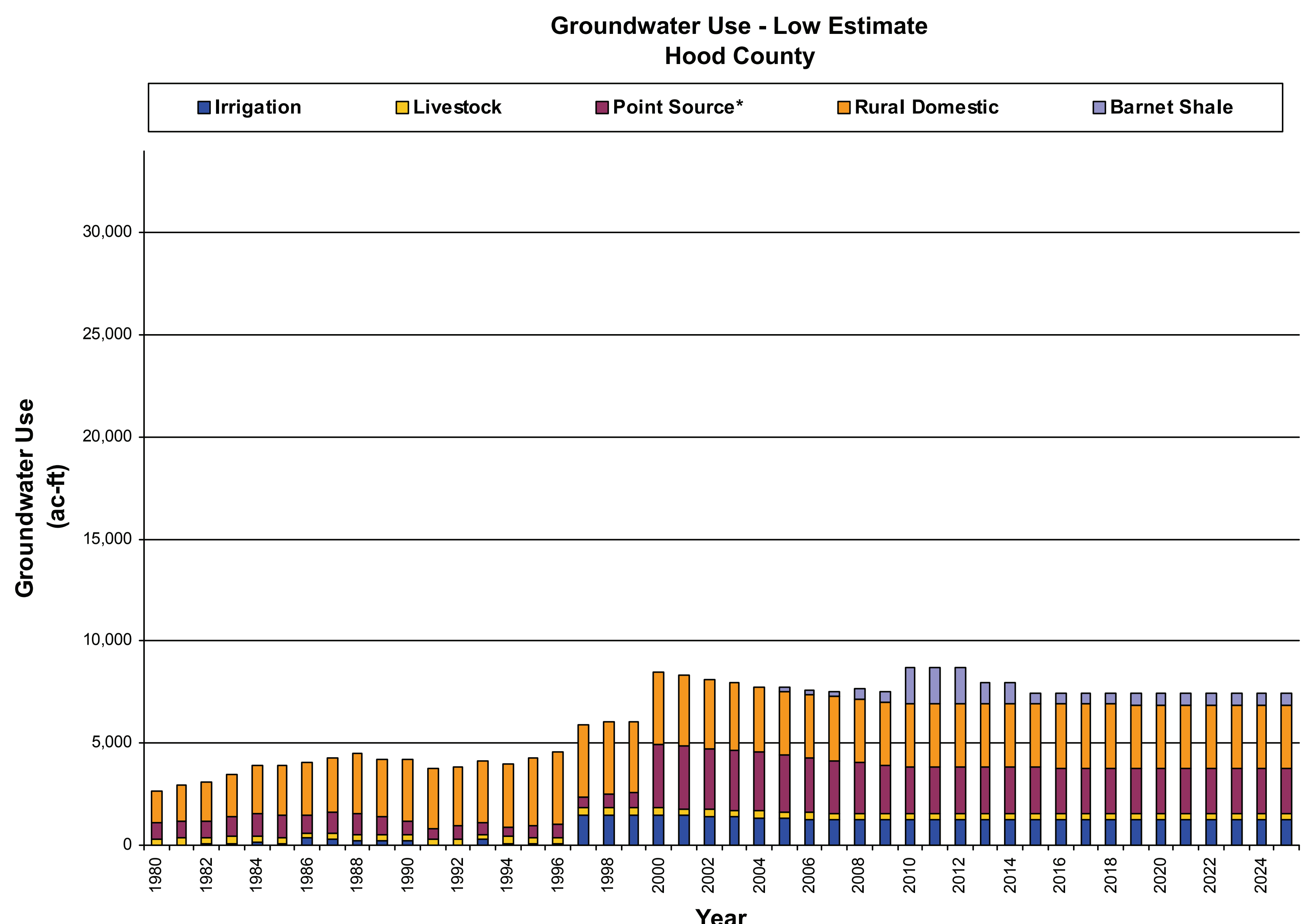

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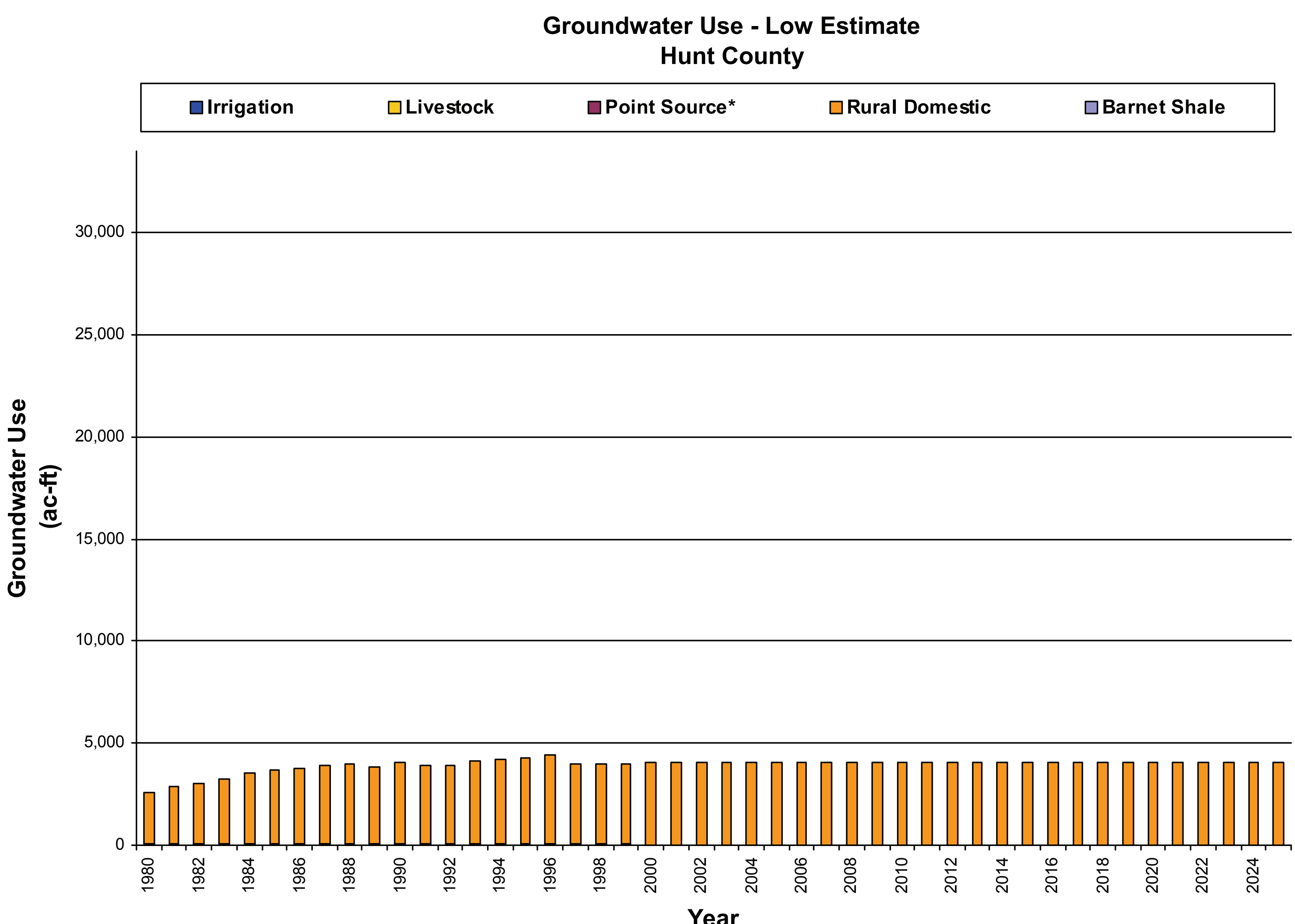

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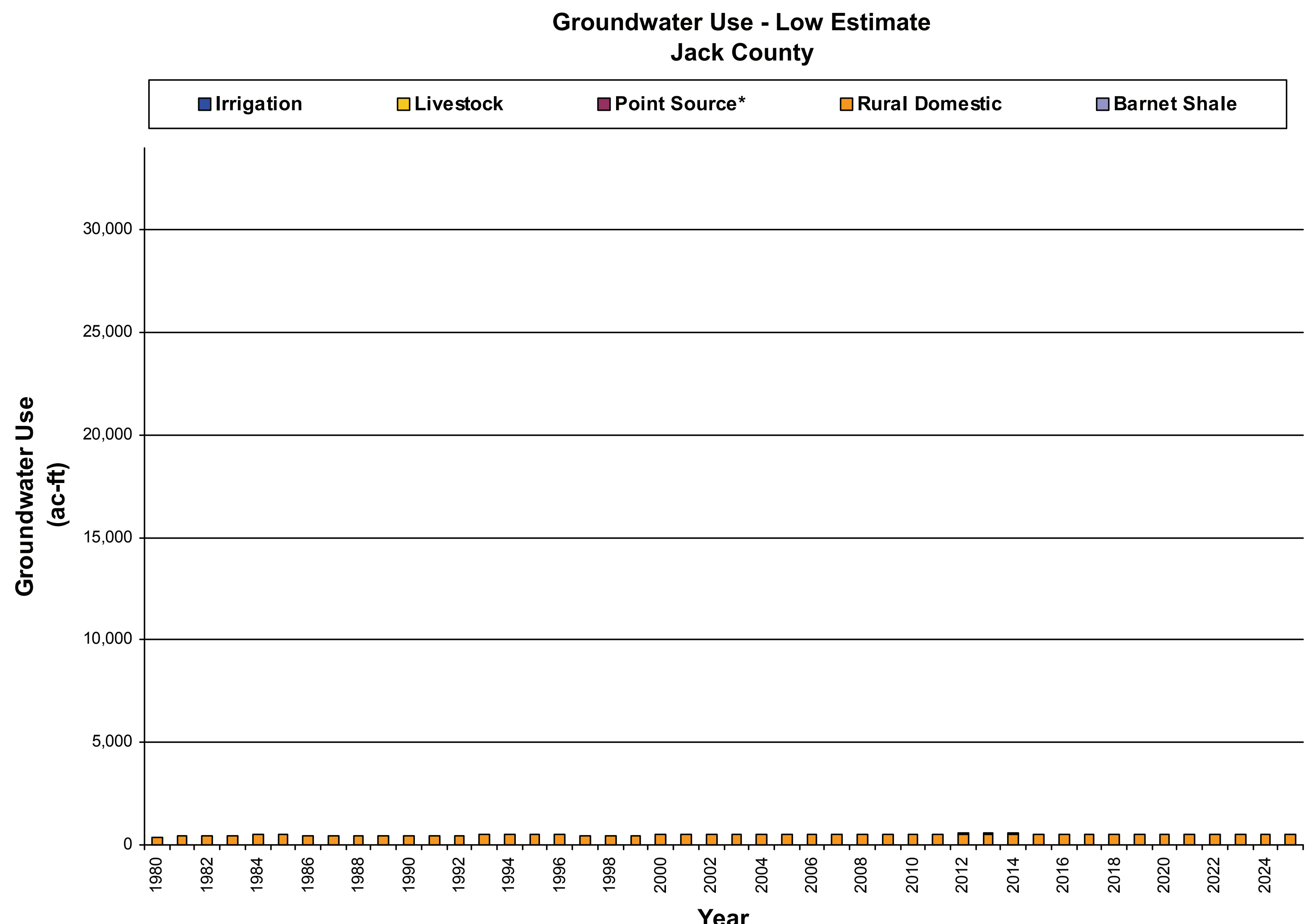
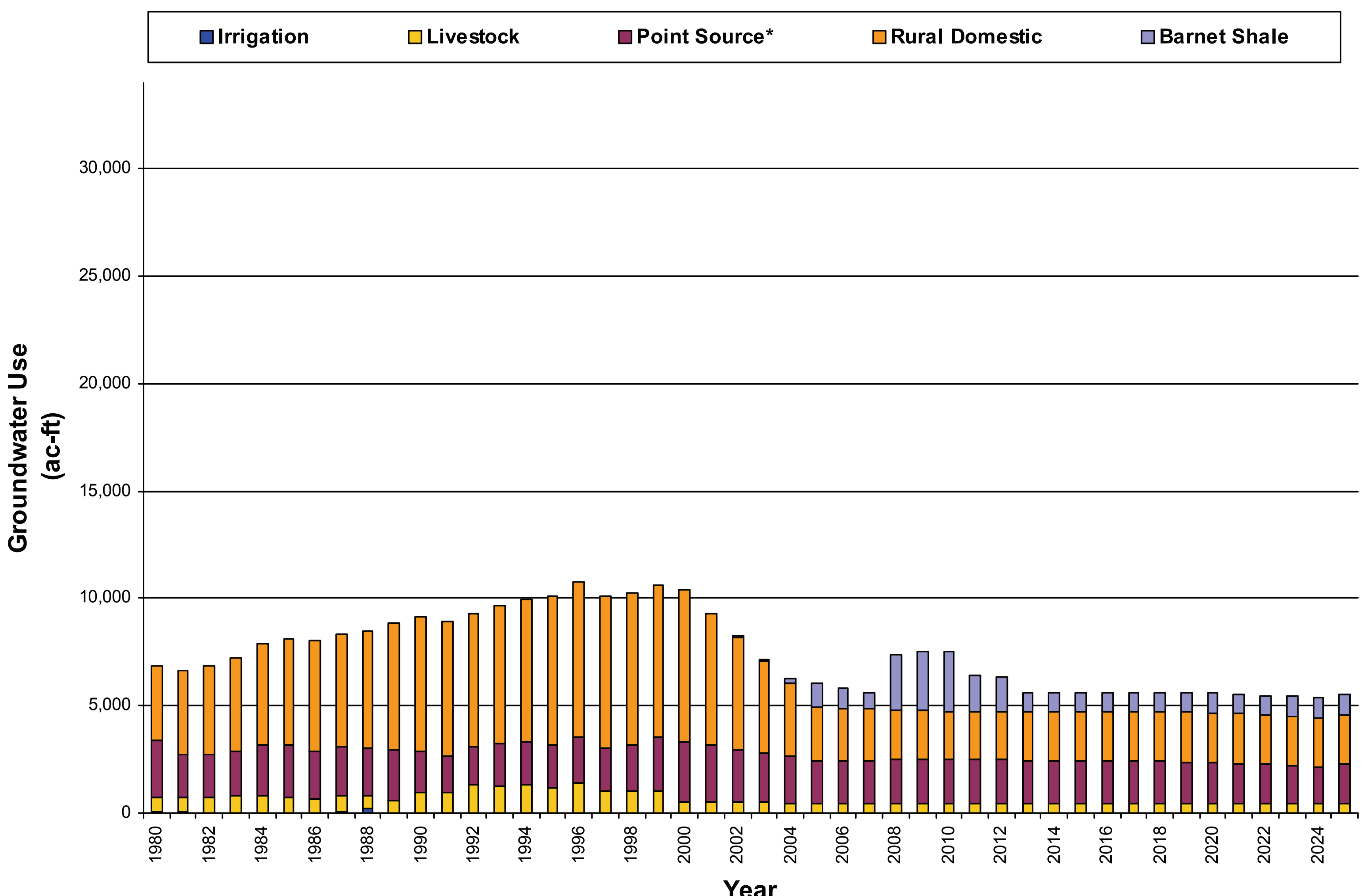


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - Low Estimate
Johnson County



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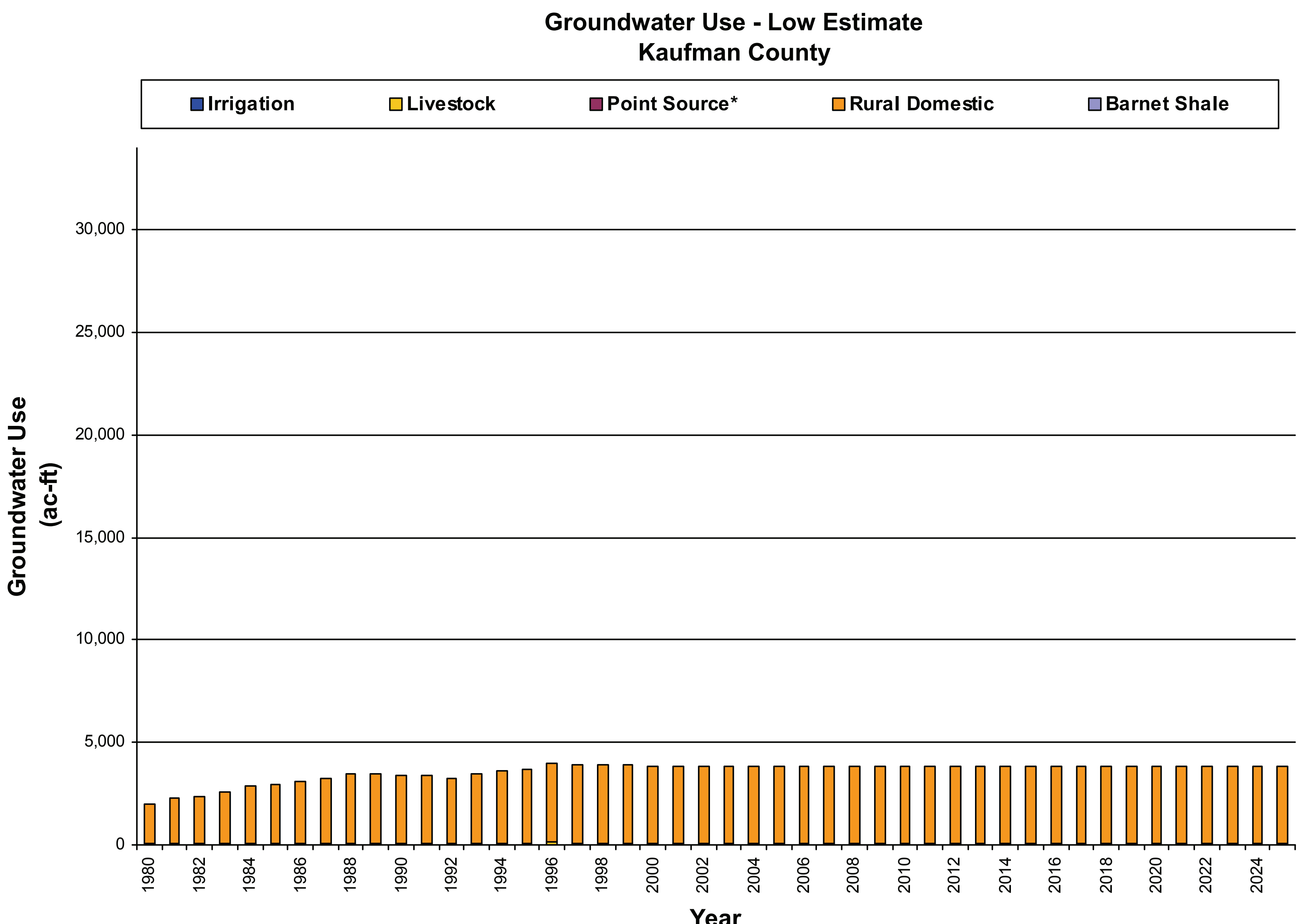

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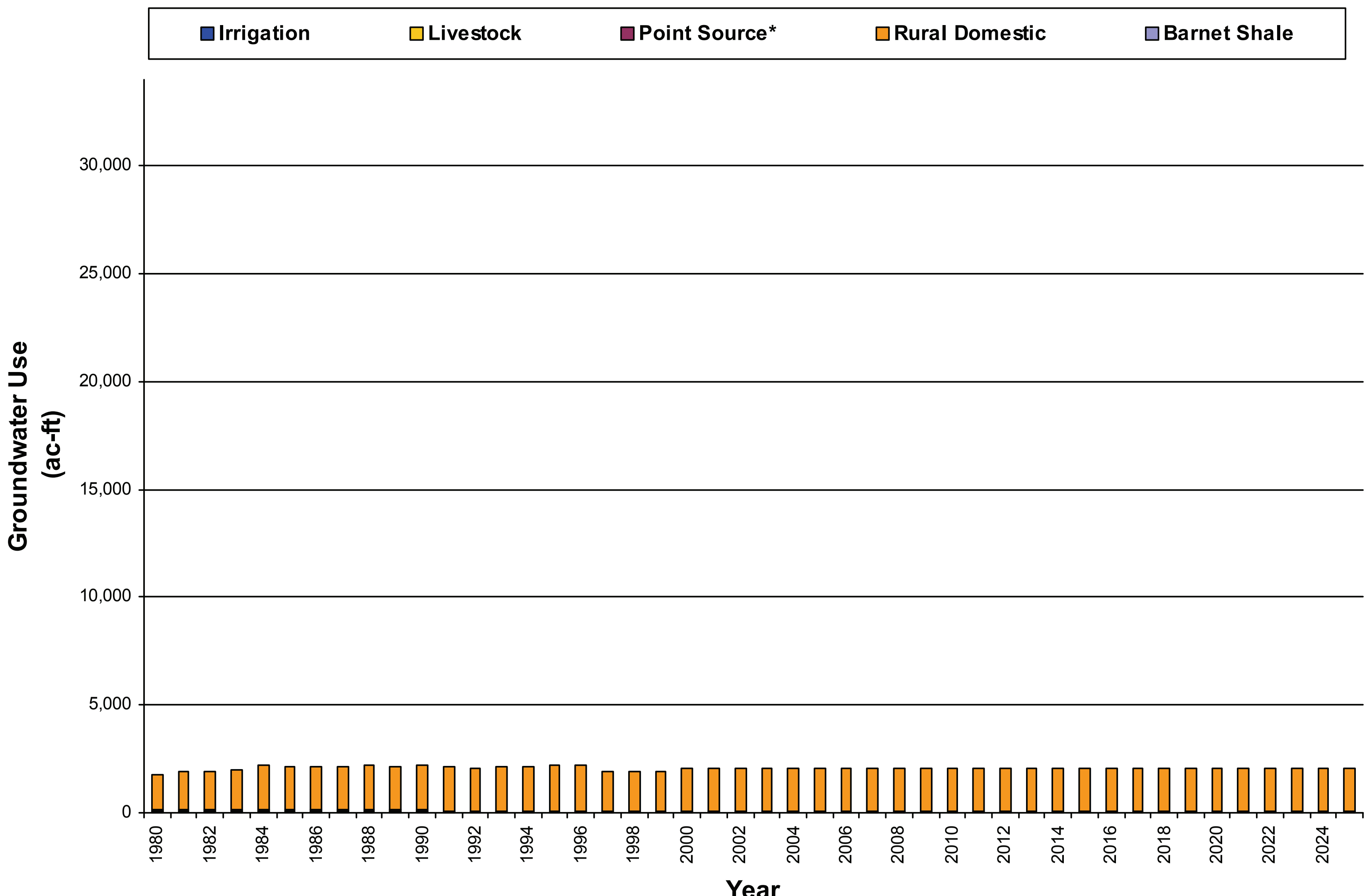
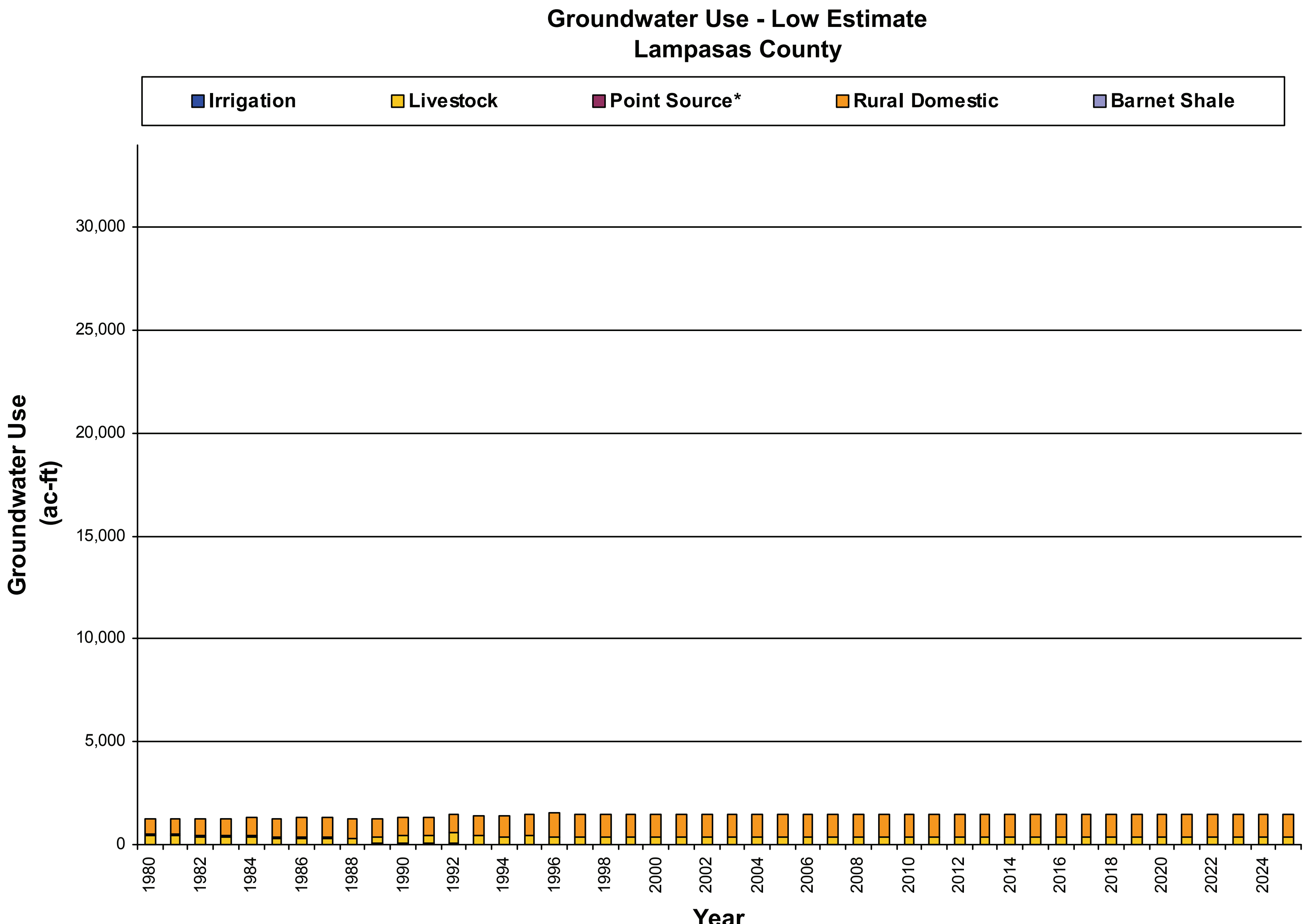
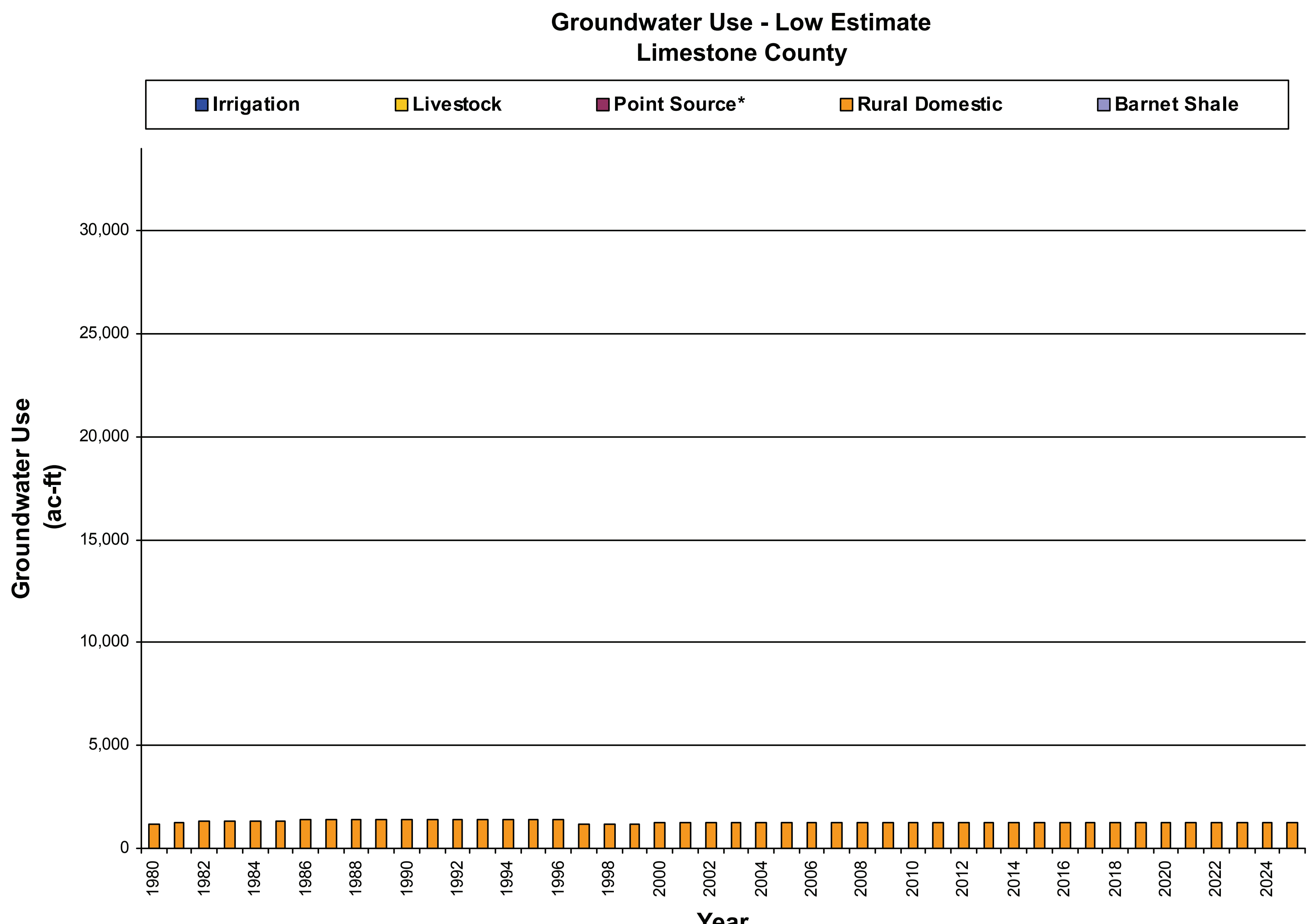
Groundwater Use - Low Estimate
Lamar County



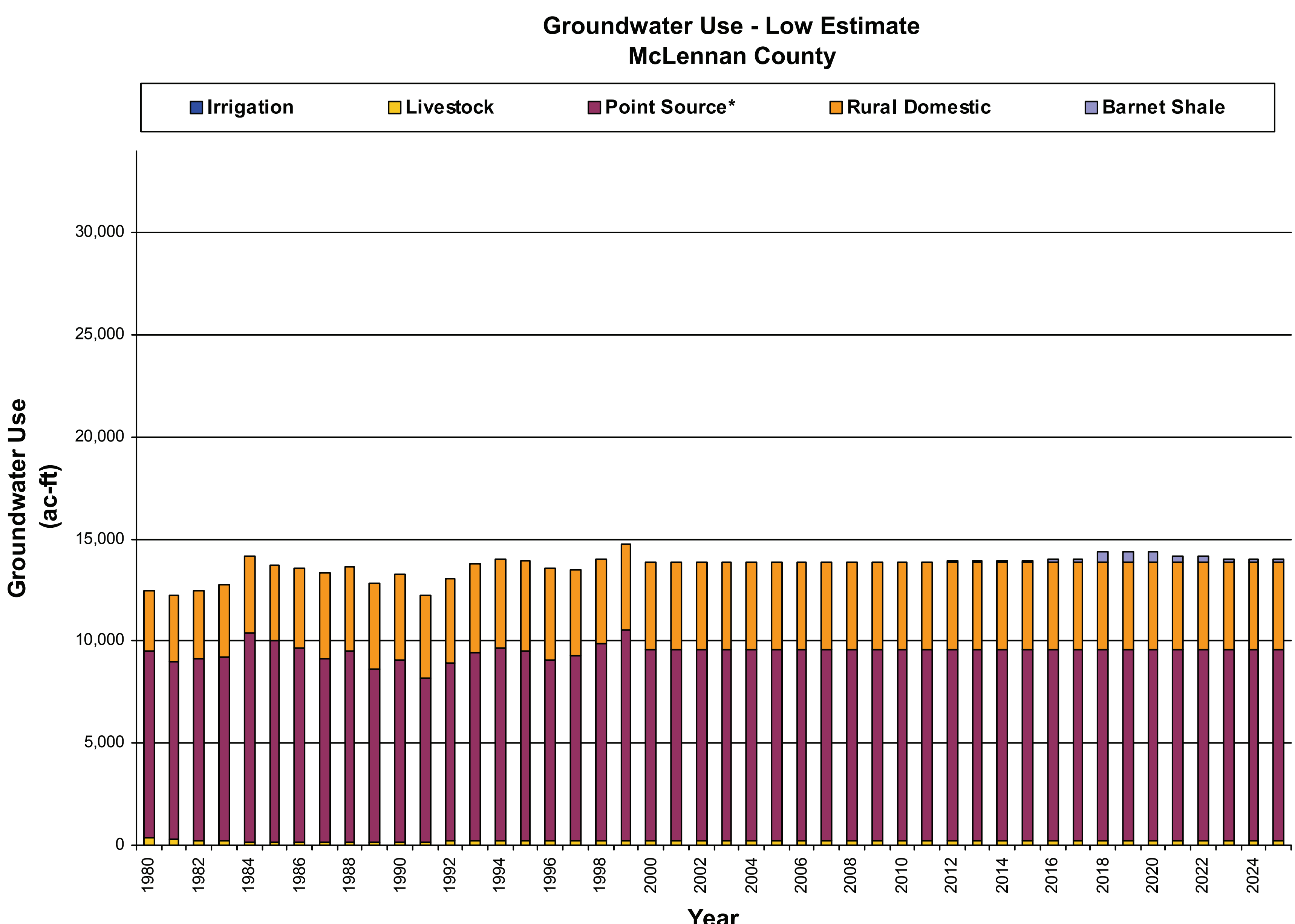
*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



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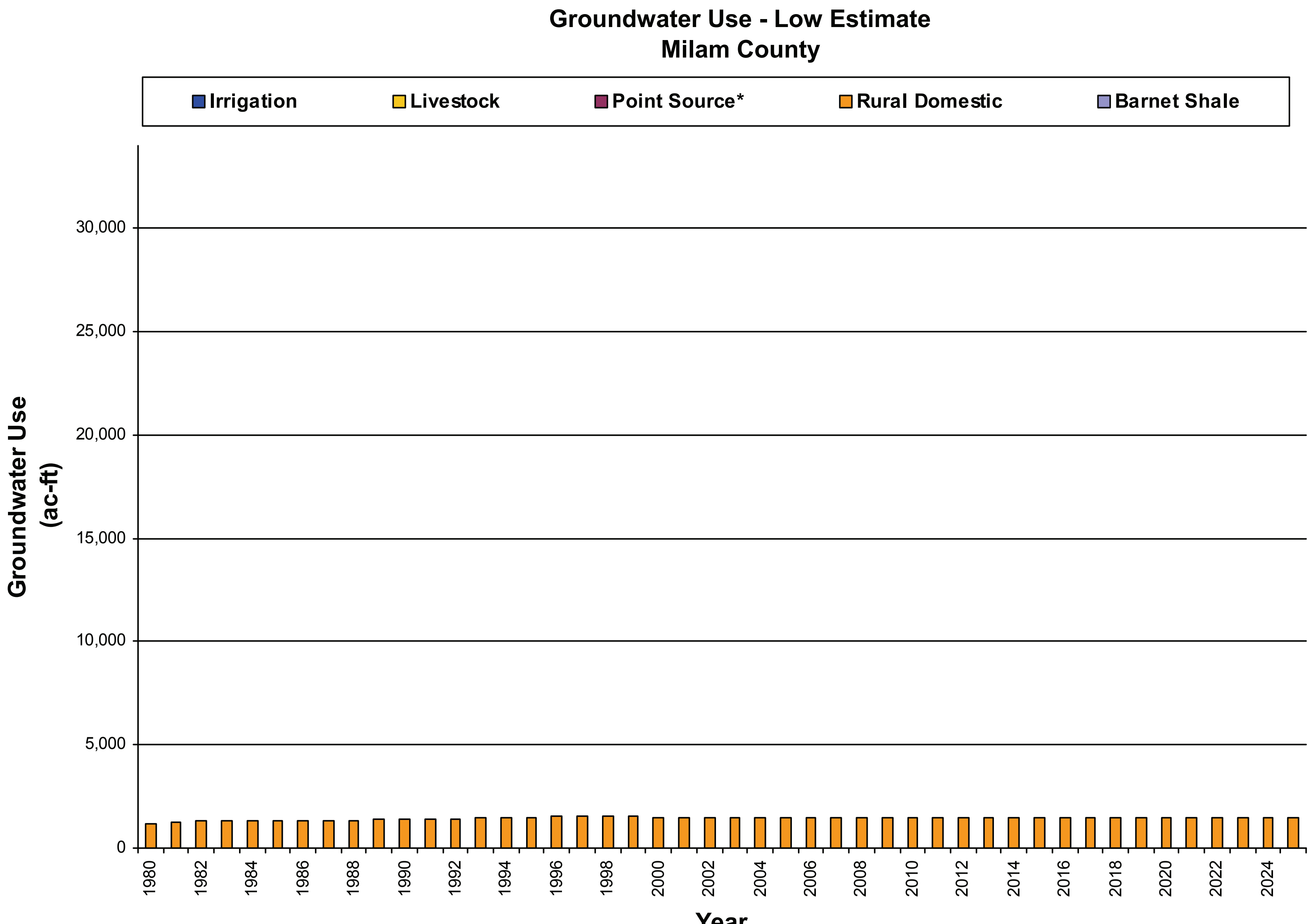

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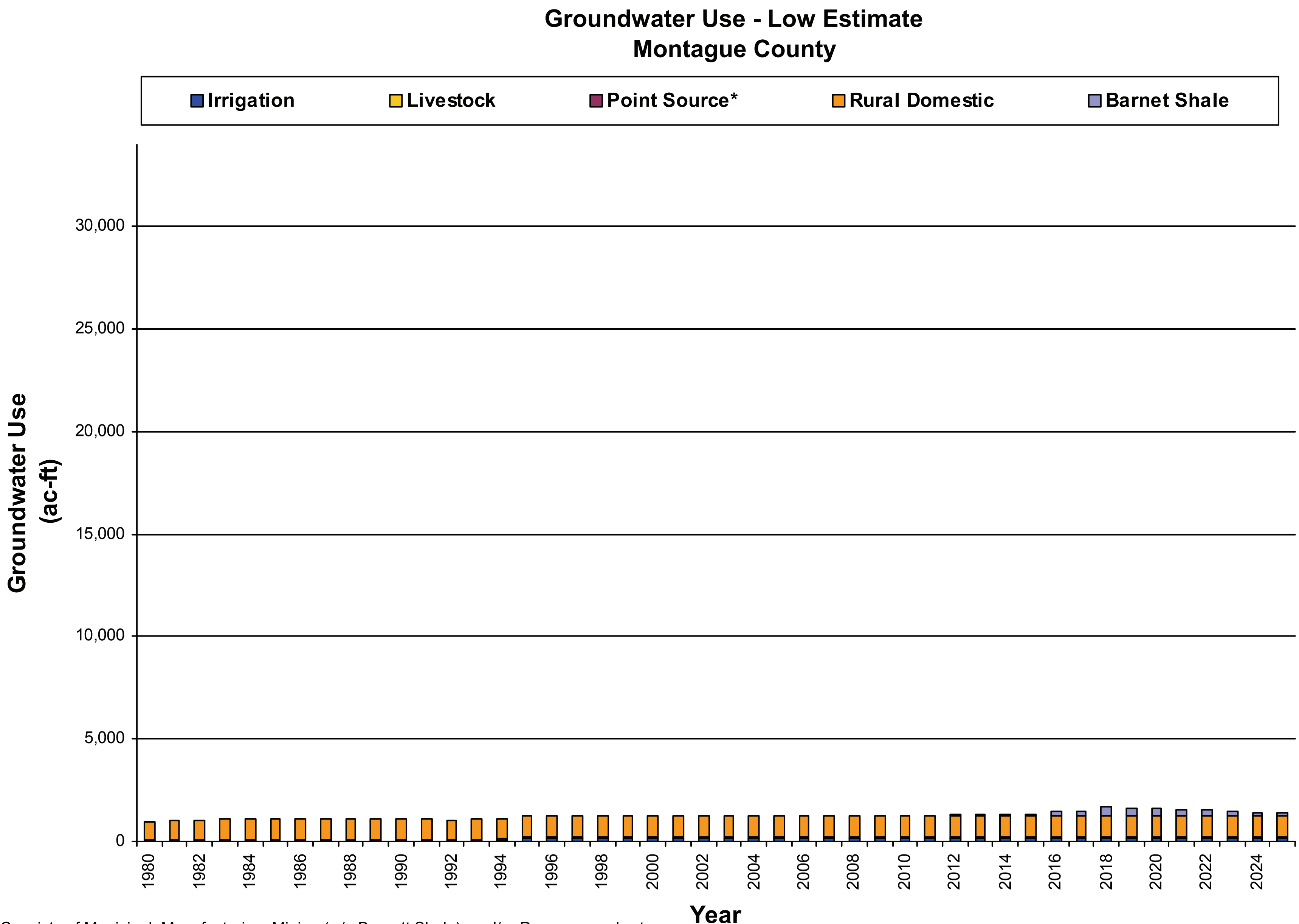

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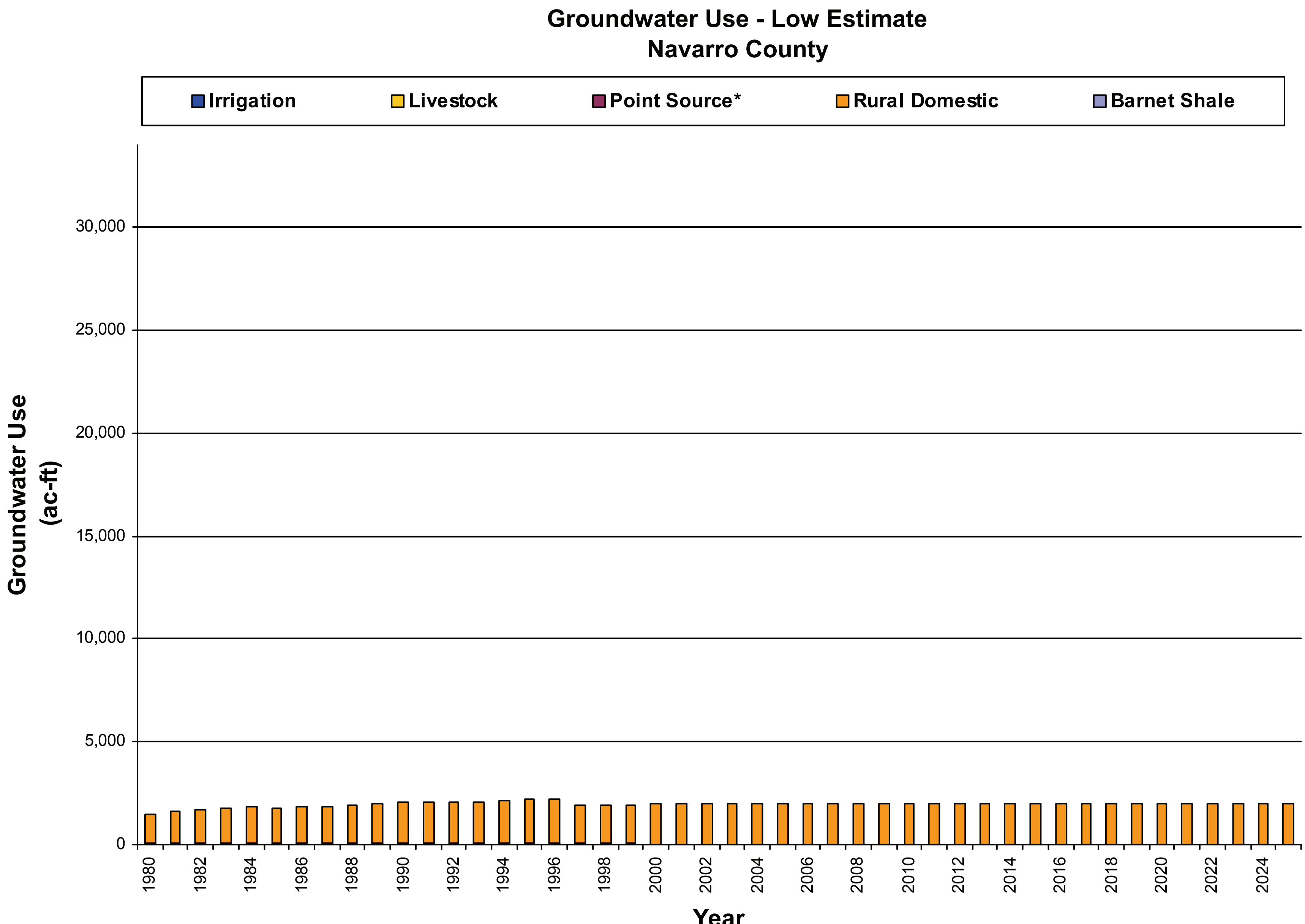

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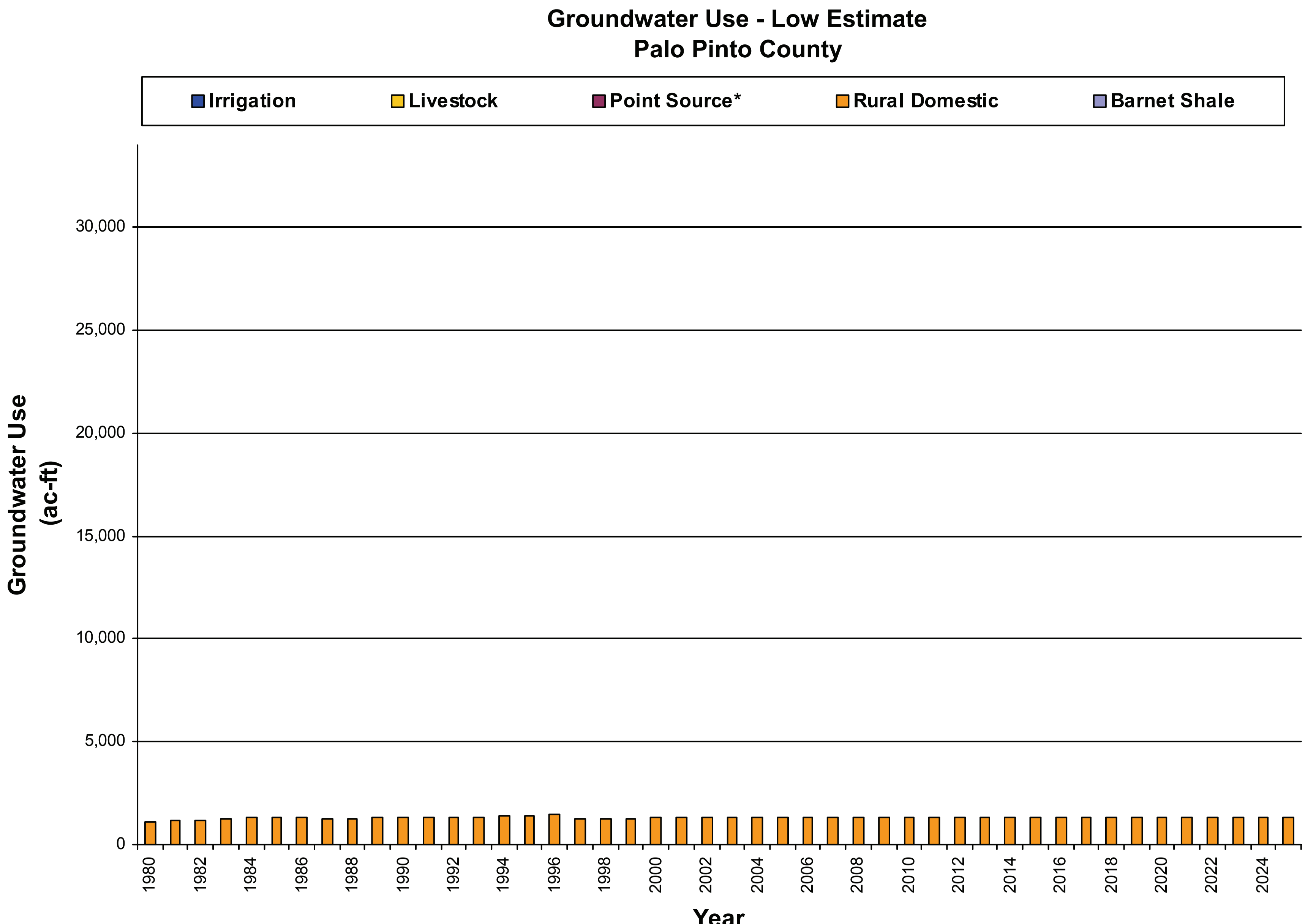

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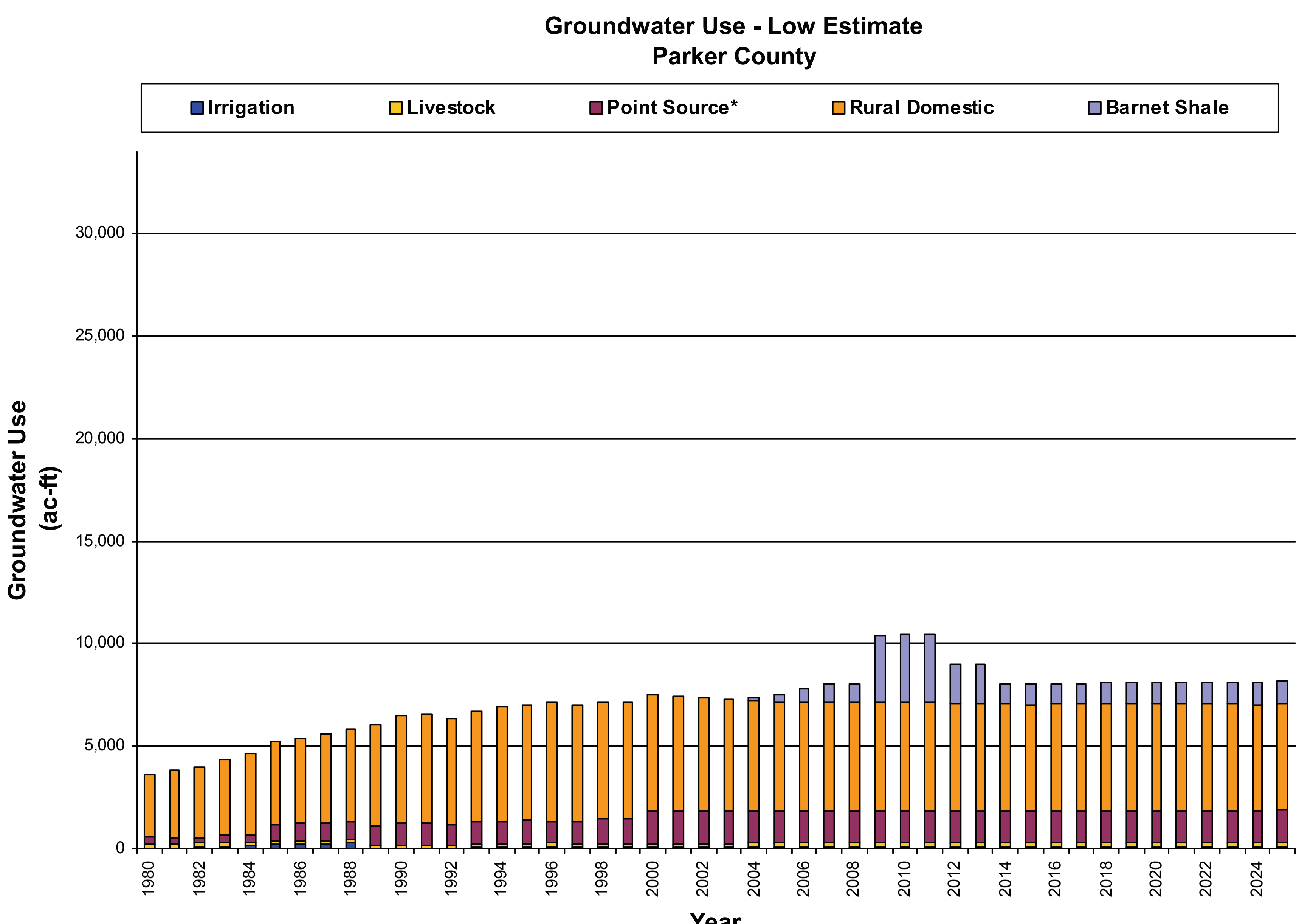

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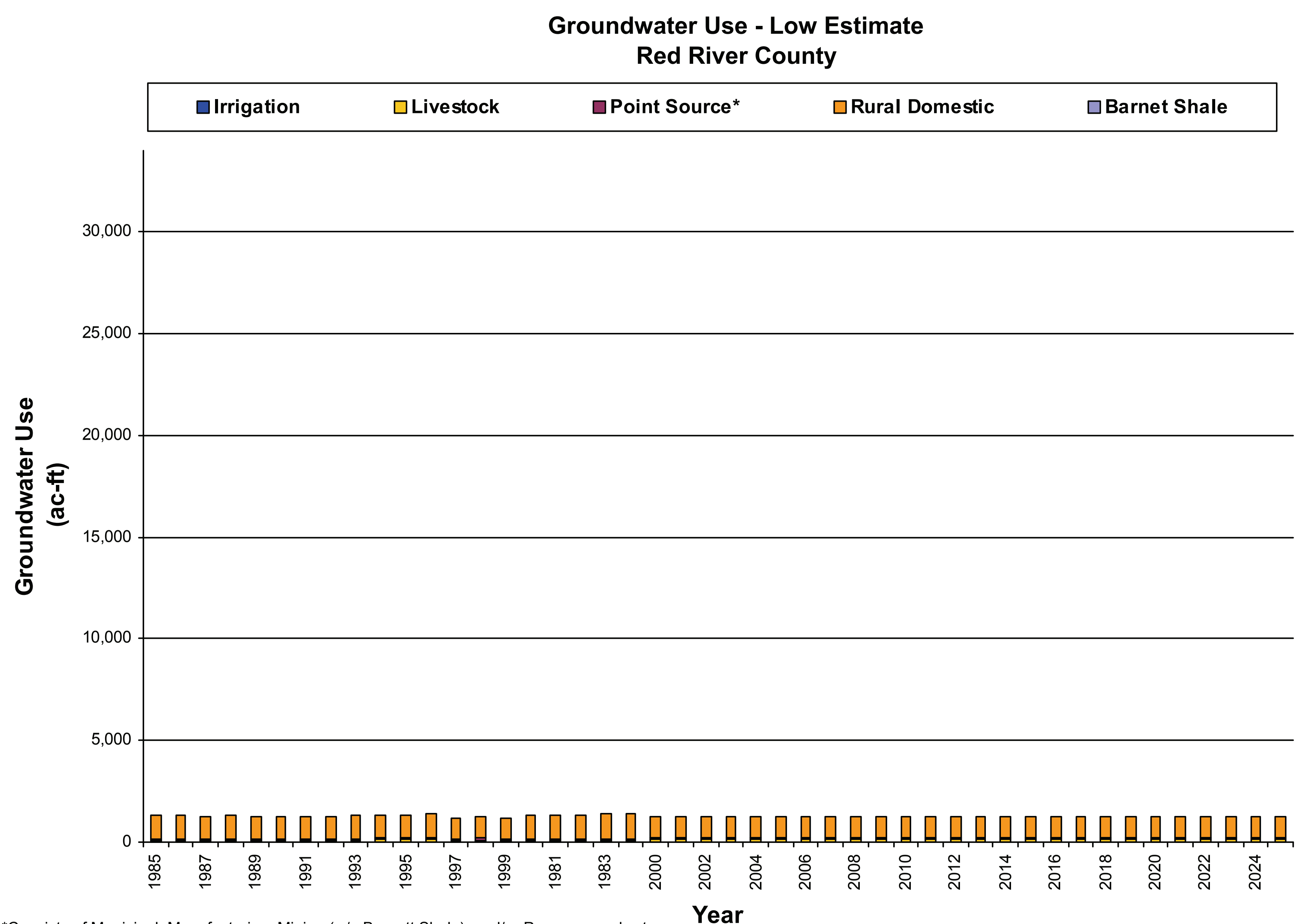

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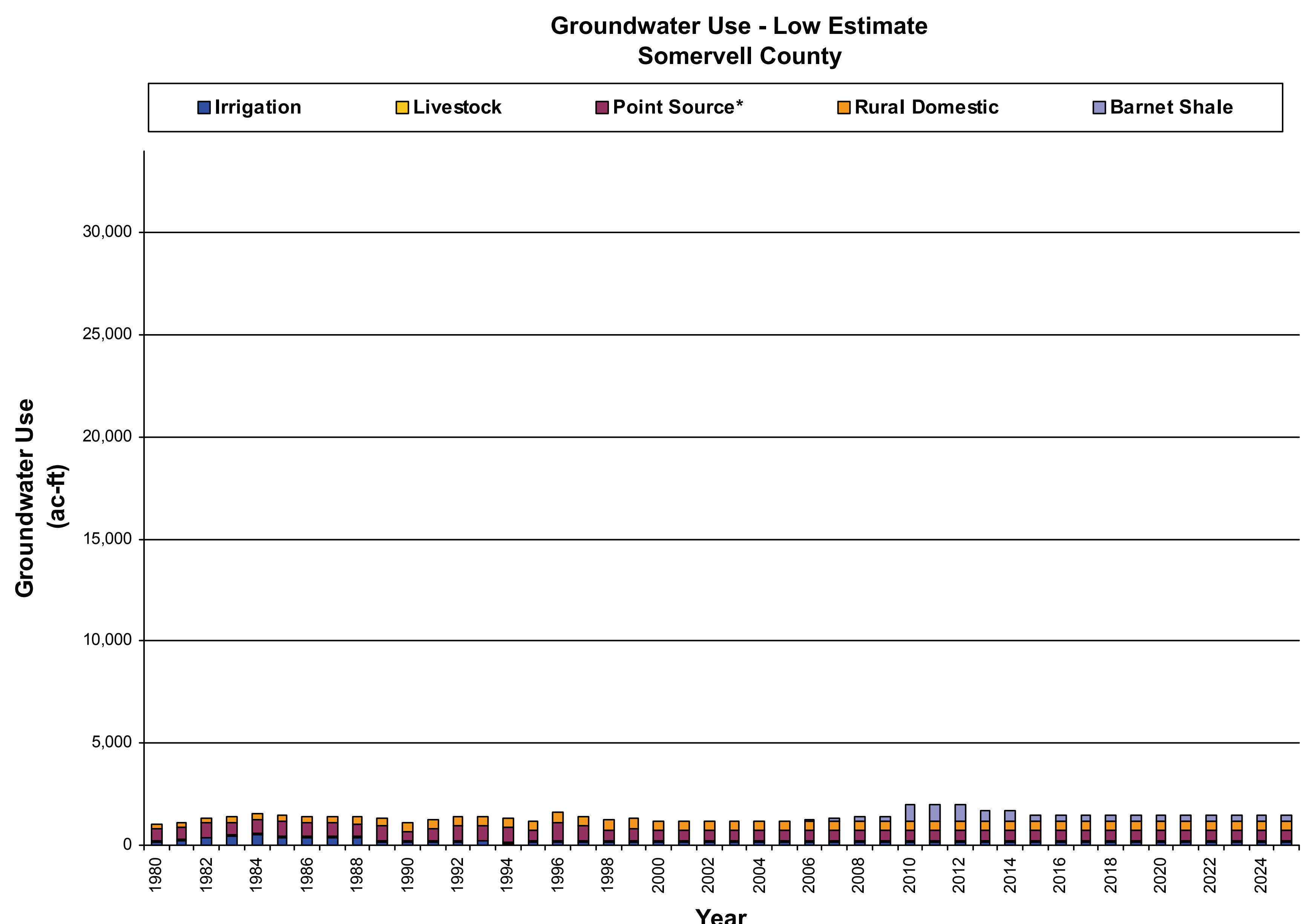

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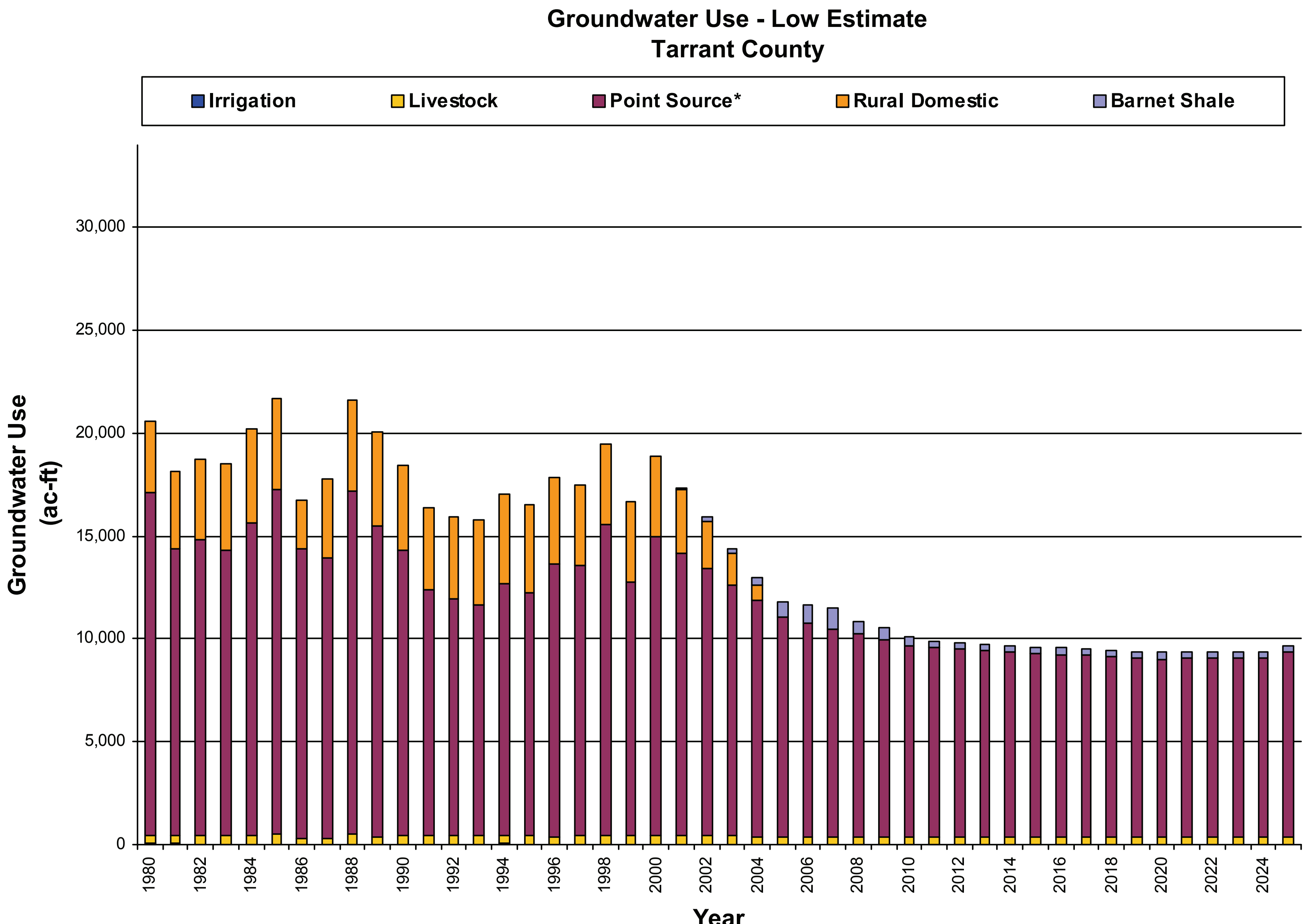

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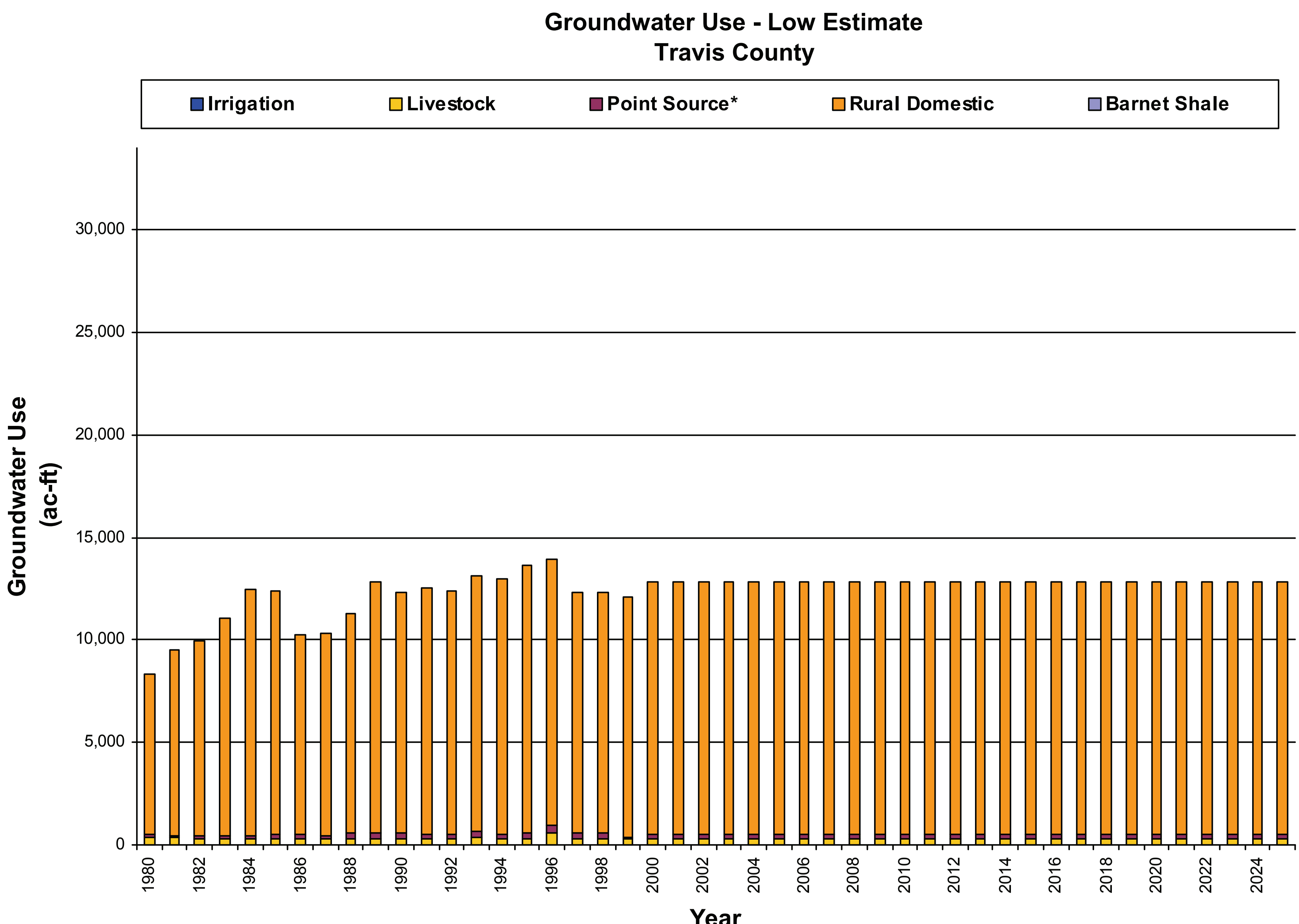

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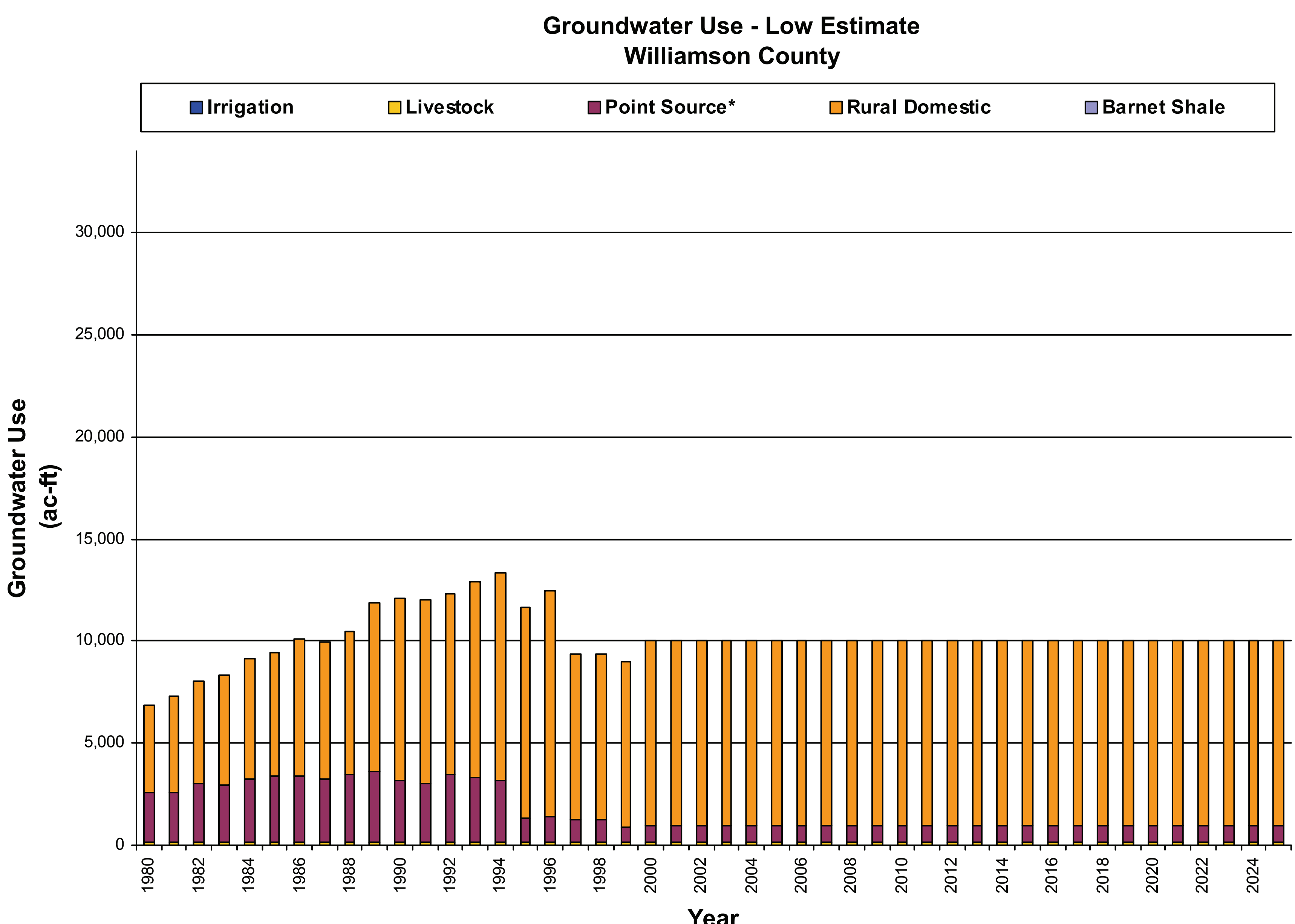

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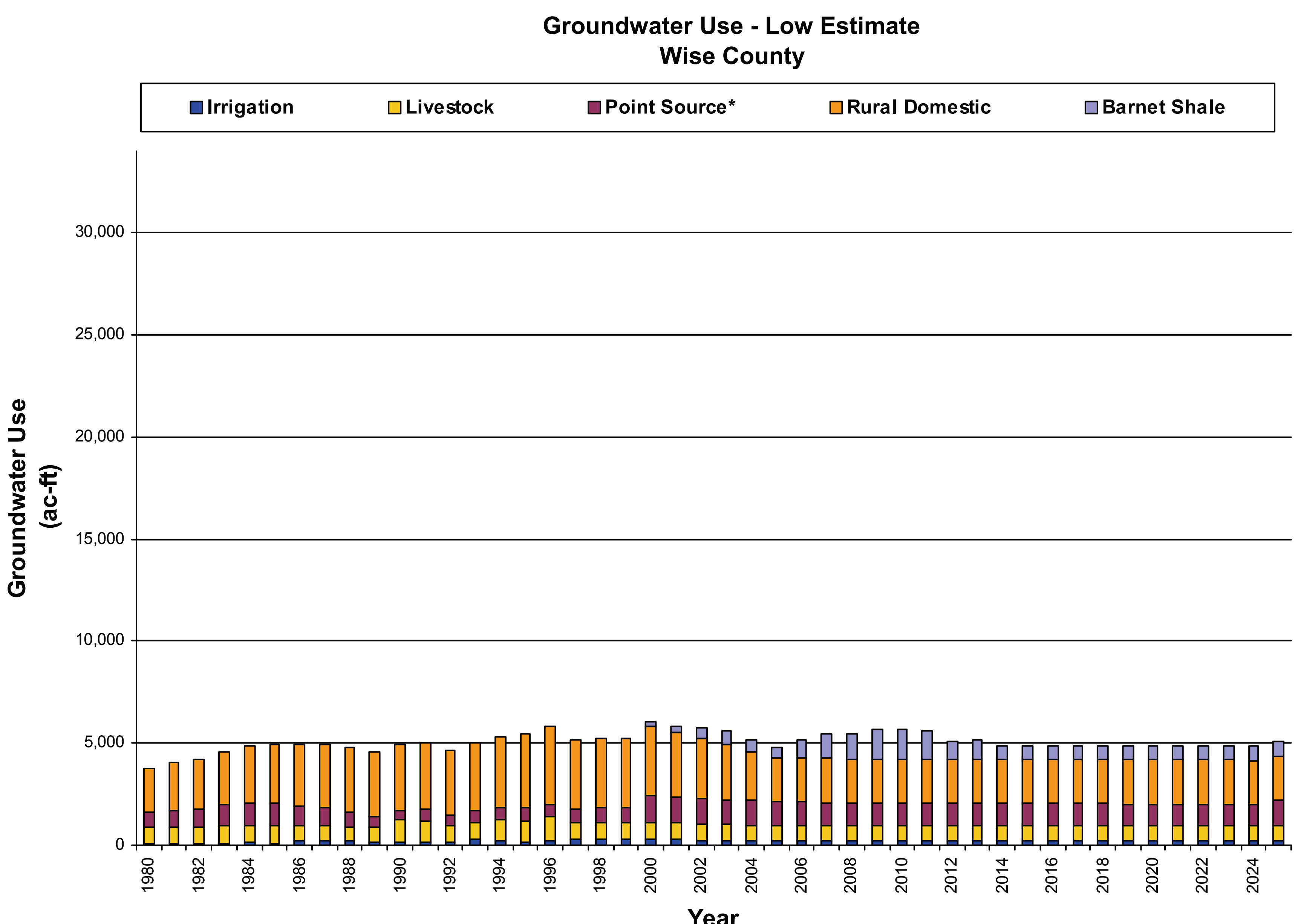

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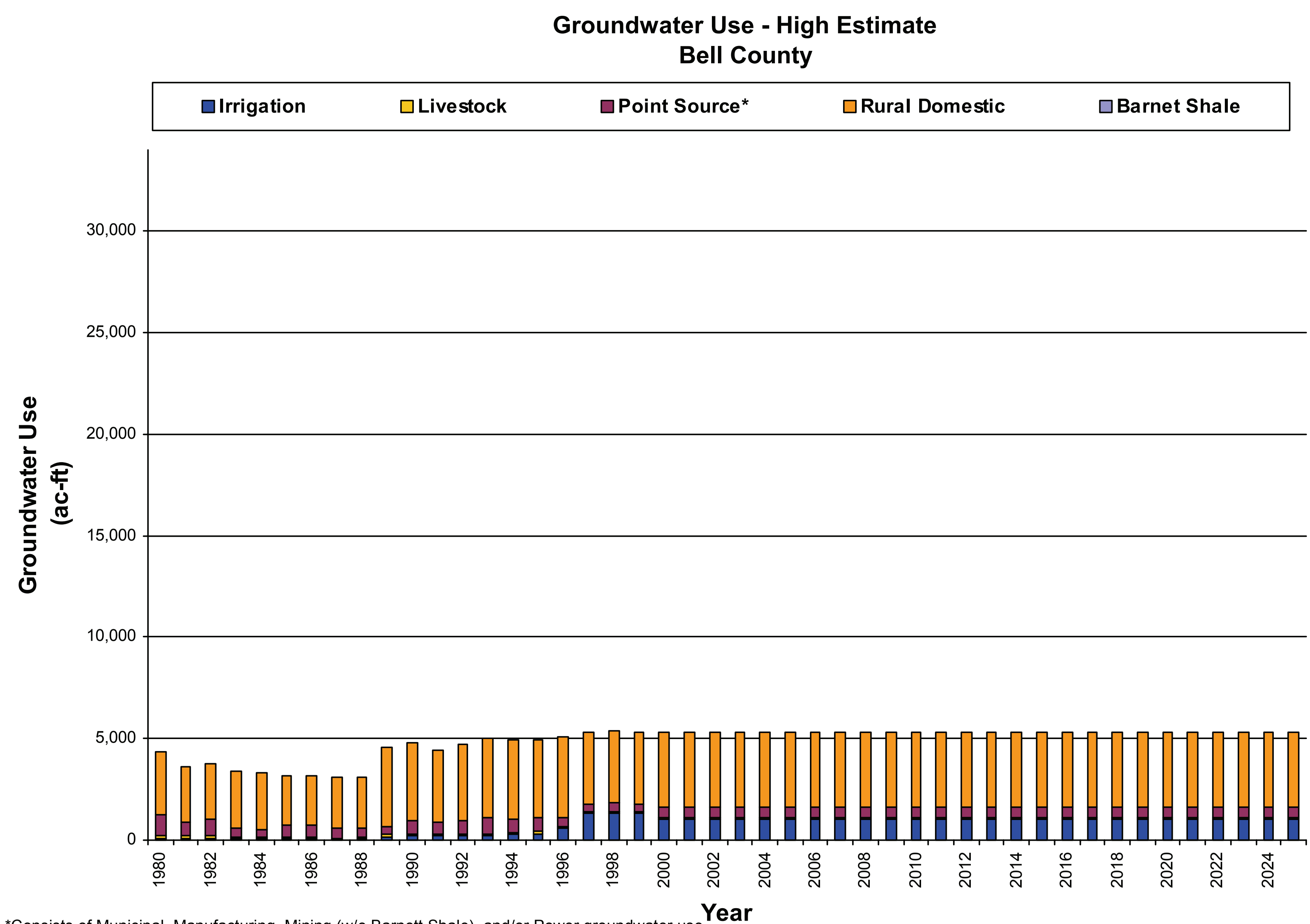

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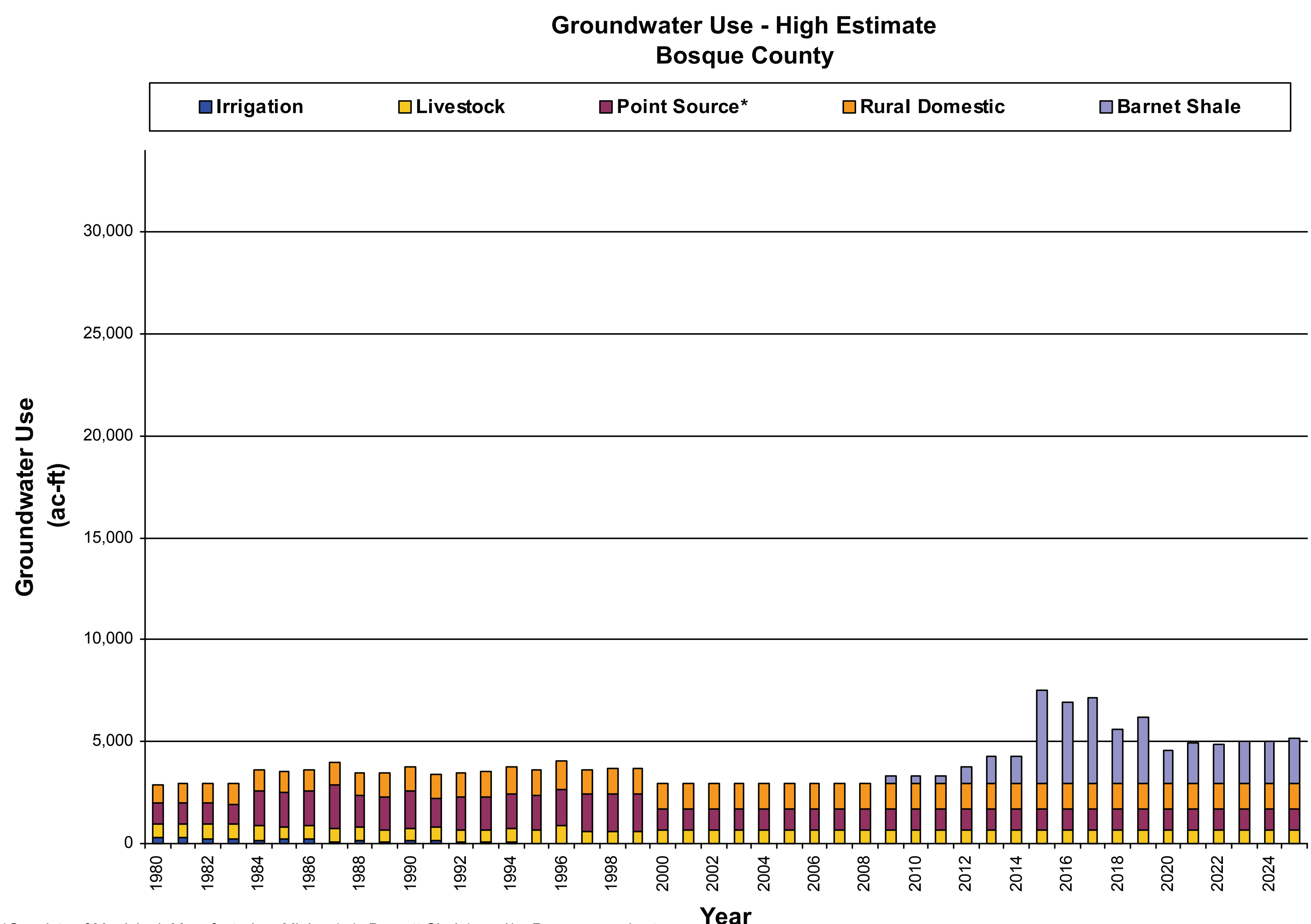

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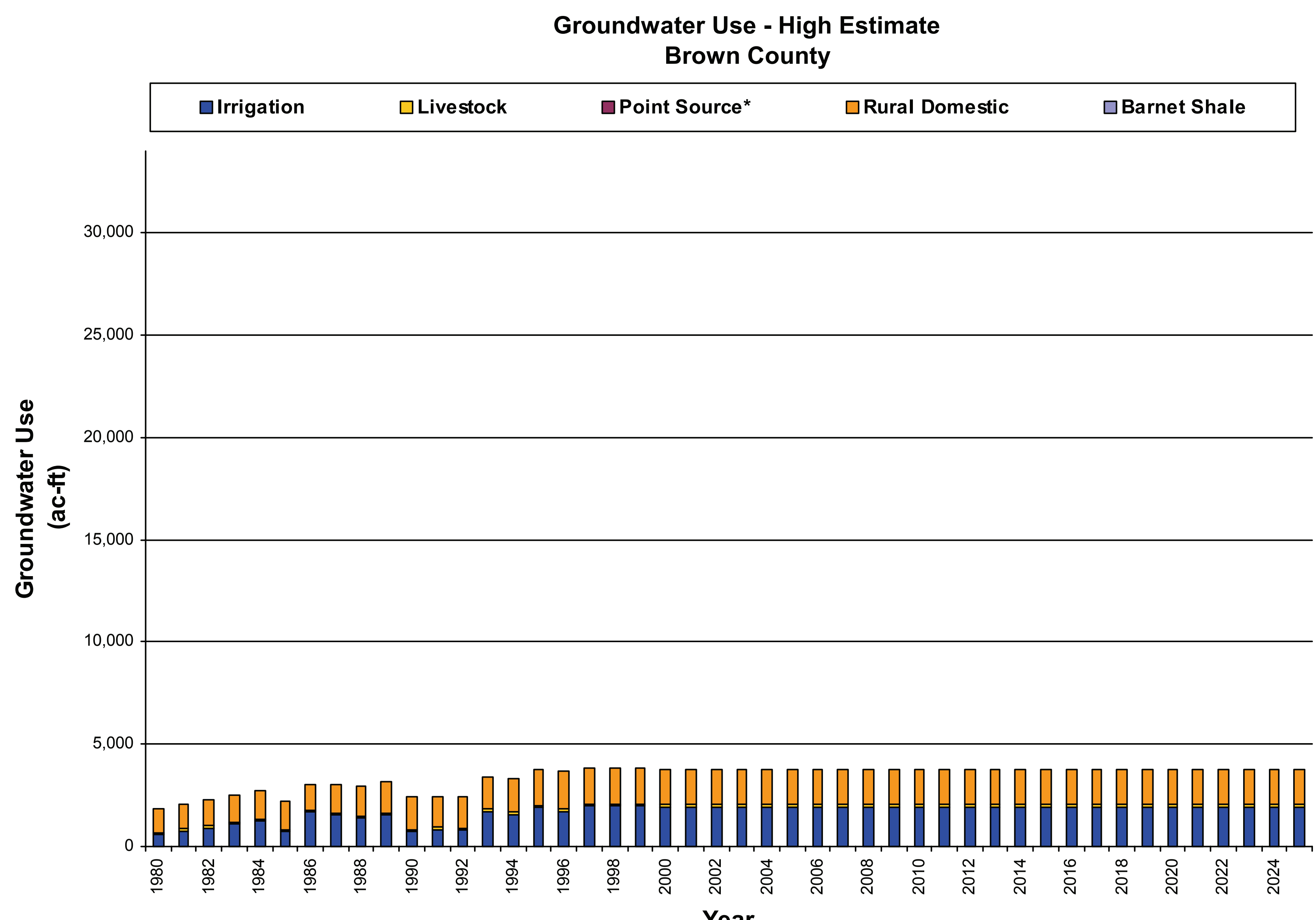

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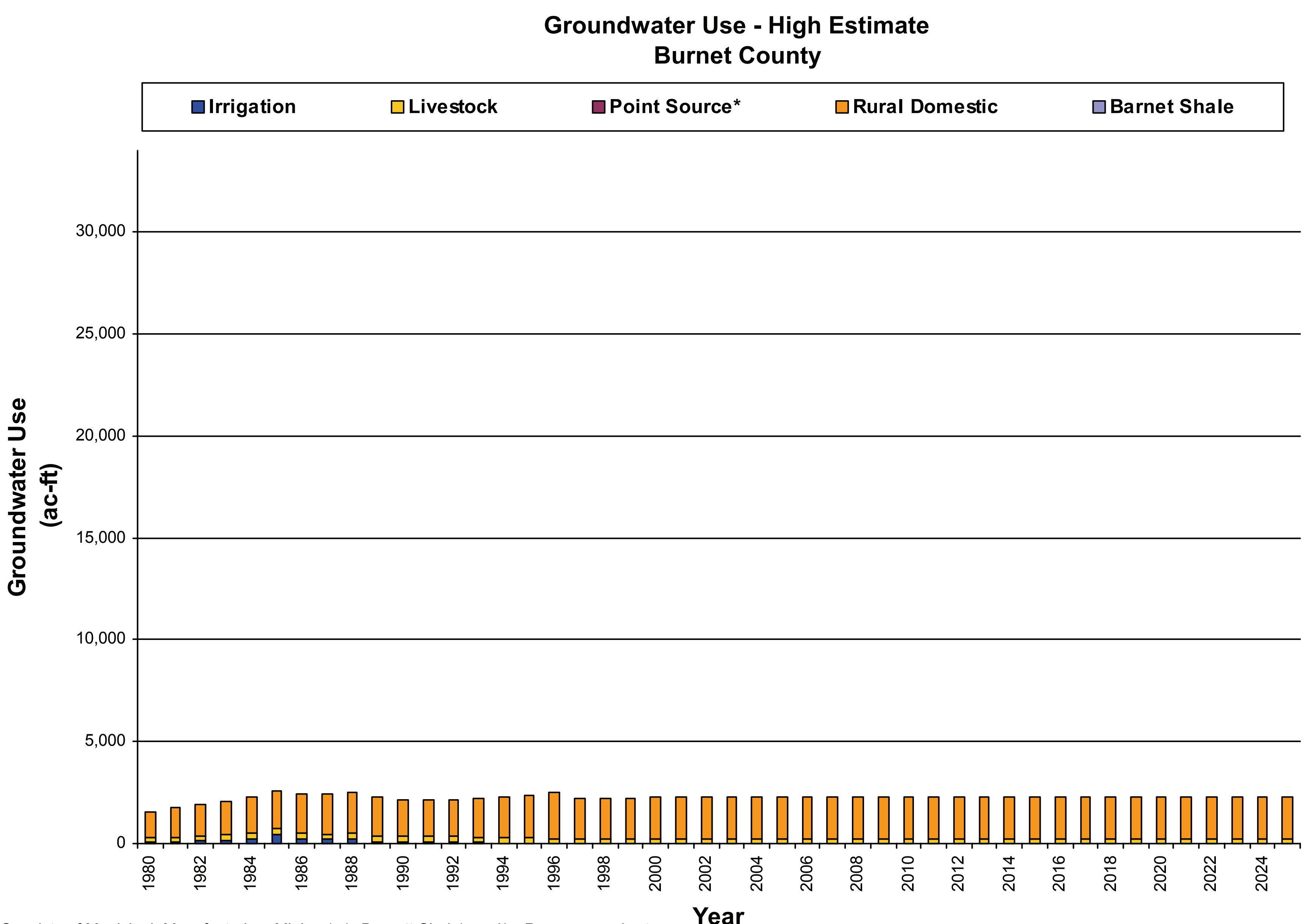

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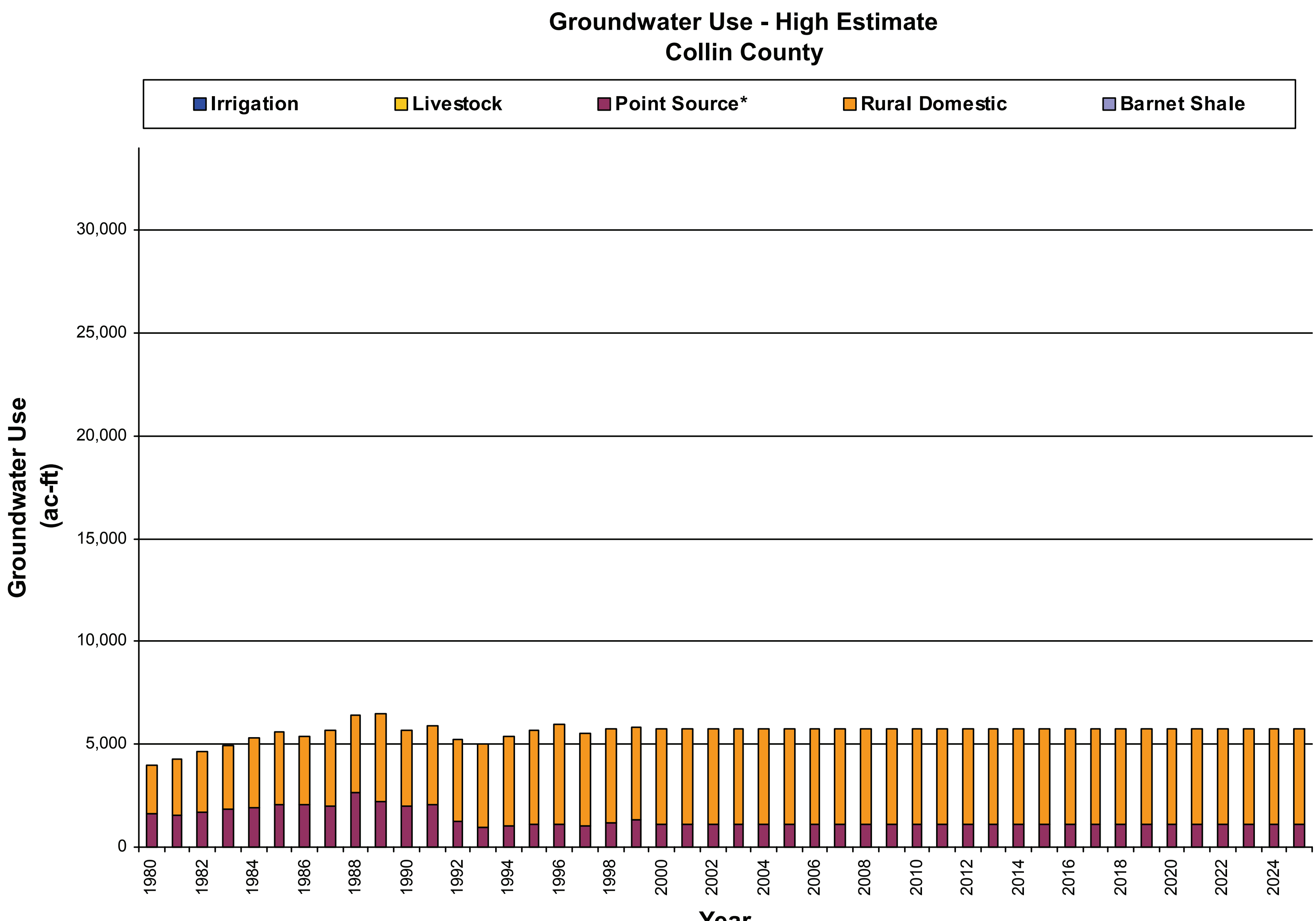
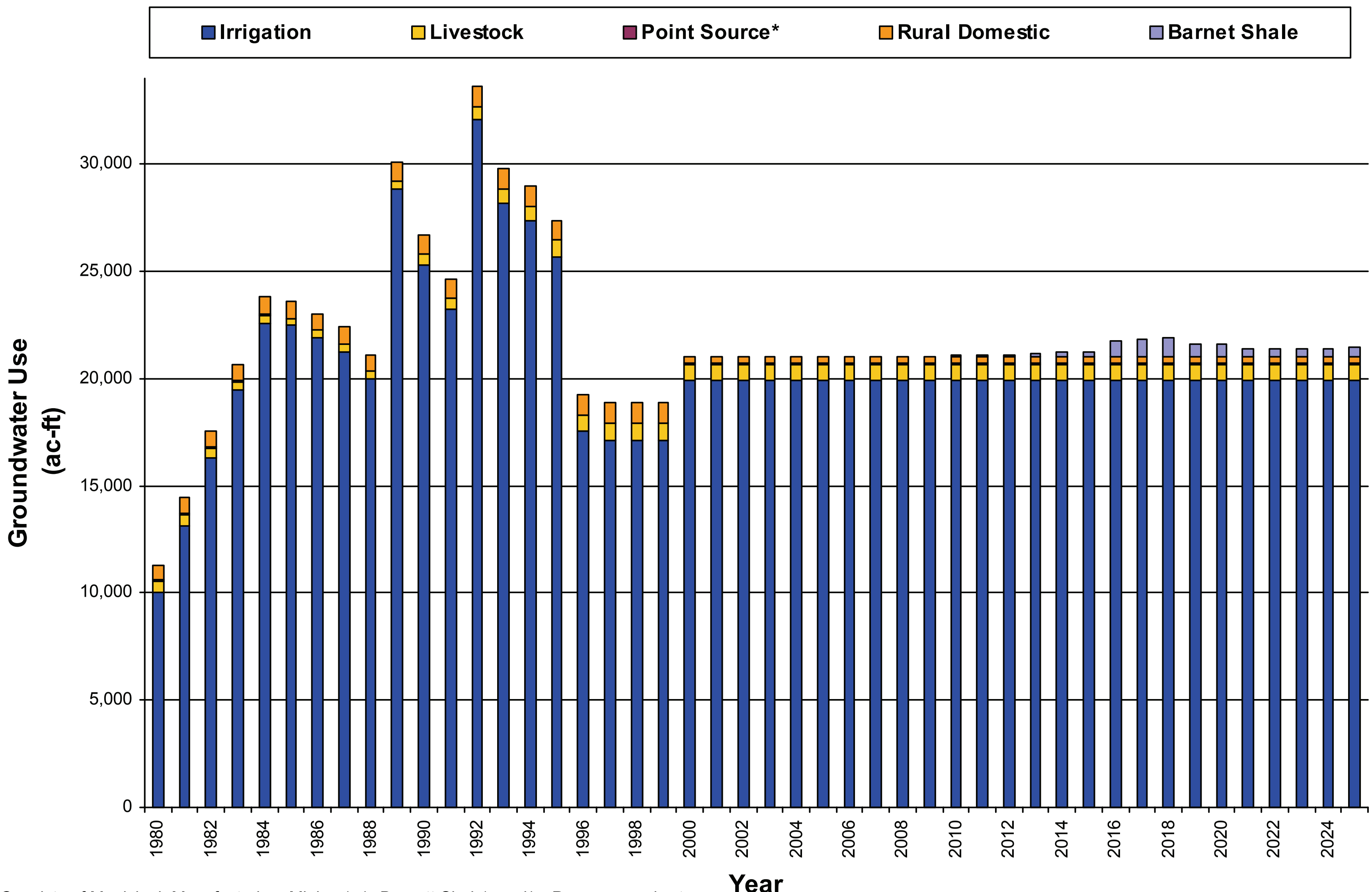


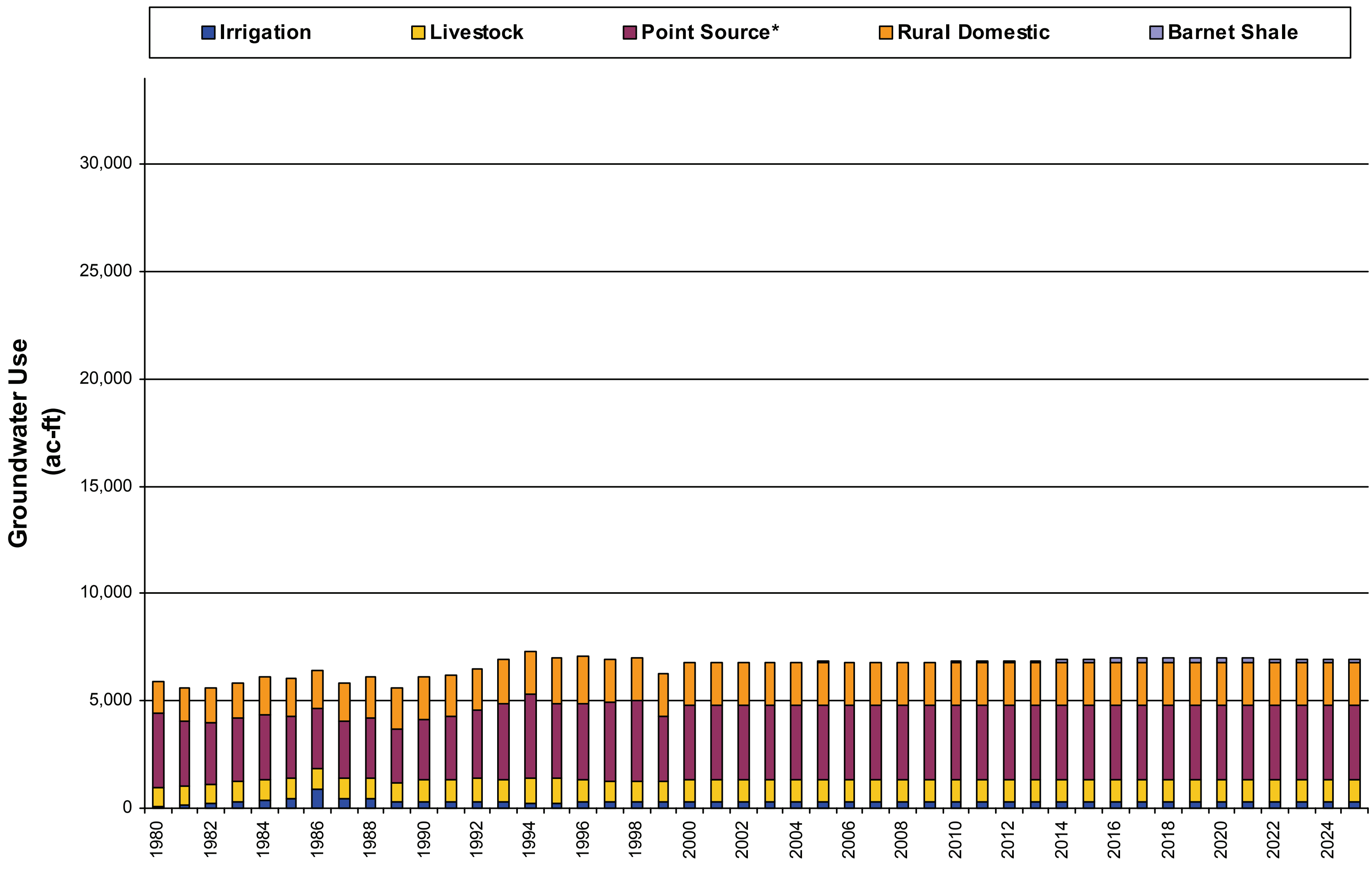
*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - High Estimate
Comanche County

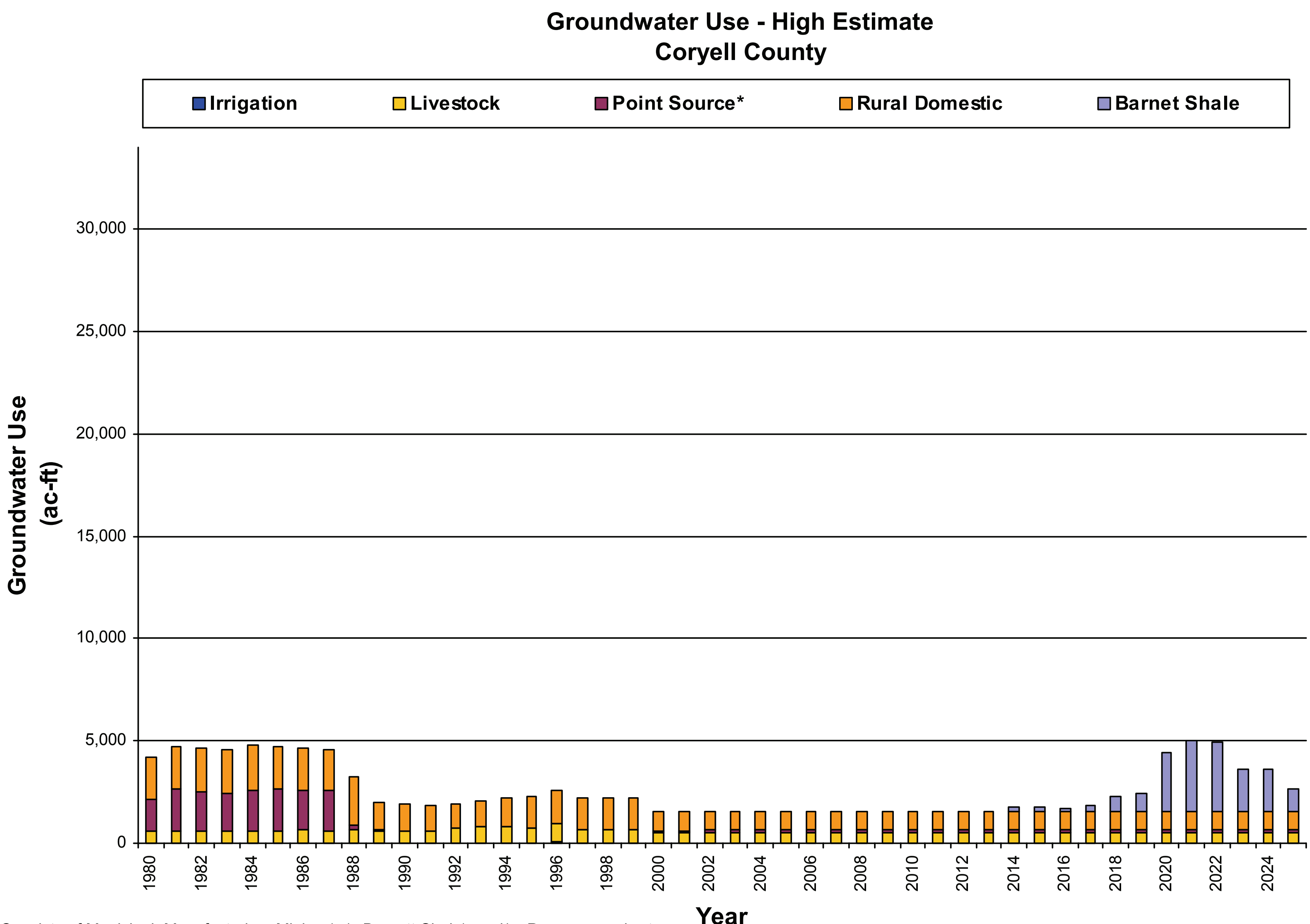


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - High Estimate
Cooke County



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



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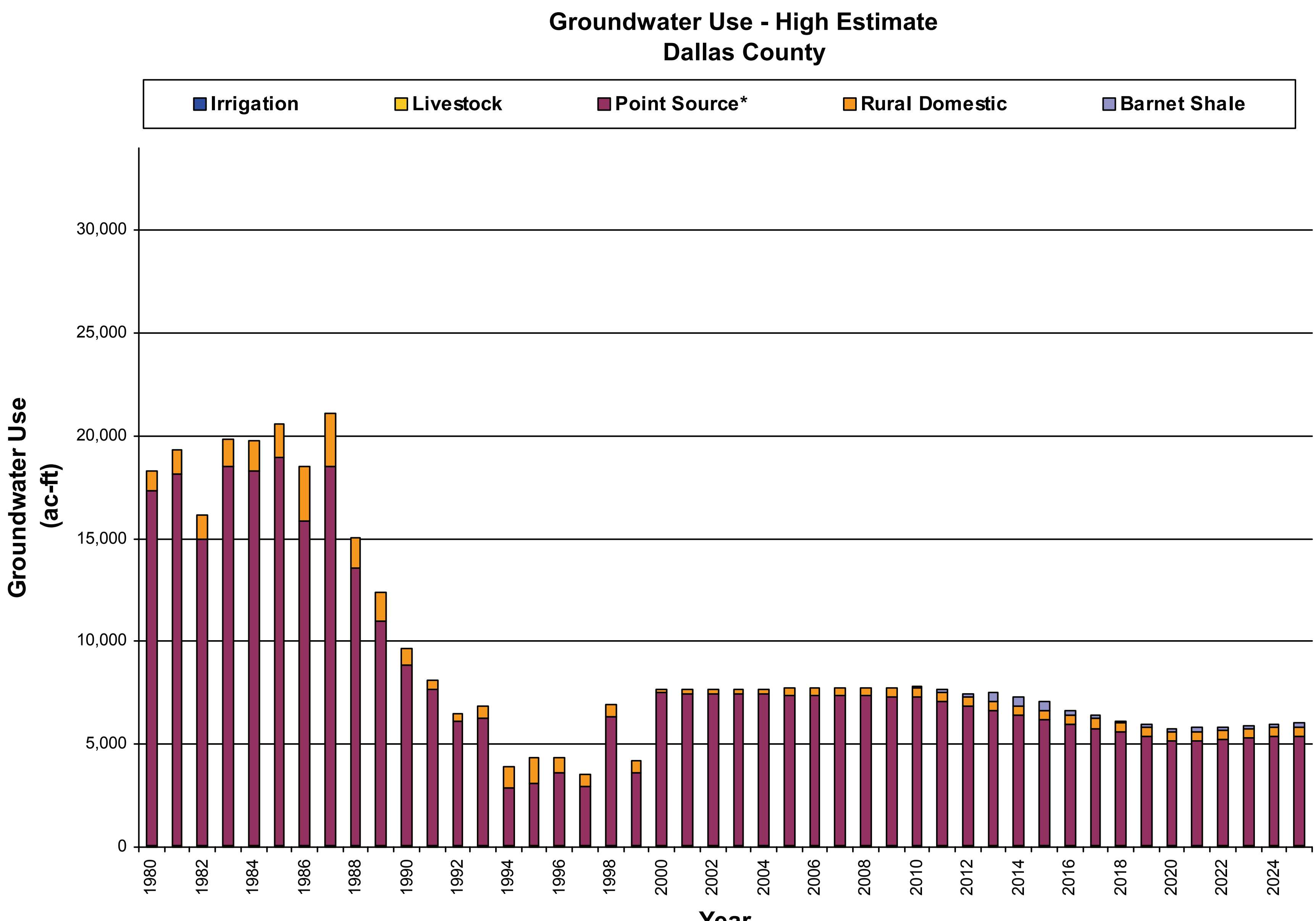
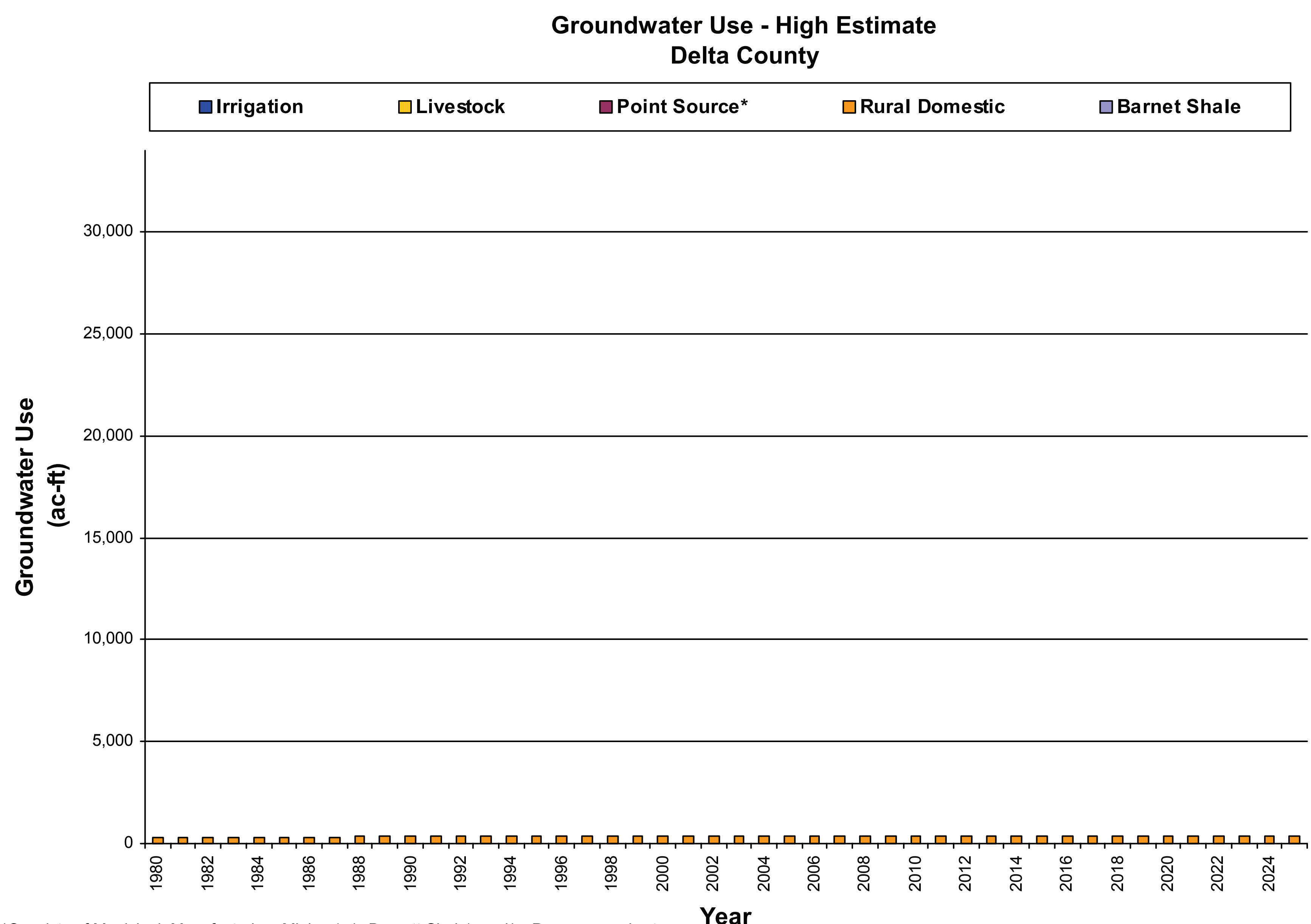


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



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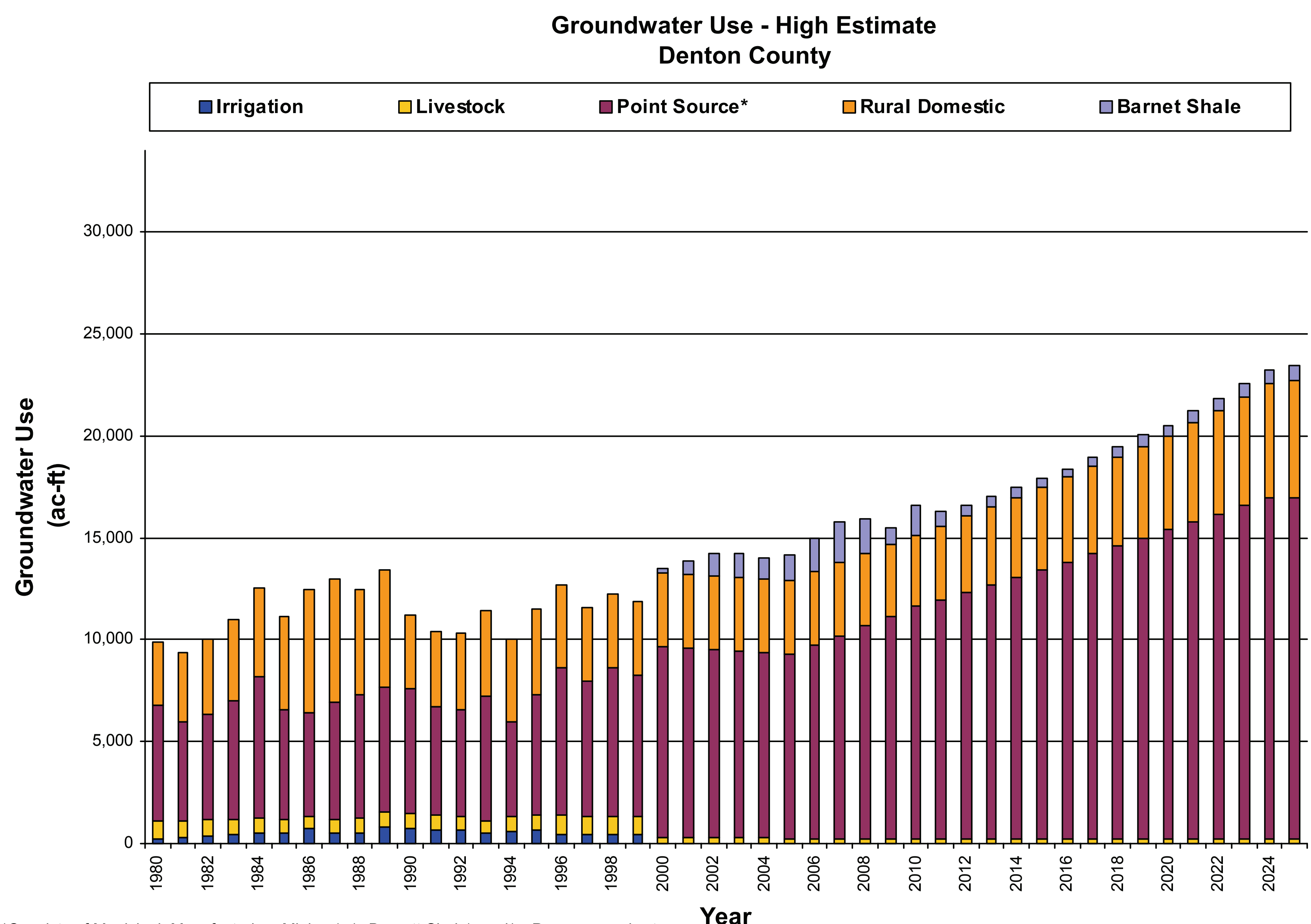

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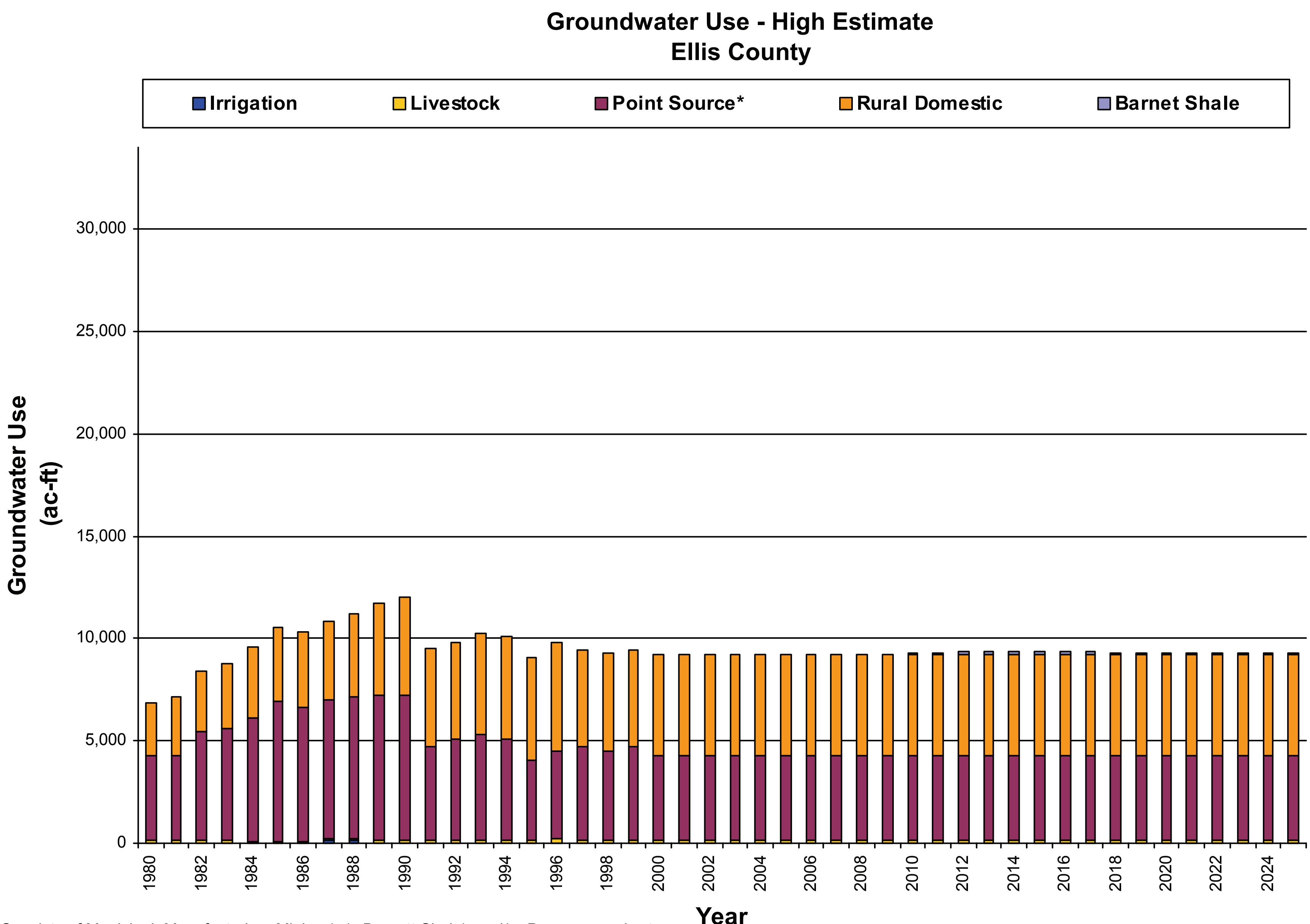

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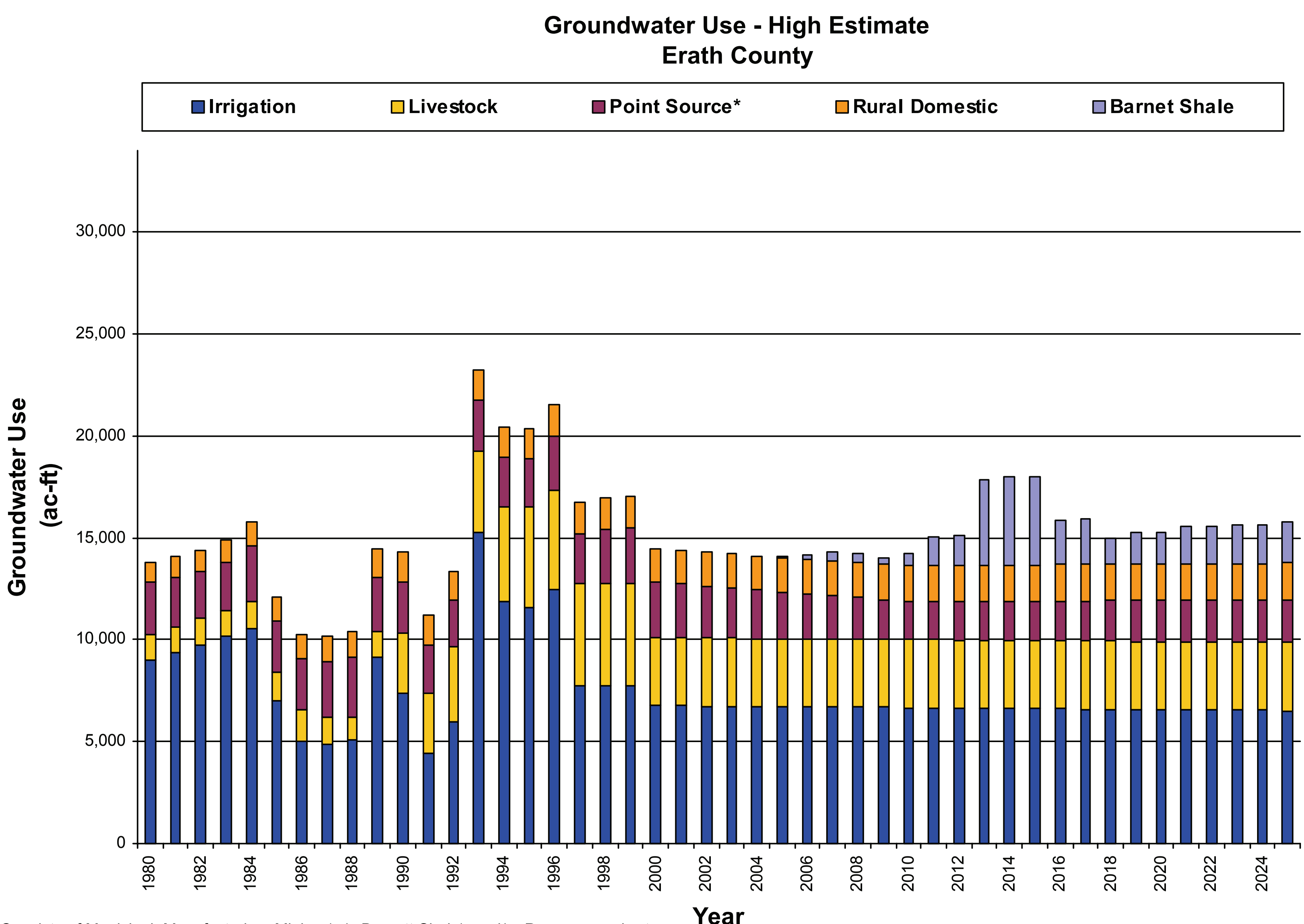
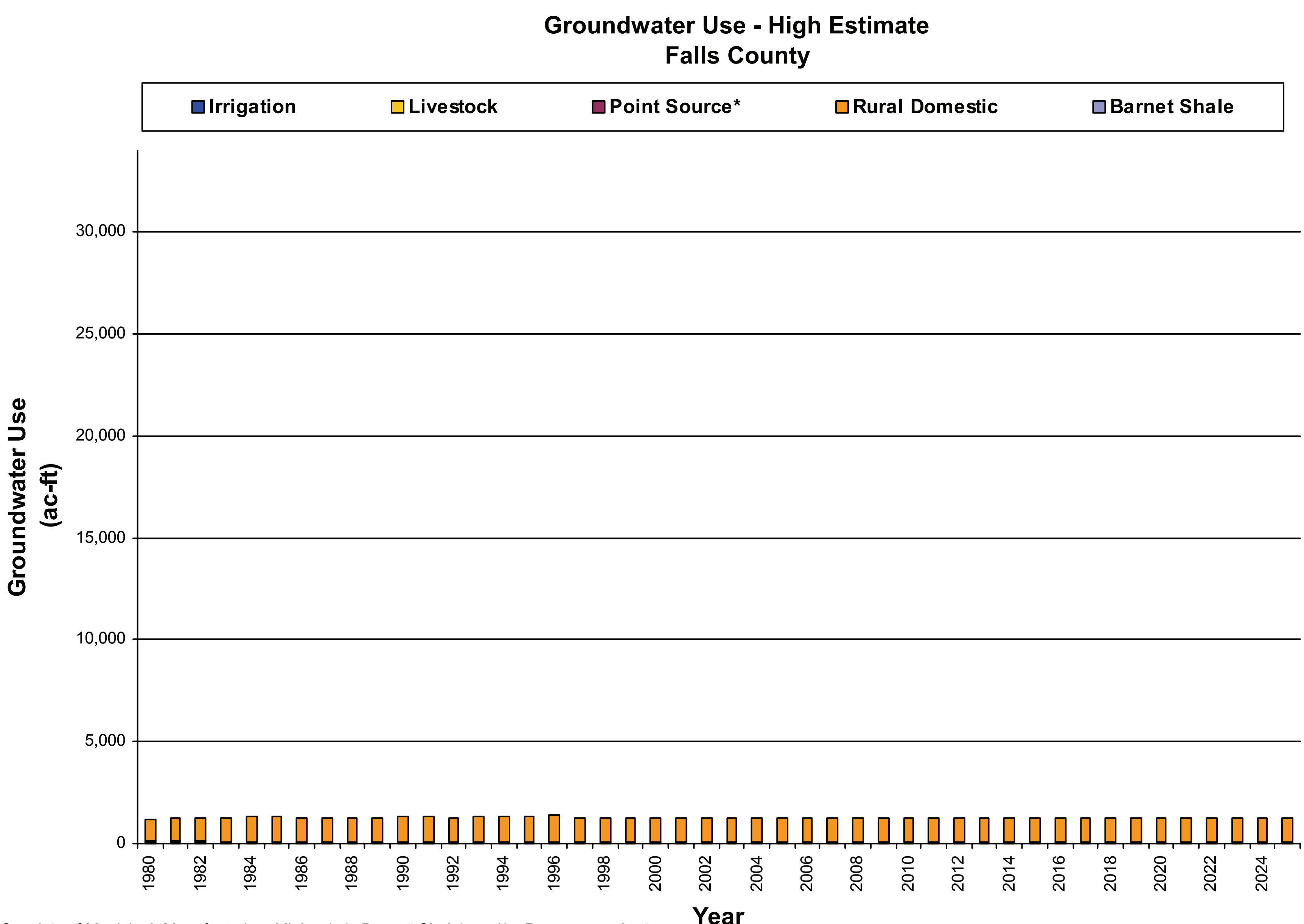
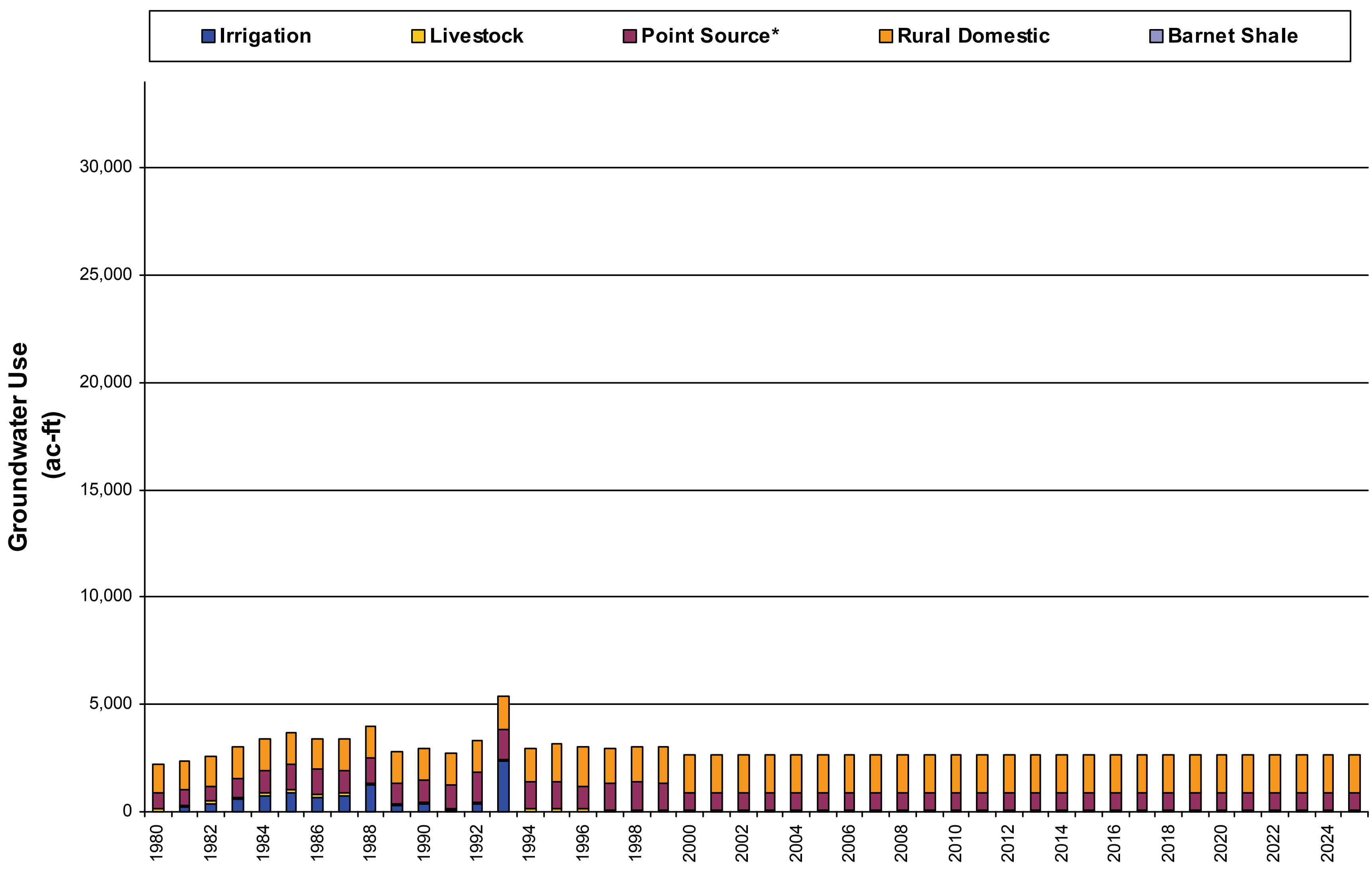


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

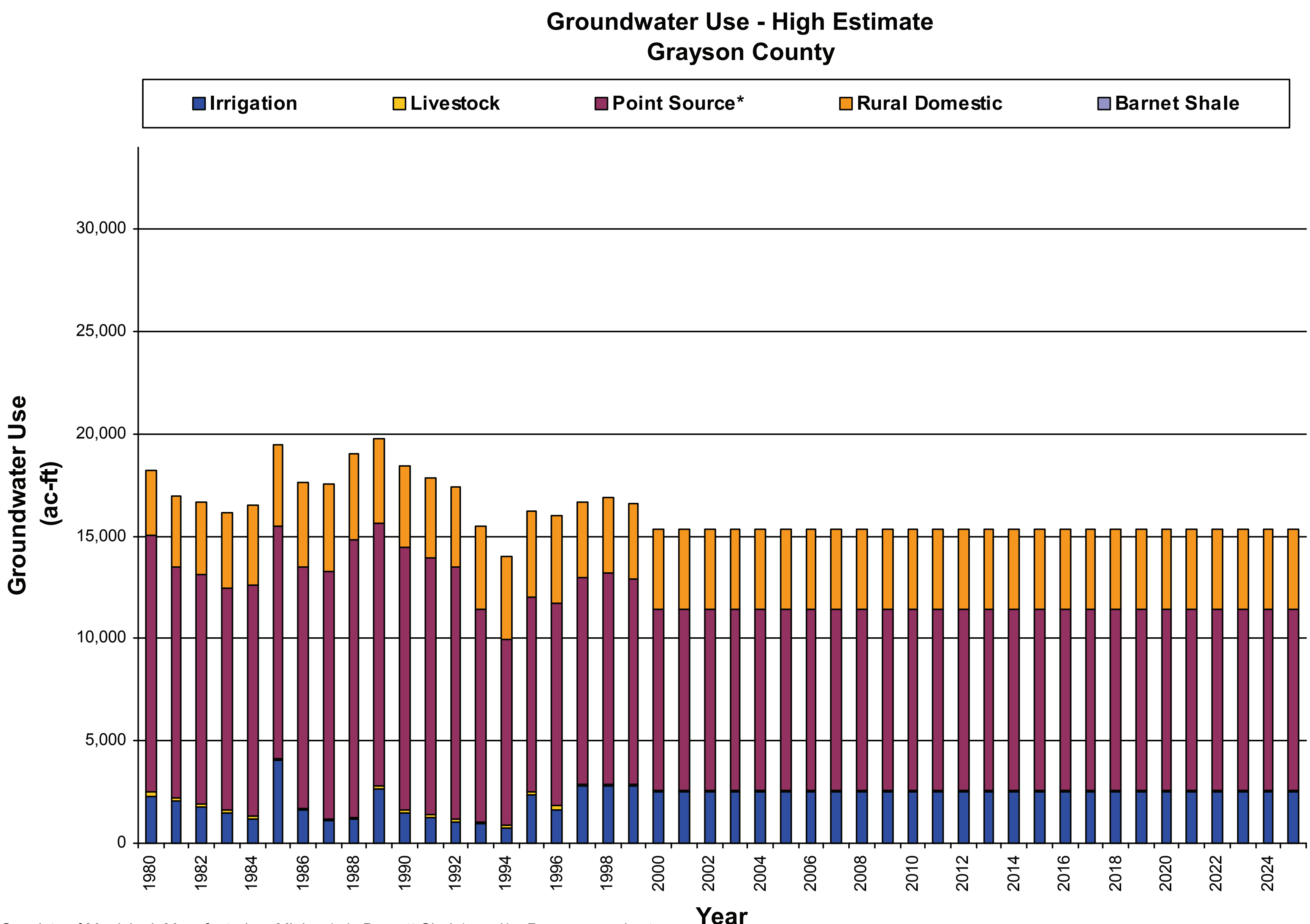


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - High Estimate
Fannin County

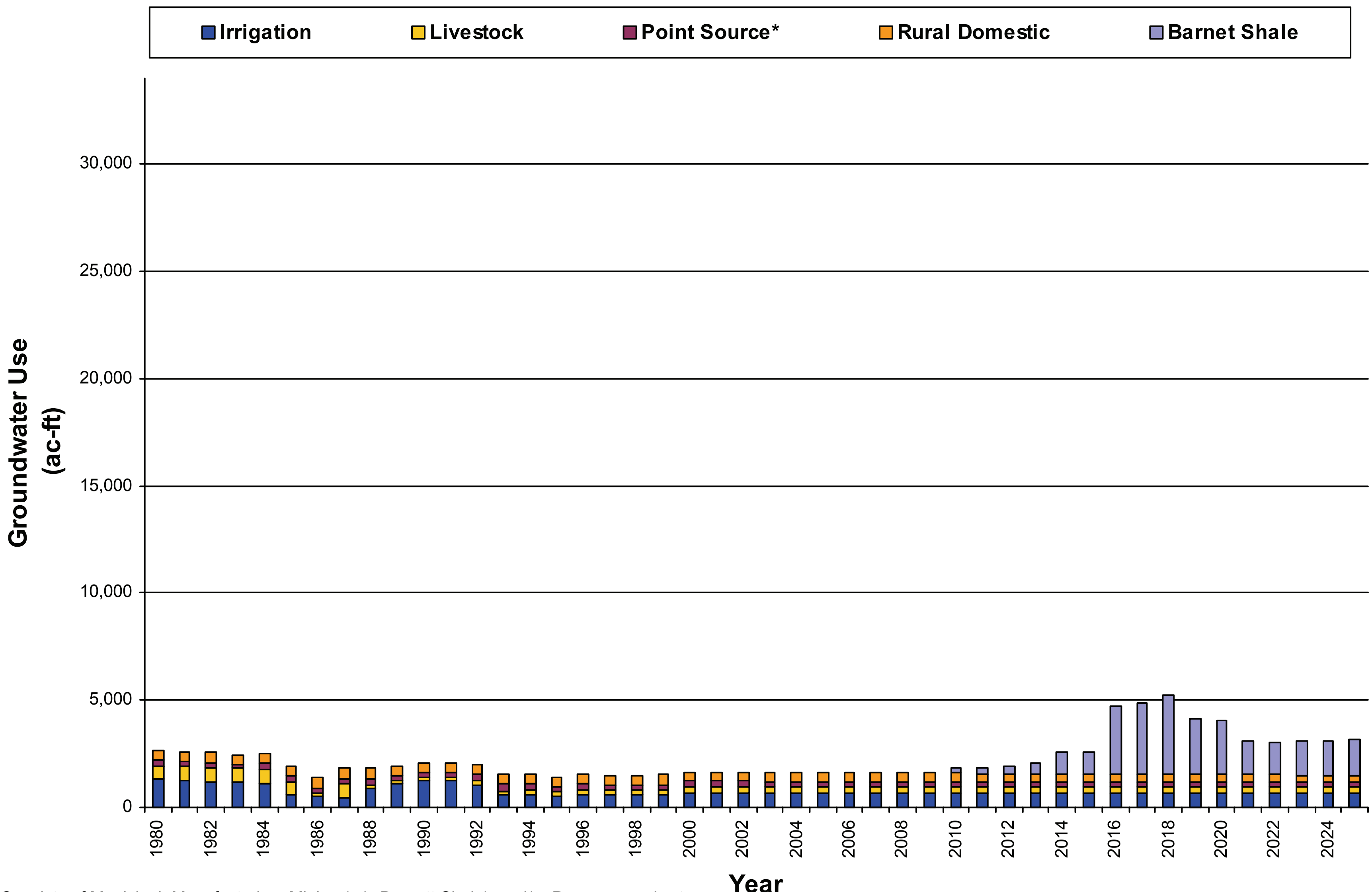


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

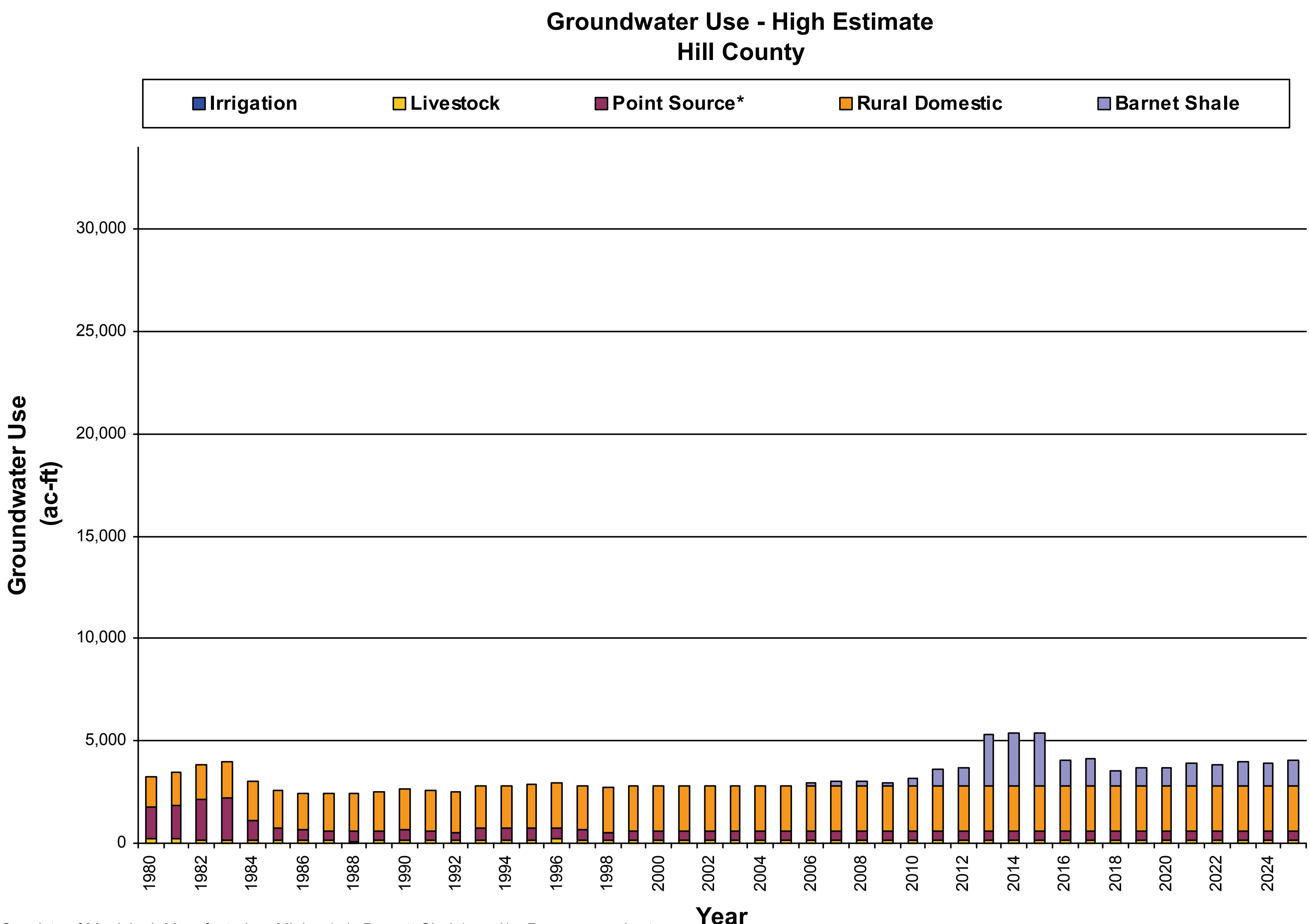


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - High Estimate
Hamilton County



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



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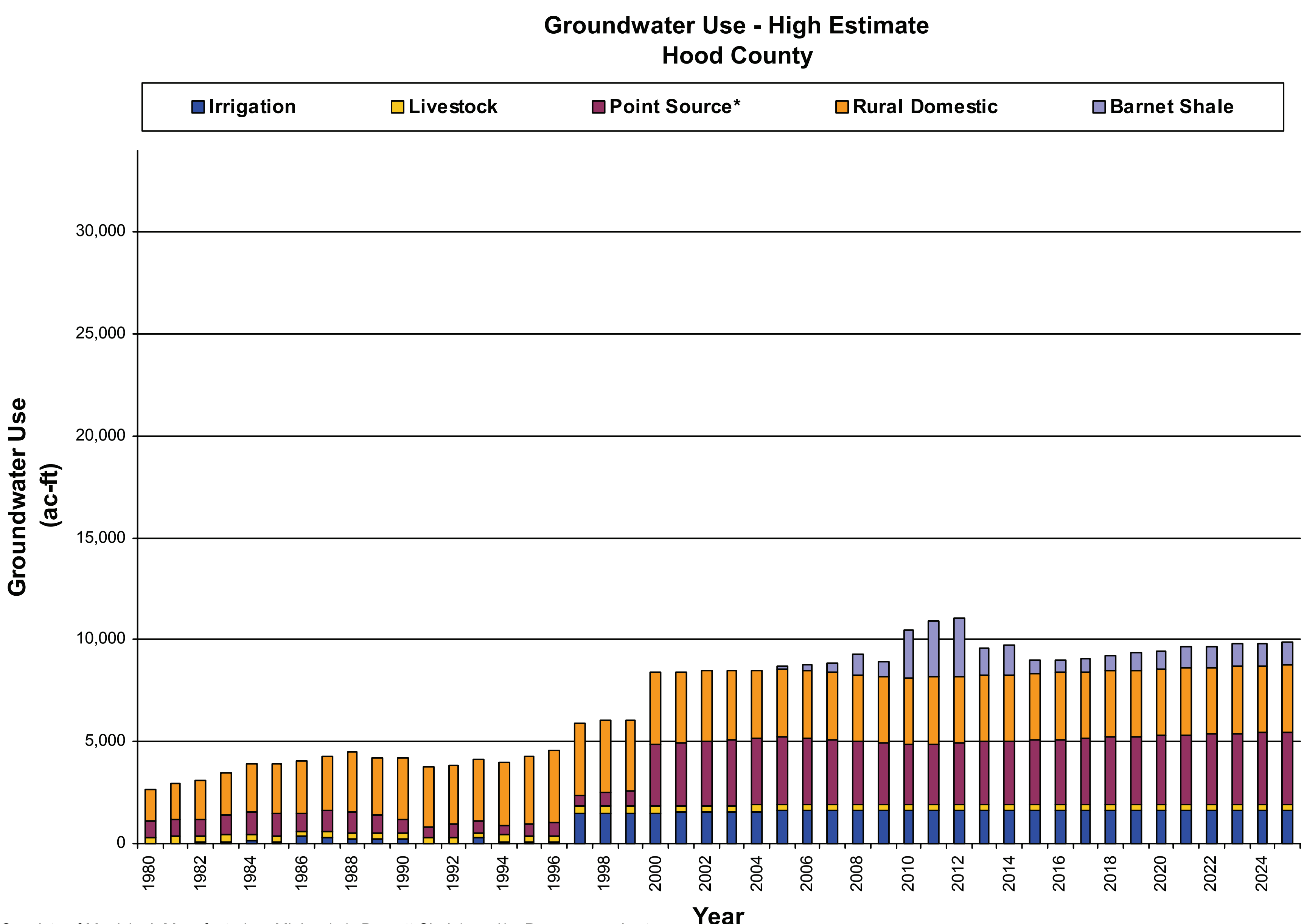

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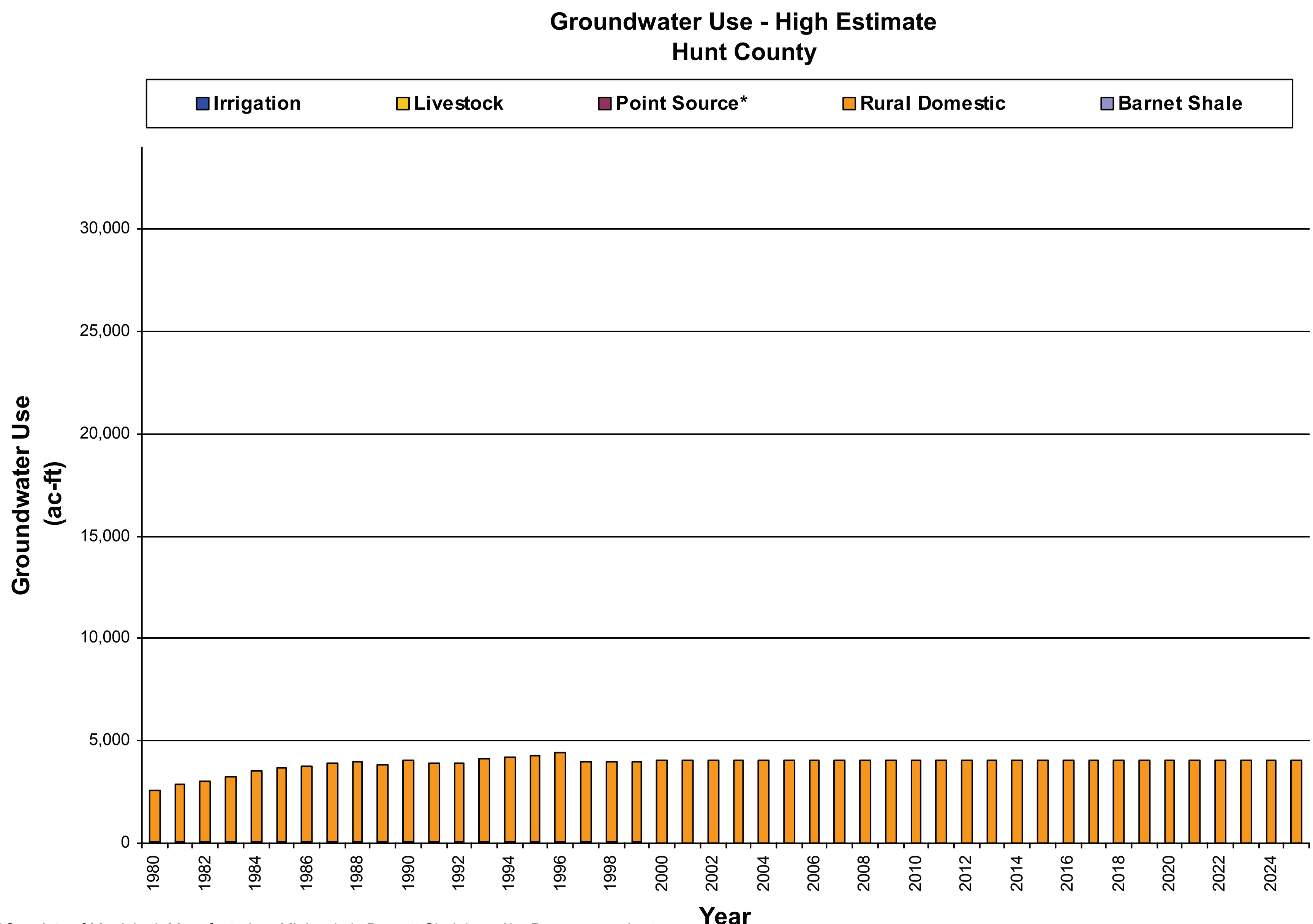

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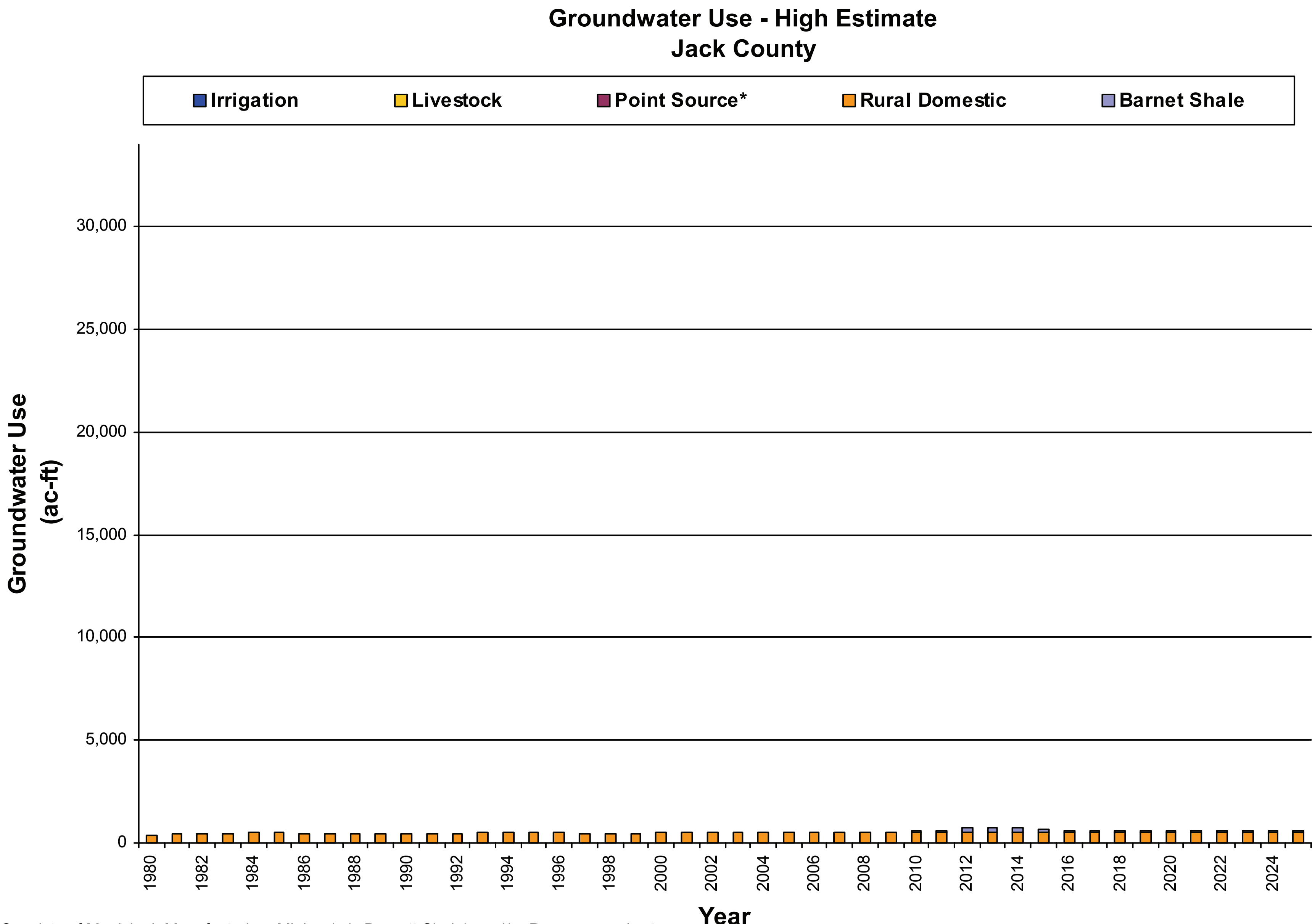
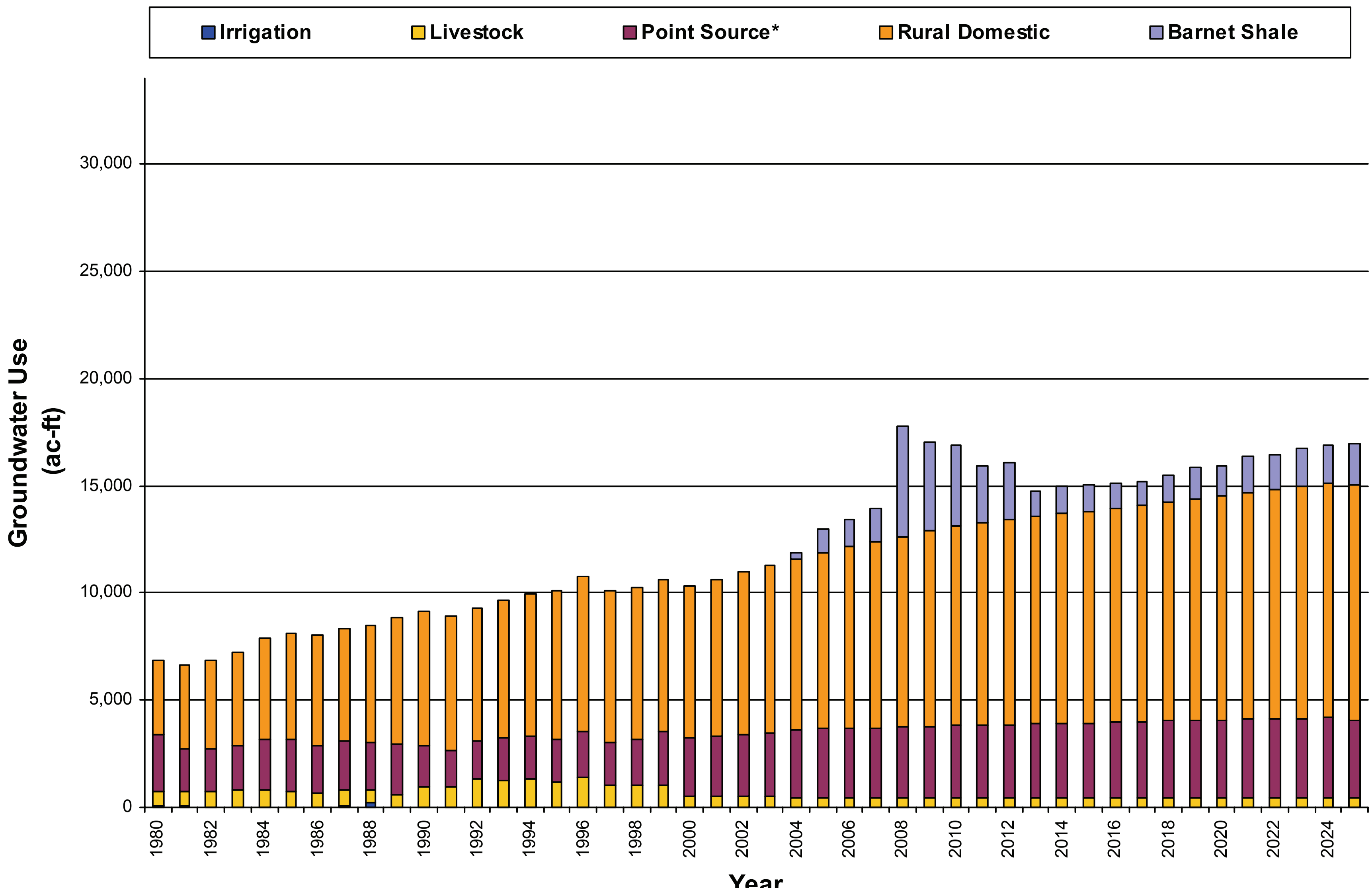
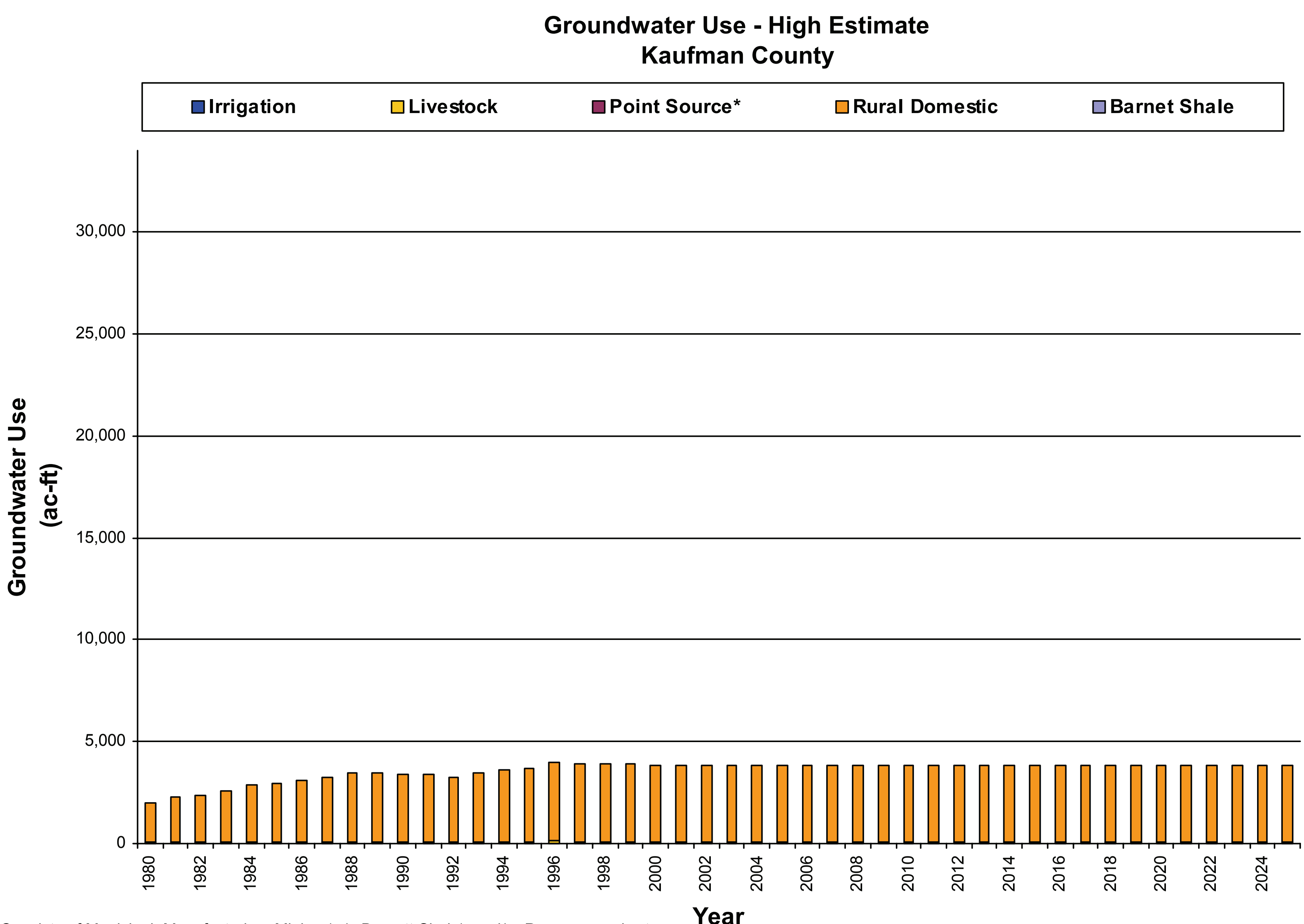


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - High Estimate
Johnson County

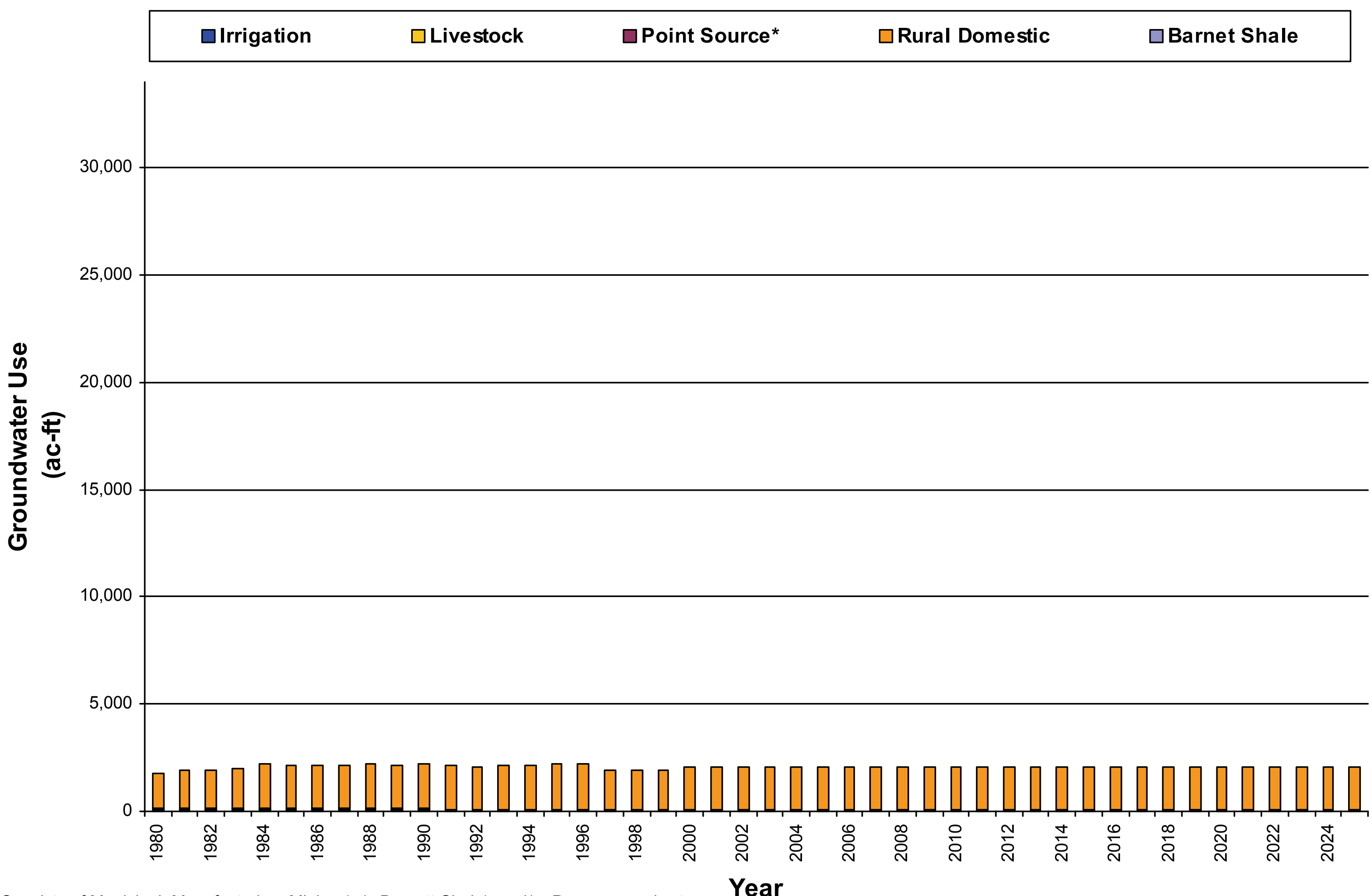


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

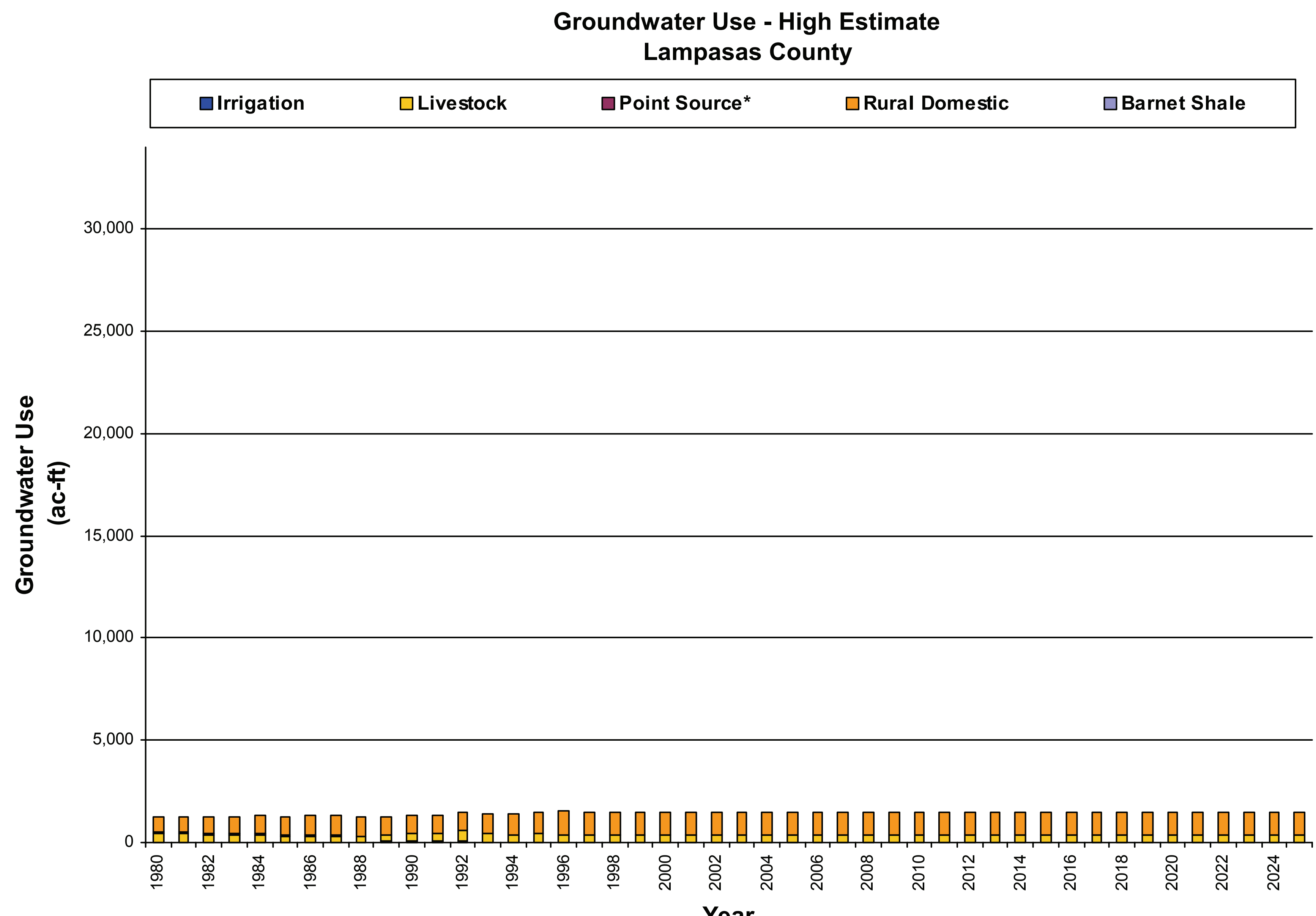


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - High Estimate
Lamar County

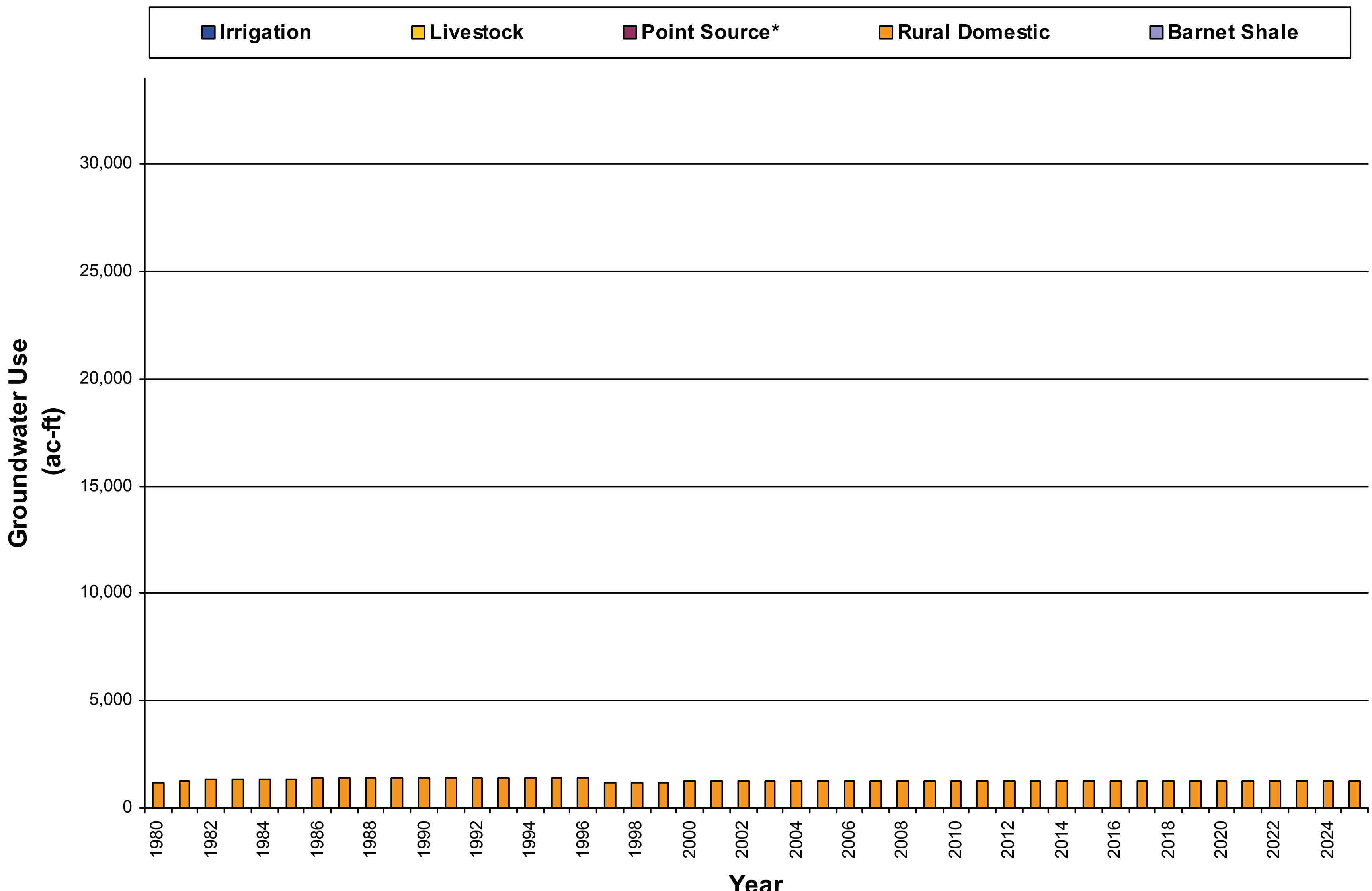


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

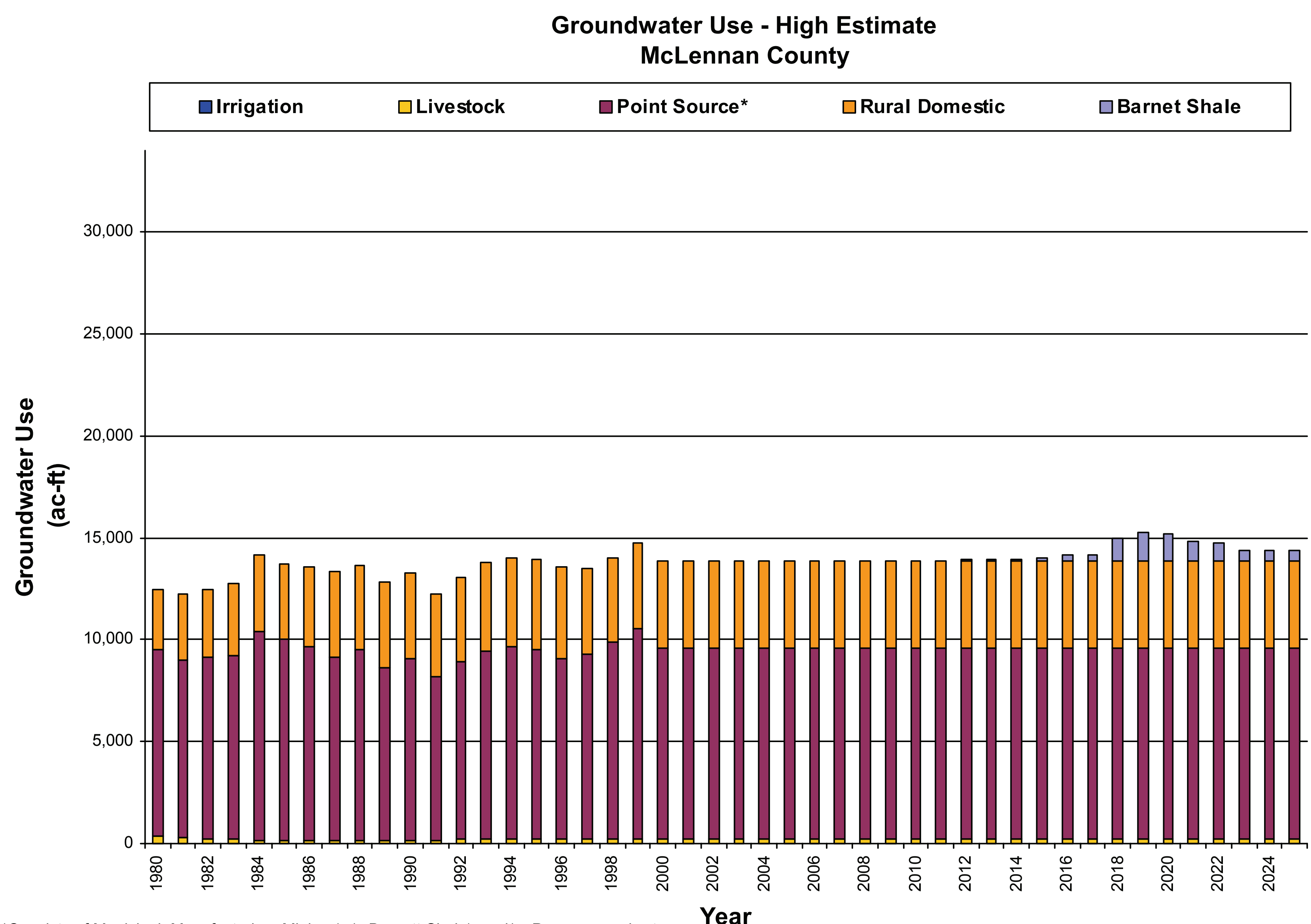


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

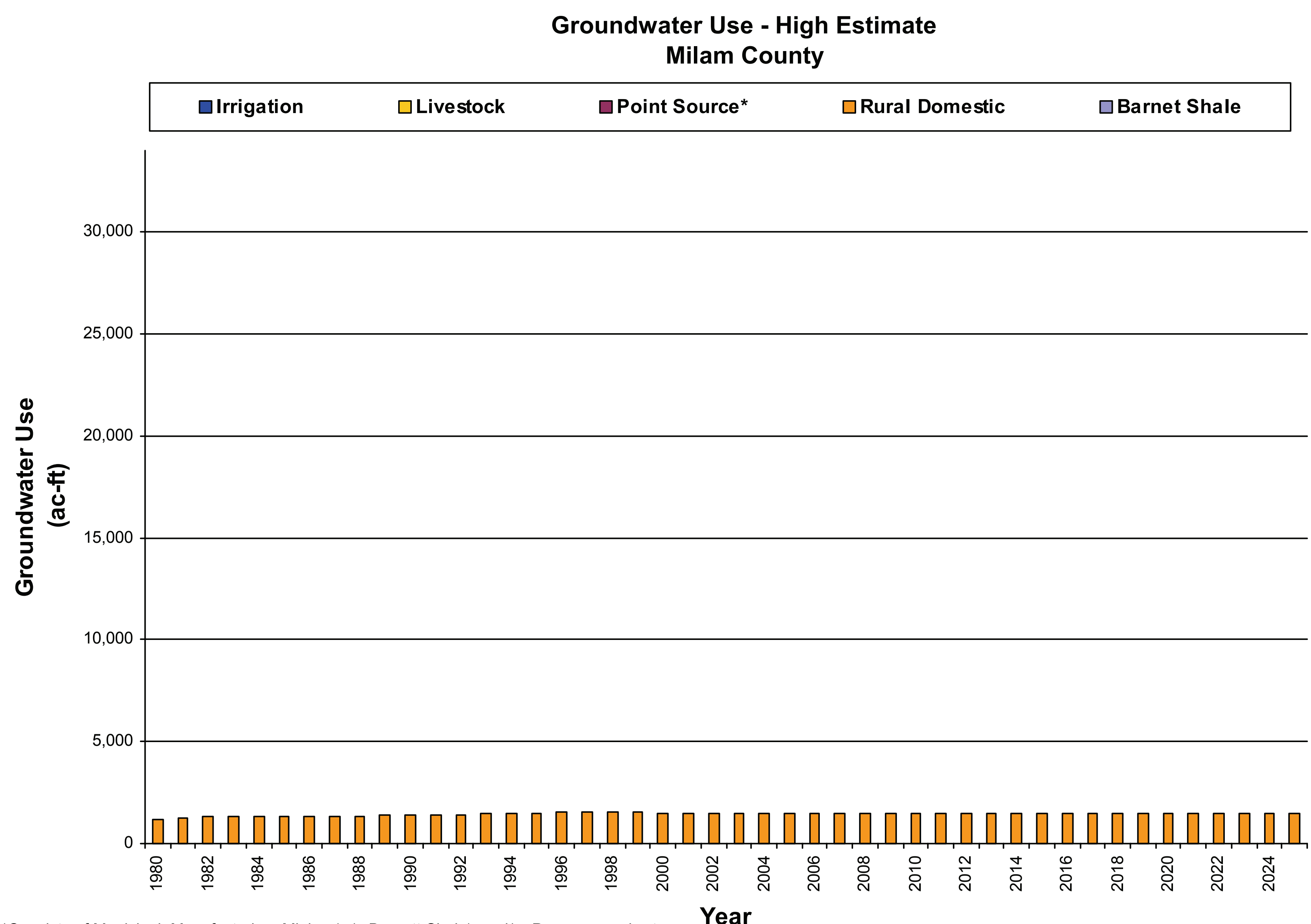
Groundwater Use - High Estimate
Limestone County



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

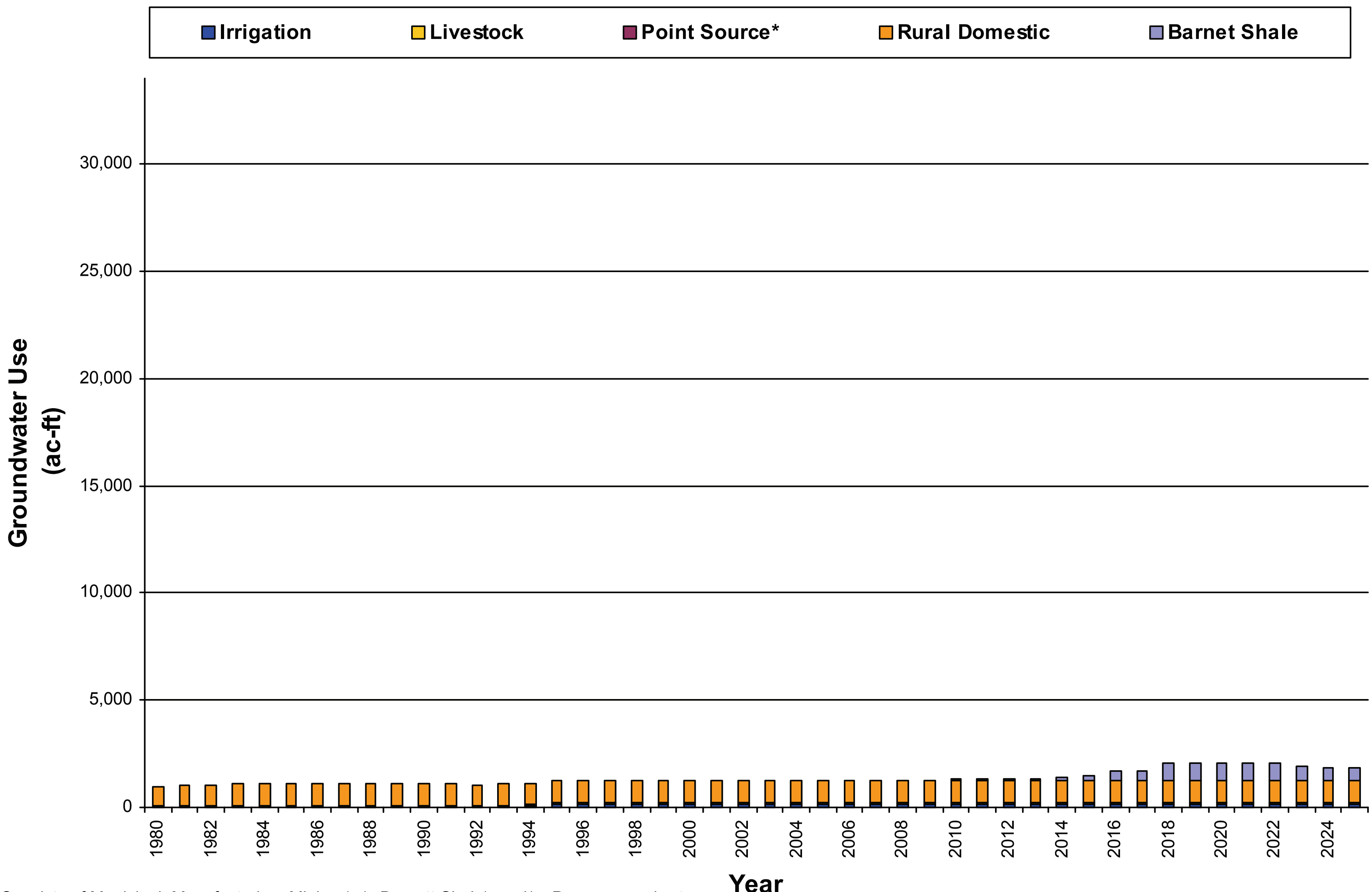


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

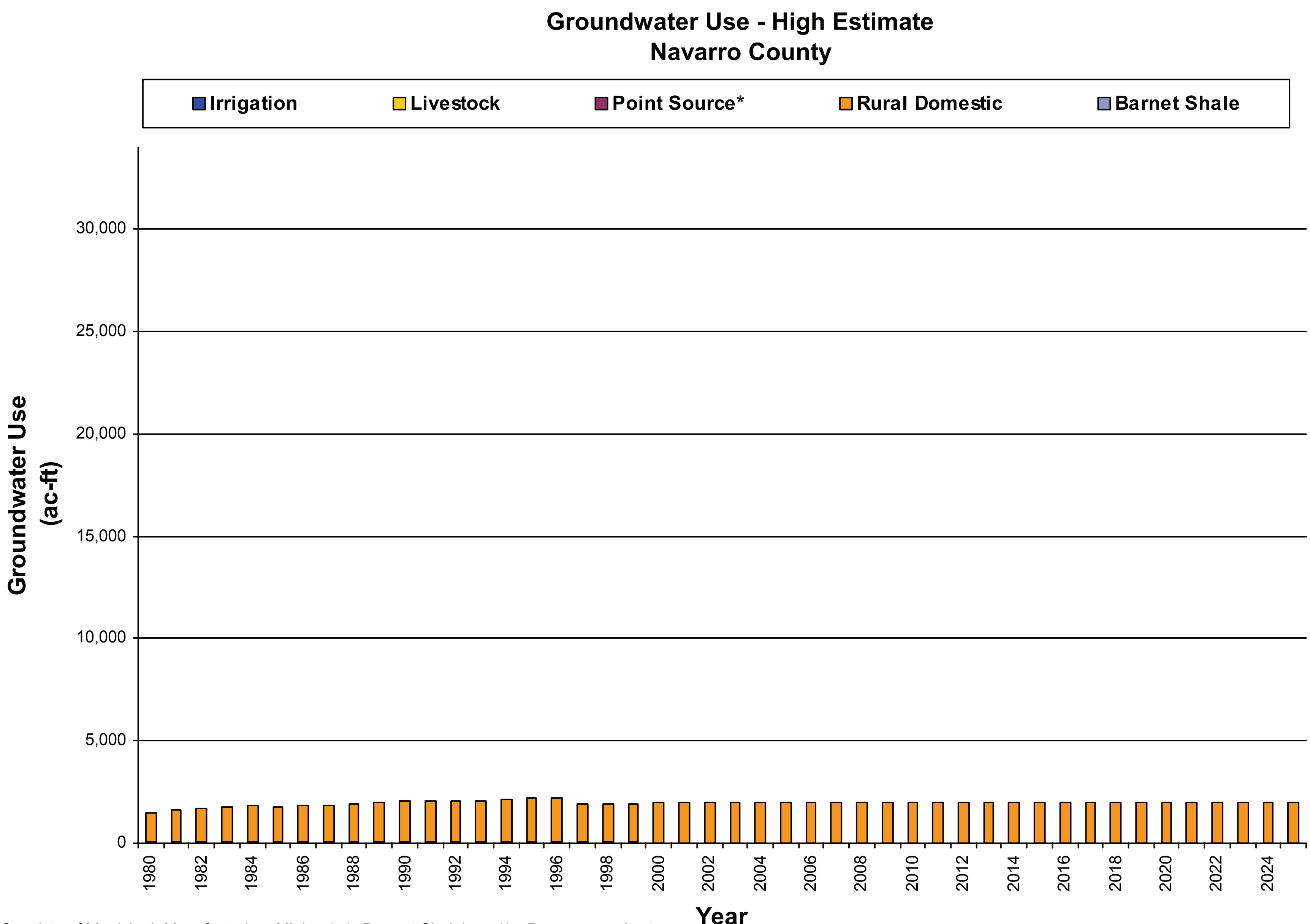


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Groundwater Use - High Estimate
Montague County

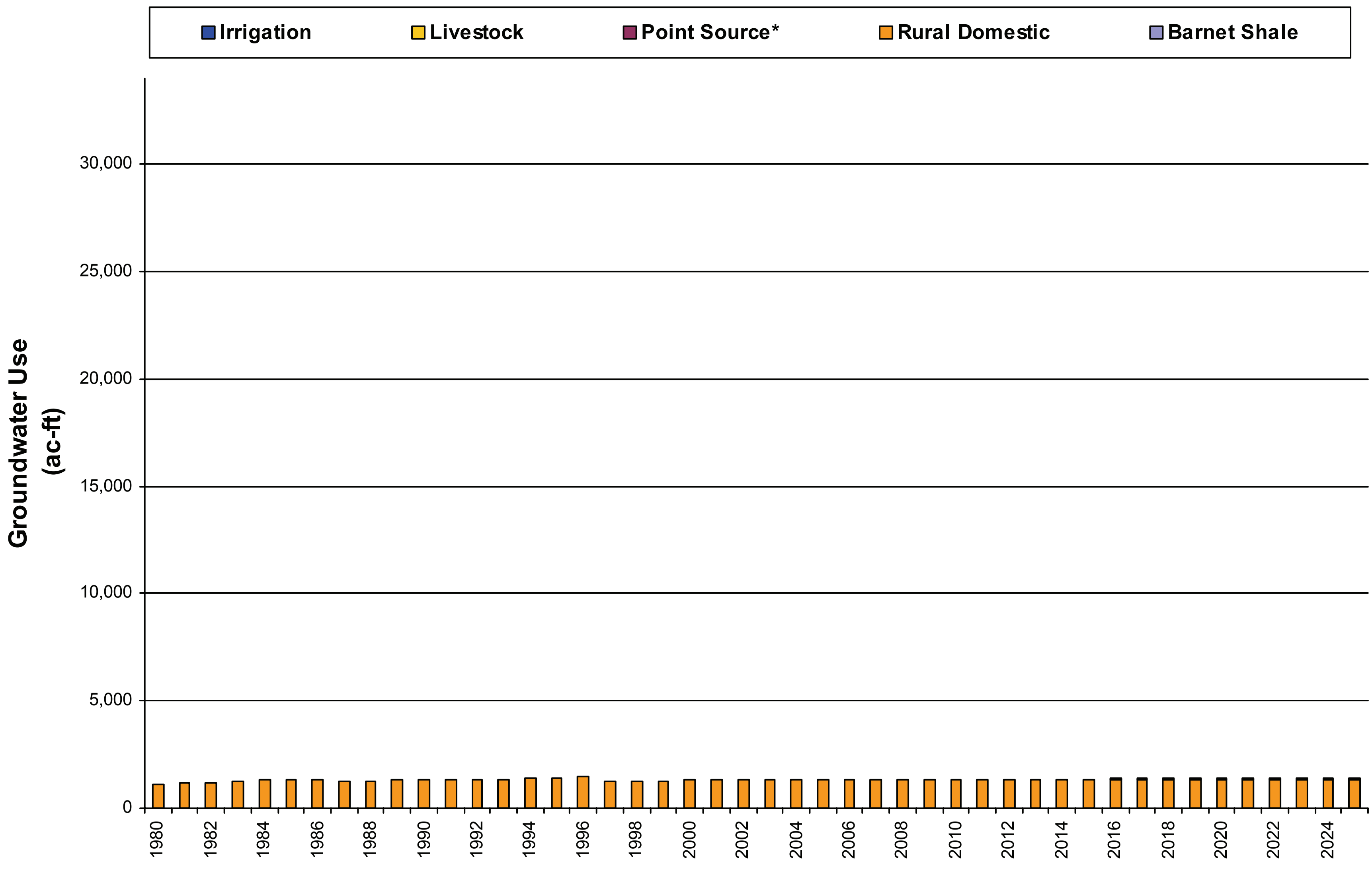


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

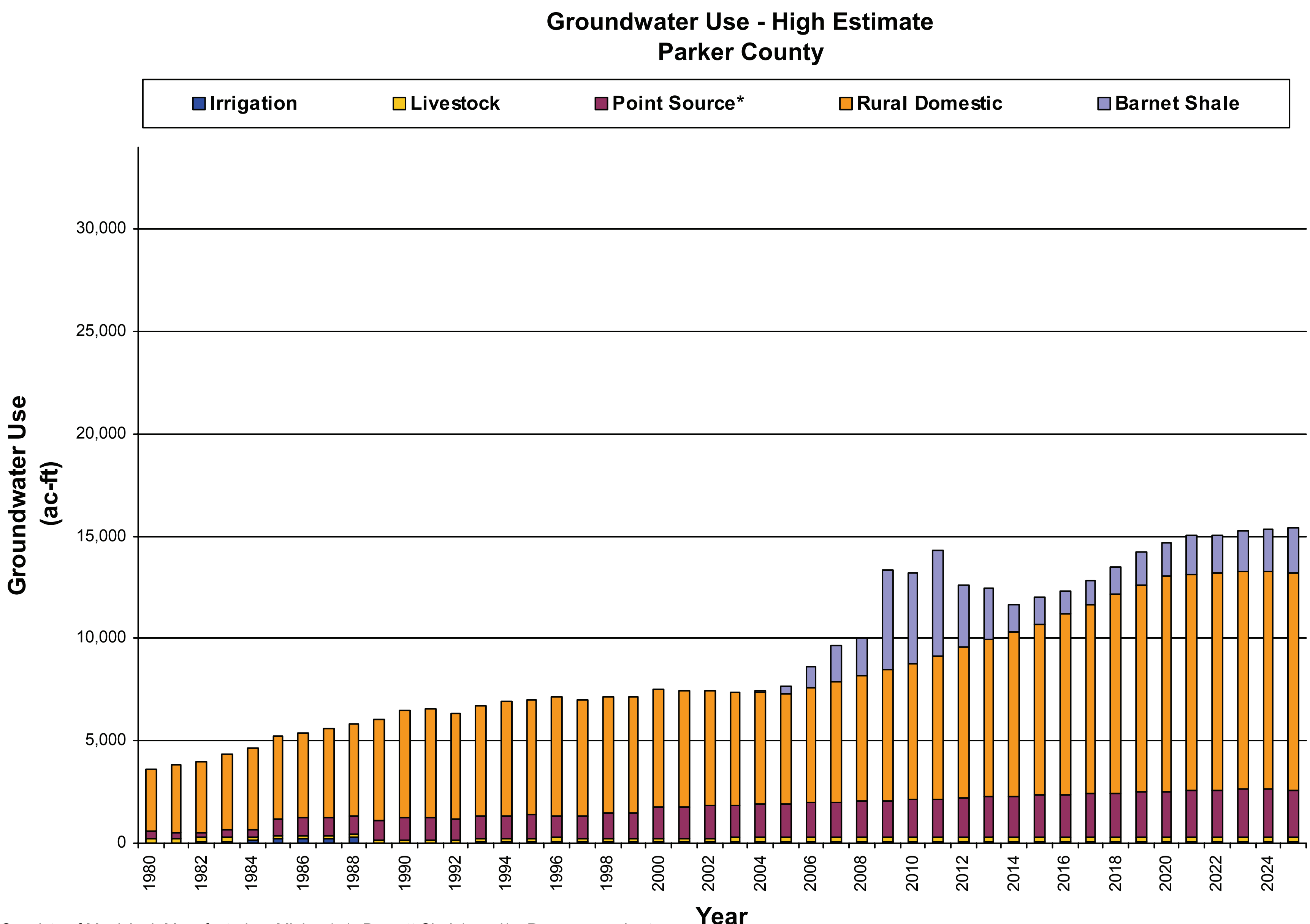


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

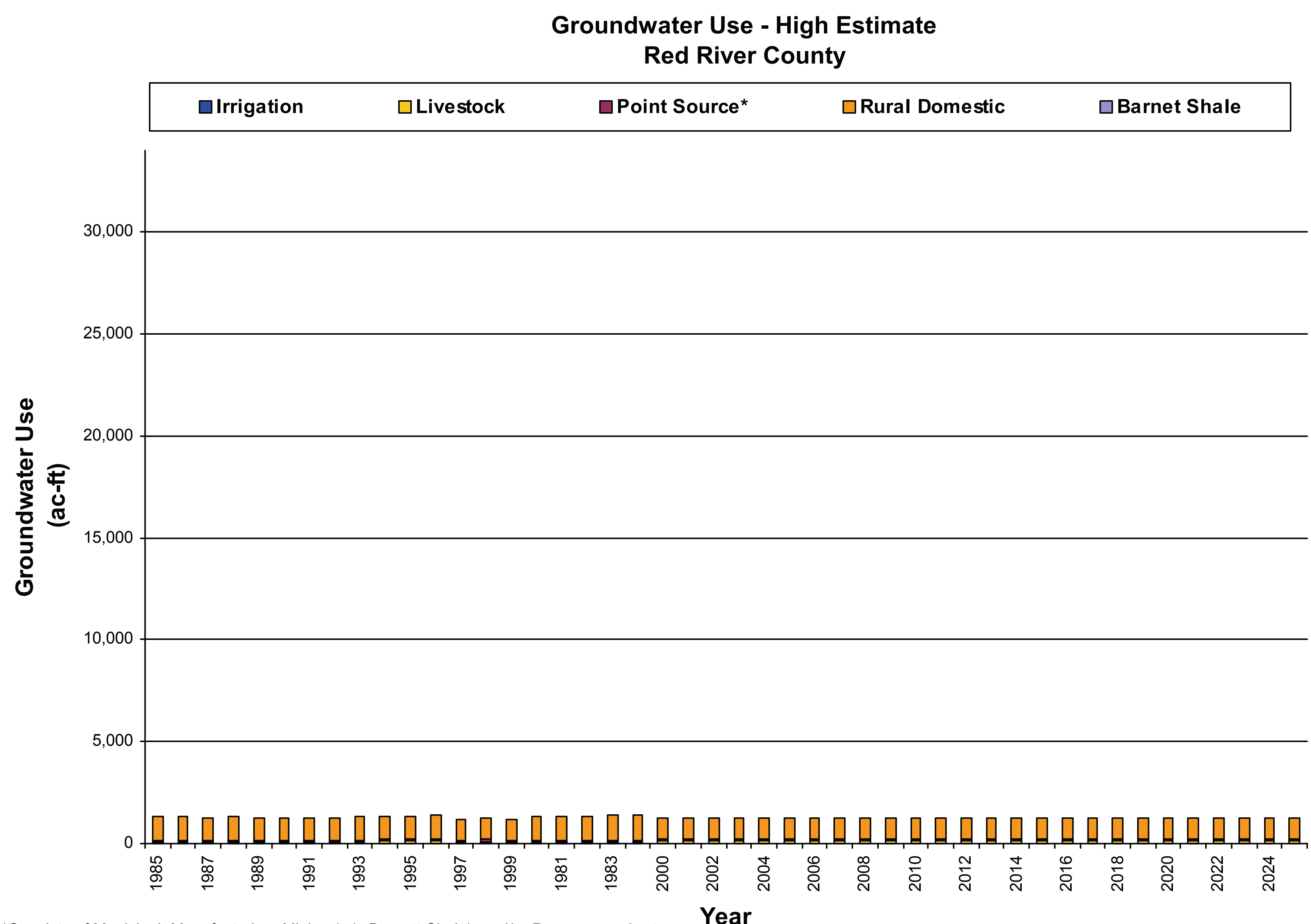
Groundwater Use - High Estimate
Palo Pinto County



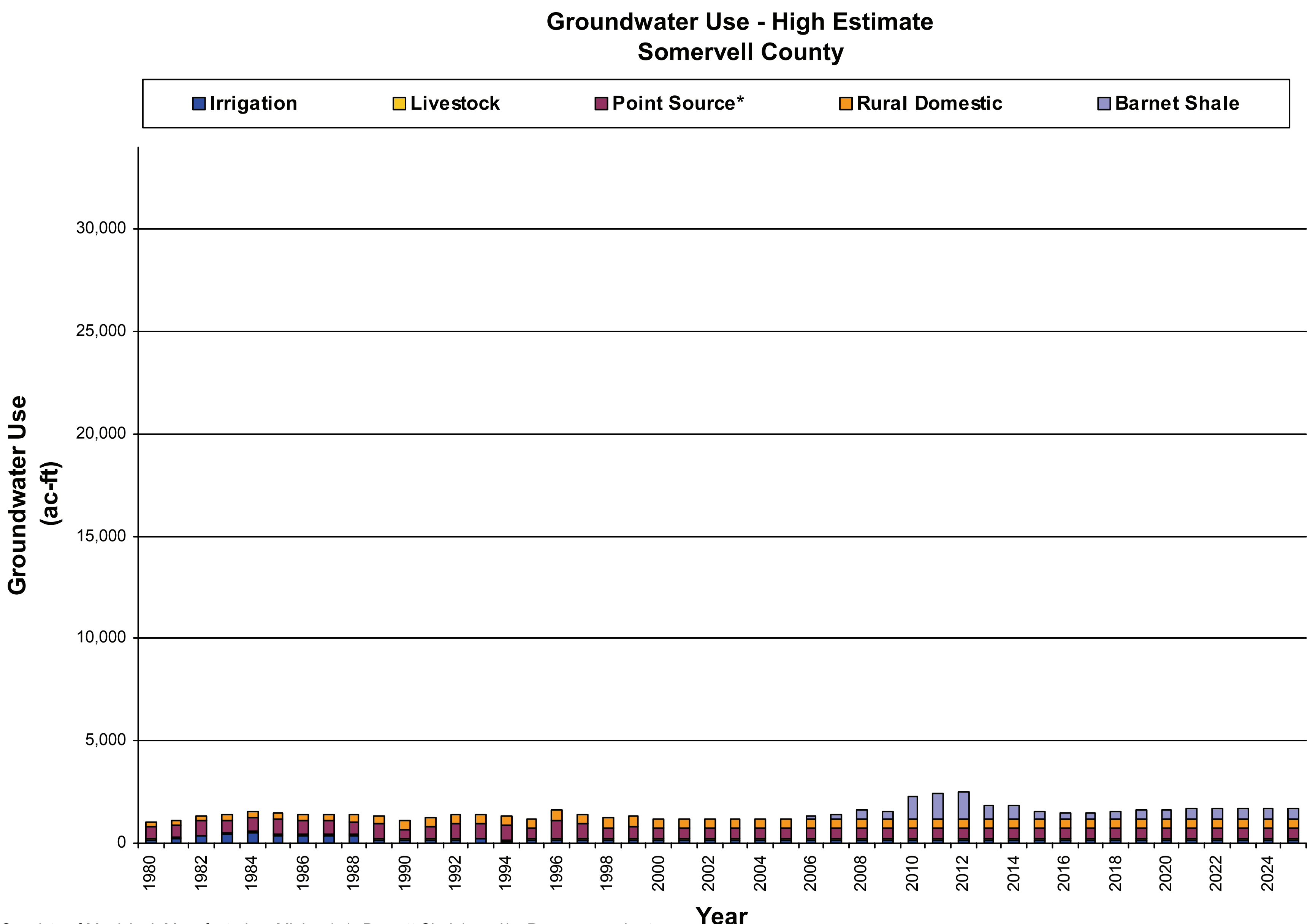
*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



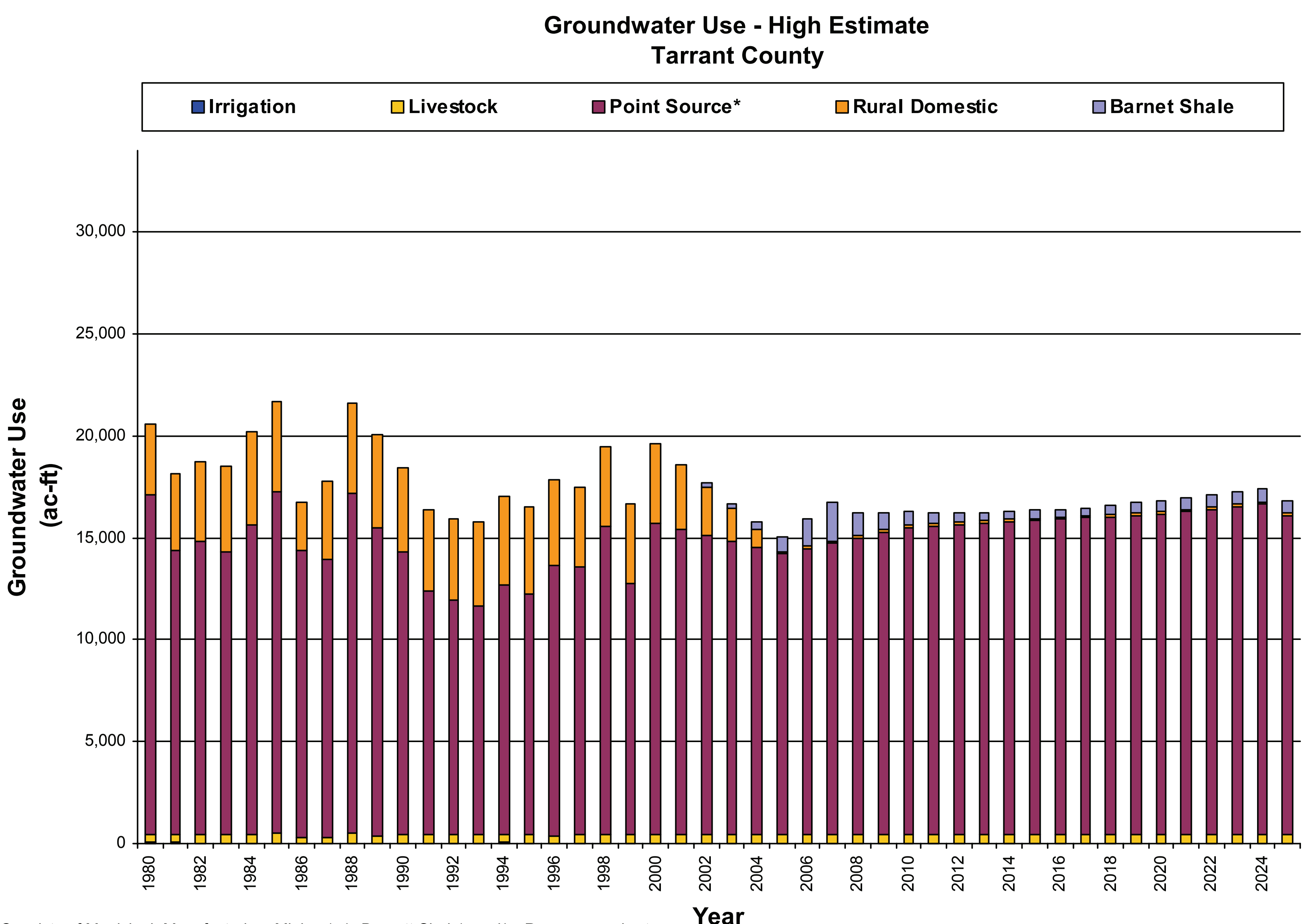
*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

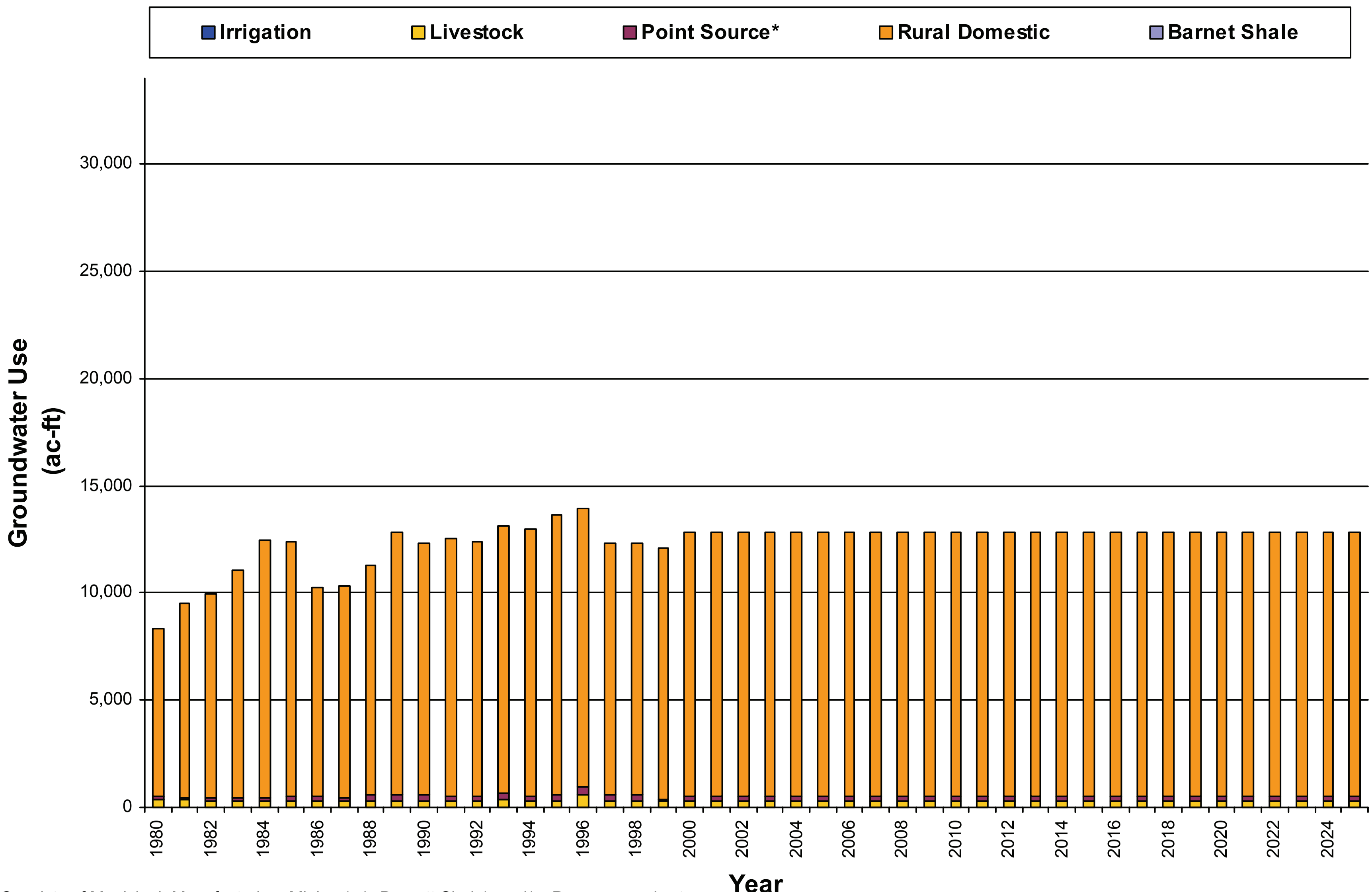


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

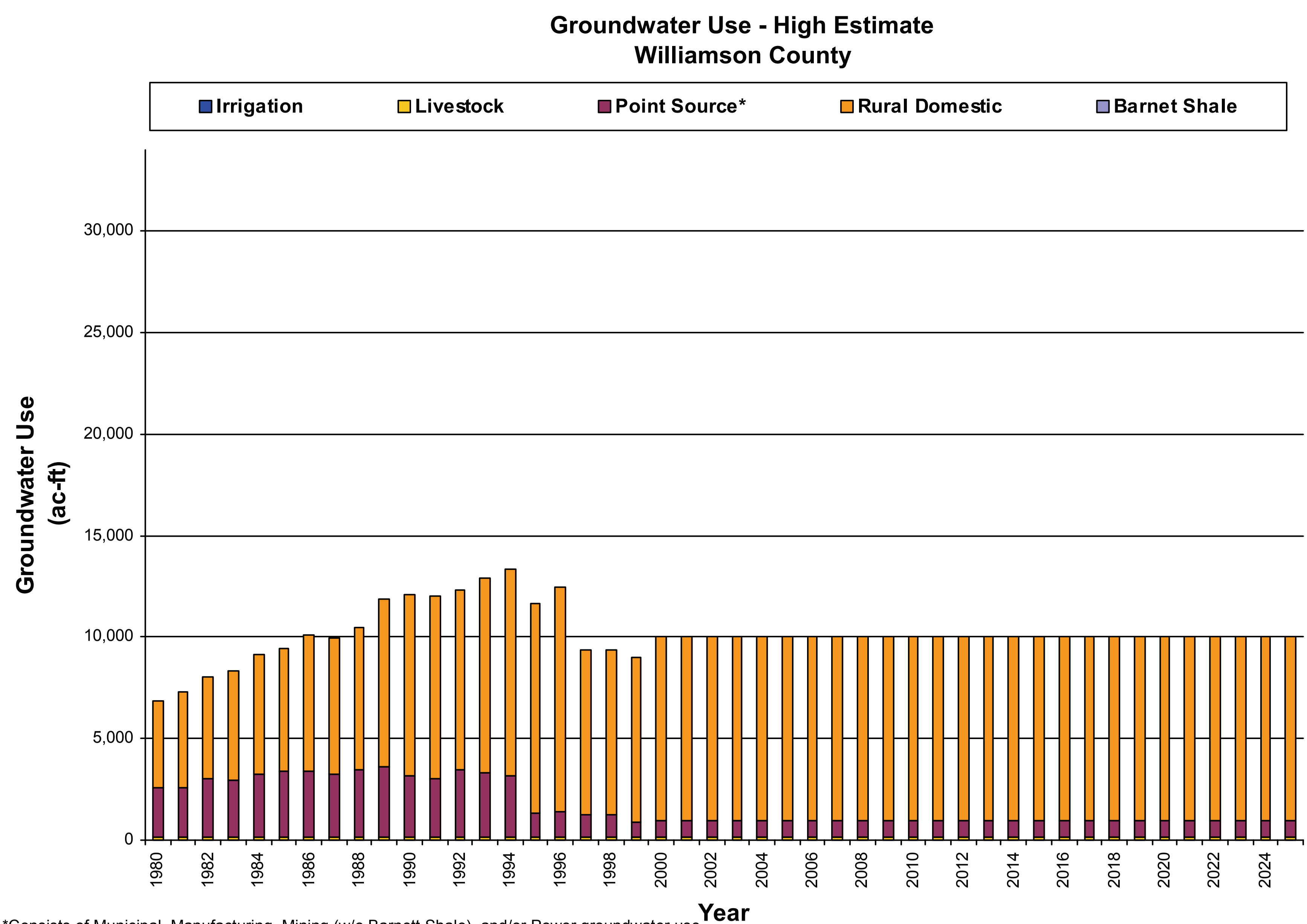


*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

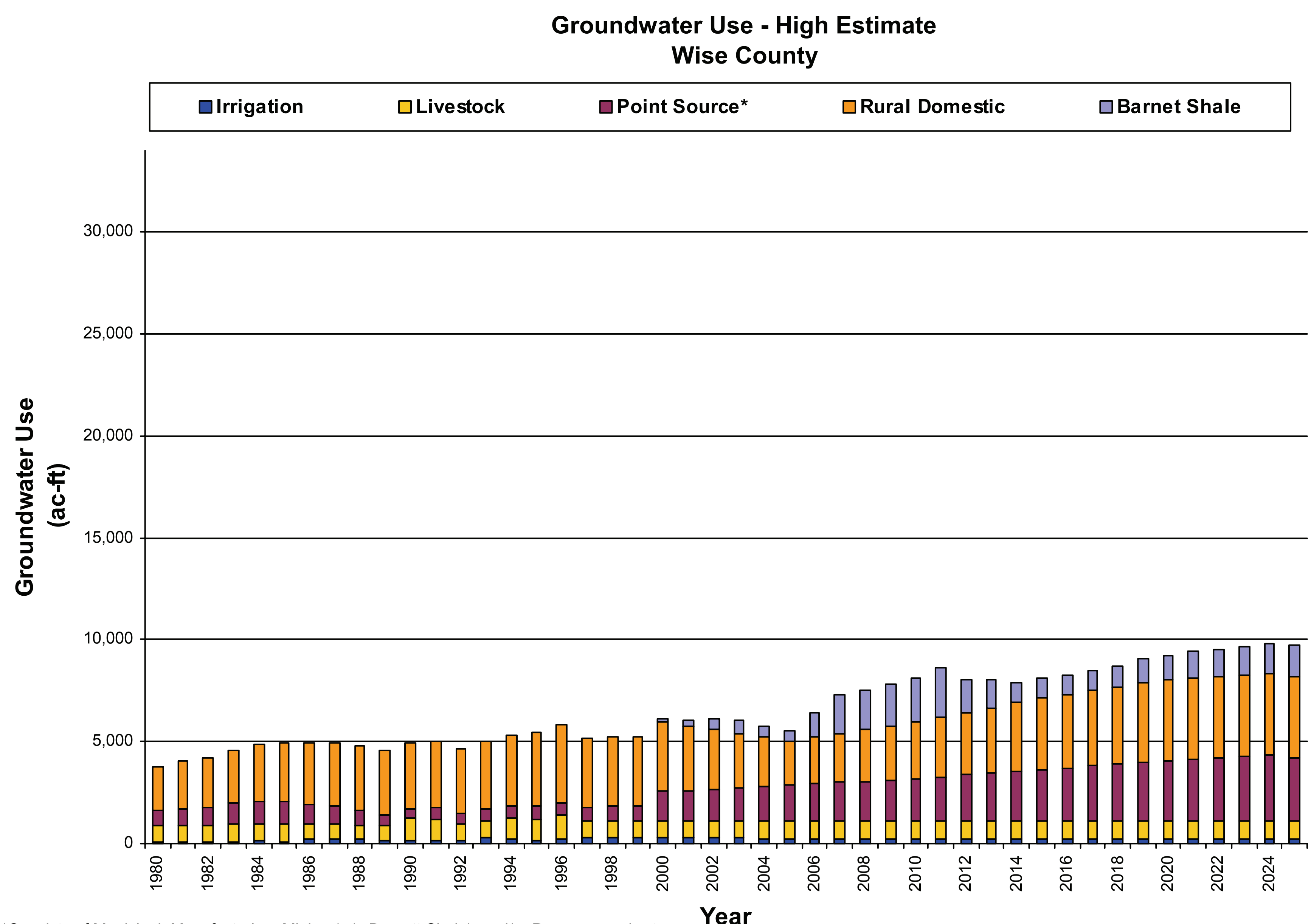
Groundwater Use - High Estimate
Travis County



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.



*Consists of Municipal, Manufacturing, Mining (w/o Barnett Shale), and/or Power groundwater use.

Table 3-1

Historical Groundwater Use Input in GAM

County	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Bell	4,374	3,649	3,785	3,361	3,312	3,143	3,140	3,088	3,086	4,597
Bosque	2,906	2,973	2,950	2,953	3,617	3,533	3,607	3,955	3,497	3,450
Brown	1,830	2,100	2,297	2,509	2,746	2,181	3,048	3,005	2,916	3,154
Burnet	1,572	1,781	1,918	2,077	2,272	2,567	2,434	2,441	2,480	2,255
Collin	4,017	4,268	4,650	4,938	5,293	5,635	5,394	5,713	6,453	6,462
Comanche	11,303	14,453	17,560	20,683	23,809	23,612	23,014	22,398	21,098	30,084
Cooke	5,888	5,630	5,590	5,862	6,118	6,023	6,413	5,798	6,144	5,593
Coryell	4,237	4,714	4,665	4,572	4,765	4,724	4,632	4,573	3,224	1,998
Dallas	18,303	19,304	16,177	19,865	19,762	20,550	18,489	21,126	15,078	12,370
Delta	294	318	320	322	330	324	319	316	337	346
Denton	9,856	9,335	9,999	11,019	12,555	11,122	12,461	12,959	12,457	13,423
Ellis	6,888	7,145	8,426	8,805	9,566	10,513	10,353	10,852	11,177	11,698
Erath	13,796	14,101	14,379	14,916	15,776	12,102	10,262	10,150	10,366	14,446
Falls	1,149	1,260	1,287	1,256	1,303	1,312	1,250	1,243	1,229	1,285
Fannin	2,189	2,372	2,595	2,998	3,428	3,680	3,422	3,366	3,961	2,803
Grayson	18,186	16,961	16,684	16,153	16,512	19,435	17,663	17,526	19,048	19,799
Hamilton	2,619	2,578	2,547	2,453	2,525	1,954	1,394	1,821	1,817	1,933
Hill	3,230	3,474	3,803	3,978	2,999	2,559	2,448	2,452	2,434	2,523
Hood	2,684	2,925	3,067	3,434	3,897	3,923	4,048	4,286	4,479	4,181
Hunt	2,554	2,893	3,009	3,238	3,548	3,664	3,791	3,944	3,954	3,851
Jack	401	437	456	464	480	485	462	457	468	465
Johnson	6,888	6,627	6,838	7,245	7,917	8,110	8,024	8,318	8,453	8,868
Kaufman	2,016	2,274	2,388	2,587	2,842	2,921	3,106	3,257	3,446	3,495
Lamar	1,791	1,915	1,931	2,013	2,186	2,116	2,120	2,159	2,178	2,170
Lampasas	1,222	1,229	1,221	1,253	1,296	1,257	1,301	1,314	1,264	1,286
Limestone	1,159	1,257	1,291	1,308	1,347	1,354	1,408	1,385	1,423	1,394
McLennan	12,429	12,258	12,472	12,726	14,149	13,699	13,568	13,361	13,668	12,807
Milam	1,188	1,276	1,297	1,318	1,362	1,348	1,330	1,358	1,304	1,410
Montague	966	1,033	1,063	1,081	1,117	1,107	1,085	1,086	1,098	1,082
Navarro	1,473	1,601	1,668	1,739	1,830	1,804	1,839	1,847	1,909	1,985
Palo Pinto	1,091	1,170	1,213	1,264	1,339	1,319	1,340	1,278	1,248	1,308
Parker	3,645	3,856	4,007	4,316	4,615	5,214	5,421	5,613	5,834	6,073
Red River	1,307	1,347	1,364	1,369	1,386	1,353	1,300	1,284	1,336	1,275
Somervell	1,053	1,128	1,341	1,390	1,560	1,487	1,385	1,377	1,366	1,348
Tarrant	20,610	18,146	18,750	18,522	20,203	21,656	16,723	17,780	21,628	20,024
Travis	8,355	9,550	9,979	11,037	12,437	12,362	10,280	10,316	11,292	12,851
Williamson	6,827	7,274	8,039	8,326	9,124	9,404	10,091	9,954	10,482	11,901
Wise	3,731	4,078	4,236	4,565	4,863	4,907	4,962	4,957	4,795	4,604

*Note: All units are in acre-feet.

Table 3-1 (cont.)

Historical Groundwater Use Input in GAM

County	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Bell	4,830	4,450	4,739	5,021	4,938	4,957	5,090	5,299	5,377	5,297
Bosque	3,789	3,422	3,465	3,550	3,735	3,634	4,037	3,618	3,656	3,664
Brown	2,411	2,460	2,405	3,393	3,283	3,733	3,652	3,842	3,842	3,842
Burnet	2,157	2,160	2,126	2,199	2,252	2,341	2,525	2,236	2,236	2,239
Collin	5,655	5,866	5,214	5,003	5,354	5,649	5,957	5,546	5,719	5,850
Comanche	26,709	24,622	33,595	29,779	28,952	27,382	19,240	18,869	18,869	18,869
Cooke	6,086	6,222	6,500	6,901	7,335	6,981	7,047	6,919	7,004	6,260
Coryell	1,911	1,868	1,921	2,067	2,236	2,278	2,604	2,233	2,233	2,233
Dallas	9,626	8,128	6,471	6,828	3,905	4,324	4,366	3,513	6,923	4,175
Delta	351	348	348	361	362	370	365	367	367	367
Denton	11,221	10,388	10,305	11,422	10,040	11,505	12,688	11,576	12,270	11,894
Ellis	11,996	9,492	9,789	10,219	10,112	9,087	9,777	9,467	9,273	9,435
Erath	14,281	11,195	13,334	23,219	20,432	20,391	21,519	16,717	16,964	17,025
Falls	1,307	1,296	1,263	1,332	1,329	1,351	1,384	1,230	1,230	1,230
Fannin	2,980	2,753	3,318	5,360	2,914	3,197	3,026	2,978	3,011	3,002
Grayson	18,441	17,865	17,407	15,509	14,049	16,192	15,990	16,668	16,885	16,593
Hamilton	2,075	2,096	1,992	1,563	1,549	1,422	1,572	1,502	1,501	1,529
Hill	2,620	2,600	2,501	2,788	2,832	2,872	2,947	2,835	2,712	2,814
Hood	4,182	3,749	3,852	4,141	4,019	4,301	4,596	5,896	6,033	6,076
Hunt	4,023	3,946	3,915	4,100	4,184	4,252	4,398	3,965	3,955	3,953
Jack	472	468	459	484	488	493	513	444	444	444
Johnson	9,111	8,916	9,299	9,695	9,986	10,122	10,769	10,093	10,270	10,610
Kaufman	3,358	3,408	3,277	3,488	3,650	3,686	4,002	3,874	3,874	3,874
Lamar	2,202	2,105	2,077	2,149	2,159	2,193	2,218	1,947	1,947	1,947
Lampasas	1,338	1,339	1,472	1,401	1,429	1,507	1,548	1,443	1,443	1,443
Limestone	1,420	1,384	1,372	1,430	1,402	1,402	1,423	1,147	1,147	1,147
McLennan	13,255	12,266	13,062	13,788	14,042	13,918	13,602	13,492	14,021	14,717
Milam	1,434	1,425	1,408	1,477	1,472	1,446	1,526	1,521	1,521	1,521
Montague	1,105	1,079	1,060	1,118	1,134	1,247	1,282	1,264	1,264	1,264
Navarro	2,070	2,035	2,038	2,100	2,106	2,179	2,225	1,942	1,943	1,898
Palo Pinto	1,341	1,314	1,328	1,364	1,399	1,369	1,481	1,280	1,280	1,280
Parker	6,475	6,543	6,333	6,701	6,962	6,988	7,179	6,996	7,166	7,175
Red River	1,278	1,254	1,249	1,298	1,328	1,331	1,386	1,207	1,219	1,215
Somervell	1,134	1,230	1,391	1,419	1,361	1,207	1,623	1,416	1,231	1,320
Tarrant	18,429	16,378	15,910	15,817	17,032	16,540	17,873	17,487	19,446	16,649
Travis	12,299	12,565	12,371	13,113	12,968	13,667	13,974	12,325	12,316	12,110
Williamson	12,105	12,023	12,288	12,883	13,344	11,618	12,427	9,396	9,361	8,983
Wise	4,954	5,040	4,661	5,028	5,292	5,470	5,813	5,175	5,273	5,256

*Note: All units are in acre-feet.

Table 3-2

Predictive Groundwater Use – Low Estimate

County	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Bell	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323
Bosque	2,966	2,966	2,966	2,966	2,966	2,968	2,967	2,966	2,966	3,200	3,203	3,206	3,451
Brown	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782
Burnet	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315
Collin	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853
Comanche	21,053	21,051	21,049	21,047	21,045	21,043	21,041	21,039	21,037	21,035	21,033	21,031	21,030
Cooke	6,798	6,798	6,798	6,804	6,812	6,827	6,813	6,798	6,802	6,802	6,824	6,813	6,822
Coryell	1,551	1,552	1,553	1,555	1,556	1,557	1,559	1,560	1,561	1,563	1,564	1,566	1,568
Dallas	7,669	7,677	7,685	7,693	7,701	7,709	7,728	7,746	7,754	7,763	7,792	7,619	7,403
Delta	367	367	367	367	367	367	367	367	367	367	367	367	367
Denton	13,494	13,557	13,527	13,194	12,632	12,427	12,394	12,361	11,944	11,101	11,035	10,564	10,533
Ellis	9,210	9,210	9,210	9,210	9,210	9,221	9,221	9,221	9,228	9,233	9,283	9,279	9,325
Erath	14,440	14,360	14,280	14,200	14,121	14,052	13,966	13,880	13,800	13,720	13,640	13,648	13,656
Falls	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285
Fannin	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622
Grayson	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342
Hamilton	1,647	1,641	1,636	1,630	1,624	1,618	1,612	1,606	1,601	1,595	1,589	1,584	1,578
Hill	2,785	2,785	2,785	2,785	2,785	2,785	2,850	2,915	2,917	2,919	3,055	3,331	3,338
Hood	8,509	8,316	8,124	7,930	7,743	7,729	7,605	7,518	7,651	7,540	8,695	8,714	8,733
Hunt	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051
Jack	534	532	529	527	524	522	522	521	518	521	530	529	586
Johnson	10,393	9,301	8,266	7,149	6,305	6,020	5,820	5,620	7,385	7,529	7,524	6,442	6,370
Kaufman	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862
Lamar	4,782	4,818	4,854	4,890	4,926	4,961	4,997	5,033	5,069	5,105	5,140	5,134	5,128
Lampasas	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477
Limestone	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253
McLennan	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,916
Milam	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507
Montague	1,264	1,267	1,268	1,282	1,266	1,286	1,275	1,264	1,264	1,264	1,283	1,271	1,291
Navarro	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002
Palo Pinto	1,338	1,338	1,338	1,338	1,338	1,338	1,338	1,338	1,338	1,338	1,339	1,339	1,339
Parker	7,501	7,437	7,376	7,323	7,369	7,531	7,799	8,066	8,074	10,404	10,440	10,458	9,031
Red River	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Somervell	1,210	1,210	1,210	1,210	1,210	1,216	1,267	1,318	1,430	1,433	1,999	2,008	2,018
Tarrant	18,854	17,312	15,916	14,401	12,993	11,807	11,671	11,535	10,833	10,545	10,087	9,894	9,818
Travis	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821
Williamson	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053
Wise	6,031	5,836	5,760	5,572	5,130	4,807	5,129	5,460	5,448	5,652	5,693	5,581	5,120

*Note: All units are in acre-feet.

Table 3-2 (cont.)

Predictive Groundwater Use – Low Estimate

County	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Bell	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323
Bosque	3,947	3,958	6,476	6,513	6,551	5,036	5,057	4,022	4,032	4,043	4,053	4,063	4,073
Brown	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782
Burnet	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315
Collin	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853
Comanche	21,028	21,027	21,025	21,024	21,022	21,021	21,019	21,018	21,018	21,017	21,017	21,016	21,016
Cooke	6,832	6,890	6,891	6,965	6,945	6,946	6,908	6,909	6,880	6,867	6,867	6,858	6,859
Coryell	1,569	1,571	1,573	1,575	1,577	1,579	1,580	1,582	1,582	1,582	1,582	1,582	1,582
Dallas	7,406	7,193	6,980	6,631	6,416	6,109	5,893	5,677	5,731	5,785	5,839	5,893	5,947
Delta	367	367	367	367	367	367	367	367	367	367	367	367	367
Denton	10,546	10,558	10,571	10,563	10,556	10,548	10,541	10,533	10,529	10,524	10,519	10,515	10,898
Ellis	9,307	9,308	9,287	9,288	9,271	9,260	9,260	9,253	9,253	9,253	9,254	9,254	9,255
Erath	13,664	13,672	13,681	13,689	13,697	13,705	13,713	13,721	13,729	13,737	13,745	13,753	13,760
Falls	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285
Fannin	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622
Grayson	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342
Hamilton	1,573	1,568	1,563	1,558	1,552	1,547	1,542	1,537	1,525	1,514	1,503	1,491	1,480
Hill	4,741	4,763	4,785	3,940	3,952	3,375	3,381	3,387	3,393	3,399	3,404	3,410	3,416
Hood	7,964	7,974	7,447	7,448	7,449	7,450	7,451	7,453	7,456	7,459	7,463	7,466	7,469
Hunt	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051
Jack	586	585	549	548	522	521	520	519	517	516	514	513	511
Johnson	5,622	5,599	5,603	5,607	5,588	5,591	5,579	5,582	5,533	5,483	5,434	5,384	5,522
Kaufman	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862
Lamar	5,122	5,116	5,109	5,103	5,097	5,091	5,085	5,078	5,073	5,067	5,062	5,056	5,050
Lampasas	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477
Limestone	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253
McLennan	13,916	13,916	13,949	14,016	14,017	14,355	14,359	14,364	14,161	14,164	14,025	14,027	14,028
Milam	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507
Montague	1,299	1,314	1,339	1,458	1,460	1,679	1,645	1,649	1,528	1,531	1,443	1,420	1,422
Navarro	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002
Palo Pinto	1,341	1,344	1,344	1,359	1,359	1,360	1,350	1,351	1,344	1,344	1,344	1,344	1,345
Parker	9,032	8,048	8,037	8,051	8,064	8,077	8,090	8,103	8,110	8,116	8,122	8,128	8,204
Red River	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Somervell	1,677	1,682	1,449	1,451	1,454	1,456	1,459	1,461	1,464	1,466	1,468	1,471	1,473
Tarrant	9,748	9,679	9,609	9,557	9,505	9,453	9,401	9,349	9,356	9,363	9,370	9,377	9,680
Travis	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821
Williamson	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053
Wise	5,127	4,858	4,861	4,865	4,868	4,871	4,875	4,878	4,880	4,882	4,884	4,885	5,085

*Note: All units are in acre-feet.

Table 3-3

Predictive Groundwater Use – High Estimate

County	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Bell	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323
Bosque	2,966	2,966	2,966	2,966	2,966	2,968	2,967	2,966	2,966	3,316	3,286	3,335	3,731
Brown	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782
Burnet	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315
Collin	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853
Comanche	21,053	21,051	21,049	21,047	21,045	21,043	21,041	21,039	21,037	21,035	21,093	21,101	21,102
Cooke	6,798	6,798	6,798	6,804	6,812	6,827	6,813	6,798	6,808	6,806	6,844	6,823	6,840
Coryell	1,551	1,552	1,553	1,555	1,556	1,557	1,559	1,560	1,561	1,563	1,564	1,566	1,568
Dallas	7,669	7,677	7,685	7,693	7,701	7,709	7,738	7,766	7,775	7,773	7,807	7,665	7,453
Delta	367	367	367	367	367	367	367	367	367	367	367	367	367
Denton	13,485	13,891	14,204	14,215	13,996	14,135	14,960	15,785	15,952	15,500	16,617	16,301	16,611
Ellis	9,210	9,210	9,210	9,210	9,210	9,221	9,227	9,232	9,247	9,244	9,314	9,324	9,403
Erath	14,440	14,360	14,280	14,200	14,121	14,052	14,179	14,306	14,235	14,050	14,242	15,040	15,099
Falls	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285
Fannin	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622
Grayson	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342
Hamilton	1,647	1,641	1,636	1,630	1,624	1,618	1,612	1,606	1,601	1,595	1,842	1,877	1,882
Hill	2,785	2,785	2,785	2,785	2,785	2,785	2,914	3,043	3,048	2,985	3,149	3,626	3,657
Hood	8,396	8,425	8,453	8,480	8,512	8,719	8,798	8,858	9,272	8,945	10,498	10,916	11,064
Hunt	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051
Jack	534	532	529	527	524	522	530	538	536	545	571	580	771
Johnson	10,334	10,645	11,016	11,302	11,863	12,981	13,445	13,908	17,767	17,005	16,891	15,927	16,046
Kaufman	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862
Lamar	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050
Lampasas	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477
Limestone	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253
McLennan	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,884	13,975
Milam	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507
Montague	1,264	1,267	1,268	1,282	1,266	1,286	1,275	1,264	1,264	1,264	1,311	1,291	1,324
Navarro	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002
Palo Pinto	1,338	1,338	1,338	1,338	1,338	1,338	1,338	1,338	1,338	1,338	1,343	1,343	1,344
Parker	7,488	7,456	7,427	7,405	7,483	7,678	8,642	9,661	10,003	13,339	13,218	14,295	12,593
Red River	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Somervell	1,210	1,210	1,210	1,210	1,210	1,216	1,321	1,425	1,649	1,543	2,274	2,439	2,485
Tarrant	19,615	18,576	17,681	16,667	15,761	15,077	15,917	16,757	16,253	16,237	16,300	16,190	16,245
Travis	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821
Williamson	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053
Wise	6,149	6,080	6,126	6,062	5,745	5,545	6,414	7,287	7,495	7,789	8,128	8,643	8,046

*Note: All units are in acre-feet.

Table 3-3 (cont.)

Predictive Groundwater Use – High Estimate

County	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Bell	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323	5,323
Bosque	4,242	4,284	7,509	6,933	7,132	5,636	6,227	4,576	4,912	4,869	5,007	5,000	5,141
Brown	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782
Burnet	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315	2,315
Collin	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853	5,853
Comanche	21,149	21,276	21,271	21,775	21,812	21,906	21,637	21,628	21,386	21,378	21,403	21,402	21,428
Cooke	6,852	6,937	6,935	6,996	6,985	6,998	7,018	7,014	6,977	6,939	6,952	6,928	6,934
Coryell	1,569	1,737	1,736	1,717	1,876	2,250	2,401	4,416	5,009	4,933	3,635	3,629	2,676
Dallas	7,499	7,295	7,072	6,652	6,446	6,135	5,945	5,726	5,810	5,859	5,924	5,977	6,043
Delta	367	367	367	367	367	367	367	367	367	367	367	367	367
Denton	17,018	17,449	17,898	18,390	18,922	19,444	20,033	20,539	21,236	21,863	22,542	23,200	23,442
Ellis	9,359	9,356	9,351	9,354	9,339	9,297	9,308	9,285	9,293	9,293	9,299	9,304	9,308
Erath	17,877	18,022	17,966	15,827	15,943	14,964	15,251	15,239	15,565	15,532	15,670	15,671	15,811
Falls	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285	1,285
Fannin	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622	2,622
Grayson	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342	15,342
Hamilton	2,080	2,614	2,594	4,708	4,861	5,257	4,132	4,093	3,071	3,025	3,123	3,107	3,207
Hill	5,330	5,412	5,374	4,077	4,142	3,546	3,714	3,702	3,894	3,869	3,948	3,944	4,024
Hood	9,612	9,702	9,034	8,990	9,065	9,186	9,388	9,421	9,644	9,663	9,779	9,818	9,918
Hunt	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051	4,051
Jack	726	732	630	612	557	563	576	574	589	585	590	587	593
Johnson	14,768	14,962	15,070	15,098	15,220	15,469	15,821	15,947	16,366	16,474	16,736	16,881	16,953
Kaufman	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862	3,862
Lamar	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050
Lampasas	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477	1,477
Limestone	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253
McLennan	13,960	13,962	14,038	14,152	14,166	14,990	15,234	15,217	14,805	14,785	14,367	14,366	14,399
Milam	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507	1,507
Montague	1,337	1,388	1,438	1,678	1,698	2,043	2,078	2,067	2,036	2,040	1,942	1,832	1,850
Navarro	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002	2,002
Palo Pinto	1,347	1,358	1,357	1,397	1,400	1,408	1,387	1,386	1,367	1,366	1,368	1,368	1,370
Parker	12,475	11,636	12,004	12,315	12,847	13,465	14,233	14,687	15,072	15,080	15,268	15,312	15,389
Red River	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Somervell	1,817	1,837	1,519	1,480	1,493	1,528	1,598	1,593	1,673	1,663	1,696	1,694	1,727
Tarrant	16,233	16,302	16,357	16,379	16,463	16,569	16,723	16,783	16,996	17,099	17,258	17,375	16,850
Travis	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821	12,821
Williamson	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053	10,053
Wise	8,070	7,907	8,116	8,233	8,459	8,688	9,052	9,221	9,463	9,517	9,690	9,801	9,753

*Note: All units are in acre-feet.

Appendix 4
Draft Report Comments and Responses

Prepared for:

Texas Water Development Board, Austin, TX

Prepared by

Bob Harden, R. W. Harden & Associates, Inc.,
James Bené, R. W. Harden & Associates, Inc.,
Stephanie Griffin, Freese and Nichols, Inc.
Jean-Philippe Nicot, P.E., P.G., Bureau of Economic Geology

The draft report entitled "Assessment of groundwater use in the Northern Trinity Aquifer due to urban growth and Barnett Shale development" prepared by R. W. Harden and Associates, Inc., Freese and Nichols, Inc., and Bureau of Economic Geology was reviewed by the various stakeholders with an interest in water use in the northern parts of the Trinity Aquifer . These stakeholders included representatives of the Texas Commission on Environment Quality, Texerra, Railroad Commission of Texas, Texas Water Development Board, Texas Oil and Gas Association, and Barnett Shale Water Management and Conservation Committee (BSWMCC). Texerra is a hydrologic consultant and is retained by the BSWMCC.

The responses to individual comments are described below each entry.

REVIEW COMMENTS BY THE TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

Executive Summary

(1) Needs to clearly state purpose of assessment, methodology, and limitations
(2) Needs to inform reader of present levels of groundwater use and aquifer conditions
(3) Needs to provide assessment results and how assessment results affect present levels of groundwater use and aquifer conditions
(4) Needs to describe how assessment results may affect existing groundwater users (reader should be able to place new information into context with 2006 RWP projections)
(5) Needs to be unbiased – positively or negatively

Response: The Executive Summary has been completely rewritten to address the above concerns.

Introduction

(6) 2nd paragraph needs to clearly identify six counties FNI updated and which counties BEG assessed

Response: Counties updated for domestic and municipal water uses by FNI have been included in the text. Counties assessed for water use in gas well development in the Barnett Shale by the BEG have been included in the text.

Study Area

(7) Study area is not clearly described – six county area or larger Barnett Shale use area or larger Trinity/Woodbine GAM area – needs to be more focused

Response: Updated language has been added to the study area description. The study area includes most of the northern parts of the Trinity and Woodbine aquifers. The Trinity/Woodbine GAM includes additional counties to the south that has not been shown in Figure 1. FNI updated domestic and municipal water use for the six county area. BEG assessed water use for gas well development in the Barnett Shale.

Updated Groundwater Use Estimates

Demand Projections

(8) Five-year data presentation not similar to general format for state or regional water plans

Response: The duration of the model simulations is only through 2025. The five-year data presentation was chosen for the purpose of providing greater discretization of the data for input into the yearly time steps of the GAM.

(9) Write-up doesn't include insightful information from FNI/Appendix 1

a) Comparison of population projection assessment to 2006 RWP projections
b) 4,834 new water wells in six counties in 44-month period (56 new PWS wells)
c) ~110 new water wells drilled per month in six counties over 44-month period
d) 95% of new water wells in six counties for uses addressed by FNI
e) 61% of new water wells in Johnson County in first eight months of 2006 for rig supply

Response: Descriptive language is added to the demand projections section to better describe the numbers of new wells and the types of the wells recently completed.

(10) Write-up doesn't describe/compare new FNI demands for six counties to

a) adopted 2006 RWP demands
b) 2000 or 2003 Trinity or Woodbine aquifer use
c) adopted RWP recommendations for estimated safe supply of groundwater

Response: The comparison to the adopted regional water plan is beyond the scope of work. Generally, both the low and high demand estimates are higher than the reported 2000 actual use and higher than the adopted RWP recommendations for estimated safe supply of groundwater.

Barnett Shale Industrial Use

(11) Figure 2 data should be presented in table format for easy comparison to/addition to Table 1 (at least for six counties)

Response: Table 5 has been updated with all uses for comparison.

(12) 1st paragraph – need a reference for the "5,600 producing wells."

Response: A reference to Appendix 2 is added.

(13) 2nd paragraph, 3rd sentence – professional papers are mentioned, but not referenced.

Response: Sentence reworded and a reference to Appendix 2 is added.

(14) 3rd paragraph, 3rd sentence – Groundwater is used 60% of the time for what? Where did this number come from?

Response: Recent survey suggested that on average sixty percent of the total water use for gas well development in the Barnett Shale uses groundwater (Galuskey, 2006). Reference has been cited.

Total Groundwater Use

(15) 1st paragraph, 3rd sentence – What if use/demand remained constant or increased?

Response: Then, typically, future demand was left as is.

(16) As presented, don't find Appendix 3 of any use in supporting report/report text

Response: Text added to report to better describe purpose of Appendix 3, which is to document actual pumpage input into all counties of the model for the different simulations.

(17) Table 3 – Where did the data for this table come from? No Comanche Co. groundwater use?

Response: Table 3 is now Table 5 and has been updated to include all use categories. Table 5 represents the percent water use by category using the actual pumpage values input into the GAM under high groundwater use estimate scenario. Percent use by water use category for Comanche County is included in the table.

Distribution of Pumpage

(18) 2nd bullet – Why are some counties shown in Figure 1 study area included and others (i.e. Coryell, Hamilton, Comanche, Erath, etc.) are not? Why is Travis County listed but is not shown in Figure 1?

Response: The GAM footprint extends beyond the extents of Figure 1. Not all counties are in the study area of this report, but are included in the groundwater model. The "official" GAM pumpage is currently representative of 2001 regional planning estimates and for this work effort pumpage was updated. The bullets document the approaches used to update the GAM inputs.

Barnett Shale Production

(19) Vertical Distribution of Pumpage - 2nd paragraph, 1st sentence – Incomplete sentence. Where is Step 2?

Response: Sentence is corrected.

Conclusions

(20) GAM model simulation descriptions need to be more accurately described and described in context with historic water level / artesian pressure declines

Response: Additional descriptions concerning historical declines have been added to the conclusions.

(21) Last sentence is editorial and not needed

Response: Last sentence has been modified.

Appendix 1

(22) Drill Logs for Wells – first paragraph is not factual

Response: Reference is made to the Texas Department of Licensing and Regulation.

(23) Information from Table 1 not addressed or included for discussion in body of report

Response: Table 1 summary information added to report.

(24) Text ends abruptly without summary

Response: A summary conclusion is added to Appendix 1.

(25) Would benefit most readers if adjusted low and high demand projections were compared to historic use and 2006 regional water planning demand projections

Response: A detailed comparison to the adopted regional water plan is beyond the scope of work. Generally, the low demand estimate is equal or lower than the 2000 reported annual use and the high demand estimate is higher than 2000 reported use.

Appendix 2

(26) Restimulation - It is stated that refrac'ing wells every few years does improve the total production, yet you chose to show that wells are refrac'ed only once after 5 years in the high demand scenario. If the price of gas remains high, isn't it likely that at least a percentage of the total wells would be refrac'ed more than once in the time period in question? And only one refrac'ing in the medium demand scenario.

Response: The scenario proposed in the comment was also our initial understanding of the play and the way we planned to compute total water use. However, after discussions with engineers and managers from oil&gas companies involved in the play, we realized that refrac'ing of wells was not a common strategy to get the most out of the play (see comment by Texerra). Operators would rather optimize the initial frac jobs. This is particularly true of horizontal wells where spacing of laterals and distance between frac jobs in a given lateral can be adapted to local conditions.

(27) Restimulation - Why is refrac'ing of horizontal wells completely left out of the all demand scenario? Again, in the high demand scenario, if prices remain high, isn't it likely that they will refract the horizontal wells as well? If not, why not?

Response: See response to previous comment

Appendix 3

(28) Value of appendix not clear in body of report

Response: The purpose of Appendix 3 is to document the pumpage input into the GAM for both the low and high use estimates. It provides a breakdown of amount and categories of groundwater use by year.

(29) Appendix seems to cover many more counties than are of interest to the main issues of this report

Response: Appendix 3 includes all Texas counties within the GAM footprint and some of these are outside of the study area. Because aquifer effects may extend beyond the main study area, the total use input into the model is documented for all Texas counties.

General Comments

(30) In Denton, Hood, Johnson, Parker, Tarrant, and Wise counties, about 110 new water wells were drilled each month over a 44-month period ending in August 2006. About five percent of the water wells drilled during this span in the six-county area was to support drilling and fracturing of Barnett Shale gas wells. In Johnson County, over 60 percent of the new wells drilled in the first eight months of 2006 were for Barnett Shale drilling supply. It is not clear how many new water wells represent new demands on the Trinity and Woodbine aquifers or are supplemental wells that have been drilled to replace existing groundwater supplies. However, the 260 new rig supply wells drilled during this period should be considered new demands on the aquifers for planning purposes because the water demands for Barnett Shale gas exploration have not been included in the regional water planning demand projections to date.

Response: The updated rural demands and Barnett Shale mining demands reflect this increased rural use.

(31) For the FNI municipal, manufacturing, irrigation, and livestock demand projections for the six-county area, the 2005 low demand projection is about 7,000 acft/yr below 2000 historic water use and the 2005 high demand projection starts about 6,000 acft/yr higher than the 2000 historic water use values. Both the low and high water demand projections for the six-county area are above the regional water planning groups estimates for the available safe supply of groundwater – low demand by about 5,000 acft/yr and high demand by about 18,000 acft/yr.

Response: A comparison to the adopted regional water plan is beyond the scope of work.

(32) Historic artesian pressure declines of up to 1,000 feet have occurred in the Dallas, Fort Worth and Waco areas, and declines greater than 500 feet have occurred along the I-35 corridor over the past century. The GAM simulations generally predict additional artesian pressure declines to be widespread in the Trinity and Woodbine aquifers under both low and high demand projections except for the lower two zones of the Trinity aquifer in the eastern Tarrant – western Dallas county area where recovery of artesian pressure is projected in the low demand simulation. Additional reductions in artesian pressure can result in declining production ability for existing wells and will certainly lower the piezometric head below pumping levels for many existing wells. The net effect for both situations is increased operating cost for existing well owners, either because of prolonged pumping-time requirements or addition of new wells to produce the same volume of supply, lowering of well pumps and addition lift costs for the same volume of supply, or deepening of existing shallow wells to remain in contact with the aquifer to access the same volume of water. In the high demand GAM scenario that predicts 'dewatering' in some of the western portions of the Trinity aquifer, the ability by landowners to pump and use groundwater would be forfeited.

Response: Under present law, all landowners in the Trinity have an equal right to use water provided it is not done maliciously. Existing users do not have a "superior" or exclusive right to use water at the expense of another landowner's right to use water.

It cannot be concluded from the modeling results of the high demand scenario that the ability of landowners to pump and use groundwater will be forfeited. The model results indicate that a few feet of dewatering would occur, which is a small percentage of total aquifer thickness. Landowners participate in both the increased rural use and indirectly through the mining use by selling of mineral rights and, thereby, are partly responsible for the increased demands. As indicated in the report, if increased use is to occur, then by necessity it will be achieved by a greater number of smaller capacity wells because of the inherent characteristics of the Trinity and existing water levels in the aquifer. In this case, the net effect is increased operating cost.

(33) General Comments - Throughout document - Try to be consistent in using high end "demand", "use" is used too often! Also, check Figures for number sequence.

Response: Where applicable, "use" is changed to demand throughout report.

(34) 2nd and 3rd sentences should be rewritten - Page 1, 1st paragraph, 2nd and 3rd sentences - Rewrite as follows: As ….. , a corresponding decline…occurred due to a decline in artesian pressure.

Response: Executive Summary is rewritten.

(35) "..,it is very likely that Trinity groundwater would sometimes be used.." - page 1, 2nd paragraph, last sentence. - Change to : ,Trinity groundwater is presently being used..

Response: Executive Summary is rewritten.

(36) New sentence - Page 1, 2nd paragraph - Appendix 1, Table 1 shows that 260 new rig supply wells were drilled in the past 44 months.

Response: Executive Summary is rewritten and number of wells is included

(37) Delete sentence – not true for an aquifer. Page 2, 2nd paragraph, last sentence - Delete the last portion of the last sentence and end with …dewatered volume).

Response: Executive Summary is rewritten.

(38) Additional information - Page 2, last paragraph - Point of issue is increased cost to maintain present supply

Response: Executive Summary is rewritten.

(39) "This is because at current aquifer water levels declines…" - Page 2, last paragraph, 5th sentence. And commas. - because, at current aquifer water levels, declines..

Response: Executive Summary is rewritten and change is made.

(40) "for natural gas production have increased" - Page 3, 1st paragraph, 1st sentence - Add comma …gas production, have

Response: Sentence is rewritten.

(41) Not clear- Page 3, last paragraph - What does "heightened interest" mean and how is a study area defined by it?

Response: Heightened interest is removed from the sentence.

(42) "..another round water regional" - Page 5, 1st paragraph, 2nd sentence Add "of" another round of water regional…

Response: Change is made.

(43) " …water users to assist in estimates of current… - Page 5, 2nd paragraph, 1st sentence - Change to: water users for assistance in estimating current…

Response: Sentence is rewritten.

(44) "..were completed and results included" - Page 5, 2nd paragraph, 3rd sentences - Add the word "are" included

Response: Sentence rewritten.

(45) … DrillingInfo.com and IHS Databases… - Page 6, 2nd paragraph, 4th Sentence - What does IHS stand for?

Response: IHS is IHS Energy, and their website is http://energy.ihs.com.

(46) Explanation needed - Page 6, last paragraph, 3rd sentence - How as the 60% groundwater estimate derived?

Response: Reference to 60% estimate is included.

(47) Extra period - Page 7, 2nd paragraph, 2nd sentence Remove extra period

Response: Period is removed.

(48) Furthermore, Barnett Shale use of groundwater - Page 7, 3rd paragraph, 3rd sentence - Barnett Shale cannot use groundwater. Change to producers or entities

Response: Sentence is rewritten.

(49) .. the Trinity or Woodbine are - Page 7, 3rd paragraph, 3rd sentence - Change "are" to "is"

Response: Change is made as suggested.

(50) ..50 gpm to may…..most western extents.. - Page 7, 3rd paragraph, 2nd to last sentence - Remove the word "to" and change to "extent"

Response: Sentence is rewritten.

(51) "…Barnett Shale completions.." .."Barnett Shale development.." - Page 7, last paragraph - "well" should be inserted after "shale"

Response: Change is made as suggested.

(52) Incomplete sentence - Page 12, last paragraph, 1st sentence - Incomplete sentence and where is Step 2?

Response: Sentence is rewritten.

(53) Rewrite - Page 15, 2nd paragraph, 5th sentence - Rewrite sentence. What is meant by "entities"?

Response: Sentence is rewritten.

(54) Redundancy; also see comment 5 - Page 28 , 2nd paragraph, 6th and 7th sentences - Rewrite or delete one sentence.

Response: Sentences are rewritten.

(55) Regional change in aquifer water budget - Page 28 and 30 - More explanation required than provided in four sentences; expressed view is too simplistic

Response: Sentences are rewritten.

(56) Poor leading sentence - Page 33, 1st paragraph, 1st sentence - Rewrite

Response: Sentence is rewritten.

(57) Rewrite - Page 33, 1st paragraph,, 2nd sentence - Rewrite.

Response: Sentence is rewritten.

(58) …this issue… - Page 33, 1st paragraph, last sentence - Spell out which issue

Response: Sentence is rewritten.

(59) Rewrite sentence - Page 34, 2nd to last sentence - Poor sentence structure.

Response: Sentence is rewritten.

(60) Misspelling - Page 36, 1st paragraph, 5th sentence - Should be severely

Response: Correction is made.

(61) ".. the need for more specific study is required.." - Page 36, 1st paragraph, last sentence - Remove "is required" from the sentence

Response: Sentence is rewritten.

(62) Rewrite - Page 36, 2nd paragraph, 2nd sentence - Should read …is projected in Dallas and Tarrant counties…. while decline of 50 feet or greater is projected in the Paluxy along, and east of, the I35 corridor.

Response: Sentence is rewritten.

(63) Rewrite - Page 36, 2nd paragraph, 3rd sentence - …less than 10 feet in the westernmost counties to up to….

Response: Sentence is rewritten.

(64) "case by case… - Page 36, 2nd paragraph, 7th sentence - …case-by-case….

Response: Correction is made.

(65) Rewrite - Page 36, 2nd paragraph, 9th sentence - Rewrite as follows: An additional site specific study is recommended for this area to gain…groundwater availability.

Response: Sentence is rewritten.

REVIEW COMMENTS BY TEXERRA

(66) Balance. It seems that our industry (Barnett shale gas producers) is too much the focus of the report, its projections and conclusions. We are a piece of the pie, but only a piece. I think as much attention should be devoted to fleshing out the projected water use of the other categories of water users as it is to our industry. All graphs, tables, etc. that convey Barnett gas producer's projected water use should therefore be compared against other water users. This would be fair to all parties.

Response: Figure 4 and Figure 5 have been added to the report and additional language included to provide a better characterization of the likely proportion of potential Barnett gas producer's groundwater use.

(67) Well restimulation. I believe that the anticipated water use for refracturing (restimulating) vertical wells is overestimated. In speaking with senior geologists of major players in the Barnett, it is not certain that refracturing vertical wells will happen widely and/or uniformly. Thus, I would be inclined to substantially adjust downward the projected water use attributed to vertical well refracturing. If I were to venture a guess, I would take it from 100% of vertical wells to something like 25%.

Response: It is assumed horizontal wells are not restimulated. It is assumed that 100%, 50%, and 0% of the vertical wells are restimulated in the high, medium, and low scenarios, respectively. Since only one recompletion per vertical well is assumed, the final results are largely not impacted. Except from 2007 to 2010 where most of the vertical wells are recompleted, recompletion water use adds up to less than 5% of total Barnett water use, which is itself a small fraction of total water use from all usages. Wording has been changed in Appendix 2.

(68) Economic imperative. In interpreting projected water use by Barnett gas producers, I think some allowance should be made (in words, if not in the numbers) that the imperative for economic efficiency imposes substantial pressure upon drillers to use water more efficiently (less water per well). Barnett drillers have an extremely strong vested interest in minimizing their fresh water use.

Response: Language added to indicate fresh water use is a cost to Barnett Shale development.

(69) Technology. The largest players in the Barnett shale are expending substantial funds to develop effective water treatment and reuse technologies. It appears very likely that one or more of these will bear fruit within the next few years. The

results could well translate into a significant reduction in the water use demands going forward. Further, any such technology developed and commercialized through these efforts will undoubtedly yield benefits far beyond their initial scope. Water reuse technology developed by our industry may well have substantial positive benefits for the State of Texas and other regions of the U.S. While such effects cannot yet be quantified, it would only be accurate to mention that the gas industry is working like few other industries to develop water reuse options.

Response: Language added to indicate water re-use research is actively being conducted.

(70) Water use estimate: I am inclined to recommend that Harden and Associates focus on the medium and high scenarios, rather than the low and high scenarios. My reasoning is that I think that BEG hit it right on the head ... that our thinking is that the medium scenario is the most probable. On a related note, and following my comment that other water users should receive equal attention, I think that it would be helpful if TWDB also considered a range of projected water uses for them as they did for our industry. I have a hunch that the projected water use of the other water users represents a low-side estimate, only.

Response: The medium and high Barnett Shale demand estimates prepared by the BEG were combined with low and high demand estimates prepared by FNI for other uses.

(71) I would augment Table 5 (page 17) to include a table (say, Table "5a") for the low water use projection, using the one given as, say, Table "5b" for the high water use projection. This would make this tabular data summary consistent with the subsequent graphs and text.

Response: New table added listing low use projections.

(72) Since Harden and Associates chose to use BEG's "medium" water use scenario for their "low" water use forecast ... I would be sure to reiterate (particularly in the executive summary) that and why this was done. If I were a betting man, I would project that BEG's medium scenario as the most probable. Therefore, taking this as the low-demand case I believe truly paints a worst case picture.

Response: The BEG low estimate is a reduction in current use. This coupled with the low estimate prepared by FNI would result in reductions in use over a large portion of the model. To provide a more worst case simulation, the BEG's medium demand scenario was coupled with FNI's low demand scenario. Since Barnett Shale water use is a small proportion of total groundwater use, this assumption has little effect on model results.

(73) I would give consideration to changing "gas exploration" to "gas production" or perhaps (if more accurately) "gas well development" throughout the document when referring to water use by our industry, as it is not in exploration that the lion's share of water us used.

Response: Text modified where appropriate.

(74) In the 1st paragraph on page 3 of the summary, I would consider changing "After a much longer time frame ..." to "Over a much longer time frame ...". However, this is just stylistic ... I do not intend to change the meaning of what was said

(which is clear as it is written).

Response: Text modified.

REVIEW COMMENTS BY BARNETT SHALE WATER MANAGEMENT AND CONSERVATION COMMITTEE

(75) In the mention of the natural gas industry water use data, I believe many of these numbers represent a water use plateau. Without explanation, the reader may get the mistaken impression that the water use plateau associated with Barnett Shale energy development in each county reaches far into the future. In actuality, the water use plateau for this activity is of a finite time duration. In other words, the water use patterns associated with the natural gas industry development of the Barnett Shale Region is temporal in nature. Industry water use in the report for each county is reported for a plateau period generally lasting 3 to 8 years. This means that the natural gas industry demand is actually lower in its impact than most other types of continuous, high-volume users (such as agriculture, residential/commercial, and non-natural-gas industry) that are projected to maintain their maximum use for many decades into the future. These thoughts, if captured in the Executive Summary, would more accurately describe the nature of natural gas industry water use in the Barnett Shale in the future and would be consistent with the more detailed projections of the rise and decline of well drilling/completion activity of NG energy development of the Barnett Shale counties.

Response: The Executive Summary is updated and includes a discussion of the temporal nature of the groundwater use associated with Barnett Shale development.

(76) The report does not provide a comparison of categories of water users. Appendix 1 does provide a listing of the main water users in each county, but only does this for six counties in the Barnett Shale Region.

Response: An updated Table 5 and new Figures 4 and 5 are added to the report.

(77) It is not clear how the rollups of water use were conducted that led to the percent breakdowns of Table 3 in the report. Table 3 cries out for references to the literature or to an appendix that contains the procedures and the assumptions that generated the percentages.

Response: An updated Table 5 and new Figures 4 and 5 are added to the report. Percentages are based on the amount of water uses for different water use categories presented in Appendix 3.

(78) Appendix 1. Updates were only obtained in the study area of 6 counties with 123 entities that were surveyed. Please describe the methodology used in the study. How were these entities selected? How do we know we have located all of the major industrial users? Why didn't we update the information in the other counties?

Response: The methodology of the study is described in Appendix 1. The six counties were selected because of known population growth that has occurred since the GAM was first developed. The entities included in the survey are the defined water user groups in the regional water plans. The term "industrial user" refers to a county-wide category of water use in the regional water plans, excluding oil and gas development. Information regarding specific industries included in that category is not readily available. Industrial demand projection was applied to the specific industrial users previously included in the GAM model.

(79) Appendix 2. Tables 1 & 2. Need explanation of the key. H =? V = ? etc.

Response: Key is added.

(80) Appendix 2. Figure 20. Please explain "Viola".

Response: Key is added.

(81) Appendix 3. The per capita use of water numbers for "Point Source" plus "Rural Domestic" are usually well below 100 gal/cap/day. This seems substantially lower than the national average for household water use and very much lower than household plus manufacturing plus power. The reason for this need to be explained. I based this calculation on the 2005 estimated census for each of the Texas counties listed in Table 3 comprising the Barnett Shale.

Response: It is unclear what assumptions are being communicated. County-wide population estimates cannot be compared to groundwater use only. Total water use, surface and groundwater must be compared total county census numbers. Rural communities in general have lower per capita water use than communities located in the urban areas.

(82) What was the basis for choosing the levels of well completion activity between the High and Low Groundwater Use Figures of Appendix 3? Sometimes the well activity jumps from zero to 200 to 400 wells per year in both cases ---- and sometimes the level of well development goes from zero to several hundred wells per year between the Low and the High Groundwater Use Scenarios. How were these levels arrived at? The years of well installation are compressed to about 3-8 years. How was this decision made?

Response: These are estimates derived through discussions with industry representatives. Further descriptions or work is beyond the scope of this study.

(83) Need more transparency for assumptions and data sources that were used to construct the report and the appendices. Methods for rollups need to be made more clear.

Response: Due to time and budget constraints, many assumptions were made to facilitate the demand estimates. Additional explanation is added to Appendix 2.

REVIEW COMMENTS BY TEXAS OIL AND GAS ASSOCIATION

(84) General Comments – This is not what we were expecting to see. Any time that a single water user or user group is singled out in a report it opens the door for criticism when the information from other user groups and the total use are not provided for a balanced perspective. We were expecting a more balanced review of all developments in the area including municipal growth. TXOGA believes it is imperative that the report and especially the Executive Summary do a much better job of presenting the full water demand for the area so that the Barnett Shale demand can be fairly compared against all water use in the area. The gas production in the area is making a substantial economic contribution to the area and the State of Texas and that combined with the amount of water being used is needed for the public and the legislature to fairly assess the benefits vs. the problems which the activity presents.

Response: The report is revised with an updated Executive Summary to better communicate the relative proportion of groundwater use associated with Barnett Shale development in relation to total groundwater use. Figure 4, Figure 5 and an updated Table 5 specifically show the proportion of Barnett Shale groundwater use compared to total groundwater use.

(85) The 2nd Paragraph of Executive Summary - Credits hydraulic fracturing as the main reason for the gas play in the Barnett Shale. Isn't the main reason the price of natural gas? Wouldn't the play have happened at today's prices even if the newer fracturing techniques been developed? TXOGA believes the 2nd paragraph of the EC and the discussion on Page 10 need to be totally rewritten to credit both price and advances in hydraulic fracturing technologies.

Response: Reference to gas prices driving development is added to the Executive Summary and elsewhere in the report.

(86) Page 11 Table 3 and Water Use Comparison for all User Groups - We are not sure how to read Table 3? Numbers are percents but don’t total 100% in all cells of table. Also, Table 3 should be accompanied by a graph for the total use by user group similar to the graphs in Appendix 3. Graphical representation of water use by all user groups must be included in the Executive Summary to immediately present the information to every reader who chooses only to read the Executive Summary. Also, appendix 3 should begin with a total graph for each scenario followed by the graphs for each county.

Response: An updated and corrected Table 5 is included in the report and with a more descriptive explanation of the data in the table.

(87) Page 2-2 of Appendix 2 - Acknowledgements should recognize the use of RRC data and any help provided by RRC staff.

Response: An acknowledgment section is added to the report.

REVIEW COMMENTS BY THE RAILROAD COMMISSION OF TEXAS

General Comments

(88) Please include more language on page 7 to justify your use of the medium BEG predictions as the "low" predictions for TWDB. It is not as clear as it should be and is important given the large difference in the high and low predictions and the assumptions that both BEG and TWDB have made in developing the predictions.

Response: Additional language is added.

(89) In Appendix 2, BEG indicates that it did not consider that the number of wells that could be drilled would be limited by rig availability. Rig availability will be a very important limiting factor when you consider BEG's estimate of an increase from 3000 wells to over 5000 wells per year.

Response: Rig availability is actually considered in the BEG predictions as explained in the “Operational Controls” section in page 2-48 and again in page 2-64 of Appendix 2. The methodology adopted by the BEG to estimate water use was, initially, to produce a “hypothetical maximum water use” that does not account for rig availability. This led to a large number of annual well completions (>5,000 /yr) that was capped by rig availability in the following sections.

(90) In Appendix 2, the tables are NOT adequately described and in many there is no indication of the units or whether the "water" is ground water, surface water or both. The result is that the tables are confusing and/or misleading in several instances. (I like the way TWDB draft explains its tables.)

Response: Additional details and units are added to Appendix 2 tables.

(91) Page 8, Figure 1: Should be "Annual gas well completions in Barnett Shale.

Response: Correction made.

(92) Page 11, Table 3: Indicate that this is groundwater (since the assumption is that 100% groundwater will be used in the High estimate) and that some surface water could be used.

Response: Correction made.

(93) Page 36, under "Conclusions," in the third sentence, delete the word "industrial" since water use associated with oil and gas activity is not considered "industrial" by TWDB 2006 Water Plan....

Response: Correction made.

Appendix 2

(94) Page 2-13, Figure ?????, Add explanation as to what the white/non-colored dots signify.

Response: Explanation added.

(95) Page 2-19, dots are too small to be able to distinguish vertical from horizontal from unknown well...

Response: The purpose of the multi-picture figure is to show the growth of the play through time. The changes through time of the blue and red patches (with no need to distinguish individual wells) convey the pertinent information.

(96) Page 2-22, Table 1, Not clear if this is groundwater use or groundwater AND surface water use...

Response: Explanation added.

(97) Page 2-25, 2nd paragraph, second sentence, typo - "his" to "this" ?? Also, according to what??

Response: "his" is actually IHS Energy, correction made.

(98) Page 2-26, Figure 9: There is no key to this figure. Table 3, Annual completions Statistics on Barnett Shale. Why are these numbers so different?

Response: Figure 9 - Arrows show the plotted parameter. Table 3 - BEG kept only those well completion numbers provided by vendors. RRC numbers were deleted. They were available from the RRC web site at <u>http://www.rrc.state.tx.us/divisions/og/wateruse_barnettshale.html</u> but no information was given on how the numbers were derived. Well completion figures from industry vendors and from RRC are not that different and the small discrepancy has no real impact on the water use projections. The table below displays the original table:

Year	DrillingInfo / IHS Energy				RRC		
	H	V	U	Total	H	V	Total
≤2000	14	703	42	759			
2001	22	424	27	473	0	368	368
2002	50	745	23	818	6	711	717
2003	195	685	38	918	331	532	863
2004	359	430	100	889	337	490	827
2005	679	242	122	1043	714	256	970
Total	1319	3229	352	4900			

(99) Page 2-31, 1st paragraph, third sentence: Injection of frac fluids IS NOT underground injection regulated under the federal Safe Drinking Water Act (or the RRC's delegated Underground Injection Control, (UIC) program), and, therefore, a well that is frac'd IS NOT a Class V or any other class of UIC well. My recommendation is to replace that sentence with the following: "Railroad Commission regulations prohibit pollution of surface and subsurface water during drilling, treating, producing, and plugging of oil and gas wells."

Response: Correction made.

(100) Page 2-34, Table 5, Parameters used in the water-use projection: "Groundwater Use Expressed as % of Total Water Use." Not clear if this is groundwater use as a % of total surface and groundwater use or ground water use for Barnett Shale expressed as a percent of total water use for all purposes...This table is one of the most important and is the most confusing.....

Response: Table 5 summarizes the report and the methodology, but it is not intended to be a stand-alone table. Explanations of the table data is detailed in the text.

(101) Page 2-47, second paragraph under "Well Spacing-Infilling": "If vertical density is suggested by the RRC regulations, currently no consistent one is enforced relative to horizontal wells." I have no idea what this sentence means, since the RRC has very specific field rules for spacing of gas wells in the Newark field.

Response: It is the BEG's understanding that these rules are primarily applicable to vertical wells (or rather to wellheads), but no rules exist governing multilateral horizontal wells where numerous laterals can originate from a single wellhead. Explanations added in text.

(102) Page 2-51, Table 6: This table is also very confusing and needs some brief explanation, rather than make the reader go back and search the text....

Response: Explanations added to the table.

(103) Page 2-59, Table 8: I am confused as to why the "prospectivity Factor A" is "1" for Dallas, Denton U and Tarrant H (will take time to drill in urban areas) and Tarrant VU (mostly done already where possible). Seems these could have a factor somewhat less than "1".

Response: As indicated in the table, there is a start date associated with each county polygon. A prospectivity factor/risk of 1 means that the whole county polygon has been (or will be) subject to gas production with a dense coverage of wells. In essence, historical data shows that the choice of a prospectivity factor of 1 in 1996 for Denton County was justified. The Denton rural county polygon is currently mostly developed. A prospectivity/risk factor of 1 means that what is left to develop will be done thoroughly.

(104) Page 2-60, "...This high water use is not sustainable because it corresponds to more than 5,000 annual well completions. In a previous section, we mentioned and assumed that more than 3,000 completions a year is unlikely." This indicates to me that the "High" scenario is completely unrealistic - a fact that should be reflected in the TWDB report (rather than be buried in BEG's Appendix).

Response: The text states that the high scenario is limited to 3,000 completions per year. The >5000 completions per year corresponds to "uncorrected" values that are then corrected by the limited availability of rigs. Some confusion may have arisen between "high water use" and "high scenario". The expression "high water use" was changed to "large water use" to address this. As explained in several instances in the text, the "high scenario" is a reasonably conservative estimate corresponding to high gas prices.

(105) Page 2-62 and on, Table 9: There are several lines in which there are two values when there should only be one - OR there should be some explanation.

Response: Explanation added.

(106) Page 2-66 and 2-67, Table 10: Same comment as #12 above. Also, need to indicate if the "corrected annual water use.." is groundwater or all sources.

Response: Explanation added.

(107) Page 2-68, 4th paragraph, 2nd sentence: "...it is assumed that all groundwater is accounted for nowhere else." This phrase does not make sense to me. Could it be clarified?

Response: Sentence clarified. "Galusky (2006) does not specify if the groundwater origin is from municipal sources, in which case it would have already been accounted for as municipal use. It is assumed that the latter never occurs.

(108) Page 2-69, Table 11, Need units.

Response: Legend corrected.

(109) Page 2-72: Include some of the explanation on water use limits and rig availability and competition in bulk of the report. These are important assumptions....

Response: Explanation provided previously regarding rig availability and water use assumptions.

REVIEW COMMENTS BY THE TEXAS WATER DEVELOPMENT BOARD

Report

(110) Page1, paragraph 4, line 4: "industrial" should be "mining". TWDB includes water use for oil and gas exploration and production under the "mining" category.

Response: Correction made.

(111) Page 2, paragraph 2, starting at line 6: "Dewatering of aquifers causes a decrease in natural discharge (evaporations, seeps and springs), a temporary increase in groundwater availability (equal to the dewatered volume) and increases groundwater available on a sustainable basis (equal to the decline in natural discharge)." The last item (Dewatering increase groundwater available on a sustainable basis) is not always true (for example, see Ogallala Aquifer). Need to also note that dewatering can also require pumps to be lowered and wells to be deepened.

Response: Paragraph removed from Executive Summary. In Results section, correction is made to indicate that not all dewatering causes an increase in sustainability. While this is true, aquifer sustainability is enhanced by a reduction in natural discharge, and natural discharge is reduced by aquifer dewatering.

(112) Page 2, paragraph 3, starting at line 2: Please remove discussion of sustainability of the pumping. Sustainability involves more than comparing pumping to recharge, and it is unclear from the model results, especially the high use estimate, that the pumping is sustainable. The other option is to run the model to steady state to see if the pumping, according to the models, is sustainable, given your caveats on local-scale issues.

Response: Executive Summary is rewritten.

(113) Page 8: Figure 1. Caption is incomplete. Please rewrite: Annual gas well (?) completions in the Barnett Shale.

Response: Correction made.

(114) As indicated earlier, the predictive pumpage dataset contained in the original Trinity/Woodbine GAM was based on [2001 regional water plan] projected demands.

Response: Correction made.

(115) Page 11: Table 3 footnote states "Point source represents municipal, irrigation, industrial other than Barnett Shale, mining, and power generation uses." This statement deviates from GAM pumpage instructions, where 'non-point' encompasses irrigation, livestock, and rural domestic and 'point' source covered city municipal, industrial /manufacturing, mining, and power electric. This suggests that well locations for all irrigation and livestock wells were assigned as point sources in the model domain? If this is so, please clarify and possibly re-word the footnote.

Response: Footnote is corrected. Standard GAM pumpage methodology was used during this study.

(116) Page 11, Table 3: Please explain why the numbers do not add up to 100 percent. Several Denton (2000–2005) and Parker (2006–2010) have entries that add up to greater than 100 percent. Parker County shows) percent Barnett Shale use between 2000 and 2005, which is surprising since there was groundwater use during this period for this use in this county. Please review the numbers in this table.

Response: Table is corrected.

(117) General comment: Please only refer to “GAM” instead of “GAM model”. “GAM model” literally translates to “groundwater availability model model”.

Response: Text is corrected.

(118) Page 15, paragraph 3, line 3: Please change “availability” to “volume” or other appropriate word. “Availability” has special meaning at TWDB that includes policy decisions.

Response: Availability changed to well yields.

(119) Page 22, Figure 10: If possible and practical, please include 10, 20, 30, and 40 foot contours. It is difficult to discern water levels declines in the western part of the aquifer.

Response: Additional contour intervals added to appropriate figures.

(120) Figure 7 and 11: Comment: Concerned that people in Fannin, Lamar, and surrounding counties are going to be unduly alarmed by model results for the Woodbine.

Response: Pumpage input has been corrected in the Woodbine.

(121) Page 28, paragraph 3, line 4: Please change “availability” to “volume”, “yield”, or other appropriate word. “Availability” has special meaning at TWDB that includes policy decisions.

Response: Report section modified.

(122) Page 28: “Dewatering of water table storage can reduce natural discharge, provide temporary availability and increase long term sustainable production rates.” This sentence may appear contradictory and needs to be re-worded.

Response: Sentence is modified.

(123) Page 29: Figure 16: Please provide a more descriptive figure caption.

Response: New caption provided.

(124) Page 30: See comment for Page 2, paragraph 3, starting at line 2.

Response: Report section is modified.

(125) Page 33, paragraph 1, starting at line 2: See comment for Page 2, paragraph 3, starting at line 2.

Response: Report section is modified.

(126) Page 33, paragraph 1, line 12: “As such, this issue is essentially irrelevant over the time period of this study.” However, this issue may affect the sustainability of the pumping.

Response: Sentence is modified.

(127) Page 37, paragraph 1, line 1: Please change “piezometric head levels” to “water levels” to be more readable for non-technical readers.

Response: Change is made.

(128) Page 36: “The GAM model successfully simulates both the low and high demand scenarios.” This sentence is not necessary. Suggest deleting sentence.

Response: Sentence is modified.

(129) Page 37, paragraph 1, line 3: Please change “piezometric head levels” to “water levels” to be more readable for non-technical readers.

Response: Sentence is modified.

(130) In the acknowledgements section of the Executive Summary, "Texas Oil and Gas Industry" should be reported as "Texas Oil and Gas Association".

Response: Change is made.

(131) Page 8, Table 1: Please insert the reference for the source data at the bottom of table 1: (Data from Craig Caldwell, Water Uses Section, Texas Water Development Board, December 22, 2006).

Response: Reference inserted.

(132) Page 9, Table 2: Please replace year 2000 (column 2) pumpage data in table 2 with county total pumpage (column 4) from table 1. Please replace the footnote at the bottom of the table from “2007 Regional Water Use Plan” to 2007 State Water Plan.

Response: Changes made.

(133) Page 10, paragraph 4. Please correct the reference to the tables. Reference should be to tables 3 and 4 not 1 and 2.

Response: Sentence is modified.

(134) Page 11, Tables 3 and 4. Please correct the footnotes at the bottom of table 3 and 4. Footnote refers to Table 1 and 2.

Response: Footnotes corrected.

(135) Page 12: Please change the caption from “Barnett Shale Industrial Use” to “Barnett Shale Water Use”.

Response: Change is made.

(136) Page 13, paragraph 3; and page 16, para 1 There appears to be some contradiction between statements on page 13 and 16: “:…the BEG medium estimate was combined with the FNI low estimate..” and “A low estimate of use was developed by combining the low use estimates for rural domestic/municipal uses with the

low use estimates for the Barnett Shale”.

Response: Sentences have been modified and rewritten.

(137) Page 16, paragraph 2: Please correct reference to table 3 to table 5.

Response: Change is made.

(138) Page 24, line 1: Report states “Figures 14 through 17 show the historical simulated drawdown in the Trinity and Woodbine up to year 2000”. Please mention the time period for the historical drawdown in the text and also include the time period in figure captions.

Response: Text and captions modified.

(139) Page 37, paragraph 3: Please complete the citation from “Bene et al., “ to Bene et al., 2004”.

Response: Change is made.

(140) Page 39, figure 18: Please consider rewording caption from “ New Water Table Depletion Areas in High Demand Estimate – Hosston” to “Location of water table depletion areas under high demand estimate – Hosston Aquifer”.

Response: The areas shown in the figure do not represent all of the regions that are projected to undergo water table depletion during 25 years of high demand estimate pumpage. Rather, the areas depicted represent regions where initial (year 2000) water levels were above the top of the Hosston Formation, but were subsequently reduced to levels below the top of the aquifer during the simulated 25-year high demand estimate. In other words, these are areas of the Hosston that converted from artesian (confined) conditions to water table (unconfined) conditions during the simulation. Figure caption modified to “Location of New Water Table Depletion Areas in High Demand Estimate-Hosston”

(141) Page 20, paragraph 1, bullet 2: Please explain clearly what “single values of pumpage rates” are or use better terms.

Response: Bullet text modified.

(142) Page 23, paragraph 2: The following statements “ In both the low and high demand scenario there are pressure reductions in the Woodbine aquifer in Lamar County. This is direct results of assumptions regarding category of use between rural domestic and irrigation” has not been changed from the previous draft although the pumpage has been adjusted that now reflects a lowering of the drawdown from 250 feet in the draft (Figure 7) to 50 feet in the current version of the report (Figure 9).

Response: Pumpage inputs in Fannin and Lamar Counties has been modified from the original GAM inputs to better isolate and identify the effects of pumpage specific to this study.

(143) Please correct McCleannan to McLeannan county all through the report.

Response: Correction is made.

(144) Please ensure that all figure captions are correct and completely illustrate the figure content. For example, some figure captions do not clearly state the time period for drawdown or projected water level changes. Also, legend in some figures have been cutoff (fig 8...."contour interval varies ???...).

Response: Figure captions modified to include the time period of the simulation. In some instances, an irregular contour interval was chosen to enhance the readability of the figure.

General Comments

(145) I was hoping to see water level decline maps divided out for (1) Barnett Shale related pumping and (2) the rest of the pumping.

Response: This is a complicated issue because multiple maps could be made for a variety of different time periods. The easiest way to get a feel for the magnitude of the effect of a particular water use is to look closely at Table 5, Figure 4, Figure 5, and particular counties in Appendix 3. Effects on aquifer water levels are, in general, proportional to the amount of demand for a particular use.

(146) In the updated groundwater use estimates section, need to present the Barnett Shale use and other use in the same manner. In other words, please add a plot similar to Figure 2 for other use and please add a table similar to Table 1 for the Barnett Shale groundwater use.

Response: Table 5 is updated to show percentage for all use groups by county for the high demand estimate and Figure 4 and Figure 5 show estimated use totals by group within the confines of the study area.

Appendix 1

(147) Page 1-1, paragraph 1: The report states that “ The original Trinity/Woodbine Groundwater Availability Model (GAM) was based on 1999 water usage”. Please consider re-writing it to “The original groundwater availability model (GAM) developed for the northern Trinity Aquifer was calibrated to water levels from 1980 to 1999 based on groundwater pumping estimates for the same period.”

Response: Text modified as suggested.

(148) Page 1-3, paragraph 1: A range of demands have been discussed for different entities in Denton, Hood, Johnson, Parker, Tarrant, and Wise counties and the data presented in Tables 2 to 7. Although the basis for this estimation has been presented, the rationale used for low and high demand scenarios have not been explained. Please consider providing some explanation on the necessary conditions/strategies that may lead to the low and high demands.

Response: Additional description is added to further explain the low and high projections.

(149) Page 1-1: It will also be useful to cite references for the various source datasets used to develop the groundwater demand trends. For example, historical population data was collected from the Texas State Data Center, the U.S. Census, and the North Central Texas Council of Governments. Please consider citing references to sources of these data.

Response: Reference citations are added.

(150) Please consider including a short section on conclusion. Currently, there is no conclusion section in the report. A conclusion section can capture some of the salient information on the proposed groundwater pumping trends in the studied counties.

Response: Conclusion section is added.

(151) Appendix 1, Page 1-5: Please correct reference in table caption to TDLR instead of TWDB " ... by well drillers to the Texas Department of Licensing and Regulation".

Response: Correction is made.

Appendix 2

(152) Page i, Paragraph 1: Please check whether the total water use value of 8,000 ac-ft reported for 2005 is accurate in light of the number of wells and water use per well. It was reported that more than 5,600 wells were producing gas from the Barnett Shale and each vertical well uses 1.2 million gallons and each horizontal well uses 3.0 to 3.5 million gallons.

Response: There are about 1,000 completions per year. The 5,600 well total includes wells stimulated in the previous years, and 8,000 ac-ft agrees fairly well with the approximate 10,000 ac-ft estimate provided by the RRC on their web page for 2005.

(153) Pages 8 and 9: Figures 4 and 5 are not legible particularly the color zones and the legend. Please consider presenting clearer figures.

Response: Those maps were scanned from larger paper copies. The version presented in the final report has a clearer legend.

(154) Survey data incorporated from Galuskey (2006) has been frequently discussed in the text. Please consider including the complete survey results from Galuskey (2006) in a table or in an appendix and make cross-reference to it if there is more information available than what was presented in Table 9.

Response: It is anticipated Pete Galusky will publish the final results of his survey in January 2007. The BEG report used Mr. Galusky's industry survey data as the information became available. However, because of the timing of the survey and the schedule requirements for this report, only partial and preliminary data were used.

(155) Page 7, Figure 3 legend covers Montague County which is discussed in the text (page 5) relative to this figure. Please consider adjusting the location of the legend so the points made in the text are clearly legible in the figure.

Response: Correction is made.

(156) Page 44. The report states the high scenario yields high water use, for example >50 AF in 2016. Please consider correcting to >50,000 AF in 2016.

Response: Correction is made.

(157) Page 47. The report states that an average water use of 1.3 MGal/vertical well and 3.6 MGal/horizontal well is assumed, however on page 20 the report states average water use of 1.2 MGal/vertical well and 2.65 MGal/horizontal well. Please consider clarifying which value was considered in the final estimation of water use and adjust the text accordingly to maintain consistency.

Response: 1.3 MGal has been changed to 1.2 MGal for vertical wells (1.2 was used in the calculations). Neither value is used for horizontal well projections. They are done using water use per linear distance of lateral not the water use per well because there is too much variability. The 3.6 MGal is used to compute the number of annual completions and comes from preliminary results of Pete Galusky's survey of the industry trends over the next few years. The 2.65 MGal includes historical data, but it seems that laterals are currently getting longer translating into a larger water use per well. The 3.6 MGal value is subsequently applied to all future wells.

(158) Page 52, Figure 30: Please consider describing the differences between grey and darker shaded squares in the legend. If there is no difference, please make the squares the same levels of grey.

Response: Change is made.

Appendix 3

(159) Please include two tables showing total groundwater use by year (1980 to 2025) and by county for high and low water use estimate scenarios matching the histograms.

Response: New tables inserted.