WELL FIELD EVALUATION

CITY OF ALPINE, TEXAS

PHASE II REPORT

November 2007

LBG-GUYTON ASSOCIATES

Professional Groundwater and Environmental Engineering Services

A Division of Leggette, Brashears & Graham, Inc.

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1.0 INTRODUCTION

Groundwater pumped from igneous (volcanic) rock formations is the sole source of water supply for the City of Alpine. Beginning in the 1920s, public supply wells have been drilled to extract groundwater from the Igneous aquifer in various areas in and around the City. As the City's need for water continues to evolve, increased pressure will be placed on the aquifer system. The proper management (schedule and location of pumping withdrawals) of the water resource is important in regards to maintaining a sustainable water supply.

To help evaluate the water resources for the City of Alpine, the current study focused on the following tasks.

1) Staff for the City of Alpine was consulted in order to review and update the current well conditions and current municipal well-field operations and potential expansion. LBG-Guyton Associates extends appreciation to Mrs. Cynthia Williams-Hollander, Director of Utilities and Mr. Jesus Garcia, City Manager for the City of Alpine for their assistance. Sul Ross State University staff were consulted on recent aquifer characterization academic studies and water-level monitoring. We thank Dr. Kevin Urbanczyk and Ms. Adelina Beall of Sul Ross State University for their assistance with water-level data and other hydrogeologic information.

2) A GIS database of current well locations and their associated well hydrological information, including well construction, pumping history, and water-level measurements was compiled. Evaluation of the aquifer characteristics at each well field was made. Adjacent private well development stress on each well field was surmised.

3) An aquifer simulation model was developed to predict future well field conditions utilizing a numerical groundwater flow model. Well data, pumping history, water-level measurements, and aquifer hydrologic characteristics were utilized in the construction of the model. Using the model, the potential for increasing production from the existing well fields was made. The model was also used to determine sustainable pumping rates for each well field and predict future water-level impacts resulting from various pumping scenarios. These predictive runs thus provide the basis for establishing best management decisions pertaining to future groundwater withdrawal from each well field.

4) Recommendations on locations for possible future wells sites are made. Hypothetical predictive simulations were made using a potential well site to supplement and spread out future demand from the City of Alpine.

2.0 PREVIOUS WORK

2.1 Previous Reports on Alpine Well Fields

Previous groundwater supply reports prepared by LBG-Guyton Associates for the City of Alpine include:

December 1998 – *Preliminary Evaluation of Potential Ground-Water Supply Development for the City of Alpine, Texas* – This first report provides a historical account of Alpine's public supply well development, a description of the volcanic rock aquifer from which groundwater is being withdrawn, and recommends areas for future well placement.

May 1999 – *Lewis No. 1 Test Hole Evaluation – Alpine, Texas* – Based on recommendations in the first report, the Lewis No. 1 test hole was drilled at a location near the center of the Sunny Glen well field. This report provides a description of the drilling process and the results of an aquifer pumping test conducted on the test hole.

August 1999 – Sunny Glen Well Field Evaluation – Alpine, Texas – This report describes the physical condition of each well in the Sunny Glen well field, discusses water-level change over time, provides the results of three pumping tests conducted on wells in the field, and provides recommendations for future well field management and individual well rehabilitation.

November 2005 – Well Conditions and Recommendations for Sunny Glen and In-Town Fields – Alpine, Texas – This report provides the results of the first phase of the current project. The report gives a detailed description of the physical condition of all public supply wells except for those in the Musquiz well field and the Meriwether wells. Rehabilitation recommendations are also provided for each well.

2.2 Historical Perspective

The following short account of the historical development of public supply wells in Alpine is reprinted from the first groundwater report prepared by LBG-Guyton Associates in 1998.

> *Alpine's water-supply wells are located in three general areas, inner city, Sunny Glen, and Musquiz Canyon. The first wells to supply water for the city were drilled in the 1920s along the flanks of Alpine Hill and in the vicinity of the railroad. Other wells in the city were added to the supply system in the late 1940s and early 1950s. By the mid 1950s, the inner city wells could no longer provide the peak demands during the ongoing drought period; therefore, additional water was secured from wells located west of town in the Sunny Glen area. Additional wells were added to the Sunny Glen field in the 1960s and 1970s, and for a while, water was obtained from two wells on the Meriwether ranch. In the early 1970s, exploration for water to meet increasing demands was in the Musquiz Canyon 11 miles northwest of town. A sufficient water source was located and four wells were completed. Two additional wells were added to the field in the 1980s.*

In 1999, the Lewis No.1 test well was drilled to a depth of 904 feet near the center of the Sunny Glen well field. Although testing suggested favorable hydrologic conditions, the test hole has not been converted into a production well.

3.0 WELLS AND WELL FIELDS

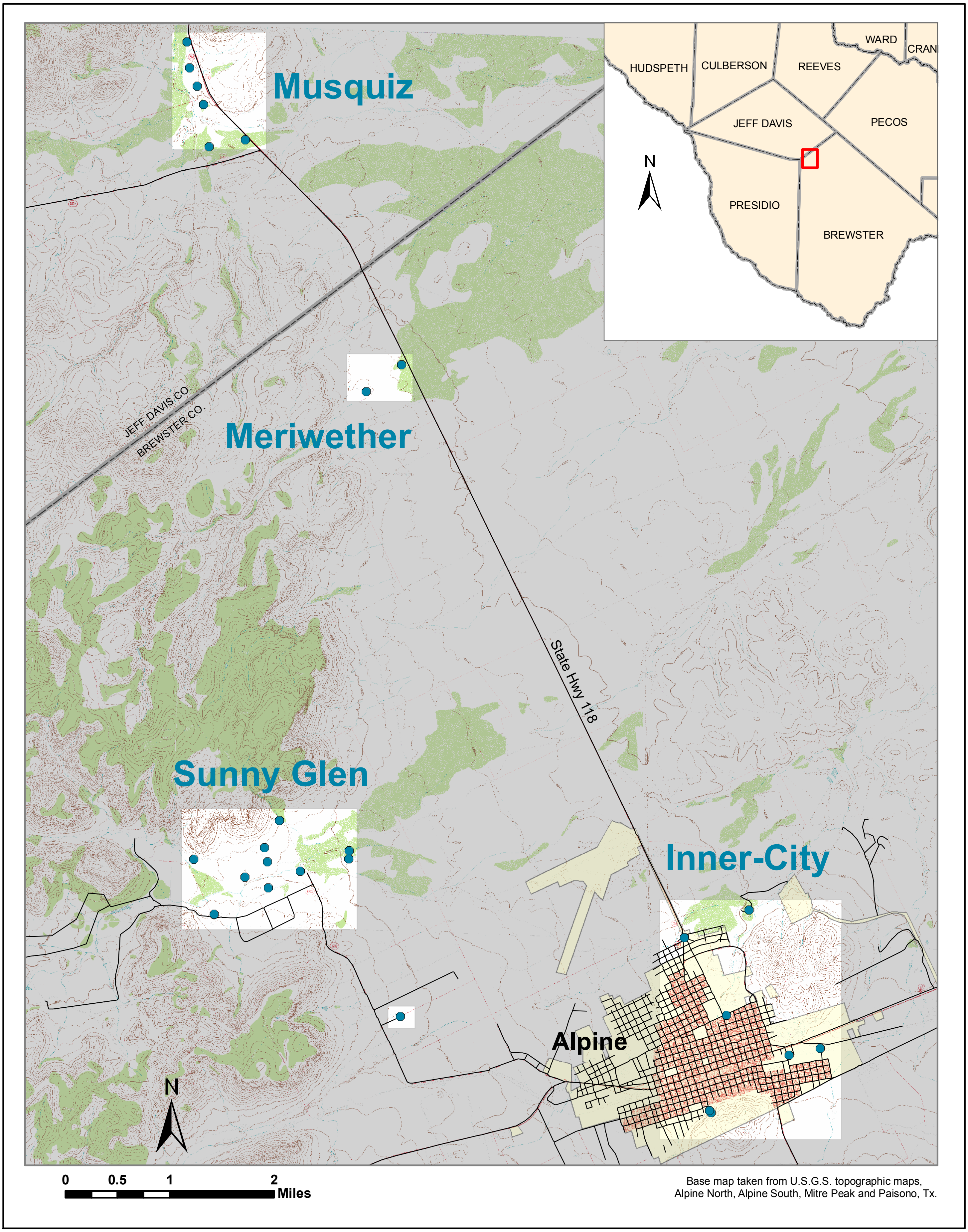
3.1 Location

Twenty-three wells of the City's inventory of 26 active (Table 3-1), non-drinking water, and test wells are grouped into three hydrologically separate areas or well fields; Sunny Glen, Musquiz, and Inner City (Figure 3-1). Figures 3-2, 3-3, and 3-4 show more detailed locations of each well within the three well fields. Three wells (Meriwether #1 and #2, and Terry #2) are located away from the designated well field boundaries. Table 3-1 provides the most current information on each well including latitude/longitude, date drilled, depth, casing construction details and pump size and settings. Some information was determined from original drilling reports and from TWDB and USGS well inventory records. For the Sunny Glen and Inner City wells, the depth and casing information was re-examined and verified during the 2005 well evaluation project. The 2005 report also provides schematics of each surveyed well and a discussion pertaining to current physical condition and recommended action for each well.

TABLE 3-1 CITY OF ALPINE WELL DATA

Well Name	State Well Numbers	Latitude (GPS) (* topo)	Longitude (GPS) (*topo)	Date Drilled	Driller	Surface Elevation (ft.)	Total Depth (ft.)	Casing Size and Depth	Slotted and Open Interval Depths (ft.)	Pump Size (as of 8-05)	Pump Setting Depth (ft.) (as of 8-05)	Static Water Level (ft. below land surface)
Sunny Glen Wells												
Roberts No.1	52-35-704	30-23-14	103-43-50	Apr-57	Paul Gooden	4621	451 originally. 435 after cleaning in 1998	Original 13" 0-145' removed in 1957. Original 10-3/4" steel 0 - 370'. 6" pvc 0 - 138' added in 1997.	Slotting 139 - 360 Open hole 370 - 434	5 hp	320	101.9 (9-22-07)
Roberts No. 2	52-35-705	30-22-50	103-44-05	May-57	Paul Gooden	4644	394 originally. Deepened to 800 Dec. 1998; Well bridged at 515 (8-16-05.)	Original 13" 0 - 129'. Perf. 79' - 129' removed in 1957. 10-3/4" steel 0 - '352'	Slotted 22 - 352. 10" open-hole 352 - 400. 6" open hole 400 - 800.	No pump		199 (8-16-05)
Roberts No. 3	52-35-706	30-22-55	103-44-19	Jul-57	Paul Gooden	4658	485 (377 TCEQ)	13-3/8" steel 0 - 144' 10-3/4" steel 0 - 377'	Slotted 94- 144 in 13-3/8". 77 - 377 in 10-3/4". Open hole 377 - 485.	50 hp	378	248.1 (9-22-07)
Roberts No. 4	52-35-702	30-22-36	103-44-36	Jul-71	M.B. Virdell	4708	798 Partial bridge at 711.	12" steel 0' - 83'	Open hole 83 - 798. Possible leak at 59.	20 hp	504	289.2 (9-22-07)
Roberts No. 5	52-35-703	30-23-03	103-44-49	May-77	Roy H. Kent Jr. Big "3" Machine and Supply	4700	905 (850 TCEQ)	10-3/4" steel 0' - 850'	.25" slots 83 - 850. 15" open hole 850 - 905.	30 hp	567	296.7 (5-24-07)
Daugherty	52-35-710	30-23-06	103-43-19	Jul-65	Continental Geophysics Co.	4580	345 Measured at 331 on 5-25-70	8-5/8" steel 0' - 190'	14" open hole 190 - 345. Max camera depth 323 (8/17/05)	60 hp	252	127.2 (9-22-07)
Cartwright	52-35-709	30-23-10	103-43-19	Mar-58	Nolland Schuler	4575	400	16" steel 0 -? 12" steel 0 - 320' 10" steel 320' - 400'	3/8" slotted 166 - 400	15 hp	350	83.73 (9-22-07)
Gardner	52-35-708	30-23-24	103-44-00	Jan-59	Charles Watson; deepened by W. Skinner	4678	567	7" steel 0 - 204'	Slotted 95 - 204; 6-5/8" open hole 204 - 567. Hole in csg at 35.	25 hp	357	245.3 (9-22-07)
Miles (NDW)	52-35-707	30-23-03	103-44-06	1925	Herbert Pruett	4638	212. Originally reported as 240.	6" steel 0 - ?	Open hole ? - 212	No pump		187.86 (3-15-00)
Lewis (*Test Well*)	52-35-716	30-23-10	103-44-08	Mar-99	W. Skinner	4652	904 originally; Bridged at 502 and 625 (8/16/05)	8" steel 0 - 20'	Open hole 20 - total depth	No pump		245 (8-16-05)

Well Name	State Well Numbers	Latitude (GPS) (* topo)	Longitude (GPS) (*topo)	Date Drilled	Driller	Surface Elevation (ft.)	Total Depth (ft.)	Casing Size and Depth	Slotted and Open Interval Depths (ft.)	Pump Size (as of 8-05)	Pump Setting Depth (ft.) (as of 8-05)	Static Water Level (ft. below land surface)
Inner-City Wells												
East Well	52-43-308	30-21-39	103-38-42	1927	Charles Watson	4495	750 (580 TWDB)	12.5" steel sleeve, 10" steel casing 0 - 443'	Slotted 112 - 750 ?	7.5 hp	357	30 (1-1-06)
Railroad	52-43-307	30-21-35	103-39-00	1923	Emmett Harrel	4510	325 (320 TWDB) (313 TCEQ)	8" steel 0 - 325'	Slotted 92 - 110 178 - 195 226 - 244	10 hp	147	25 (12-1-05)
Upper A Hill	52-43-311	30-21-05	103-39-44	1929		4656	700	10" steel 0 - 700'	Slotted 185 - 700 (every other joint slotted)	20 hp	250	120 (12-1-05)
Lower A Hill	52-43-310	30-21-06	103-39-45	May-24	Anton Hess	4630	443 (385 TCEQ)	10" steel 0 - 443'	Slotted 178 - 443	20 hp	340	202 (9-22-07)
Golf Course (NDW)	52-43-312	30-21-54*	103-39-37*	Dec-50	Paul Gooden	4450	350					60.94 (3-12-55)
Parker (NDW)	52-35-801	30-22-32*	103-40-03*	Feb-49	Charles Watson	4447	300	12" 0-57' 10" 57 - 138' 8" 138 - 300'				191.5 (2-14-55)
Kokernot (NDW)	52-35-905	30-22-47	103-39-26	Jul-54	Paul Gooden	4395	255	12" steel 0' - ? 8-7/8" steel 0 - 255	Slotted 32 - 255	No pump		13 (8-18-05)
Musquiz Wells												
Musquiz No. 6	52-35-104	30-29-21*	103-44-58*	1972 ?	M. Virdell ?	4390	540 (536 TCEQ)	8-5/8" steel 0 - 530'	Slotted 100 - 526			124 (12-28-06)
Musquiz No. 7	52-34-301	30-29-30*	103-45-02*	Nov-71	M. Virdell	4415	409	14" steel 0 - 66' 10" steel 66 - 409'	Slotted 66 - 409			138 (12-28-06)
Musquiz No. 8	52-35-106	30-29-04*	103-44-33*	1971	M. Virdell	4375	500	14" steel 0 - 66' 12-3/4" steel 66 - 355'	Slotted 100 - 120; 145 - 206; 235 - 295; 345 - 355			125 (12-28-06)
Musquiz No. 9	52-35-107	30-29-00*	103-44-54*	Nov-71	M. Virdell	4395	500 (482 TCEQ)	14" steel 0 - 66' 10-3/4" steel 66 - 335'	Slotted 66 - 335			115 (12-28-06)
Musquiz No. 10	52-34-302	30-29-39*	103-45-07*	Nov-84	Spruill Bros.	4410	450	16" steel 0 - 50' 10-/3/4" steel 0 - 400'	Slotted 150 - 220; 300 - 380			159 (10-15-06)
Musquiz No. 11	52-34-303	30-29-52*	103-45-09*	Nov-84	Spruill Bros.	4410	400	16" steel 0 - 54' 10-/3/4" steel 0 - 400'	Slotted 160 - 220; 280 - 380			151.88 (1-31-07)
Other Wells												
Meriwether No. 1 (NDW)	52-35-402	30-27-14*	103-42-58*	Jan-61 7/1/1966	R.G. Dickson Frank Galyon	4435	435 485	12" 0 - ? 8" 0 - 361	Slotted 120 - 361 Open hole 361 - 485			100 (7-18-66)
Meriwether No. 2 (NDW)	52-35-401	30-27-00*	103-43-18*	Feb-67	Frank Galyon	4483	410 originally; 372 measured in 1970	12.5" 0 - 16.5' 10-3/4" 0 - 167' 8-5/8" 0 - 274'	Slotted 0 - 274 Open hole 274 - 410			90.93 (8-19-99)
Terry No. 2	52-43-110	30-21-48*	103-42-46*	Jul-54	Nolland Schuler	4628	540	8-5/8 0-540'				202 (9-22-07)



CITY OF ALPINE WELL FIELDS

FIGURE 3-1

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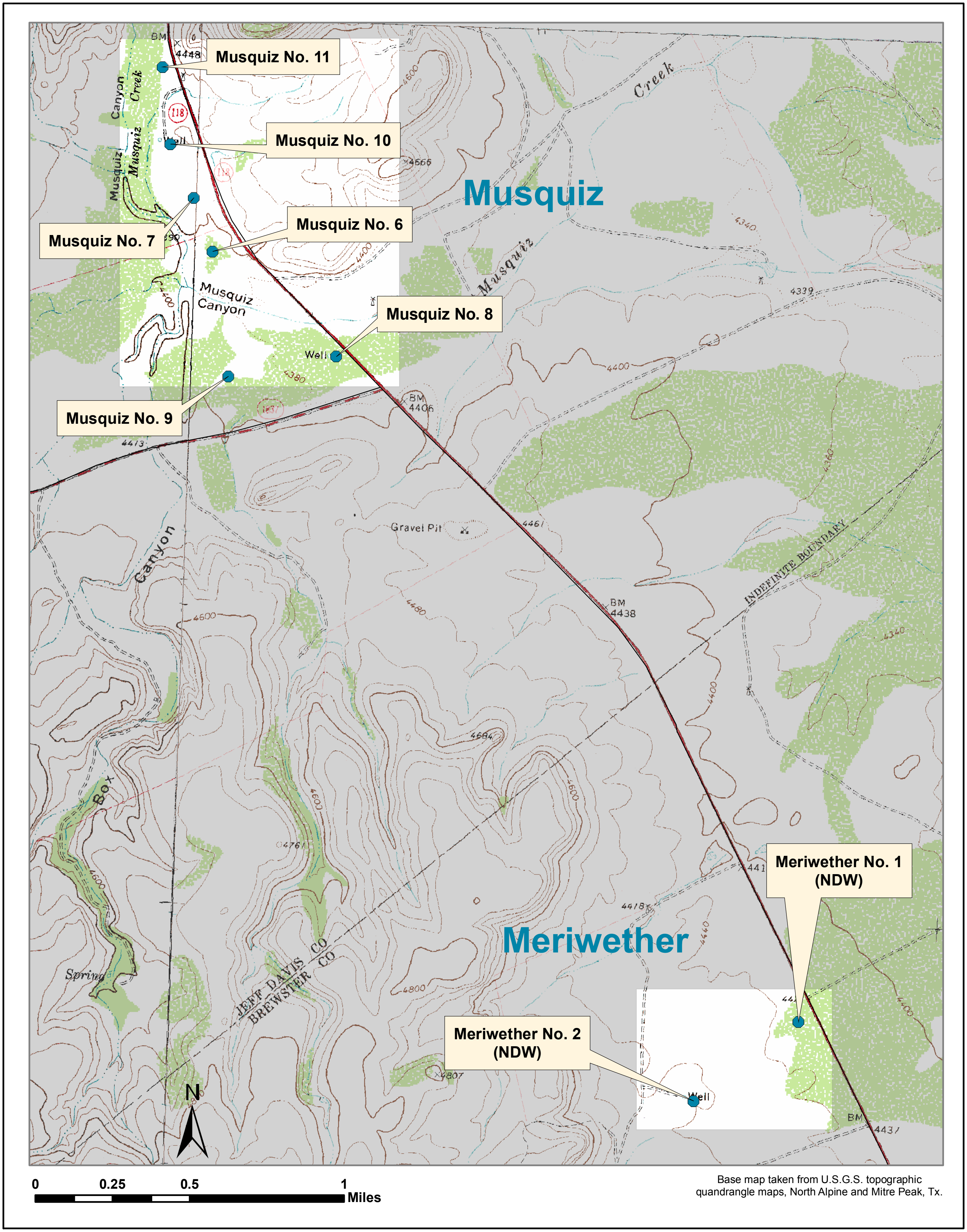
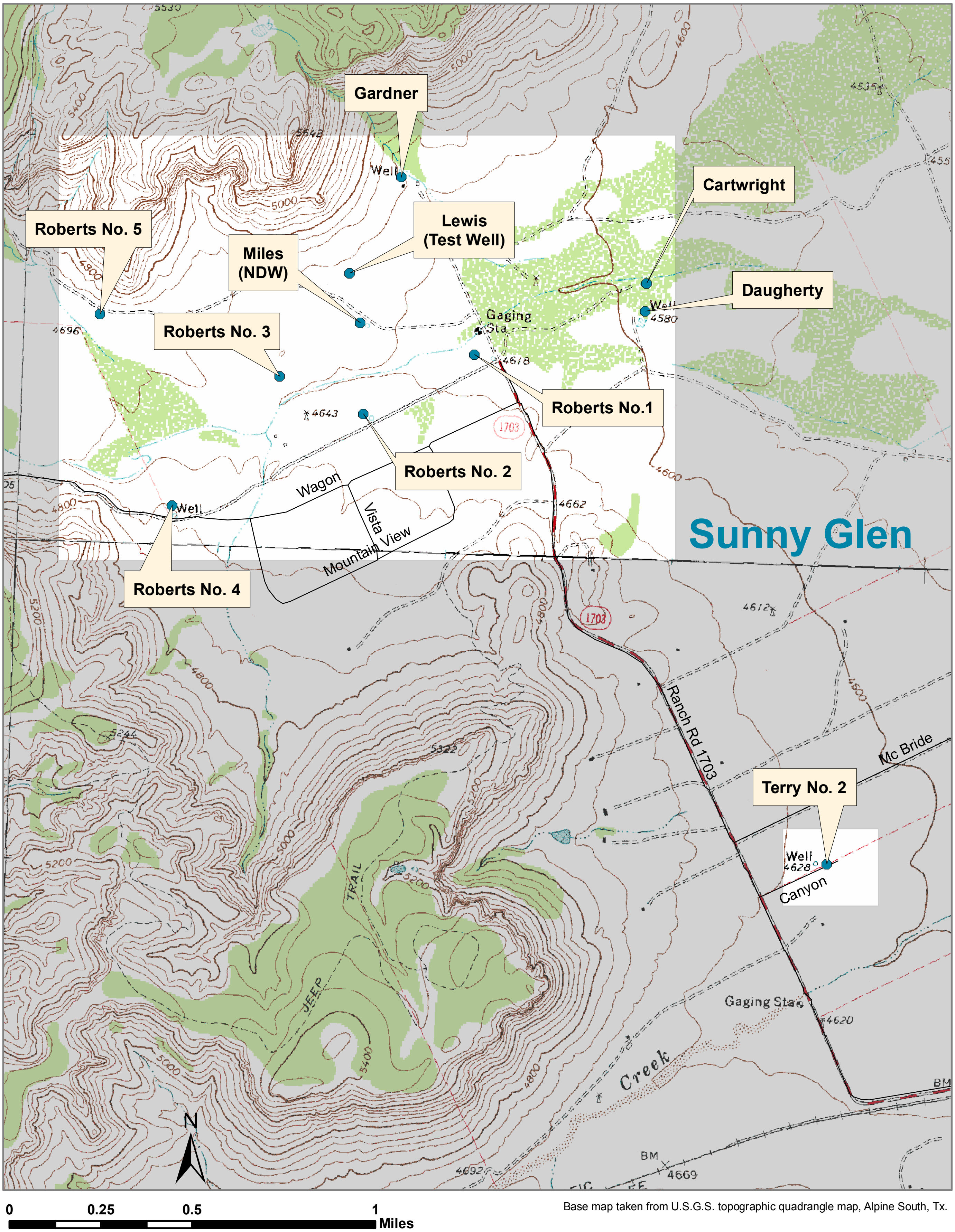
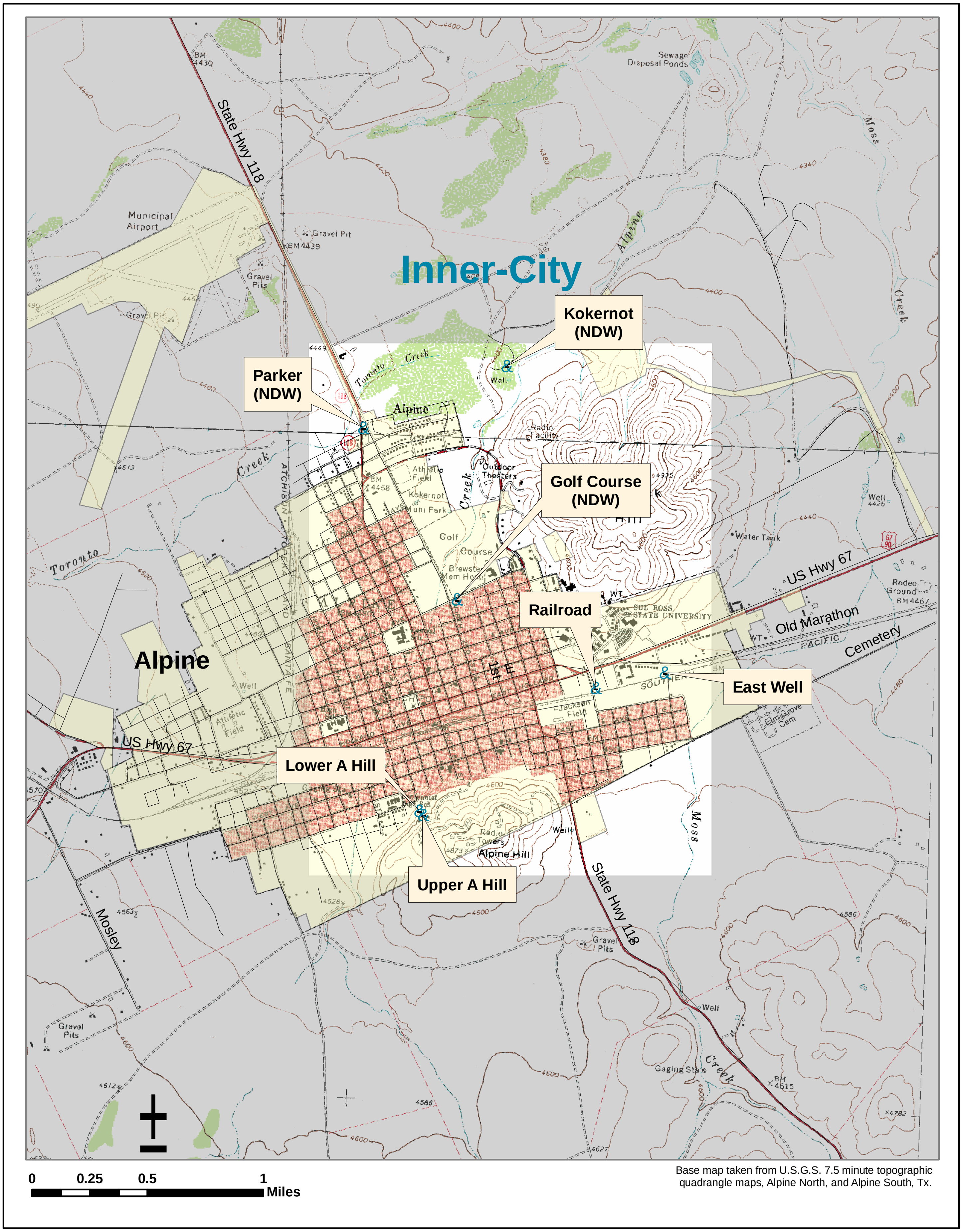


MUSQUIZ AND MERIWETHER WELL FIELDS **FIGURE 3-2**



Base map taken from U.S.G.S. topographic quadrangle map, Alpine South, Tx.

SUNNY GLEN WELL FIELD **FIGURE 3-3**



INNER-CITY WELL FIELD

FIGURE 3-4

3.2 Historical Water Levels

The historical water use by the City of Alpine from the igneous aquifer dates back prior to the 1930s. During this time the City of Alpine began drilling wells near the City for municipal water use. During the 1950s, wells were drilled in the Sunny Glen area, which added to the City's water supply. Finally, as the City grew beyond the means of both of these water resources, wells were drilled and produced in the Musquiz well field in Jeff Davis County.

The availability of historical water-level measurements varies from well to well. We have assimilated all the relevant water-level measurements that were sufficiently documented. Appendix A contains the hydrographs for all wells over the entire period of record and gives a good representation of the water levels since each well was constructed. The depth and construction of each well are factors in determining the water-level response through time. A shallow well that is located far from pumping wells may not show the same trend as actively pumped wells in a well field. Each of the relevant hydrographs shown in Appendix A was used to help calibrate the groundwater flow model.

Hydrographs shown in Appendix B are for the recent period of record from the year 2005 through date of data acquisition in 2007. These graphs show more recent trends in water levels for the wells. Any data that is relevant to wells within the study area are included in these appendices. The figures sorted as "Other Wells" are wells not in the Inner City, Sunny Glen, or Musquiz well fields but are included because of their proximity to each of these fields and are useful in model calibration.

In general, the Sunny Glen wells have experienced some water-level decline since each well's initial construction, most in the 1950s, up until about 1997. The water levels in some wells have dropped as much as 300 feet from the initial measurements, but then have seen a flattening or slight rise (rebound) of as much as 50 to 100 feet since 1997 (Figures A.1-A.10). This is likely due to a slight decrease in pumping in the vicinity of the well field since 1997. From 2005 to 2007, water levels are fairly consistent with only a slight rise in water level (Figures B.1-B.8).

The Inner City wells have remained relatively flat since many of them came on-line in the 1930s and 1940s (Figures A.14-A.20). The one exception to this is the Lower A Hill well that has experienced a decline of about 100 feet since the year 2006. This is the one Inner City well that has significant water-level data reported during the 2005-2007 period (Figure B.10). This well has reportedly been used very hard in recent years to supply the Inner City area. Other wells in this field report only one or two water levels after 2005, which makes a recent head fluctuation evaluation difficult to perform for this well field.

The Musquiz wells have experienced as much as 50 feet of decline in water levels since many of those wells came on-line in the 1970s (Figures A.21-A.26). The Musquiz well data ends in 2007 so the 2006 water-level trend is the only recent data source for this well field. Most of the wells exhibit a decrease in head during the year of 2006 (Figures B.15-B.20).

3.3 Well and Aquifer Testing

Production rate or yield of a well is the measured volume of water being withdrawn over a given period of time (gallons per minute) and is partially dependent on the pump size and efficiency and the aquifer's capacity at that well. The Texas Commission on Environmental Quality's (*TCEQ) reported pumping rates* as reported to them by the City can be queried at: (http://www3.tceq.state.tx.us/iwud/pws/index.cfm?fuseaction=DetailPWS&ID=1200).

A more descriptive measurement often provided by water well drillers is *specific capacity*. Specific capacity is a measurement of a well's yield (gpm) per foot of water-level drawdown at a given rate and point in time. This measurement provides an estimate of sustainable discharge that can be achieved from a well at a particular rate and is primarily used in selecting the appropriate pump size for the well. Specific capacity is highly dependent on the efficiency of the well and pump to withdraw water from the aquifer.

Pumping test results are the most useful information pertaining to a well's ability to move water from the aquifer to the well bore. When a well is pumped and water is withdrawn from an aquifer, water levels in the vicinity are drawn down to form an inverted cone with its apex located at the pumping well. This is referred to as a cone of depression. Groundwater flows from higher water levels to lower water levels and, therefore, in the case of a pumping well, toward the well or the center of the cone of depression. The shape and size of the cone is directly related to the aquifer parameters. When more than one well is pumped, each well superimposes its cone of water-level depression on the cones created by the pumping of neighboring wells. When the cone of one well overlaps the cone of another, interference occurs and the lowering of water levels is additive because both wells are competing for the same water in the aquifer. The amount of additional water-level decline depends on the rate of pumping from each well, the spacing between wells and the hydraulic characteristics of the aquifer.

Various hydrologic parameters are required to make a quantitative evaluation of an aquifer. The primary aquifer characteristics of concern are transmissivity, which is an index of the aquifer's ability to transmit water (sometimes measured in gallons per day per foot (gpd/ft) or ft^2/day), and the storage coefficient (unitless), which is an index of the amount of water released from or taken into storage as water levels change. Hydraulic conductivity can be calculated by dividing the calculated transmissivity by the aquifer thickness. The unit of measurement is gallons per day per foot squared (gpd/ft^2) or feet per day (ft/day). Important measurements made during a pumping test are well discharge and water-level decline versus time.

One of the basic assumptions in determining these parameters from pumping-test data is that flow takes place through a homogeneous medium having the same properties in all directions. In properly applying the results of a pumping test, one must be mindful of the limitations and take into consideration the physical characteristics of the aquifer, which are usually not the same in all directions.

Over the years, LBG-Guyton Associates, the US Geological Survey, and Ed Reed & Associates have conducted pumping tests on several of the Alpine wells, which are summarized in this report. Well production rates and pumping tests reported on individual wells are shown in Table 3-2.

Pumping tests allow for the comparison of a well's pumping rate with the change in water level over a given period of time. The combination of pumping test results within a well field provides an important aquifer characterization component in the modeling process.

TABLE 3-2 PRODUCTION RATES AND PUMPING TESTS

Well Name	Production Rate	TCEQ Reported Pumping Rate (gpm) R = Rated T = Tested	Specific Capacity (gpm/ft)	Pumping Tests
Sunny Glen Wells				
Roberts No.1	60 gpm (City 4-98). 35 gpm (TWDB 2-10-98).	R = 50 T = 65		Conducted by USGS on April 18-19, 1957. Pumping rate: 50 to 200 gpm for first 6 hours; 80 gpm for 11.5 hours. Water-level drawdown = 178' to 203' T= 3,800 g/d/ft Storage Coef. = $3x10^{-5}$.
Roberts No. 2	130 gpm	R = 120 T = 120		Conducted by USGS on June 3-5, 1957. Pumping rate: 80 to 180 gpm for first 5 hours. Average 162 gpm for 30 hours. Water-level drawdown = 110' to 133' T= 1,650g/d/ft Storage Coef. = $1.7x10^{-4}$. K = 6 gpd/ft2 from GAM data.
Roberts No. 3	83 gpm (TWDB 2-12-98).	R = 40 T = 40		T = 1694 g/d/ft, K = 6 gpd/ft^2 from GAM data.
Roberts No. 4	65 gpm (TWDB 2-10-98). 50 gpm (TWDB 5-6-98).	R = 120 T = 85	2.8 in 1999	Conducted by LBG-Guyton in March 1999. Pumping rate: 270 gpm; recovery T=439 g/d/ft
Roberts No. 5	170 gpm (TWDB 2-10-98). 65 gpm (City 9-22-98).	R = 50 T = 65	1.1 in 1976	Conducted by driller and Ed Reed on 6-30-76 on test hole prior to completion as production well. Pumping rate: 112 gpm for 24 hours. Water-level drawdown: 98'.
Daugherty		R = 80 T = 110	3.6 in 1999	Conducted by LBG-Guyton on 3-25-99. 96 gpm w/27' drawdown (3.6 gpm/ft) T= 12,700 g/d/ft Storage Coef.=$2.8x10^{-4}$. 150 gpm on 5-25-58, T = 11,700 g/d/ft, Storage Coef. = $2.0x10^{-4}$.
Cartwright		R = 140 T = 160	1.4 in 1958	175 gpm with 128.26' drawdown for 24 hours on 5-21-58. Six-day pumping test (October 1964) of original Daughtery (C22) well with water-level measurements in Cartwright well: T=21,193 g/d/ft Storage Coef. = $2.03x10^{-4}$. 150 gpm on 5-29-58, 1.4 gpm/ft, T = 6100 gpd/ft, K = 19
Gardner	63 gpm (TWDB 5-6-98).	R = 200 T = 140		145 gpm for 24 hours with 6.18' drawdown on 3-9-61. Also see Feb-March 1959 test.
Miles (NDW)		R = 35		Originally pumped continuously for 2 weeks at 225 gpm without exhausting well.
Lewis (*Test Well*)			2.8 in 1999	Conducted by LBG-Guyton on 3-23-99. 270 gpm w/94' drawdown; 2.8 gpm/ft T = 4,700 to 8,800 g/d/ft.

Well Name	Production Rate	TCEQ Reported Pumping Rate (gpm) R = Rated T = Tested	Specific Capacity (gpm/ft)	Pumping Tests
Inner-City Wells				
East Well	40 gpm	R = 50 T = 105	4.25 in 2003	T = 9106 g/d/ft in 2003
Railroad	85 gpm	R = 100 T = 75		T = 13,855 g/d/ft, K = 127 gpd/ft^2 from GAM data.
Upper A Hill	250 gpm	R = 200 T = 190		
Lower A Hill	260 gpm	R = 90 T = 240		
Golf Course (NDW)		R = 100		
Parker (NDW)				
Kokernot (NDW)				
Musquiz Wells				
Musquiz No. 6	448 gpm (Reed 3-23-72). 481 gpm (TWDB 2-11-98).	R = 350 T = 220		Conducted by Ed Reed on 3-23-72. Measured between Wells 6 (pumping) and 7. T=65,820 g/d/ft Storage Coef.=$3.52x10^{-3}$.
Musquiz No. 7	479 gpm (TWDB 2-11-98).	R = 300 T = 300		Conducted by Ed Reed on 12-13-71. Measured between Wells 7 (pumping) and 6. T=27,150 g/d/ft Storage Coef.=$5.8x10^{-3}$.
Musquiz No. 8	203 gpm (Reed 1972). 127 gpm (TWDB 2-11-98).	R = 85 T = 160		Conducted by Ed Reed in 1972. Recovery T=1,300 g/d/ft.
Musquiz No. 9		R = 135 T = 95		
Musquiz No. 10	500 gpm (1987). 572 gpm (TWDB 2-11-98).	R = 500 T = 380	38.5 in 2003	T = 10,748 g/d/ft in 2003
Musquiz No. 11	225 gpm (1984).	R = 400 T = 425	5 in 1984	T = 6591 g/d/ft, K = 41 gpd/ft^2 from GAM data.
Other Wells				
Meriwether No. 1 (NDW)		R = 60	0.9 in 1961	T = 778 g/d/ft, K = 3 gpd/ft^2 from GAM data.
Meriwether No. 2 (NDW)		R = 40		
Terry No. 2	31 gpm	R = 65 T = 90		T = 2731 g/d/ft, K = 228 gpd/ft^2 from GAM data.

4.0 WELL FIELD MODELING

4.1 Conceptual Model

4.1.1 Structure and Stratigraphy

In the vicinity of the City of Alpine, the late-Tertiary-aged volcanics and associated volcaniclastic sediments can be as great as 3,000 feet thick. However, much of the explored groundwater in the Igneous aquifer generally is found at depths less than 1,000 feet. Much of the water is found in fissures and fractures of tuffs and related intrusive and extrusive rocks. Additionally, Quaternary alluvium is found overlying volcanic rocks in much of the lower lying areas along streams and out-washed terrains.

The Igneous aquifer is not a single homogeneous aquifer but rather a system of complex water-bearing formations that are in varying degrees of hydrologic communication. In a study of the hydrogeology of the Davis Mountains, for example, Hart (1992) reported that groundwater in Jeff Davis County is found in 11 distinct water-bearing units. The individual aquifers occur in lava and pyroclastic flows (ignimbrites), in clastic sedimentary rocks deposited in an overall volcanic sequence, and possibly in ash falls (tuffs).

The best aquifers are found in igneous rocks with primary porosity and permeability such as vesicular basalts, interflow zones in lava successions, sandstones, conglomerates, and breccias. Faulting and fracturing can enhance aquifer productivity in poorly permeable rock units.

On a microscopic scale the porosity and preferred pathway for water in the volcanics is extremely restricted to secondary fracturing of the rock and is directed along this fracturing. There is also some stratification of the porosity found in specific layers that might be inherent to the deposition of alluvium or volcanic extrusion at depth in the aquifer. However, on a macroscopic scale, some of these heterogeneities have a lesser degree of impact to the flow of water. As a result, the aquifer can be simplified in order to make computer simulations of the system possible. A single layer model is used to simulate the aquifer in the vicinity of the City's wells.

Both Musquiz and Sunny Glen well fields are located in valley terrain that has been eroded through time likely as a result of additional fracturing in those locales. This geologic environment has also likely produced more permeable productive areas in the aquifer. In the flow model, the transmissivities at the two well fields are slightly higher as compared to the region between the two well fields.

4.2 Groundwater Model Development

4.2.1 Model Extent and Boundaries

Figure 4-1 shows the finite-difference grid used for the MODFLOW model. The extent of the model covers all three well fields of interest and extends far enough away from the well fields so that boundary effects are limited. The grid size is 500 feet near the well fields and increases to 1,000 feet near the boundaries of the model.

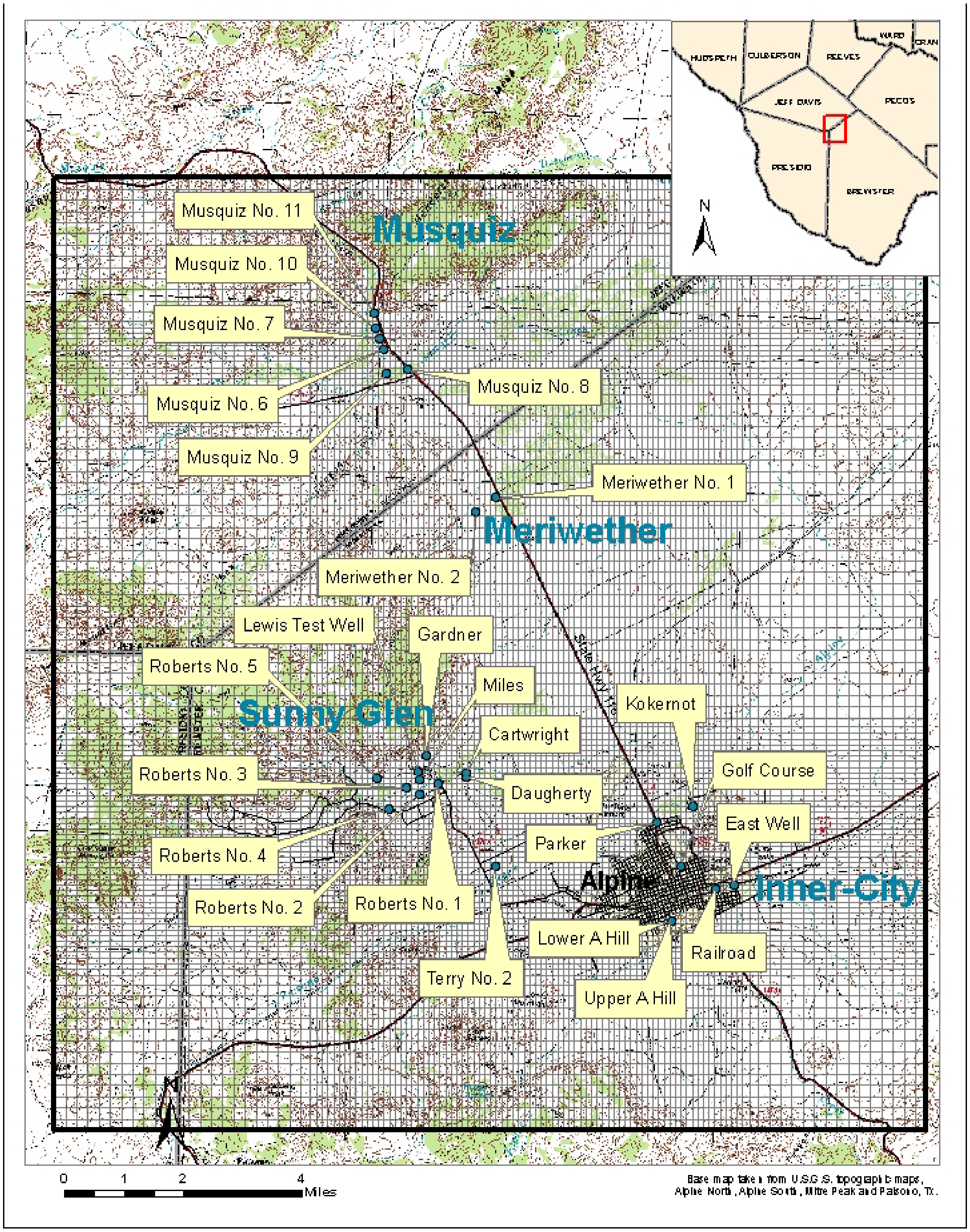


Figure 4–1 MODFLOW Finite-Difference Grid for Alpine Well Fields

4.2.2 Hydraulic Properties

Aquifer hydraulic conductivity, transmissivity, and storage estimates were collected from groundwater availability studies in the well fields. Pumping tests were completed on wells in the Musquiz field when they were drilled in 1972. In 1999, LBG-Guyton Associates performed pumping tests on several wells in the Sunny Glen well field. The hydraulic properties used in the West Texas Igneous and Bolson GAM (Beach, et al, 2004) for the igneous aquifer in this area were also added to the collection of hydraulic properties as well as properties reported from pumping tests performed between the years 1955 and 1958 in TWDB Report 98 (Myers, 1969). The range of reported transmissivities, hydraulic conductivities, and storage coefficient values reported and geometric means for each of the well fields are included in Table 4-1.

Table 4–1 Summary of hydraulic property ranges and geometric means by well field

Well Field	Transmissivity (g/d/ft)	Transmissivity (ft^2/d)	Hydraulic Conductivity (g/d/ft^2)	Hydraulic Conductivity (ft/d)	Storage Coefficient
Sunny Glen	439 to 21,193	59 to 2,840	8 to 571	1 to 77	$3e^{-5}$ to $2.8e^{-4}$
Geometric Mean	*4055*	*543*	*92*	*7*	*$1.7e^{-4}$*
Musquiz	778 to 65,820	104 to 8,820	3 to 41	0.5 to 5	$3.5e^{-3}$ to $5.8e^{-3}$
Geometric Mean	*7069*	*947*	*11*	*5*	*$4.5e^{-3}$*
Inner City	234 to 26,357	31 to 3,532	8 to 222	1 to 30	NR
Geometric Mean	*5282*	*708*	*61*	*5*	*NR*

4.2.3 Historical Pumping Estimates

Pumping allocation for the City of Alpine was based on historical records and on discussions with City personnel. Pumping was implemented into the model so that historical water-level declines could be simulated. Figure 4-2 plots the City of Alpine yearly municipal water usage from the year 1966 to 2004 obtained from the TWDB.

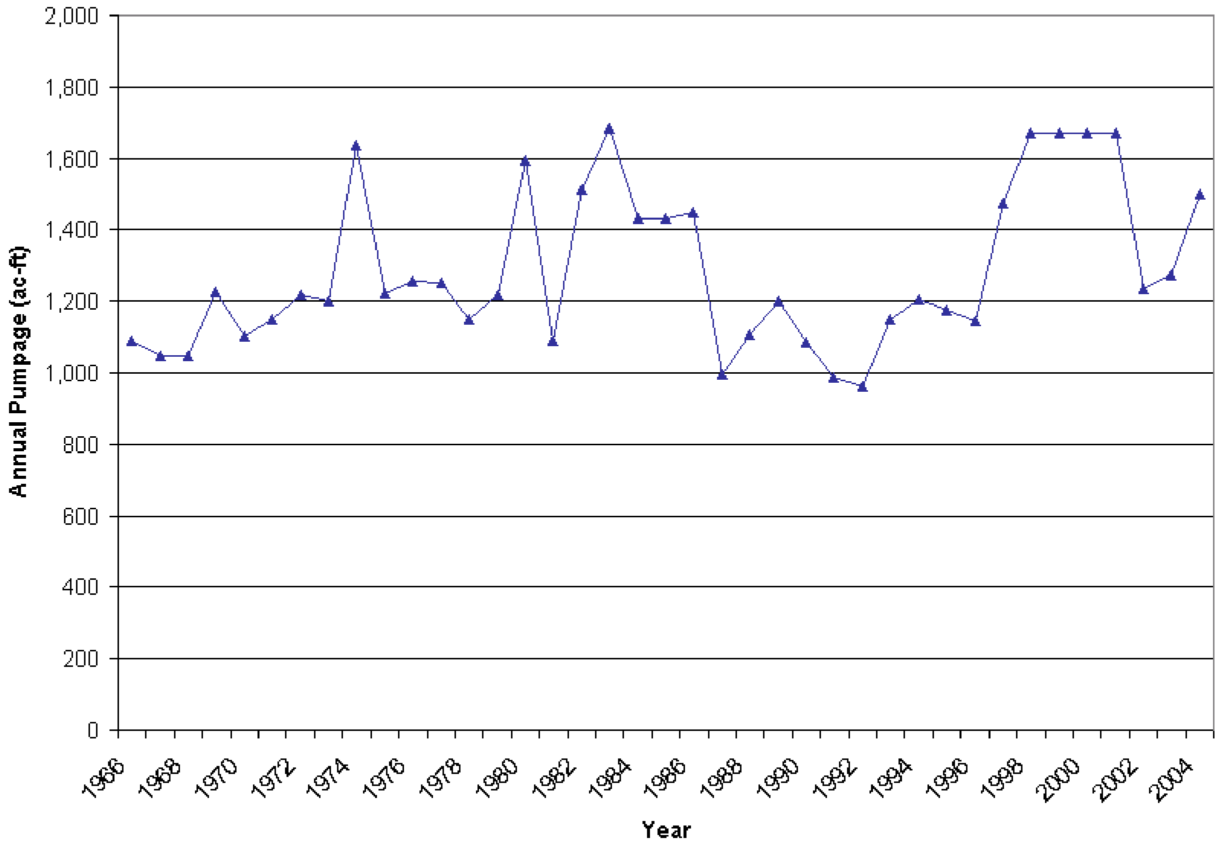


Figure 4–2 City of Alpine annual municipal water use (acre-ft) since 1966

From this data, values for water-use were projected back beginning in 1950 and forward to 2006 using the linear trend of yearly water used by the City of Alpine. Each well field was assigned a percentage of this water use according to number of wells on-line and their reported pumping rates. Total pumpage was then dispersed by well according to reported pump rates.

Pumping was only assigned during the years each well was assumed to be pumping for the City of Alpine. The assumption for the time each well was on-line for the City was estimated as the year the well was drilled until the year of the last water-level measurement if no other documentation was available. Estimated pumpage using the reported pumping rates for each well was then compared to City of Alpine records of well production from 2005 to 2007 and then adjusted based on individual well pumping records as well as well field pumping records recorded by the City. Figure 4-3 shows the estimated pumping rate in each well field used in the model from 1950-2006.

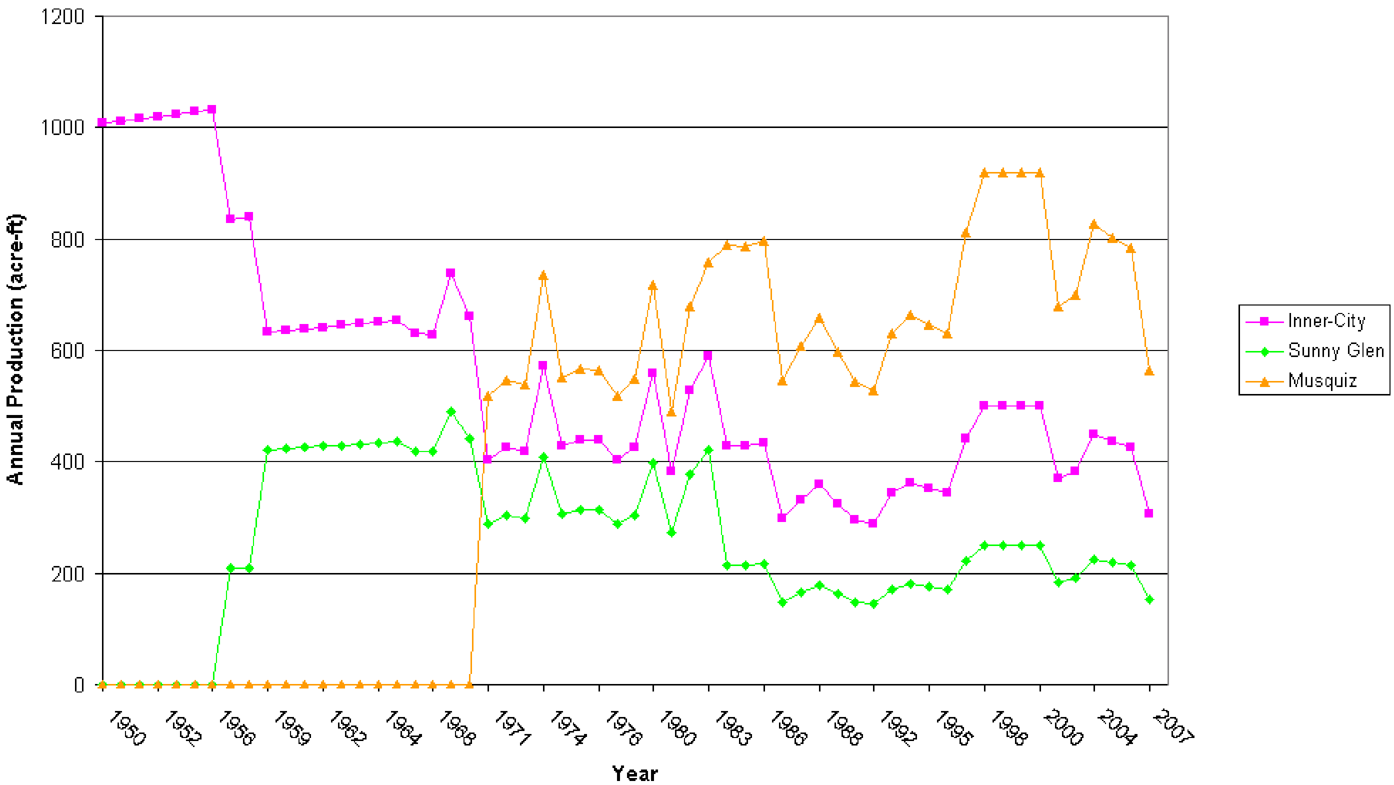


Figure 4–3 Estimated annual pumpage (acre-ft) by well field, 1950-2006

4.2.4 Water Levels

Historical water levels were incorporated into the model as calibration targets. The historical water-level data were collected from the TWDB groundwater database, the City of Alpine, and Sul Ross State University records. Other pumping test records performed by LBG-Guyton Associates were also incorporated into this dataset. Hydrographs created from this collection of water-level data are included as appendices and are sorted according to well field (Appendix A, Appendix B).

Although pumpage is not the only factor leading to water-level fluctuation within these well fields, general water-level elevation in each of the wells fields is still related to the amount withdrawn in any given year. As discussed earlier, observed pumping in each of the well fields has shifted as more wells were drilled and used for the City's municipal water supply. The Inner City wells had been pumped the most until the Musquiz wells were drilled and then major water supply shifted to this well field. More drawdown has occurred in the Sunny Glen well field since its inception than has occurred in the Inner City or Musquiz wells. This may also be associated with the nearby additional irrigation pumpage and domestic well pumpage. The Sunny Glen well field has been the least used by the City of Alpine of all three fields possibly due to the smaller diameter pipeline moving water from the Sunny Glen area to the City. As pumping has decreased in the Inner City wells, the water level has risen. Since water-level data is sparse from each well within the Musquiz well field from drill date until 2006, it is difficult to observe the effect pumping has had on this well field except to note the lower water levels when data was continued again in 2006.

4.2.5 Recharge

Recharge estimates are very critical in developing an appropriate model, and yet they are difficult to measure directly. Recharge estimates were taken from Beach and others (2004).

4.3 Model Calibration

Existing hydrologic and hydrogeologic data were evaluated with respect to long-term groundwater availability. The well database, driller's logs, geophysical logs, water-level measurements, and historical pumping information were used to develop and calibrate the groundwater model. Pumping test information regarding the hydraulic conductivity and storativity of the aquifer were also used to help parameterize the model.

Calibration of a groundwater flow model is the process of adjusting model parameters until the model reproduces field-measured values of water levels (heads) and discharge rates. Successful calibration of a flow model to observed heads and flow conditions is usually a prerequisite to using the model for prediction of future groundwater availability. Parameters that are typically adjusted during model calibration are hydraulic conductivity, storativity, and recharge. Model calibration typically includes completion of a sensitivity analysis and a verification analysis. Sensitivity analysis entails running the model with a systematic variation of the parameters and stresses in order to determine which parameter variations produce the most change in the model results. Those parameters that change the simulated aquifer heads and discharges the most are considered important parameters to the calibration. The sensitivity analysis guides the process of model calibration by identifying potentially important parameters but does not in itself guarantee a calibrated model.

The model was calibrated for two hydrologic conditions, one representing steady-state conditions (i.e., prior to major pumping) and the other representing transient conditions after pumping started. There is very little, if any, water-level data available prior to development of the Alpine well fields. However, the earliest water-level measurements were used to represent "predevelopment" conditions and the water-level measurements from that time period were used to calibrate the steady-state model. Historical records indicate that pumping started in the 1920s in the Inner City well field, 1950s in the Sunny Glen well field, and about 1972 in the Musquiz well field. Simulated water levels from the steady-state period were then used as the initial water levels for the calibration period, which was from 1950 to 2007. All stress periods during the calibration period were one year long because that was consistent with the level of data available regarding well field production.

The advantage of calibrating the model to 57 years of historical data is that this period incorporates a wide range of hydrologic and pumping conditions. The goal of the steady-state predevelopment calibration was to simulate a period of equilibrium where aquifer recharge and discharge are roughly equal. The goal of the transient calibration was to adjust the model to appropriately simulate the water-level changes that were occurring in the aquifer due to pumping. The model has one-year stress periods. This means that the annual average recharge and total pumping were varied each year from 1950 through 2007. Recharge was also varied spatially. Irrigation pumping associated with the pecan orchard west of the Sunny Glen well field and the residential area west of Alpine was also incorporated into the model.

4.3.1 Calibration Targets and Measures

In order to calibrate a model, targets and calibration measures must be developed. The primary type of calibration target is hydraulic head (water level). Table 4–2 summarizes the available water-level measurements for the steady state and transient model calibration periods. These water-level measurements were assimilated from data contained in City of Alpine, Sul Ross, and TWDB records.

Table 4–2 Summary of the water-level data used to develop head targets

Well Field	Predevelopment or Steady-state Calibration	Transient Calibration
Sunny Glen	16	457
Musquiz	6	293
Inner City	1	103

Predevelopment and transient head targets were averaged on a calendar year basis to be consistent with the one-year stress periods in the model. Therefore, the final number of head targets was reduced to 347. Figure 4-4 shows the location of the wells containing calibration data.

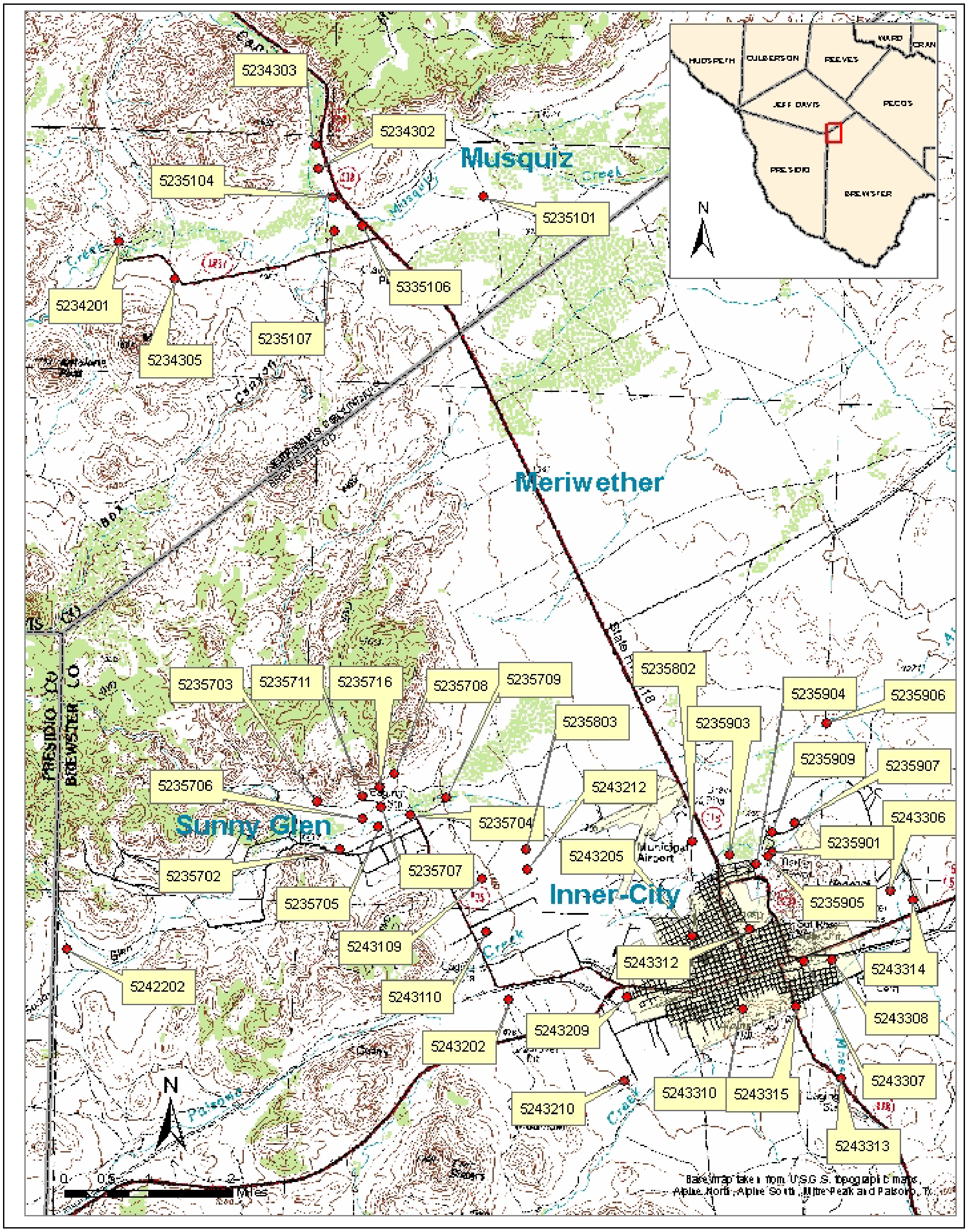


Figure 4–4 Location of wells containing water-level data that were used to calibrate the model

Model calibration is judged by quantitatively analyzing the difference (or residual) between observed and model computed (i.e., simulated) values. Several graphical and statistical methods are used to assess the model calibration. These statistics and methods are described in detail in Anderson and Woessner (1992). The mean error is defined as:

$$ME = \frac{1}{n}\sum_{i=1}^{n} (h_m - h_s)_i \qquad 4.1$$

where:

h_m is measured hydraulic head, and

h_s is simulated hydraulic head, and

$(h_m - h_s)$ is known as the head error or residual.

A positive mean error (ME) indicates that the model has systematically underestimated heads, and a negative error indicates the model has systematically overestimated heads. It is possible to have a mean error near zero and still have considerable errors in the model (i.e., errors of +50 and -50 give the same mean residual as +1 and -1). Thus two additional measures, the mean absolute error and the root mean square of the errors, are also used to quantify model goodness of fit. The mean absolute error is defined as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} \left|(h_m - h_s)_i\right| \qquad 4.2$$

and is the mean of the absolute value of the errors. The standard deviation (SD) of errors or root mean squared (RMS) error is defined as:

$$RMS = \left[\frac{1}{n}\sum_{i=1}^{n} (h_m - h_s)_i^2 \right]^{0.5} \qquad 4.3$$

A large SD means that there is wide scattering of errors around the mean error. Generally, the root mean square error between measured hydraulic head and simulated hydraulic head shall be less than ten percent of the measured hydraulic head drop across the model area and better if possible.

These statistics were calculated for the entire calibration period. In addition, the distribution of residuals was evaluated to determine if they are randomly distributed over the model grid and not spatially biased. Head residuals were plotted on the simulated water-level maps to check for spatial bias. Scatter plots were used to determine if the head residuals are biased as compared to the observed head surface.

4.3.2 Calibration Results

Table 4-3 shows the calibration statistics for the model, and includes the calibration data from the steady-state and transient periods. As this table shows, the root mean square error between measured hydraulic head and simulated hydraulic head is 5.7% of the measured hydraulic head drop across the model area, which meets the calibration goal for the model. The root mean squared error of 25 feet indicates that the model provides a reasonable approximation of the water-level surface throughout the model area and the water-level trends through time.

There are many reasons why the model does not simulate the measured water levels exactly, including lack of aquifer characterization and parameter data based on aquifer drilling and testing. Lack of detail in historical production from well fields increases the difficulty in calibrating the model. In addition, as discussed above, the physical hydrogeology is actually a fractured media that is in some cases overlain by alluvium. However, the model simulates the system as a continuous porous media.

Table 4–3 Calibration statistics

Number of Observations	347
Mean Error (feet)	12.6
Mean Absolute Error (feet)	31.6
Min. Residual (feet)	-79
Max. Residual (feet)	123
Range of Observed Heads (feet)	551
RMS (feet)	25.5
% RMS / Range (%)	5.7

Figures 4-5 through 4-16 illustrate the simulated and measured water levels in eleven different wells. The comparison of measured and simulated heads in the well fields indicates that the model is generally able to mimic historical responses in each of the well fields.

Figures 4-5 through 4-10 show hydrographs for six wells located in the Sunny Glen well field. The model simulates the water-level declines in the Sunny Glen well field relatively well with the exception of a few wells located on the east end of the well field.

Figures 4-11 through 4-14 show hydrographs for four wells located in the Inner City well field. The model simulates the water-level responses in the Inner City well field relatively well, but the model is limited in it's ability to simulate the water-level dynamics around the Lower A Hill wells, probably due to the fracture flow in the area and the incomplete pumping records for these wells, which affected the model calibration in this area. Because the simulated drawdown is significantly less in recent years than measured, we suspect that the pumping may have been greater in these wells than we estimated. Based on the limited information available regarding historical production, only 21 percent of the total production is assigned to the Inner City well field in the future. Furthermore, for modeling purposes, the pumping is assumed to be equally distributed among all the Inner City wells in the model. But we suspect that the Lower A Hill well may currently provide a large percentage of the production from the Inner City well field, and if this is true, that may explain why the measured and simulated water levels do not match very well.

Figures 4-15 and 4-16 show hydrographs for wells located in the Musquiz well field. The model simulates the water-level declines in the Musquiz well field relatively well.

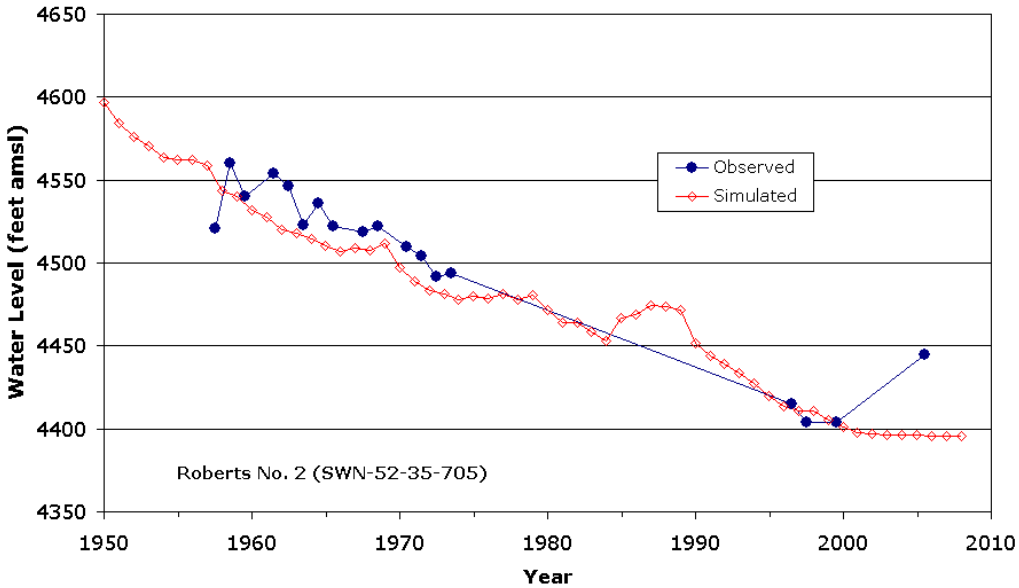


Figure 4–5 Simulated and observed hydrographs for Roberts No. 2 well in the Sunny Glen well field

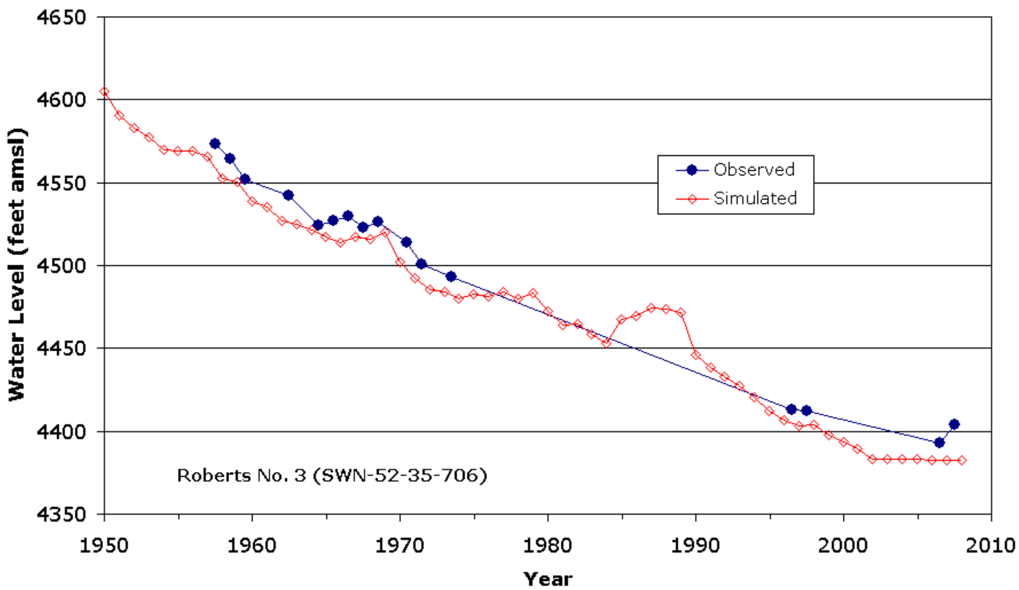


Figure 4–6 Simulated and observed hydrographs for Roberts No. 3 well in the Sunny Glen well field

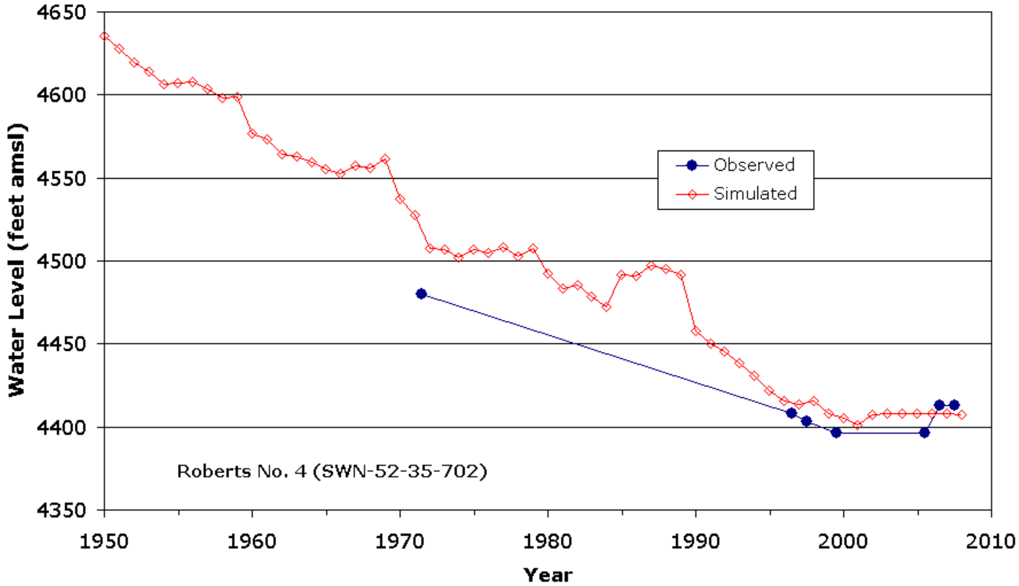


Figure 4–7 Simulated and observed hydrographs for Roberts No. 4 well in the Sunny Glen well field

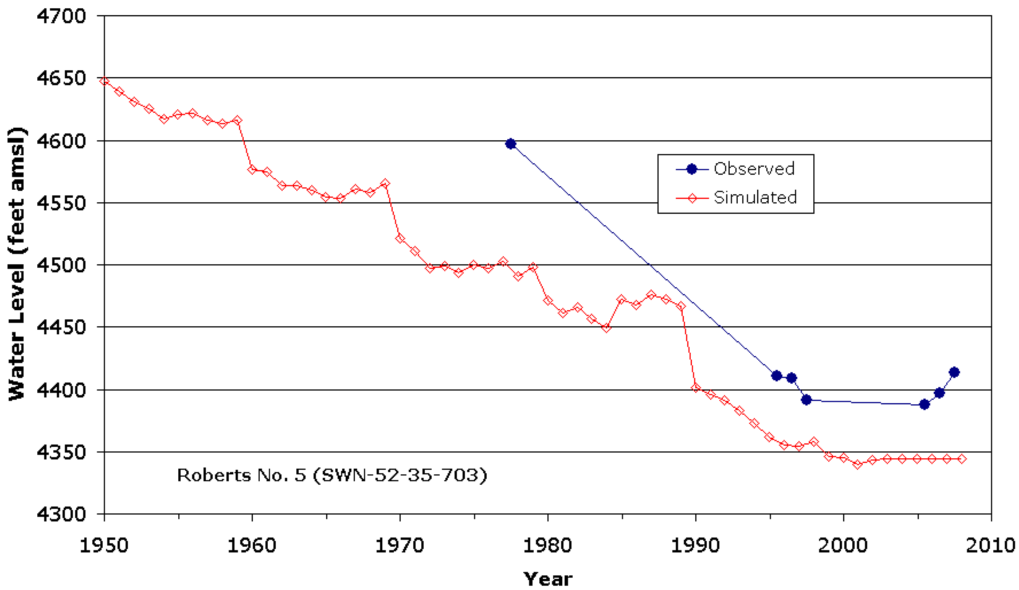


Figure 4–8 Simulated and observed hydrographs for Roberts No. 5 well in the Sunny Glen well field

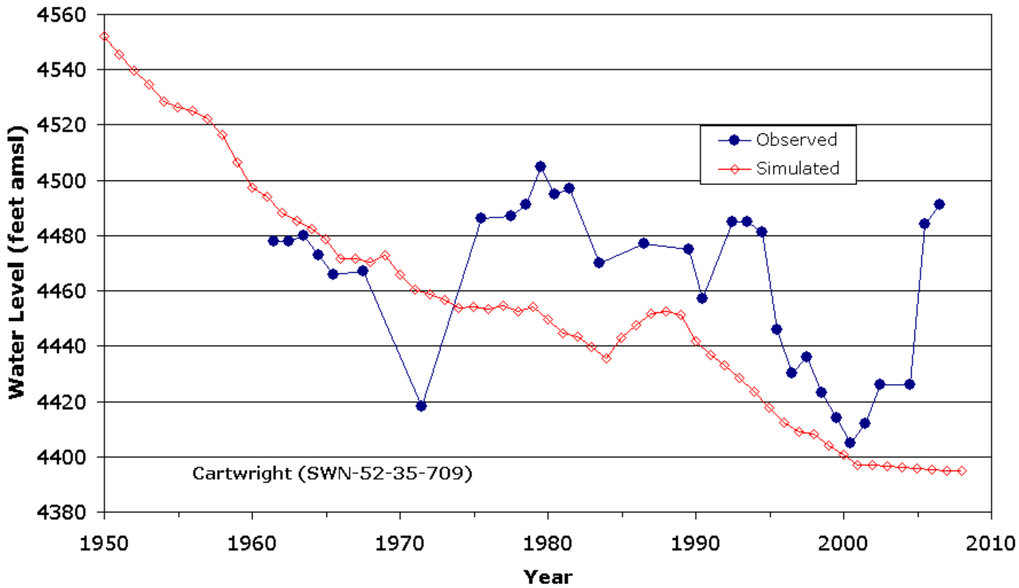


Figure 4–9 Simulated and observed hydrographs for Cartwright well in the Sunny Glen well field

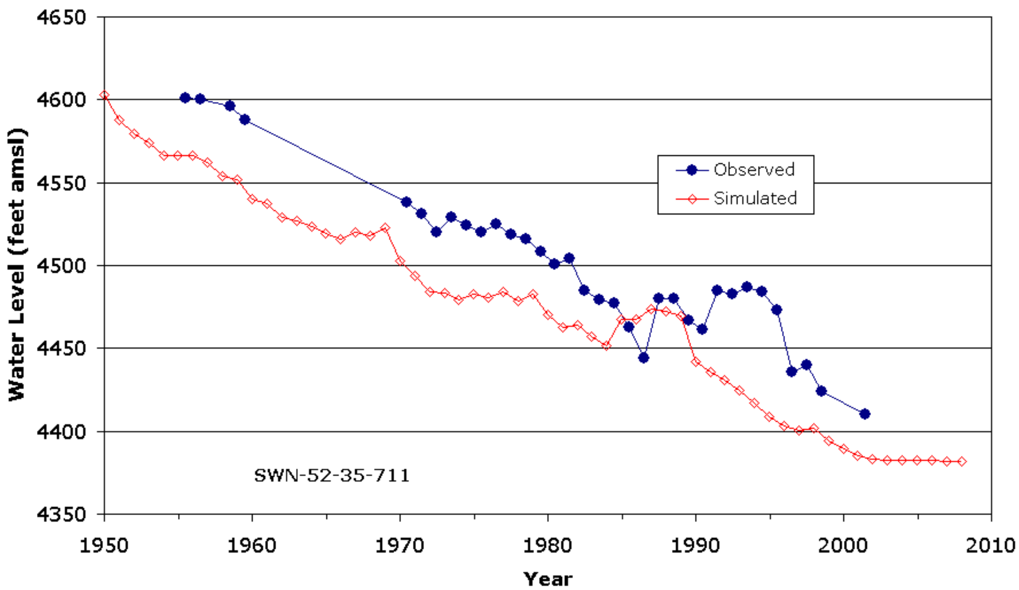


Figure 4–10 Simulated and observed hydrographs for observation well (SWN 52-35-711) in the Sunny Glen well field

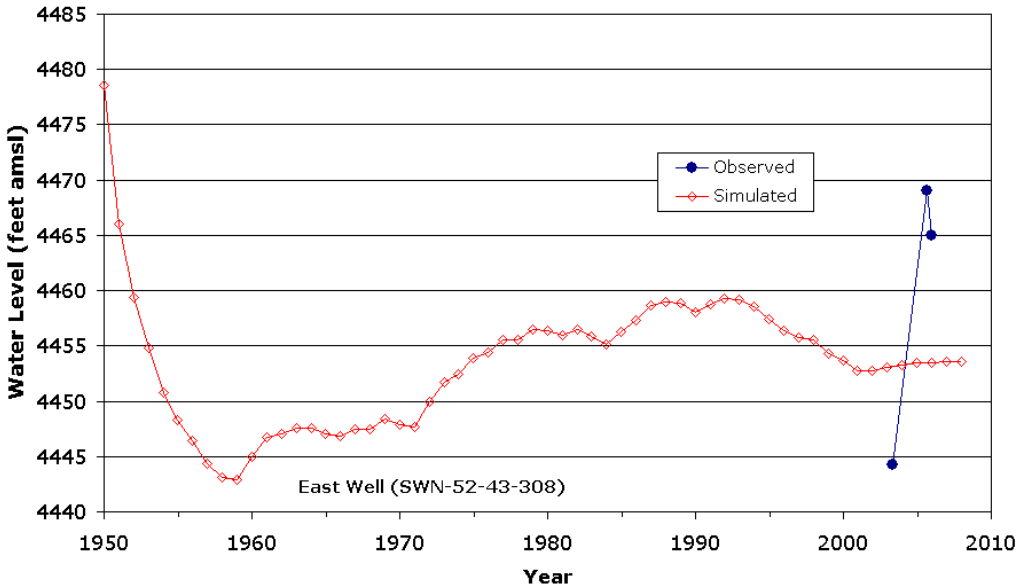


Figure 4–11 Simulated and observed hydrographs for the East well in the Inner City well field

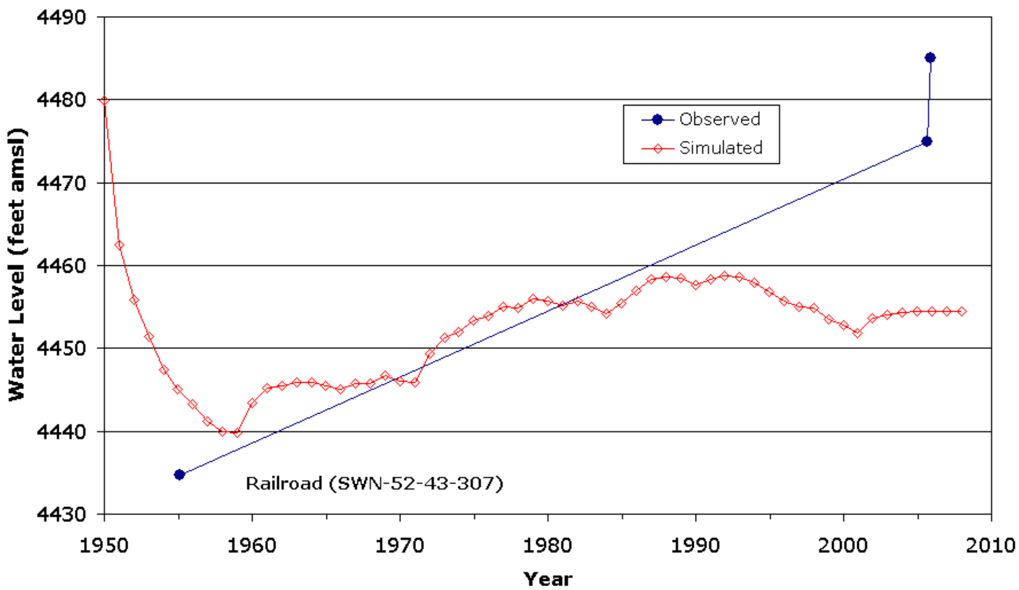


Figure 4–12 Simulated and observed hydrographs for the Railroad well in the Inner City well field

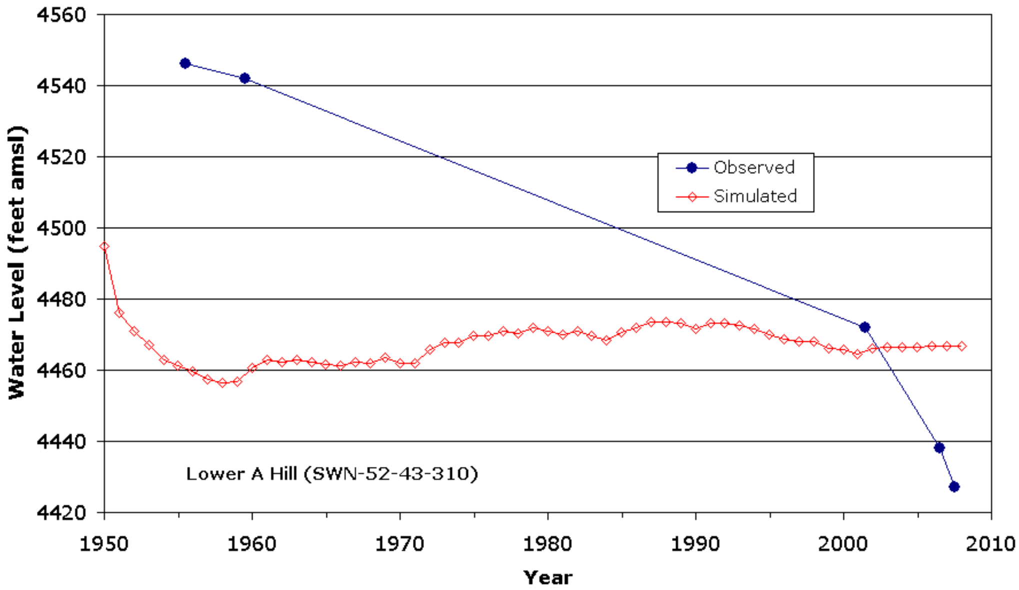


Figure 4–13 Simulated and observed hydrographs for the Lower A Hill well in the Inner City well field

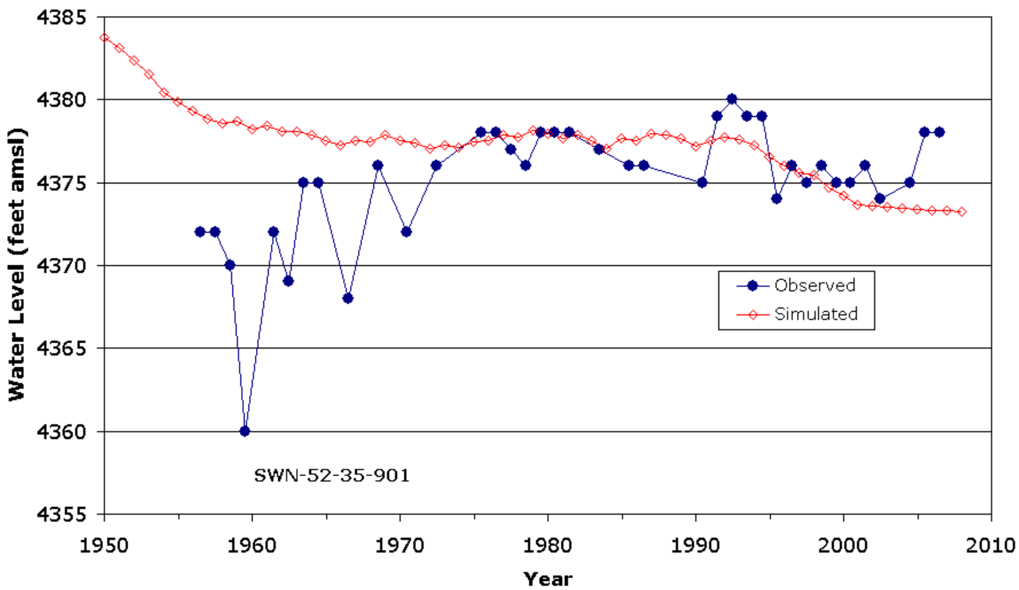


Figure 4–14 Simulated and observed hydrographs for the observation well (SWN 52-35-901) in the Inner City well field

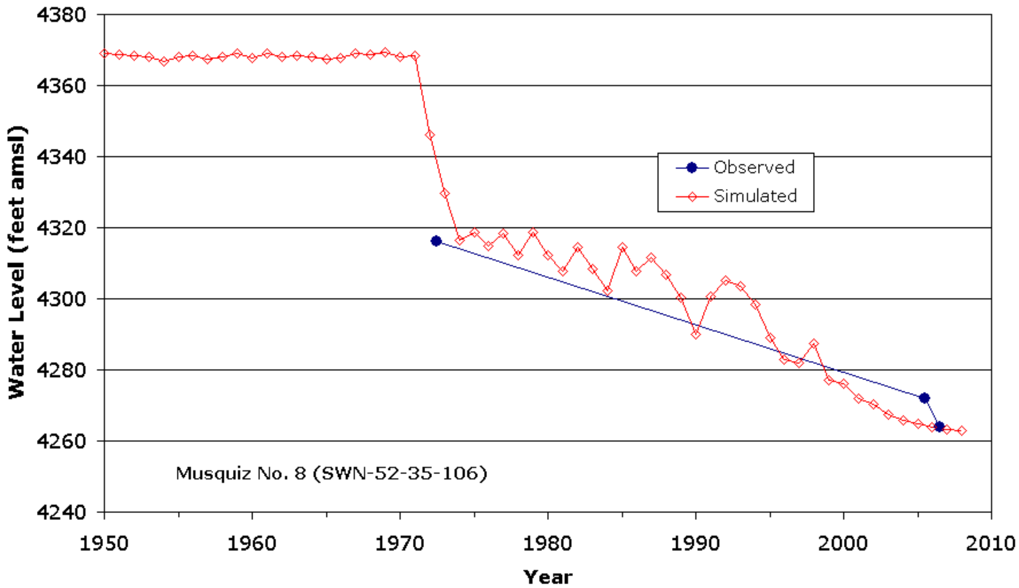


Figure 4–15 Simulated and observed hydrographs for the Musquiz No. 8 well in the Musquiz well field

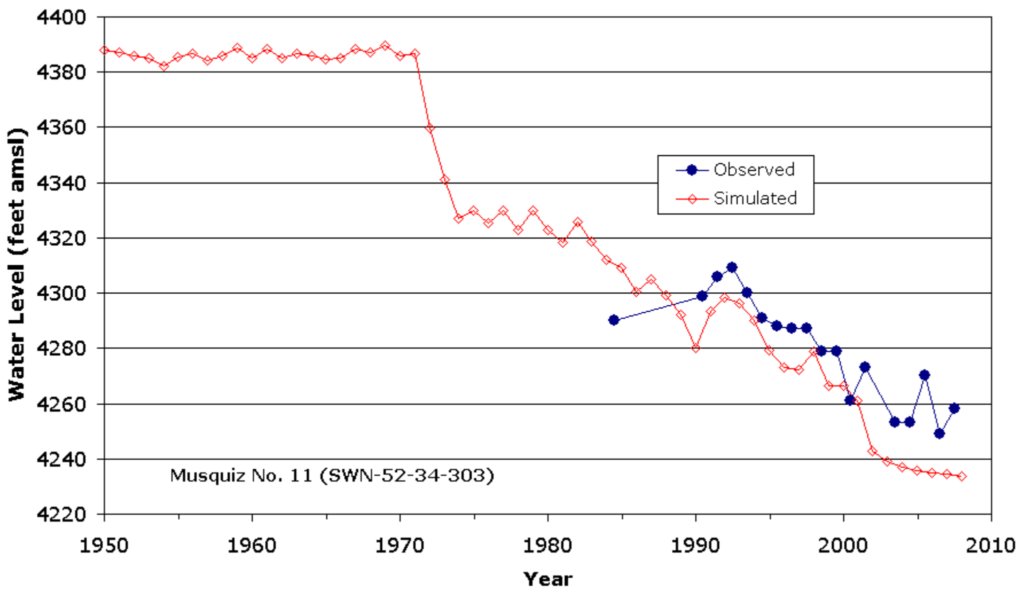


Figure 4–16 Simulated and observed hydrographs for the Musquiz No. 11 well in the Musquiz well field

5.0 WELL FIELD MODEL RESULTS

5.1.1 Predictive Simulations

The calibrated model was used to evaluate two different predictive scenarios. Both scenarios simulated production of groundwater to meet the City of Alpine demands that were estimated by the Region E Water Planning Group for the 2007 State Water Plan. Table 5-1 tabulates the demands estimated for the City of Alpine from 2010 through 2060.

Table 5–1 Projected water demand for the City of Alpine based on the 2007 State Water Plan

Year	City of Alpine Demand (acre-feet per year)
2010	1791
2020	1888
2030	1917
2040	1928
2050	2014
2060	2034

Scenario 1 assumes that the City increases production from existing well fields to meet demands to year 2060. The allocation of pumping currently used by the City (i.e., the percentage of pumping from each wellfield) remained the same throughout the simulation period (2010 through 2060). The percentage of production coming from each well field is shown in Table 5-2.

Table 5–2 Percentage of total production assigned to each well field

Well Field	Estimated Portion of Total Production (percent)
Inner City	21
Sunny Glen	22
Musquiz	57

Scenario 2 assumes that the City continues production from Inner City and Sunny Glen well fields at levels similar to current production (with a very slight increase) and reduces production from the Musquiz well field over time while increasing the production from another (hypothetical) well field near the municipal airport that is developed between 2010 and 2040. Essentially, the production is shifted from Musquiz to the hypothetical well field. As in Scenario 1, the percentage of pumping from Inner City and Sunny Glen remained the same from 2010 through 2060. Simulated production from the airport well field (and reduction in the production from Musquiz wells) is shown in Table 5-3.

Table 5–3 Simulated Production from Proposed Airport Well Field

Year	Simulated Production from Hypothetical Airport Well Field (acre-feet per year)
2010	100
2020	200
2030	300
2040	400
2050	400
2060	400

5.1.2 Sunny Glen Well Field

Figure 5-1 shows the historical and future hydrographs for the Roberts No. 3 well in the Sunny Glen well field under the two production scenarios. Because the production from the Sunny Glen well field has been assumed to be 22 percent of the total production, the predicted declines to year 2060 are only about 40 to 50 feet under either scenario, as simulated at the Roberts No. 3 well. This amount of water-level decline is probably sustainable if new pumpage in surrounding areas from irrigation or domestic wells does not increase through time. Scenario 2 produces slightly higher drawdown in the Sunny Glen well field because of the increased water-level declines associated with the hypothetical airport well field.

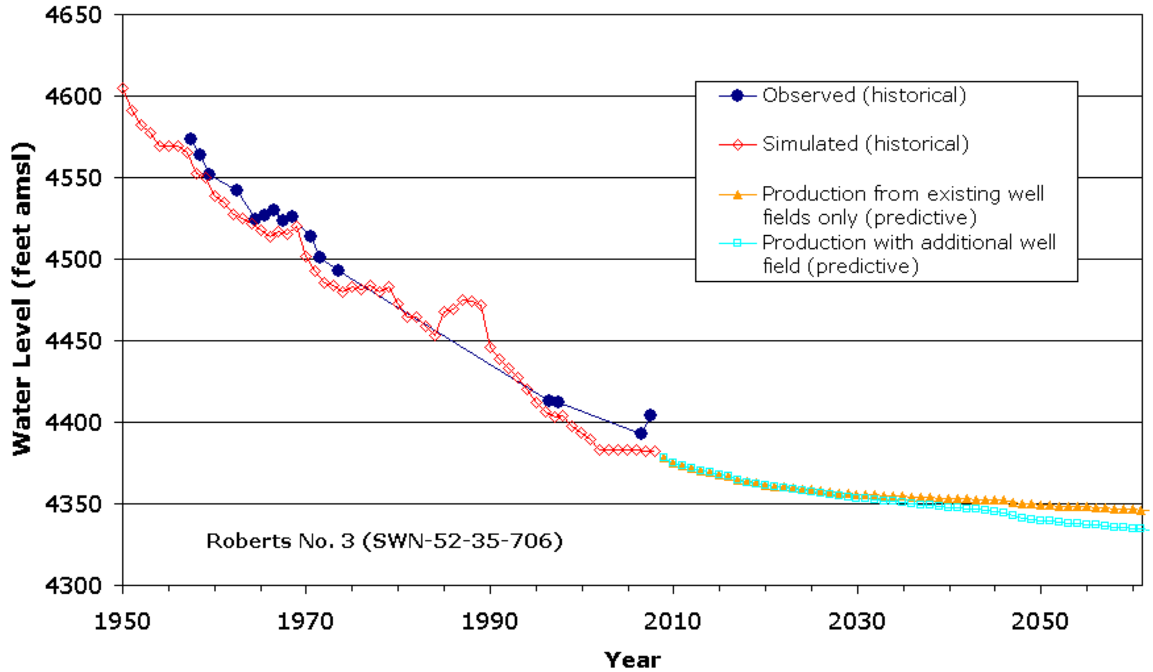


Figure 5–1 Simulated historical and future hydrographs for Roberts No. 3 well in the Sunny Glen well field under two production scenarios

5.1.3 Musquiz Well Field

Figure 5-2 shows the historical and future hydrographs for the Musquiz No. 11 well in the Musquiz well field under the two production scenarios. Because the production from the Musquiz well field has been assumed to be 57 percent of the total production, the predicted declines to year 2060 are about 135 feet under Scenario 1, as simulated at the Musquiz No. 11 well. These results indicate that the Musquiz well field can expect significant continued decline if the current pumping scenario is projected into the future.

Musquiz wells have already experienced declines of about 50 to 60 feet and the wells are relatively shallow at about 500 feet or less. Current static water levels are about 150 feet from land surface. A long-term decline of 135 feet, added to the 150 feet deep static level today indicates that future static water levels might be 280 to 290 feet below ground surface. This continued water-level decline will most likely reduce the specific capacity of the well, and may increase the wellbore drawdown when the well is pumping. These cumulative effects reduce the safety factor for the wells in the Musquiz well field.

Scenario 2 produces significantly less drawdown in the Musquiz well field because production is shifted from the Musquiz well field to the proposed airport well field in 2010. As expected, Scenario 2 confirms that shifting some of the production away from Musquiz well field will diminish the impact and prolong the life of the well field. The model indicates that by 2040, when the pumping has been reduced by 400 acre-feet per year, the water levels will rebound to 2007 levels.

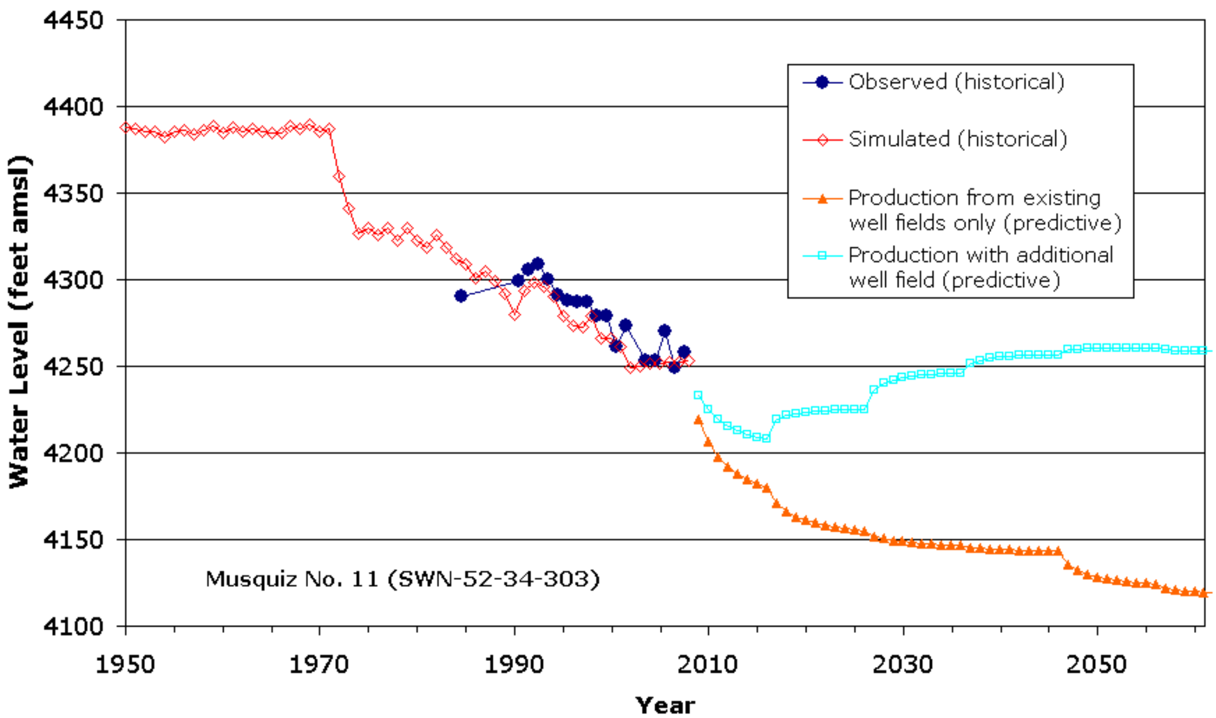


Figure 5–2 Simulated historical and future hydrographs for Musquiz No. 11 well in the Musquiz well field under two production scenarios

5.1.4 Inner City Well Field

Figure 5-3 shows the historical and future hydrographs for the Lower A Hill well in the Inner City well field under the two production scenarios. As discussed above, the pumping records for the Inner City wells are incomplete, and we suspect that the pumping has been greater in the Lower A Hill well than we estimated. Based on the limited information available regarding historical production, only 21 percent of the total production is assigned to the Inner City well field in the future. Furthermore, the pumping is assumed to be equally distributed among all the Inner City wells in the model. But we suspect that the Lower A Hill well may currently provide a large percentage of the production from the Inner City well field, and if this is true, the predictions made herein for this well may not be appropriate. Lower A Hill well has experienced declines of about 50 feet in the last 5 years. If pumping continues at a relatively high rate as indicated by these declines, then the predicted water-level declines in Figure 5-3 may be too small.

Scenarios 1 and 2 produce an additional 20 and 40 feet of water-level decline in 2060 according to the assumptions simulated here. As expected, Scenario 2 confirms that shifting some of the production to the proposed airport well field will slightly increase the water-level declines in the Inner City well field.

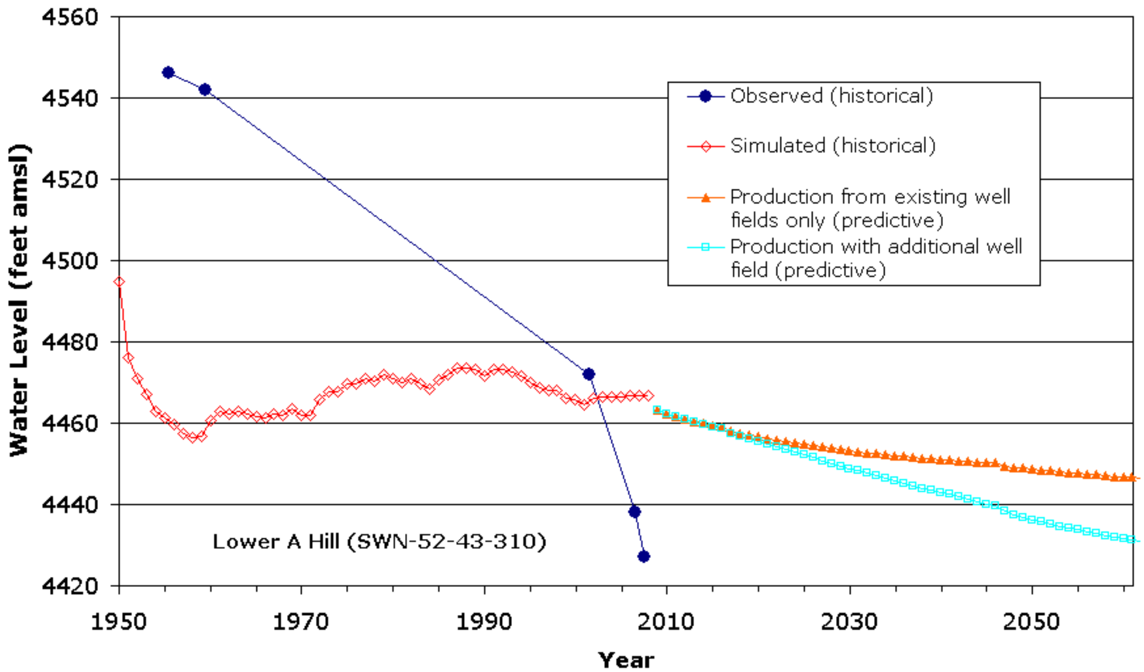


Figure 5–3 Simulated historical and future hydrographs for the Lower A Hill well in the Inner City well field under two production scenarios

6.0 CONCLUSIONS AND RECOMMENDATIONS

Available data was compiled for water levels and pumpage on the City of Alpine wells located in the three well fields (Inner City, Sunny Glen and Musquiz). Some trends are observable in the historic water levels. Early trends were downward for each of the well fields as they came on-line. As pumpage has been shifted from Inner City to Sunny Glen and then to Musquiz, the trends in the Inner City and Sunny Glen have flattened or have actually rebounded. However, Musquiz is currently utilized and pumped the most and has experienced continued water-level decline to present.

Aquifer simulations using a numerical groundwater flow model show continued decline in the Sunny Glen and Inner City well fields but at levels that are probably sustainable. However, current water-level declines in the Musquiz well field and simulated future declines indicate that the City should plan to reduce production from that well field in the future. Because of the shallower nature of the wells and current downward trends in water levels, the cumulative declines may be great enough to reduce the production capacity of the wells in the Musquiz well field.

One obvious solution to the current well field pumping is to spread the pumping over a greater area of the aquifer. As a result, three areas that LBG-Guyton Associates recommends for possible future test wells are 1) the Airport area, 2) the Golf Course/Park area, and 3) west of A Hill along Alpine Creek. The first two areas not only show good hydrologic promise, but also are conveniently located near existing pipelines, water storage tanks, and other existing infrastructure.

All three areas are located some distance from the three existing well fields, which may help to minimize well interference with the existing wells. The airport location is also located near a previously mapped fault, which may have resulted in additional fracturing of the bedrock and thus enhancing the porosity and potential yield of wells completed in that area. New wells near the airport should be drilled to depth of at least 1,000 feet or greater to make sure that the entire depth of the aquifer is penetrated. Previous wells in these areas have been drilled but many were stopped after only a few hundred feet and may not have penetrated the more productive layers of the aquifer. A more thorough evaluation of potential test well sights should be conducted before selecting specific locations.

A hypothetical well field near the airport was simulated. In this scenario, 400 acre-feet per year of production were shifted away from the Musquiz well field to the proposed well field between 2010 and 2040. The model indicates that this shift helps reduce the water-level declines in the Musquiz well field and should increase the life of the well field.

7.0 REFERENCES

Anderson, M.P and Woessner, W.W., 1992, Applied Groundwater Modeling: Academic Press, San Diego, CA, 381 p.

Beach, J.A., Ashworth, J.B., Finch, S.T., Jr., Chastain-Howley, A., Calhoun, K., Urbanczyk, K.M., Sharp, J.M., Olson, J., 2004, Groundwater Availability Model for the Igneous and parts of the West Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat) Aquifers, Consultant's report prepared for the Texas Water Development Board.

Hart, Margaret A., 1992, The hydrogeology of the Davis Mountains, Trans-Pecos, Texas: University of Texas at Austin, unpublished Masters Thesis.

LBG-Guyton Associates, December 1998, Preliminary Evaluation of Potential Ground-Water Supply Development for the City of Alpine.

LBG-Guyton Associates, May 1999, Lewis No. 1 Test Hole Evaluation - Alpine, Texas.

LBG-Guyton Associates, August 1999, Sunny Glen Well Field Evaluation - Alpine, Texas.

LBG-Guyton Associates, November 2005, Well Conditions and Recommendations for Sunny Glen and In-Town Fields - Alpine, Texas.

Myers, B.N., 1969, Compilation of Results of Aquifer Tests in Texas, Texas Water Development Board Report 98.

Texas Water Development Board, State Water Plan, 2007.

APPENDIX A

Well hydrographs containing all water-level data (1947-2008)

Sunny Glen Well Field

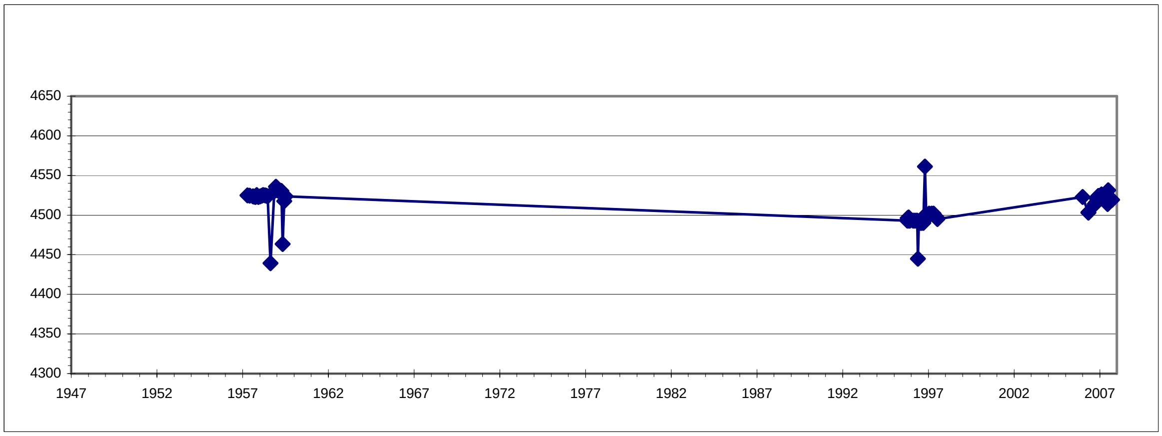


Figure A.1. Roberts No. 1 (52-35-704)

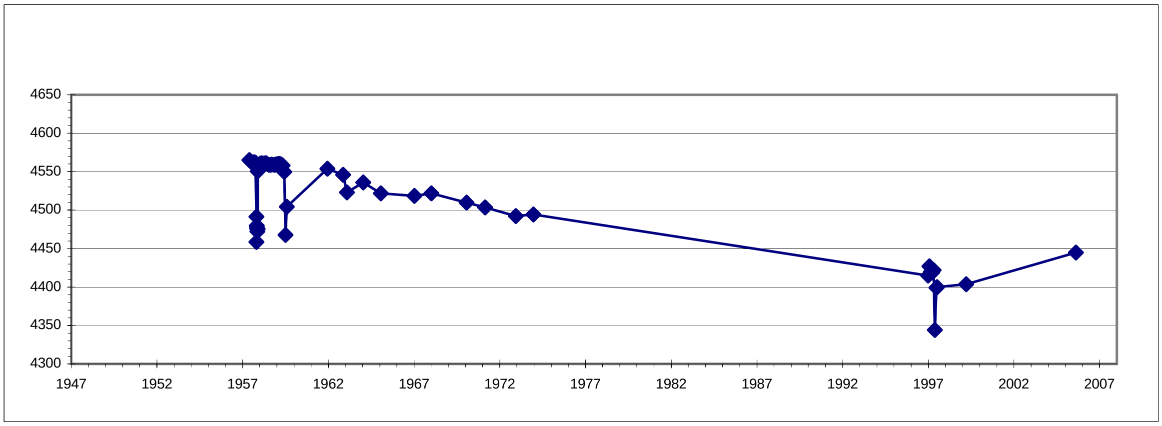


Figure A.2. Roberts No. 2 (52-35-705)

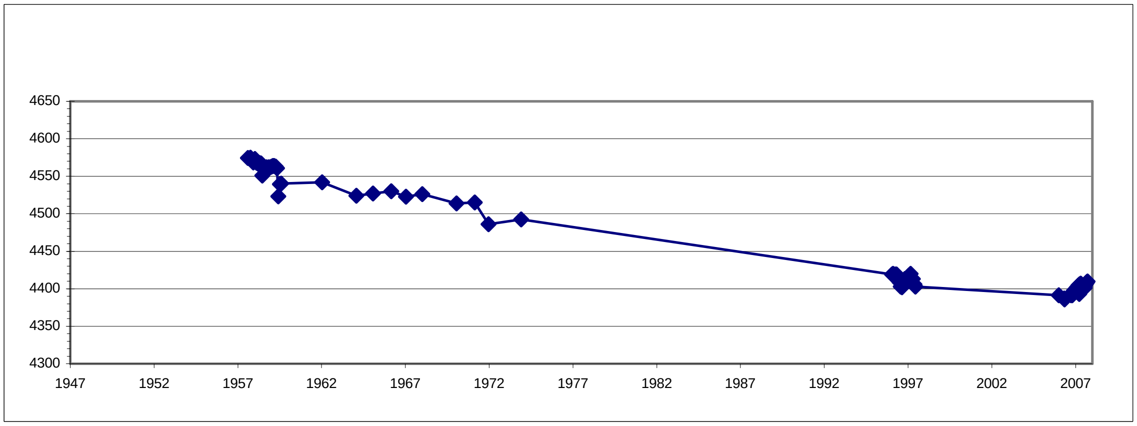


Figure A.3. Roberts No. 3 (52-35-706)

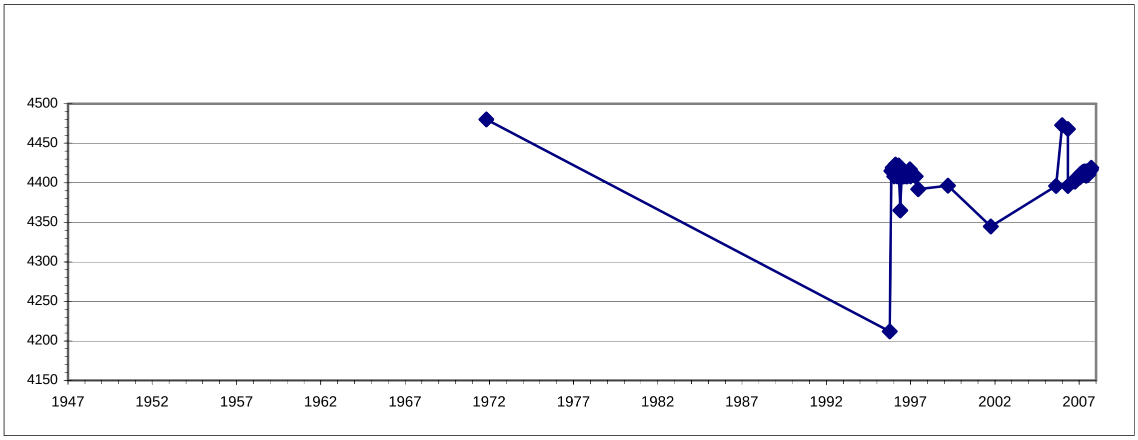


Figure A.4. Roberts No. 4 (52-35-702)

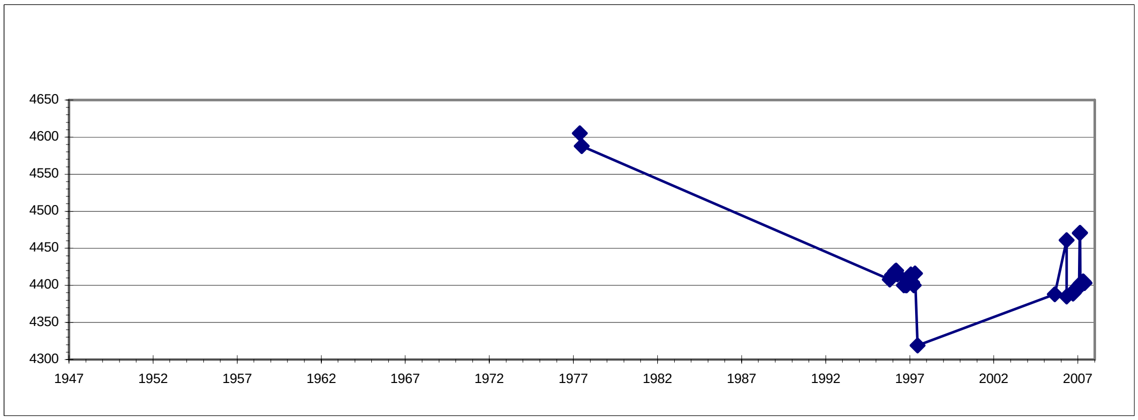


Figure A.5. Roberts No. 5 (52-35-703)

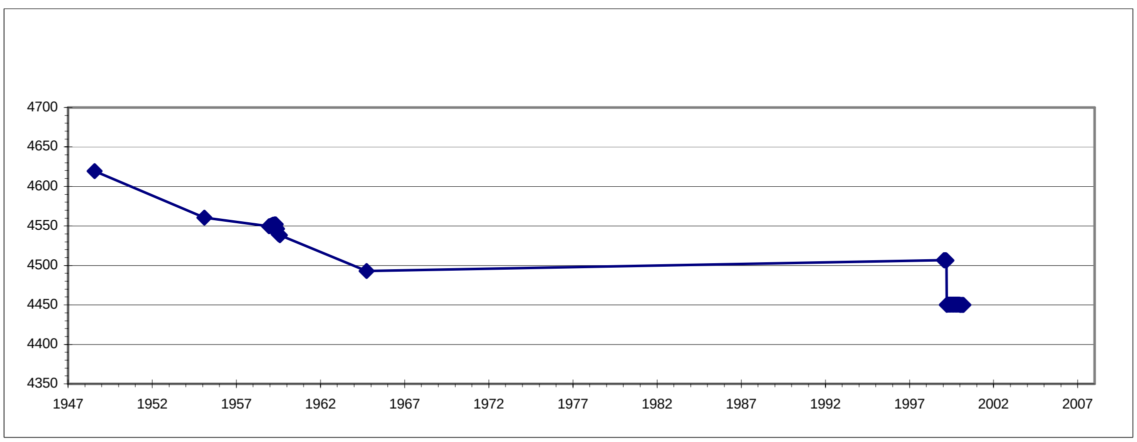


Figure A.6. Miles (52-35-707)

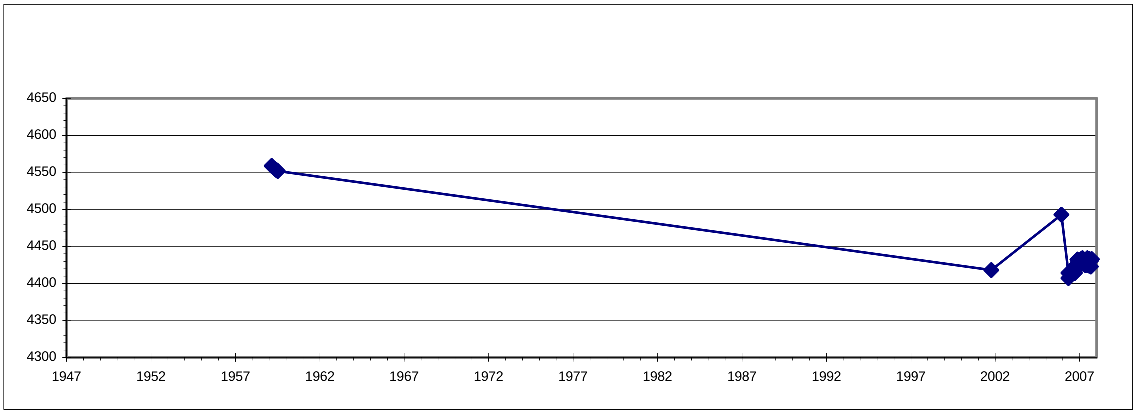


Figure A.7. Gardner (52-35-708)

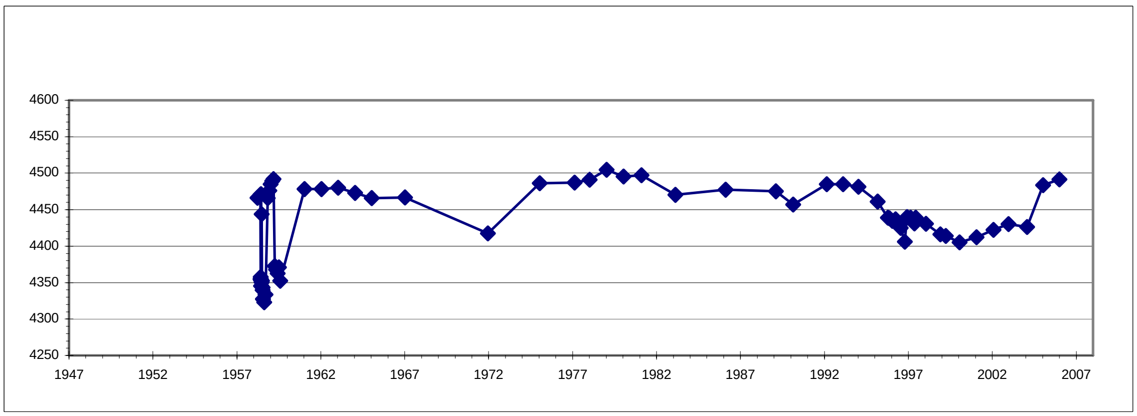


Figure A.8. Cartwright (52-35-709)

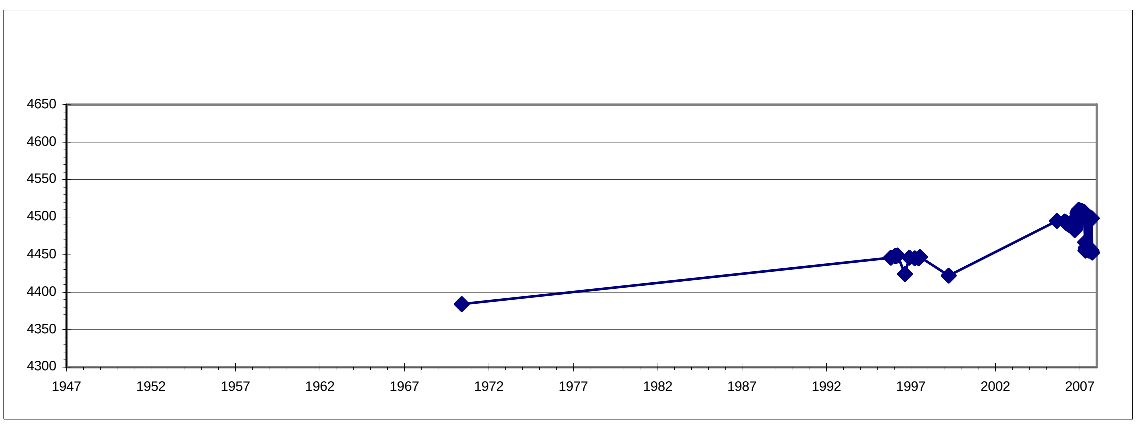


Figure A.9. Daugherty (52-35-710)

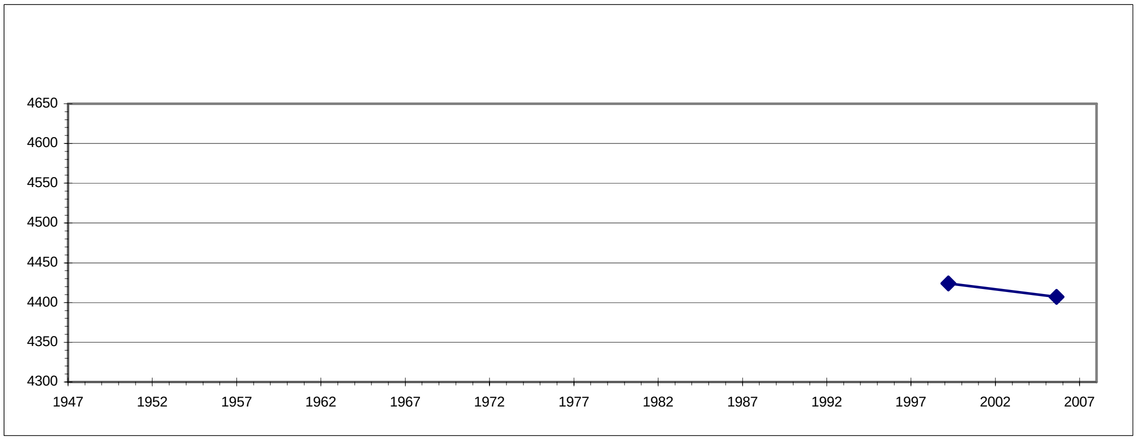


Figure A.10. Lewis Test Well (52-35-716)

Other Wells

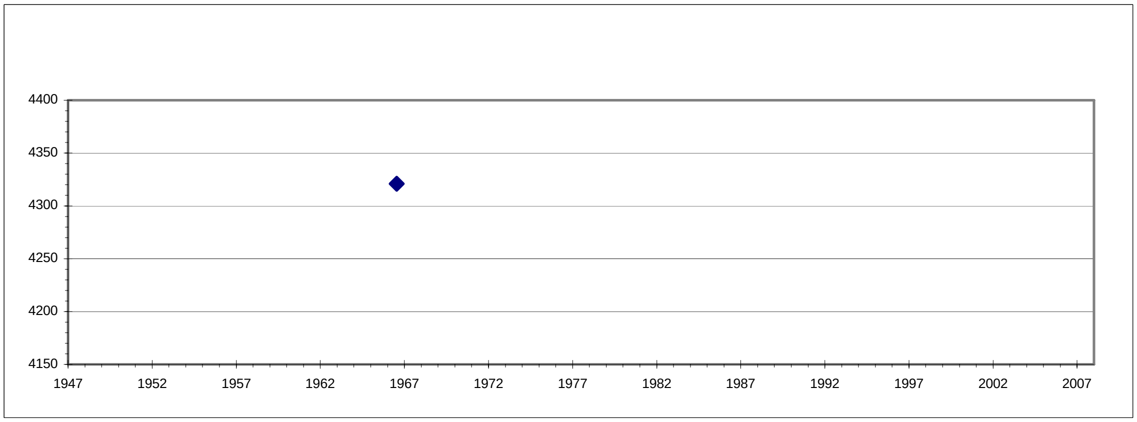


Figure A.11. Meriwether No. 1 (52-35-402)

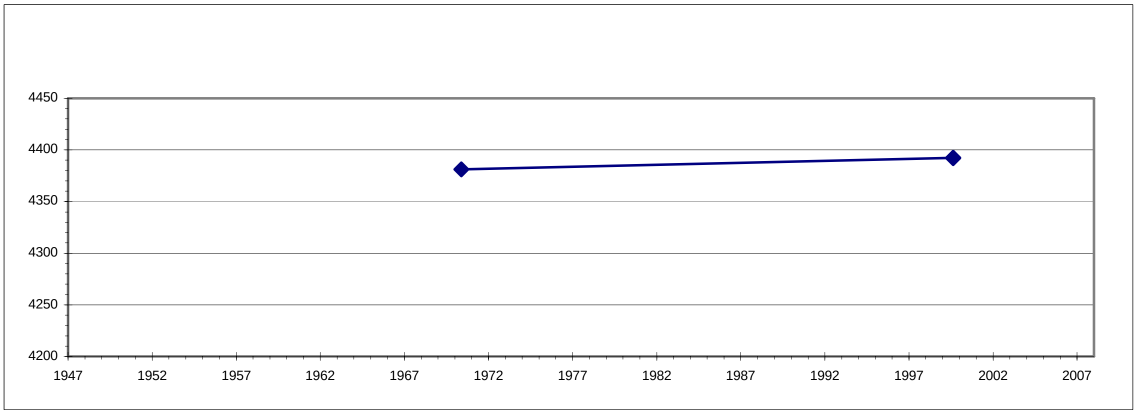


Figure A.12. Meriwether No. 2 (52-35-401)

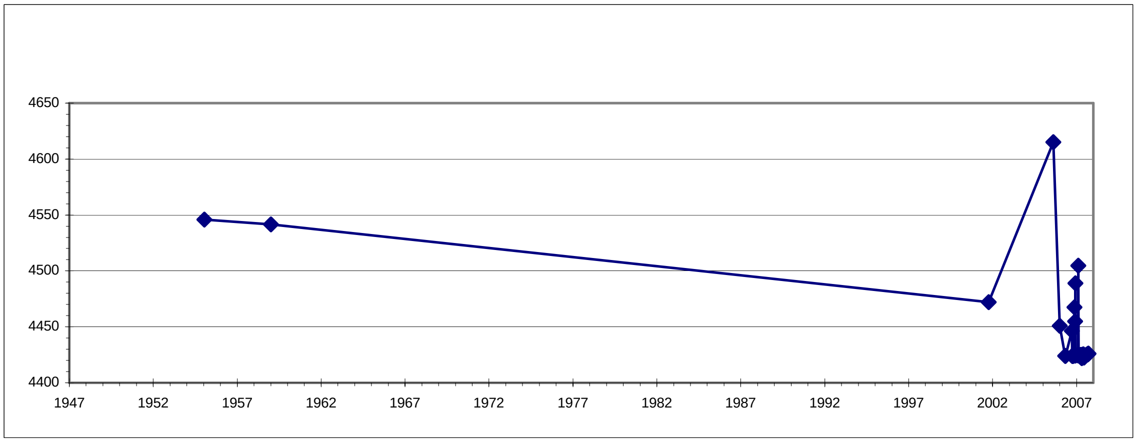


Figure A.13. Terry No. 2 (52-43-110)

Inner-City Wells

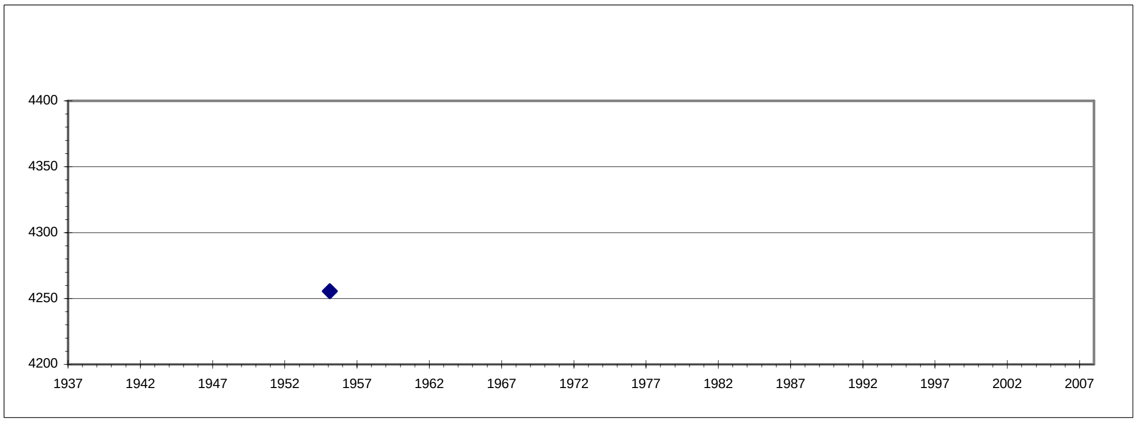


Figure A.14. Parker (52-35-801)

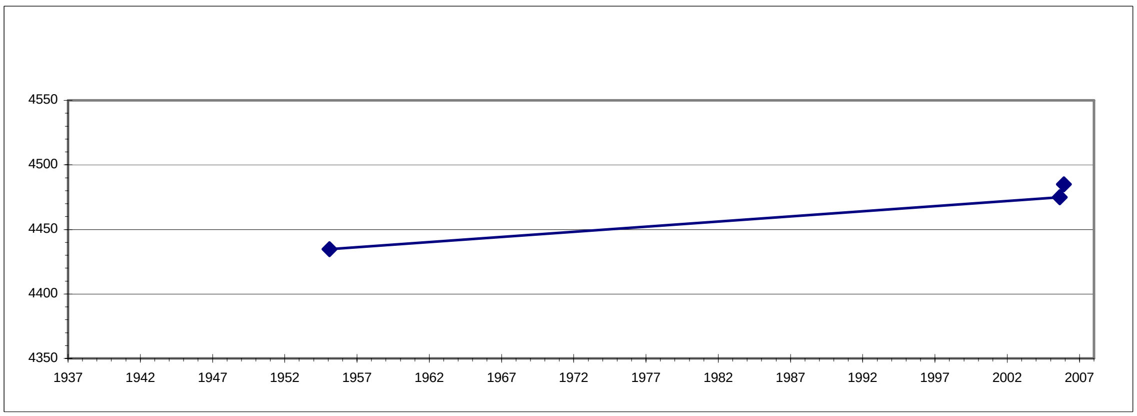


Figure A.15. Railroad (52-43-307)

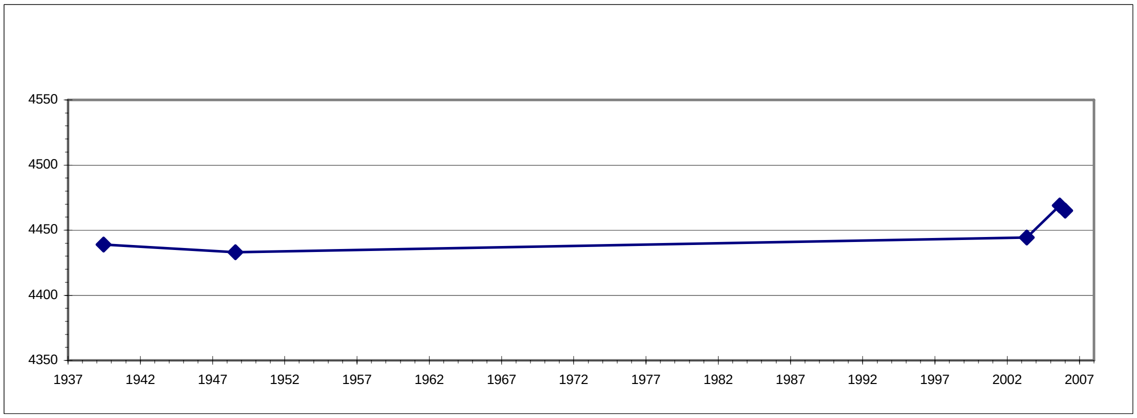


Figure A.16. East Well (52-43-308)

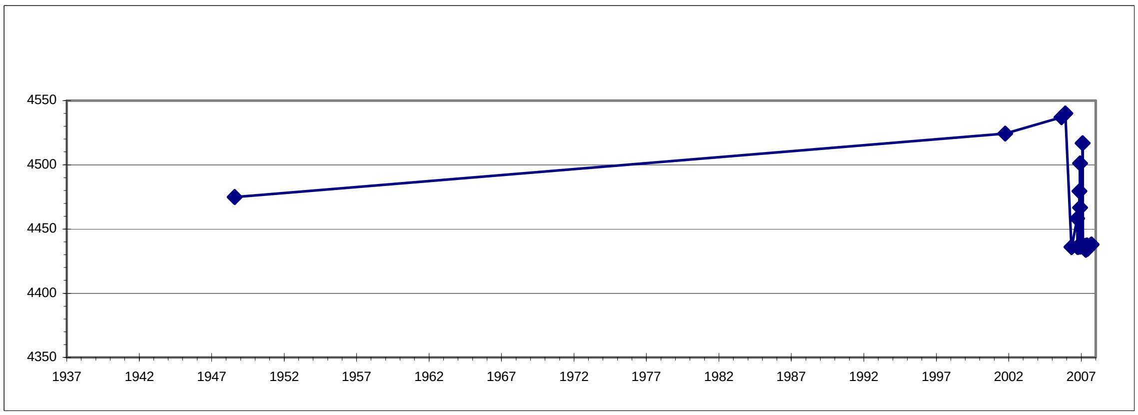


Figure A.17. Lower A Hill (52-43-310)

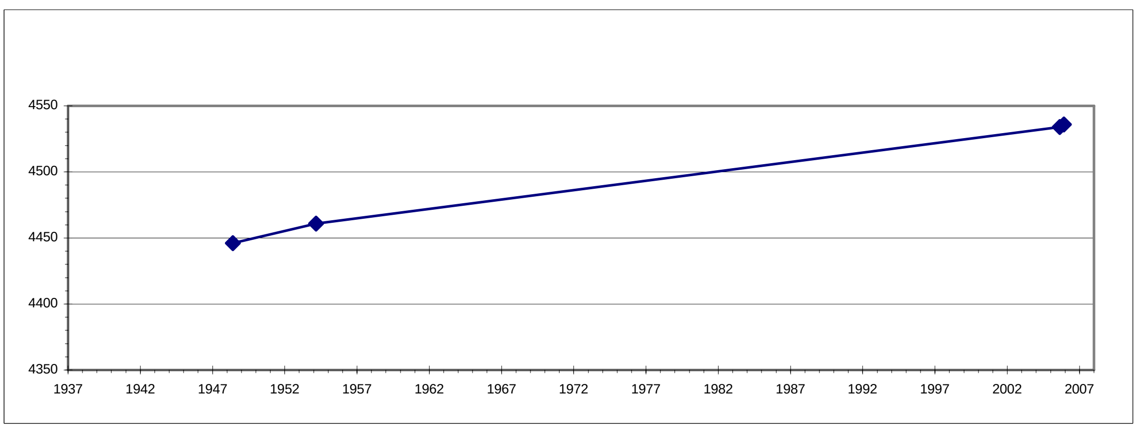


Figure A.18. Upper A Hill (52-43-311)

Figure A.19. Golf Course (52-43-312)

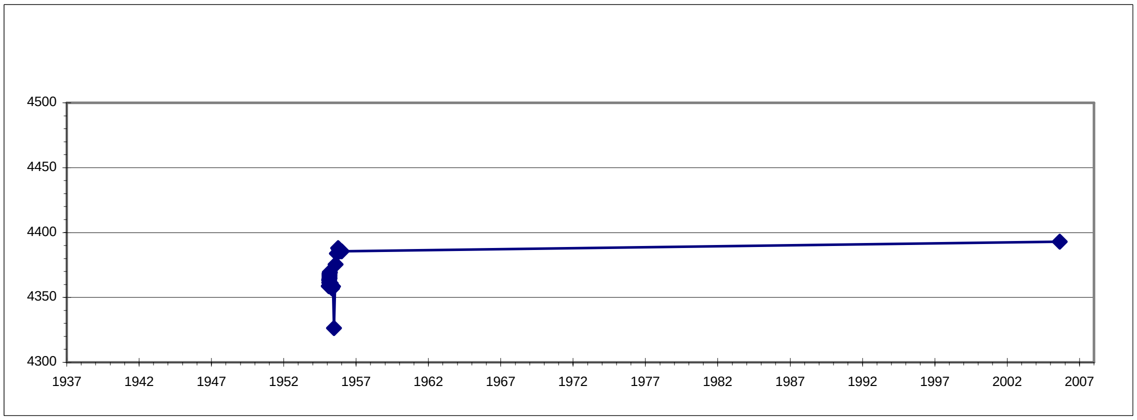


Figure A.20. Kokernot (52-35-905)

Musquiz Well Field

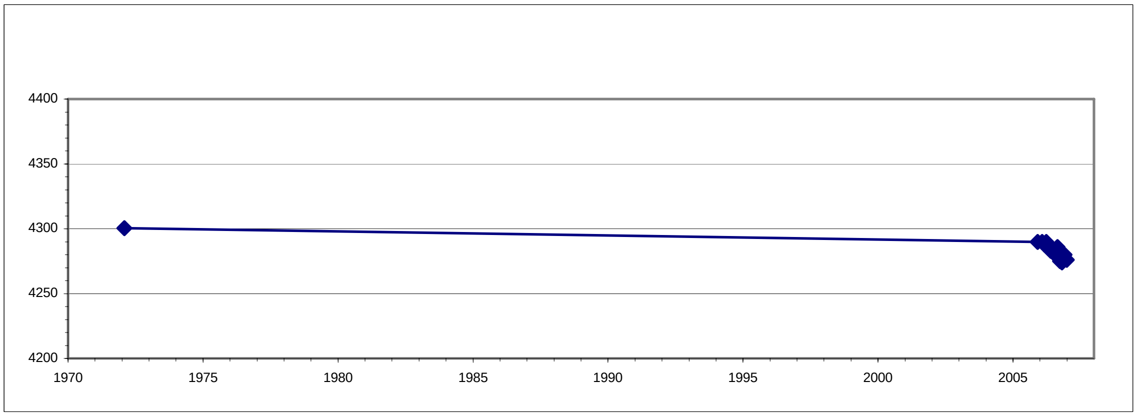


Figure A.21. Musquiz No. 6 (52-35-104)

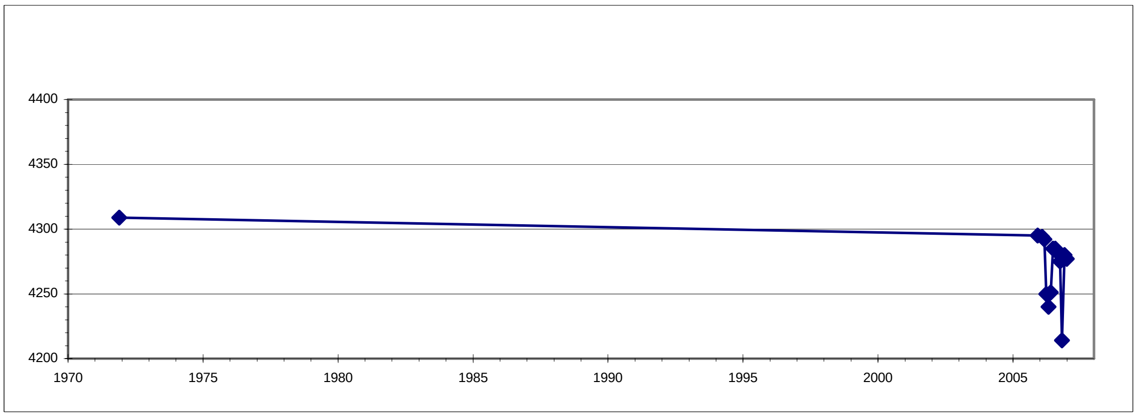


Figure A.22. Musquiz No. 7 (52-34-301)

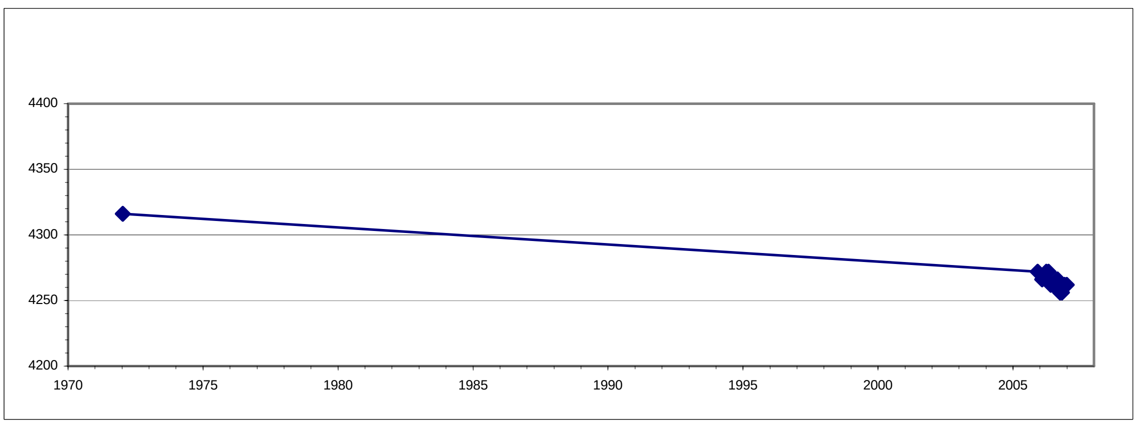


Figure A.23. Musquiz No. 8 (52-35-106)

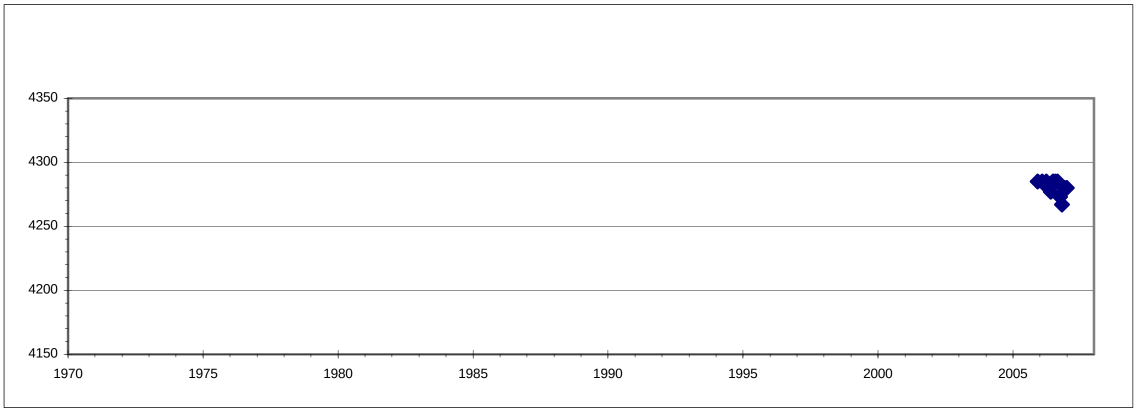


Figure A.24. Musquiz No. 9 (52-35-107)

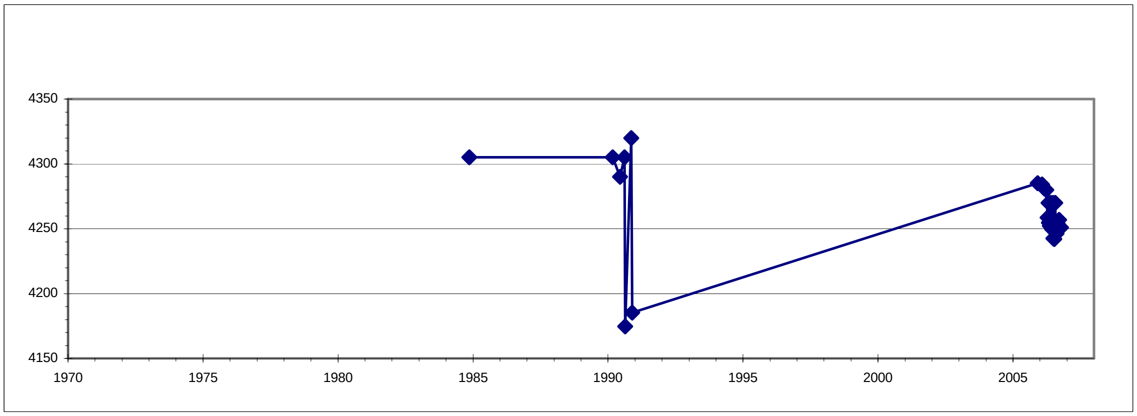


Figure A.25. Musquiz No. 10 (52-34-302)

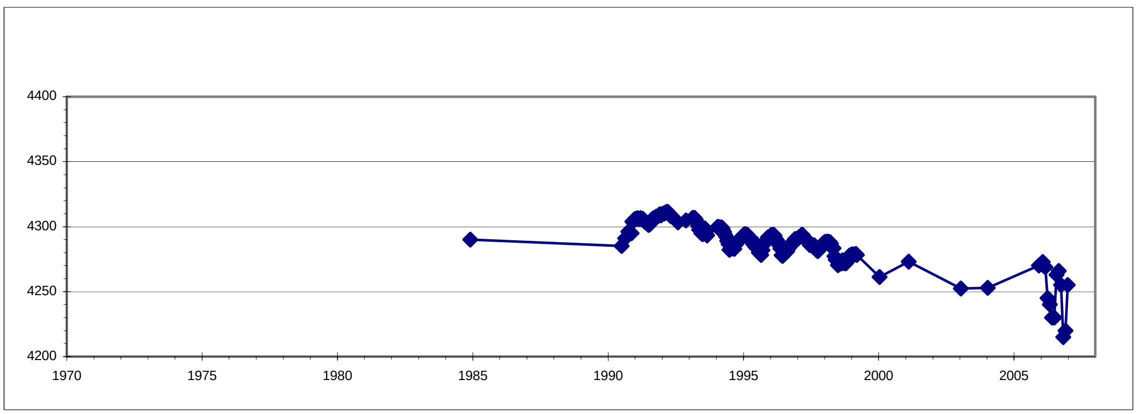


Figure A.26. Musquiz No. 11 (52-34-303)

APPENDIX B

Well hydrographs containing recent water-level data (2005-2008)

Sunny Glen Well Field

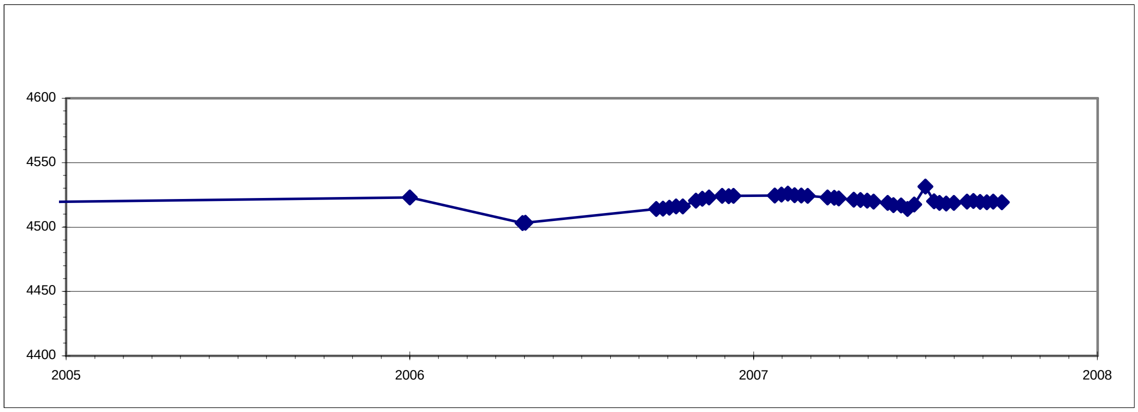


Figure B.1. Roberts No. 1 (52-35-704)

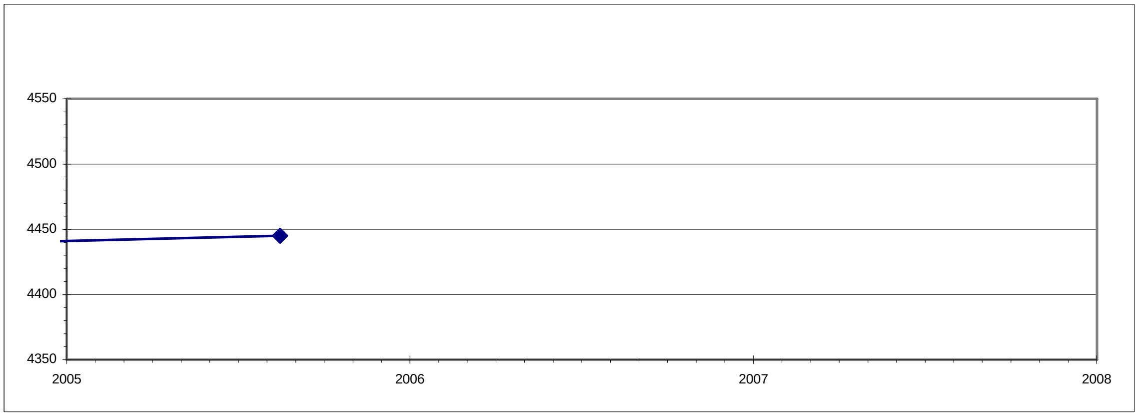


Figure B.2. Roberts No. 2 (52-35-705)

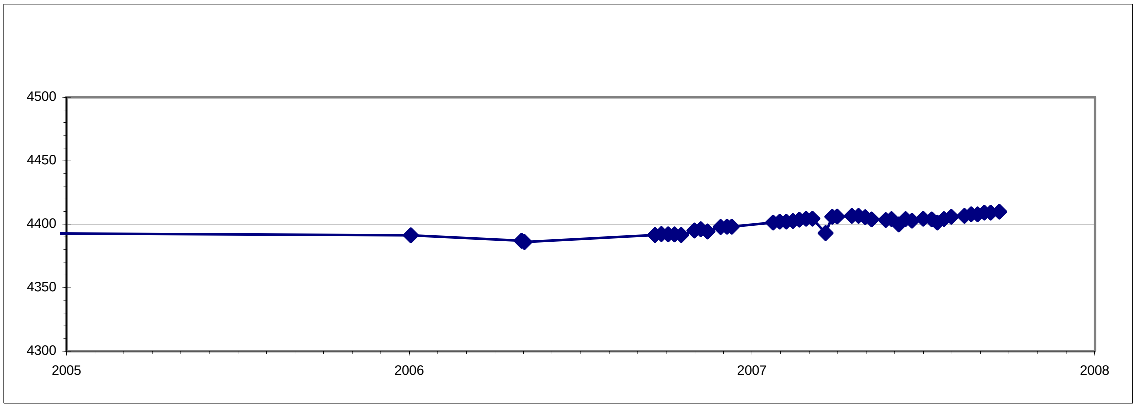


Figure B.3. Roberts No. 3 (52-35-706)

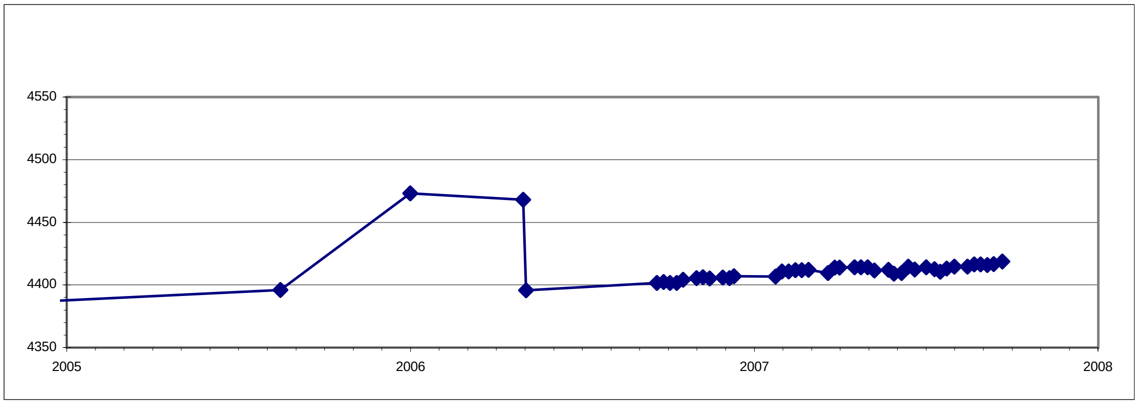


Figure B.4. Roberts No. 4 (52-35-702)

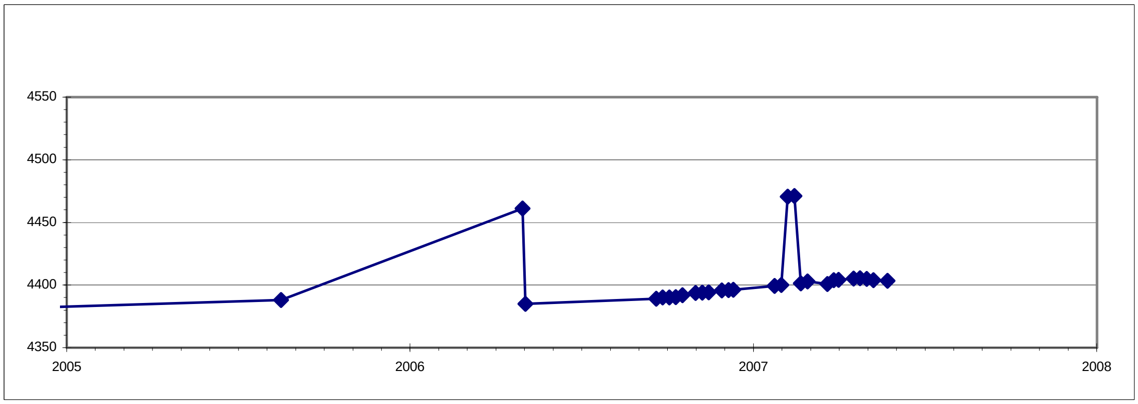


Figure B.5. Roberts No. 5 (52-35-703)

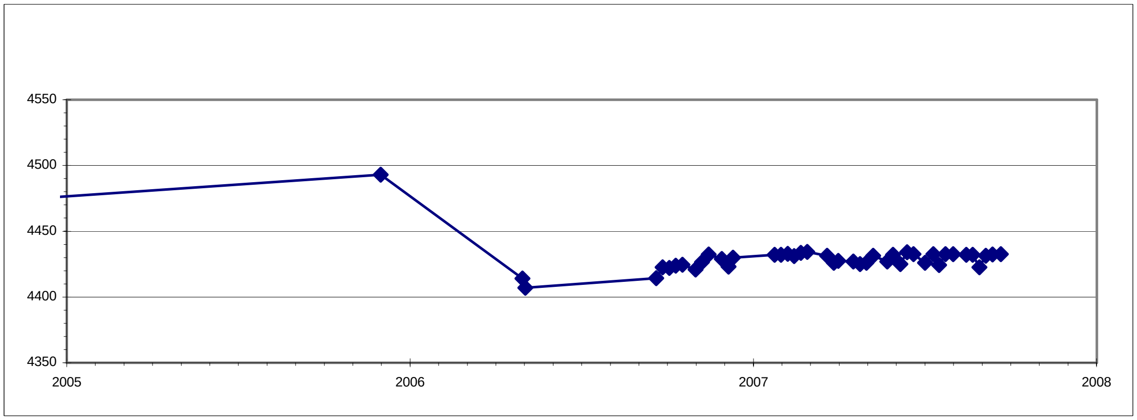


Figure B.6. Gardner (52-35-708)

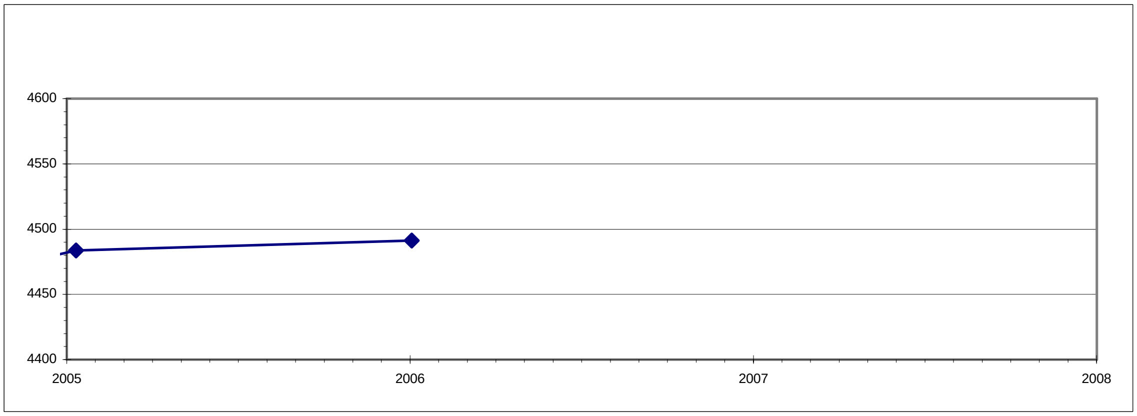


Figure B.7. Cartwright (52-35-709)

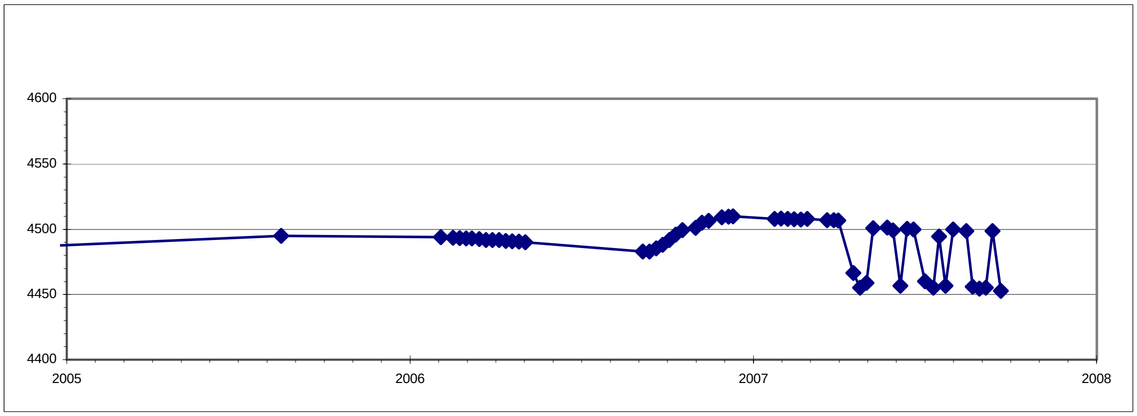


Figure B.8. Daugherty (52-35-710)

Other Wells

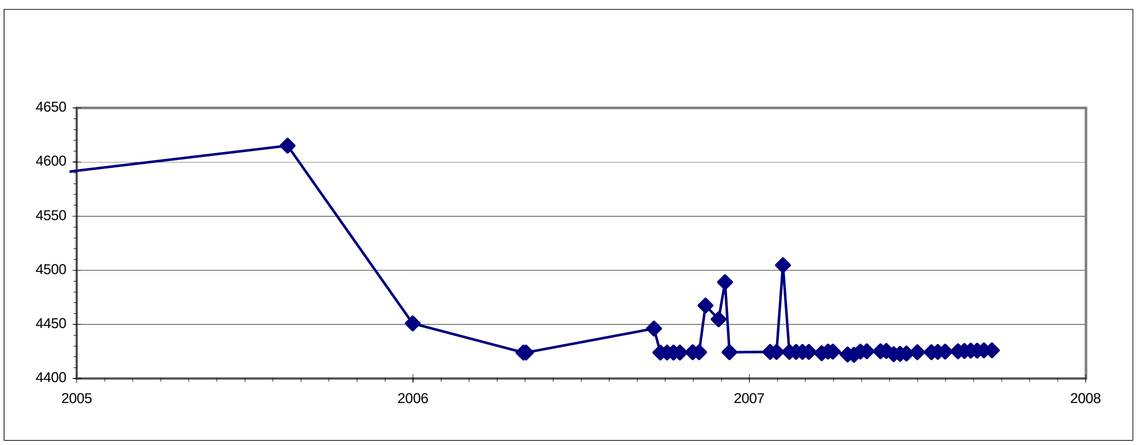


Figure B.9. Terry No. 2 (52-43-110)

Inner-City Wells

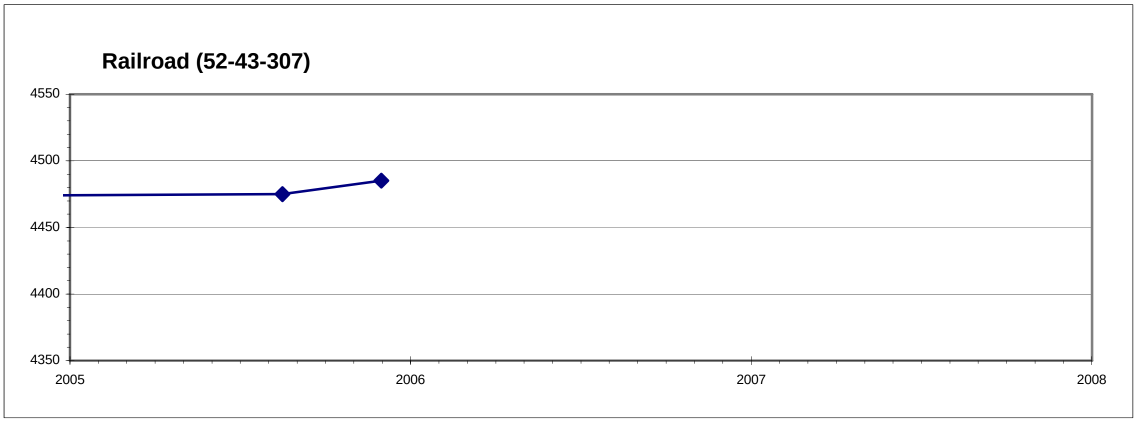


Figure B.10. Railroad (52-43-307)

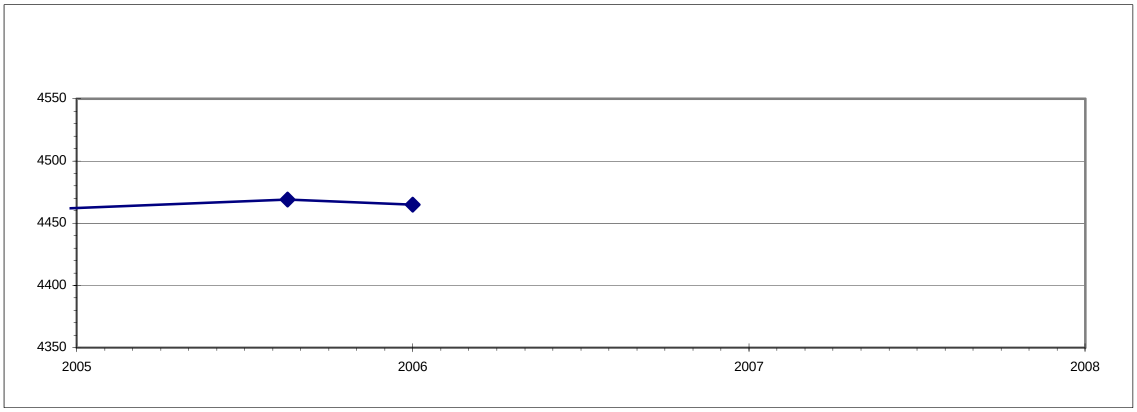


Figure B.11. East Well (52-43-308)

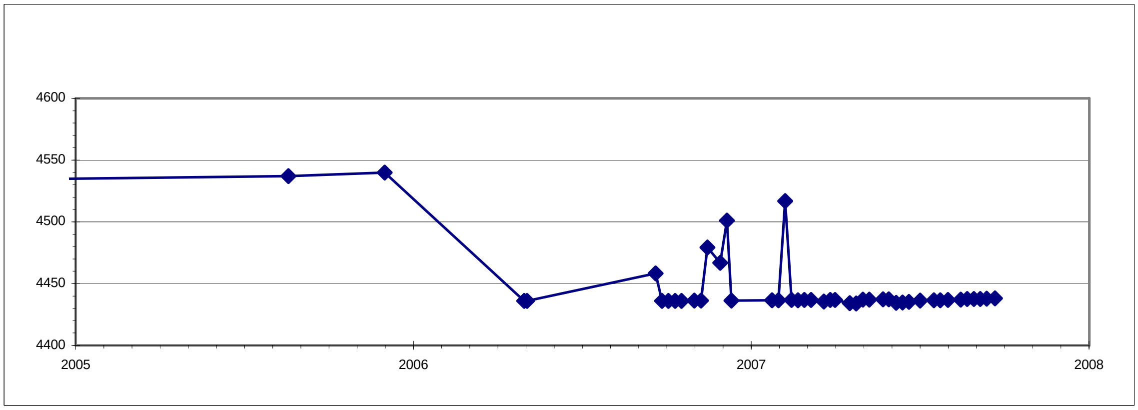


Figure B.12. Lower A Hill (52-43-310)

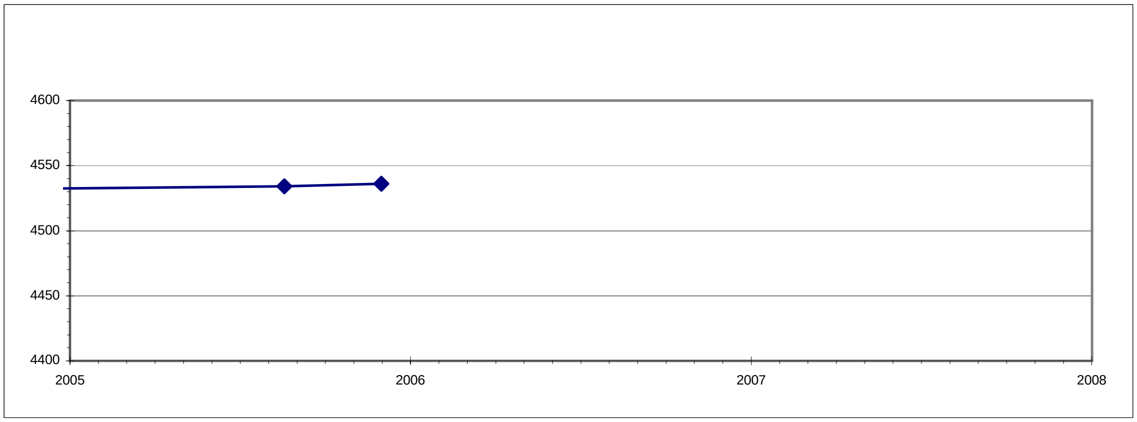


Figure B.13. Upper A Hill (52-43-311)

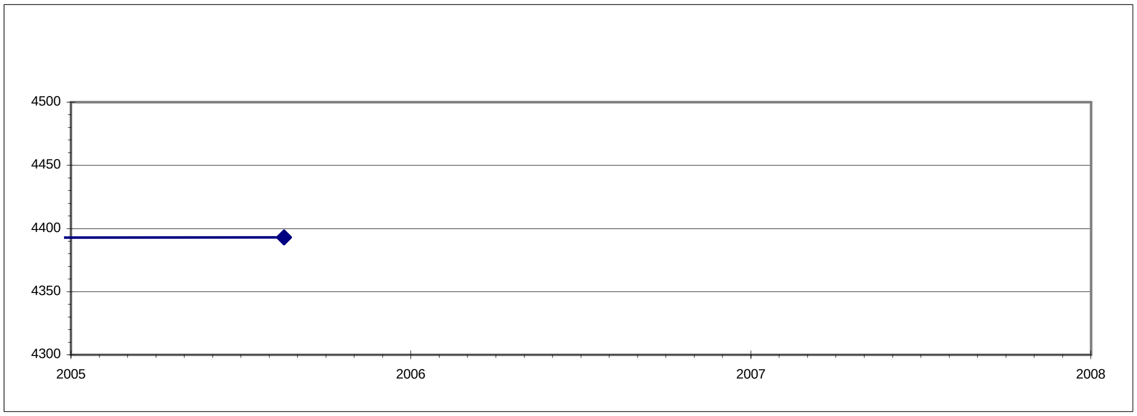


Figure B.14. Kokernot (52-35-905)

Musquiz Well Field

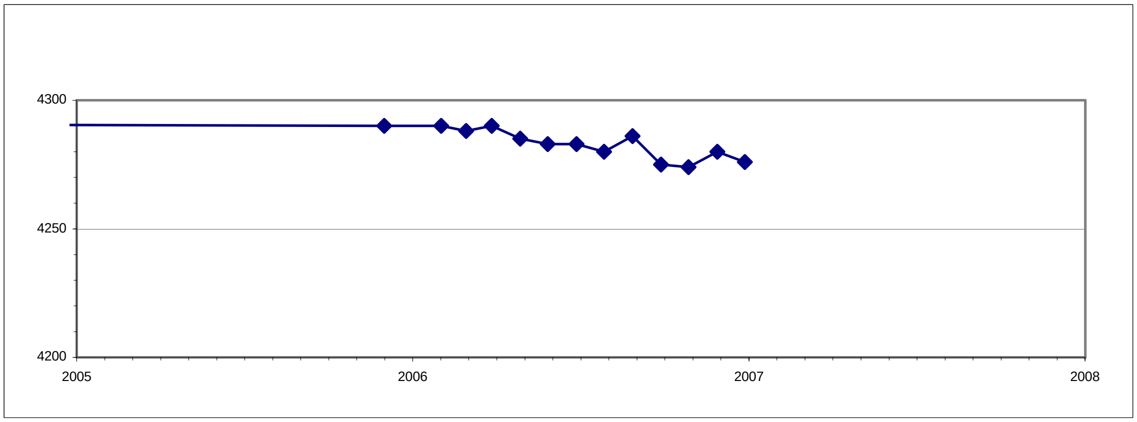


Figure B.15. Musquiz No. 6 (52-35-104)

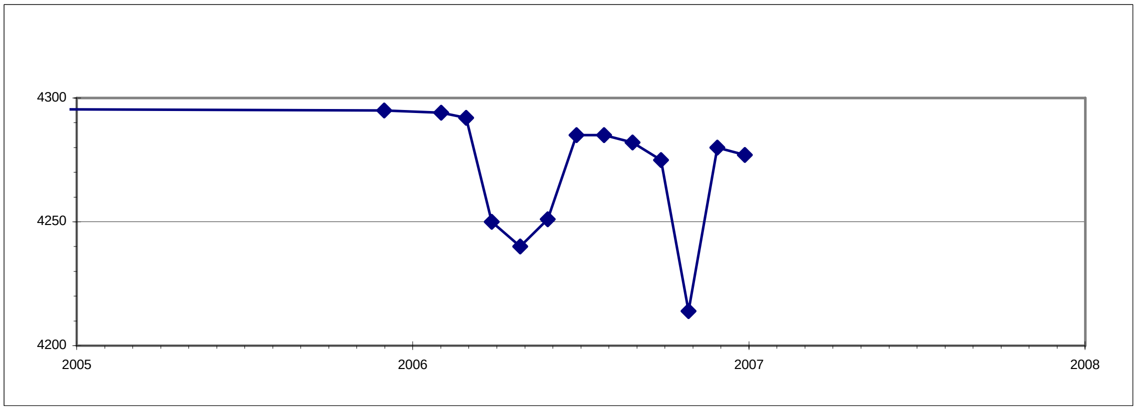


Figure B.16. Musquiz No. 7 (52-34-301)

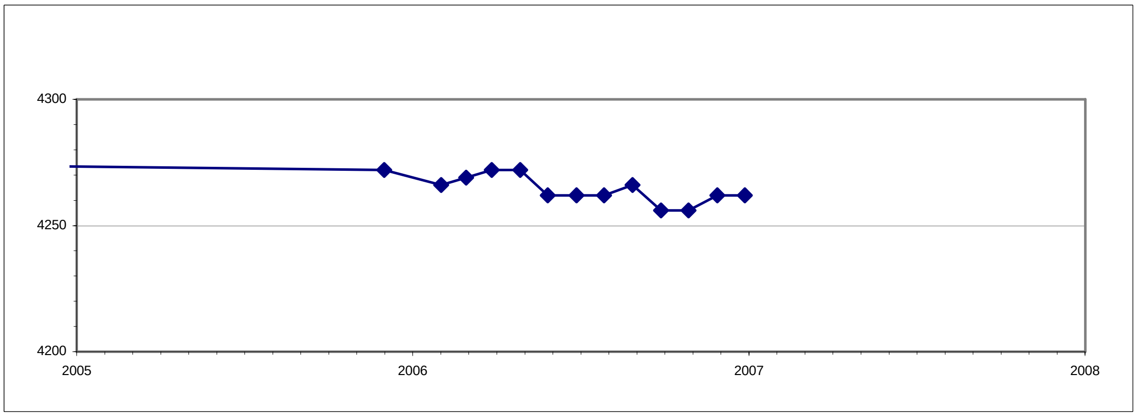


Figure B.17. Musquiz No. 8 (52-35-106)

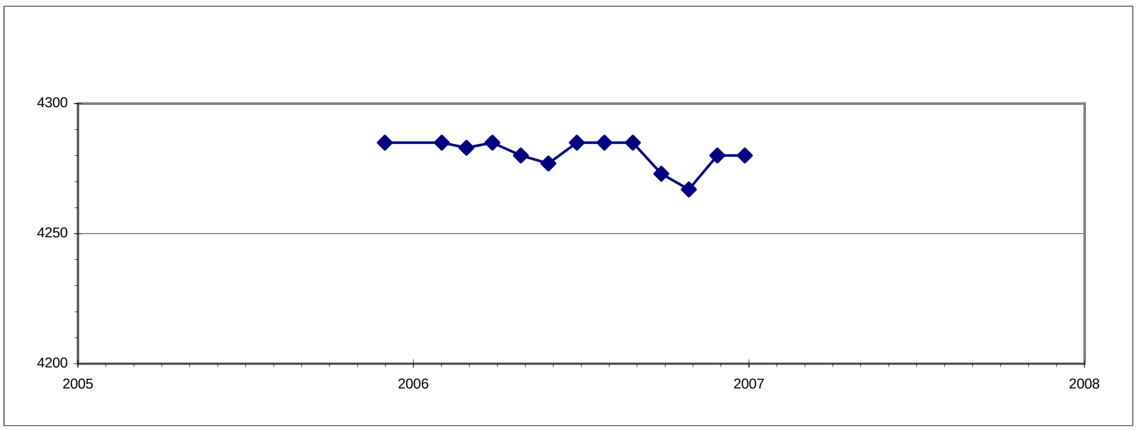


Figure B.18. Musquiz No. 9 (52-35-107)

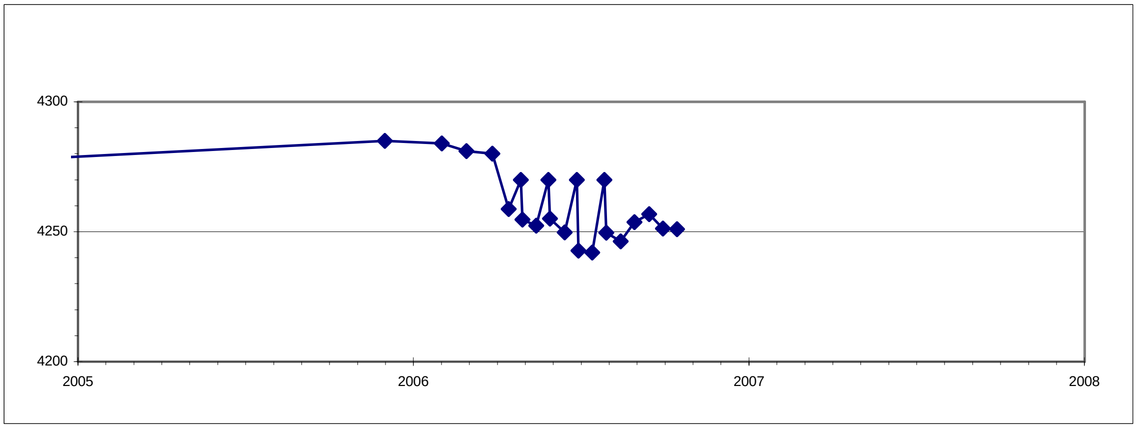


Figure B.19. Musquiz No. 10 (52-34-302)

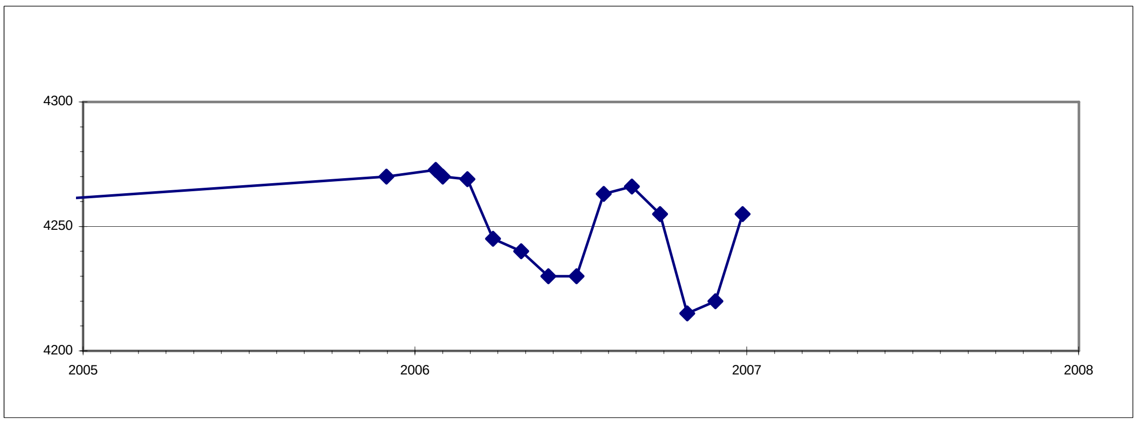


Figure B.20. Musquiz No. 11 (52-34-303)