Val Verde County / City of Del Rio Hydrogeological Study FINAL DRAFT REPORT

May 2014

EcoKai

Hydrogeological Study

For

Val Verde County & City of Del Rio, Texas

FINAL DRAFT REPORT

MAY 2014

Prepared for

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Val Verde County / City of Del Rio Hydrogeological Study FINAL REPORT – June 2014

Geoscientist and Engineering Seal

This report documents the work and supervision of work of the following licensed Texas Professional Geoscientist and licensed Texas Professional Engineers:

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Table of Contents

List of Figures

List of Tables

1.0 Introduction

1.1 Background and Objectives

The City of Del Rio and the County of Val Verde, Texas have formed a Partnership to complete a hydrogeologic study of the groundwater conditions in the Val Verde County area. In January 2013, EcoKai Environmental, Inc. (in association with William R. Hutchison, Ph.D., P.E., P.G., an independent groundwater consultant), provided a Statement of Qualifications to the partnership in response to their Request for Qualifications for Professional Hydrogeologic Services. In April 2013, EcoKai and Dr. Hutchison met with the Partnership, and the detailed scope of work for this study was mutually developed and discussed. The final scope of work and contract was finalized on May 20, 2013.

The overall objective of the requested hydrogeologic study was to determine correlations and potential impacts of groundwater pumping on local spring flows, lake elevations, and groundwater levels. An understanding of these correlations is necessary to evaluate the potential effects of additional groundwater pumping for export would have on the overall groundwater system. During the meeting in April 2013, the partnership expressed its desire to meet these objectives with a groundwater flow model of the area.

1.2 Groundwater Model Overview

The groundwater model developed in 2010 by Dr. Hutchison (while employed at the Texas Water Development Board) for the Kinney County area also encompassed Val Verde County. The early TWDB groundwater model was proposed as the foundation for this new groundwater model that covers Val Verde County. Specifically, the half-mile grid spacing, the geologic framework, and many of the boundary conditions of the Kinney County model were used as the foundation of this new model. The early model was developed using annual stress period while the new Val Verde County model was developed using monthly stress periods from 1968 to 2013.

Model calibration was completed using 3,605 groundwater elevations from 498 wells in Val Verde County from 1968 to 2013, and using spring flows from three springs (Cantu, McKee and San Felipe). Calibration of the model was considered sufficient to advance the objectives of the Partnership with regard to providing technical information that could be used in developing groundwater management guidelines (e.g. identification and delineation of the boundaries of groundwater management areas, conservation triggers, exportation cessation triggers, and generally characterizing groundwater conditions based on groundwater elevations and spring flows).

Specific applications of the calibrated model included: 1) a simulation to estimate the effect of Lake Amistad on groundwater elevations in the area, 2) a series of runs that were designed to provide information useful for management zone delineation, and 3) a series of simulations to evaluate the effects of large-scale pumping in three different areas to develop a better understanding of the nature and character of potential impacts of groundwater pumping on spring flow, river baseflow, aquifer drawdown, and other changes to the groundwater flow system.

1.3 Report Organization

This report summarizes activities related to model development, calibration, and application. Preliminary data analysis that was used in model conceptualization is covered in Chapter 2. Model development and calibration is covered in Chapter 3. Model application is covered in Chapter 4. A discussion of specific items of interest to the City of Del Rio and the County of Val Verde are discussed in Chapter 5. References are presented in Chapter 6.

2.0 Preliminary Data Analysis and Conceptual Model

Data used for this effort were obtained from the Texas Water Development Board groundwater database and from the International Boundary and Water Commission. The preliminary analyses presented here were completed to gain a conceptual understanding of the relationship between precipitation, lake levels, spring flows, and groundwater elevations.

2.1 Precipitation and Evaporation

The Texas Water Development Board maintains monthly precipitation and evaporation data on a grid system for the entire state, and includes data from 1940 to current. Val Verde County is covered by portions of four quadrangles as shown in Figure 1. A data summary for monthly precipitation is presented in Table 1, and a data summary for monthly evaporation is presented in Table 2.

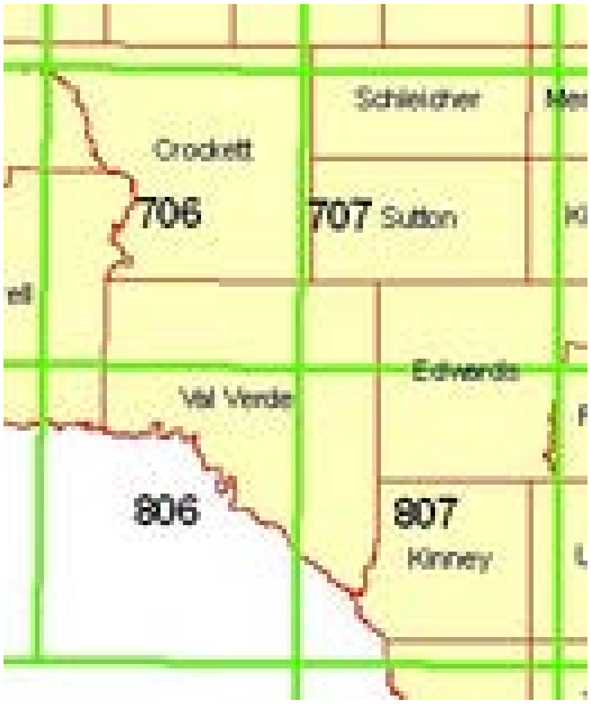

Figure 1. Precipitation and Evaporation Quadrangles of Val Verde County

Table 1. Summary of Average Precipitation for Four Quadrangles (in/mo and in/yr)

Month	Q706	Q707	Q806	Q807	Average
January	0.96	1.06	0.70	1.15	0.97
February	0.99	1.26	0.84	1.41	1.13
March	1.06	1.31	0.83	1.59	1.20
April	1.56	1.92	1.28	2.13	1.72
May	2.31	2.76	2.17	3.09	2.58
June	2.14	2.55	2.07	2.78	2.38
July	1.60	1.87	1.56	2.00	1.76
August	1.95	2.41	1.70	2.29	2.09
September	2.46	2.60	2.39	2.93	2.60
October	2.15	2.44	1.93	2.53	2.26
November	0.99	1.26	0.73	1.45	1.11
December	0.80	0.97	0.57	1.24	0.90
Annual	18.97	22.41	16.75	24.59	20.68

Table 2. Summary of Average Evaporation for Four Quadrangles (in/mo and in/yr)

Month	Q706	Q707	Q806	Q807	Average
January	2.54	2.47	2.57	2.53	2.53
February	2.97	2.84	3.06	3.00	2.97
March	4.76	4.63	5.02	4.87	4.82
April	5.80	5.78	6.20	5.98	5.94
May	6.06	6.00	6.38	6.23	6.17
June	7.67	7.50	8.34	8.07	7.90
July	8.59	8.51	9.39	9.13	8.90
August	7.99	7.90	9.01	8.74	8.41
September	6.04	5.85	6.80	6.58	6.32
October	4.81	4.67	5.30	5.19	4.99
November	3.29	3.22	3.58	3.48	3.39
December	2.54	2.51	2.62	2.58	2.56
Annual	63.05	62.00	68.42	66.53	64.90

Annual precipitation data were used to evaluate 5-year and 10-year running averages to characterize the current drought conditions in the context of the drought of the 1950s. The graphs associated with this analysis are presented in Figures 2 and 3.

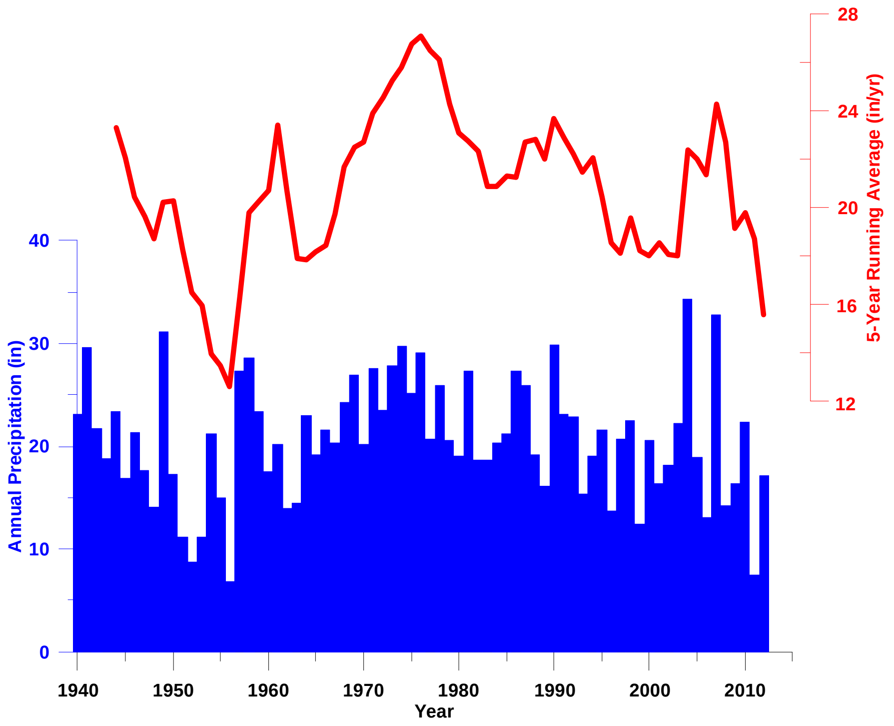

Figure 2. Annual Precipitation and 5-Year Running Average Precipitation

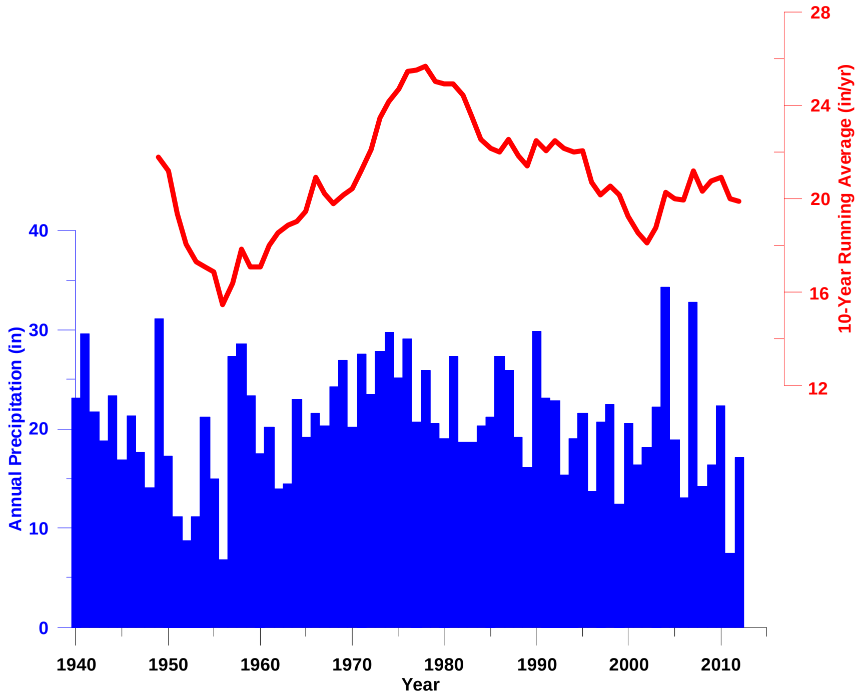

Figure 3. Annual Precipitation and 10-Year Running Average Precipitation

For both Figures 2 and 3, annual precipitation is shown as blue bars in in/yr, and the running average (5-year in Figure 2 and 10-year in Figure 3) is shown as red lines. It can be seen that the 1950s had lower average precipitation than recent years. Based on the 5-year running average, the current drought is the second worst on record. However, based on the 10-year running average, the late 1990s/early 2000s were drier than current times. It can also be seen that the 1970s was the wettest period in the record, which coincided with the period of time when Lake Amistad was initially in operation.

2.2 Lake Amistad Elevation

Monthly data for Lake Amistad elevations are summarized in Figure 4. Note that the elevation data includes the period prior to the initial operation of the reservoir, and that even at "low" reservoir conditions (in the early 2000s), the elevation is over 100 feet higher than prior to reservoir operation.

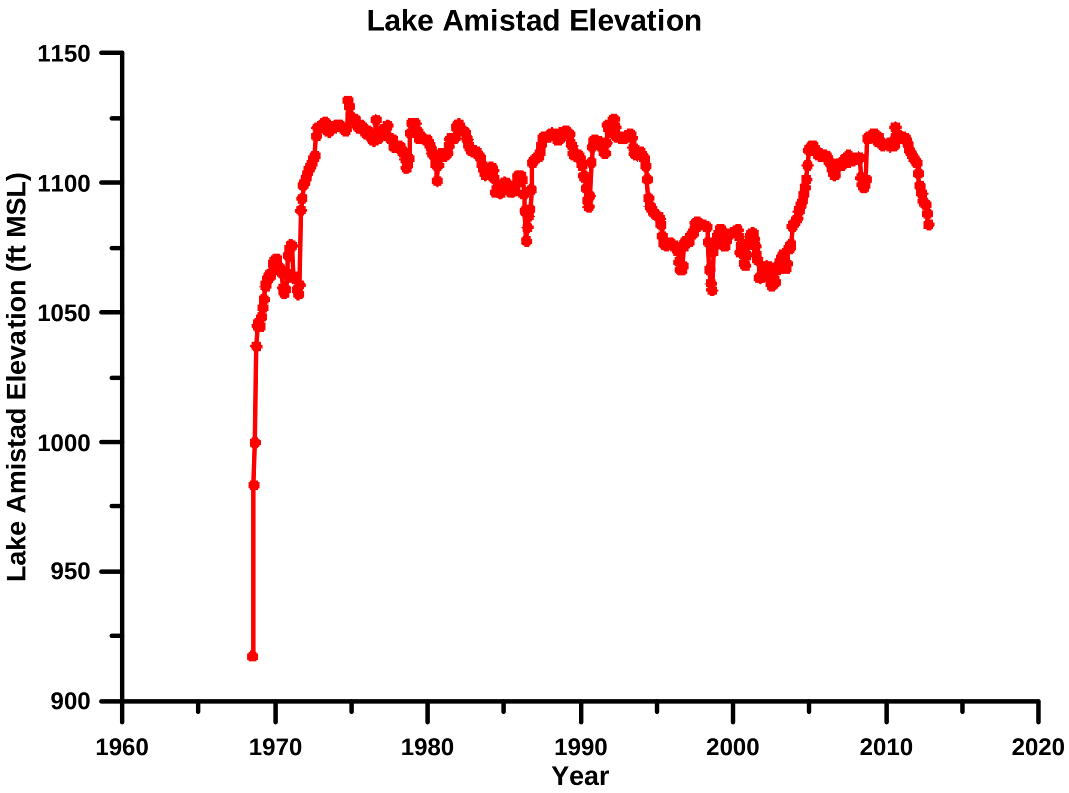

Figure 4. Monthly Lake Amistad Elevation

2.3 San Felipe Spring

Monthly data for San Felipe Spring flow (in million gallons per day) are summarized in Figure 5. Please note that the lowest flows occurred in 1969 (prior to the initial operation of Lake Amistad), in 1996 and in 2012. Conceptually, it appears that Lake Amistad has had an effect on San Felipe Spring, and the low flows in 1996 and 2012 appear to be related to low precipitation periods.

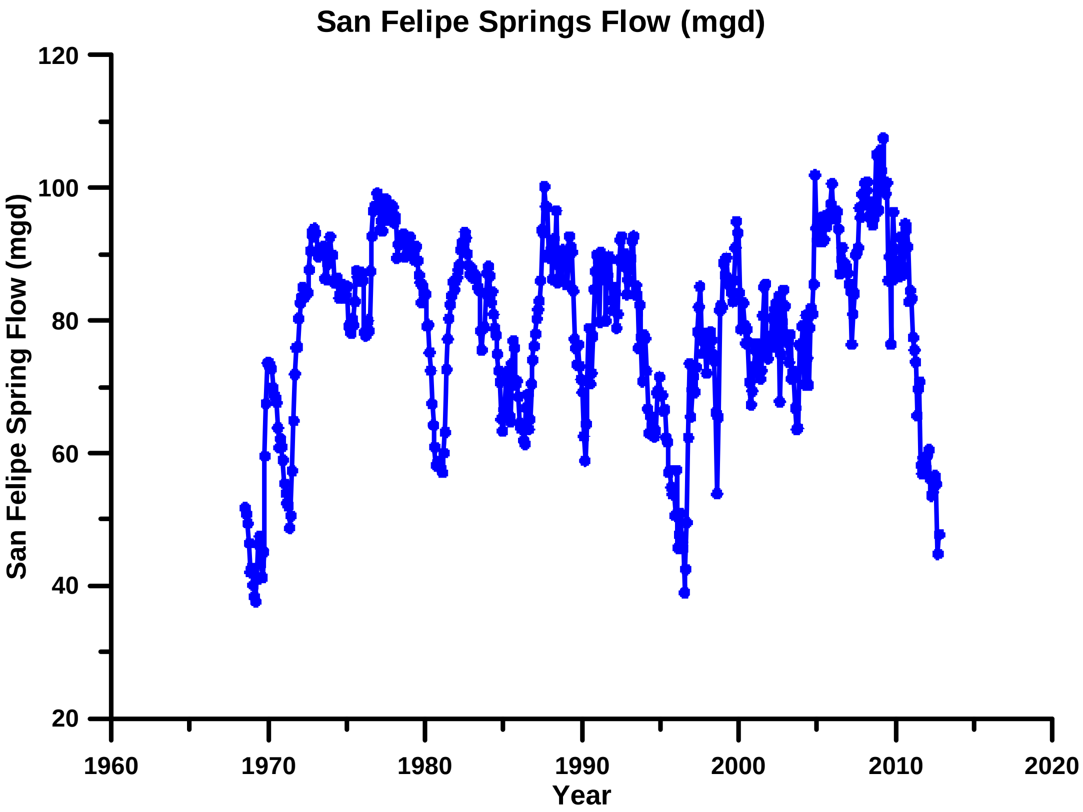

Figure 5. Monthly San Felipe Spring Flow

2.4 Correlation of Spring Flow and Lake Amistad Elevation

The lake elevation and spring flow data summarized above were evaluated together to improve the conceptual understanding of the controlling influences on spring flow variation. Figure 6 shows a hydrograph of Lake Amistad Elevation (in red) and San Felipe Spring flow (in blue).

Please note the strong correlation in the early 1970s. As Lake Amistad began to fill, spring flow rose from about 40 million gallons per day (mgd) to over 90 mgd. Lower lake elevations seem to correlate well to lower spring flows in the 1980s, 1990s and in recent years.

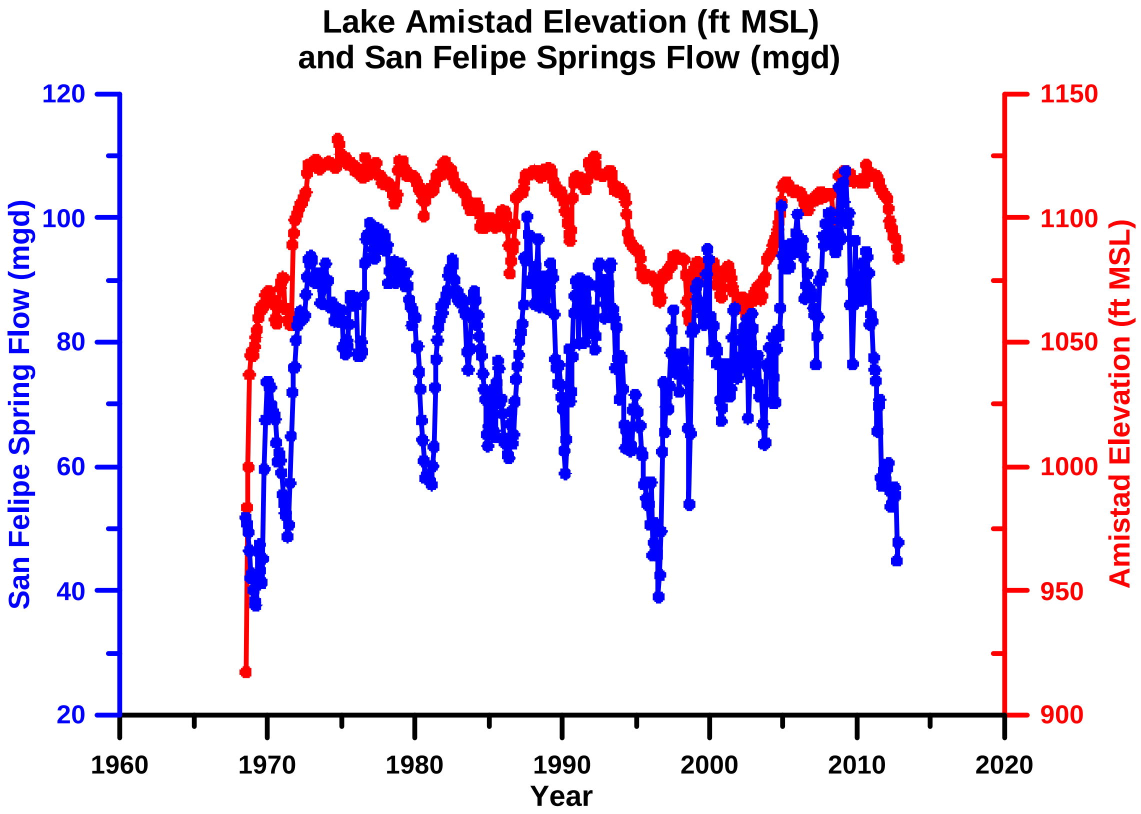

Figure 6. Hydrograph of Lake Amistad Elevation and San Felipe Spring Flow

2.5 Correlation of Spring Flow and Precipitation

Similar to the analysis with lake elevations, spring flow and precipitation data were evaluated together to improve the conceptual understanding of the controlling influences on spring flow variation. In order to preliminarily investigate the effects of several months of cumulative precipitation, hydrographs were developed for:

- 6-month precipitation and San Felipe Spring flow (Figure 7)
- 9-month precipitation and San Felipe Spring flow (Figure 8)
- 12-month precipitation and San Felipe Spring flow (Figure 9)
- 18-month precipitation and San Felipe Spring flow (Figure 10)
- 24-month precipitation and San Felipe Spring flow (Figure 11)

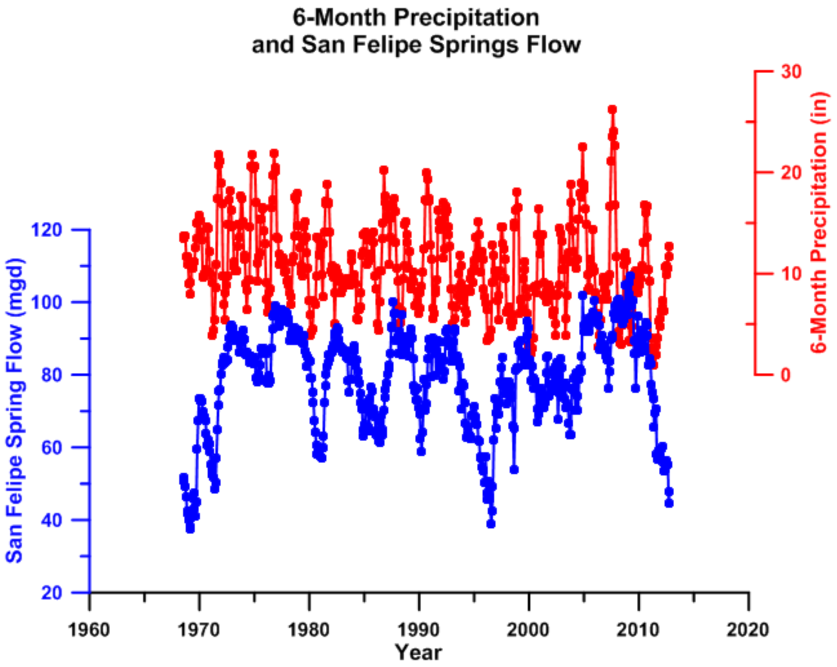

Figure 7. 6-Month Precipitation and San Felipe Spring Flow

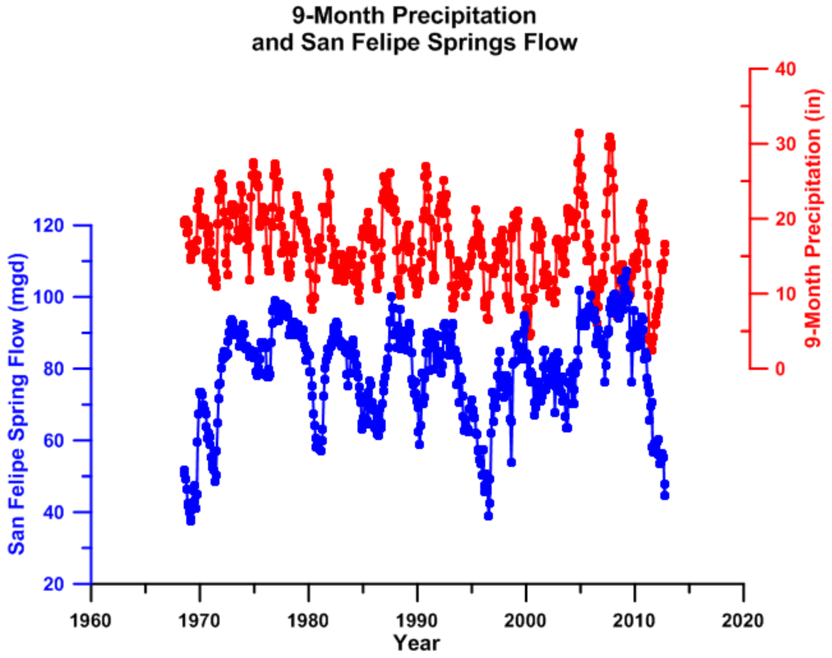

Figure 8. 9-Month Precipitation and San Felipe Spring Flow

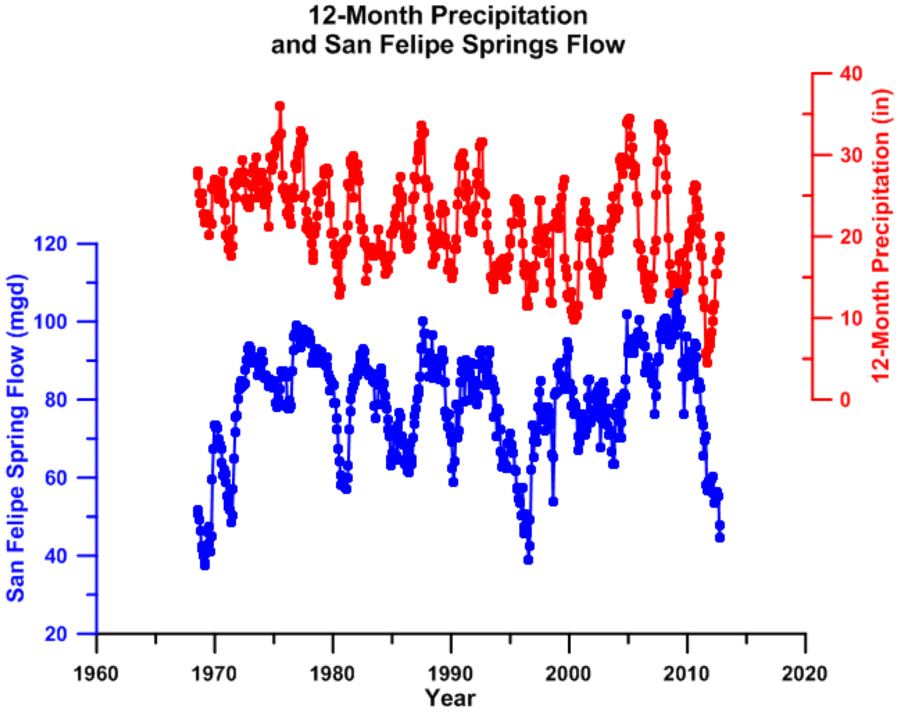

Figure 9. 12-Month Precipitation and San Felipe Spring Flow

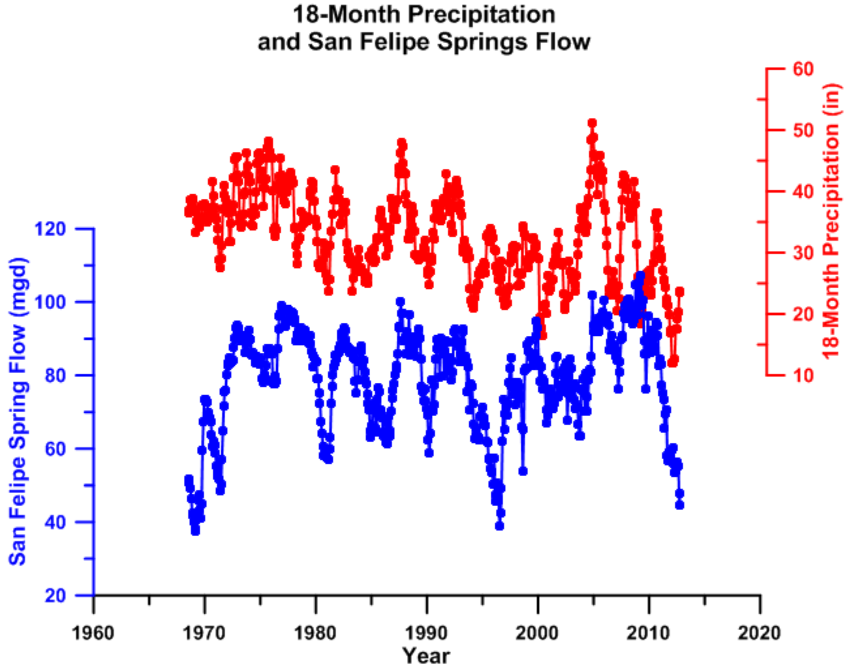

Figure 10. 18-Month Precipitation and San Felipe Spring Flow

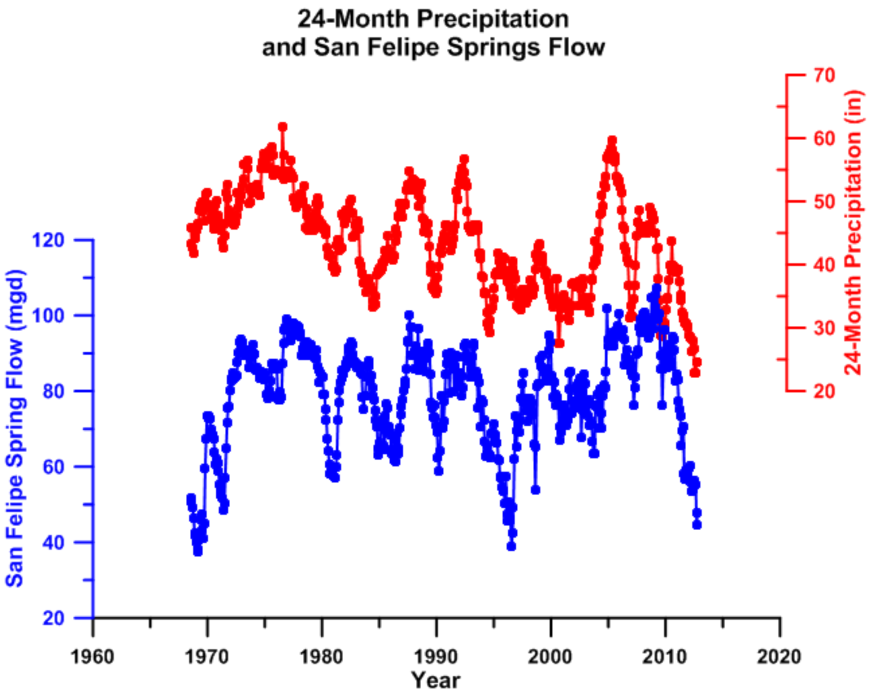

Figure 11. 24-Month Precipitation and San Felipe Spring Flow

In all plots, precipitation appears to be declining from 1970 to present. The correlation between cumulative precipitation and spring flow improves as the period of cumulative precipitation increases. Qualitatively, it appears that the correlations for the 18-month and 24-month cumulative precipitation are better than the 6-month or 9-month cumulative precipitation correlations. This observation suggests that there is some "memory" in the system that lasts several months.

2.6 Multiple Regression Analysis of Spring Flow, Precipitation and Lake Amistad Elevation

San Felipe Spring flow appears to be correlated with Lake Amistad elevation and precipitation. The combined effects of precipitation and Lake Amistad elevation were investigated by developing multiple regression models of spring flow as the dependent variable with precipitation and lake elevation as the independent variables. Plots of actual spring flow and predicted spring flow are presented for the following cumulative precipitation scenarios:

- 6-month precipitation (Figure 12)
- 9-month precipitation (Figure 13)
- 12-month precipitation (Figure 14)
- 18-month precipitation (Figure 15)
- 24-month precipitation (Figure 16)

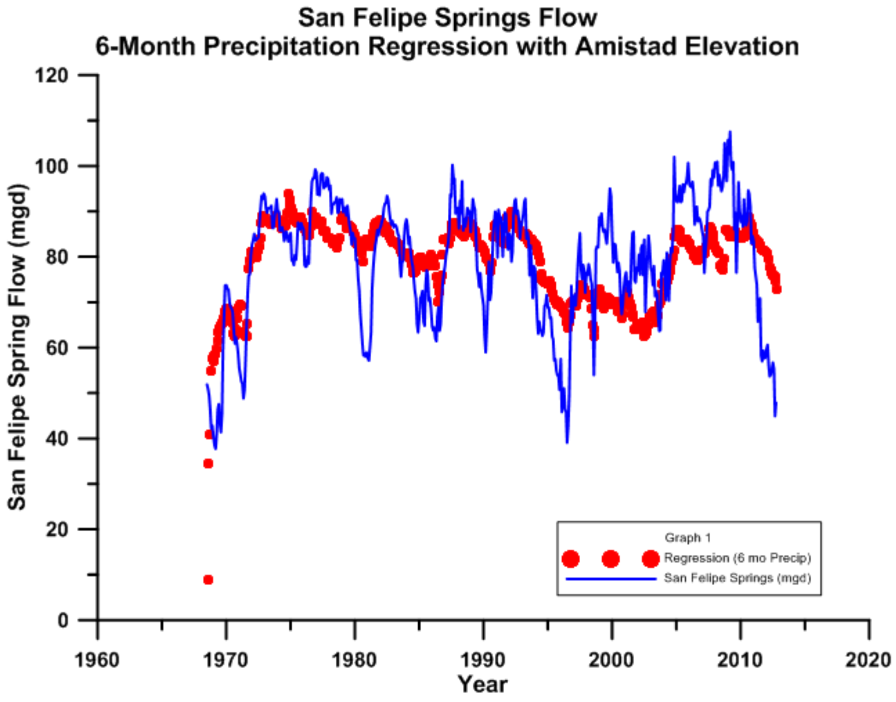

Figure 12. San Felipe Spring Flow - 6-Month Precipitation Regression with Amistad Elevation

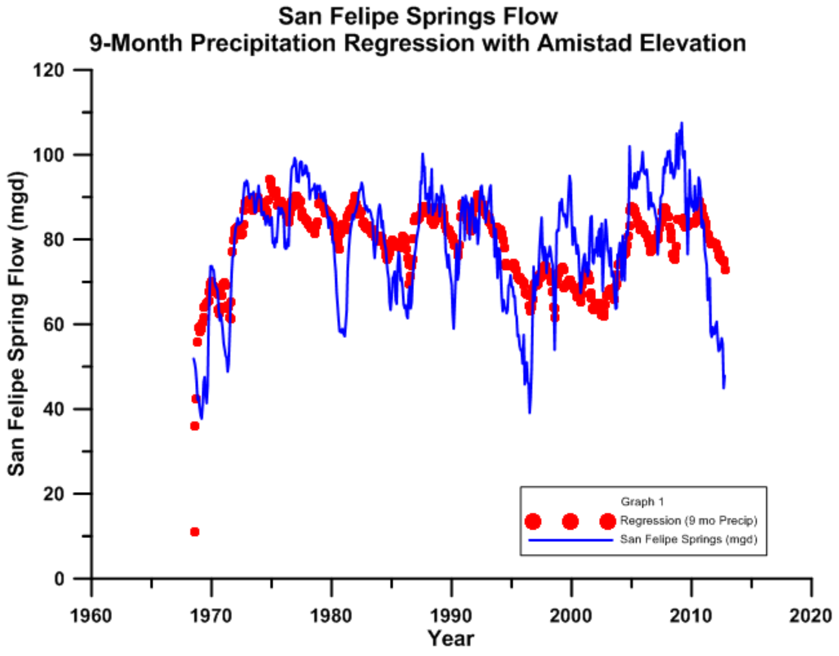

Figure 13. San Felipe Spring Flow - 9-Month Precipitation Regression with Amistad Elevation

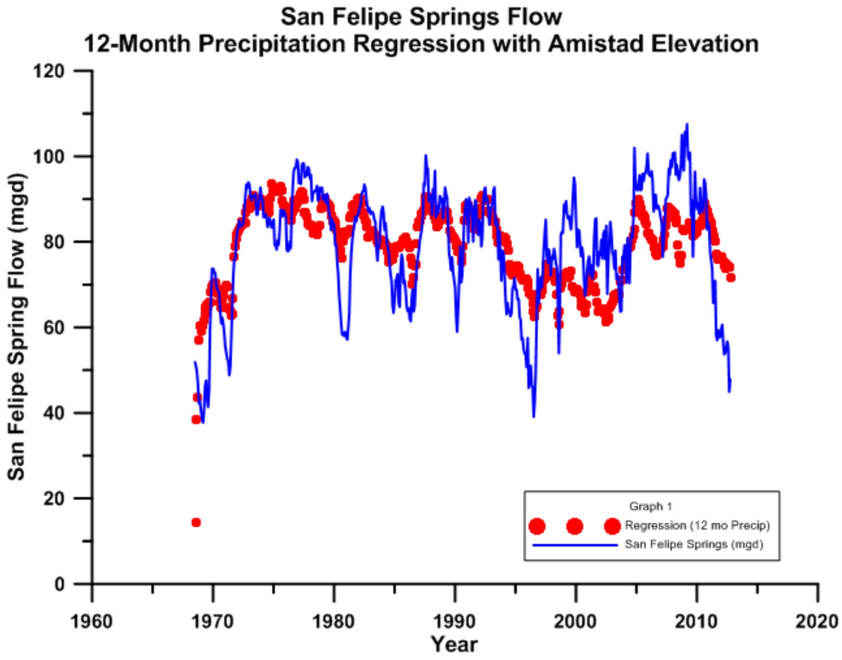

Figure 14. San Felipe Spring Flow - 12-Month Precipitation Regression with Amistad Elevation

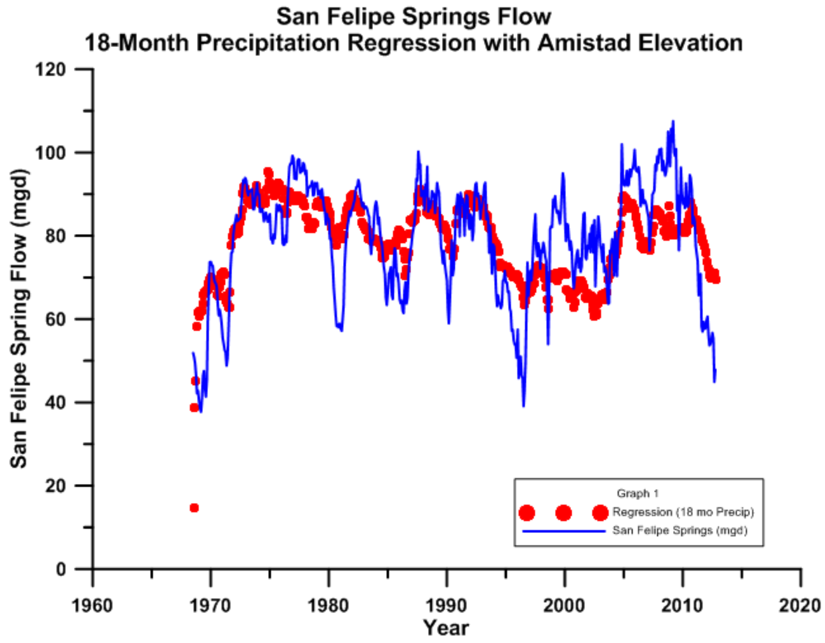

Figure 15. San Felipe Spring Flow - 18-Month Precipitation Regression with Amistad Elevation

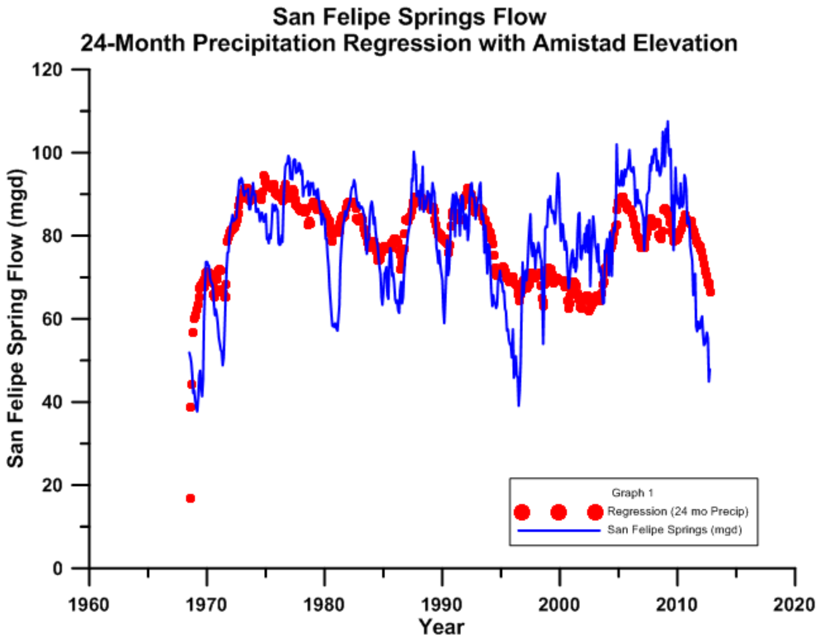

Figure 16. San Felipe Spring Flow - 24-Month Precipitation Regression with Amistad Elevation

The predicted spring flow using cumulative precipitation and lake elevation for all periods of cumulative precipitation all show a fair degree of correlation with actual spring flow. The multiple r-squared values ranged from about 0.40 to about 0.43, which means that 40 to 43 percent of the variation in spring flow can be explained with variations in lake elevations and precipitation using this analysis. This particular approach, however, provides no further insight regarding the “memory” of the groundwater system to past precipitation events given that the all the cumulative precipitation alternatives yielded similar results.

2.7 Correlation of Spring Flow to Groundwater Elevations

Preliminary analyses of the correlation between groundwater elevations and San Felipe Spring flow was completed using four wells, the location of which are shown in Figure 17. The comparison hydrographs are as follows:

- Well 70-25-502 (Figure 18)
- Well 70-33-604 (Figure 19)
- Well 70-41-209 (Figure 20)
- Well 70-42-205 (Figure 21)

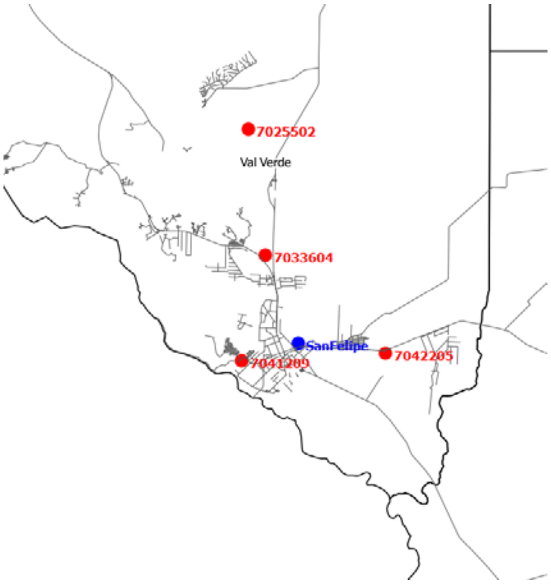

Figure 17. Location of Wells and San Felipe Spring

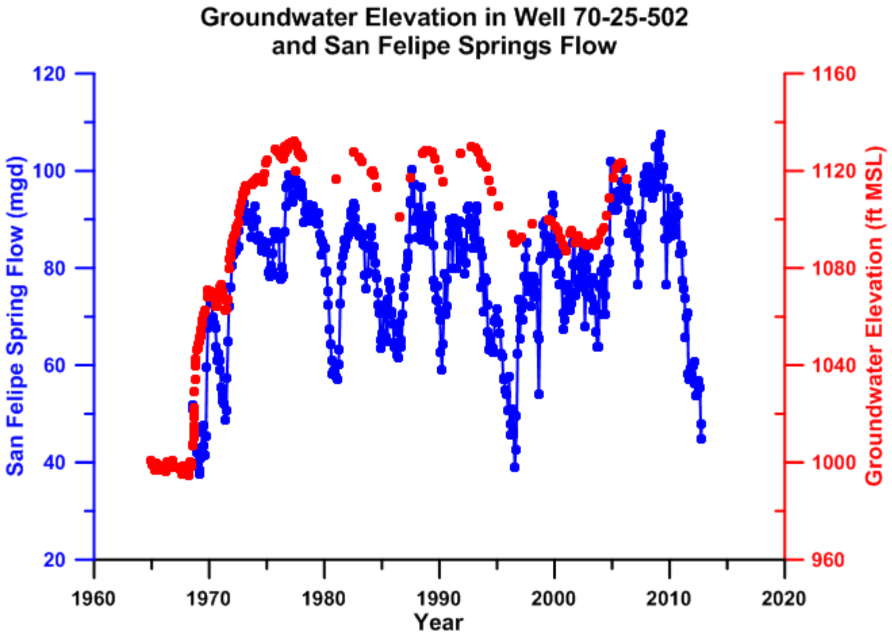

Figure 18. Groundwater Elevation in Well 70-25-502 and San Felipe Spring Flow

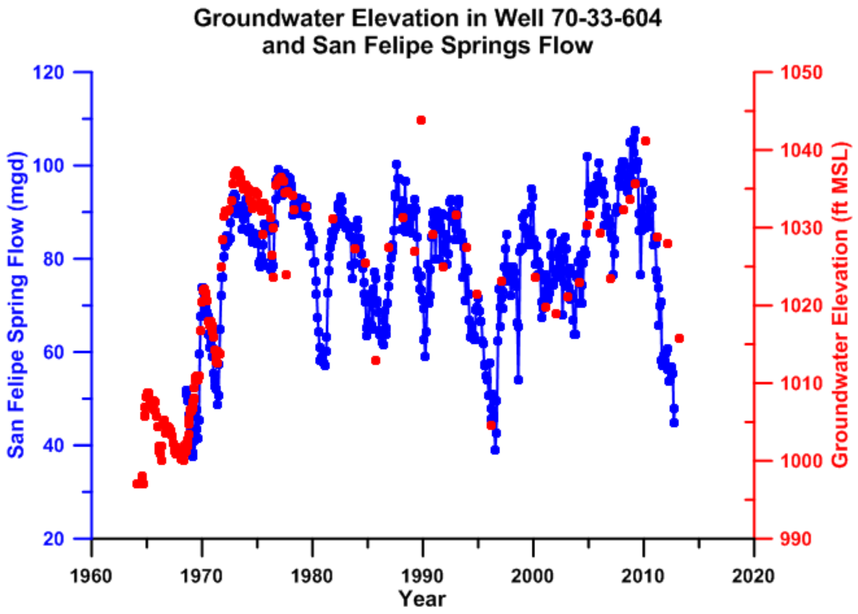

Figure 19. Groundwater Elevation in Well 70-33-604 and San Felipe Spring Flow

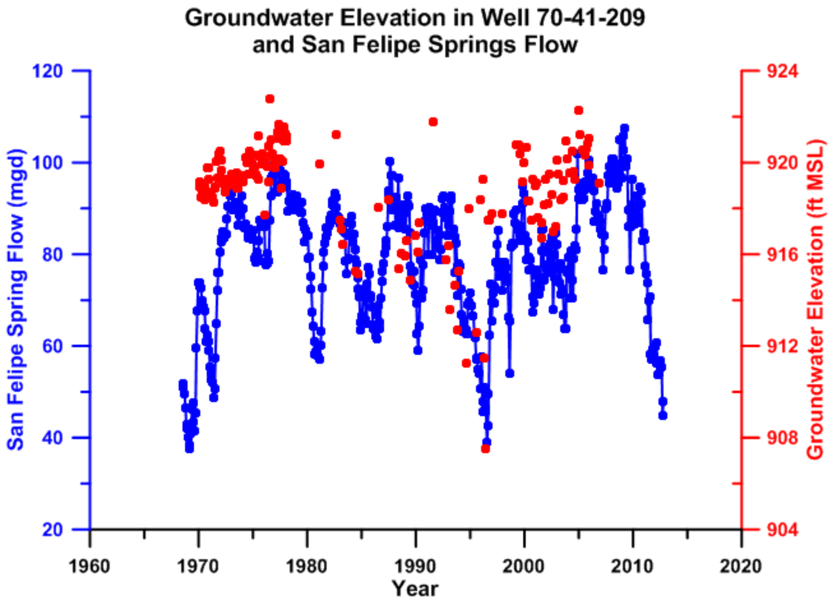

Figure 20. Groundwater Elevation in Well 70-41-209 and San Felipe Spring Flow

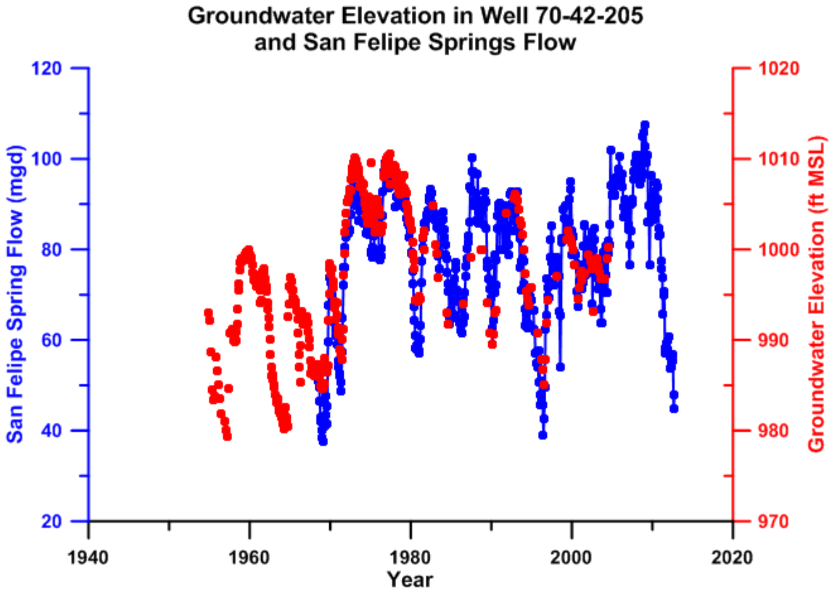

Figure 21. Groundwater Elevation in Well 70-42-205 and San Felipe Spring Flow

In each case, the correlation between spring flow and groundwater elevation is good. The well furthest to the north (70-25-502, Figure 18) shows good correlation between spring flow and groundwater elevation in the early 1970s, which suggests that the effects of Lake Amistad extends at least this far north. However, the low spring flow observations in later years (e.g. 1996 and 2011) do not correlate as well with lowered groundwater elevations in this well. In contrast, the variation in groundwater elevation in the other three wells located to the north east and west of San Felipe Spring all show good correlation in years of low spring flow.

3.0 Groundwater Model Development and Calibration

The groundwater model developed as part of this effort for Val Verde County used a previously developed groundwater model of the Kinney County area as an initial foundation and starting point (Hutchison and others, 2011b). The previous Kinney County area model was developed in parallel with the groundwater model of the Edwards-Trinity Plateau area (Hutchison and others, 2011a), which was an update to the original Groundwater Availability Model of the Edwards-Trinity Plateau (Anaya and Jones, 2009).

The decision to use the previous Kinney County area model was based in part because the model domain covered all of Val Verde County, and, thus, included a geologic framework and boundary conditions that were based on a half-mile grid spacing. A significant improvement in this new model as compared to the Kinney County area model was the use of monthly stress periods from 1968 to 2013 to more accurately address monthly groundwater fluctuations.

The Val Verde County groundwater model was developed with MODFLOW-2005 (Harbaugh, 2005), the industry standard finite-difference code to simulate groundwater flow that was developed by the US Geological Survey.

The coordinate system for the Val Verde County model is based on the GAM coordinate system, which is an Albers Equal Area projection with parameters suited for Texas (Table 3). The model grid offset for the southwest corner of the model grid is 4,353,592 ft. in the x-direction and 18,916,520 ft.. in the y-direction.

Table 3. GAM Coordinate System

Projection	Albers equal area conic
Datum	North American datum 1983
Spheroid	Geodetic reference system 1980
Longitude of origin	-100.00 degrees west
Latitude of origin	31.25 degrees north
Lower standard parallel	27.50 degrees north
Upper standard parallel	35.00 degrees north
False easting	4921250.00000 feet
False northing	19685000.00000 feet
Unit of linear measure	U.S. Survey feet

3.1 Model Packages

MODFLOW packages used in the Val Verde County groundwater model are listed in Table 4, along with the names of the input files. File names of the output files are listed in Table 5. The input and output files are read by MODFLOW in the name file *drvv02.nam*.

Table 4. Summary of Model Input Packages and Filenames

MODFLOW Package	Input Filename
Basic (BAS)	drvv02.bas
Discretization (DIS)	drvv02.dis
Layer Property Flow (LPF)	drvv02.lpf
Well (WEL)	drvv02.wel
Drain (DRN)	drvv02.drn
River (RIV)	drvv02.evt
General Head Boundary (GHB)	drvv02.ghb
Recharge (RCH)	drvv02.rch
Output Control (OC)	drvv02.oc
Geometric Multigrid Solver (GMG)	drvv02.gmg
Hydraulic Conductivity	hc.dat
Specific Storage	ss.dat

Table 5. Summary of Model Output Filenames

Output File Description	Output Filename
List Output	drvv02.lst
Cell-by-Cell Flow Output	drvv02.cbb
Head Output	drvv02.hds
Drawdown Output	drvv02.ddn

Each of the MODFLOW packages is discussed below. The model domain and the location of boundary conditions (WEL, DRN, RIV and GHB) in Appendix A as Figure A-1.

3.1.1 Basic (BAS) Package

The Basic Package specifies the status of each cell (active or inactive), the assigned head for inactive cells (-999), and specification of starting heads. Starting heads for the simulation were taken from the Kinney County model, and are used to initialize the simulation as discussed further below in the DIS package summary.

3.1.2 Discretization (DIS) Package

The Discretization Package specifies the spatial and temporal discretization of the model. The model consists of one layer (representing the Edwards-Trinity Plateau Aquifer), 167 rows and 142 columns. Cell size is 2,640 ft. by 2,640 ft. (½ mile by ½ mile).

The time unit for the model is days, and the distance unit for the model is feet. The DIS file also contains the land surface elevation for each cell, and the bottom elevation of the model flow system. These elevation values were taken from the Kinney County area model (Hutchison and others, 2011b).

The DIS file defines 544 stress period used for the calibration simulation. The first stress period is specified as steady-state, and stress periods 2 to 544 are specified as transient. Each stress period from 2 to 544 are monthly stress periods, and the number of days for each stress period is specified (28, 29, 30 or 31, as appropriate). Stress periods 2 to 544 correspond to June 1968 to August 2013.

The first stress period was implemented to provide a numerically stable set of head values for the transient portion of the simulation. No conclusions or analyses of the steady state results should be made.

The choice of June 1968 as a starting time was based on availability of data and providing a few months prior to the start of Lake Amistad filling. The choice of August 2013 as an ending time was based on data availability.

3.1.3 Layer-Property Flow (LPF) Package

The Layer-Property Flow Package specifies the hydraulic conductivity of each cell in the model domain and the specific storage of each cell in the model domain. LAYTYP is set to zero (constant transmissivity) and LAYAVG is set to zero (interblock transmissivity is based on the harmonic mean).

Hydraulic conductivity in the Kinney County area model (Hutchison and others, 2011b) were developed using pilot points. Hydraulic conductivity in the regional model of the Edwards Trinity Plateau (Hutchison and others, 2011a) were assigned based on a zonation pattern that followed regional geology. An initial version of this model used a hybrid approach that considered the geologic controls suggested by the regional model and the pilot point/stochastic aspects of the Kinney County model to develop a zonation pattern for hydraulic conductivity and specific storage.

Recently, there has been considerable discussion regarding the use of zonation patterns for hydraulic conductivity and specific storage verse the idea of assigning preferential flow paths in the various stream channels within the County. For example, Dr. Ron Green of the Southwest Research Institute, in a presentation made at the Texas Water Conservation Association meeting on March 6, 2014 (Green and others, 2014), pointed out that the geologic-based hydraulic conductivity zonation used in the regional Edwards Trinity Plateau model was not consistent with his recent findings of preferred flow paths that follow stream channels.

The first version of the Val Verde County model was developed using a zonation approach based on the Kinney County Area Model. This initial zonation conceptualization was updated to incorporate the concept of preferential flow paths for the major stream channels in the County. Both versions were developed in an effort to compare the two approaches and ascertain the difference in results. The zonation pattern that incorporated the concept of preferred flow paths along creek channels and the resulting calibrated zonation and values for hydraulic conductivity and specific storage are presented in Appendix A as Figures A-2 and A-3, respectively. During calibration, hydraulic conductivity and specific storage values were varied, and the values in Figures A-2 and A-3 are the calibrated values.

Calculated transmissivity and storativity values are presented in Appendix A as Figures A-4 and A-5. Aquifer transmissivity is hydraulic conductivity multiplied by thickness, and is calculated on a cell-by-cell basis. Similarly, storativity is specific storage multiplied by thickness, and is also calculated on a cell-by-cell basis.

The resulting values are generally consistent with the estimates provided in Dr. Green's presentation, and with results of aquifer tests completed by LBG-Guyton (2001). However, the earlier version of the zonation Val Verde County model was also calibrated satisfactorily and had values that were also consistent with the LBG-Guyton (2001) results. This suggests that both the earlier zonation version that did not use preferred flow paths and the current version that does use preferred flow paths are simply two non-unique solutions. This is a common limitation of all models. Given the nature of the objectives of this effort, it is reasonable to expect that as data availability increases and modeling objectives are refined, this conceptualization regarding preferred flow paths may need to be refined further.

3.1.4 Well (WEL) Package

The Well Package was used to simulate pumping from wells. As part of the preliminary work associated with this effort, the locations of pumping specified in the original Kinney County area model in 1964 and 2000 were evaluated (Figures 22 and 23). Pumping amounts were initially estimated using Texas Water Development Board data and groundwater pumping estimates from 1980 and 1984 to 1999 are summarized in Table 6. Table 7 summarizes groundwater use and surface water use estimates for 2000 to 2011 in Val Verde County. Water production data from the City of Del Rio are summarized for the years 2000 to 2013 in Table 8, which represents most, but not all the municipal water use in the county.

Municipal use has been the dominant use of water in Val Verde County as shown in Table 7. Although there are wide fluctuations in municipal use between surface water and groundwater presented in Table 7, it is recognized that the City of Del Rio diverts its municipal supply from San Felipe Spring. It appears that the TWDB's classification of the source of this water was groundwater from 2000 to 2006 and then again from 2010 and 2011. However, in 2007 to 2009, the source seems to have shift.ed to surface water. Because this water use is from a diversion of spring flow, it would be incorrect to categorize it as a groundwater supply for the groundwater model since no groundwater pumping occurred.

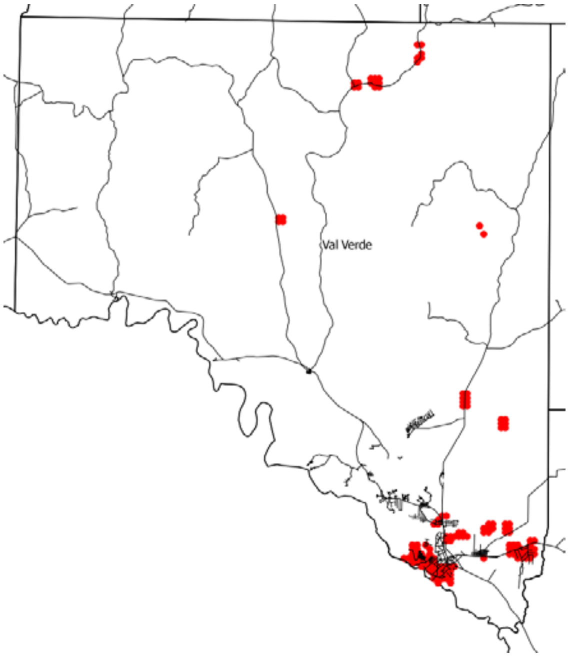

Figure 22. Pumping Locations in Val Verde County in 1964

Source: Kinney County Area Groundwater Flow Model

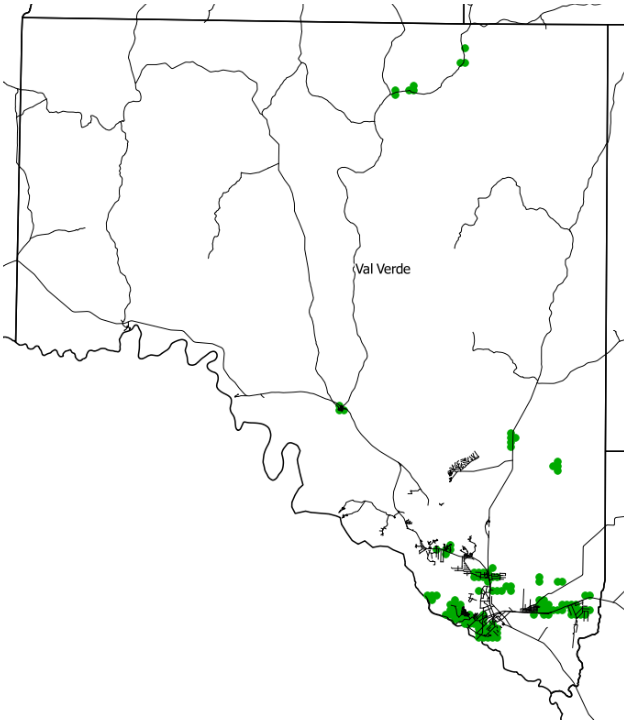

Figure 23. Pumping Locations in Val Verde County in 2000

Source: Kinney County Area Groundwater Flow Model

Table 6. TWDB Historic Groundwater Pumping Estimates (1980 - 1999)
All Values in acre-feet per year

Year	Municipal	Mfg.	Mining	Power	Irrigation	Livestock	Total
1980	740	0	0	0	90	844	1,674
1984	4,823	0	99	0	736	377	6,035
1985	1,782	0	99	0	613	396	2,890
1986	5,069	0	3	0	114	436	5,622
1987	4,524	0	87	0	0	477	5,088
1988	7,014	0	95	0	428	550	8,087
1989	4,865	0	95	0	386	543	5,889
1990	3,214	0	95	0	350	553	4,212
1991	6,415	0	98	0	361	599	7,473
1992	5,335	0	98	0	362	530	6,325
1993	7,147	0	98	0	301	541	8,087
1994	6,494	0	98	0	363	474	7,429
1995	5,378	0	98	0	307	452	6,235
1996	6,385	0	99	0	304	427	7,215
1997	6,346	0	99	0	304	372	7,121
1998	11,086	0	99	0	304	479	11,968
1999	13,389	0	99	0	304	586	14,378

Data Source: http://www.twdb.state.tx.us/waterplanning/waterusesurvey/historical-pumpage.asp

Table 7. Water Use Survey Data from TWDB for Val Verde County (2000 to 2011)
All Values in acre-feet per year (except population)

Year	Population	Total	Groundwater					
			Municipal	Mfg.	Mining	Power	Irrigation	Livestock
2000	44,856	15,339	14,455	0	0	0	270	614
2001	45,494	15,391	14,457	0	0	0	316	618
2002	46,011	15,343	14,471	0	0	0	322	550
2003	46,471	15,717	15,015	0	0	0	230	472
2004	47,294	15,582	15,049	0	0	0	107	426
2005	47,268	15,766	15,130	0	0	0	146	490
2006	47,362	11,987	11,365	0	0	0	150	472
2007	47,690	2,133	1,684	0	0	0	34	415
2008	47,858	2,292	1,759	0	9	0	18	506
2009	48,257	3,445	2,926	0	23	0	0	496
2010	48,879	12,308	11,529	0	37	0	276	466
2011	49,106	13,935	13,316	0	9	0	143	467

Year	Population	Total	Surface Water					
			Municipal	Mfg.	Mining	Power	Irrigation	Livestock
2000	44,856	2,889	1,312	0	166	0	1,258	153
2001	45,494	3,005	1,312	0	98	0	1,440	155
2002	46,011	3,032	1,312	0	116	0	1,467	137
2003	46,471	3,327	764	0	103	0	2,342	118
2004	47,294	2,778	697	0	51	0	1,923	107
2005	47,268	3,271	697	0	94	0	2,454	26
2006	47,362	4,064	0	0	108	0	3,931	25
2007	47,690	9,780	7,312	0	97	0	2,349	22
2008	47,858	10,702	8,867	0	98	0	1,710	27
2009	48,257	11,295	9,144	0	125	0	2,000	26
2010	48,879	2,357	0	0	149	0	2,184	24
2011	49,106	3,088	0	0	63	0	3,000	25

Data Source: http://www.twdb.state.tx.us/waterplanning/waterusesurvey/estimates/index.asp

Table 8. City of Del Rio Water Production (AF/yr)

Year	City of Del Rio Water Production (AF/yr)
2000	13,561
2001	12,166
2002	10,564
2003	9,415
2004	8,451
2005	9,608
2006	10,273
2007	8,106
2008	9,661
2009	10,175
2010	8,750
2011	10,963
2012	9,449
2013	9,125

During a meeting in November 2013 with Mr. Jerry Simpton and County Commissioner Beau Nettleton, the pumping locations and amounts were reviewed, and it was agreed that the locations of pumping in 1964 were reasonable representations of known significant pumping locations, and the amounts pumped (aft.er accounting for City of Del Rio water use) in the TWDB database were reasonable starting points for model development.

Monthly pumping estimates were developed under the assumption that pumping was highest in the summer and at a minimum during the winter. During model calibration, pumping amounts were adjusted, partly in response to population changes with time (i.e. it was assumed that more pumping occurred in later years of the simulation than in early years of the simulation), and in response to drought conditions (i.e. it was assumed that pumping generally increased in years with low precipitation and generally decreased in years with high precipitation). The final calibrated model estimates of annual pumping are summarized in Figure 24.

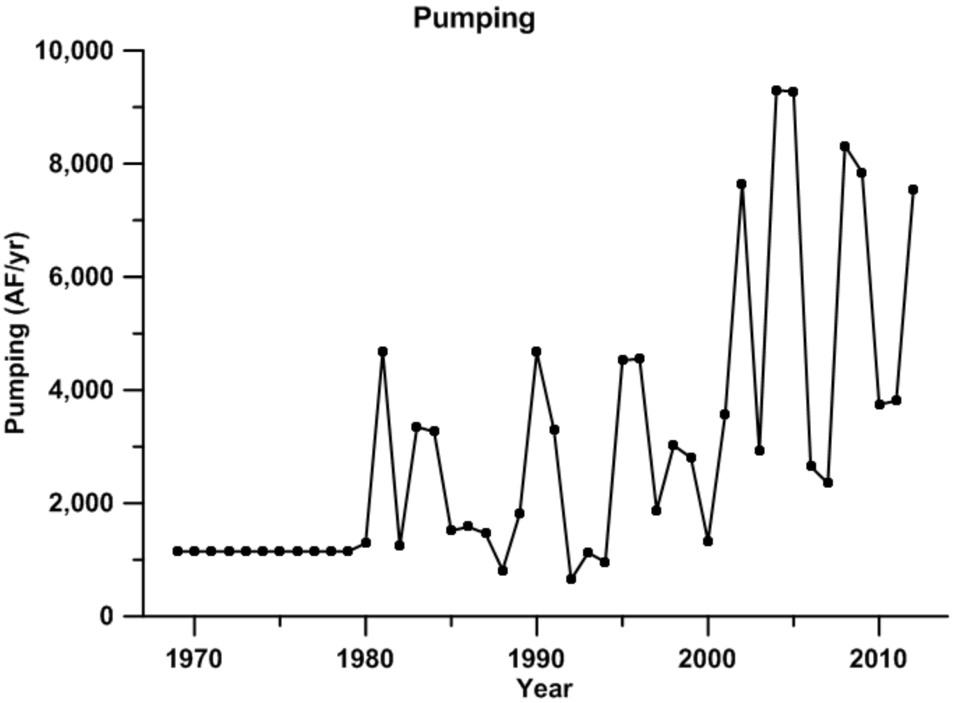

Figure 24. Calibrated Model Estimates of Annual Groundwater Pumping (AF/yr)

3.1.5 Drain (DRN) Package

The Drain Package was used to simulate flow from 11 known springs. The locations of these springs were taken from the original Kinney County area model, and are summarized in Table 9.

Measured spring flow data were available for Cantu, McKee and San Felipe springs. Conductance for these springs was estimated and varied as a function of measured spring flow as suggested by McDonald and Harbaugh (1988, pg. 9-5) in the original MODFLOW documentation.

Table 9. Spring Names and Location (Model Row and Column)

Row	Column	Name
31	32	YR_54_60_302
63	97	YR_70_01_703
63	98	YR_70_01_701
73	29	Guy Skiles
112	65	Goodenough
123	141	Mud
133	93	McKee
133	103	Cantu
135	109	San Felipe
136	103	Cienega
145	124	Yoas

3.1.6 River (RIV) Package

The River Package was used because it was part of the earlier TWDB model in Kinney County and is applicable to Val Verde County. However, the earlier TWDB model also implemented the River Package for streams and creeks tributary to the Rio Grande and Lake Amistad, which was not done for this Val Verde County. Future updates to this model may consider using the Streamflow-Routing (SFR) package in conjunction with either the Lake (LAK) or Reservoir (RES) package to potentially better simulate the tributaries to the Rio Grande and Lake Amistad, and develop better surface water budget estimates.

The River Package was used specifically in the Val Verde model to simulate the Rio Grande and Lake Amistad. Four segments were identified: 1) Rio Grande upstream of Lake Amistad, 2) the original Rio Grande in Lake Amistad, 3) Lake Amistad outside the Rio Grande proper, and 4) Rio Grande below Amistad Reservoir.

For the Rio Grande segments above and below Lake Amistad, the river bottom was assumed to be at, or slightly below the top elevation of the cell. The actual elevation was adjusted during calibration. River stage was assumed to be 0.5 ft. above the river bottom. Riverbed conductance was also adjusted during calibration.

For Lake Amistad and the original Rio Grande in Lake Amistad, the river bottom was set equal to the top elevation of the cell. For the Lake Amistad cells, river stage was set at equal to cell top elevation if the elevation of Lake Amistad, for the stress period, was below the cell top elevation (i.e. the exposed portion of the lake bed when the reservoir is low), and equal to the reservoir elevation if it was greater than the cell top elevation (the submerged portion of the reservoir). For the original Rio Grande, the same test of elevation was made, but the minimum elevation was always set to 0.5 feet above the cell top elevation.

3.1.7 General Head Boundary (GHB) Package

The General Head Boundary Package was used to simulate inflows from the northern, western, eastern, and southern boundaries of the model domain. GHB cells were assigned in the first column (western boundary) to simulate flow from Terrell County. GHB cells were assigned in the first row (northern boundary) to simulate flows from Crockett and Sutton counties. GHB cells were assigned in the last column (eastern boundary) to simulate flows from Sutton, Edwards, and Kinney counties. GHB cells were assigned in the last row (southern boundary) to simulate flows in Mexico.

GHB head values were allowed to vary with stress period and were initially assigned values from the output of the Kinney County area groundwater model. Adjustments to head and conductance were made during calibration.

3.1.8 Recharge (RCH) Package

The Recharge Package was used to simulate recharge from rainfall. Because this was a monthly stress period model, substantial changes to the recharge simulation were needed as compared to the original Kinney County area groundwater model, which used annual stress periods.

Monthly estimates of recharge were developed based on actual rainfall and evaporation from current and past months. The reciprocal of monthly evaporation was multiplied by monthly rainfall, if the rainfall was more than an assigned threshold value, and then raised to an assigned exponent. This approach is similar to one used by Dr. Ron Green in his current work in developing a new monthly groundwater flow model of the San Antonio segment of the Edwards Aquifer for the Edwards Aquifer Authority.

The threshold value and the exponent were adjusted during calibration. Also, the number of prior months was adjusted during calibration to investigate the lag time or memory of the system to precipitation in prior months. Finally, the estimated values were adjusted during calibration based on location to simulate focused recharge areas (streams and drainages) and distributed recharge areas (upland areas). Summaries of annual recharge values and the annual recharge rates in Val Verde County used in the calibrated model are presented in Figure 25.

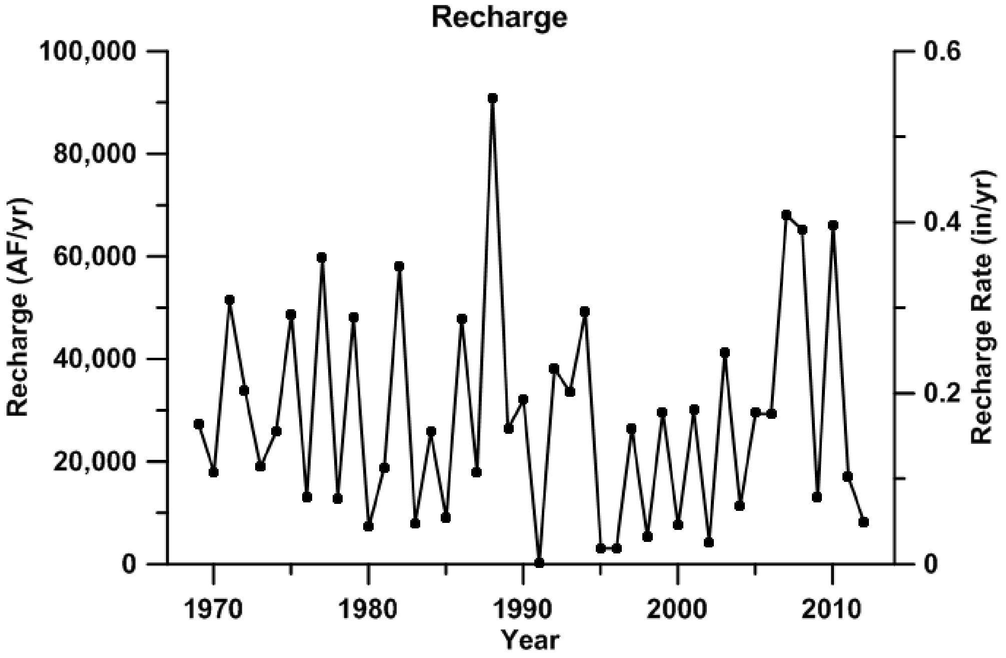

Figure 25. Calibrated Model Recharge and Recharge Rates

The resulting average recharge rate for Val Verde County from the calibrated model (0.17 in/yr) is lower than those reported by Green and Bertetti (2010), who estimated an average recharge rate in Val Verde County of 0.63 in/yr based on baseflow analyses, which are based on a surface watershed or a groundwater capture zone. To the extent that the county boundary is different from the watershed area or groundwater capture zone, the comparison may not be appropriate.

Green and Bertetti (2010, pg. 31) originally estimated a recharge rate in the Devils River watershed of 0.95 in/yr, and stated that it was "believed to be excessive". They then assumed that if the groundwater catchment area was 50 percent greater than the surface watershed area, the average recharge rate would be reduced from 0.95 in/yr to 0.63 in/yr, the value that was reported on their Figure 13 (Green and Bertetti, 2010, pg. 55). This statement is illustrative of the difficulty in comparing the estimates from this effort with those of Green and Bertetti (2010), since the earlier effort considered baseflow at a particular stream gage, but was not able to specifically delineate the origin of that baseflow on a county scale. Also, in the discussion of recharge rates in the Pecos River watershed, Green and Bertetti (2010, pg. 31) stated that there was higher uncertainty in the Val Verde County estimate due to a lack of gauging stations in the western part of the county. Finally, Green and Bertetti (2010) only evaluated average recharge rates, and no attempt was made to estimate annual variation in recharge.

3.1.9 Output Control (OC) Package

The Output Control Package contains specifications for how output is written. This particular version of the file specifies saving heads, drawdowns, and cell-by-cell flows for each stress period.

3.1.10 Geometric Multigrid Solver (GMG) Package

The Geometric Multigrid solver package contains specifications to solve the groundwater flow equation. Note that in this particular implementation, the head closure criterion is 0.1 feet and the residual closure criterion is 1.00.

3.2 Model Calibration

Calibration of the Val Verde groundwater flow model was accomplished by adjusting various input parameters until groundwater elevations and spring flows were in reasonable agreement with actual groundwater elevations and measured spring flows. Model calibration was completed using 3,605 groundwater elevations from 498 wells in Val Verde County from 1968 to 2013, and using spring flows from three springs (Cantu, McKee and San Felipe). The locations of the 498 wells and the three springs used in the calibration are presented in Appendix A (Figure A-6).

The year that the 3,605 groundwater elevation measurements were taken is summarized in Figure 26. Please note that there appeared to be a significant effort to measure groundwater elevations as Lake Amistad began to fill in the late 1960s/early 1970s. Measurement frequency declined aft.er that initial filling, but appears to have increased to between 50 and 100 measurements since 2000.

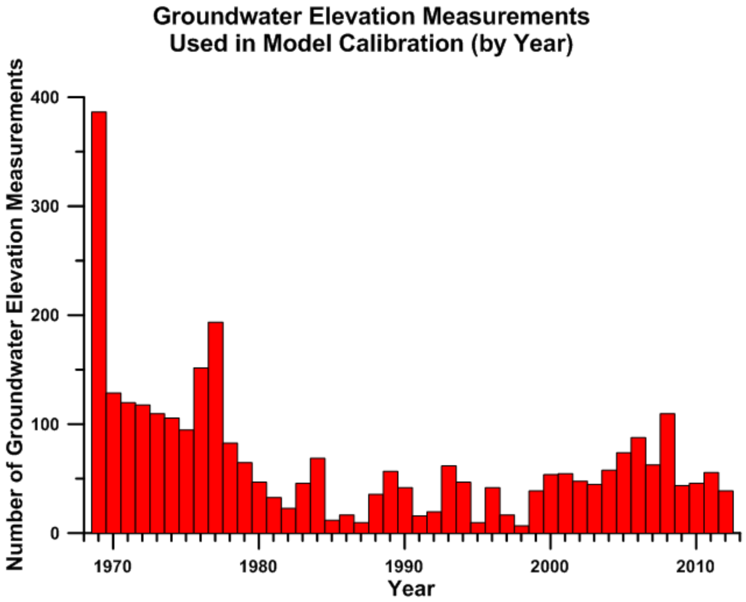

Figure 26. Groundwater Elevation Measurements Used in Model Calibration by Year

The model was calibrated using a combination of trial-and-error parameter adjustments and automated adjustments using PEST, an industry-standard inverse modeling soft.ware package. Parameter adjustments included hydraulic conductivity, specific storage, and various parameters associated with recharge, general head boundary elevation and conductance, drain elevation and conductance, riverbed elevation and conductance, and groundwater pumping.

The overall calibration statistics for groundwater elevations are summarized in Table 10, which summarizes the minimum residual (the difference between estimated groundwater elevation and measured groundwater elevation), maximum residual, and average residual. The standard deviation of the residuals and the range of measured groundwater elevations are also presented. A common statistical test to examine calibration is the standard deviation of the residuals divided by the range of measured groundwater elevations. Typically this statistic should be less than 0.10, and in this case is about 0.04. Finally, the frequency of residuals within 10 ft.., 25 ft.. and 50 ft.. are presented.

Table 10. Statistical Summary of Model Calibration for Groundwater Elevations

Calibration Statistics	**Value**
Number of Wells	498
Number of Measured Groundwater Elevations	3605
Minimum Residual (ft..)	-421.82
Maximum Residual (ft..)	379.38
Average Residual (ft..)	-1.61
Standard Deviation of Residuals	44.78
Range of Measured Groundwater Elevations (ft..)	1051.51
Standard Deviation/Range	0.0426
Percentage of Residuals Within:	
± 10 ft.	32
± 25 ft.	62
± 50 ft.	86

Graphical summaries of the match between measured groundwater elevations and model estimated groundwater elevations are presented in Figures 27 and 28. Figure 27 is a plot of measured groundwater elevation versus simulated groundwater elevation. If the simulated groundwater elevation is the same as the measured groundwater elevation, the black point will plot on the red line (which represents the 1 to 1 relationship between measured and simulated). Figure 28 presents the histogram of “model error” or difference between the measured groundwater elevation and simulated groundwater elevation.

Groundwater elevation comparisons on a well-by-well basis for 51 wells are presented in Appendix B. These are wells with at least 10 groundwater elevation measurements.

Comparisons of spring flow at the three springs for which there were sufficient data (Cantu, McKee, and San Felipe) are presented in Figures 29 to 31.

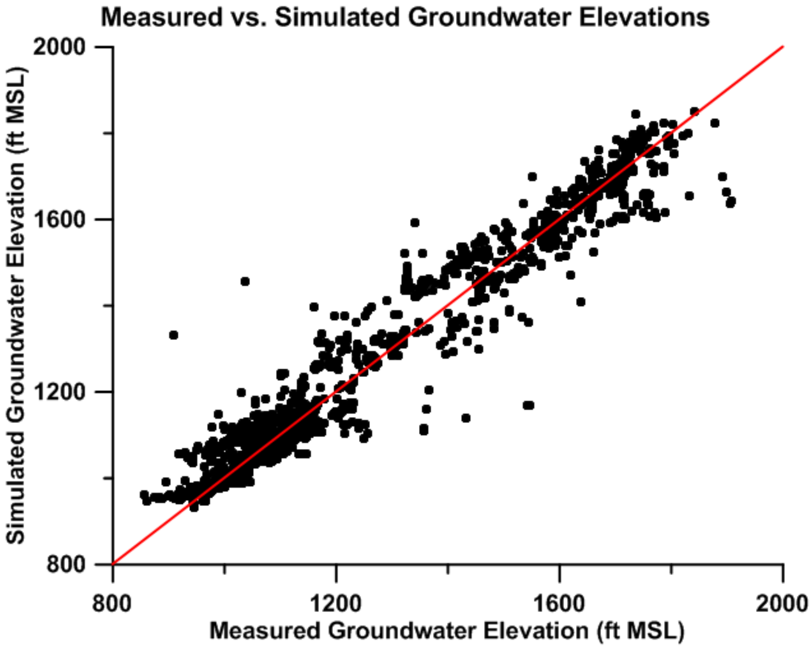

Figure 27. Measured versus Simulated Groundwater Elevations

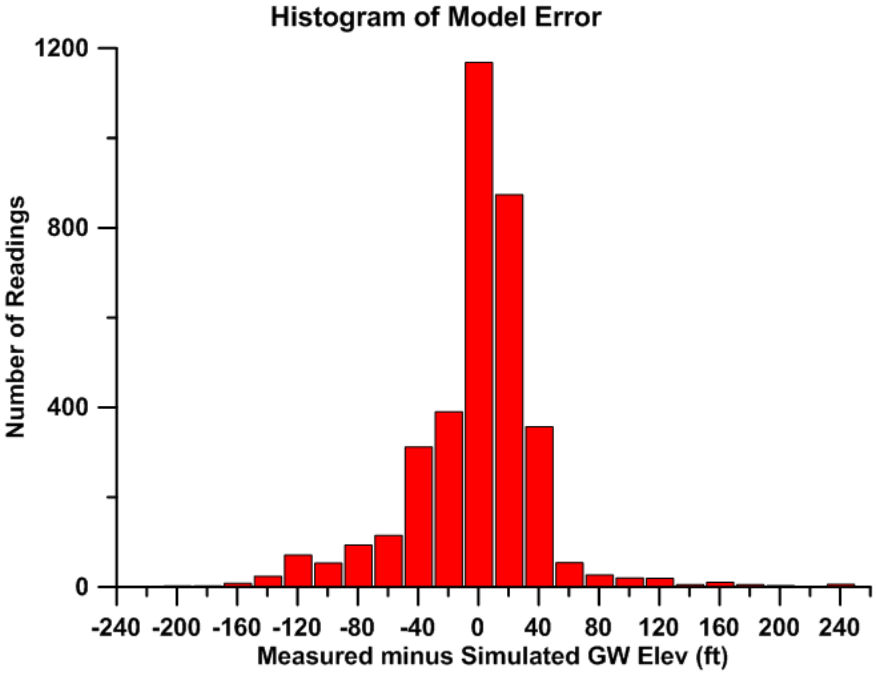

Figure 28. Histogram of Model Error

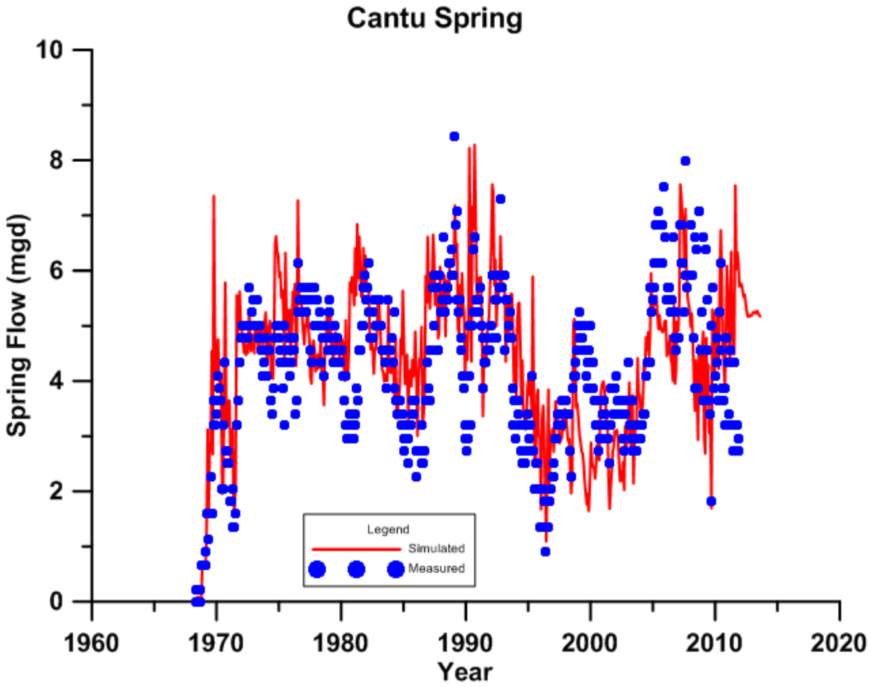

Figure 29. Cantu Spring Comparison

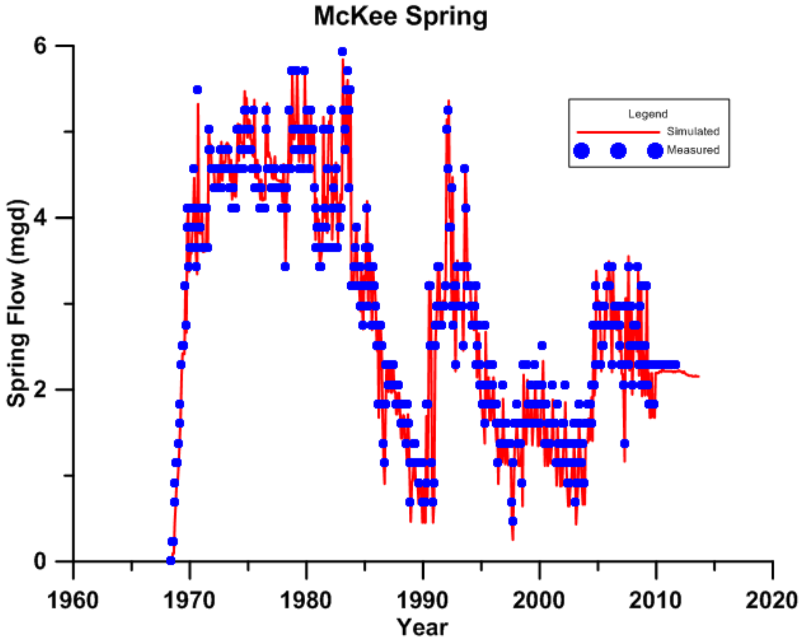

Figure 30. McKee Spring Comparison

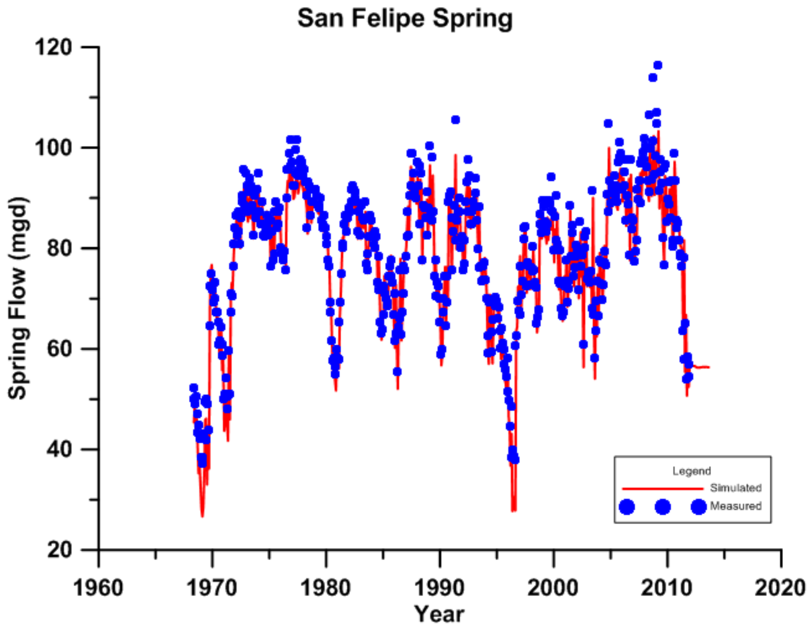

Figure 31. San Felipe Spring Comparison

In general, calibration of the model was considered sufficient to advance the objectives of the Partnership with regard to providing technical information that could be used in developing groundwater management guidelines (e.g. identification and delineation of the boundaries of groundwater management areas, conservation triggers, exportation cessation triggers, and generally characterizing groundwater conditions based on groundwater elevations and spring flows).

3.3 Water Budget Analysis

3.3.1 Background

Groundwater budgets are developed by quantifying all inflows to a defined system, all outflows from a defined system, and the storage change within the defined system over a specified period of time. Literature on the development of ground water budgets dates back to at least the 1930s with the work of Meinzer (1932). Tolman (1937) noted that, at the time, methods to develop ground water budgets had not reached the accuracy necessary to be accepted by all investigators. This was largely due to extensive data collection requirements and the lengthy time needed to observe the range of hydrologic conditions.

Bredehoeft. (2002) reviewed the evolution of analysis of ground water systems. The earliest methods in the 1940s and 1950s revolved around the analysis of flow to a single well. Understanding ground water flow on an aquifer or basin scale became possible with the analog model in the 1950s. Improvements in computer technology in the 1960s and 1970s led to the development of digital computer models or numerical models of ground water flow. By 1980, Bredehoeft. (2002) reported that numerical models had replaced analog models in the investigations of aquifer dynamics. The principal objective of such models is to understand the impacts of pumping on the system.

A groundwater system is in near steady-state (or near equilibrium) prior to development (prior to groundwater pumping for irrigation or other human use) as shown in Figure 32. In this condition, groundwater inflow equals groundwater outflow and no change in storage occurs over time. Inflows can include recharge from precipitation, recharge from streamflow, and inflows from adjacent basins (where applicable). Outflows can include discharge to surface water bodies (springs, streams and lakes), evapotranspiration through shallow groundwater vegetation and evaporation (including playa discharge), and outflow to adjacent basins.

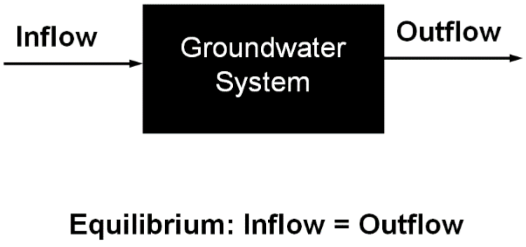

Figure 32. Groundwater System Prior to Development (Alley and others, 1999)

Development of groundwater resources (i.e. pumping of wells) results in three “impacts” to the system that is in “near steady-state”: 1) storage decline (manifested in the form of lowered groundwater levels), 2) induced inflow (generally manifested by increased recharge from surface water features or increased groundwater inflow from outside the area of interest), and 3) captured natural outflow (generally manifested in decreased spring flows, decreased stream baseflow, decreased evapotranspiration, or decreased groundwater outflow outside the area of interest).

The initial response to pumping is a lowering of the groundwater level or a “cone of depression” around the well, which results in a decline in storage. The cone of depression deepens and extends radially with time. As the cone of depression expands, it causes groundwater to move toward the well thereby increasing the inflow to the area around the well.

As the cone of depression extends, there can be a decrease of natural groundwater outflow from the area adjacent to the well as the pumped well acts to “capture” this natural outflow. If the cone of depression causes water levels to decline in an area of springs, spring flow can be reduced and the pumping is said to capture the spring flow. At some point, the induced inflow and captured outflow (collectively the capture of the well) can cause the cone of depression to stabilize or equilibrate.

Figure 33 illustrates the case of a groundwater system aft.er pumping begins. Note that the groundwater storage is decreased, inflow is increased, and outflow is decreased in response to the pumping. The inflow does not equal the total outflow (natural outflow plus pumping). The system is not in equilibrium, and groundwater storage is decreasing.

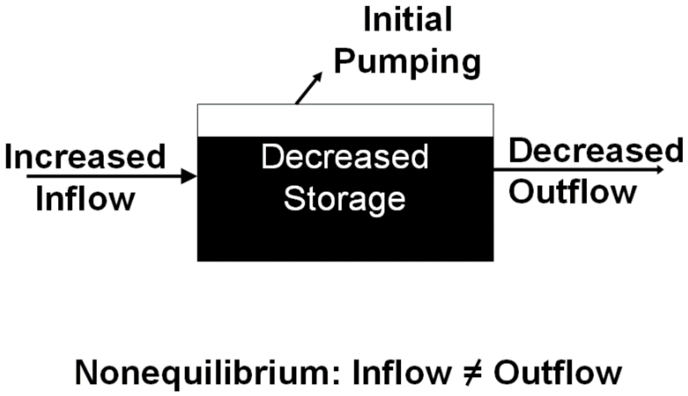

Figure 33. Groundwater System aft.er Initial Pumping (Alley and others, 1999)

If the hydraulic conductivity is sufficiently large and initial pumping rate is relatively constant, the inflow and natural outflow will adjust to a new near steady-state condition in response to the pumping. Groundwater storage is decreased from the predevelopment level. This reduction in storage is the result of the new near steady-state condition of the system because the location and the nature of the outflow have changed (i.e. pumping wells). Figure 34 presents a diagram of this new near steady-state or new equilibrium condition.

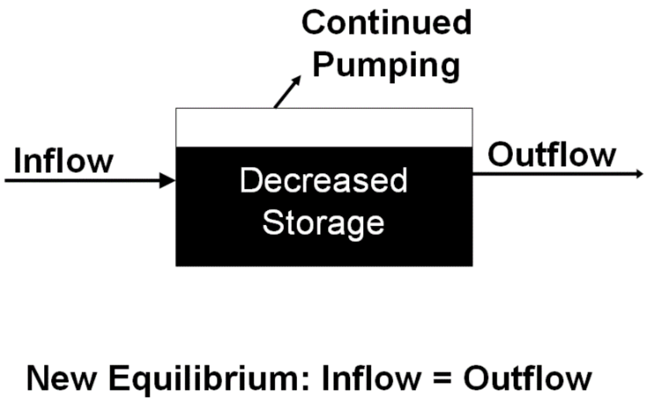

Figure 34. Groundwater System under Continued Pumping – New Equilibrium Condition (Alley and others, 1999)

If pumping were to increase aft.er this new near steady-state condition was established, the system inflow increases again, the natural outflow decreases again, and groundwater storage is further decreased. Figure 35 depicts this condition.

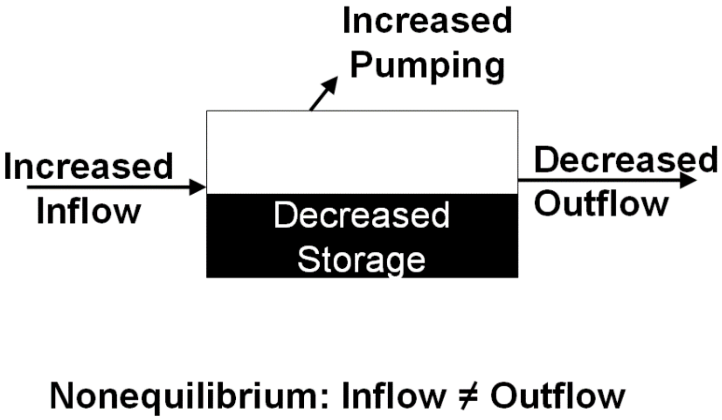

Figure 35. Groundwater System under Additional Increment of Increased Pumping (Alley and others, 1999)

In response to this new increase in pumping, inflow would continue to increase, outflow would continue to decrease, and storage would continue to decrease as the system is equilibrating. If the pumping is relatively constant, it is possible for a groundwater basin to exhibit stable groundwater levels at a lower level than had been previously observed. Stable groundwater levels are an indication that a new near steady-state condition has been reached.

Pumping can increase to the point where no new near steady-state condition is possible. In this condition, inflow can be induced no further and/or natural outflow can be decreased no further. From an outflow perspective, this condition would be reached once all springs have ceased to flow (no more spring flow to "capture") or the water table has declined to the point that shallow groundwater evapotranspiration has ceased.

In summary, groundwater pumping dynamically alters the direction and magnitude of hydraulic gradients, induces inflow, decreases natural discharge from the system (e.g. spring flow), and affects fluxes between hydraulically connected aquifer systems. Bredehoeft. (2002) noted that understanding the dynamic response of a ground water system under pumping stress distills down to understanding the rate and nature of "capture" attributable to pumping, which is the sum of the change in recharge and the change in discharge caused by the pumping. A calibrated numerical ground water model of a region is an ideal tool in meeting the objective of understanding capture. Output from the models includes estimates of various components of the water budget.

Groundwater budgets were developed for the Val Verde County portion of the model domain from the model using ZONEBUDGET (Harbaugh, 1990) to evaluate inflows, outflows and storage changes.

3.3.2 Groundwater Budget of Val Verde County

The groundwater budget for Val Verde County is summarized in Table 11. Please note that five time periods are used: 1) 1969 to 1980, 2) 1981 to 1990, 3) 1991 to 2000, 4) 2001 to 2012, and

5) 1969 to 2012. The first four are essentially decadal periods that can be used to evaluate changes with time. The final period represents the entire simulation period for which entire calendar year estimates are available.

The upper portion of the table summarizes the various components of inflow to the groundwater flow system in Val Verde County. Note that recharge from precipitation is less than 10 percent of the total groundwater inflow. Inflow from surrounding counties represents over 80 percent of the total inflow. The final component of inflow to the groundwater system is leakage from Lake Amistad.

The middle portion of the table summarizes the various components of outflow from the groundwater system in Val Verde County. Note that pumping, even in the most recent decade, is a minor portion of the total outflow. Spring flow and baseflow to the Rio Grande constitute over 95 percent of the outflow from the groundwater flow system of Val Verde County.

The lower portion of the table summarizes storage change in the groundwater flow system in Val Verde County. The first entry is the difference between the total inflow and the total outflow as reported in the upper portions of Table 11. The groundwater model also provides an estimate of storage change that can be compared to the inflow minus outflow approach, and this is listed as "Storage Change (Model)" in Table 11. The final entry (Water Budget Residual) is simply confirmation that the water budget closes to within one acre-foot per year (the difference between the two methods of evaluating storage change).

Please note that the initially (from 1969 to 1980), Lake Amistad leakage to the groundwater system was over 30,000 AF/yr. This was followed by a relative dry decade (recharge of about 19,000 AF/yr) and the Lake Amistad leakage rate dropped to about 20,000 AF/yr. However, from 2001 to 2012, recharge increased to over 30,000 AF/yr, but Lake Amistad leakage continued to drop to about 11,000 AF/yr. Although this likely due to reservoir operations (e.g. less storage in these years), it is instructive to note that the rate of Lake Amistad leakage in early years of operation will be higher than in later years as a new equilibrium is reached.

The variation in spring flow also appears to be linked to variations in both recharge from precipitation and Lake Amistad leakage. Note the decline in spring flow from 1991 to 2000 that corresponds to reduced recharge and reduced leakage from Lake Amistad.

Finally, please note that the overall storage change in three of the decades and over the entire model period is positive, which means that groundwater storage is slightly increasing with time. This appears to be associated with Lake Amistad leakage. However, during the period 1991 to 2000, groundwater storage was declining, apparently due to reduced recharge. Also note that during this dry period, inflow from adjacent counties increased slightly (apparently due to increased gradients), and baseflow to the Rio Grande decreased slightly, although these increases and decreases are small.

Table 11. Groundwater Budgets for Val Verde County for Five Time Periods
All Values in AF/yr

Inflow	1969-1980	1981-1990	1991-2000	2001-2012	1969-2012
Recharge from Precipitation	30,012	33,006	19,359	31,480	28,672
Inflow from Terrell County	37,163	36,896	38,286	37,860	37,547
Inflow from Crockett County	42,078	41,474	43,044	42,022	42,145
Inflow from Sutton County	13,025	12,883	13,741	12,846	13,106
Inflow from Edwards County	96,510	96,131	97,557	102,177	98,208
Inflow from Kinney County	103,038	103,334	104,342	112,340	105,939
Net Inflow from Amistad	33,964	33,047	20,146	10,936	24,335
Total Inflow	355,789	356,770	336,475	349,662	349,952
Outflow					
Pumping	1,167	2,445	2,419	5,754	2,993
Spring Flow	137,027	137,432	123,749	132,891	132,973
Base flow to Rio Grande (Above Amistad)	90,321	91,617	89,688	90,889	90,627
Base flow to Rio Grande (Below Amistad)	124,561	124,080	123,546	116,429	122,003
Total Outflow	353,076	355,575	339,402	345,964	348,596
Storage					
Total Inflow - Total Outflow	2,713	1,196	-2,927	3,699	1,355
Storage Change (From Model)	2,713	1,195	-2,927	3,699	1,355
Water Budget Residual	< 1	< 1	< 1	< 1	< 1

4.0 Model Application

Specific applications of the calibrated model included: 1) a simulation to estimate the effect of Lake Amistad on groundwater elevations in the area, 2) a series of runs that were designed to provide information useful for management zone delineation, and 3) a series of simulations to evaluate the effects of large-scale pumping in three different areas to develop a better understanding of the nature and character of potential impacts of groundwater pumping on spring flow, river baseflow, aquifer drawdown, and other changes to the groundwater flow system.

4.1 Simulation to Evaluate Impact of Lake Amistad

As discussed in the water budget analysis, the filling of Lake Amistad caused lake water to recharge the groundwater flow system. Previously presented data from monitoring wells document groundwater level rises aft.er the lake was filled. This simulation included assuming that the lake was not constructed and comparing groundwater elevations and groundwater budgets with and without the lake to gain an understanding of the effect of Lake Amistad on the groundwater flow system in Val Verde County.

Figure A-7 (in Appendix A) depicts the extent and degree of groundwater elevation impact of Lake Amistad, and Table 12 summarizes the Val Verde County groundwater budget of the calibrated model for the period 1969 to 2012 as well as the Val Verde County groundwater budget of the simulation where Lake Amistad is assumed to not exist. Table 12 also summarizes the difference in the two groundwater budgets to highlight the impact that Lake Amistad has had on the groundwater flow system of Val Verde County

Please note that if Lake Amistad did not exist, the reach of the Rio Grande where Amistad currently exists would receive about 2,000 AF/yr of baseflow from groundwater. In addition, spring flow would be about 13,000 AF/yr less, and baseflow to other portions of the Rio Grande would be about 10,000 AF/yr less. All the other differences are relatively minor. From this analysis, it can be seen that the net effect of Lake Amistad has been increased spring flow and increased baseflow to the Rio Grande downstream of the dam.

Table 12. Val Verde County Groundwater Budgets: Calibrated Model, No Lake Amistad Simulation, and Difference
(1969 to 2012, all values in AF/yr)

Inflow	**Calibrated Model**	**No Amistad Simulation**	**Difference**
Recharge from Precipitation	28,672	28,672	0
Inflow from Terrell County	37,547	37,634	87
Inflow from Crockett County	42,145	42,314	169
Inflow from Sutton County	13,106	13,209	102
Inflow from Edwards County	98,208	99,420	1,212
Inflow from Kinney County	105,939	107,891	1,952
Net Inflow from Amistad	24,335	-2,397	-26,731
Total Inflow	349,952	326,743	-23,209
Outflow			
Pumping	2,993	2,993	0
Spring Flow	132,973	120,216	-12,757
Baseflow to Rio Grande (Above Amistad)	90,627	89,902	-725
Baseflow to Rio Grande (Below Amistad)	122,003	112,733	-9,270
Total Outflow	348,596	325,844	-22,753
Storage			
Total Inflow - Total Outflow	1,355	899	-456
Storage Change (From Model)	1,355	899	-456
Water Budget Residual	< 1	< 1	< 1

4.2 Simulations to Delineate Management Zones in Val Verde County

One of the objectives of the City of Del Rio and the County of Val Verde in completing this investigation was to develop information that would be useful to delineate groundwater management zones. If a groundwater conservation district were to be formed in Val Verde County, the district may wish to adopt a management plan and rules to implement the management plan that differentiated permitting conditions in areas where pumping could affect spring flow and river baseflow versus areas that would have little effect on spring flow or river baseflow.

Applying the concept discussed above related to groundwater pumping and capture of natural outflows, a series of simulations were completed as follows:

- There are 12,364 model cells in Val Verde County that are not associated with the Rio Grande or Lake Amistad.
- A single well pumping 2,000 gallons per minute was specified in a single cell in the model, and the model was run for the full calibrated simulation period.
- Spring flow impacts and river baseflow impacts were recorded and associated with the cell in which pumping was assumed.
- The process was repeated for all 12,364 model cells.
- The results of the simulations were translated into maps that show the degree of capture (river baseflow and spring flow) for each cell.

The results of these simulations are summarized in Figures A-8 (baseflow capture) and A-9 (spring flow capture). Please note that the maps depict capture as a percentage of the amount pumped. These maps and the results of the simulation can be effective tools in any future deliberations associated with the delineation of management zones.

4.3 Simulations of Large Scale Pumping

Over the last several years, there have been a number of proposals advanced to pump groundwater in Val Verde County and export it to other areas of Texas. The simulations completed as part of this investigation were designed to illustrate the effects of increasing amounts of pumping at three locations. The three locations are:

- An area on the Lake Amistad peninsula and extending north from the peninsula.
- An area near the eastern boundary of Val Verde County (Northern Alternative)
- An area near the eastern boundary of Val Verde County (Southern Alternative)

The area on the peninsula was selected based on discussions with representatives of the Partnership. The areas near the eastern boundary of Val Verde County were selected based on some previous work in the area completed by HDR for the San Antonio Water System (SAWS) in 2000 or 2001. Selected portions of the HDR report and presentation were provided by members of the Partnership. In that material, it appeared that HDR developed a groundwater flow model and completed simulations with the model for a large groundwater export project in this area. Two alternatives were simulated in this effort due to the ambiguity of the location of the simulated well field in the HDR effort.

Six simulations were completed for each area. Pumping totals for these simulations ranged from 25,000 AF/yr to 150,000 AF/yr. Pumping was assumed to be 2,000 gallons per minute per cell. Thus, 46 cells were used for the highest pumping scenario. In addition, a zero pumping alternative was completed to provide a baseline to compare the increased pumping. All simulations repeated the 544 stress periods of the calibrated model (a steady state stress period followed by monthly stress periods from June 1968 to August 2012) in order to compare to the calibrated model results.

Drawdown maps for the 18 simulations are presented in Appendix A as follows:

- Peninsula Well Field: 25,000 AF/yr (Figure A-10)
- Peninsula Well Field: 50,000 AF/yr (Figure A-11)
- Peninsula Well Field: 75,000 AF/yr (Figure A-12)
- Peninsula Well Field: 100,000 AF/yr (Figure A-13)
- Peninsula Well Field: 125,000 AF/yr (Figure A-14)
- Peninsula Well Field: 150,000 AF/yr (Figure A-15)
- SAWS Well Field (Northern Alternative): 25,000 AF/yr (Figure A-16)
- SAWS Well Field (Northern Alternative): 50,000 AF/yr (Figure A-17)
- SAWS Well Field (Northern Alternative): 75,000 AF/yr (Figure A-18)
- SAWS Well Field (Northern Alternative): 100,000 AF/yr (Figure A-19)
- SAWS Well Field (Northern Alternative): 125,000 AF/yr (Figure A-20)
- SAWS Well Field (Northern Alternative): 150,000 AF/yr (Figure A-21)
- SAWS Well Field (Southern Alternative): 25,000 AF/yr (Figure A-22)
- SAWS Well Field (Southern Alternative): 50,000 AF/yr (Figure A-23)
- SAWS Well Field (Southern Alternative): 75,000 AF/yr (Figure A-24)
- SAWS Well Field (Southern Alternative): 100,000 AF/yr (Figure A-25)
- SAWS Well Field (Southern Alternative): 125,000 AF/yr (Figure A-26)
- SAWS Well Field (Southern Alternative): 150,000 AF/yr (Figure A-27)

Groundwater budgets were developed for each of the 18 simulations, and are organized and discussed by well field area below.

4.3.1 Peninsula Well Field

The Val Verde County groundwater budgets for six simulations for the Peninsula Well Field are summarized in Table 13. Table 14 summarizes the differences in the individual pumping scenarios as compared to the zero pumping scenario, and these results are organized to show the capture (induced inflow and reduced outflow) from the pumping, and the storage change in acre-feet per year. Table 15 summarizes the differences similar to Table 14, but presents the capture and storage change as a percentage of pumping.

Note that for the 25,000 AF/yr scenario, 43 percent of the pumping is induced inflow from Lake Amistad. The percentage of captured inflow from Lake Amistad declines as pumping increases, and is 20 percent of the pumping for the 150,000 AF/yr pumping scenario. Pumping captures spring flow, and becomes a larger percentage of pumping as pumping increases (18 percent for the 25,000 AF/yr scenarios to 25 percent for the 150,000 AF/yr scenario). The other large component of capture is Rio Grande baseflow (from 25 to 29 percent of pumping). Please note that storage reduction is a small portion of the impact of pumping (about one percent of pumping).

Figure 36 presents the estimated flow at San Felipe Spring for the 150,000 AF/yr scenario, and compares the estimates to those from the calibrated model. Please note that during dry periods and relatively low spring flow, the impact is less than in high spring flow periods.

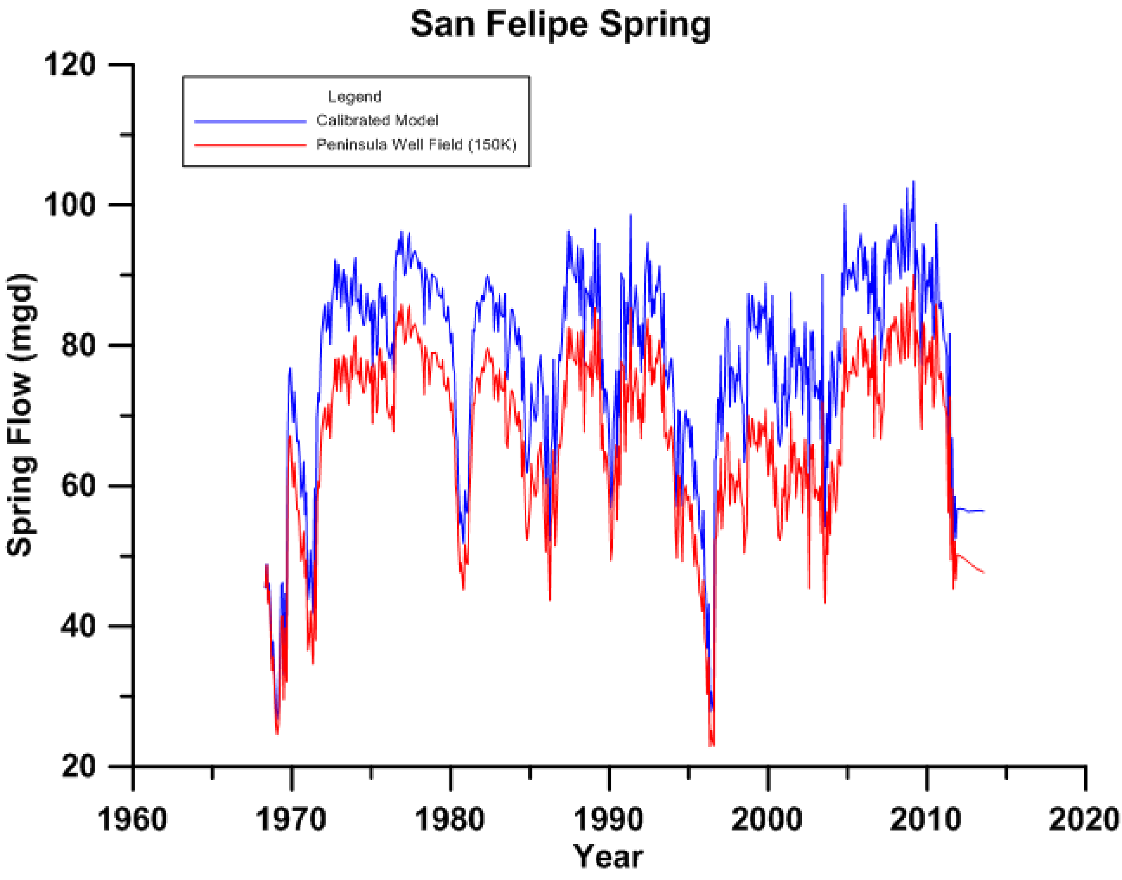

Figure 36. San Felipe Spring Flow: Peninsula Well Field Simulation (150K Scenario)

Table 13. Val Verde County Groundwater Budgets: Peninsula Well Field – Six Pumping Simulations

All Values in acre-feet per year

	Pumping Scenario						
	0K	**25K**	**50K**	**75K**	**100K**	**125K**	**150K**
Inflow							
Recharge from Precipitation	28,672	28,672	28,672	28,672	28,672	28,672	28,672
Inflow from Terrell County	37,532	37,586	37,672	37,776	37,907	38,067	38,234
Inflow from Crockett County	42,005	42,151	42,385	42,668	43,005	43,399	43,803
Inflow from Sutton County	12,992	13,087	13,241	13,427	13,644	13,892	14,148
Inflow from Edwards County	98,023	99,211	101,138	103,395	105,912	108,665	111,534
Inflow from Kinney County	105,559	107,255	109,599	112,227	114,958	117,819	120,906
Net Inflow from Amistad	24,220	34,863	41,306	45,229	48,439	51,343	53,831
Total Inflow	349,002	362,825	374,014	383,393	392,536	401,858	411,128
Outflow							
Pumping	0	25,016	50,031	75,047	100,062	125,078	150,093
Spring Flow	133,689	129,277	123,321	116,416	109,534	103,188	96,685
Baseflow to Rio Grande (Above Amistad)	90,683	90,258	89,599	88,799	87,771	86,481	85,139
Baseflow to Rio Grande (Below Amistad)	123,211	116,872	109,801	102,080	94,370	86,608	79,035
Total Outflow	347,583	361,422	372,753	382,343	391,738	401,354	410,952
Storage							
Total Inflow - Total Outflow	1,419	1,403	1,261	1,051	798	504	175
Storage Change (From Model)	1,419	1,403	1,261	1,051	798	504	175
Water Budget Residual	< 1	< 1	< 1	< 1	< 1	< 1	< 1

Table 14. Val Verde County Groundwater Budgets: Peninsula Well Field – Induced Inflows, Reduced Outflows and Storage Change Compared to Zero Pumping for Six Pumping Simulations

All Values in acre-feet per year

	Pumping Scenario					
	25K	**50K**	**75K**	**100K**	**125K**	**150K**
Pumping	25,016	50,031	75,047	100,062	125,078	150,093
Induced Inflow						
Recharge from Precipitation	0	0	0	0	0	0
Inflow from Terrell County	55	141	245	375	536	703
Inflow from Crockett County	145	380	663	1,000	1,393	1,797
Inflow from Sutton County	95	249	434	652	900	1,156
Inflow from Edwards County	1,189	3,115	5,372	7,889	10,643	13,511
Inflow from Kinney County	1,697	4,040	6,668	9,399	12,261	15,348
Net Inflow from Amistad	10,643	17,086	21,009	24,219	27,123	29,611
Total Induced Inflow	13,823	25,012	34,391	43,534	52,856	62,126
Reduced Outflow						
Spring Flow	4,412	10,368	17,272	24,155	30,501	37,004
Baseflow to Rio Grande (Above Amistad)	426	1,084	1,884	2,912	4,202	5,545
Baseflow to Rio Grande (Below Amistad)	6,339	13,410	21,131	28,841	36,603	44,175
Total Outflow	11,176	24,861	40,287	55,907	71,307	86,724
Storage Change from Pumping	16	158	369	621	916	1,244
Total Induced Inflow, Reduced Outflow and Storage Change (should equal pumping)	25,016	50,031	75,047	100,062	125,078	150,093

Table 15. Val Verde County Groundwater Budgets: Peninsula Well Field – Induced Inflows, Reduced Outflows and Storage Change as a Percentage of Pumping for Six Pumping Simulations

All values expressed as a percentage of pumping

	Pumping Scenario					
	25K	50K	75K	100K	125K	150K
Pumping	25,016	50,031	75,047	100,062	125,078	150,093
Induced Inflow						
Recharge from Precipitation	0	0	0	0	0	0
Inflow from Terrell County	0	0	0	0	0	0
Inflow from Crockett County	1	1	1	1	1	1
Inflow from Sutton County	0	0	1	1	1	1
Inflow from Edwards County	5	6	7	8	9	9
Inflow from Kinney County	7	8	9	9	10	10
Net Inflow from Amistad	43	34	28	24	22	20
Total Induced Inflow	55	50	46	44	42	41
Reduced Outflow						
Spring Flow	18	21	23	24	24	25
Baseflow to Rio Grande (Above Amistad)	2	2	3	3	3	4
Baseflow to Rio Grande (Below Amistad)	25	27	28	29	29	29
Total Outflow	45	50	54	56	57	58
Storage Change from Pumping	0	0	0	1	1	1
Total Induced Inflow, Reduced Outflow and Storage Change (should equal 100)	100	100	100	100	100	100

4.3.2 SAWS Well Field – Northern Alternative

The Val Verde County groundwater budgets for six simulations for the SAWS Well Field (Northern Alternative) are summarized in Table 16. Table 17 summarizes the differences in the individual pumping scenarios as compared to the zero pumping scenario, and these results are organized to show the capture (induced inflow and reduced outflow) from the pumping, and the storage change in acre-feet per year. Table 18 summarizes the differences similar to Table 17, but presents the capture and storage change as a percentage of pumping.

Due to the distance of this well field to Lake Amistad, induced inflow from Lake Amistad is significantly lower than in the Peninsula Well Field simulations (6 to 7 percent of pumping versus 20 to 43 percent of pumping). Induced inflow for this well field is primarily induced inflow from Edwards County and Kinney County. Given the location of the well field near the eastern boundary of Val Verde County, this would be expected. Spring flow capture is between 15 and 16 percent for all pumping scenarios, and Rio Grande baseflow capture is between 25 and 26 percent of the pumping for all scenarios. As with the Peninsula Well Field simulations, storage reduction is a small portion of the impact of pumping (about one percent of pumping).

Figure 37 presents the estimated flow at San Felipe Spring for the 150,000 AF/yr scenario, and compares the estimates to those from the calibrated model. Please note that during dry periods and relatively low spring flow, the impact is less than in high spring flow periods.

4.3.3 SAWS Well Field – Southern Alternative

The Val Verde County groundwater budgets for the six simulations for the SAWS Well Field (Southern Alternative) are summarized in Table 19. Table 20 summarizes the differences in the individual pumping scenarios as compared to the zero pumping scenario, and these results are organized to show the capture (induced inflow and reduced outflow) from the pumping, and the storage change in acre-feet per year. Table 21 summarizes the differences similar to Table 20, but presents the capture and storage change as a percentage of pumping.

The location of this well field as compared to the Northern Alternative of the SAWS well field results in less induced inflow from Edwards County and more from Kinney County. Given the location of the two well fields, this is reasonable to expect. Spring flow capture is between 17 and 19 percent of the pumping, and captured baseflow represents about 30 to 31 percent of the pumping. As with the other two well field alternatives, storage change is about one percent of pumping.

Figure 38 presents the estimated flow at San Felipe Spring for the 150,000 AF/yr scenario, and compares the estimates to those from the calibrated model. Please note that during dry periods and relatively low spring flow, the impact is less than in high spring flow periods.

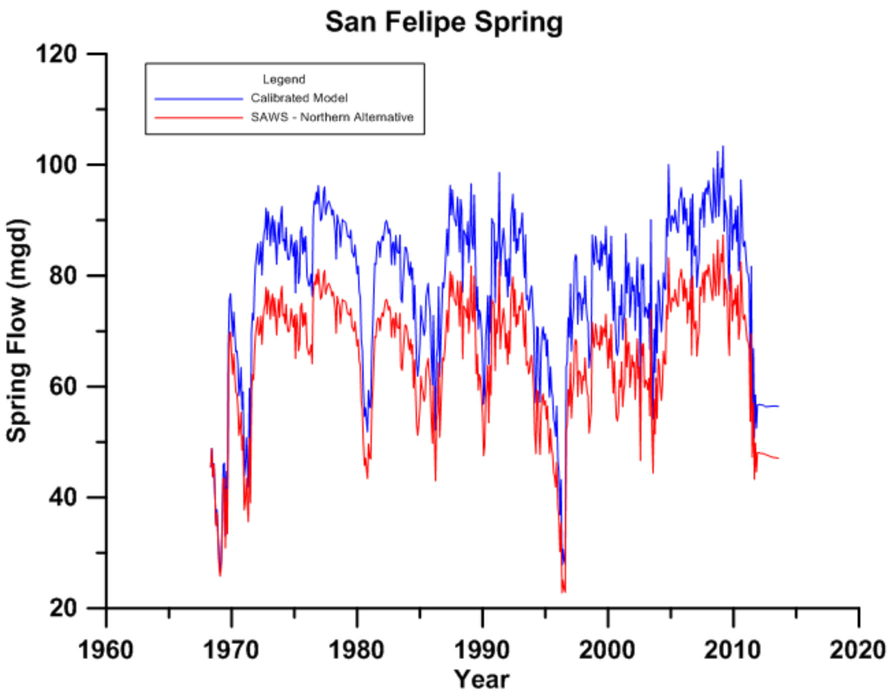

Figure 37. San Felipe Spring Flow: SAWS Well Field (Southern Alternative) Simulation (150K Scenario)

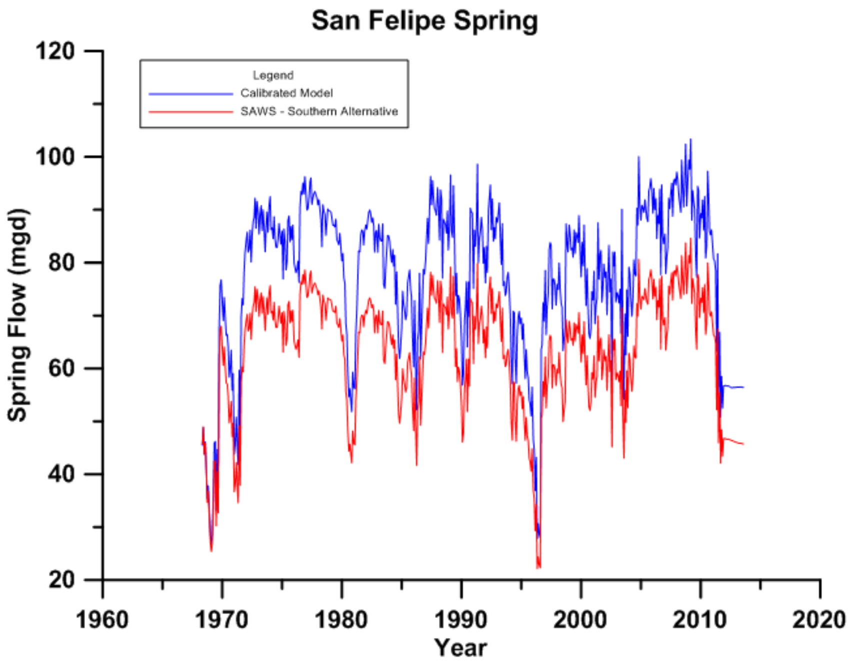

Figure 38. San Felipe Spring Flow: SAWS Well Field (Northern Alternative) Simulation (150K Scenario)

Table 16. Val Verde County Groundwater Budgets: SAWS Well Field (Northern Alternative) Well Field – Six Pumping Simulations

All Values in acre-feet per year

	Pumping Scenario						
	0K	**25K**	**50K**	**75K**	**100K**	**125K**	**150K**
Inflow							
Recharge from Precipitation	28,672	28,672	28,672	28,672	28,672	28,672	28,672
Inflow from Terrell County	37,532	37,552	37,576	37,598	37,621	37,647	37,673
Inflow from Crockett County	42,005	42,086	42,175	42,262	42,354	42,454	42,556
Inflow from Sutton County	12,992	13,061	13,137	13,211	13,290	13,376	13,463
Inflow from Edwards County	98,023	101,596	106,826	112,212	119,841	128,415	138,536
Inflow from Kinney County	105,559	114,169	121,101	128,312	133,640	137,946	141,100
Net Inflow from Amistad	24,220	25,872	27,557	29,036	30,439	31,845	33,122
Total Inflow	349,002	363,008	377,043	391,302	405,857	420,355	435,121
Outflow							
Pumping	0	25,016	50,031	75,047	100,062	125,078	150,093
Spring Flow	133,689	129,615	125,527	121,545	117,738	114,158	110,958
Baseflow to Rio Grande (Above Amistad)	90,683	90,557	90,416	90,282	90,140	89,984	89,829
Baseflow to Rio Grande (Below Amistad)	123,211	116,738	110,334	104,036	97,870	91,444	84,905
Total Outflow	347,583	361,926	376,309	390,909	405,810	420,664	435,786
Storage							
Total Inflow - Total Outflow	1,419	1,081	735	392	47	-309	-665
Storage Change (From Model)	1,419	1,081	735	392	47	-309	-665
Water Budget Residual	< 1	< 1	< 1	< 1	< 1	< 1	< 1

Table 17. Val Verde County Groundwater Budgets: SAWS Well Field (Northern Alternative) – Induced Inflows, Reduced Outflows and Storage Change Compared to Zero Pumping for Six Pumping Simulations

All Values in acre-feet per year

	Pumping Scenario					
	25K	**50K**	**75K**	**100K**	**125K**	**150K**
Pumping	25,016	50,031	75,047	100,062	125,078	150,093
Induced Inflow						
Recharge from Precipitation	0	0	0	0	0	0
Inflow from Terrell County	21	44	66	90	115	141
Inflow from Crockett County	80	170	256	348	449	550
Inflow from Sutton County	68	145	218	298	384	471
Inflow from Edwards County	3,573	8,804	14,190	21,819	30,393	40,513
Inflow from Kinney County	8,611	15,542	22,753	28,081	32,387	35,542
Net Inflow from Amistad	1,652	3,337	4,816	6,219	7,625	8,902
Total Induced Inflow	14,006	28,041	42,300	56,855	71,353	86,119
Reduced Outflow						
Spring Flow	4,074	8,162	12,144	15,951	19,531	22,731
Baseflow to Rio Grande (Above Amistad)	126	267	401	543	699	855
Baseflow to Rio Grande (Below Amistad)	6,472	12,877	19,175	25,341	31,767	38,305
Total Outflow	10,672	21,305	31,720	41,835	51,997	61,891
Storage Change from Pumping	338	684	1,027	1,373	1,728	2,084
Total Induced Inflow, Reduced Outflow and Storage Change (should equal pumping)	25,016	50,031	75,047	100,062	125,078	150,093

Table 18. Val Verde County Groundwater Budgets: SAWS Well Field (Northern Alternative) – Induced Inflows, Reduced Outflows and Storage Change as a Percentage of Pumping for Six Pumping Simulations

All values expressed as a percentage of pumping

	Pumping Scenario					
	25K	**50K**	**75K**	**100K**	**125K**	**150K**
Pumping	25,016	50,031	75,047	100,062	125,078	150,093
Induced Inflow						
Recharge from Precipitation	0	0	0	0	0	0
Inflow from Terrell County	0	0	0	0	0	0
Inflow from Crockett County	0	0	0	0	0	0
Inflow from Sutton County	0	0	0	0	0	0
Inflow from Edwards County	14	18	19	22	24	27
Inflow from Kinney County	34	31	30	28	26	24
Net Inflow from Amistad	7	7	6	6	6	6
Total Induced Inflow	56	56	56	57	57	57
Reduced Outflow						
Spring Flow	16	16	16	16	16	15
Baseflow to Rio Grande (Above Amistad)	1	1	1	1	1	1
Baseflow to Rio Grande (Below Amistad)	26	26	26	25	25	26
Total Outflow	43	43	42	42	42	41
Storage Change from Pumping	1	1	1	1	1	1
Total Induced Inflow, Reduced Outflow and Storage Change (should equal 100)	100	100	100	100	100	100

Table 19. Val Verde County Groundwater Budgets: SAWS Well Field (Southern Alternative) Well Field – Six Pumping Simulations

All Values in acre-feet per year

	Pumping Scenario						
	0K	**25K**	**50K**	**75K**	**100K**	**125K**	**150K**
Inflow							
Recharge from Precipitation	28,672	28,672	28,672	28,672	28,672	28,672	28,672
Inflow from Terrell County	37,532	37,547	37,563	37,582	37,600	37,620	37,641
Inflow from Crockett County	42,005	42,061	42,123	42,191	42,262	42,337	42,414
Inflow from Sutton County	12,992	13,038	13,090	13,146	13,205	13,269	13,333
Inflow from Edwards County	98,023	99,533	101,335	103,408	105,553	107,832	109,820
Inflow from Kinney County	105,559	114,436	123,442	132,484	141,855	151,602	161,853
Net Inflow from Amistad	24,220	25,739	27,260	28,744	30,158	31,498	32,745
Total Inflow	349,002	361,025	373,485	386,226	399,305	412,829	426,477
Outflow							
Pumping	0	25,016	50,031	75,047	100,062	125,078	150,093
Spring Flow	133,689	128,893	124,240	119,717	115,528	111,909	108,479
Baseflow to Rio Grande (Above Amistad)	90,683	90,589	90,483	90,370	90,252	90,128	90,002
Baseflow to Rio Grande (Below Amistad)	123,211	115,431	107,966	100,664	93,381	85,983	78,521
Total Outflow	347,583	359,928	372,721	385,799	399,224	413,098	427,096
Storage							
Total Inflow - Total Outflow	1,419	1,097	765	427	81	-269	-619
Storage Change (From Model)	1,419	1,097	765	427	81	-269	-619
Model Error	< 1	< 1	< 1	< 1	< 1	< 1	< 1

Table 20. Val Verde County Groundwater Budgets: SAWS Well Field (Southern Alternative) – Induced Inflows, Reduced Outflows and Storage Change Compared to Zero Pumping for Six Pumping Simulations

All Values in acre-feet per year

	Pumping Scenario					
	25K	**50K**	**75K**	**100K**	**125K**	**150K**
Pumping	25,016	50,031	75,047	100,062	125,078	150,093
Induced Inflow						
Recharge from Precipitation	0	0	0	0	0	0
Inflow from Terrell County	15	32	50	69	89	109
Inflow from Crockett County	55	118	185	256	332	408
Inflow from Sutton County	46	98	154	213	276	341
Inflow from Edwards County	1,510	3,313	5,386	7,530	9,809	11,797
Inflow from Kinney County	8,877	17,884	26,925	36,296	46,043	56,294
Net Inflow from Amistad	1,519	3,040	4,524	5,938	7,277	8,525
Total Induced Inflow	12,023	24,483	37,224	50,303	63,827	77,475
Reduced Outflow						
Spring Flow	4,796	9,449	13,972	18,160	21,780	25,210
Baseflow to Rio Grande (Above Amistad)	95	200	313	431	555	681
Baseflow to Rio Grande (Below Amistad)	7,780	15,244	22,546	29,830	37,228	44,689
Total Outflow	12,670	24,893	36,831	48,422	59,562	70,580
Storage Change from Pumping	323	654	992	1,338	1,688	2,038
Total Induced Inflow, Reduced Outflow and Storage Change (should equal pumping)	25,016	50,031	75,047	100,062	125,078	150,093

Table 21. Val Verde County Groundwater Budgets: SAWS Well Field (Southern Alternative) – Induced Inflows, Reduced Outflows and Storage Change as a Percentage of Pumping for Six Pumping Simulations

All values expressed as a percentage of pumping

	Pumping Scenario					
	25K	**50K**	**75K**	**100K**	**125K**	**150K**
Pumping	25,016	50,031	75,047	100,062	125,078	150,093
Induced Inflow						
Recharge from Precipitation	0	0	0	0	0	0
Inflow from Terrell County	0	0	0	0	0	0
Inflow from Crockett County	0	0	0	0	0	0
Inflow from Sutton County	0	0	0	0	0	0
Inflow from Edwards County	6	7	7	8	8	8
Inflow from Kinney County	35	36	36	36	37	38
Net Inflow from Amistad	6	6	6	6	6	6
Total Induced Inflow	48	49	50	50	51	52
Reduced Outflow						
Spring Flow	19	19	19	18	17	17
Baseflow to Rio Grande (Above Amistad)	0	0	0	0	0	0
Baseflow to Rio Grande (Below Amistad)	31	30	30	30	30	30
Total Outflow	51	50	49	48	48	47
Storage Change from Pumping	1	1	1	1	1	1
Total Induced Inflow, Reduced Outflow and Storage Change (should equal 100)	100	100	100	100	100	100

4.3.4 Impacts to Average San Felipe Spring Flow

Results of the simulations of large scale pumping presented above included maps of drawdown, hydrographs of San Felipe Spring flow, and groundwater budget impacts. For purposes of comparing the various well field locations and pumping amounts, average San Felipe Spring flows over the entire simulations were calculated. Because San Felipe Spring is correlated to groundwater elevations, and because San Felipe Spring responds to changes in precipitation and lake elevation, it can be considered a good indicator of groundwater conditions in Val Verde County.

Table 22 summarizes the actual (measured) average spring flow from 1968 to 2011, the calibrated model average spring flow for the same period as the measured data (1968 to 2011) and for the entire simulation period, and the average spring flow for the no pumping simulation. Note that the average of the actual data and calibrated model for the same period are within 1 mgd of each other (79.27 vs. 78.01). Also, please note that the average San Felipe Spring flow for the entire simulation period of the calibrated model (1968 to 2013) is less than 0.4 mgd lower than the average San Felipe Spring flow under the no pumping simulation for the same period (72.22 vs. 77.56). This suggests that historic levels of pumping have had no significant effect on average San Felipe Spring flow.

Table 22. Summary of Average San Felipe Spring Flow in mgd (Actual, Calibrated Model, and No Pumping Simulation)

Source of Average and Time Period	San Felipe Spring Flow (mgd)
Actual -1968 to 2011	79.27
Calibrated Model - 1968 to 2011	78.01
Calibrated Model - 1968 to 2013	77.22
No Pumping – 1968 to 2013	77.56

Table 23 presents average San Felipe Spring flow for all 18 simulations presented above. Figure 39 summarizes these results in a graph that plots the spring flow for each simulation as a function of pumping. Figure 39 also includes the average spring flow associated with the zero pumping simulation for reference purposes. As expected, pumping increases result in decreased average spring flow. Differences in the impact to average spring flow can be attributed to location of the pumped wells from the spring in terms of efficiency of capturing groundwater flow that would have moved towards the spring. For example, although the peninsula well field is closer to San Felipe Spring as compared to the two alternative locations of the “SAWS” well fields, the impact is less due to the ability of the peninsula well field to induce flow from Lake Amistad. Similarly, the SAWS south well field creates a greater impact to average flow in San Felipe Spring as compared to the SAWS north well field apparently due to the preferential flow path associated with the West Fork of Sycamore Creek (the location of the SAWS south well field).

Table 23. Summary of Average San Felipe Spring Flow in mgd (18 simulations)

Pumping (AF/yr)	Peninsula	SAWS North	SAWS South
25K	76.46	75.45	75.00
50K	75.01	73.34	72.53
75K	73.24	71.27	70.10
100K	71.27	69.24	67.69
125K	68.87	67.13	65.26
150K	66.19	64.99	62.80

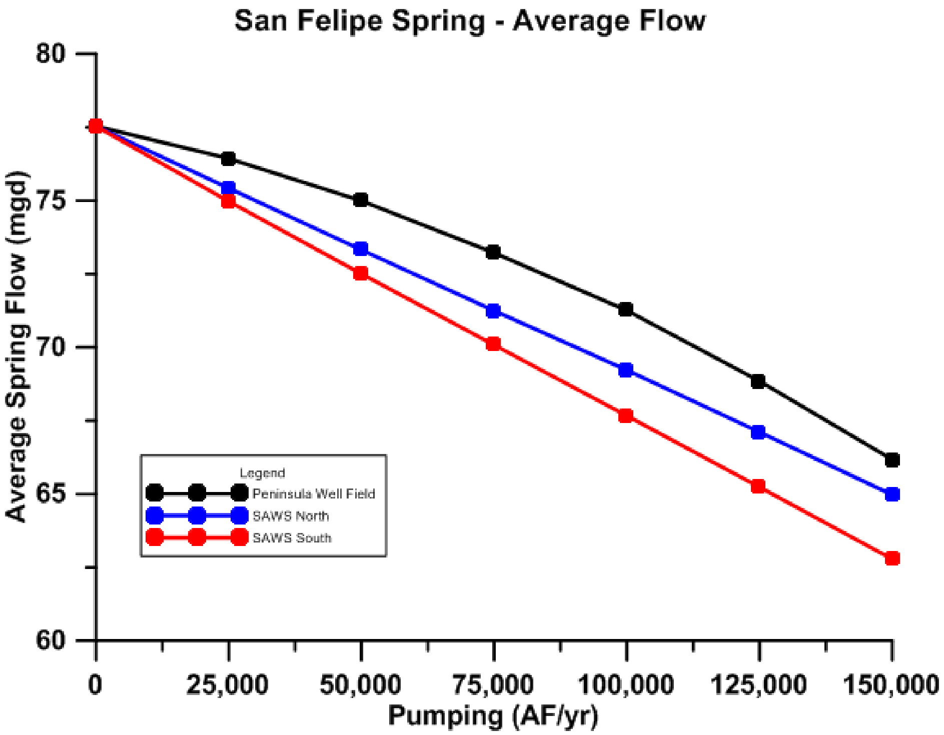

Figure 39. San Felipe Spring - Average Flow for 18 Simulations

Table 24 presents the change in average San Felipe Spring flow (in million gallons per day) for each of the 18 simulations as compared to the no pumping simulation. Table 25 presents the change in average San Felipe Spring flow for each of the 18 simulations as a percentage of spring flow under the no pumping simulation.

Table 24. Summary of Change in Average San Felipe Spring Flow in mgd for 18 Simulations as Compared to the No Pumping Simulation

Pumping (AF/yr)	Peninsula	SAWS North	SAWS South
25K	1.10	2.11	2.56
50K	2.54	4.22	5.03
75K	4.32	6.29	7.46
100K	6.28	8.32	9.87
125K	8.69	10.43	12.30
150K	11.36	12.57	14.75

Table 25. Summary of Change in Average San Felipe Spring Flow for 18 Simulations as a Percentage of the No Pumping Simulation

Pumping (AF/yr)	Peninsula	SAWS North	SAWS South
25K	1	3	3
50K	3	5	6
75K	6	8	10
100K	8	11	13
125K	11	13	16
150K	15	16	19

5.0 Discussion and Conclusions

The Request for Qualifications issued by the Partnership (the City of Del Rio and the County of Val Verde) listed specific items to cover in this investigation. This report has described the development, calibration and application of a groundwater flow model of the Edwards-Trinity Plateau Aquifer in Val Verde County that was developed at the request of the Partnership to meet these objectives. This chapter of the report lists the items and summarizes our findings and recommendations relative to each.

5.1 Relationships between Groundwater Levels, Lake Levels and Spring Flow

Chapter 2 of this report covered the data review regarding the relationships between groundwater levels, lake levels and spring flow. The groundwater model development was guided by this conceptual-level analysis. The groundwater budget analyses of the calibrated groundwater model (Chapter 3.3) and the groundwater budget analyses associated with each of the simulations discussed in Chapter 4 provide more quantitative information on these relationships.

In summary, groundwater and surface water are intimately linked in Val Verde County. The filling of Lake Amistad has resulted in increased groundwater levels and increased spring flow. Periods of low precipitation result in decreased groundwater levels and decreased spring flows. Baseflow to the Rio Grande is another example of how groundwater and surface water are linked. Large increases in pumping would result in relatively small changes in groundwater levels (i.e. groundwater storage), but would result in changes to spring flow and baseflow to the Rio Grande.

5.2 Boundaries of Aquifer

Previous regional investigations on the Edwards-Trinity Plateau Aquifer have established the boundaries of the groundwater system. The groundwater model developed as part of this effort relied on the geologic framework that was used in the Kinney County area groundwater model. The Kinney County area groundwater model had the spatial resolution that was appropriate for this investigation, and was an appropriate level of details given the objectives of the Partnership.

5.3 Monitoring Well Locations

The calibration of the model used data from 498 wells in Val Verde County. Under separate cover, we will be providing detailed recommendations regarding monitoring well locations that leverages the historic data from existing wells that were used in model calibration.

During the first week in April 2014, EcoKai personnel met with representatives of the Texas Parks and Wildlife Department and The Nature Conservancy and identified several monitoring well locations in the northern and central portions of the County. Although there are likely many other candidate locations these wells will be included in a separate memorandum for consideration by the Partnership.

5.4 Recommend Aquifer Levels at Which It Becomes Necessary to Reduce Groundwater Pumping and Implement Water Conservation Measures in the City and County

The amount of historic pumping in Val Verde County is relatively small as shown in the groundwater budget of the calibrated model (Table 10). Spring flow variation is mostly a function of precipitation and lake levels. As shown in Table 22, historic pumping has not had any significant impact on average flow of San Felipe Spring. Moreover, slight increases in pumping would likely have no significant impact on spring flow. The analyses and simulations also demonstrate that impacts to spring flow and river base flow are more significant during average and wet periods than in drought periods. Therefore, reductions in pumping during drought periods (assuming current levels of pumping) would have essentially no beneficial impact on spring flow.

If a groundwater conservation district were formed in Val Verde County, the new district would presumably review permit applications in the context of proposed pumping impacts on spring flow, among other issues. These new wells should be evaluated in terms of the potential to capture spring flow and river base flow during all years, and not focus on drought period reductions.

5.5 Recommend Aquifer Levels that Trigger Reduction and/or Cessation of Pumping of Water for Export

Eighteen simulations were completed as part of this effort: six pumping scenarios at three well field sites. The results demonstrate that the degree and nature of any impact is mainly in the form of induced inflow and reduced outflow, and are collectively referred to as capture. Groundwater storage reductions due to pumping were found to be relatively minor. The induced inflows include additional leakage from Lake Amistad and additional inflow from surrounding counties. Reduced outflows were mainly reduced spring flows and reduced baseflow to the Rio Grande below the dam. In addition, it was found that spring flow reduction during low flow periods were not as significant as high flow periods.

A specific recommendation regarding specific aquifer levels to trigger reduction is not possible without knowing the location and amount of pumping. The simulations have provided a wide range of alternatives to assist the Partnership in evaluating specific mitigation measures to a specific proposal. In general, this model provides a framework on which additional, more detailed analyses can be developed.

5.6 Determine the Amount of Managed Groundwater that is Available for Full, Average and Low Conditions

Groundwater Conservation Districts in Texas adopt desired future conditions (DFCs) for the aquifers in a Groundwater Management Area. The Texas Water Development Board uses these desired future conditions to develop modeled available groundwater (MAGs) for each district, and represents the pumping that would achieve the desired future condition. The definition of a

MAG was changed by the Texas Legislature in 2011 from Managed Available Groundwater to Modeled Available Groundwater

Val Verde County is in Groundwater Management Area 7, and since Val Verde County does not have a groundwater conservation district, the other groundwater conservation district in Groundwater Management Area 7 established a desired future condition for Val Verde County based on conversations with representatives of the City of Del Rio and the County of Val Verde. This desired future condition for Val Verde County is one foot of drawdown between the years 2006 and 2060. The modeled available groundwater for this desired future conditions was set at 25,000 AF/yr, and was based on the regional groundwater model developed for Groundwater Management Area 7 by the Texas Water Development Board. The simulation that was used to establish desired future conditions and modeled available groundwater used an average recharge for the entire simulation period (2006 to 2060), and did not consider a range of “full”, “average” and “low” conditions.

The item, as worded by the Partnership, does not include a concept similar to “desired future condition” that would place the amount of pumping into context. In other words, the Partnership or a future groundwater conservation district board (if one is created) would have to articulate its management objectives in the form of a desired future condition.

Toward this end, our recommendation regarding this item is that a desired future condition be based on spring flow at San Felipe Spring. This effort has demonstrated that the flow at San Felipe Spring is intimately connected to changes in precipitation, lake levels, and groundwater levels. The simulations of large-scale pumping also show that there is potential for spring flow reductions, so there would be a link between the desired future condition and the modeled available groundwater. It would be appropriate to base a desired future condition on San Felipe Spring flow because there is a long data history, and, thus, it could be easily tracked.

A key issue in the development of a desired future condition would be a decision to base it on average flow, a running average flow, a minimum flow, or some combination of average and minimum. Some basic information on average San Felipe Spring flow was presented in Section 4.3.4 of this report. Given that the location of future pumping could have a significant effect on the amount of spring flow impact, some care will need to be taken when establishing a desired future condition.

In summary, the current modeled available groundwater for Val Verde County (25,000 AF/yr) was simulated as part of this effort at three locations, and the impacts on groundwater elevations, water budget impacts, and impacts to San Felipe Spring were presented. Higher levels of pumping were also simulated, and could be used to guide a different desired future condition and modeled available groundwater for the next desired future condition, which is due in May 2016.

6.0 References

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Appendix A

Drawdown Simulation Maps

(Figures A-1 thru A-27)

Appendix A - List of Figures

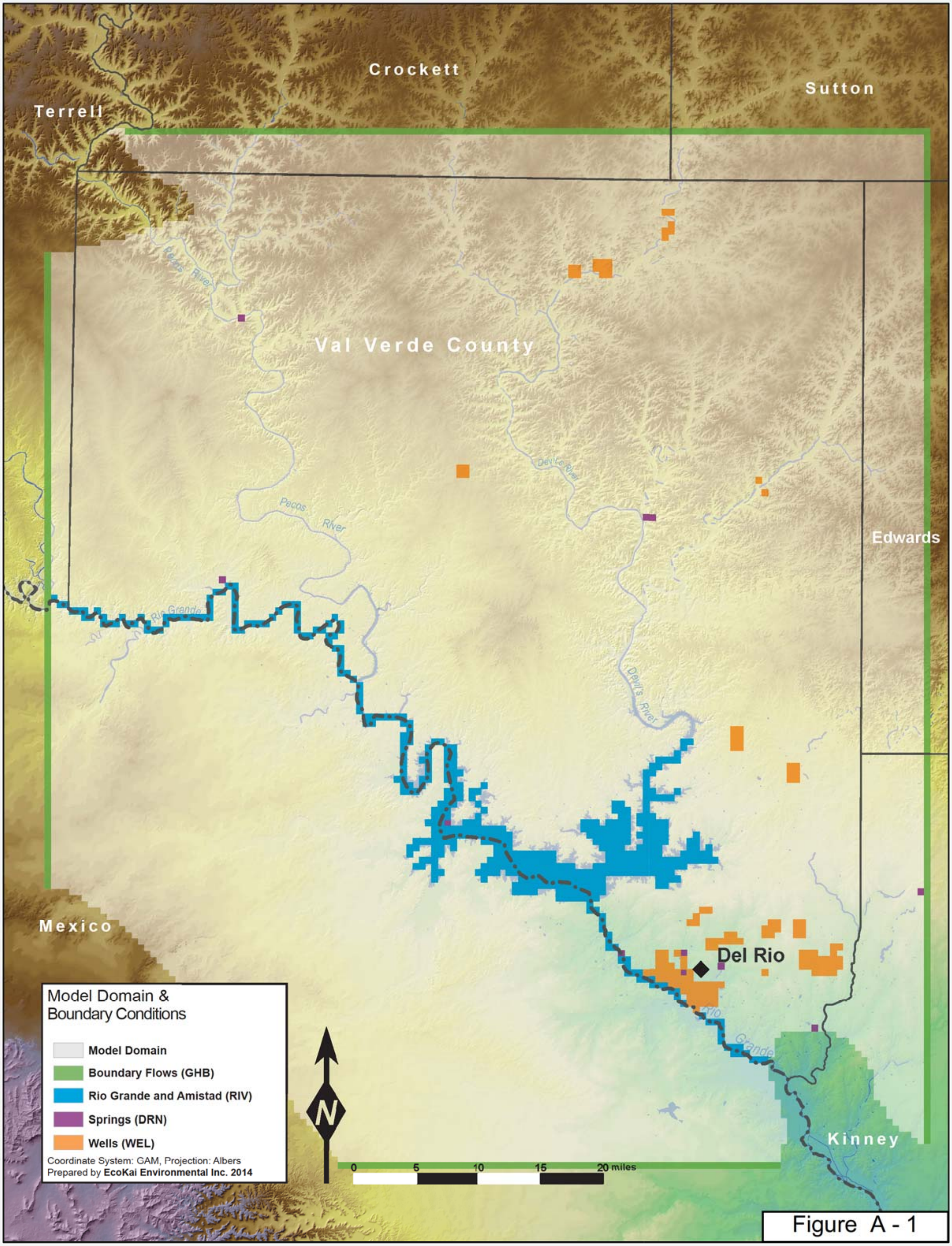

Crockett
Sutton
Terrell
Val Verde County
Edwards
Mexico
Kinney
Del Rio
Pecos River
Pecos River
Devil's River
Devil's River
Rio Grande
Rio Grande
Model Domain & Boundary Conditions
Model Domain
Boundary Flows (GHB)
Rio Grande and Amistad (RIV)
Springs (DRN)
Wells (WEL)
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 1

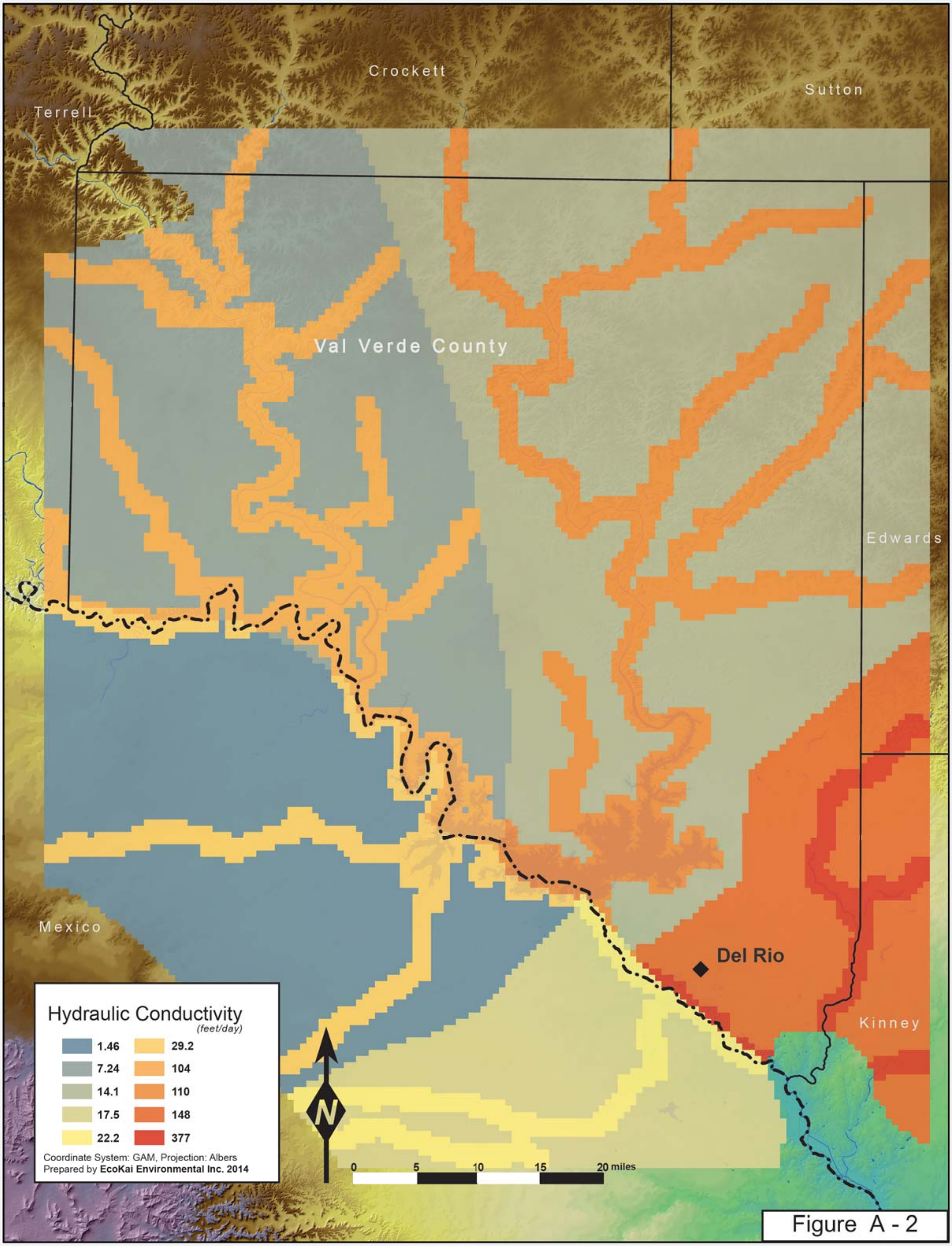

Crockett
Sutton
Terrell
Val Verde County
Edwards
Mexico
Del Rio
Kinney
Hydraulic Conductivity
(feet/day)
1.46
7.24
14.1
17.5
22.2
29.2
104
110
148
377
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 2

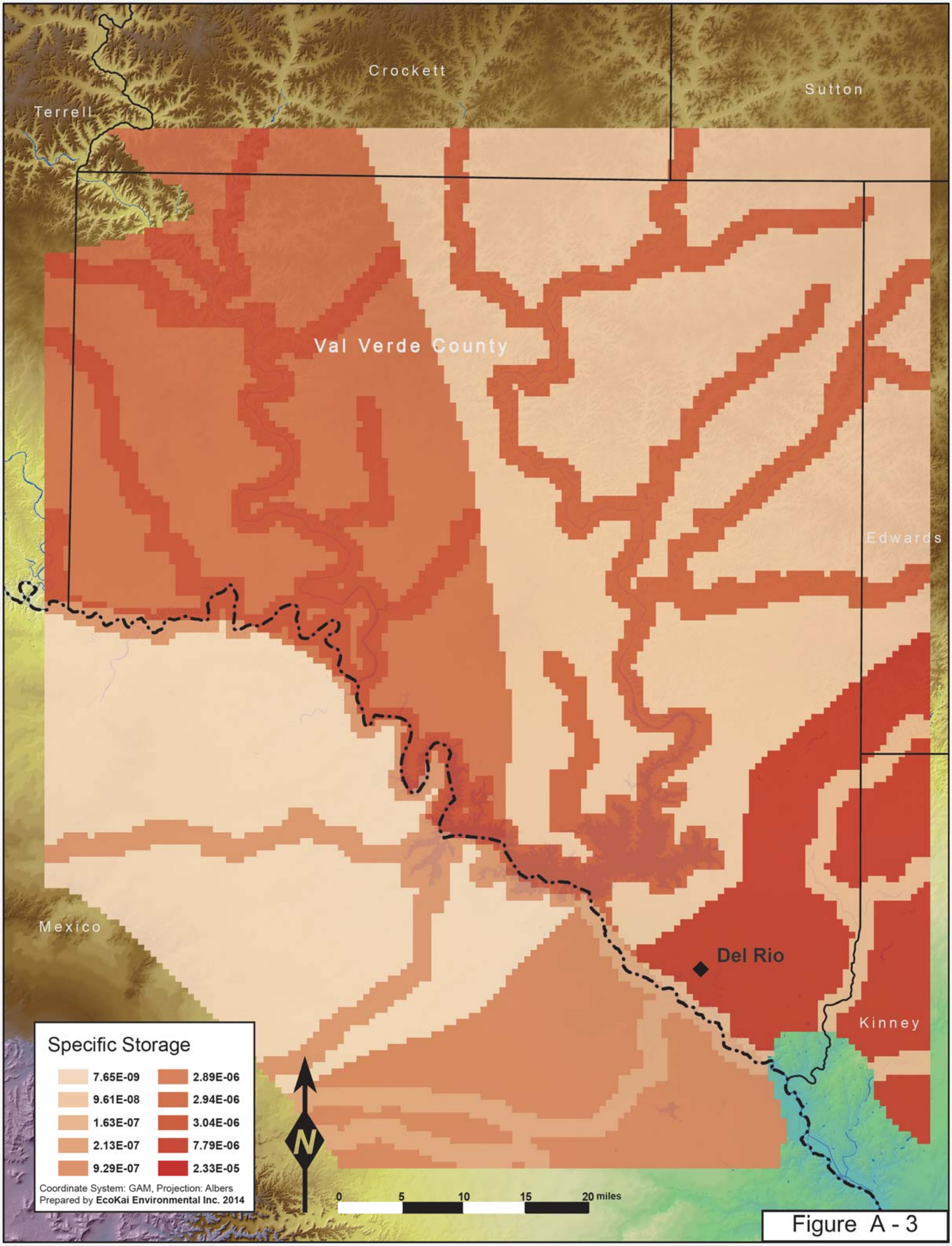

Crockett
Sutton
Terrell
Val Verde County
Edwards
Mexico
Del Rio
Kinney
Specific Storage
7.65E-09
9.61E-08
1.63E-07
2.13E-07
9.29E-07
2.89E-06
2.94E-06
3.04E-06
7.79E-06
2.33E-05
N
0
5
10
15
20 miles
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014

Figure A - 3

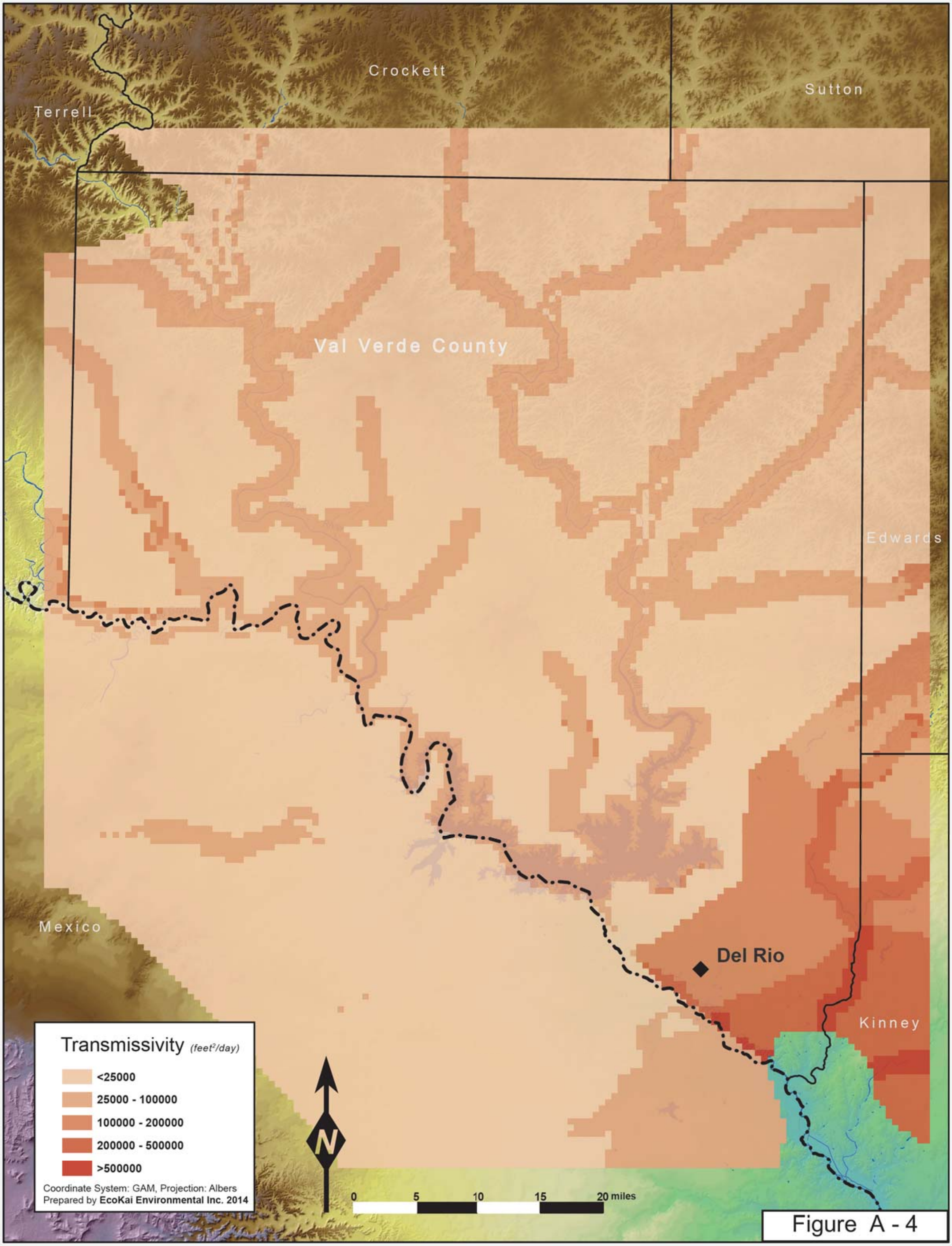
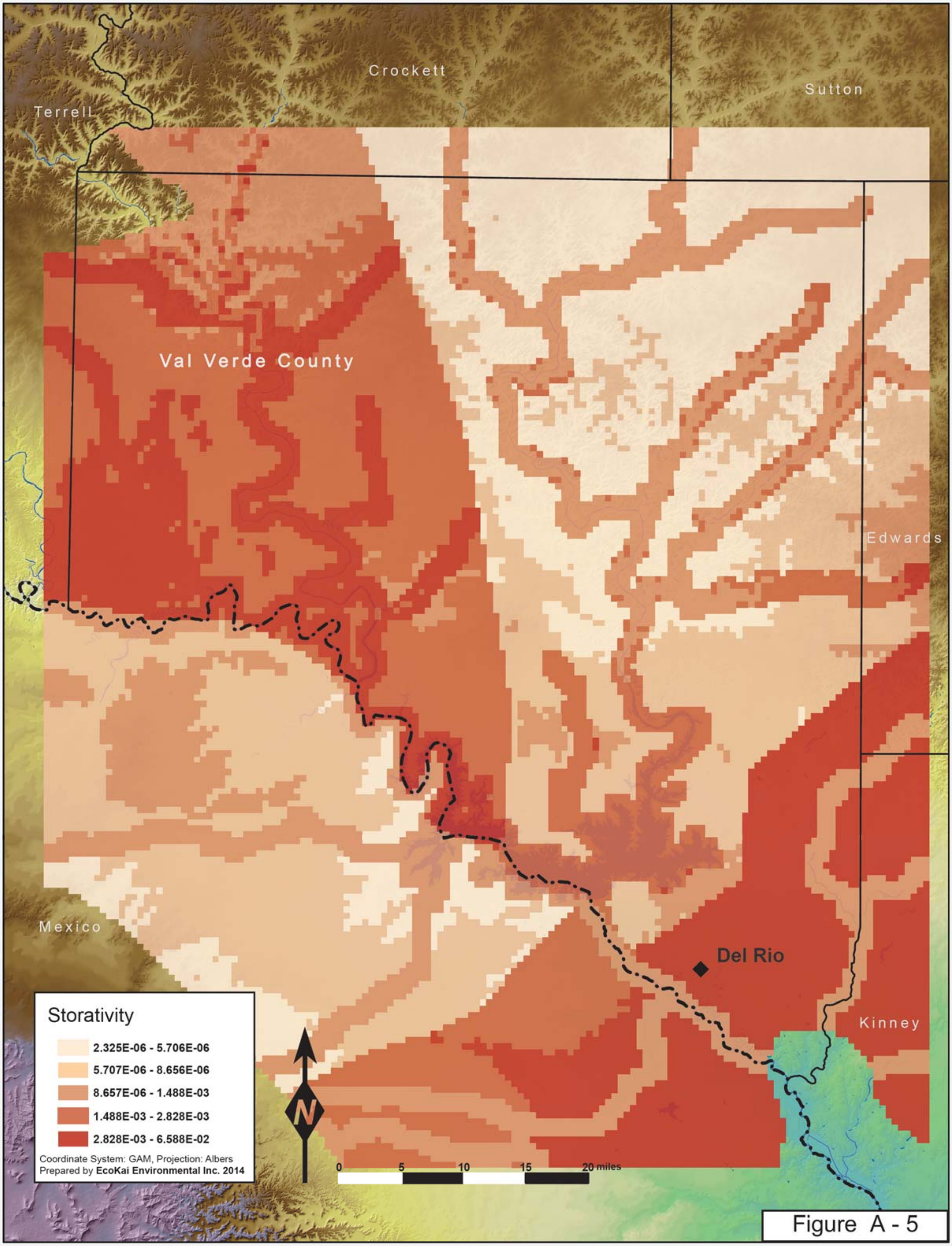

Crockett
Sutton
Terrell
Val Verde County
Edwards
Mexico
Del Rio
Kinney
Transmissivity (feet²/day)
<25000
25000 - 100000
100000 - 200000
200000 - 500000
>500000
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 4


Crockett
Sutton
Terrell
Val Verde County
Edwards
Mexico
Del Rio
Kinney
Storativity
2.325E-06 - 5.706E-06
5.707E-06 - 8.656E-06
8.657E-06 - 1.488E-03
1.488E-03 - 2.828E-03
2.828E-03 - 6.588E-02
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Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 5

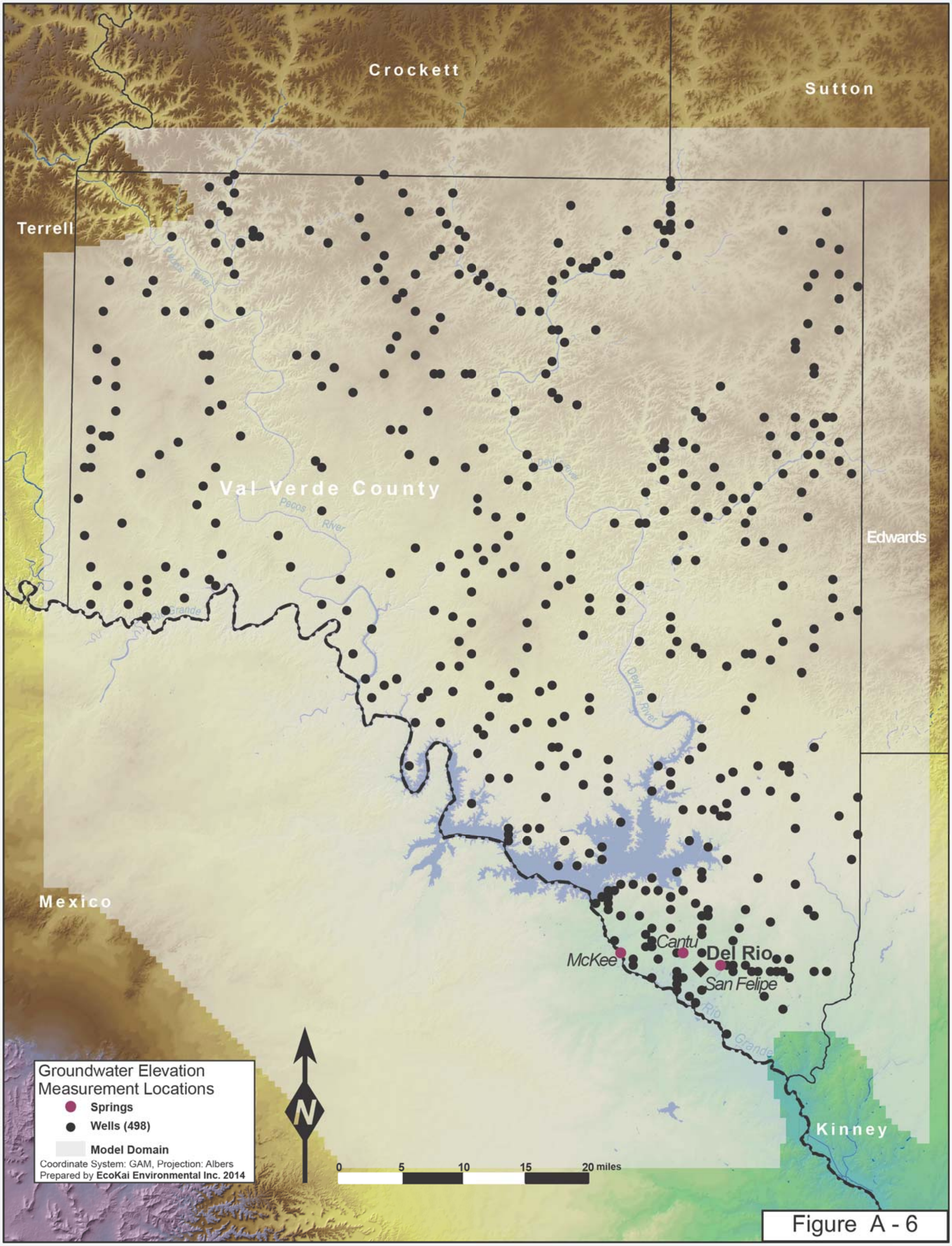

Crockett
Sutton
Terrell
Edwards
Val Verde County
Pecos River
Devil's River
Rio Grande
Mexico
Kinney
Cantu
McKee
Del Rio
San Felipe
Groundwater Elevation Measurement Locations
● Springs
● Wells (498)
Model Domain
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0 5 10 15 20 miles

Figure A - 6

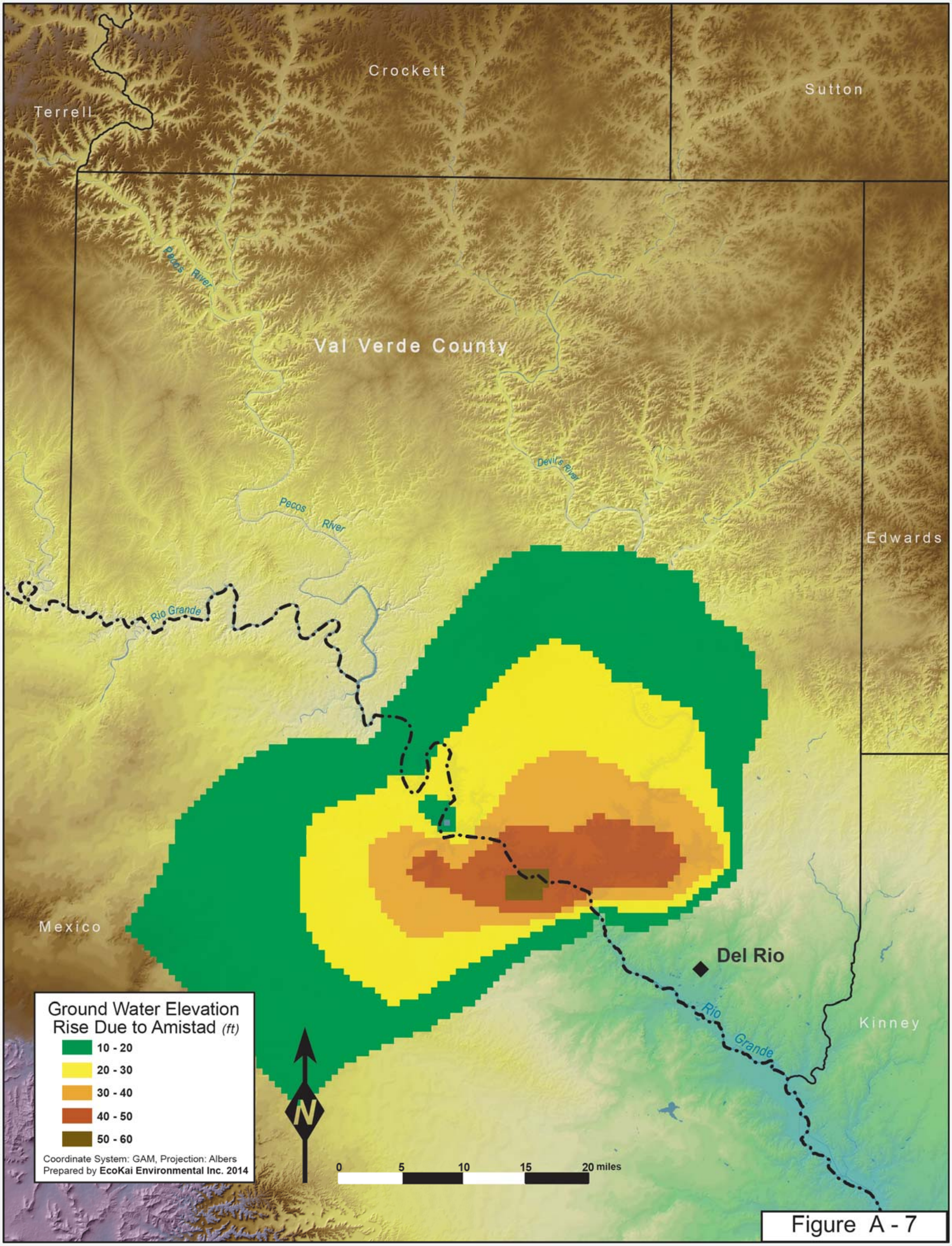
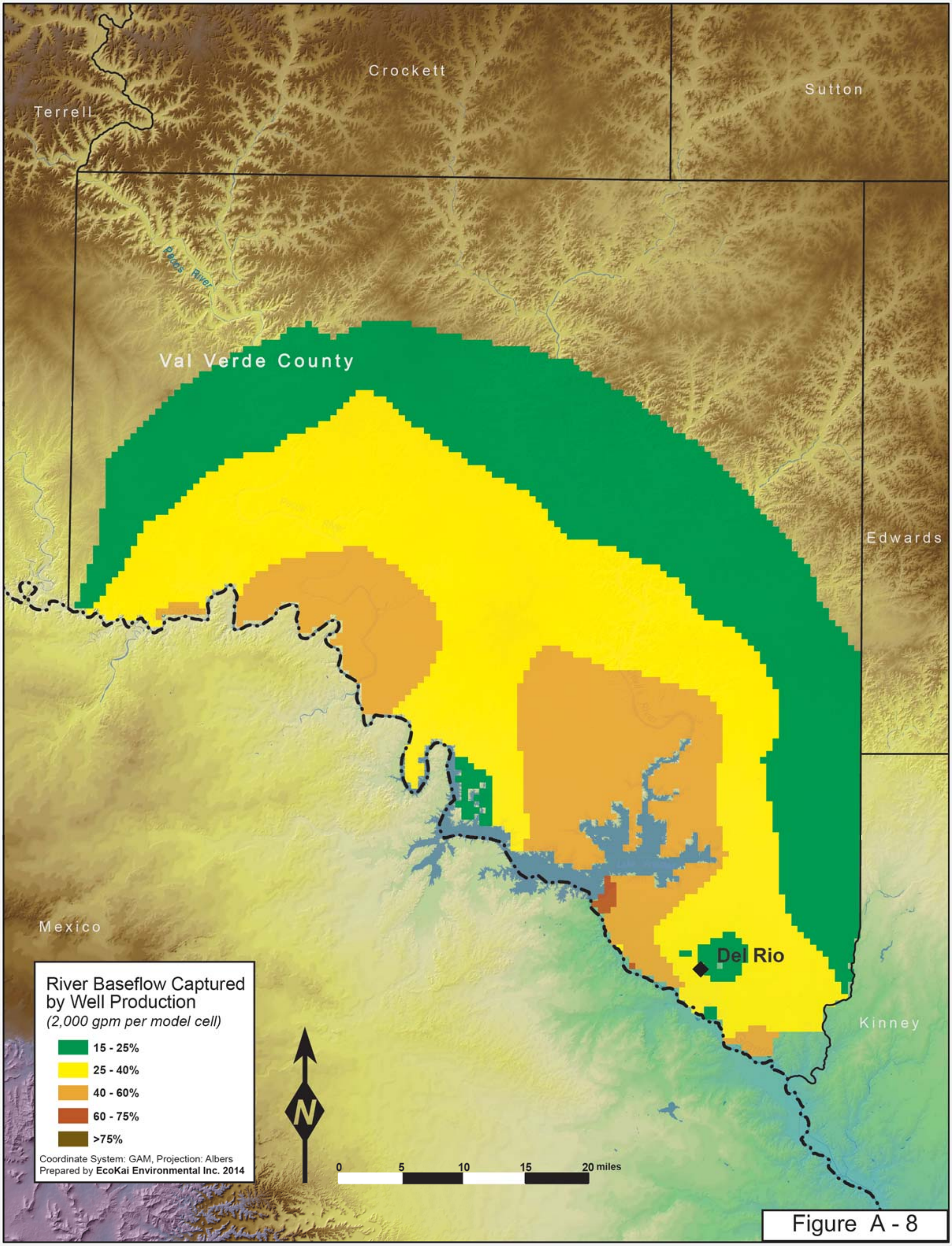

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
River
Mexico
Del Rio
Rio Grande
Kinney
Ground Water Elevation Rise Due to Amistad (ft)
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 7


Crockett
Sutton
Terrell
Pecos River
Val Verde County
Edwards
Mexico
Del Rio
Kinney
River Baseflow Captured by Well Production
(2,000 gpm per model cell)
🟩 15 - 25%
🟨 25 - 40%
🟧 40 - 60%
🟥 60 - 75%
🟫 >75%
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
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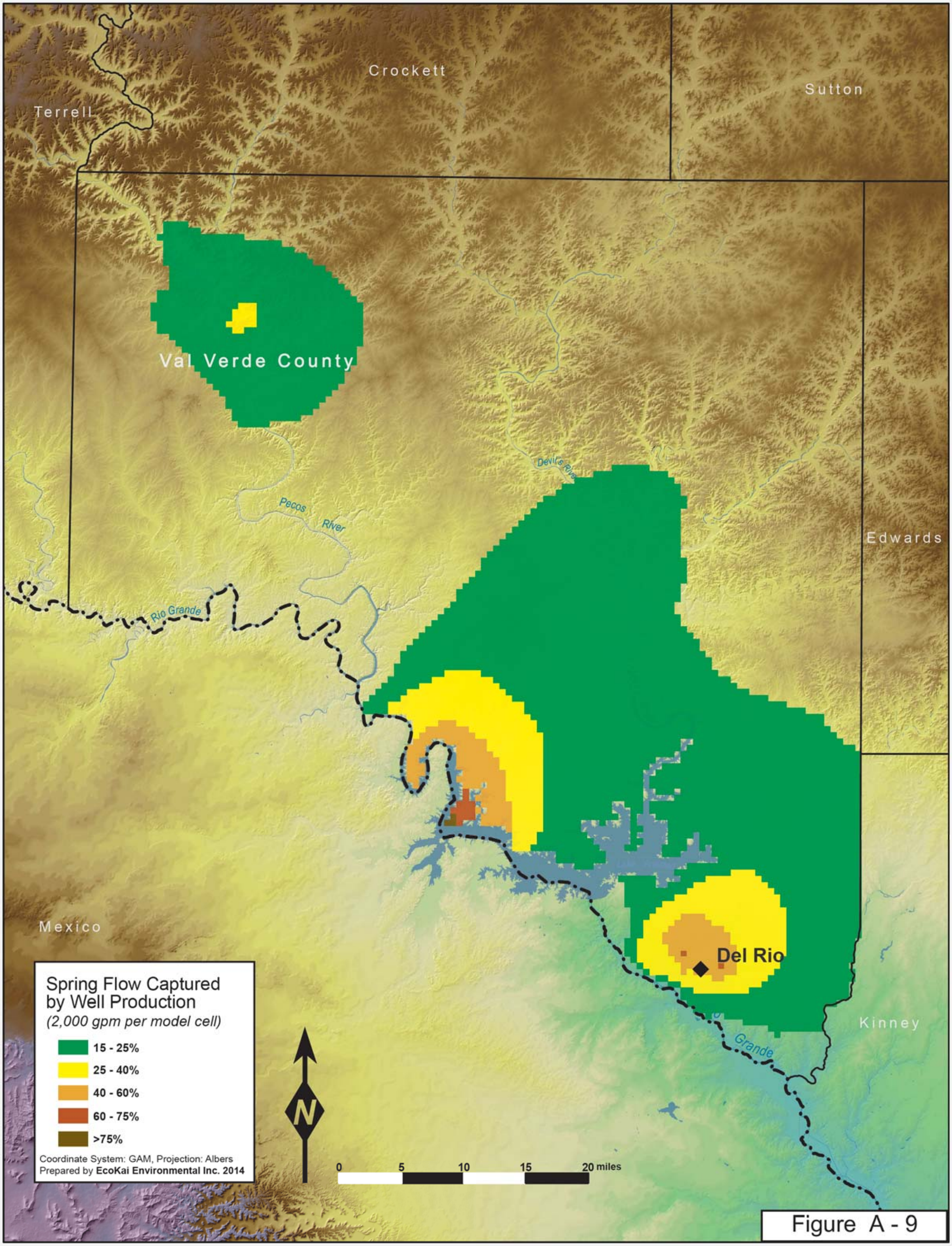
5
10
15
20 miles

Figure A - 8


Crockett
Sutton
Terrell
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Kinney
Grande
Spring Flow Captured by Well Production
(2,000 gpm per model cell)
15 - 25%
25 - 40%
40 - 60%
60 - 75%
>75%
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
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5
10
15
20 miles

Figure A - 9

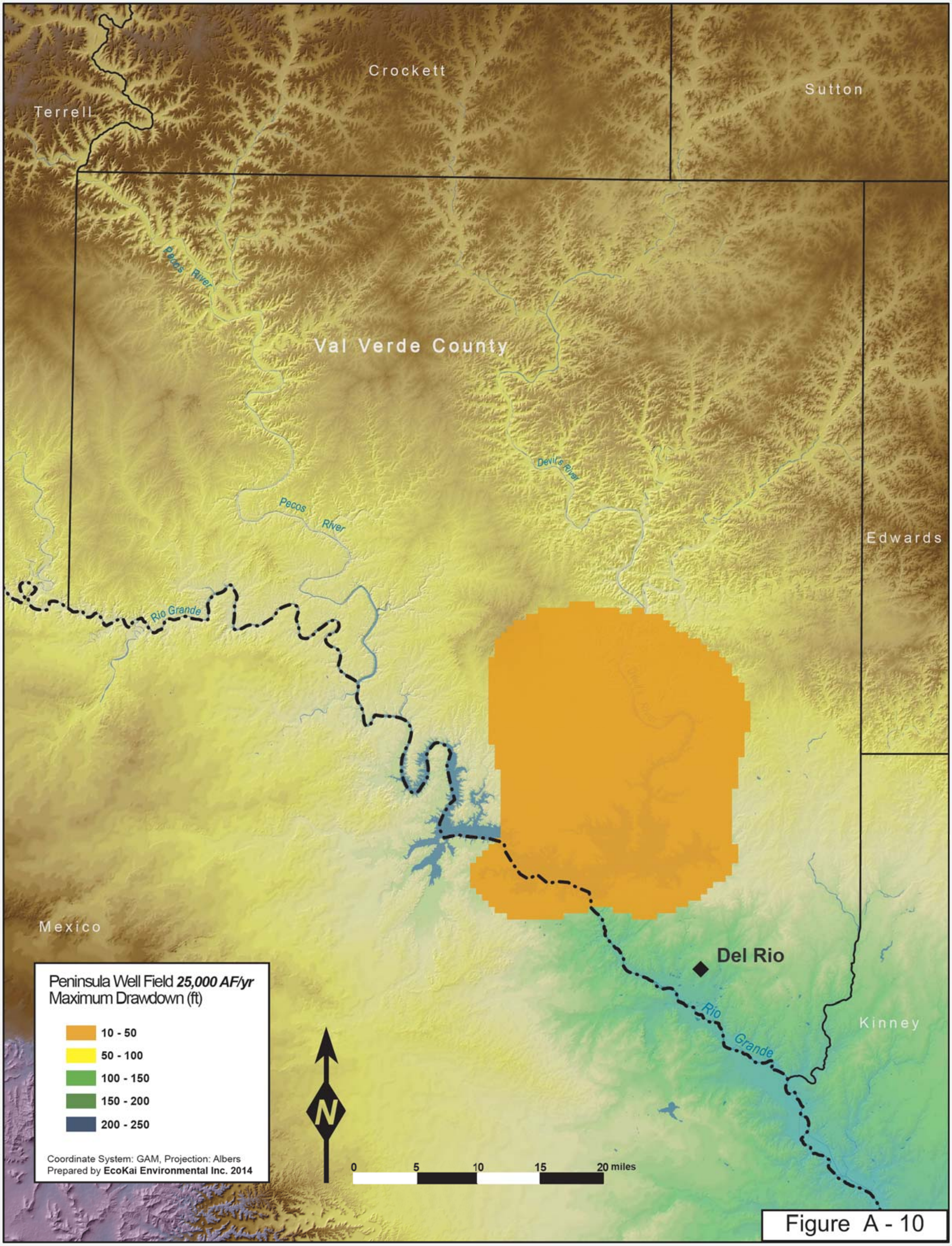
Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
Peninsula Well Field 25,000 AF/yr
Maximum Drawdown (ft)
10 - 50
50 - 100
100 - 150
150 - 200
200 - 250
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 10

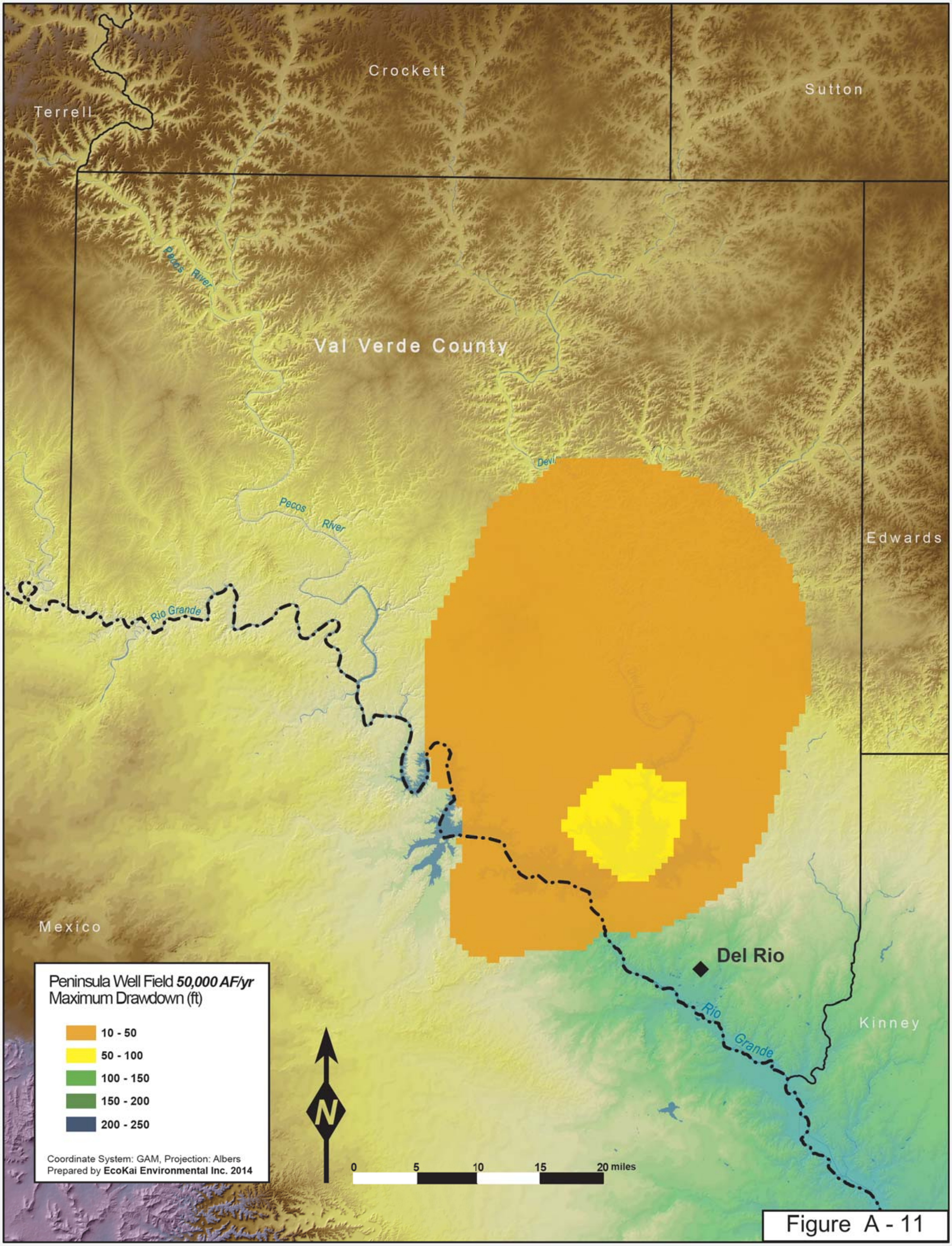
Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
Peninsula Well Field *50,000 AF/yr*
Maximum Drawdown (ft)
🟧 10 - 50
🟨 50 - 100
🟩 100 - 150
🟩 150 - 200
🟦 200 - 250
Coordinate System: GAM, Projection: Albers
Prepared by **EcoKai Environmental Inc. 2014**
N
0
5
10
15
20 miles

Figure A - 11

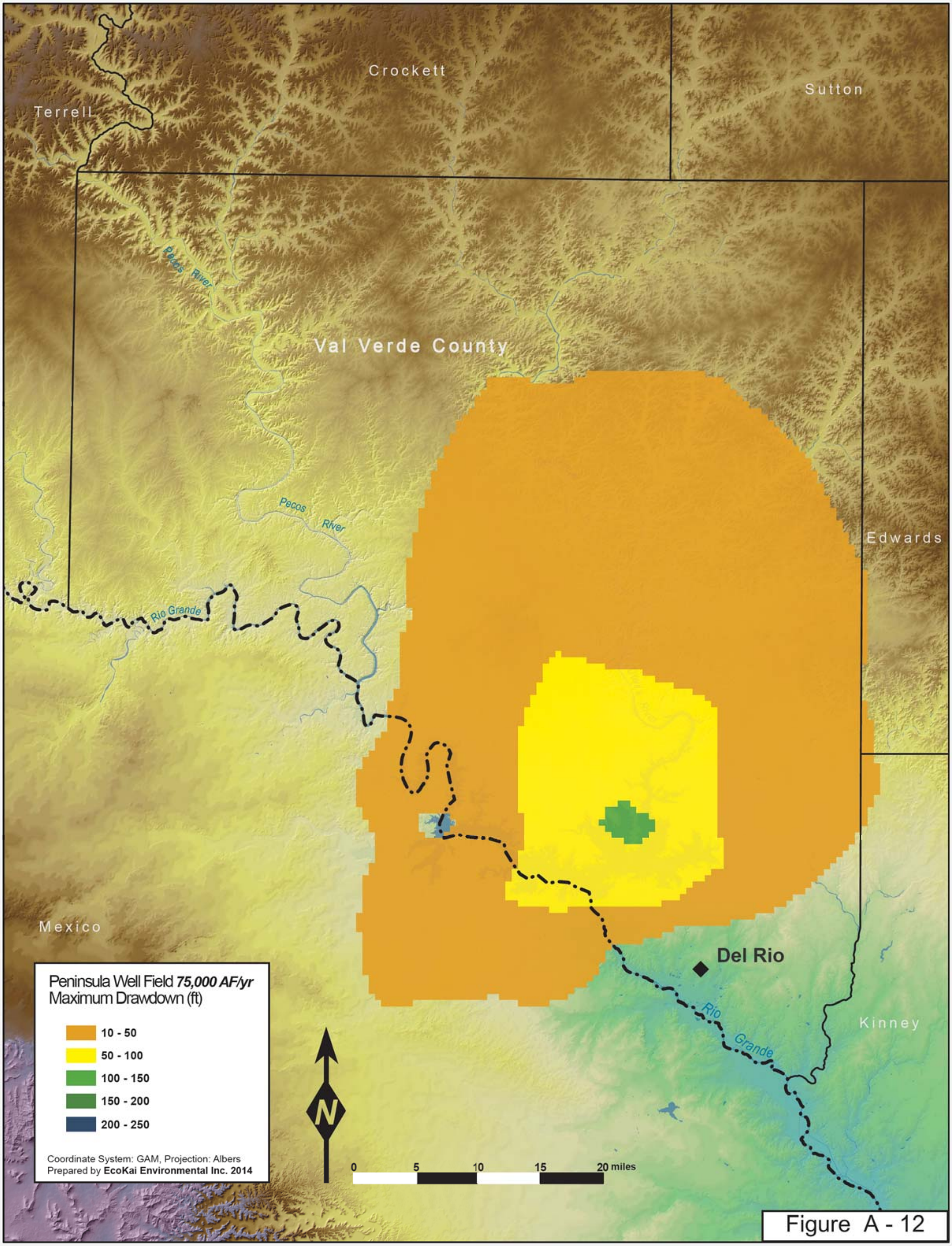
Crockett
Sutton
Terrell
Pecos River
Val Verde County
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
Peninsula Well Field *75,000 AF/yr*
Maximum Drawdown (ft)
10 - 50
50 - 100
100 - 150
150 - 200
200 - 250
Coordinate System: GAM, Projection: Albers
Prepared by **EcoKai Environmental Inc. 2014**
N
0
5
10
15
20 miles

Figure A - 12

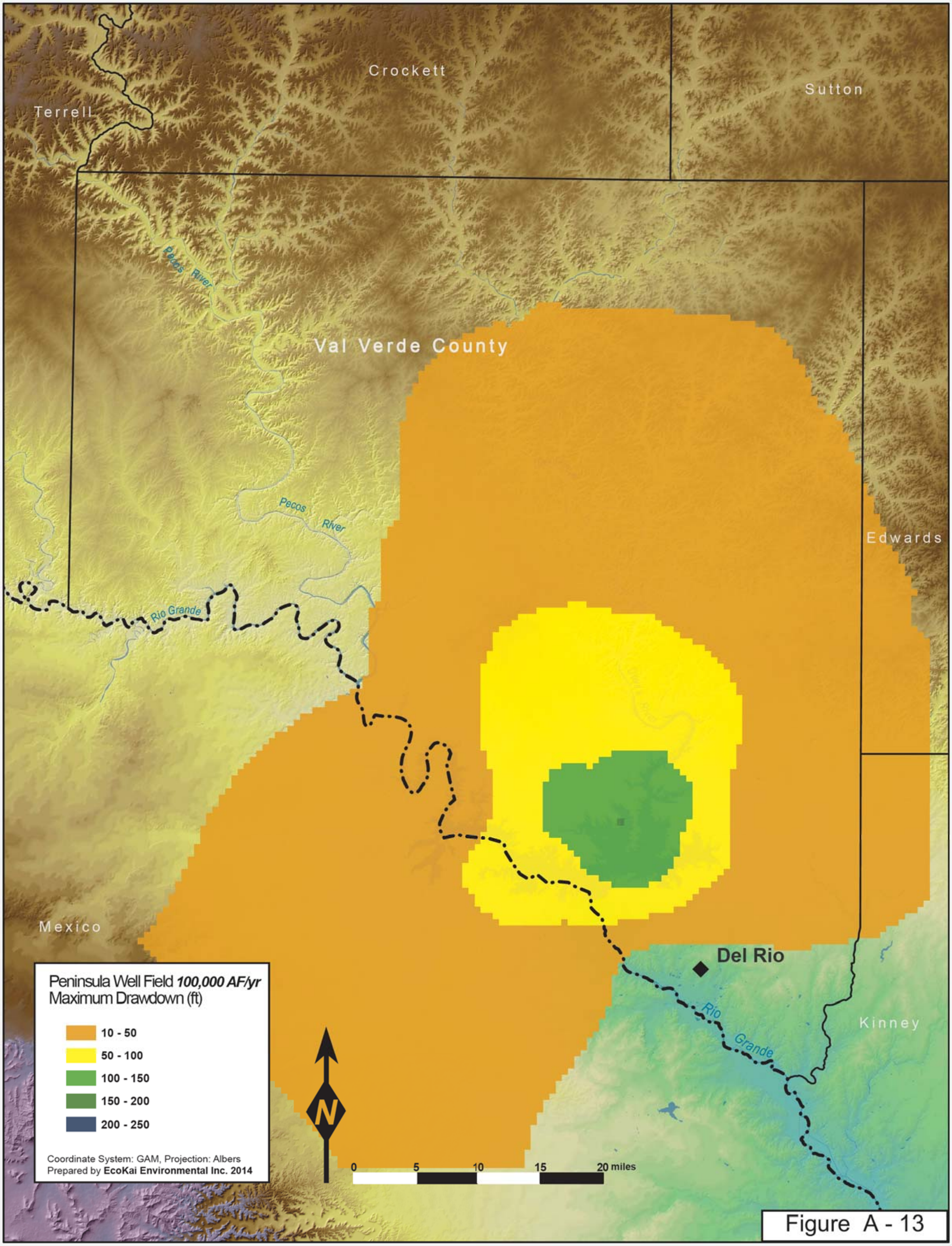
Crockett
Sutton
Terrell
Pecos River
Val Verde County
Pecos River
Edwards
Rio Grande
Devils River
Mexico
Del Rio
Rio Grande
Kinney
Peninsula Well Field *100,000 AF/yr*
Maximum Drawdown (ft)
10 - 50
50 - 100
100 - 150
150 - 200
200 - 250
Coordinate System: GAM, Projection: Albers
Prepared by **EcoKai Environmental Inc. 2014**
N
0
5
10
15
20 miles

Figure A - 13

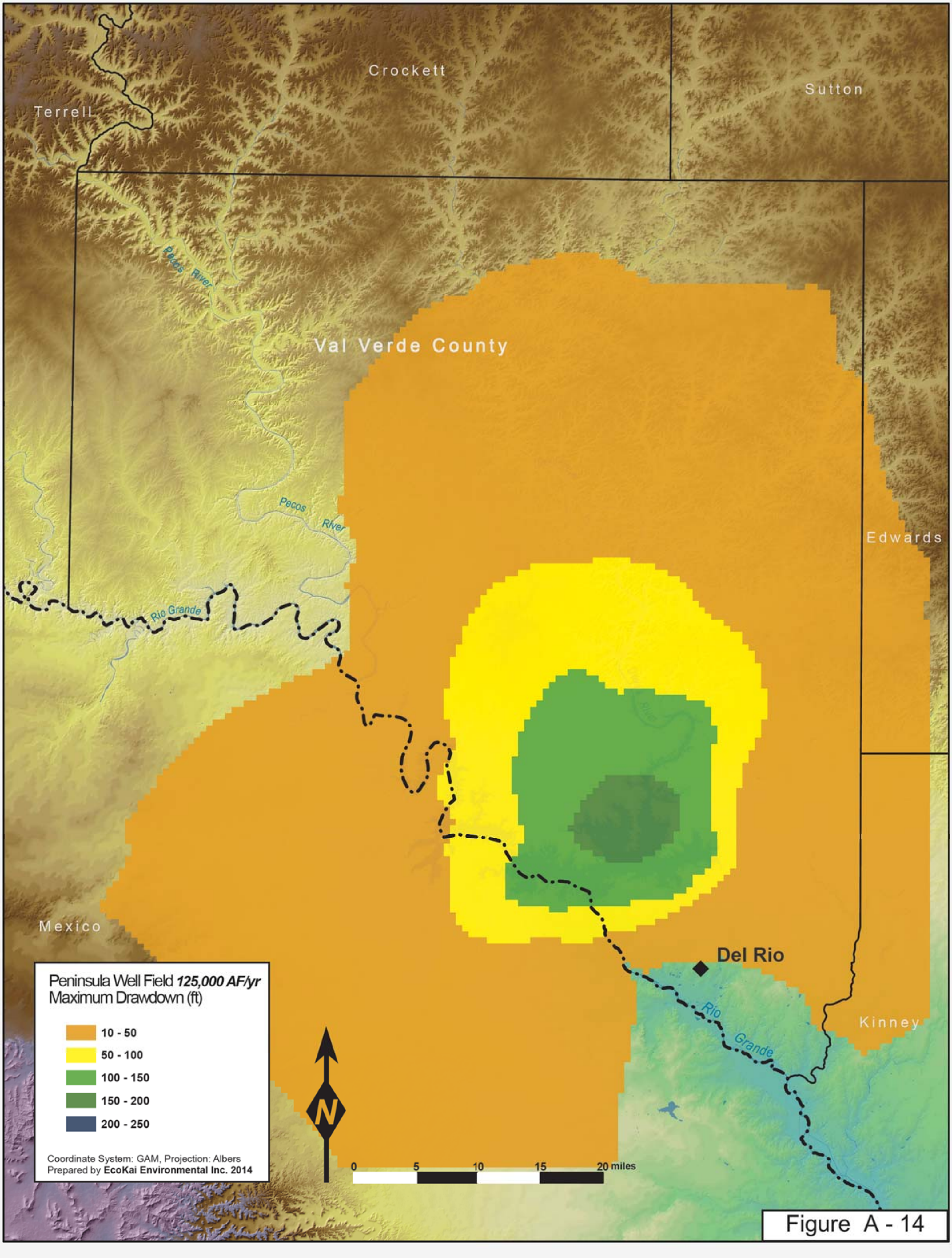

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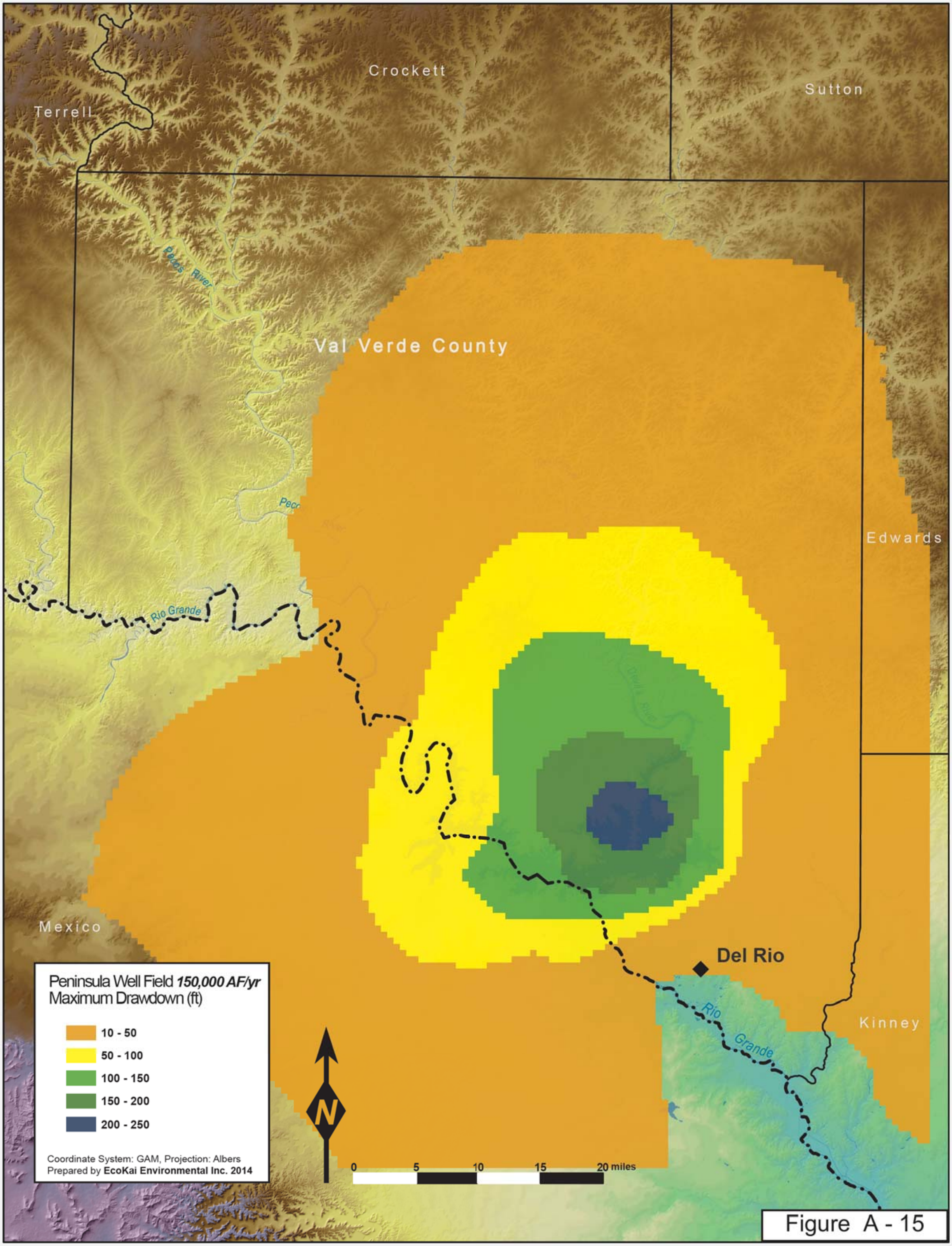
Figure A - 14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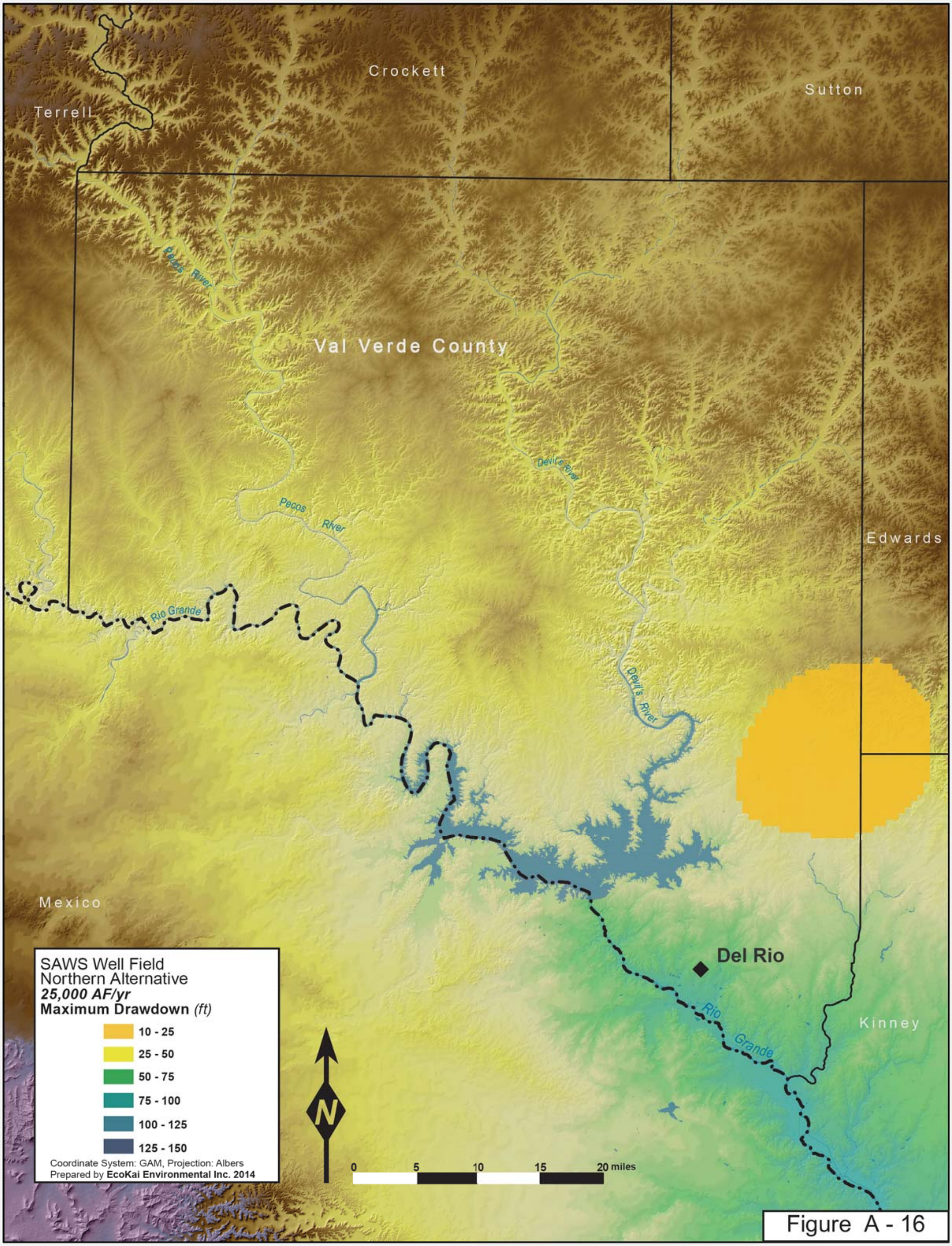
Val Verde County
Pecos River
Edwards
Rio Grande
Devils River
Mexico
Del Rio
Rio Grande
Kinney
Peninsula Well Field 150,000 AF/yr
Maximum Drawdown (ft)
10 - 50
50 - 100
100 - 150
150 - 200
200 - 250
N
0
5
10
15
20 miles
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014

Figure A - 15


Crockett
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Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Devil's River
Mexico
Del Rio
Kinney
Rio Grande
SAWS Well Field
Northern Alternative
25,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 16

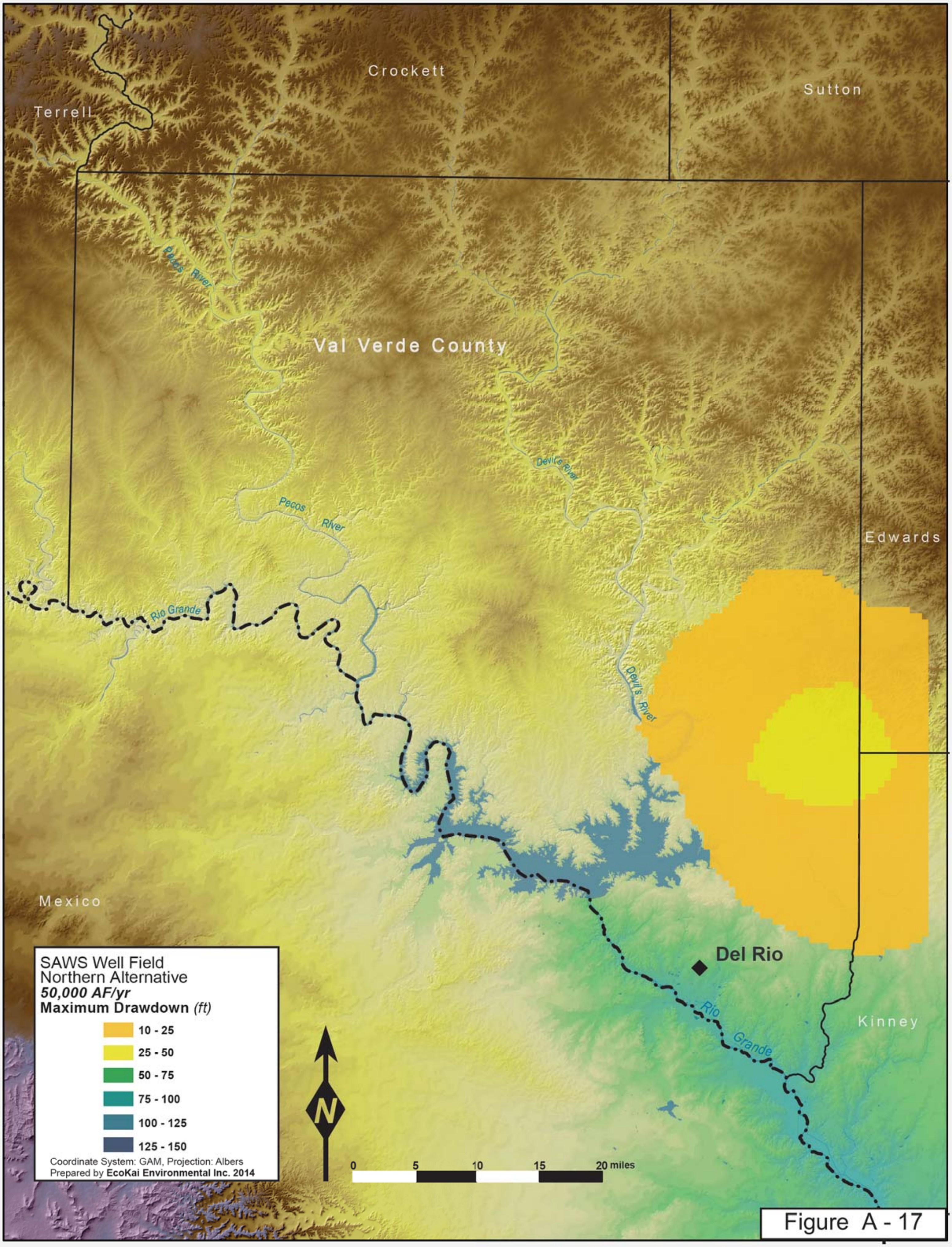

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Devil's River
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Northern Alternative
50,000 AF/yr
Maximum Drawdown *(ft)*
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by **EcoKai Environmental Inc. 2014**
N
0
5
10
15
20 miles

Figure A - 17

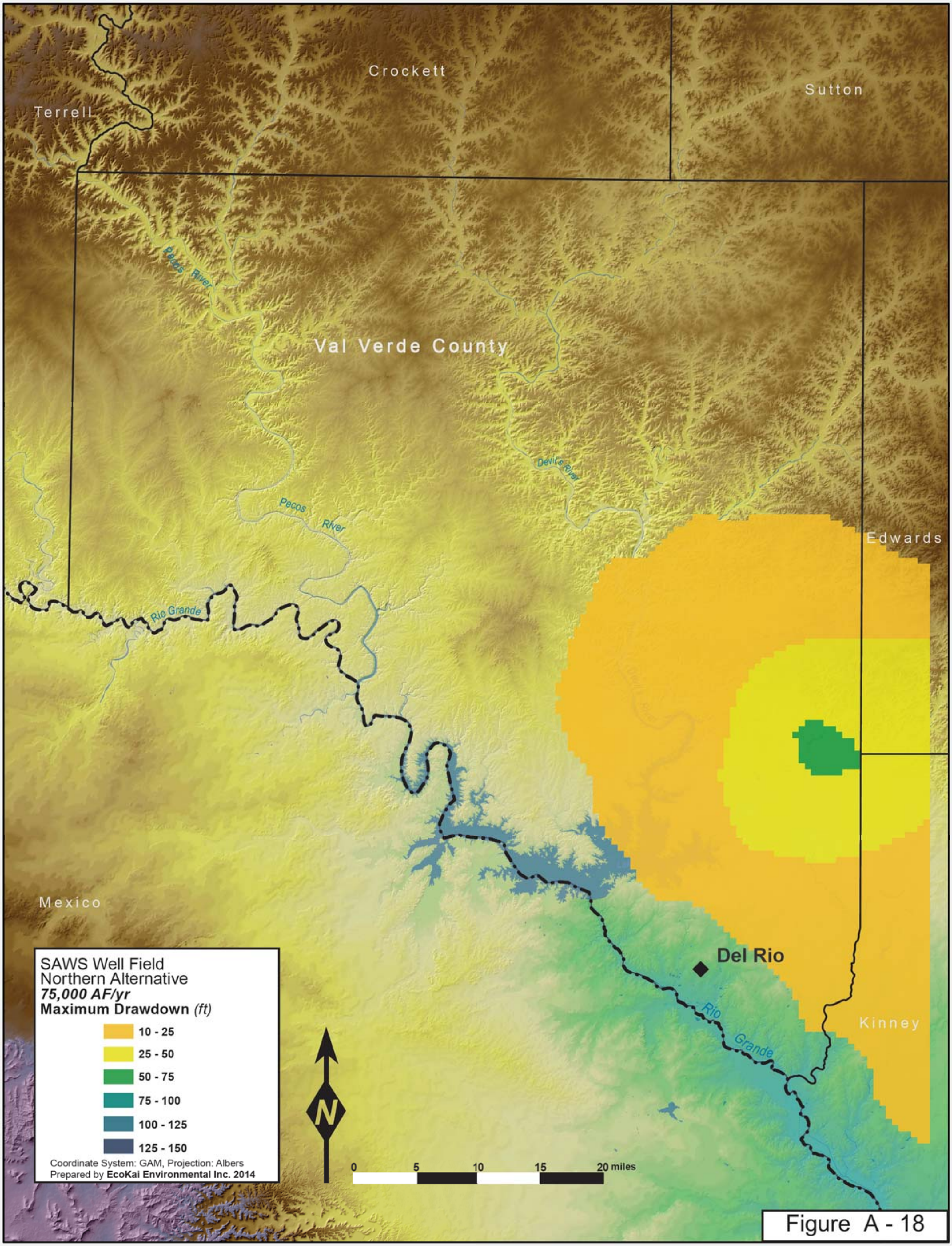

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Northern Alternative
75,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 18

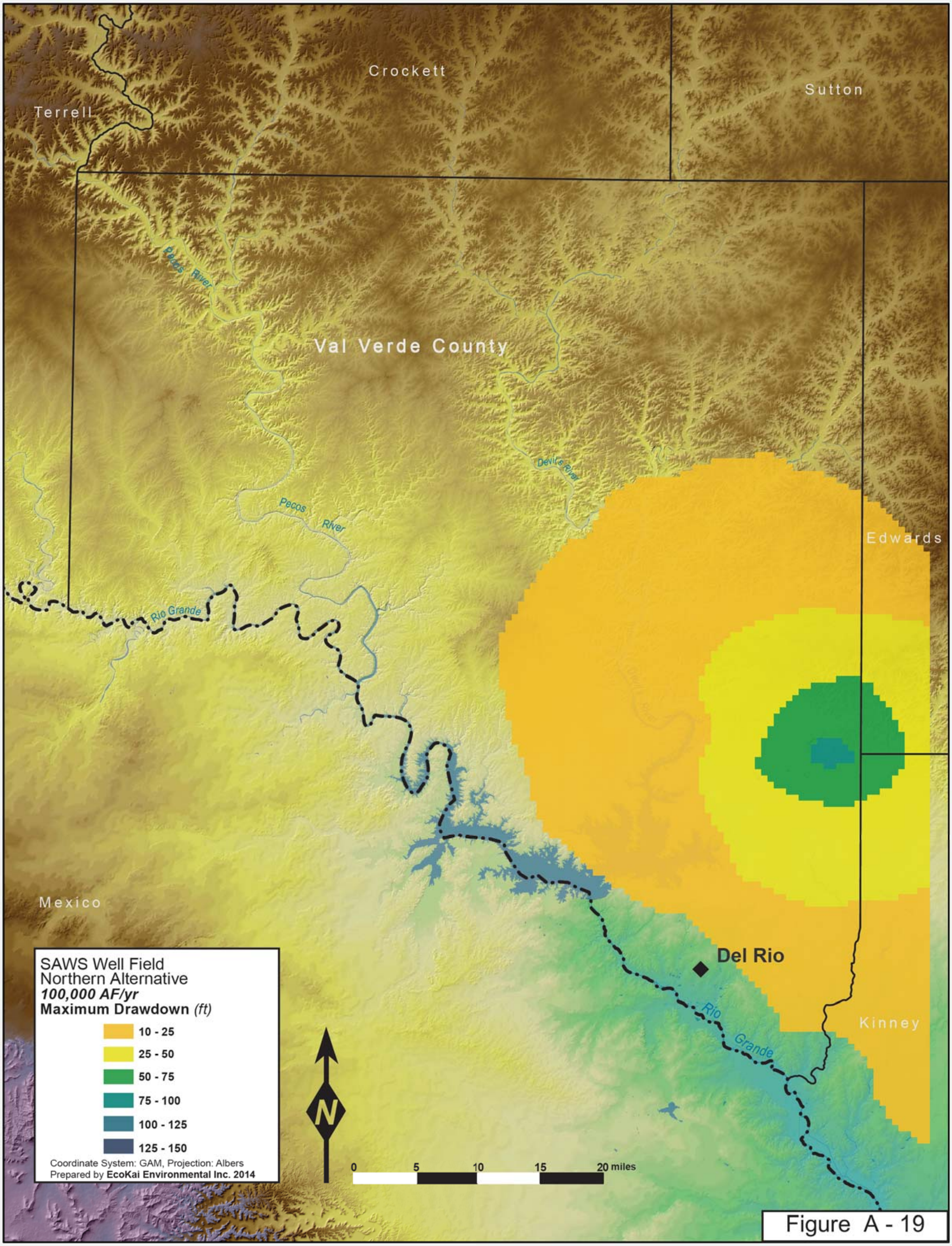

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Northern Alternative
100,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 19

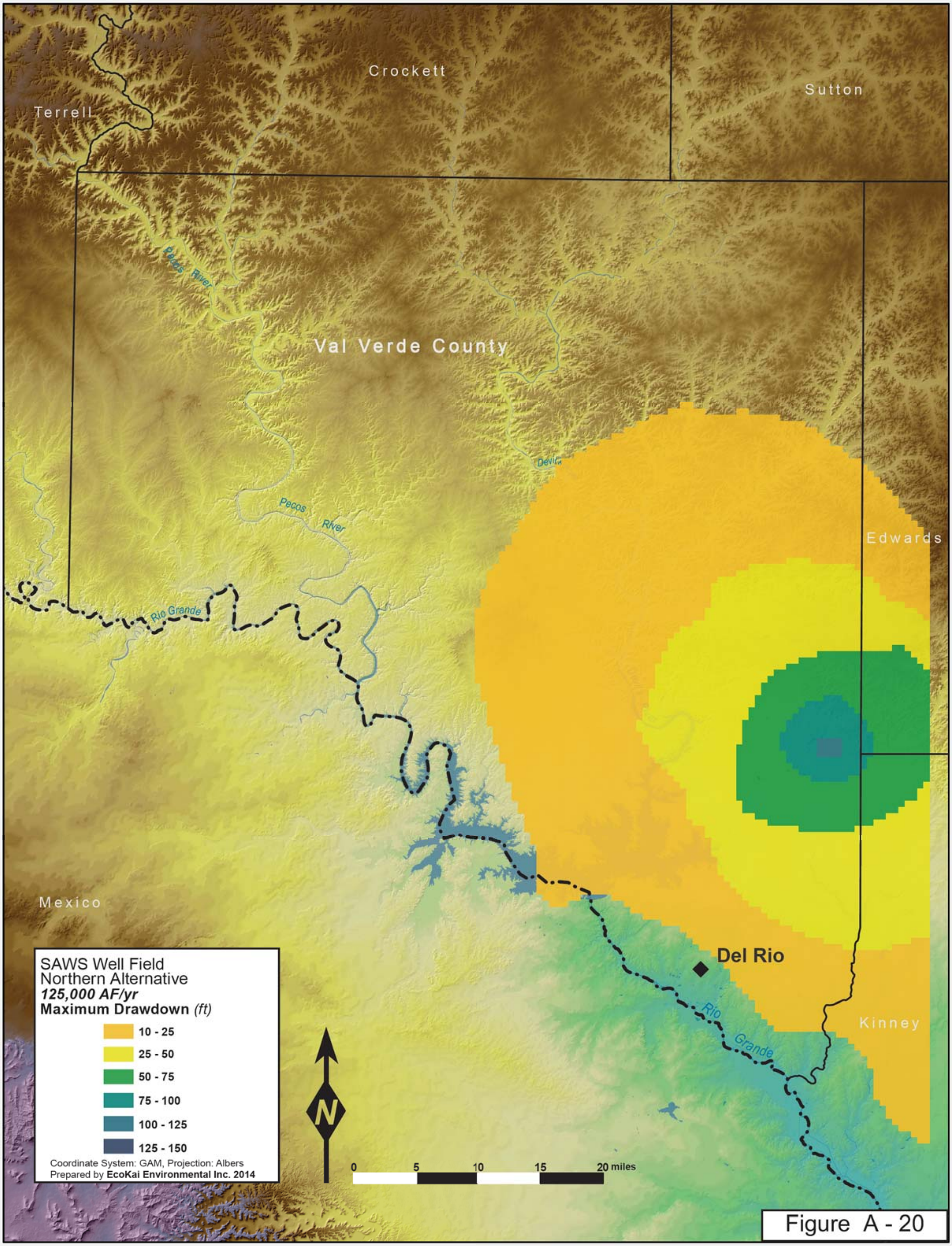

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Northern Alternative
125,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
N
0
5
10
15
20 miles
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014

Figure A - 20

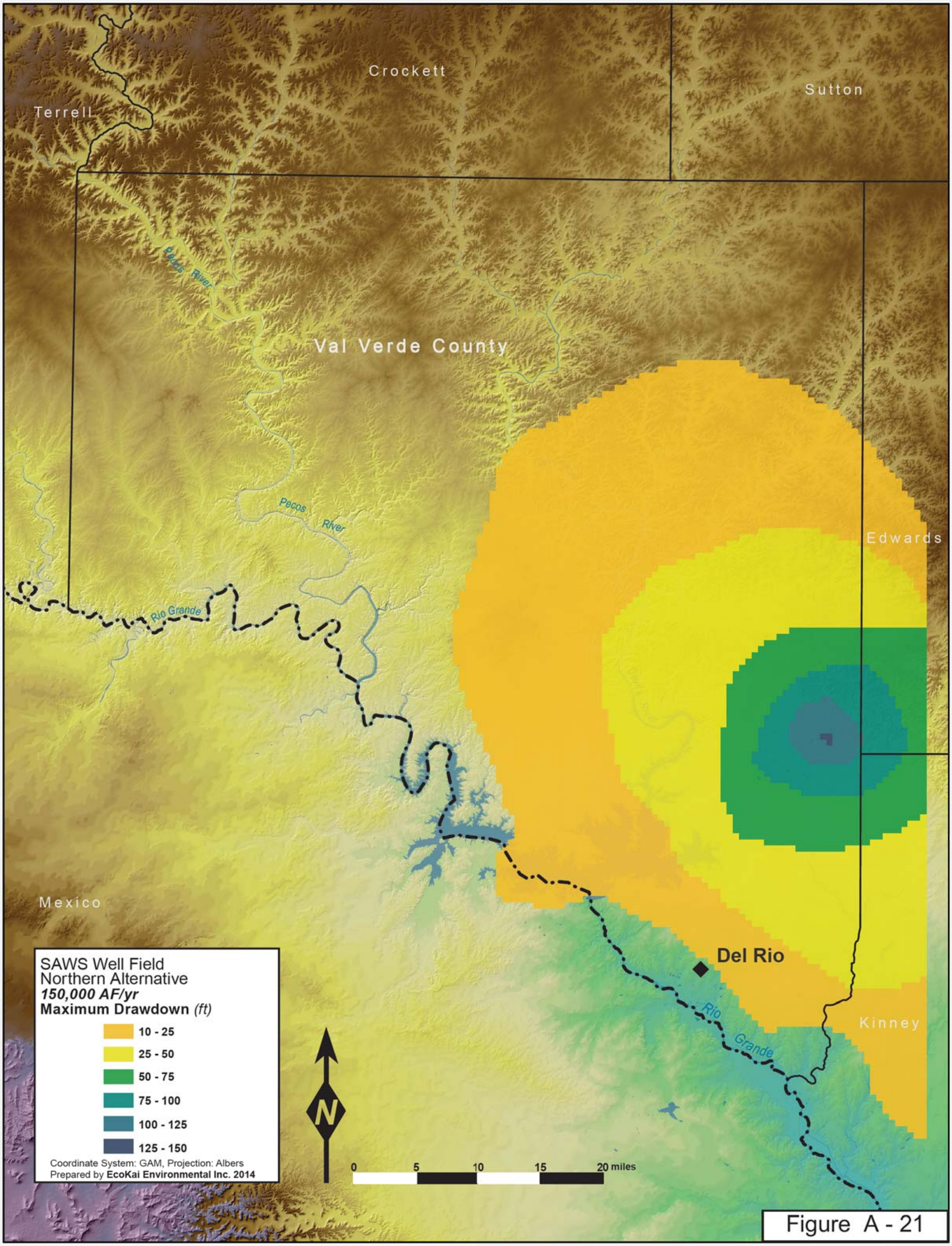

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
N
0
5
10
15
20 miles
SAWS Well Field
Northern Alternative
150,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014

Figure A - 21

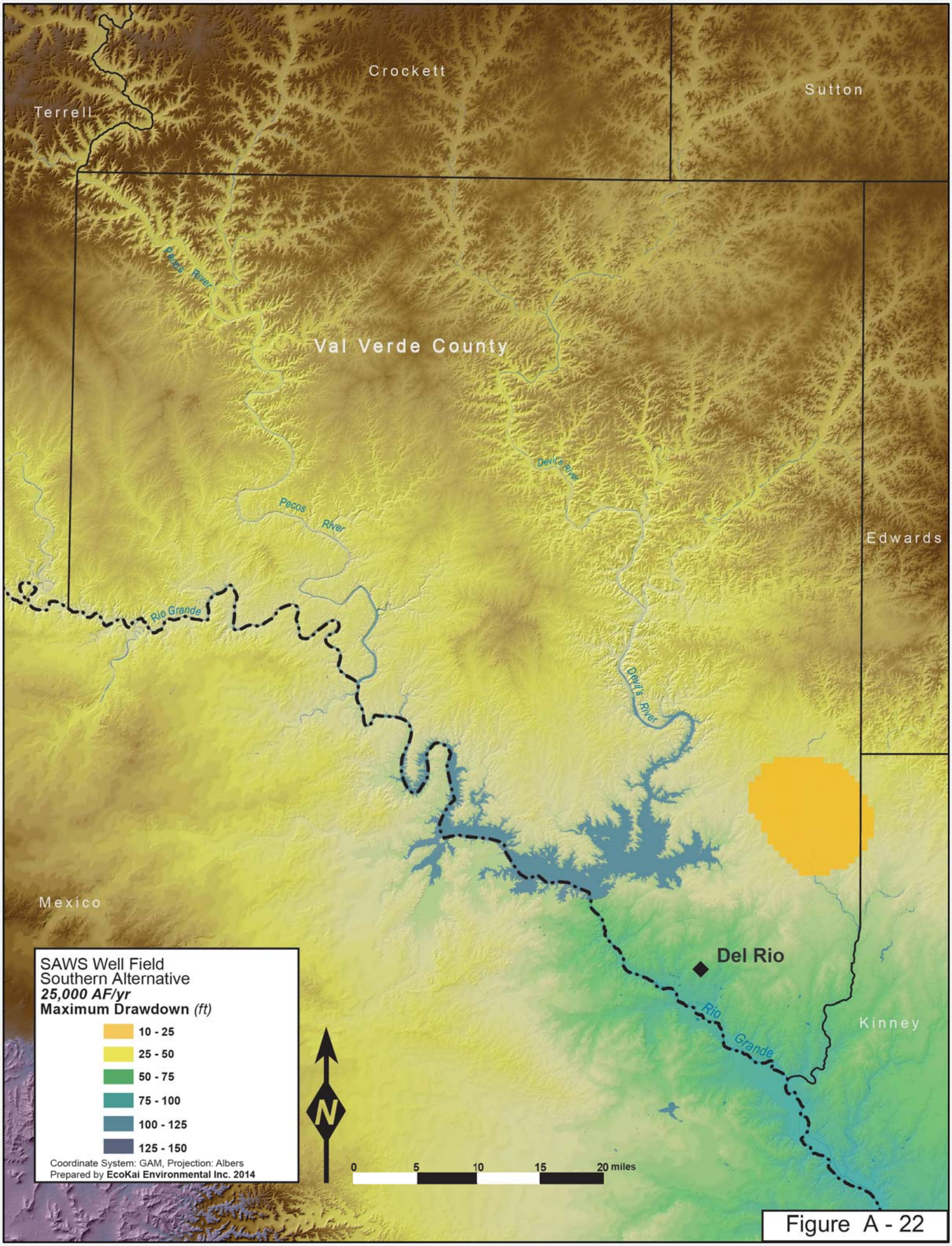

Crockett
Sutton
Terrell
Val Verde County
Pecos River
Pecos River
Devil's River
Devil's River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Southern Alternative
25,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 22

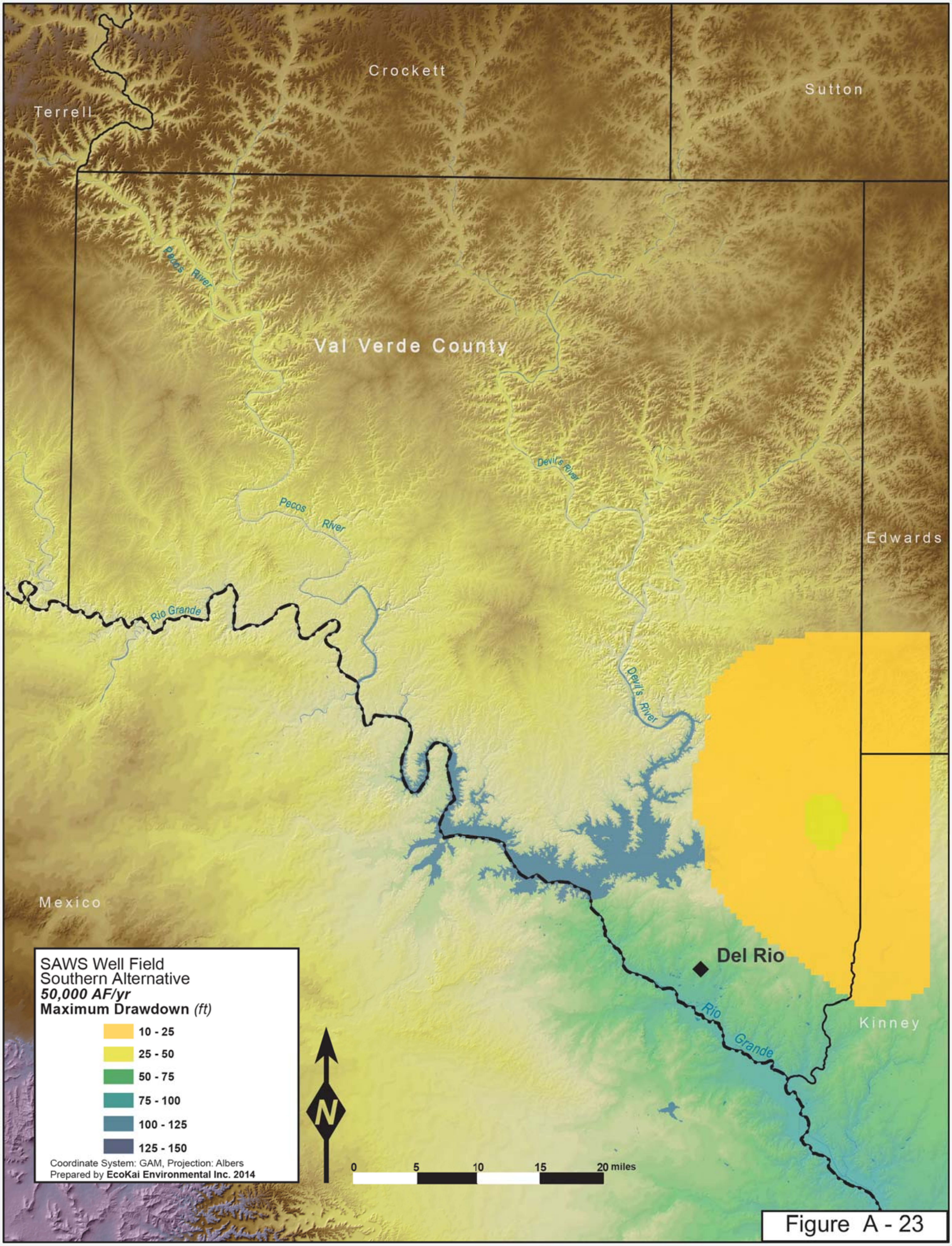

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Devil's River
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Southern Alternative
50,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0 5 10 15 20 miles

Figure A - 23

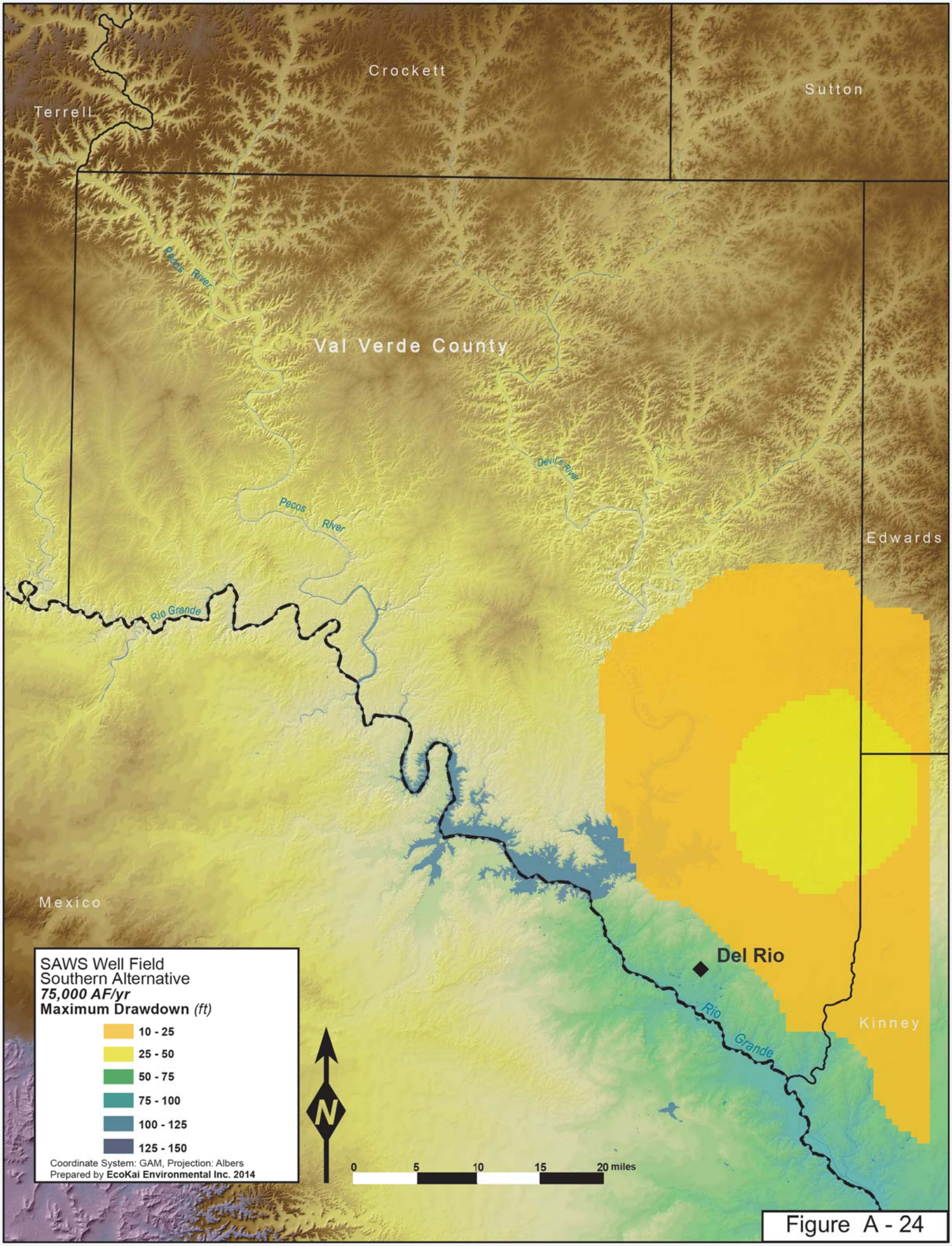

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Southern Alternative
75,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 24

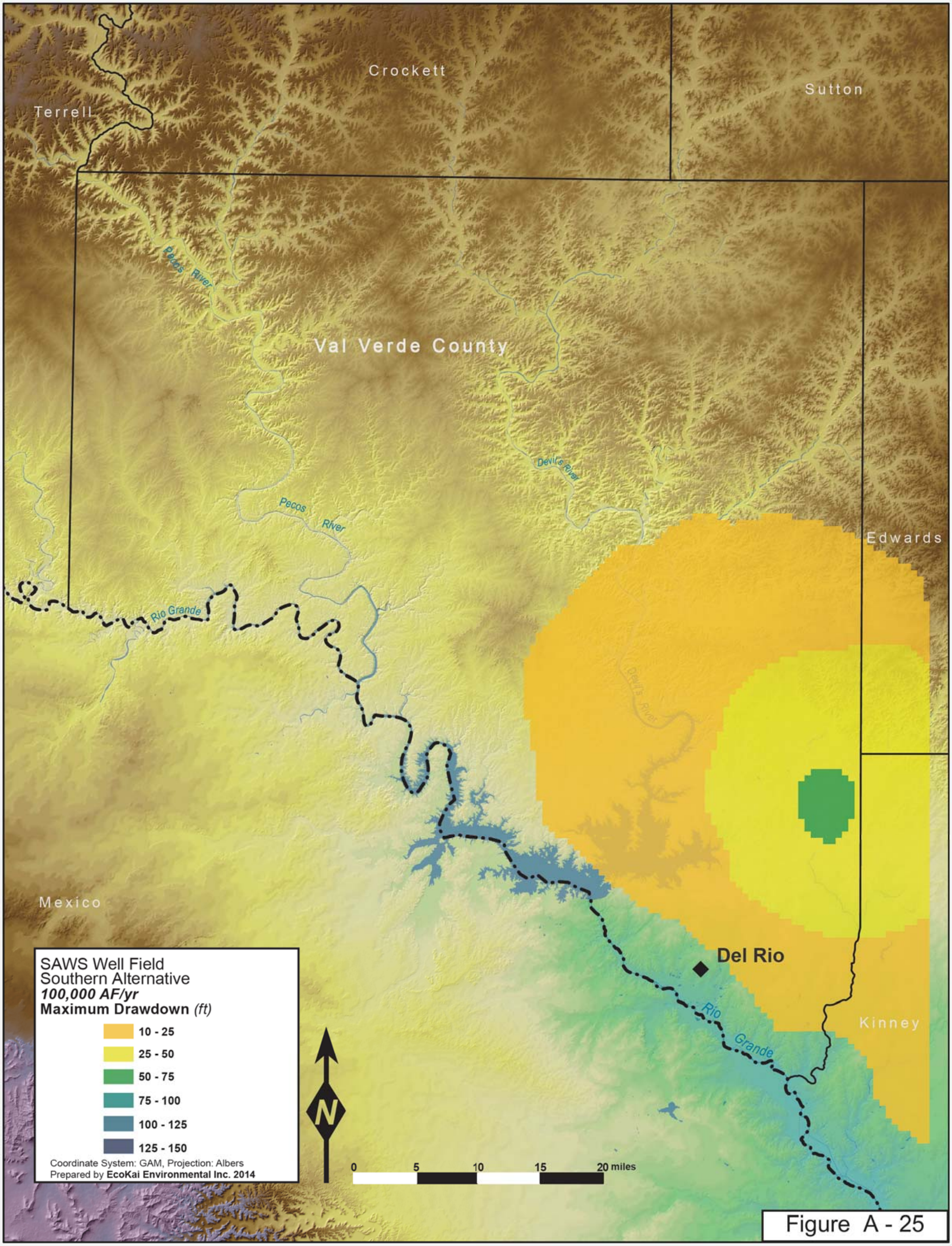

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Devil's River
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Southern Alternative
100,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 25

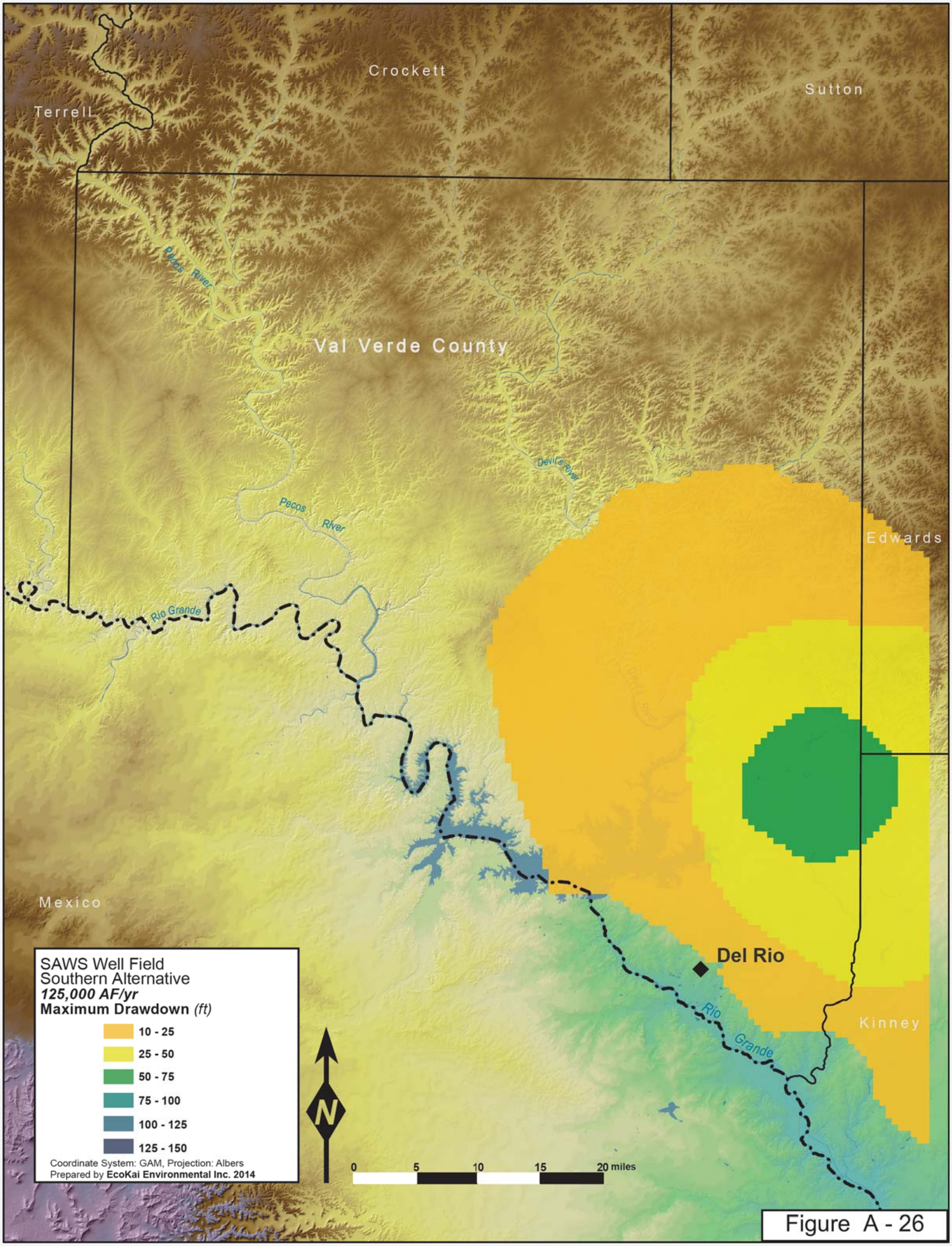

Crockett
Sutton
Terrell
Pecos River
Val Verde County
Devil's River
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Southern Alternative
125,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 26

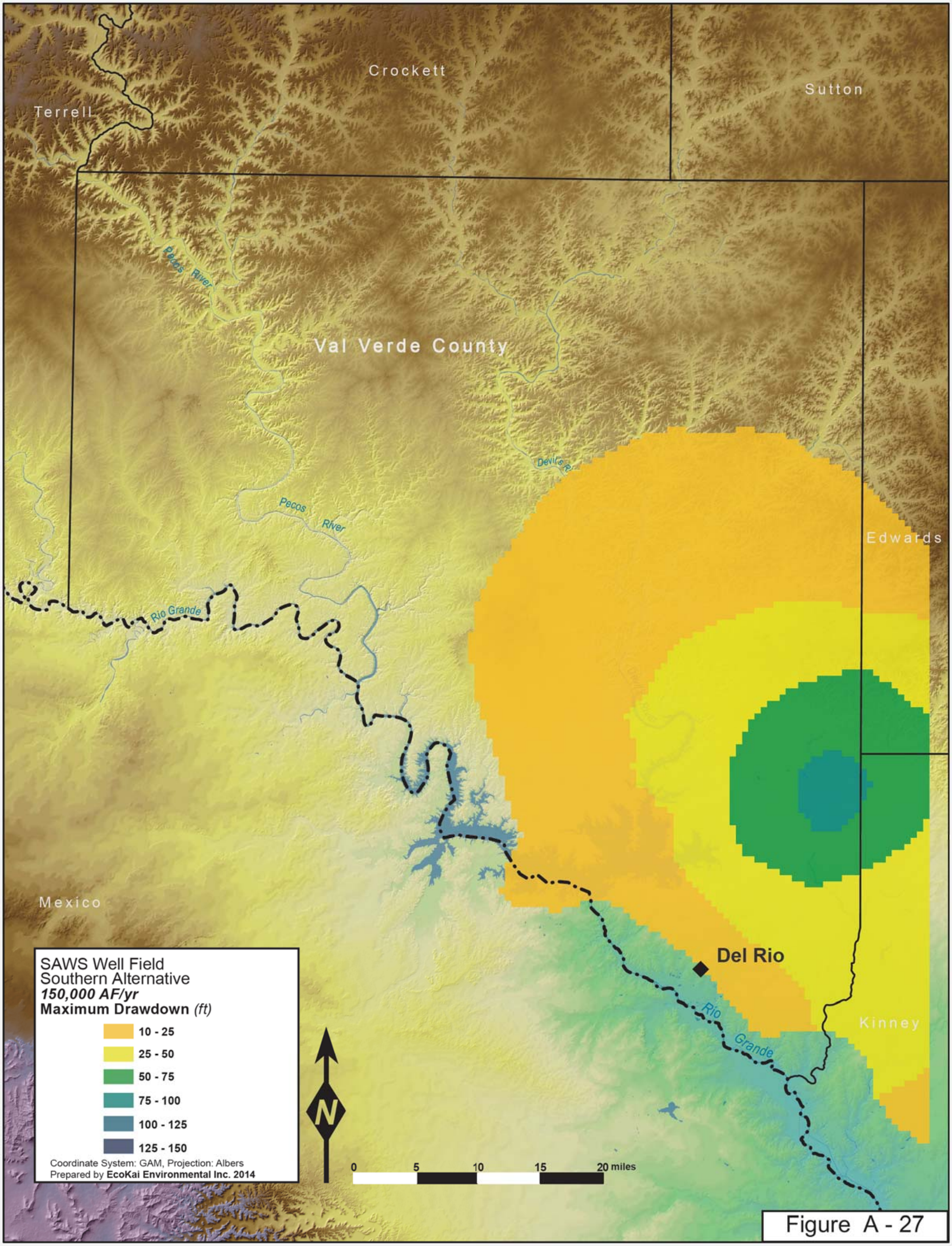

Terrell
Crockett
Sutton
Pecos River
Val Verde County
Devil's R.
Pecos River
Edwards
Rio Grande
Mexico
Del Rio
Rio Grande
Kinney
SAWS Well Field
Southern Alternative
150,000 AF/yr
Maximum Drawdown (ft)
10 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
Coordinate System: GAM, Projection: Albers
Prepared by EcoKai Environmental Inc. 2014
N
0
5
10
15
20 miles

Figure A - 27

Appendix B

Model Hydrographs

Actual vs. Simulated Groundwater Level

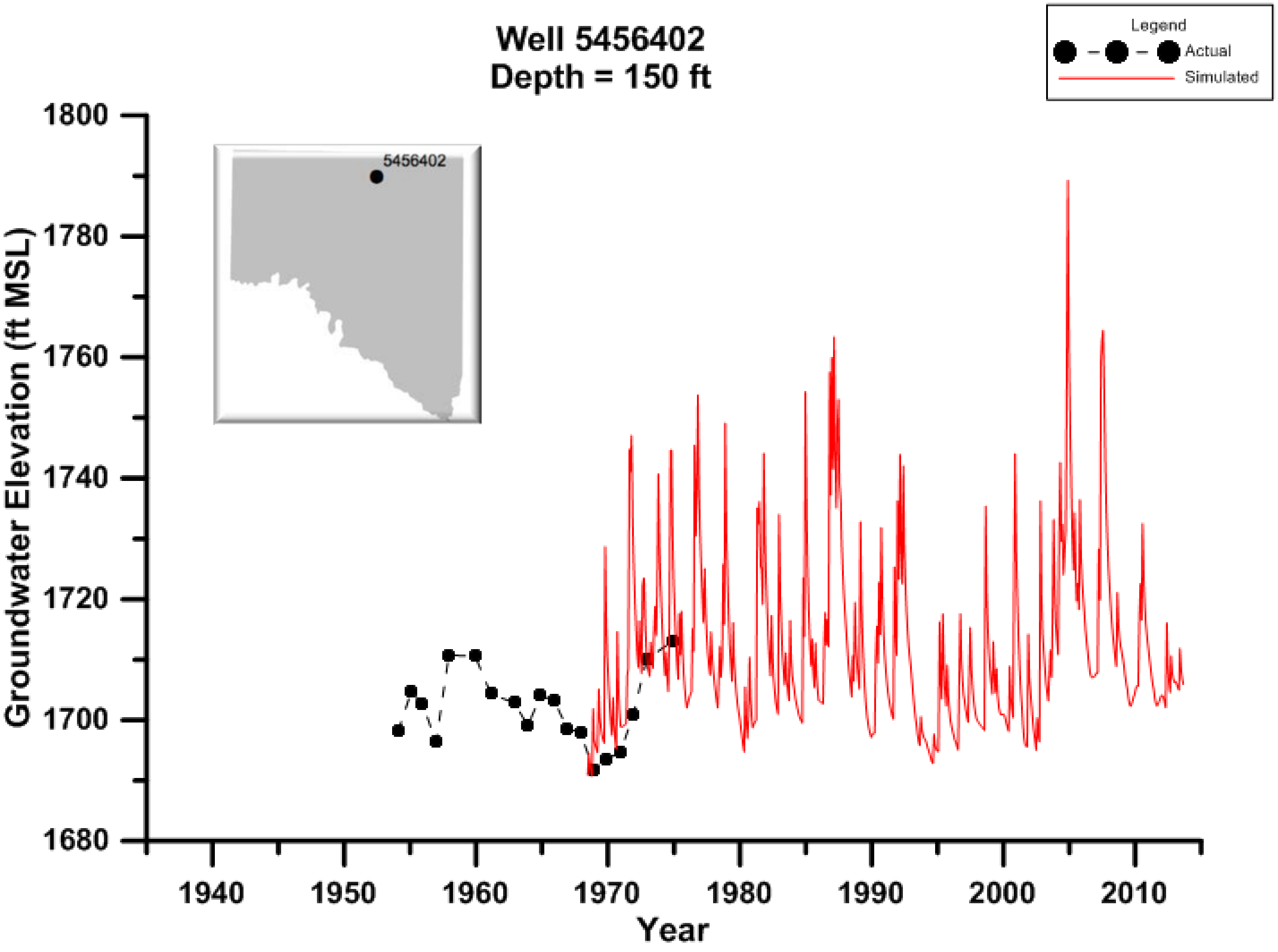
(Figures B-1 thru B-51)

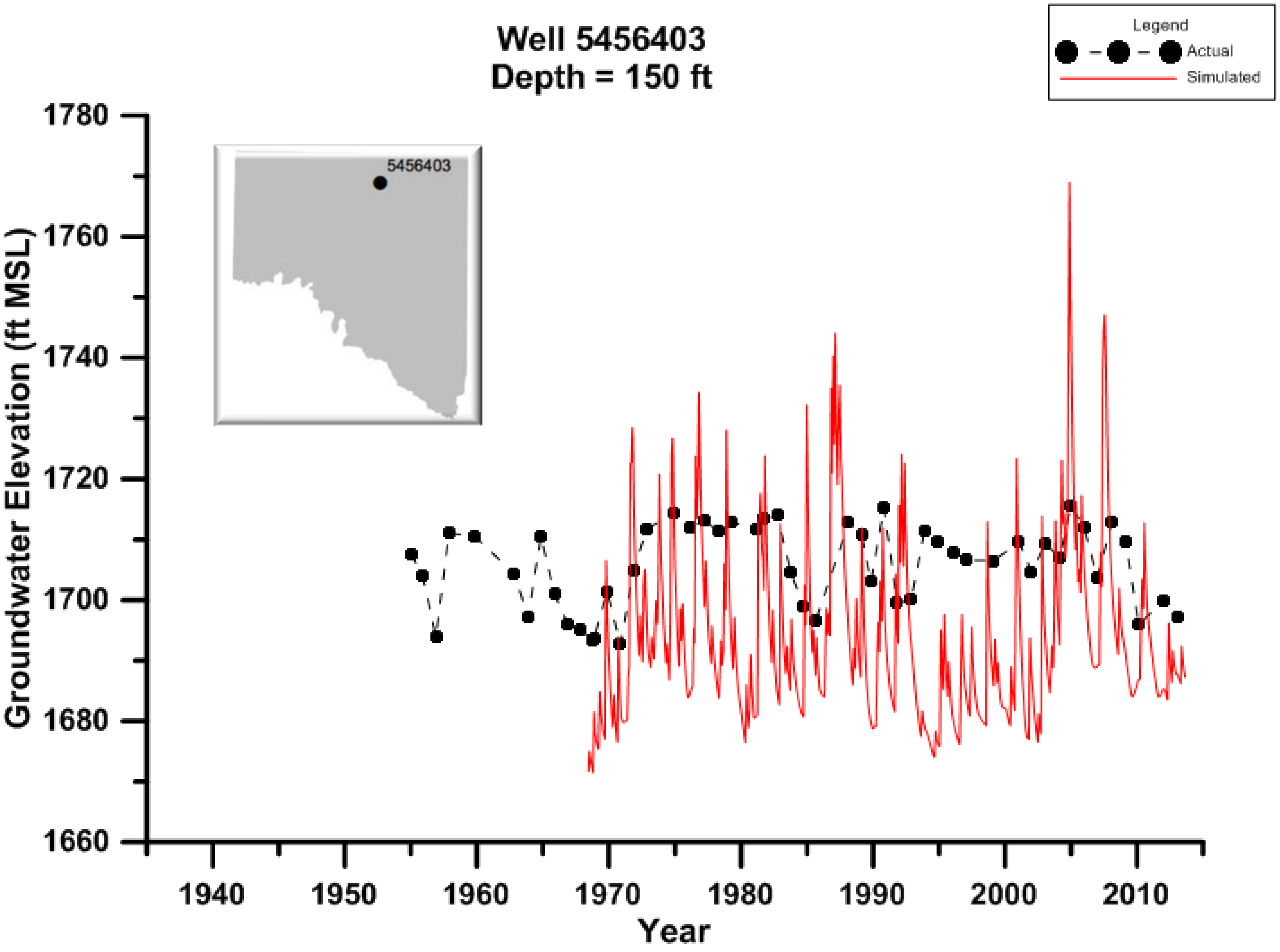
Appendix B - List of Figures

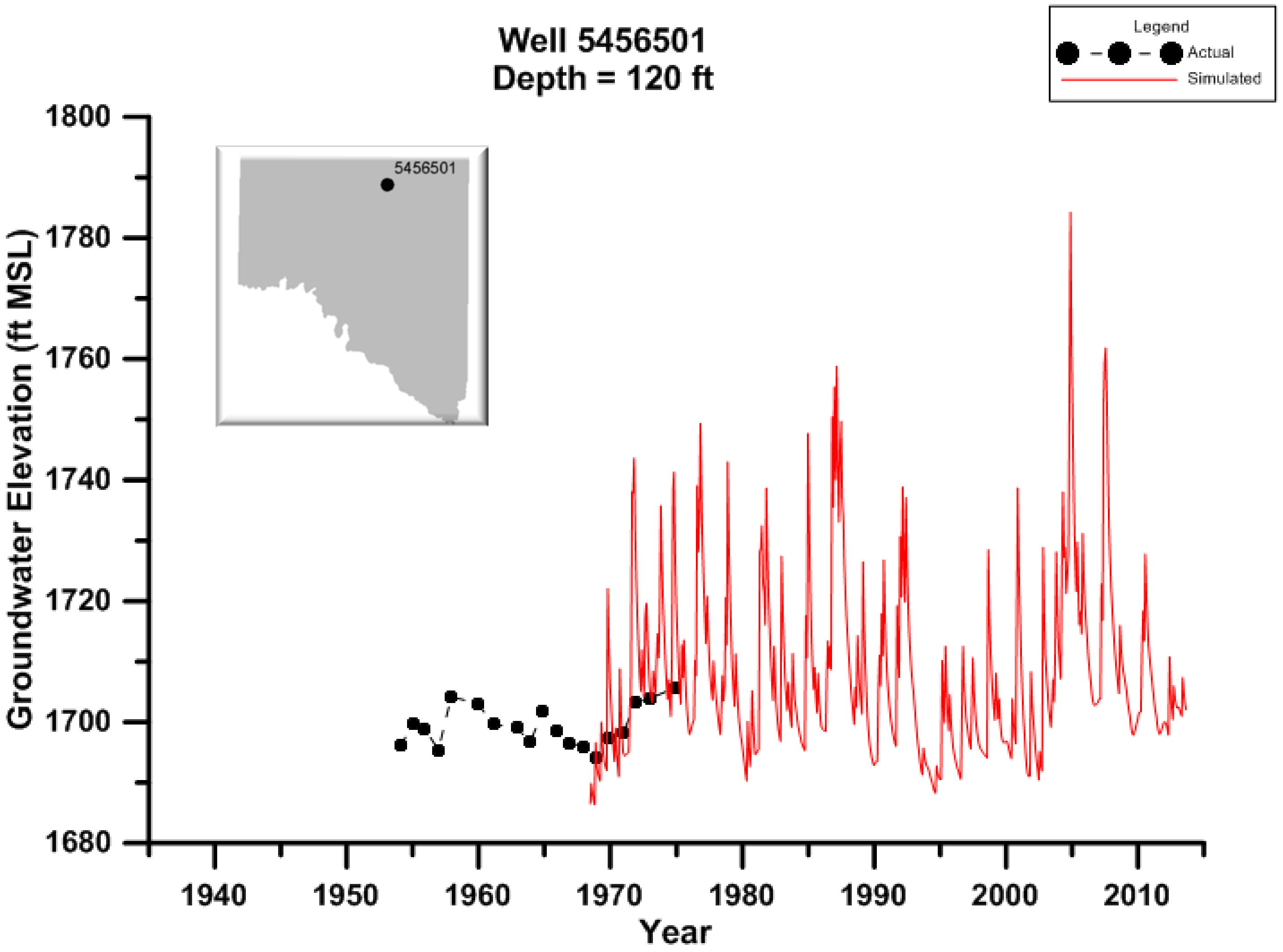
Hydrograph Well Number **Page**

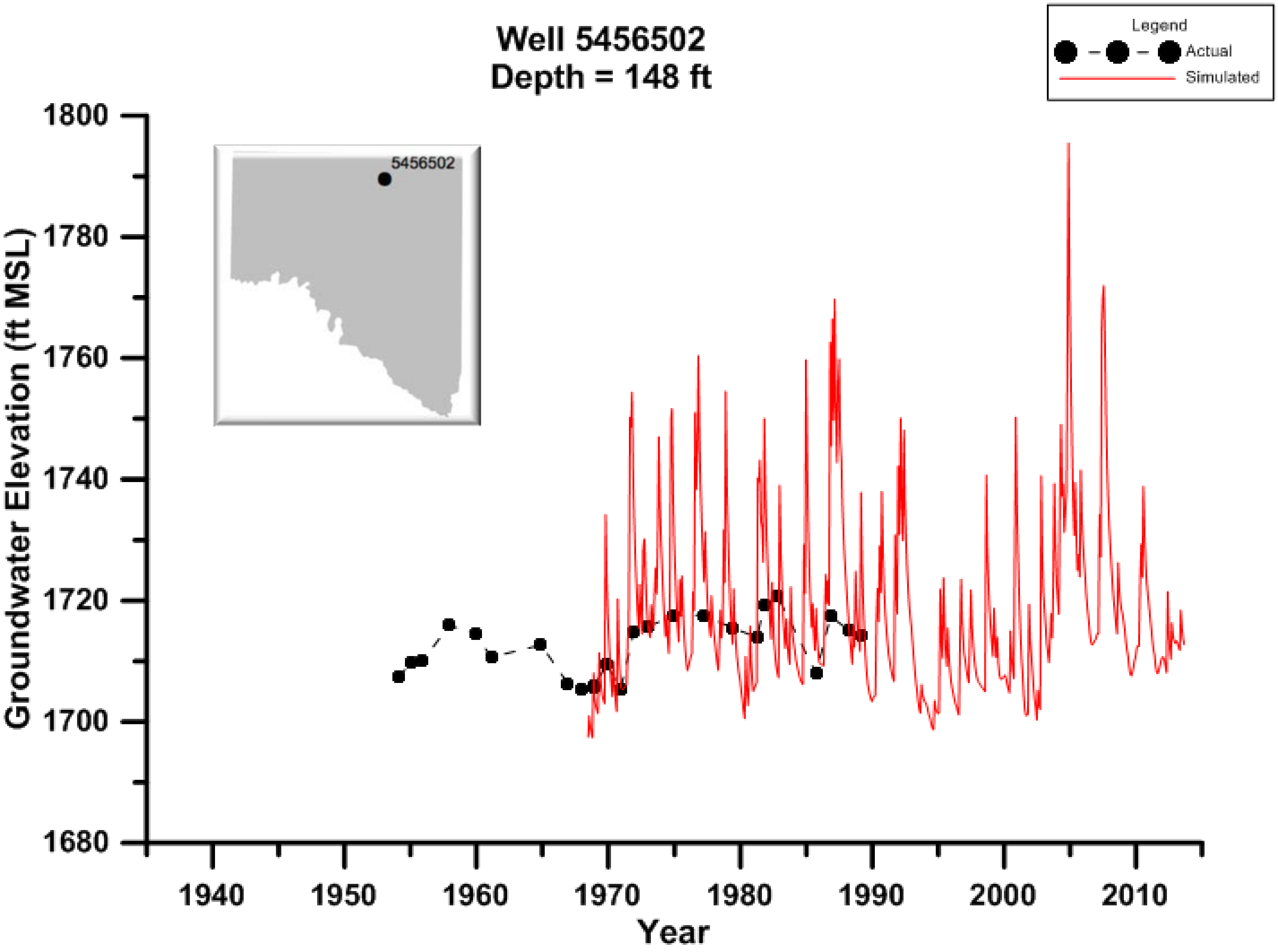
Appendix B - List of Figures

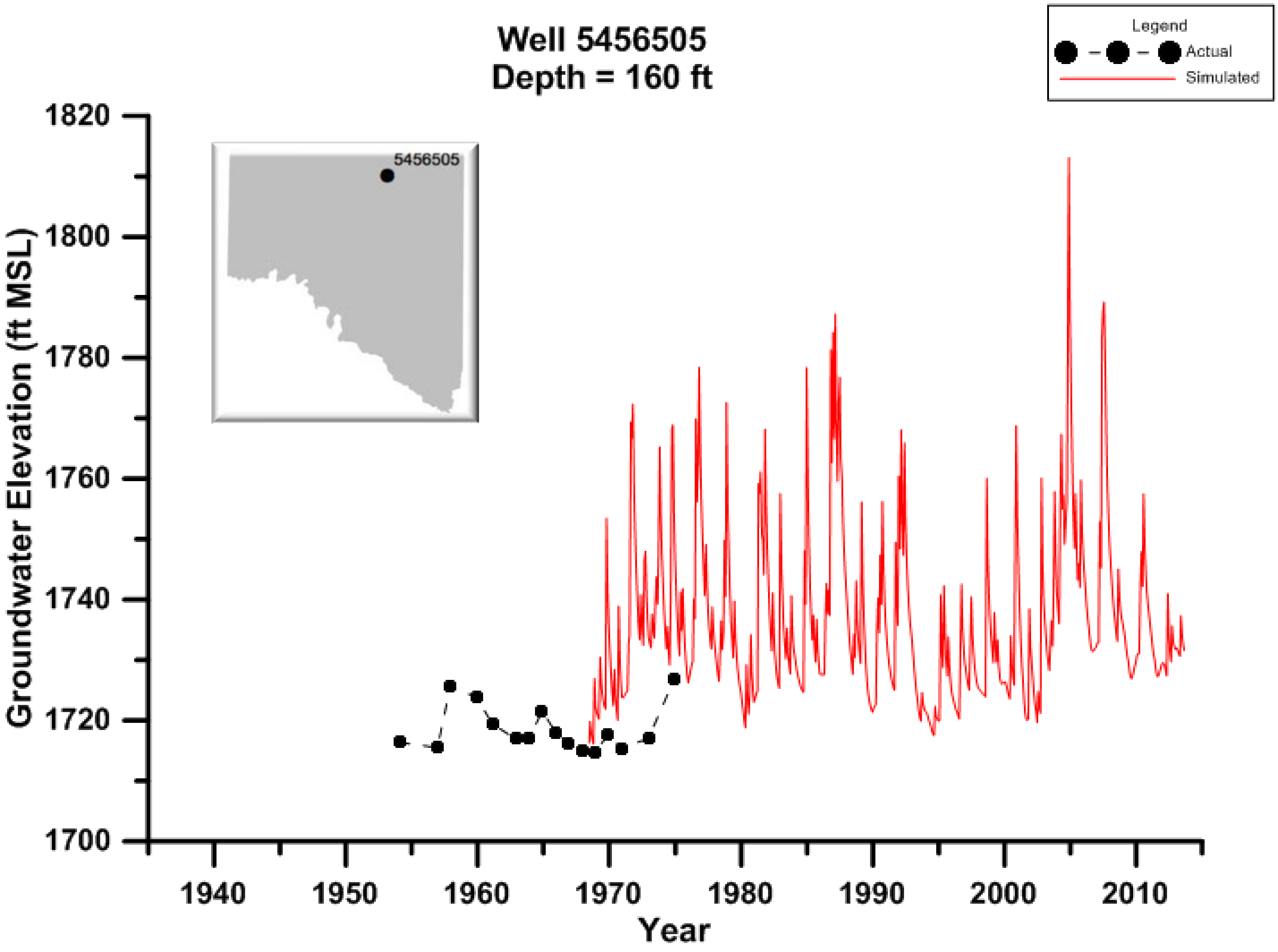
Hydrograph Well Number **Page**

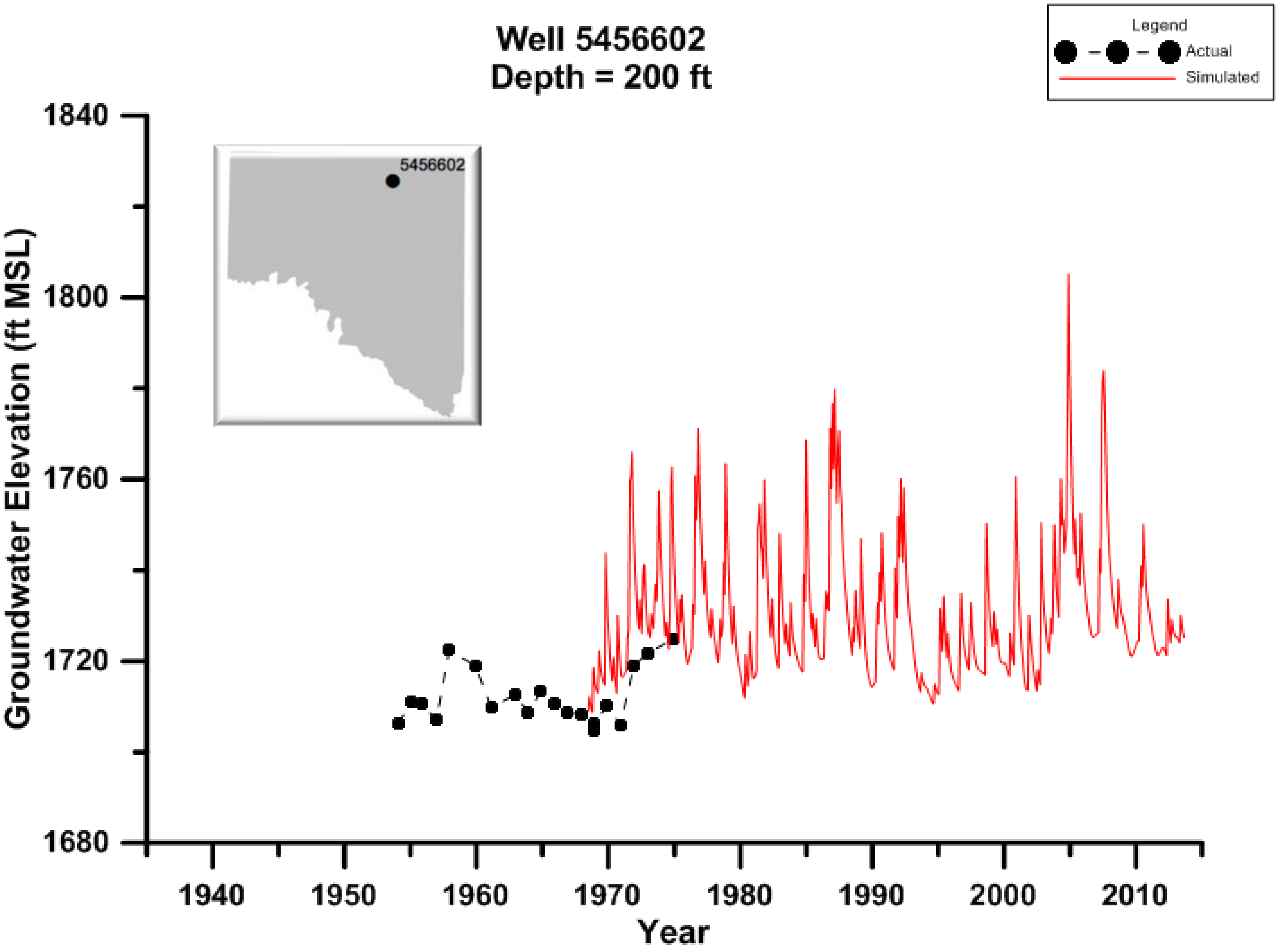

Well 5456402
Depth = 150 ft
Legend
● – ● – ● Actual
Simulated
5456402
Groundwater Elevation (ft MSL)
1800
1780
1760
1740
1720
1700
1680
1940
1950
1960
1970
1980
1990
2000
2010
Year

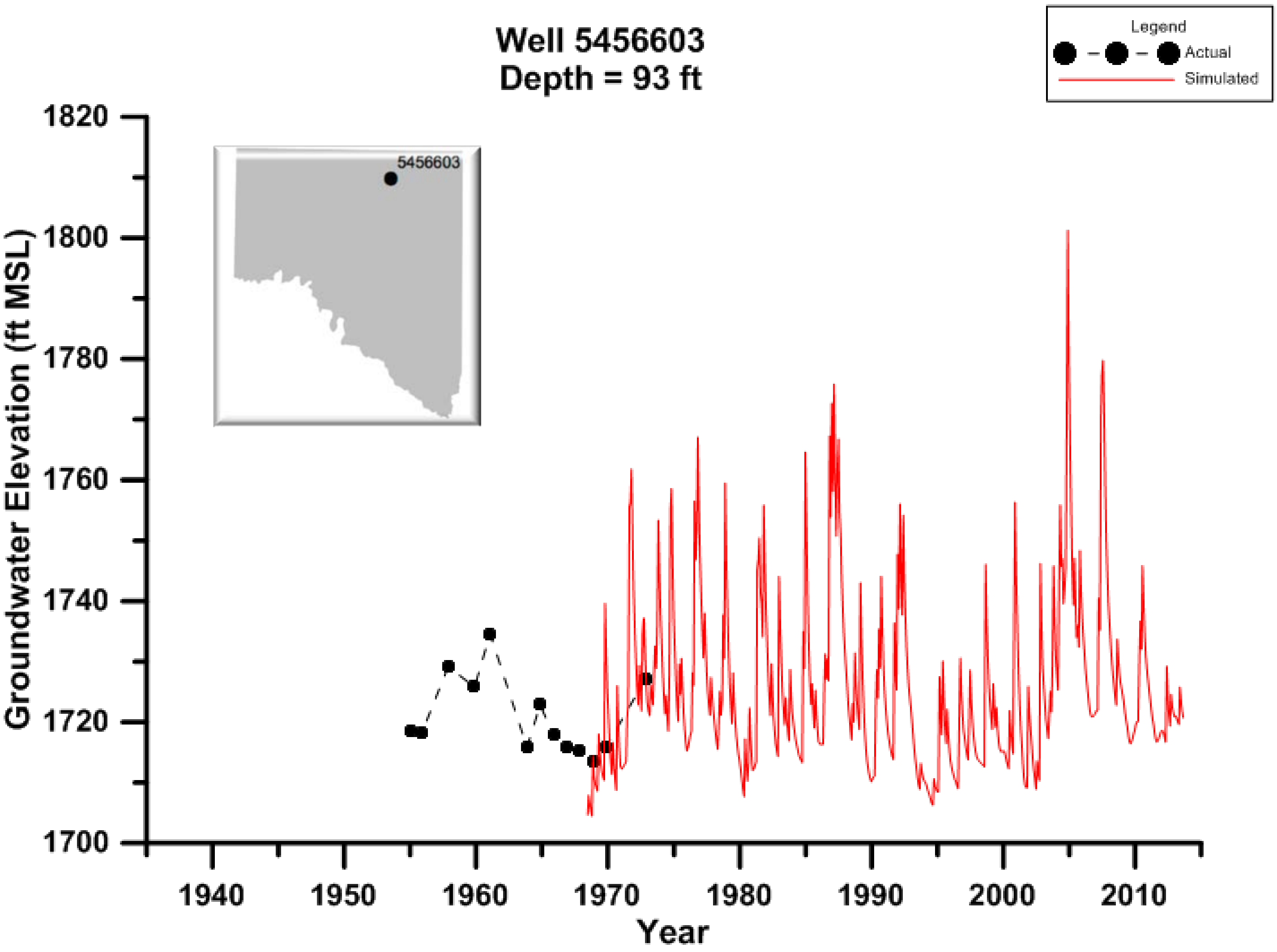

Well 5456403
Depth = 150 ft
Legend
● – ● – ● Actual
Simulated
5456403
Groundwater Elevation (ft MSL)
1780
1760
1740
1720
1700
1680
1660
1940
1950
1960
1970
1980
1990
2000
2010
Year

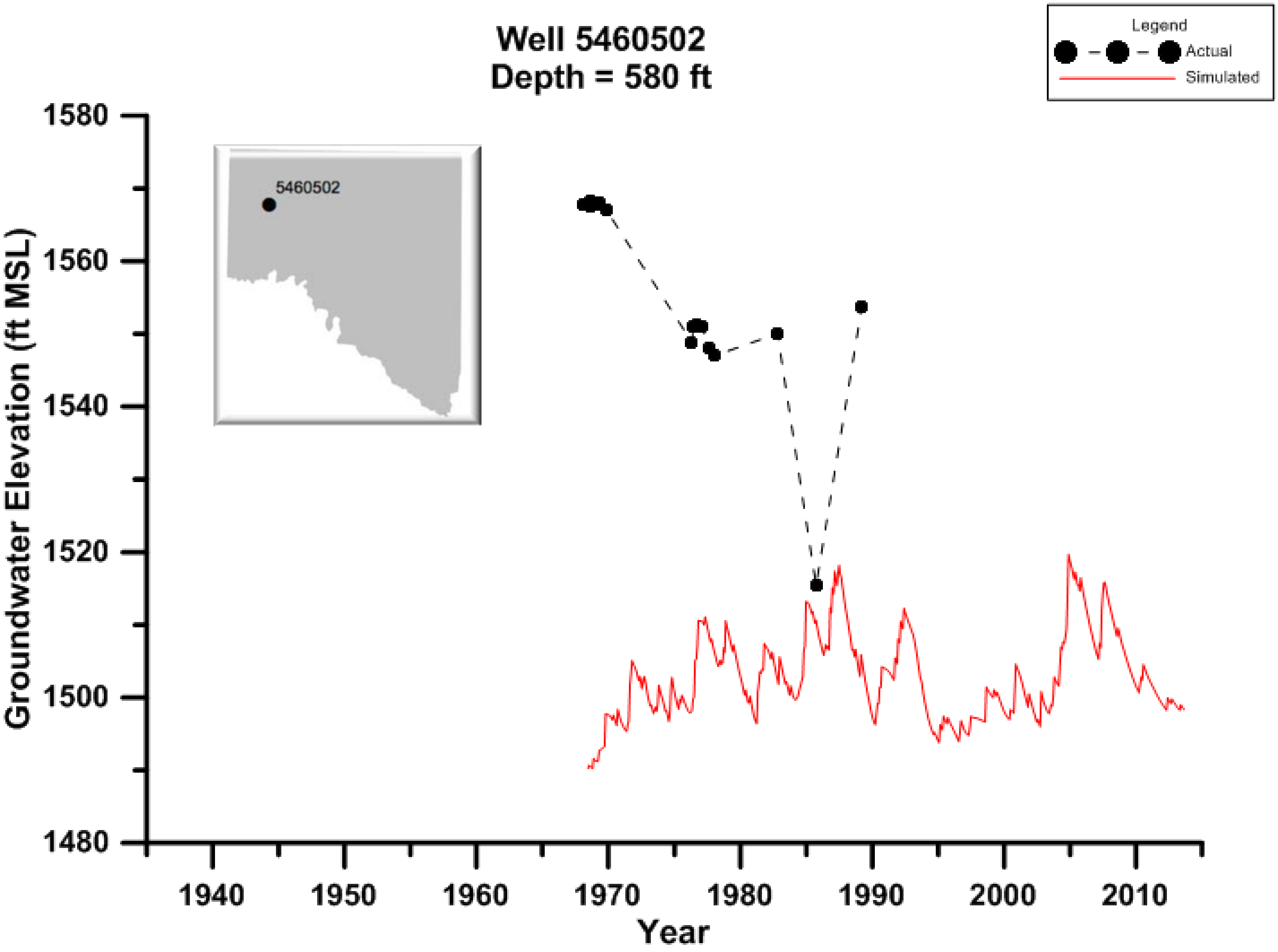

Well 5456501
Depth = 120 ft
Legend
● – ● – ● Actual
Simulated
5456501
Groundwater Elevation (ft MSL)
1800
1780
1760
1740
1720
1700
1680
1940
1950
1960
1970
1980
1990
2000
2010
Year

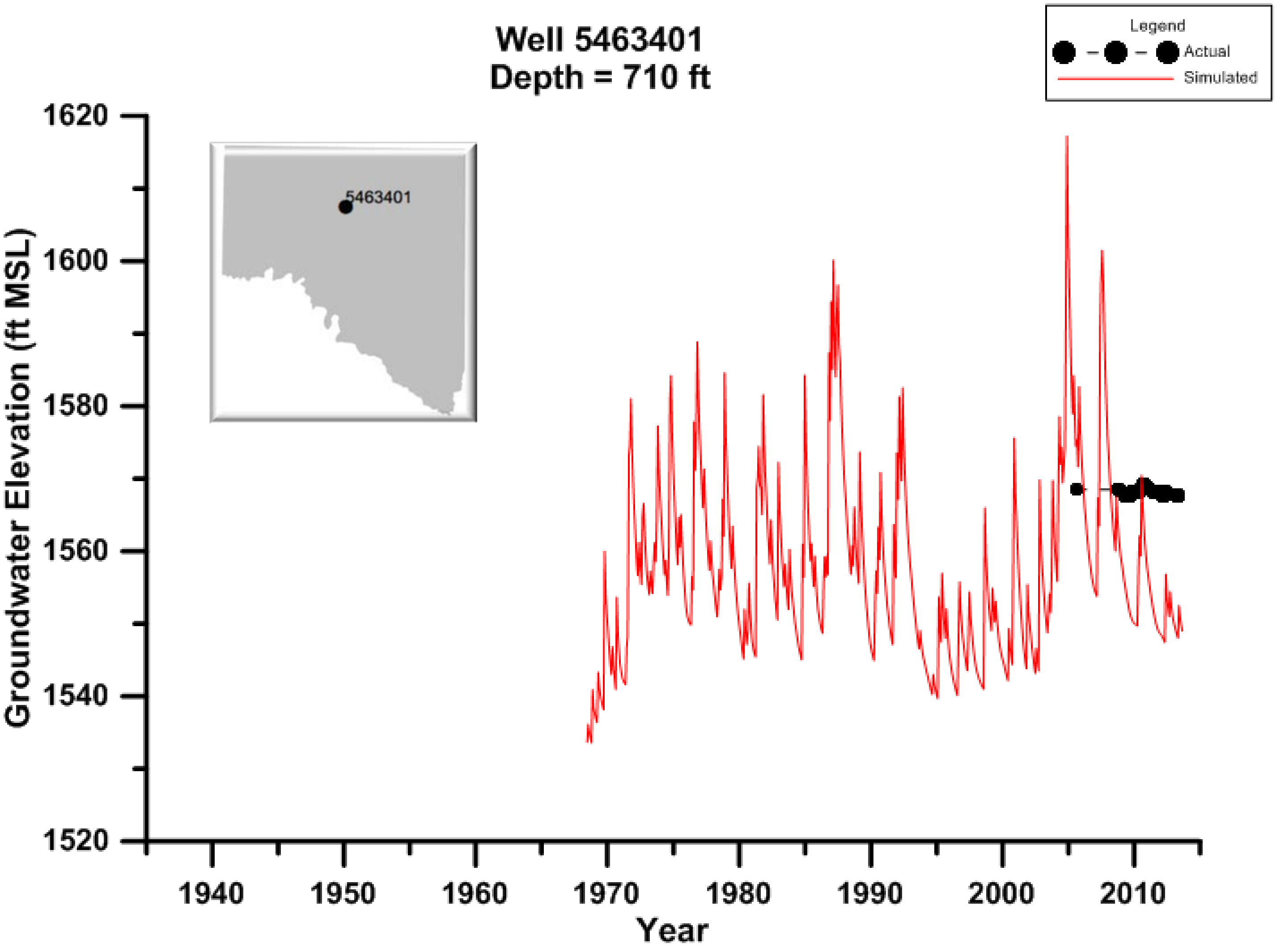

Well 5456502
Depth = 148 ft
Legend
● – ● – ● Actual
Simulated
5456502
Groundwater Elevation (ft MSL)
1800
1780
1760
1740
1720
1700
1680
1940
1950
1960
1970
1980
1990
2000
2010
Year

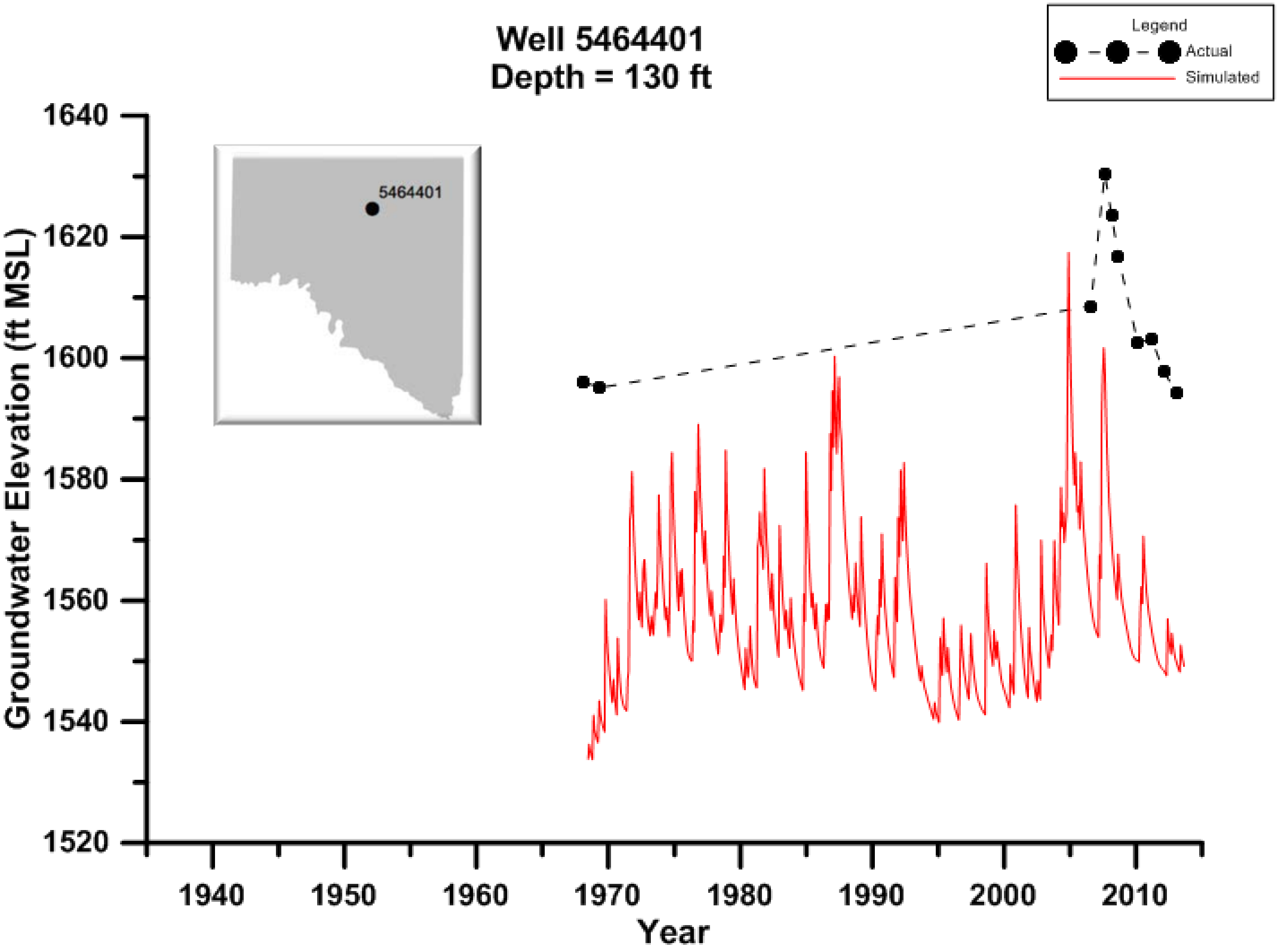
Well 5456505
Depth = 160 ft
Legend
● – ● – ● Actual
Simulated
5456505
1820
1800
1780
1760
1740
1720
1700
Groundwater Elevation (ft MSL)
1940
1950
1960
1970
1980
1990
2000
2010
Year

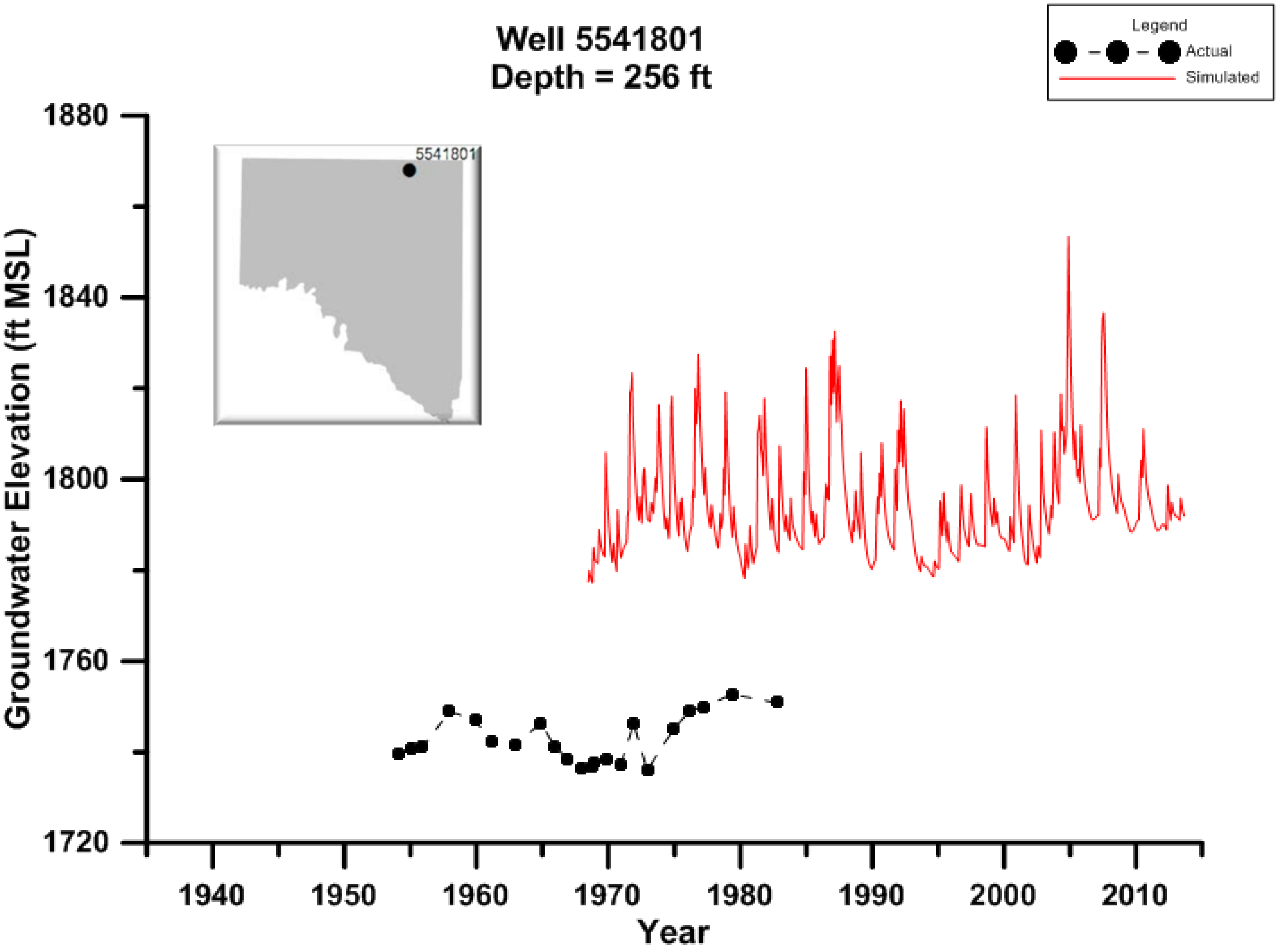

Well 5456602
Depth = 200 ft
Legend
● – ● – ● Actual
Simulated
5456602
Groundwater Elevation (ft MSL)
1840
1800
1760
1720
1680
1940
1950
1960
1970
1980
1990
2000
2010
Year

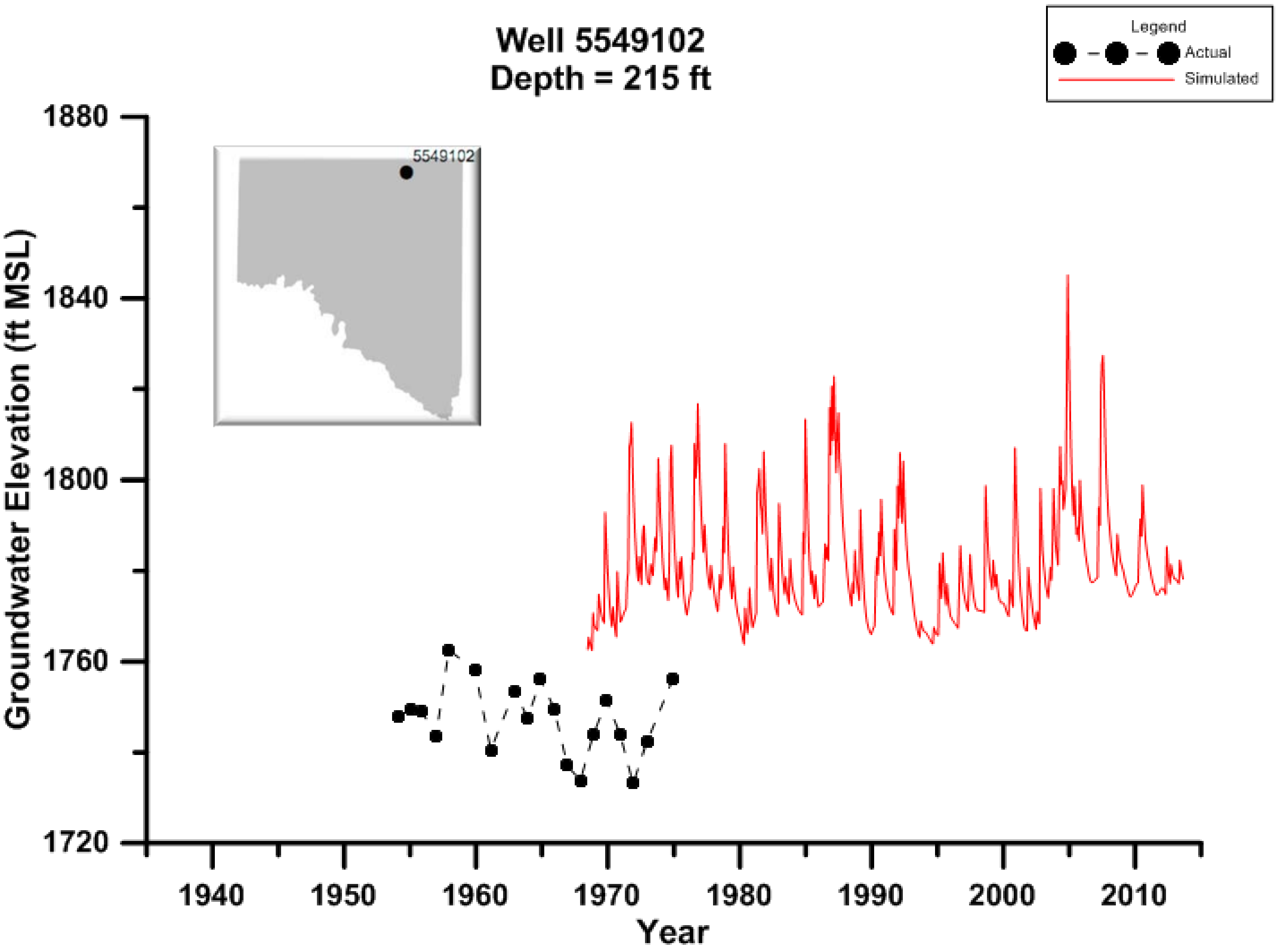

Well 5456603
Depth = 93 ft
Legend
● – ● – ● Actual
Simulated
5456603
Groundwater Elevation (ft MSL)
1820
1800
1780
1760
1740
1720
1700
1940
1950
1960
1970
1980
1990
2000
2010
Year

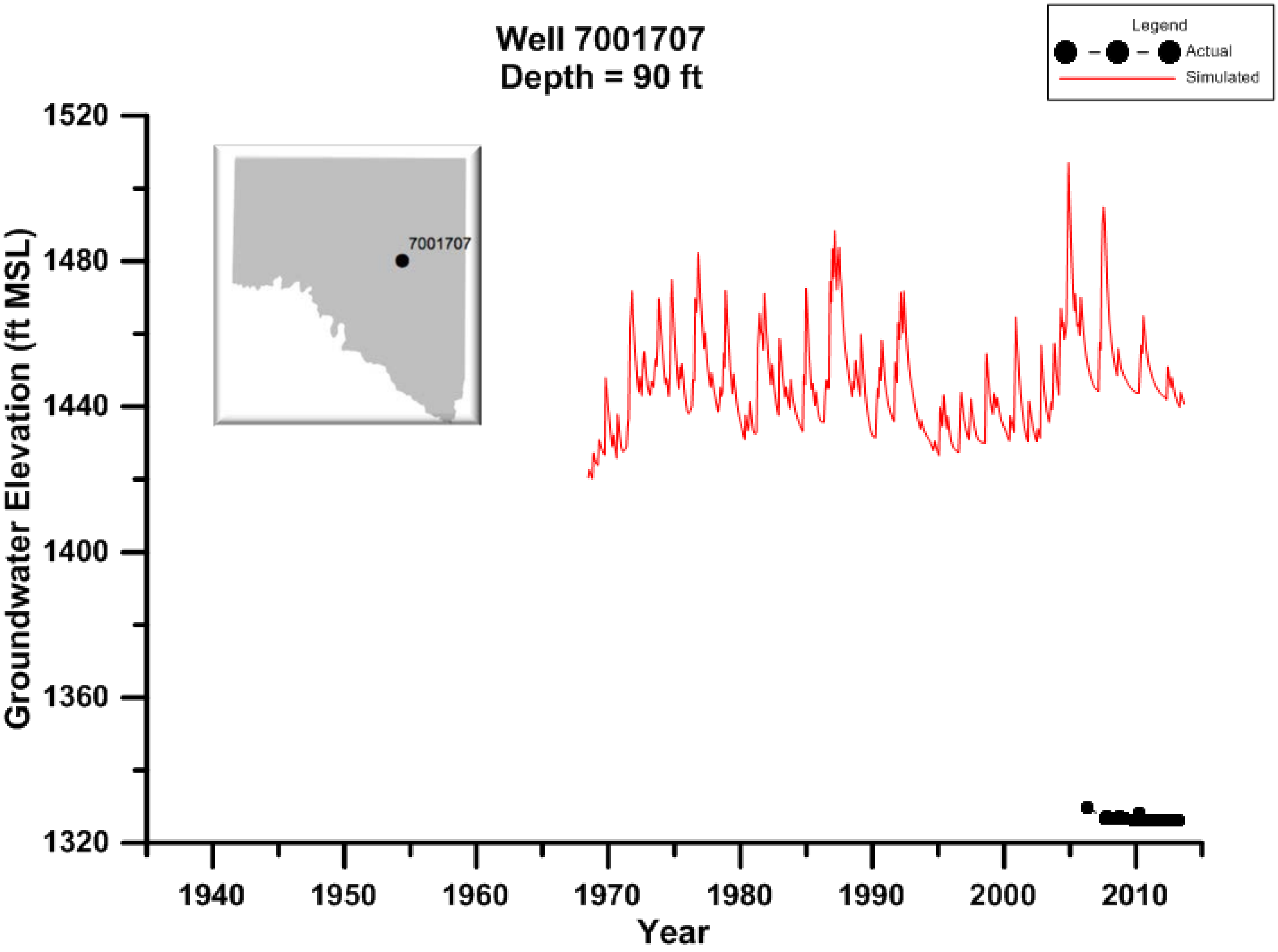

Well 5460502
Depth = 580 ft
Legend
Actual
Simulated
5460502
Groundwater Elevation (ft MSL)
1580
1560
1540
1520
1500
1480
1940
1950
1960
1970
1980
1990
2000
2010
Year

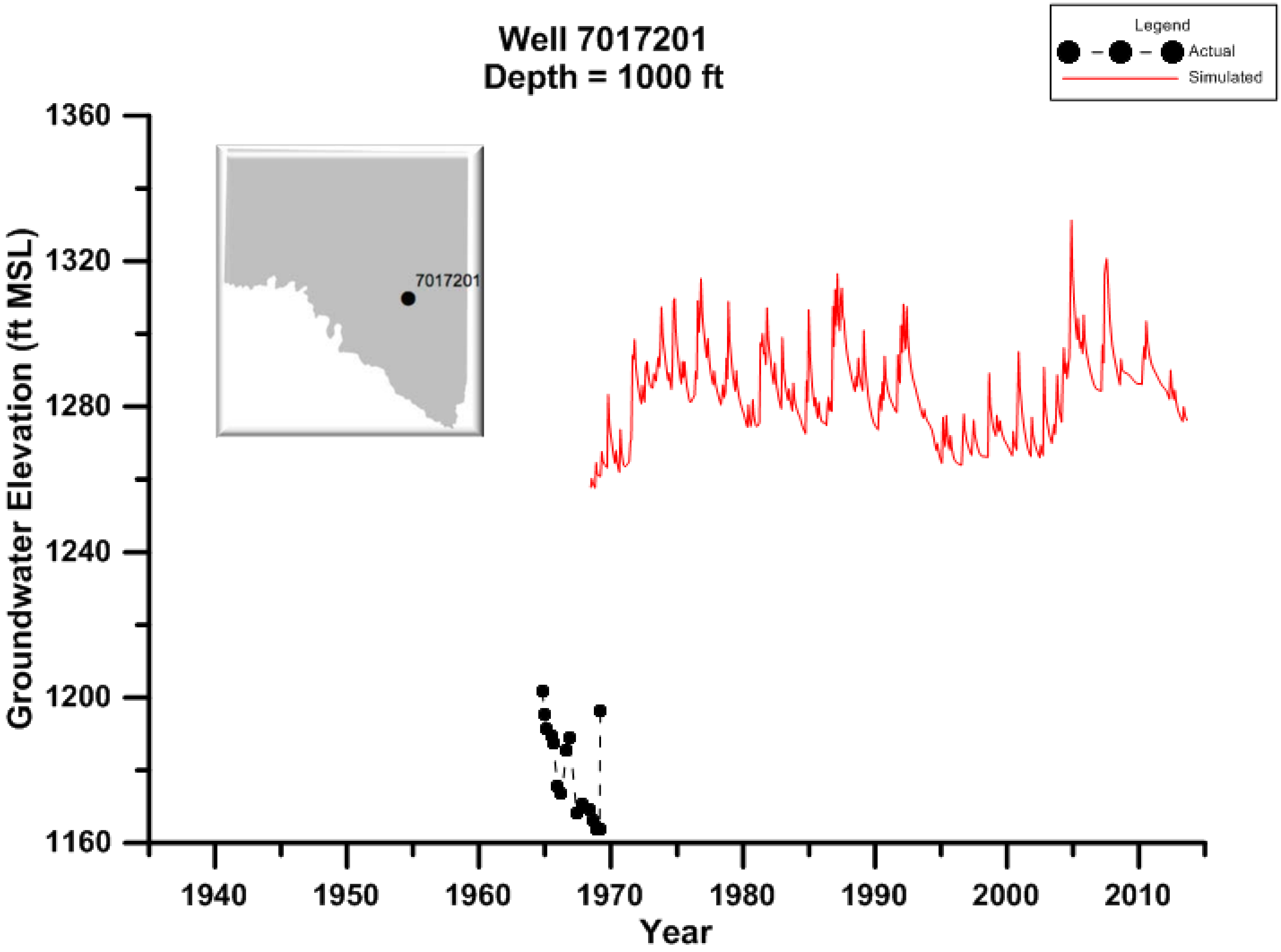

Well 5463401
Depth = 710 ft
Legend
● – ● – ● Actual
Simulated
5463401
Groundwater Elevation (ft MSL)
1620
1600
1580
1560
1540
1520
1940
1950
1960
1970
1980
1990
2000
2010
Year

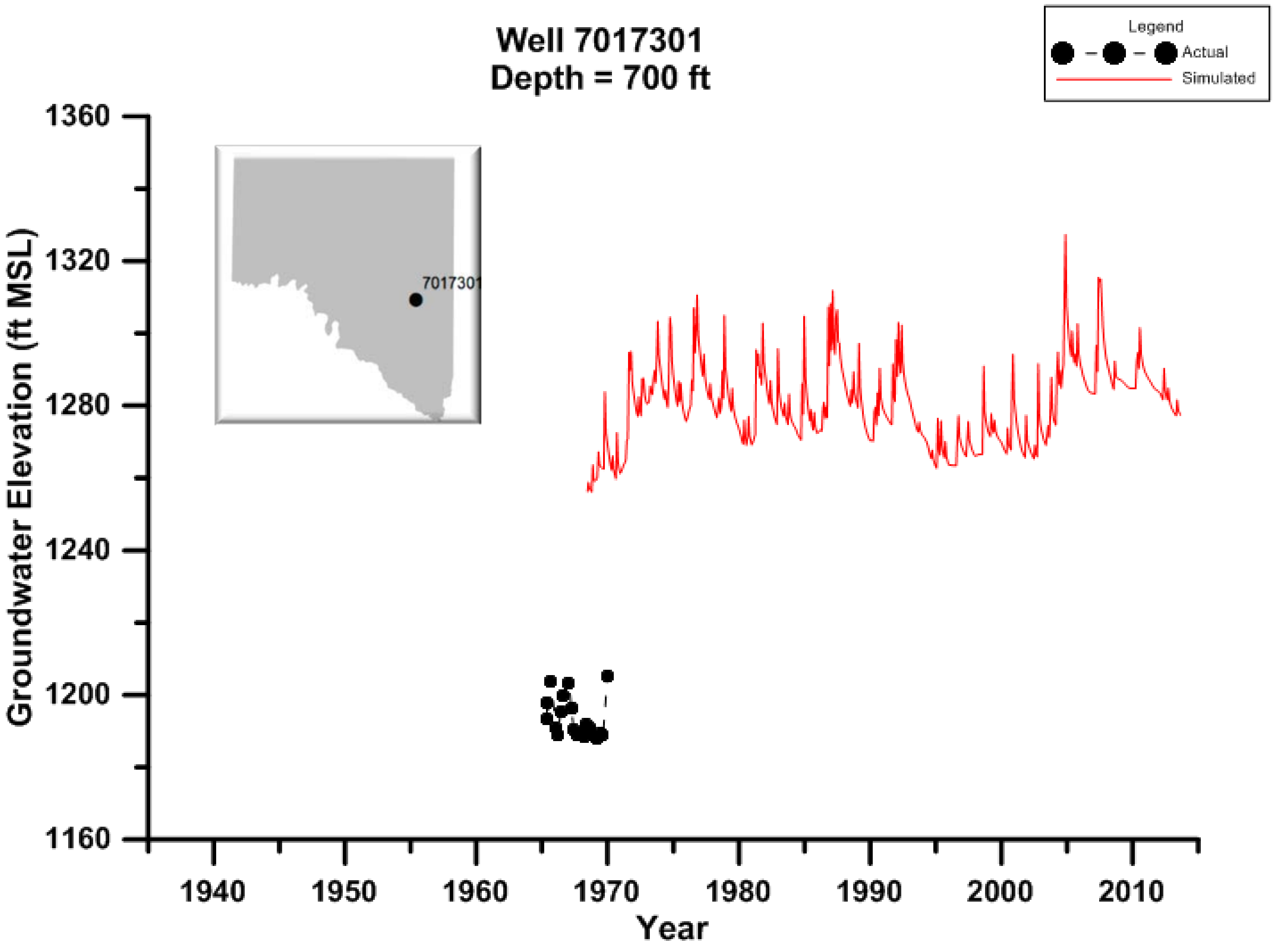

Well 5464401
Depth = 130 ft
Legend
● – ● – ● Actual
Simulated
5464401
Groundwater Elevation (ft MSL)
1640
1620
1600
1580
1560
1540
1520
1940
1950
1960
1970
1980
1990
2000
2010
Year

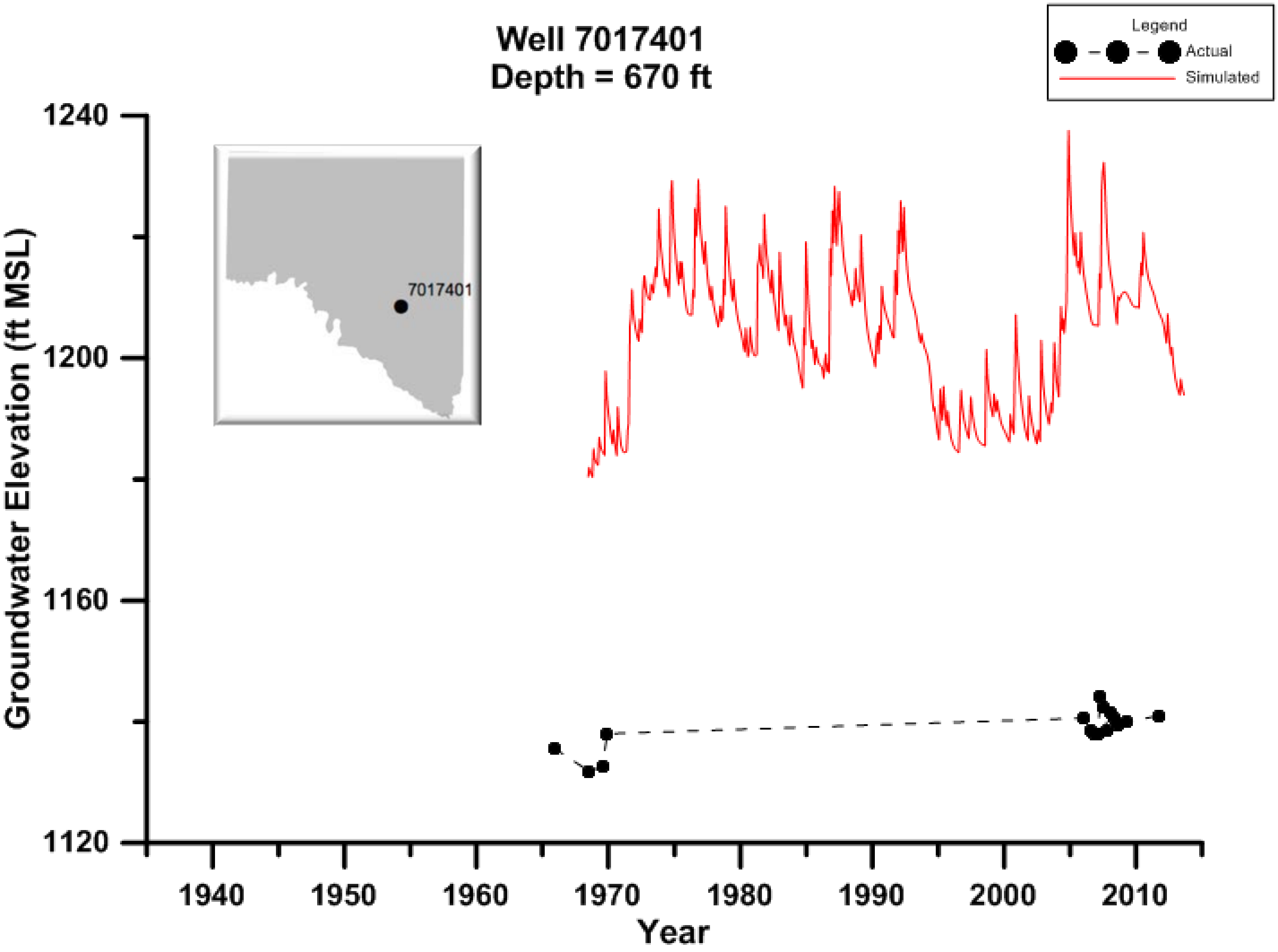

Well 5541801
Depth = 256 ft
Legend
● – ● – ● Actual
Simulated
5541801
Groundwater Elevation (ft MSL)
1880
1840
1800
1760
1720
1940
1950
1960
1970
1980
1990
2000
2010
Year

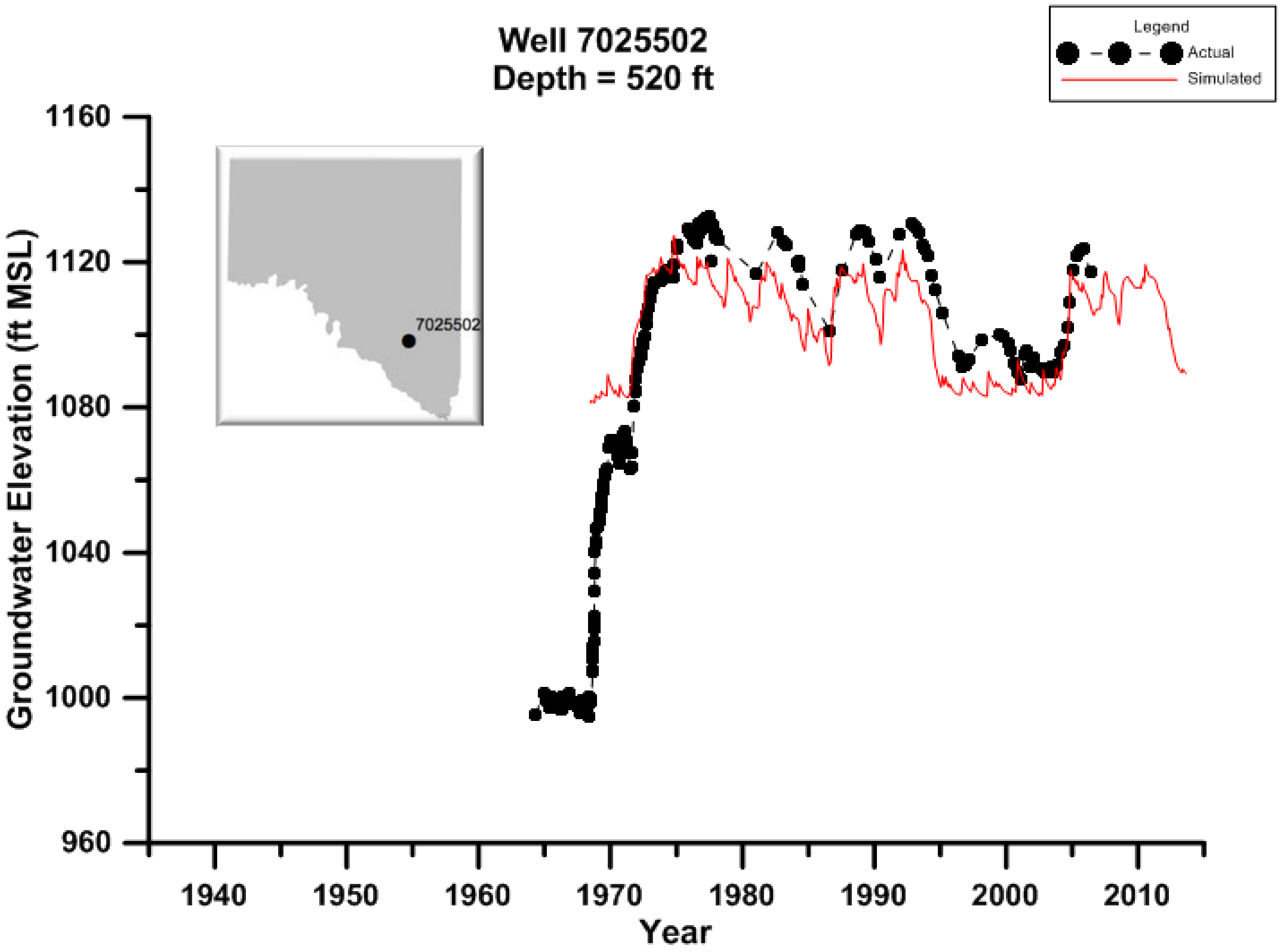

Well 5549102
Depth = 215 ft
Legend
● – ● – ● Actual
Simulated
5549102
Groundwater Elevation (ft MSL)
1880
1840
1800
1760
1720
1940
1950
1960
1970
1980
1990
2000
2010
Year

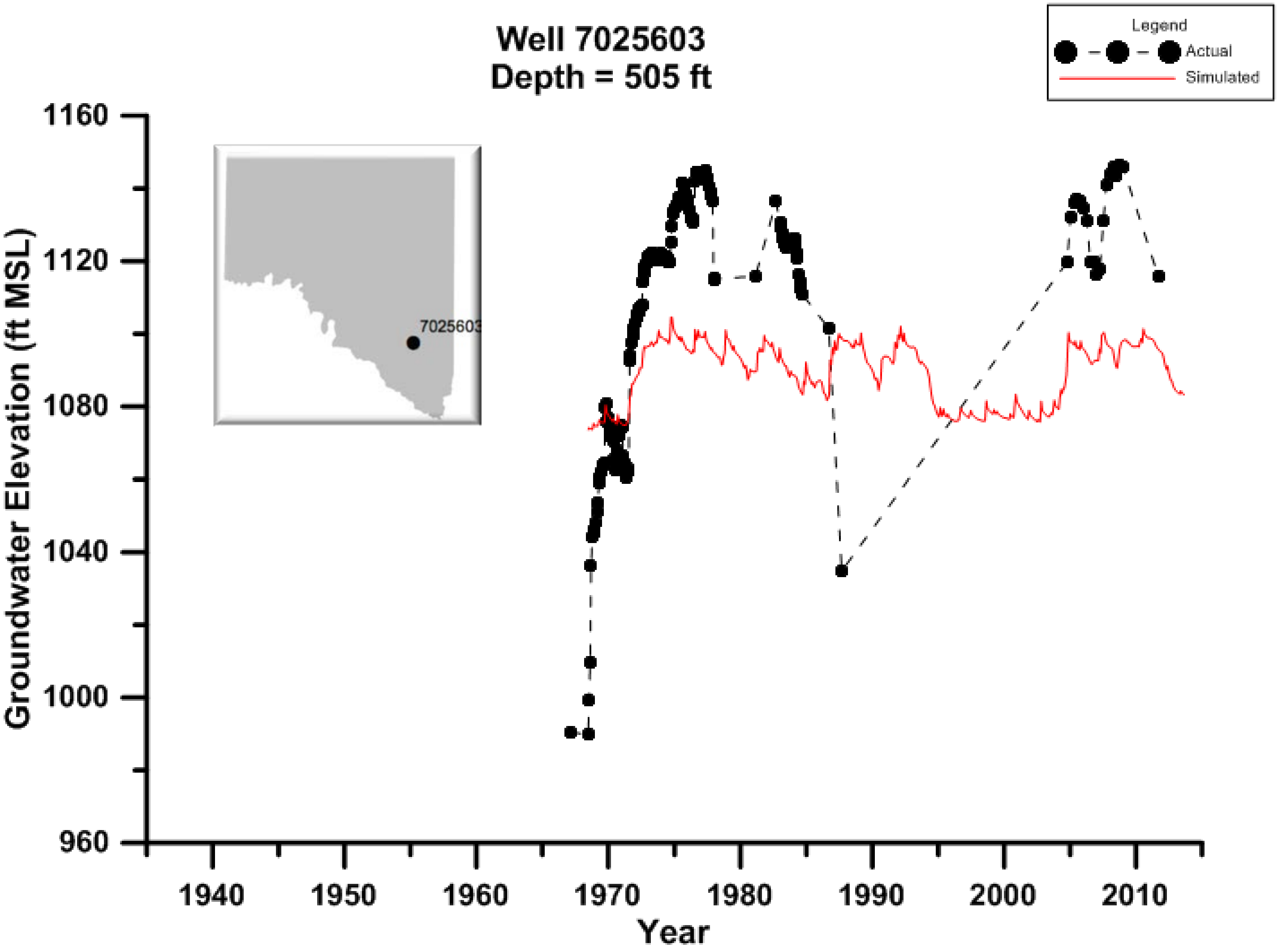

Well 7001707
Depth = 90 ft
Legend
● – ● – ● Actual
Simulated
7001707
Groundwater Elevation (ft MSL)
1520
1480
1440
1400
1360
1320
1940
1950
1960
1970
1980
1990
2000
2010
Year

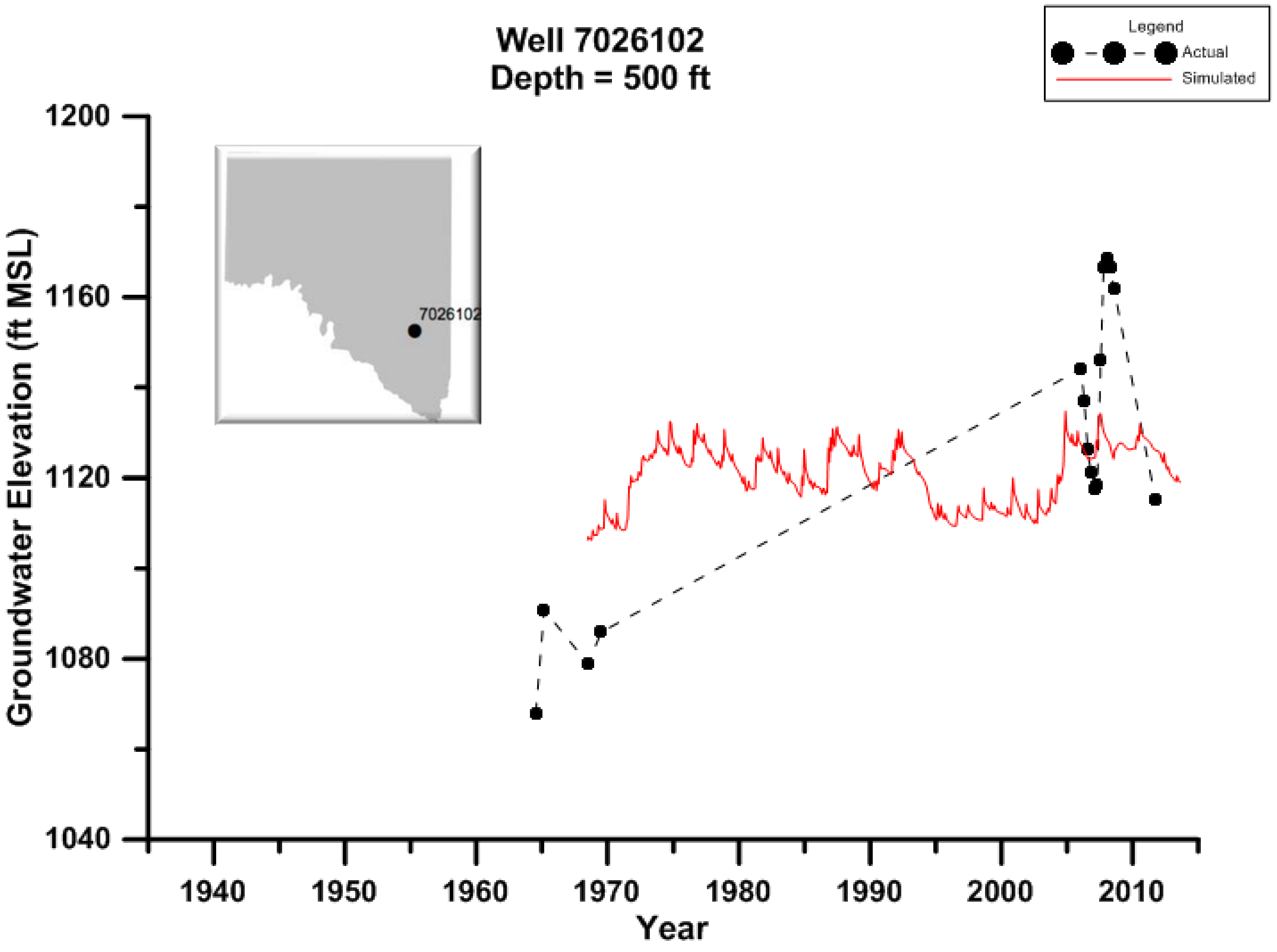

Well 7017201
Depth = 1000 ft
Legend
● – ● – ● Actual
Simulated
7017201
Groundwater Elevation (ft MSL)
1360
1320
1280
1240
1200
1160
1940
1950
1960
1970
1980
1990
2000
2010
Year

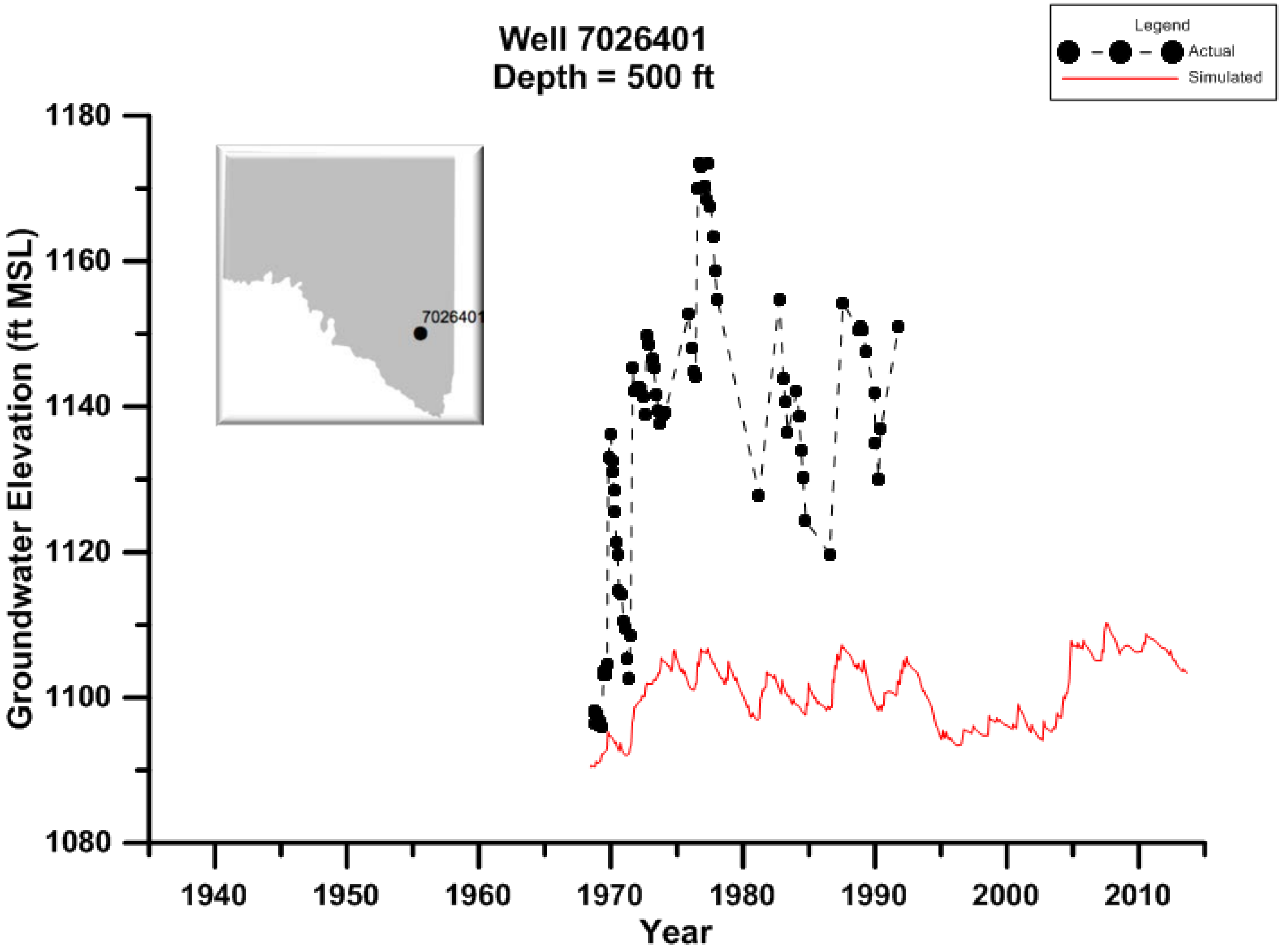

Well 7017301
Depth = 700 ft
Legend
● – ● – ● Actual
Simulated
7017301
Groundwater Elevation (ft MSL)
1360
1320
1280
1240
1200
1160
1940
1950
1960
1970
1980
1990
2000
2010
Year

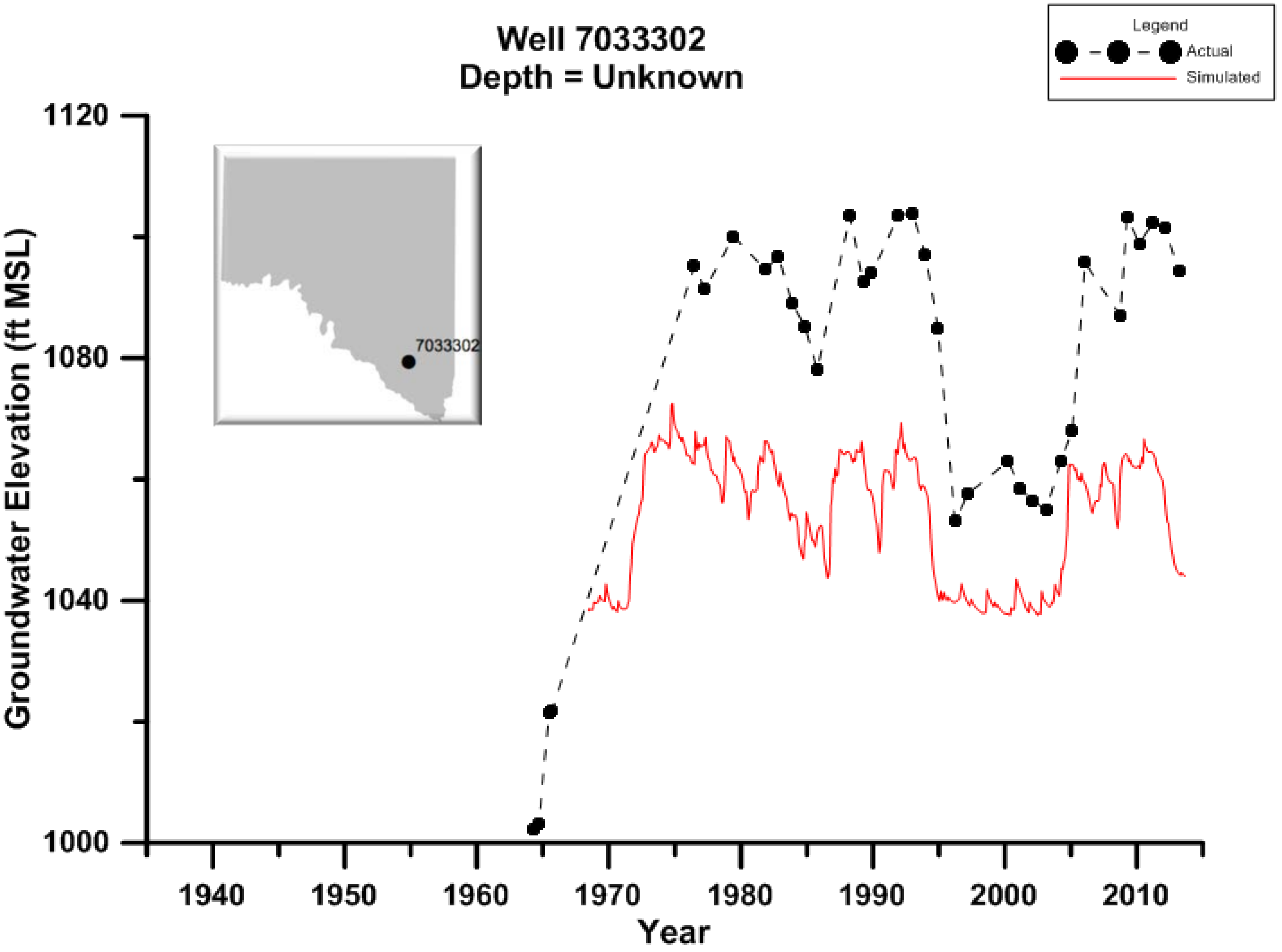

Well 7017401
Depth = 670 ft
Legend
Actual
Simulated
7017401
Groundwater Elevation (ft MSL)
1240
1200
1160
1120
1940
1950
1960
1970
1980
1990
2000
2010
Year

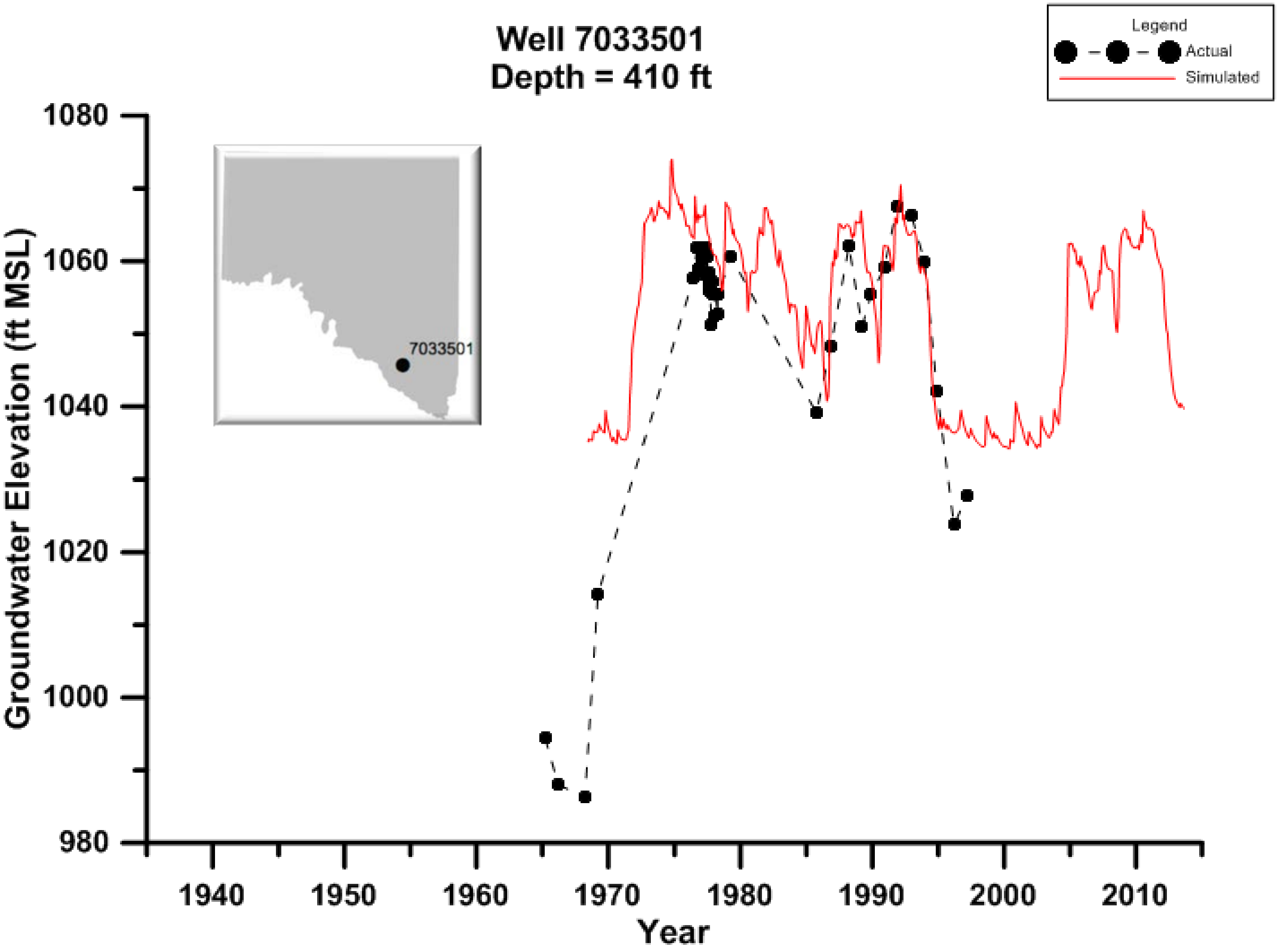

Well 7025502
Depth = 520 ft
Legend
Actual
Simulated
7025502
Groundwater Elevation (ft MSL)
1160
1120
1080
1040
1000
960
1940
1950
1960
1970
1980
1990
2000
2010
Year

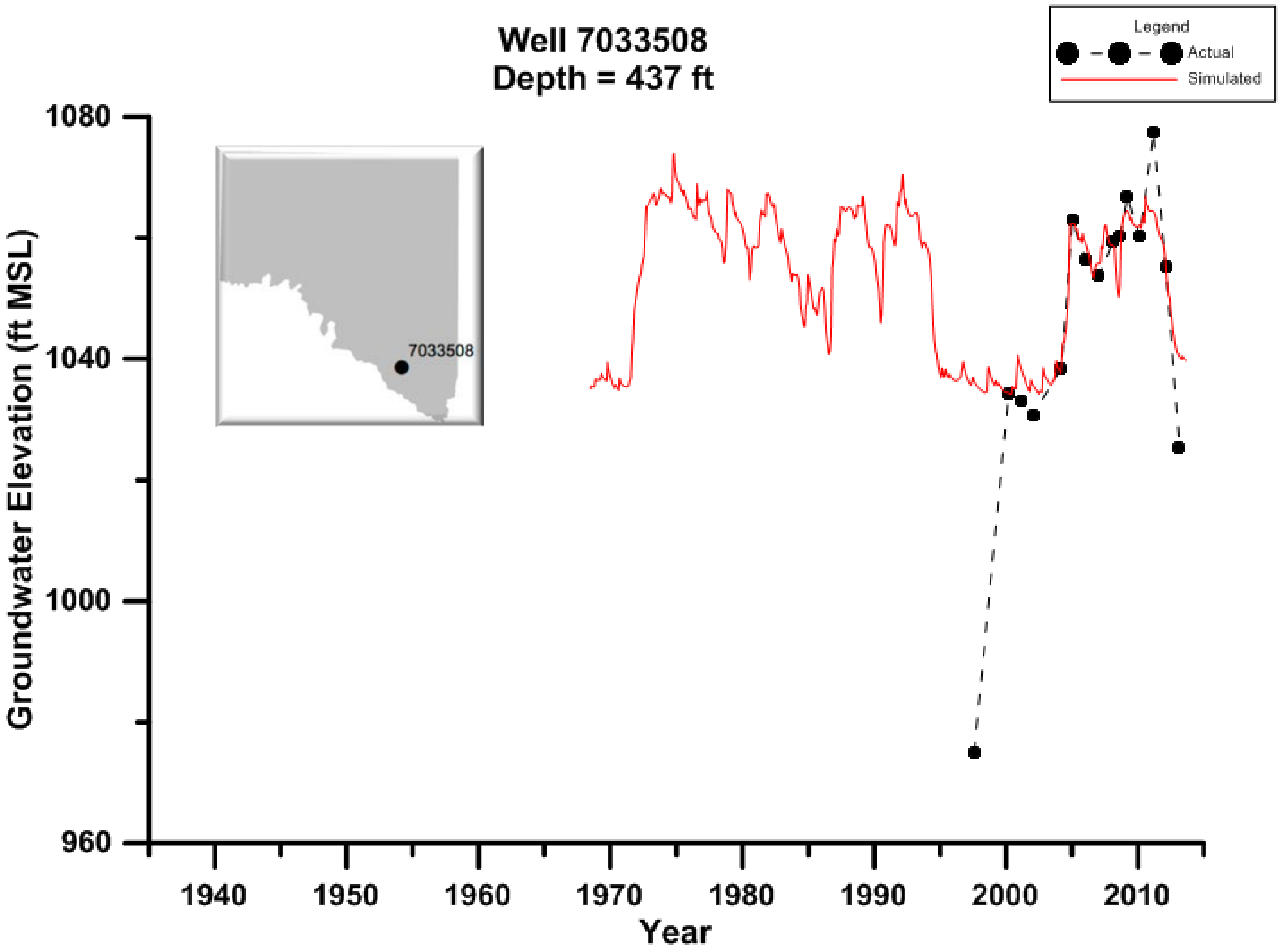

Well 7025603
Depth = 505 ft
Legend
Actual
Simulated
7025603
Groundwater Elevation (ft MSL)
1160
1120
1080
1040
1000
960
1940
1950
1960
1970
1980
1990
2000
2010
Year

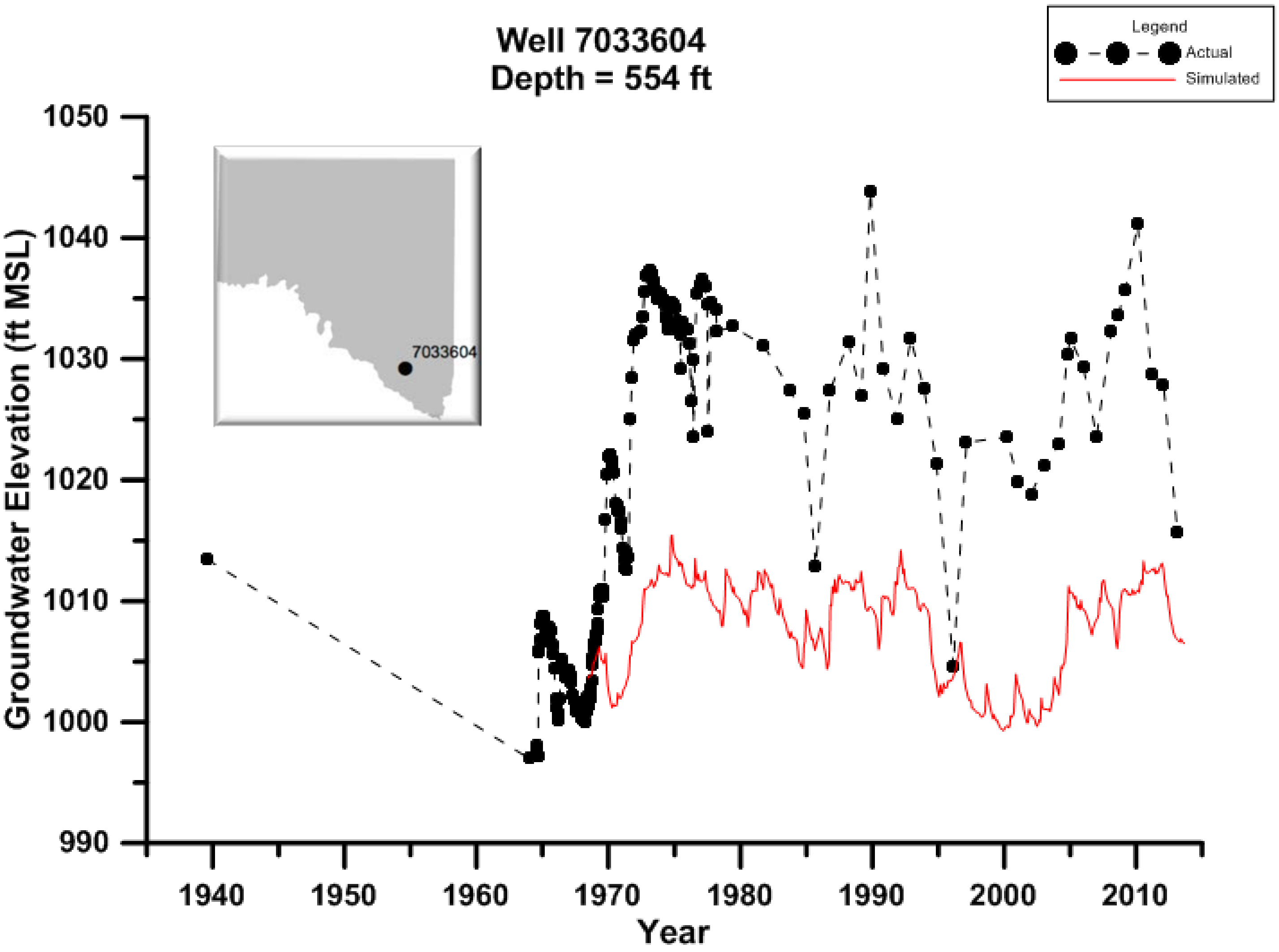

Well 7026102
Depth = 500 ft
Legend
Actual
Simulated
7026102
Groundwater Elevation (ft MSL)
1200
1160
1120
1080
1040
1940
1950
1960
1970
1980
1990
2000
2010
Year

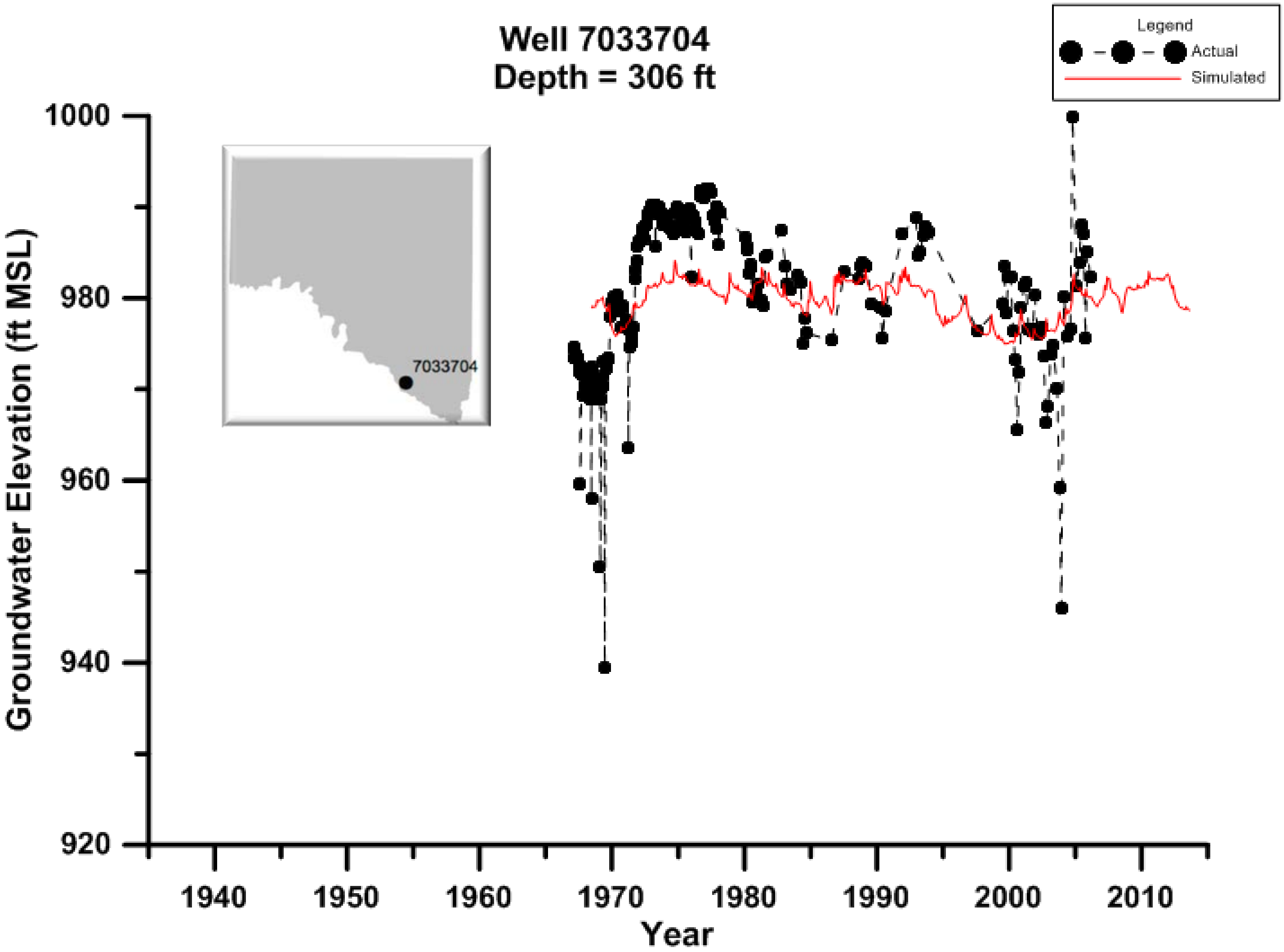

Well 7026401
Depth = 500 ft
Legend
Actual
Simulated
7026401
Groundwater Elevation (ft MSL)
1180
1160
1140
1120
1100
1080
1940
1950
1960
1970
1980
1990
2000
2010
Year

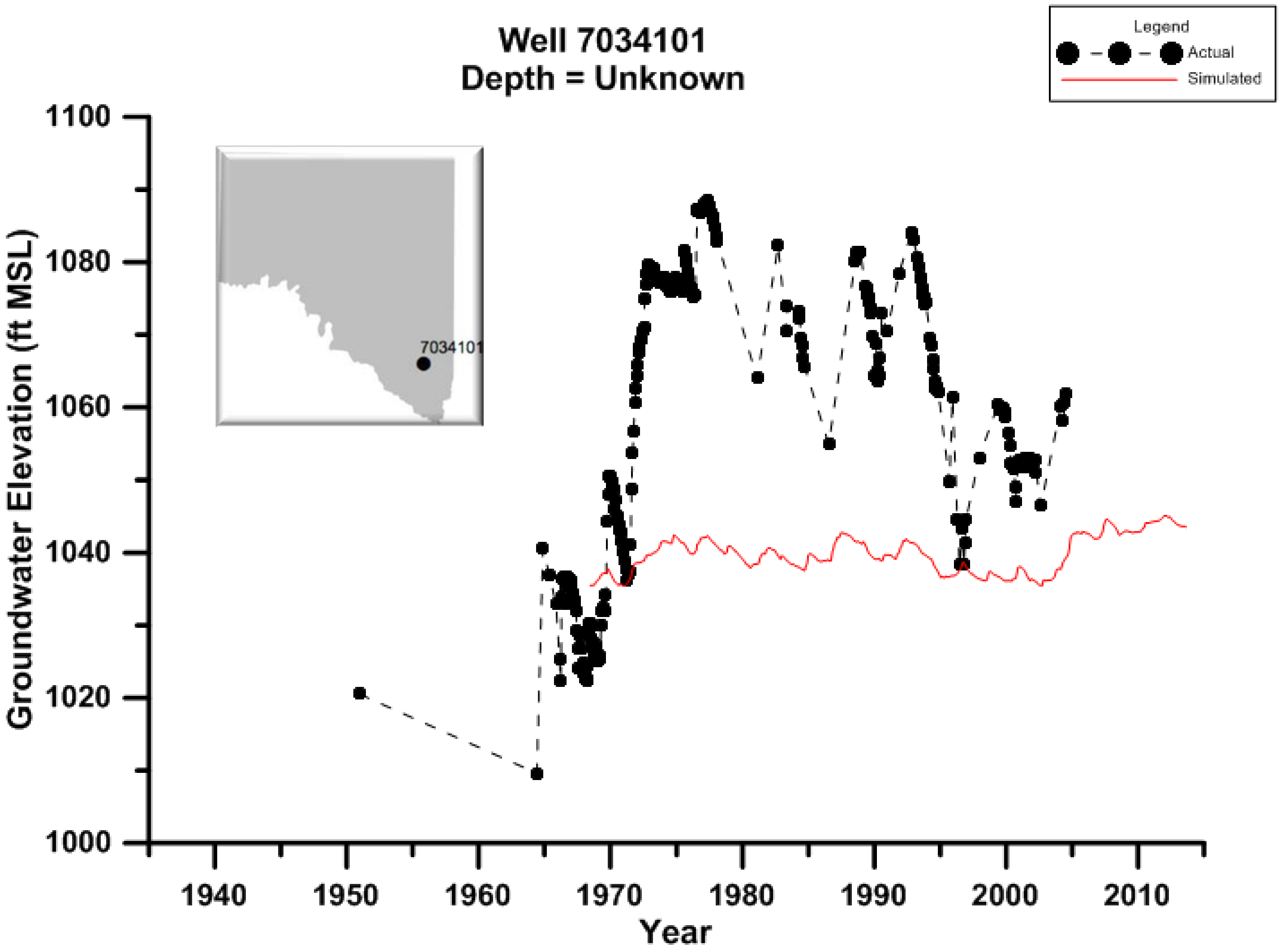

Well 7033302
Depth = Unknown
Legend
Actual
Simulated
7033302
Groundwater Elevation (ft MSL)
1120
1080
1040
1000
1940
1950
1960
1970
1980
1990
2000
2010
Year

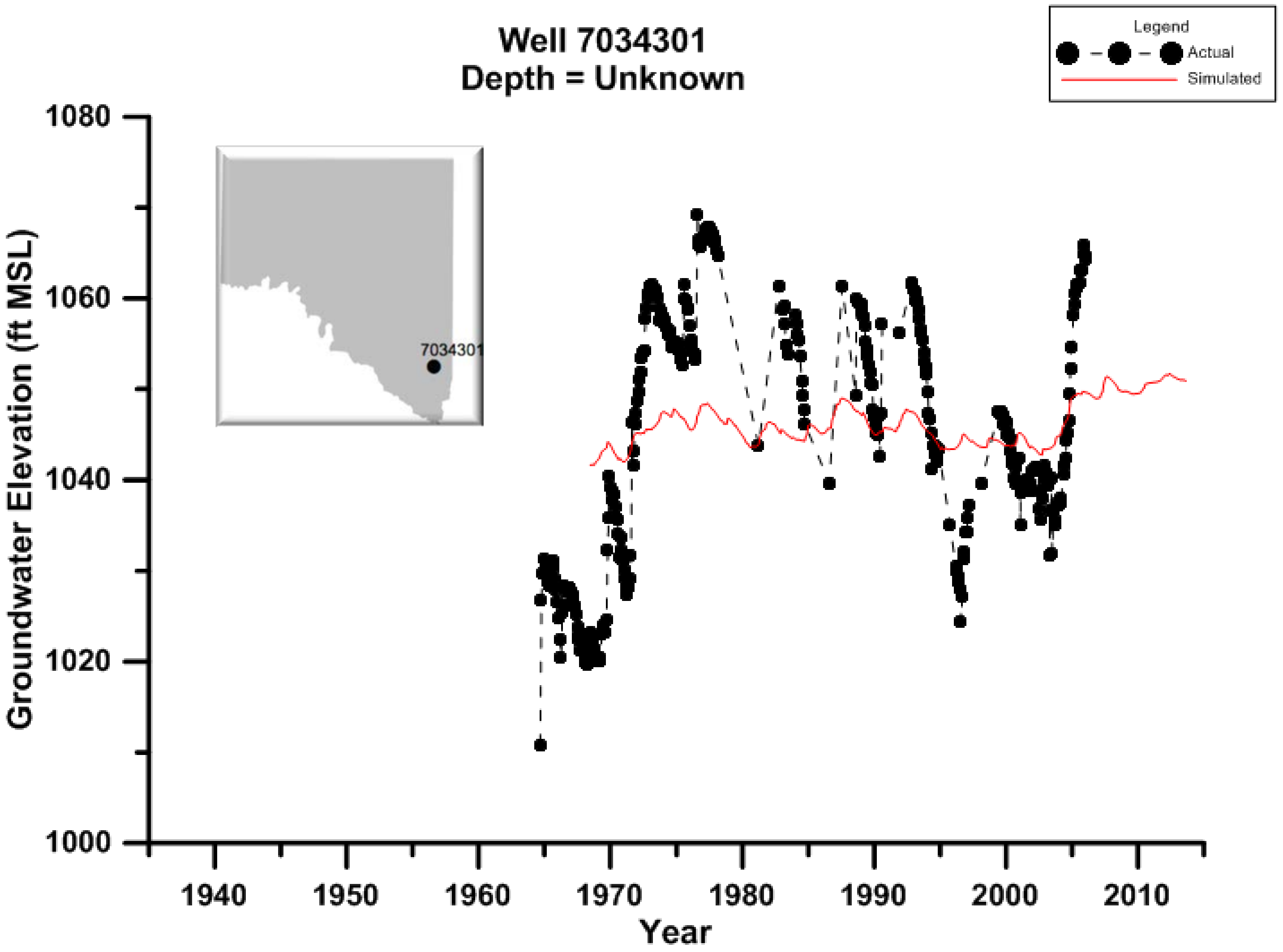

Well 7033501
Depth = 410 ft
Legend
Actual
Simulated
Groundwater Elevation (ft MSL)
1080
1060
1040
1020
1000
980
7033501
1940
1950
1960
1970
1980
1990
2000
2010
Year

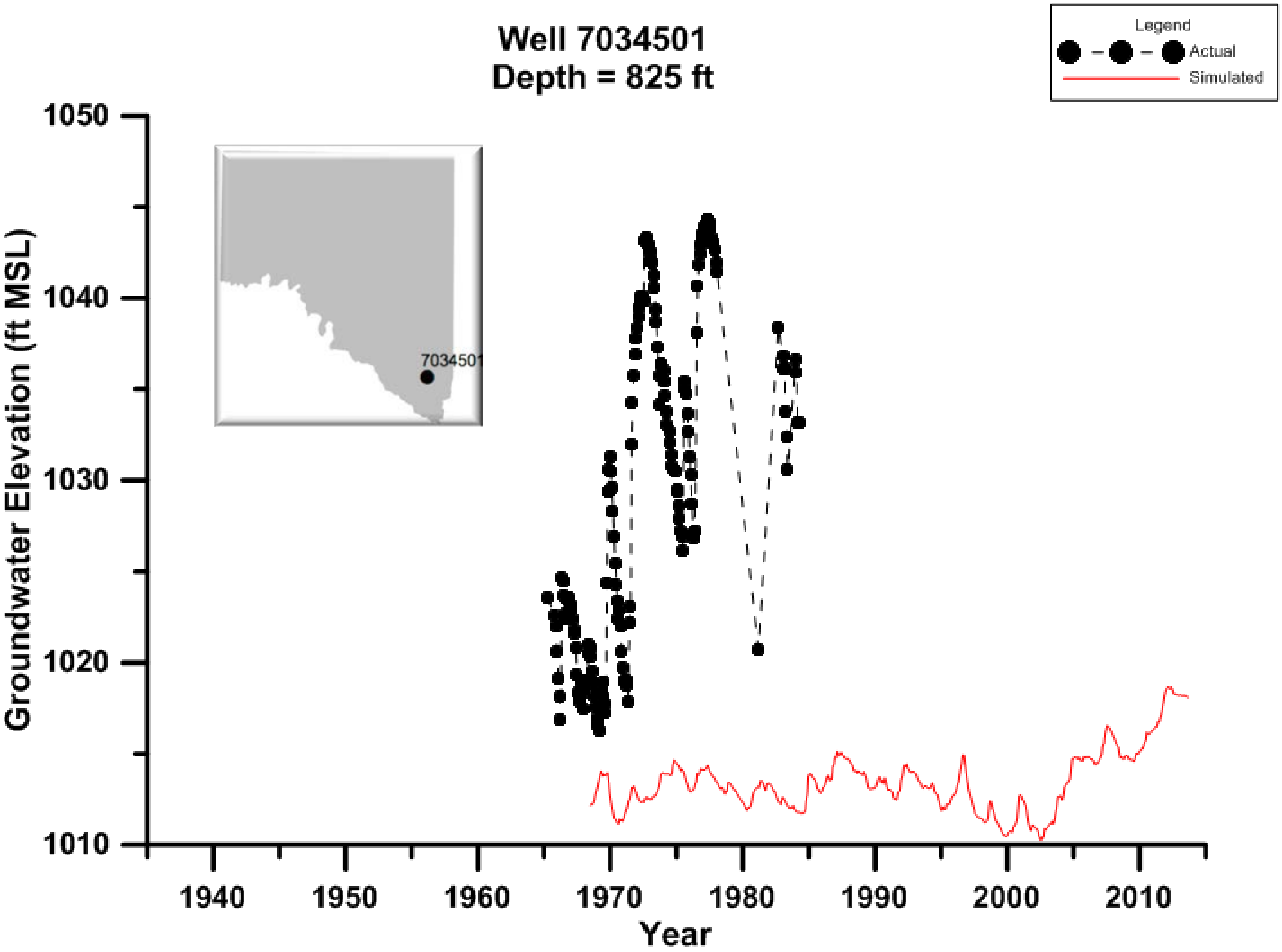

Well 7033508
Depth = 437 ft
Legend
● – ● – ● Actual
Simulated
7033508
Groundwater Elevation (ft MSL)
1080
1040
1000
960
1940
1950
1960
1970
1980
1990
2000
2010
Year

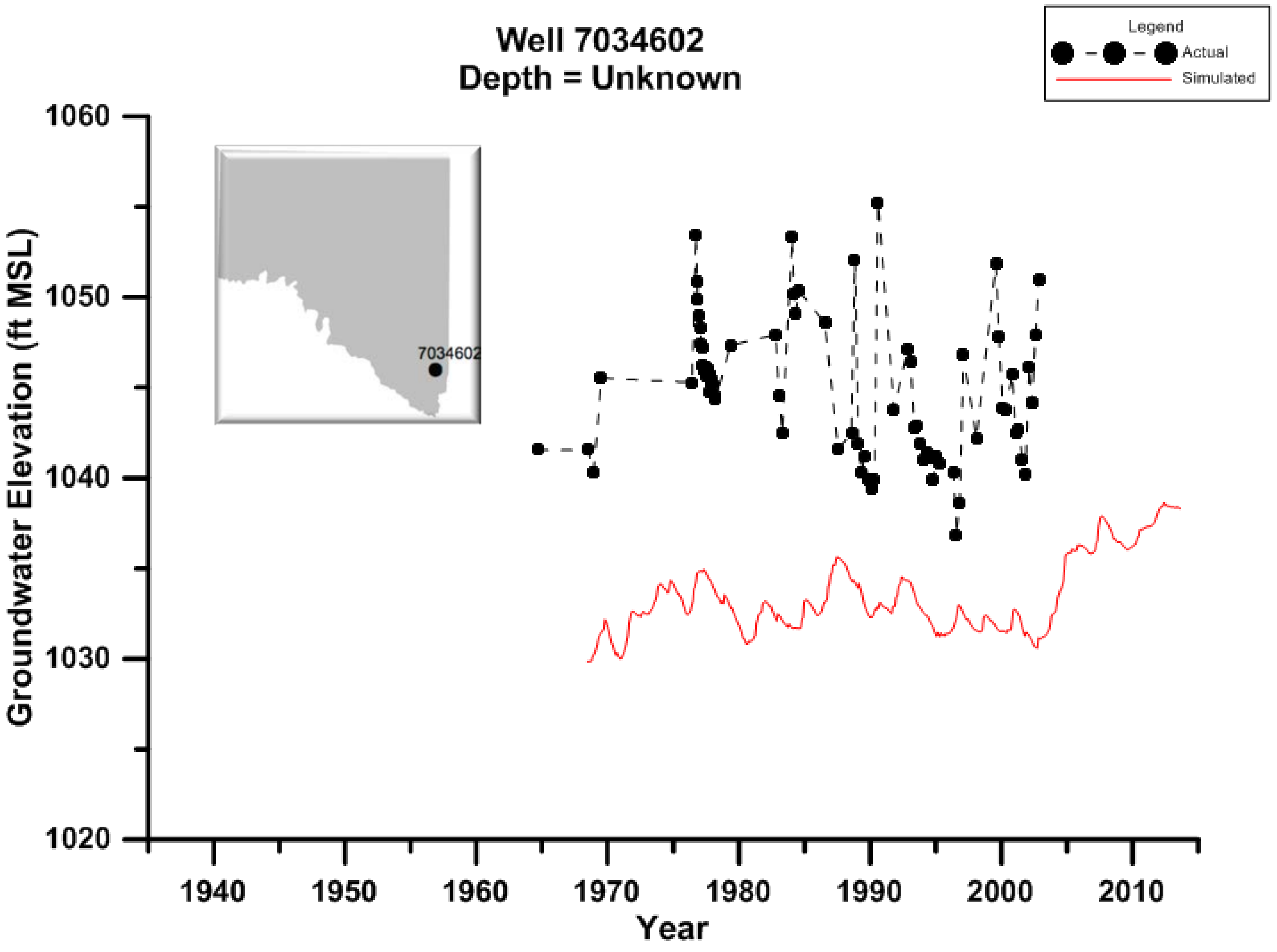

Well 7033604
Depth = 554 ft
Legend
● – ● – ● Actual
Simulated
7033604
Groundwater Elevation (ft MSL)
1050
1040
1030
1020
1010
1000
990
1940
1950
1960
1970
1980
1990
2000
2010
Year


Well 7033704
Depth = 306 ft
Legend
Actual
Simulated
7033704
Groundwater Elevation (ft MSL)
1000
980
960
940
920
1940
1950
1960
1970
1980
1990
2000
2010
Year

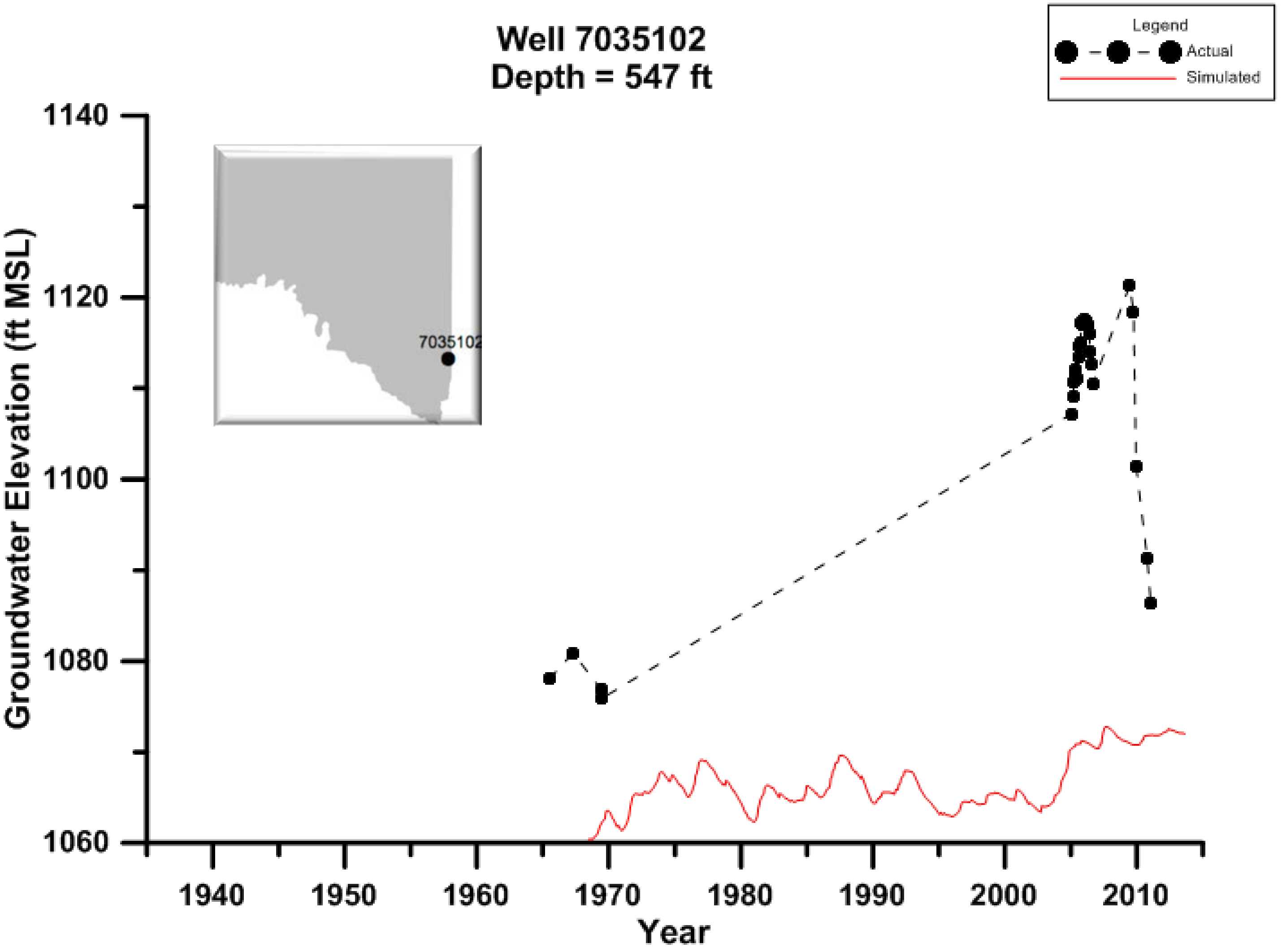

Well 7034101
Depth = Unknown
Legend
● – ● – ● Actual
Simulated
7034101
Groundwater Elevation (ft MSL)
1100
1080
1060
1040
1020
1000
1940
1950
1960
1970
1980
1990
2000
2010
Year

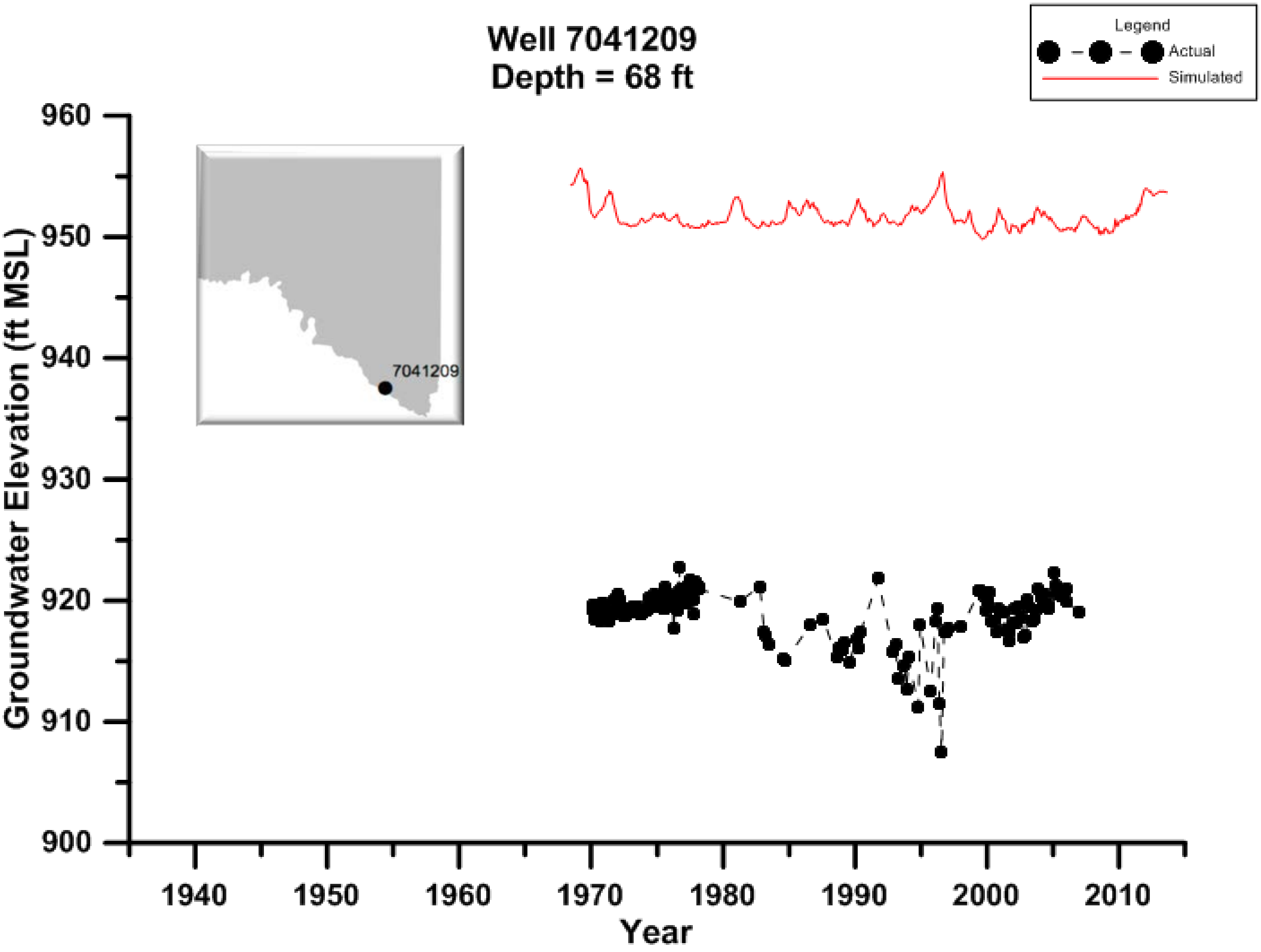

Well 7034301
Depth = Unknown
Legend
● – ● – ● Actual
Simulated
7034301
Groundwater Elevation (ft MSL)
1080
1060
1040
1020
1000
1940
1950
1960
1970
1980
1990
2000
2010
Year


Well 7034501
Depth = 825 ft
Legend
● – ● – ● Actual
Simulated
7034501
Groundwater Elevation (ft MSL)
1050
1040
1030
1020
1010
1940
1950
1960
1970
1980
1990
2000
2010
Year

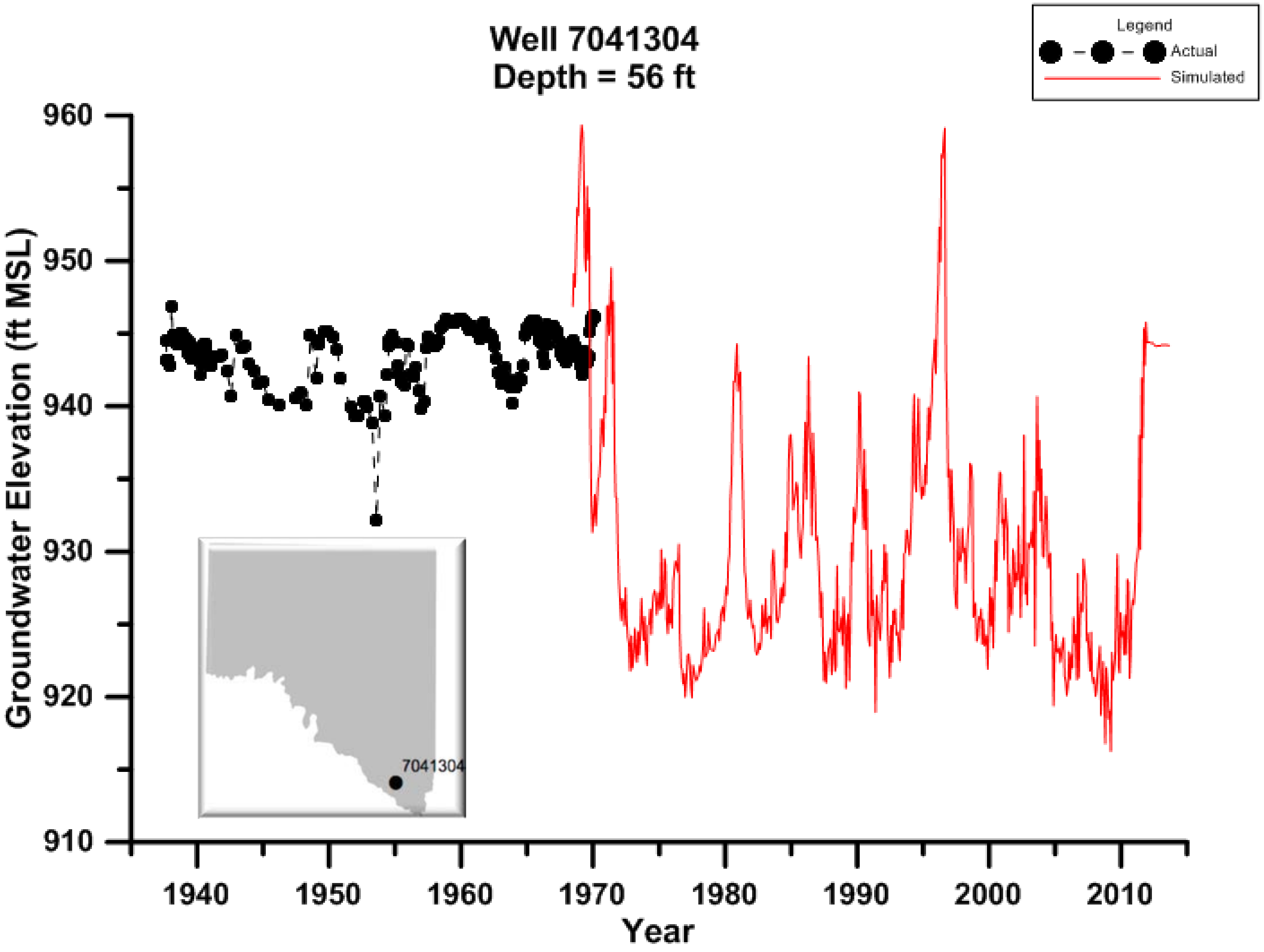


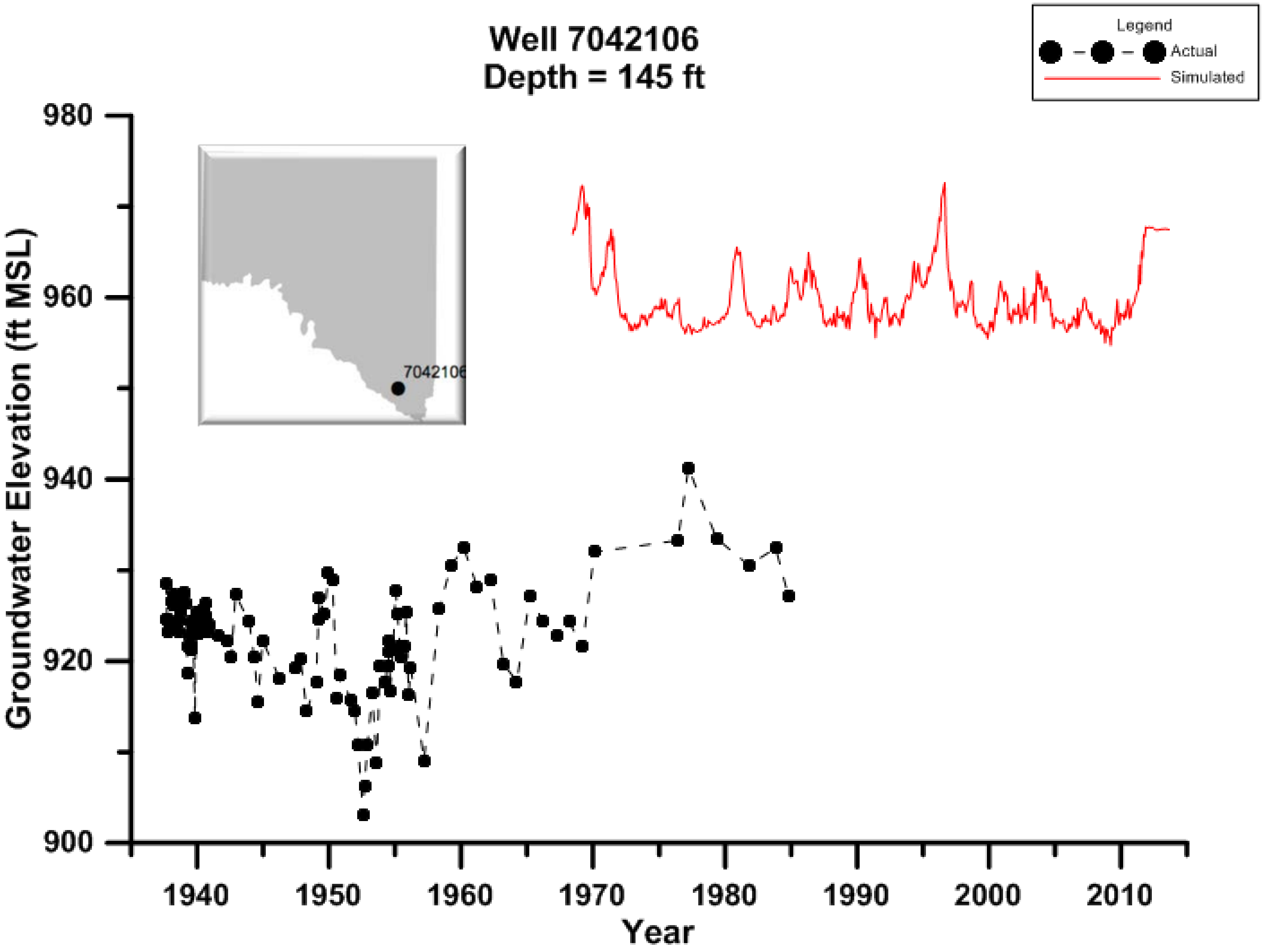
Well 7034602
Depth = Unknown
Legend
● – ● – ● Actual
Simulated
7034602
Groundwater Elevation (ft MSL)
1060
1050
1040
1030
1020
1940
1950
1960
1970
1980
1990
2000
2010
Year

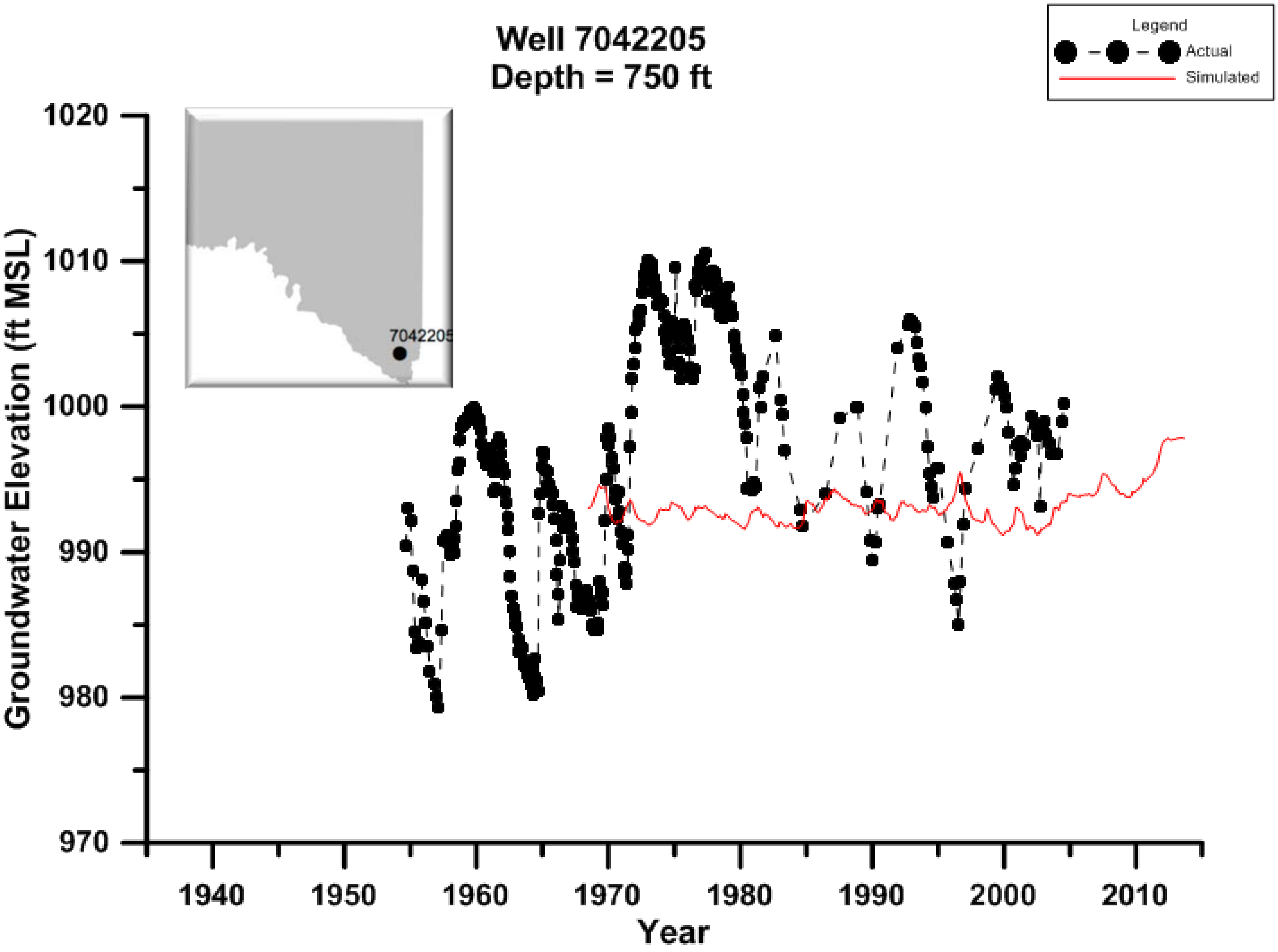

Well 7035102
Depth = 547 ft
Legend
Actual
Simulated
7035102
Groundwater Elevation (ft MSL)
1140
1120
1100
1080
1060
1940
1950
1960
1970
1980
1990
2000
2010
Year

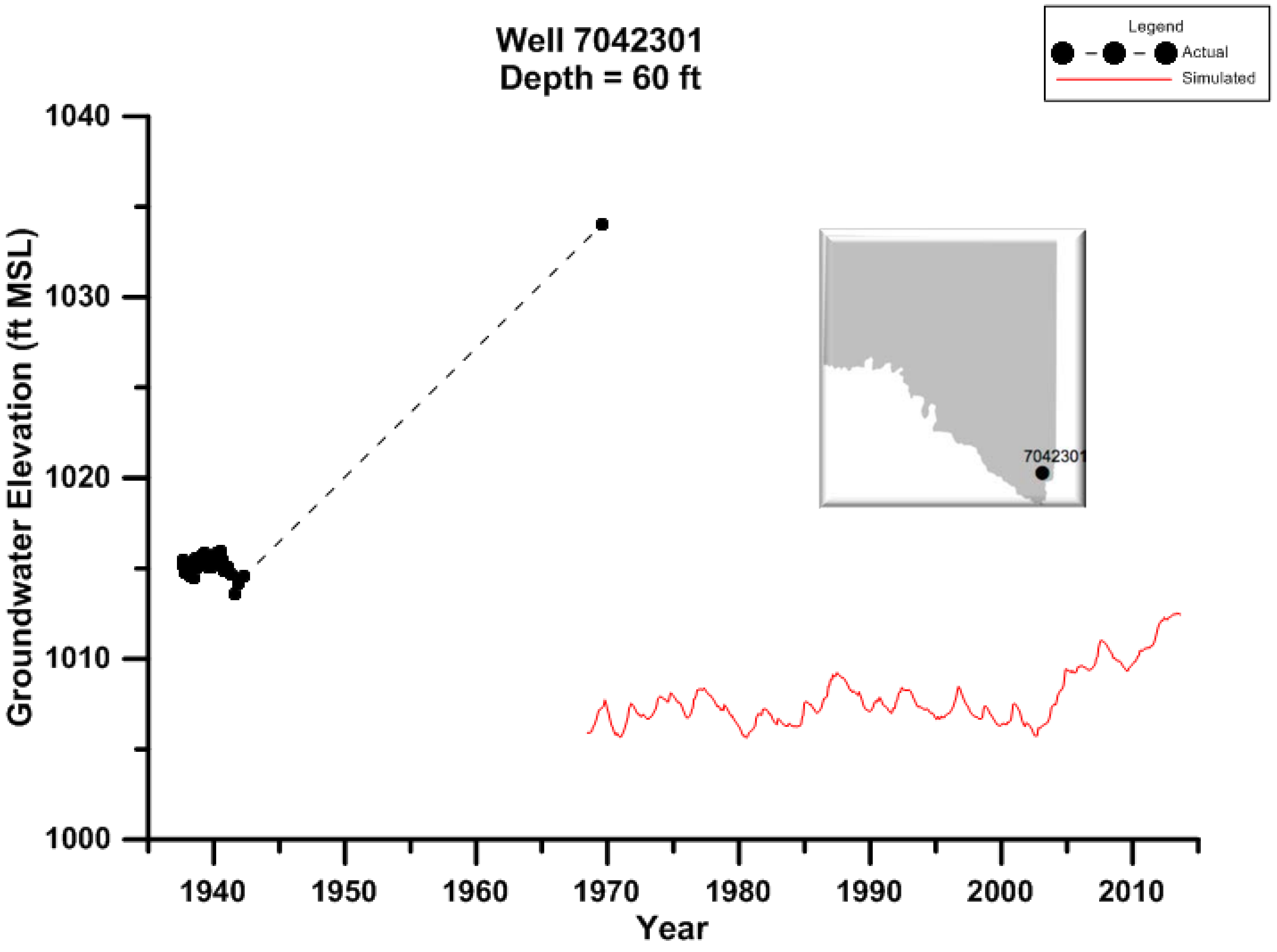


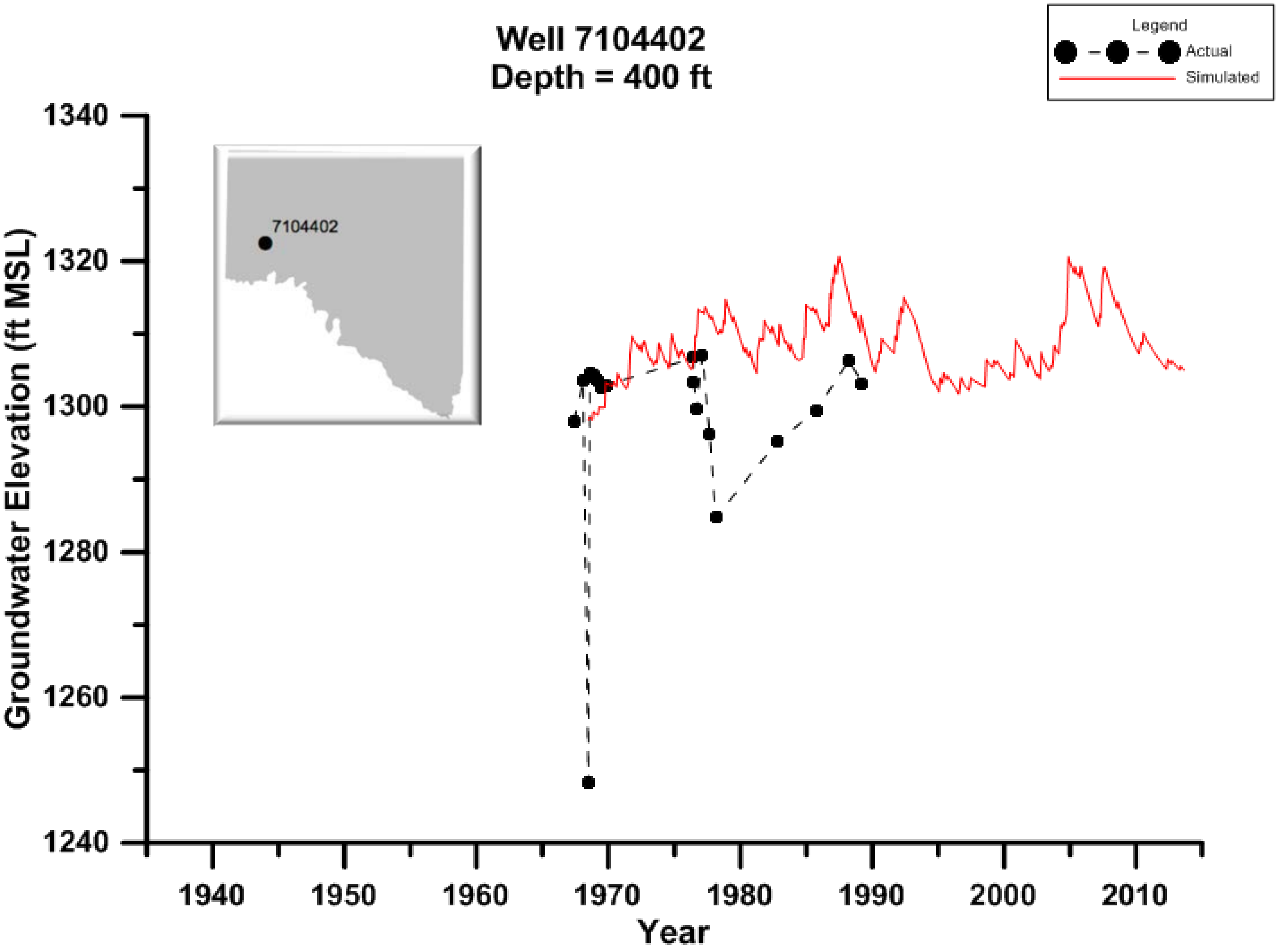
Well 7041209
Depth = 68 ft
Legend
Actual
Simulated
7041209
Groundwater Elevation (ft MSL)
960
950
940
930
920
910
900
1940
1950
1960
1970
1980
1990
2000
2010
Year

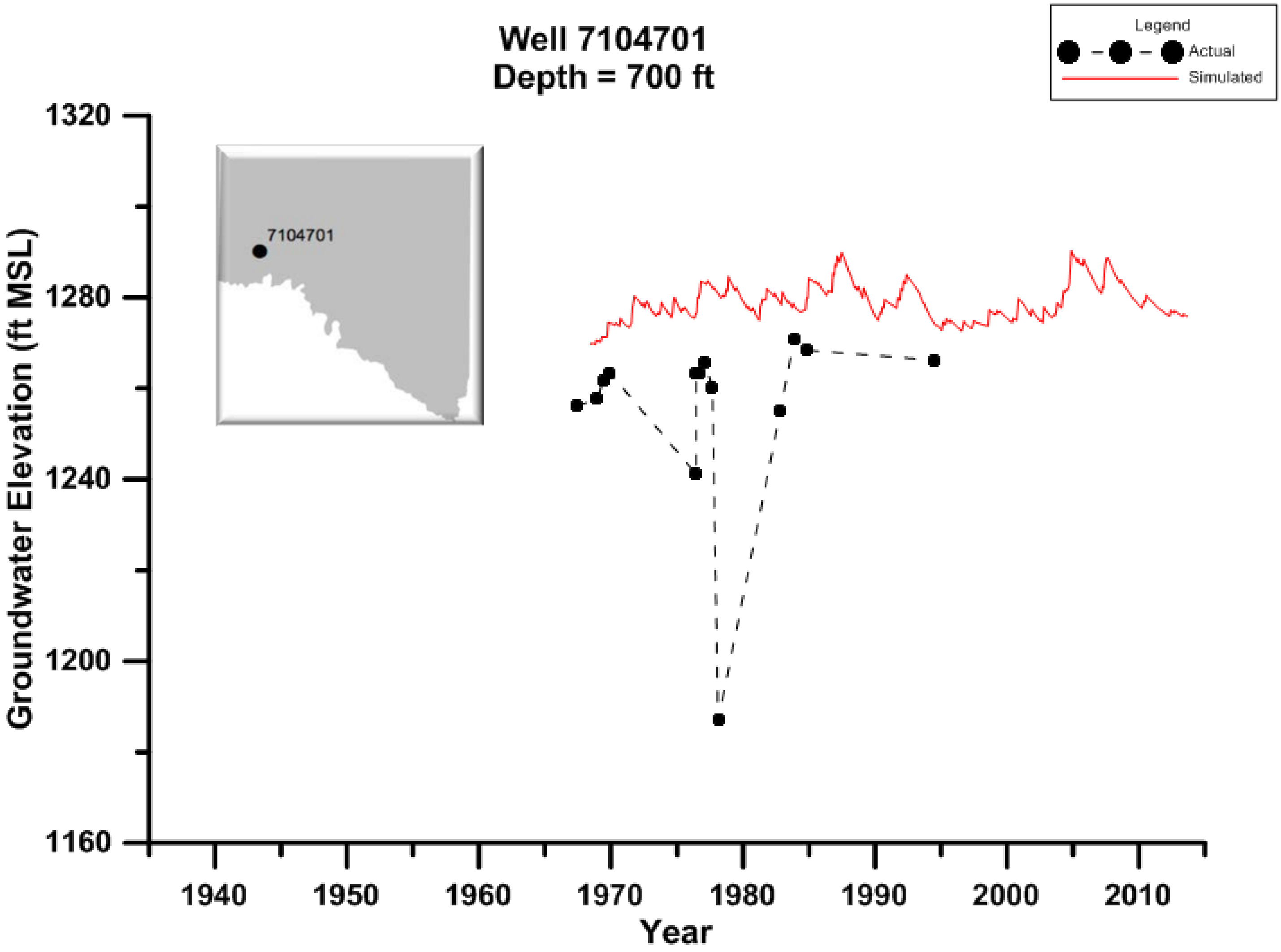

Well 7041304
Depth = 56 ft
Legend
Actual
Simulated
Groundwater Elevation (ft MSL)
960
950
940
930
920
910
1940
1950
1960
1970
1980
1990
2000
2010
Year
7041304

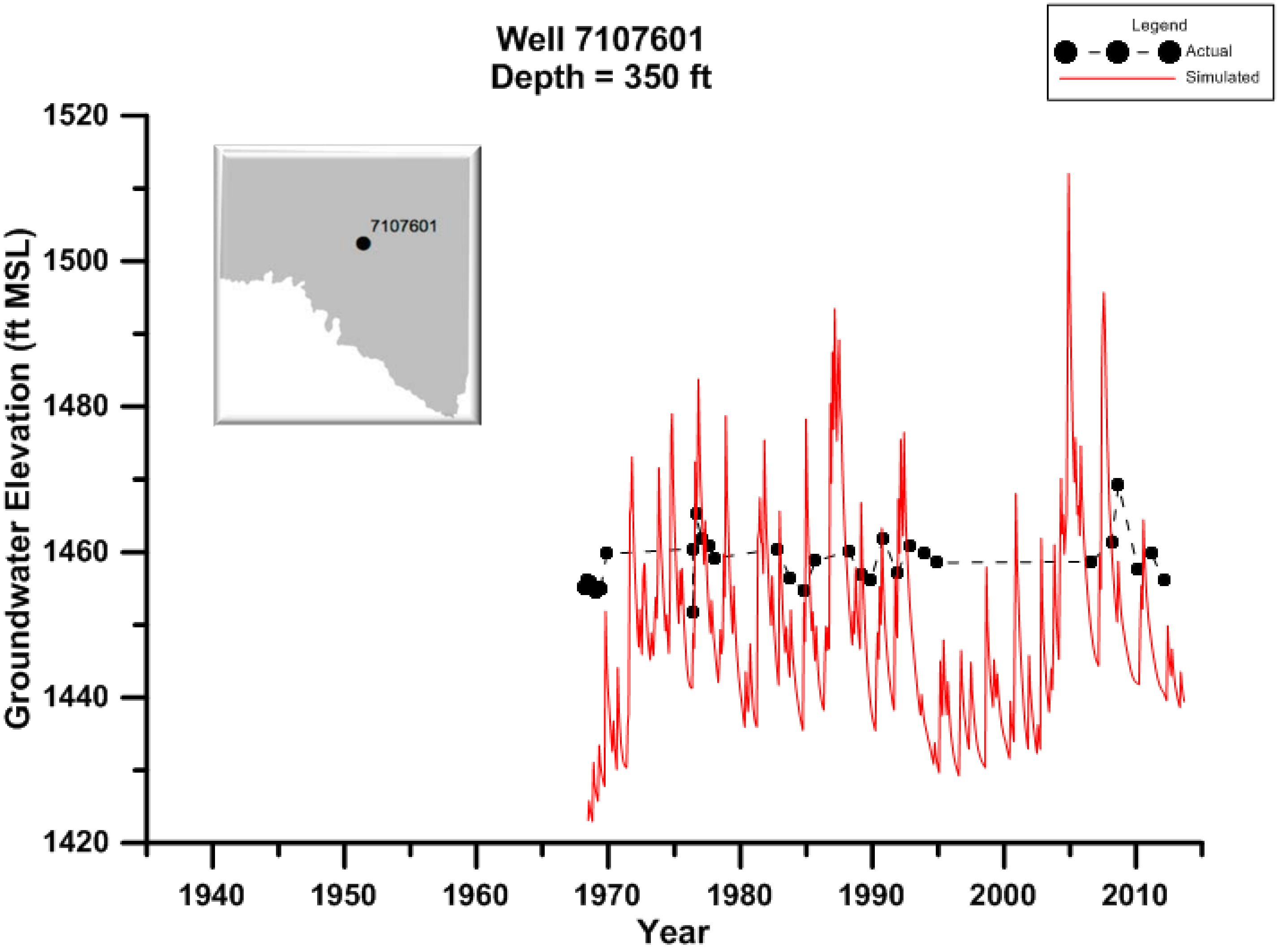

Well 7042106
Depth = 145 ft
Legend
●–●–● Actual
Simulated
7042106
Groundwater Elevation (ft MSL)
980
960
940
920
900
1940
1950
1960
1970
1980
1990
2000
2010
Year

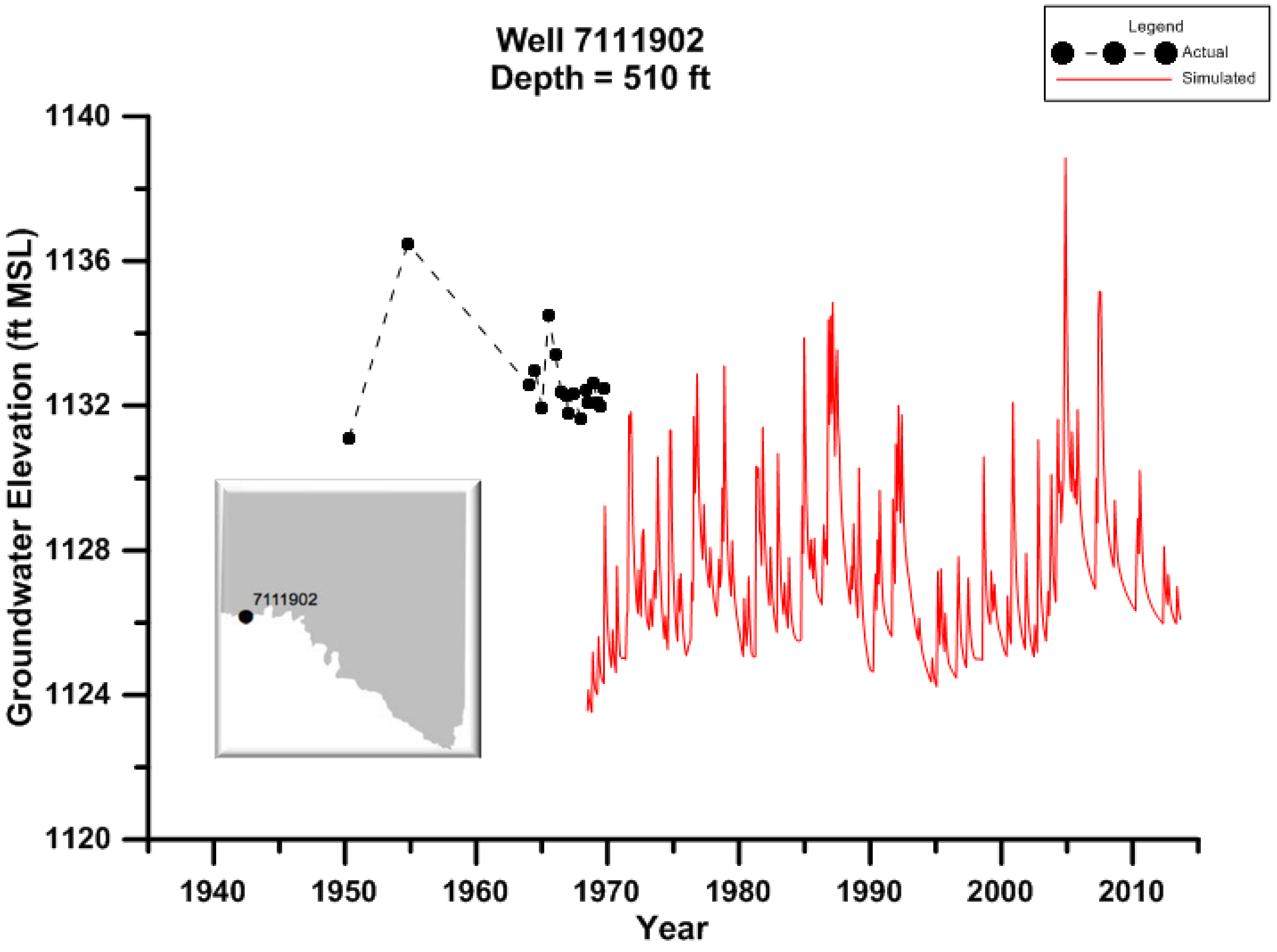

Well 7042205
Depth = 750 ft
Legend
Actual
Simulated
7042205
Groundwater Elevation (ft MSL)
1020
1010
1000
990
980
970
Year
1940
1950
1960
1970
1980
1990
2000
2010

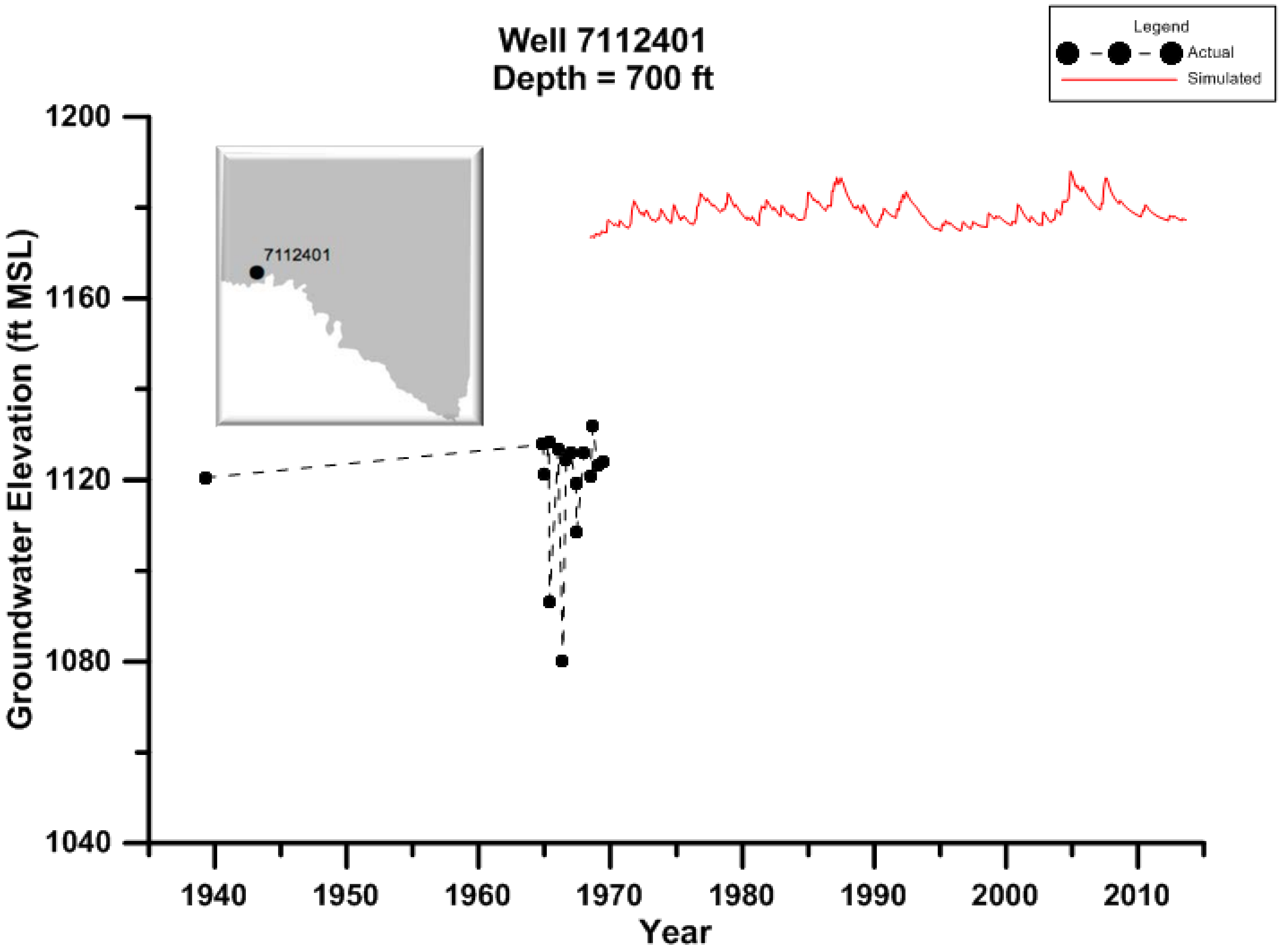

Well 7042301
Depth = 60 ft
Legend
● – ● – ● Actual
Simulated
Groundwater Elevation (ft MSL)
1040
1030
1020
1010
1000
Year
1940
1950
1960
1970
1980
1990
2000
2010
7042301

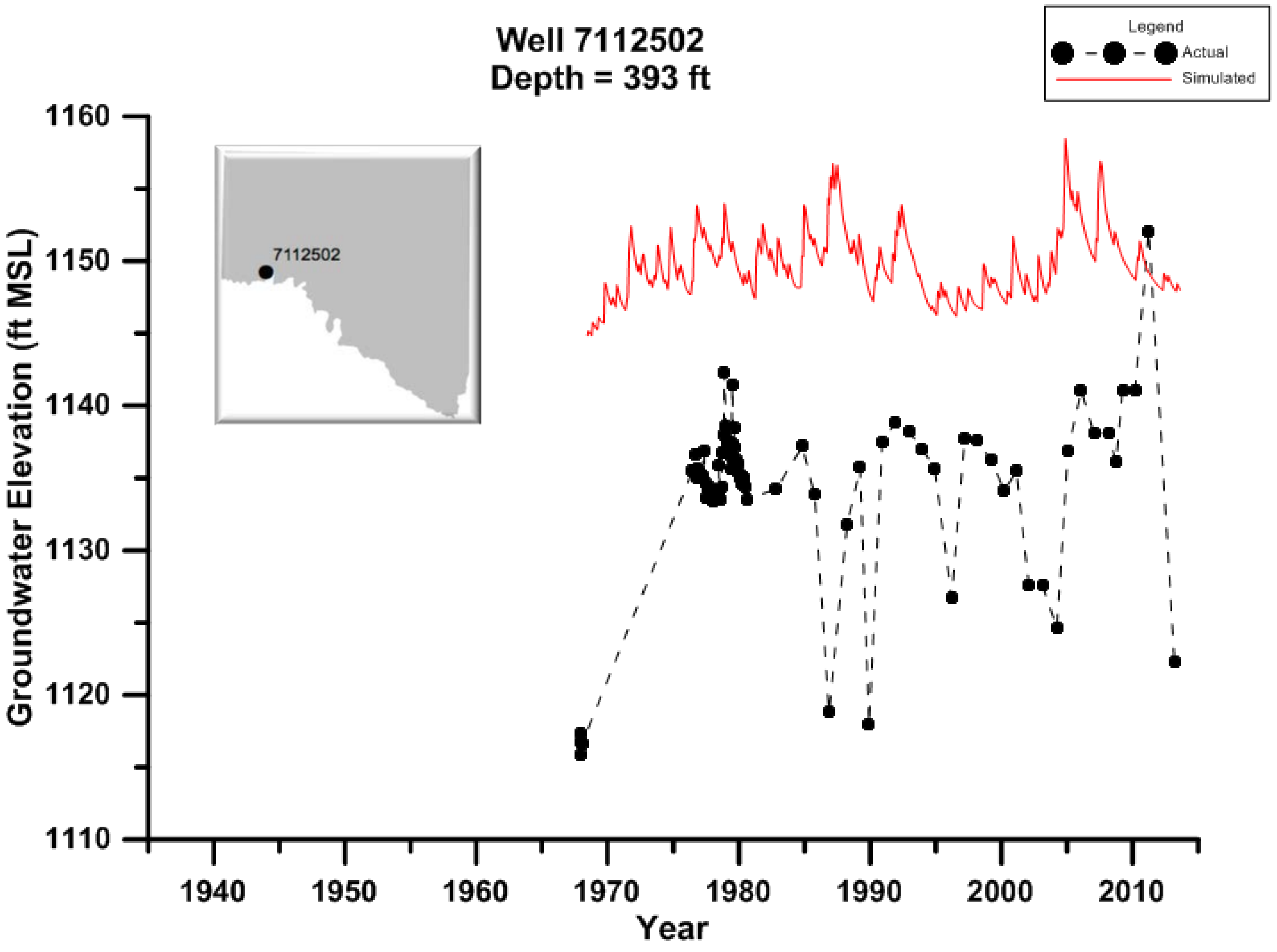

Well 7104402
Depth = 400 ft
Legend
Actual
Simulated
7104402
Groundwater Elevation (ft MSL)
1340
1320
1300
1280
1260
1240
1940
1950
1960
1970
1980
1990
2000
2010
Year

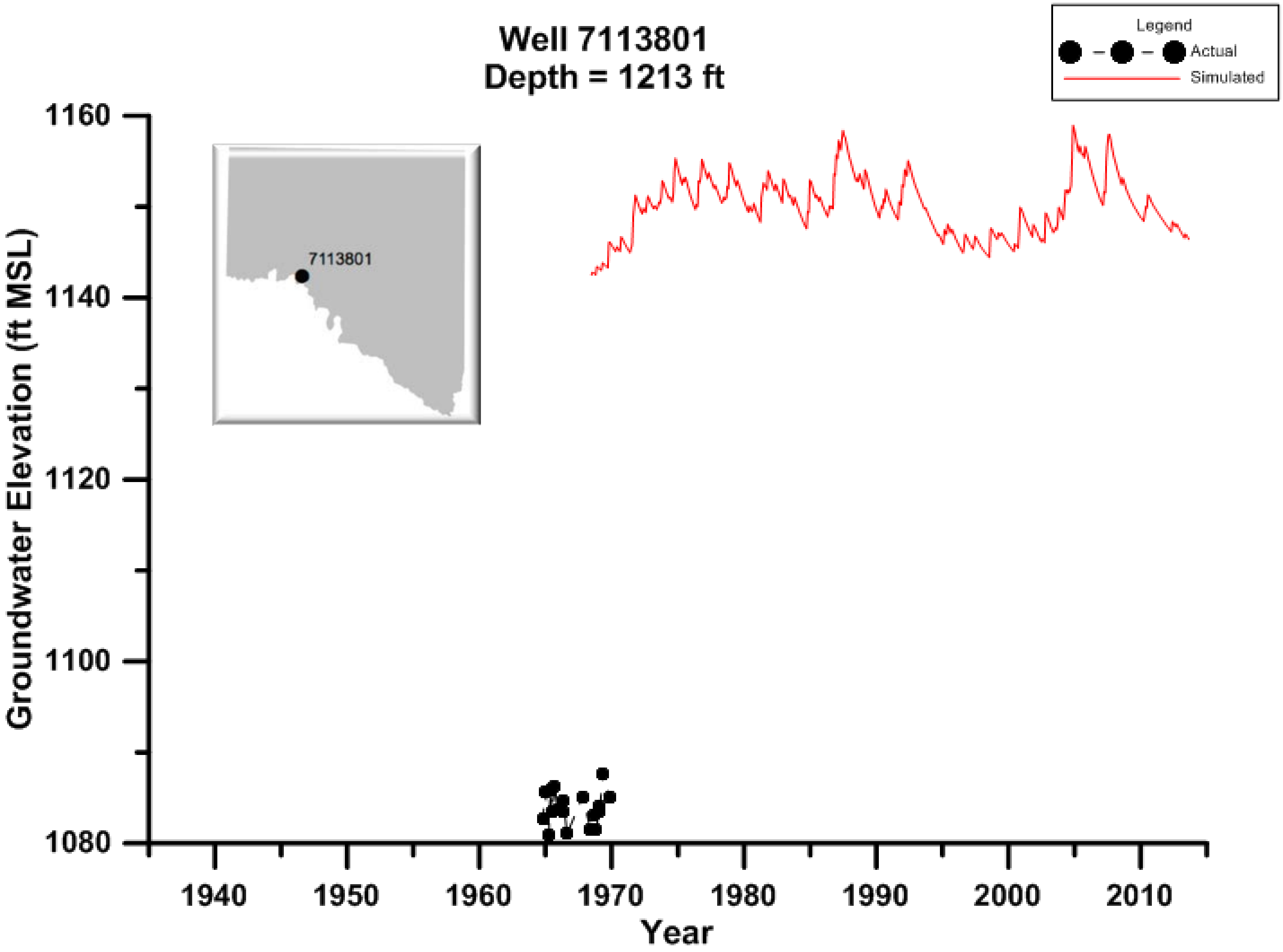

Well 7104701
Depth = 700 ft
Legend
● – ● – ● Actual
Simulated
7104701
Groundwater Elevation (ft MSL)
1320
1280
1240
1200
1160
1940
1950
1960
1970
1980
1990
2000
2010
Year

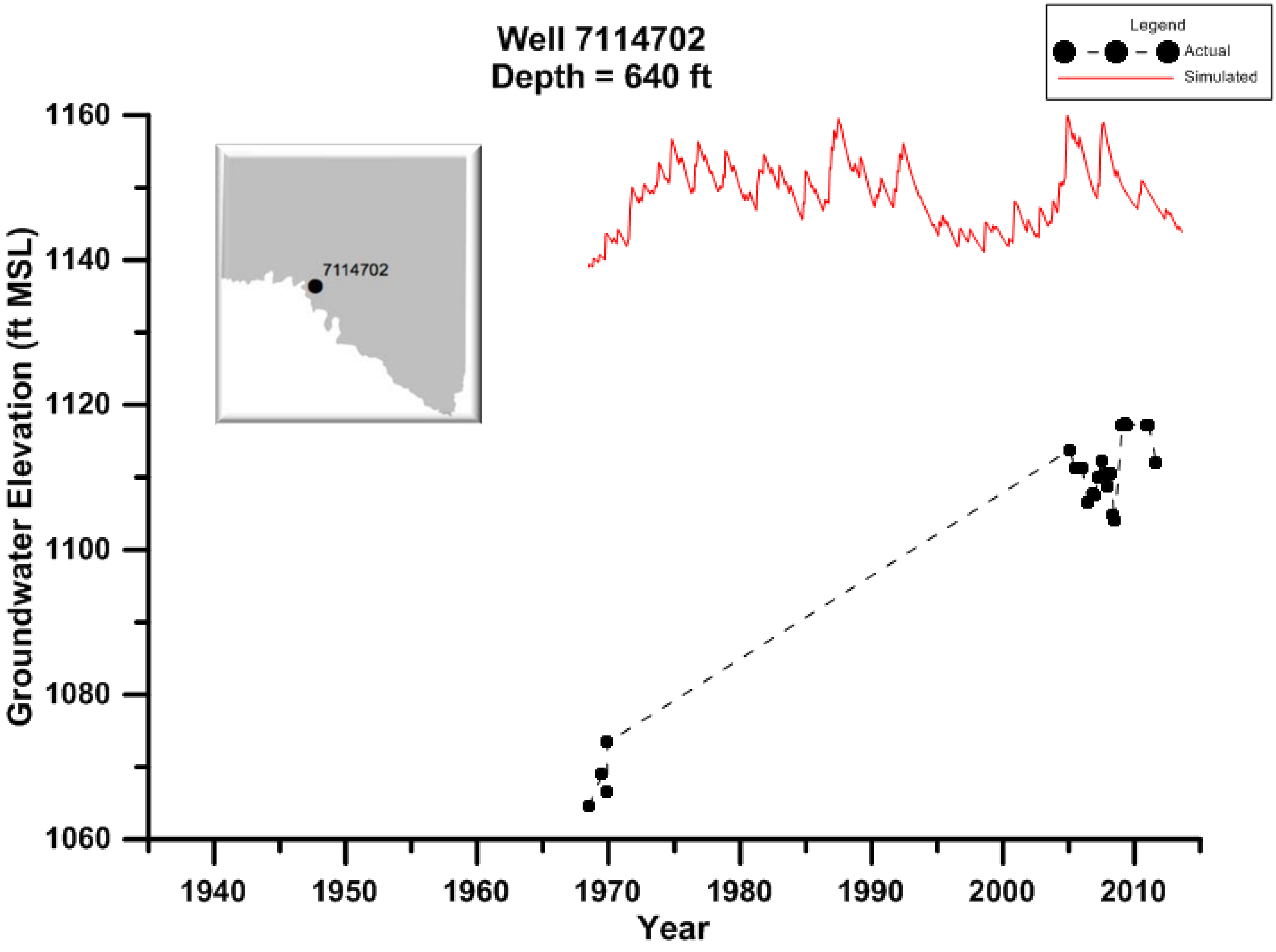

Well 7107601
Depth = 350 ft
Legend
Actual
Simulated
7107601
Groundwater Elevation (ft MSL)
1520
1500
1480
1460
1440
1420
1940
1950
1960
1970
1980
1990
2000
2010
Year

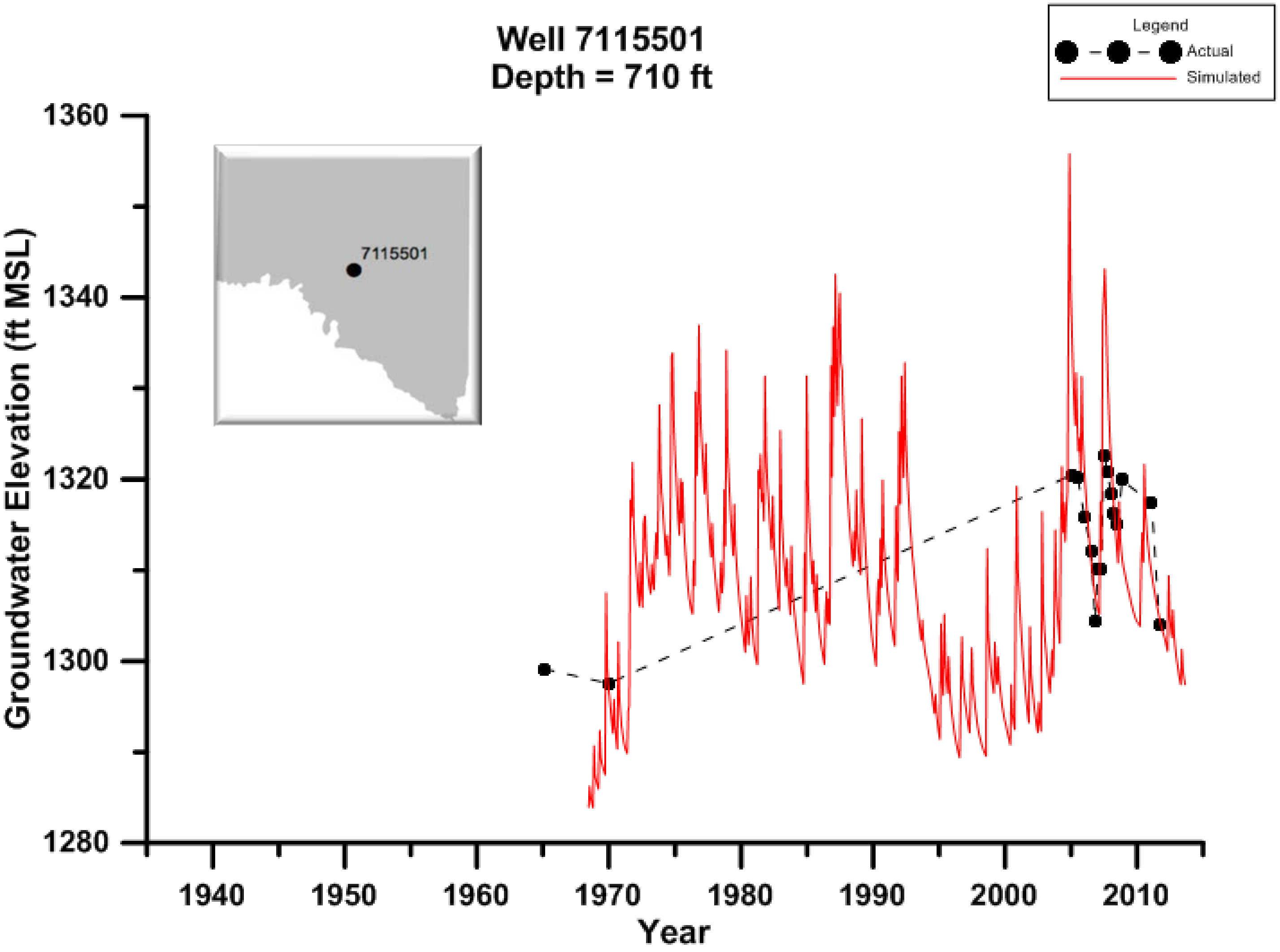

Well 7111902
Depth = 510 ft
Legend
● – ● – ● Actual
Simulated
Groundwater Elevation (ft MSL)
1140
1136
1132
1128
1124
1120
1940
1950
1960
1970
1980
1990
2000
2010
Year
7111902

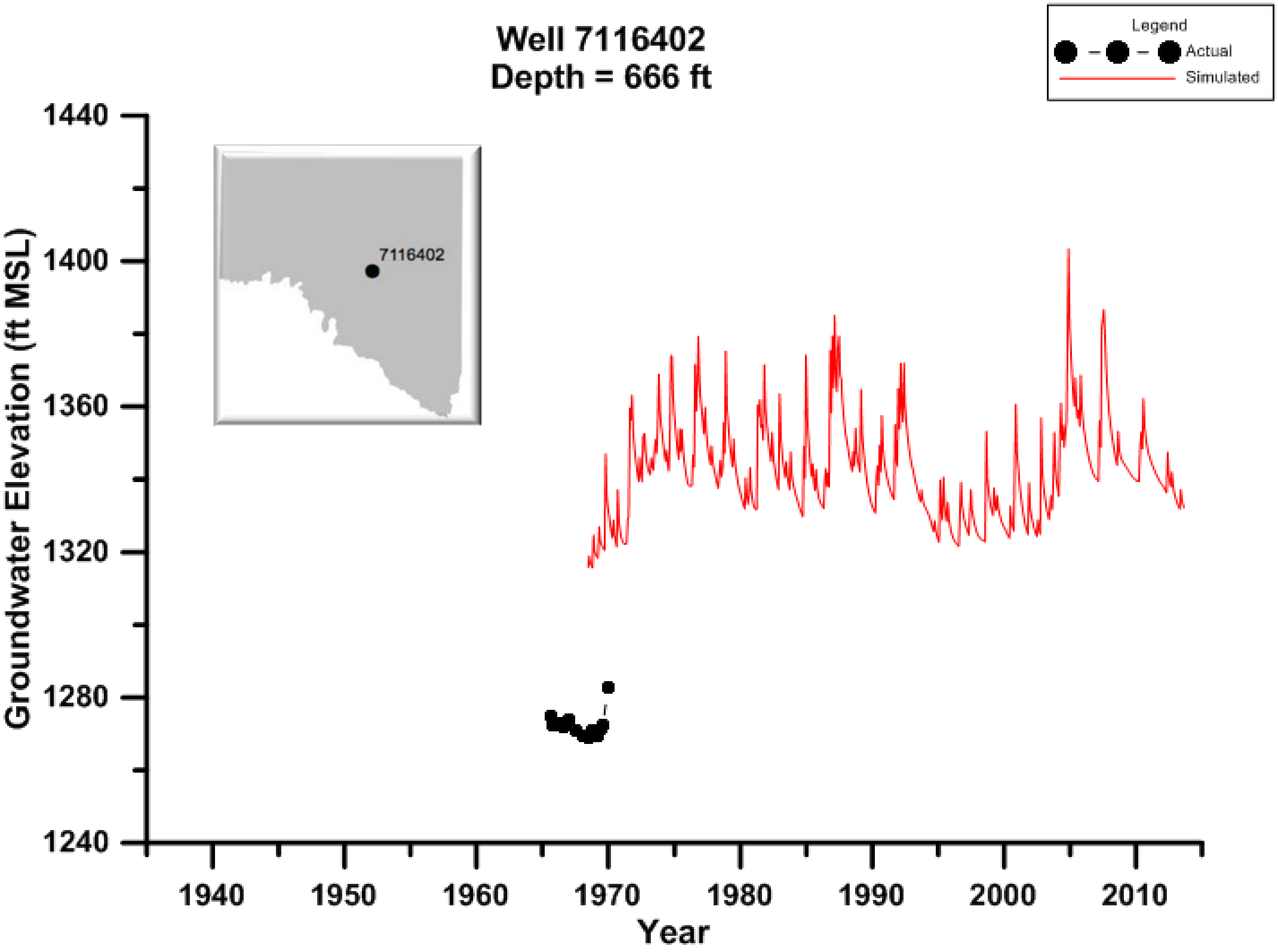

Well 7112401
Depth = 700 ft
Legend
Actual
Simulated
7112401
Groundwater Elevation (ft MSL)
1200
1160
1120
1080
1040
1940
1950
1960
1970
1980
1990
2000
2010
Year

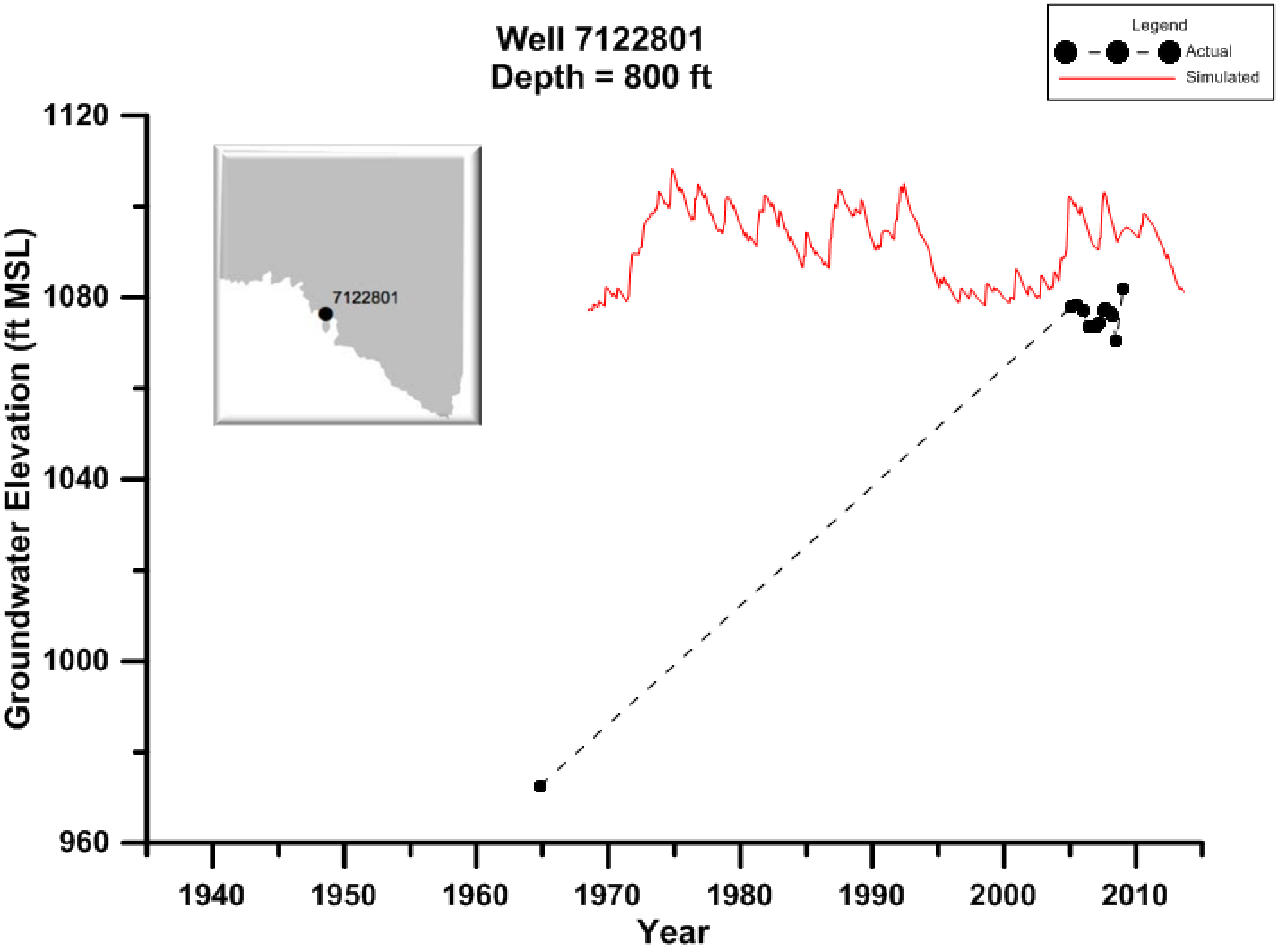

Well 7112502
Depth = 393 ft
Legend
● - ● - ● Actual
Simulated
7112502
Groundwater Elevation (ft MSL)
1160
1150
1140
1130
1120
1110
1940
1950
1960
1970
1980
1990
2000
2010
Year

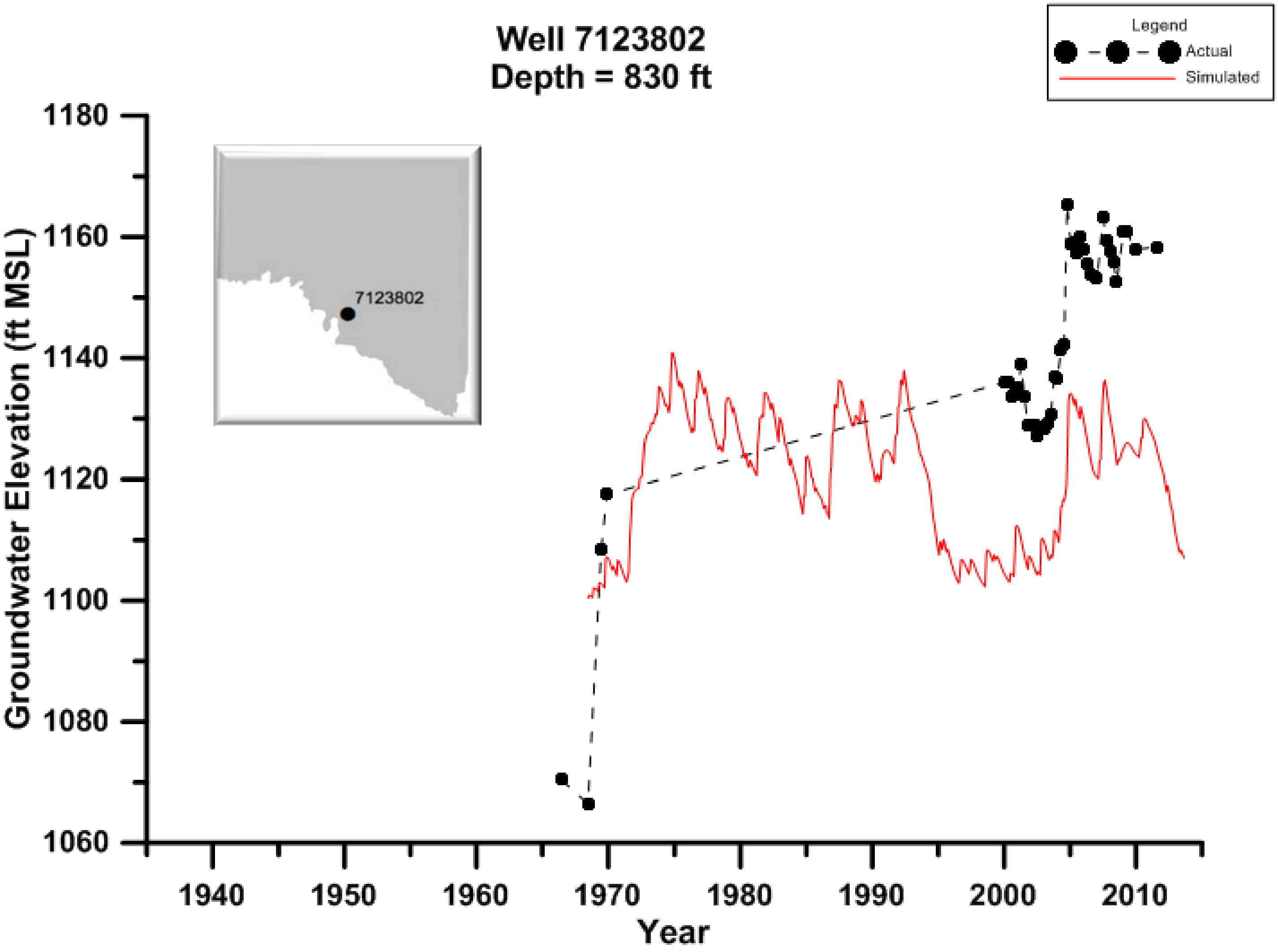

Well 7113801
Depth = 1213 ft
Legend
● – ● – ● Actual
Simulated
7113801
Groundwater Elevation (ft MSL)
1160
1140
1120
1100
1080
1940
1950
1960
1970
1980
1990
2000
2010
Year

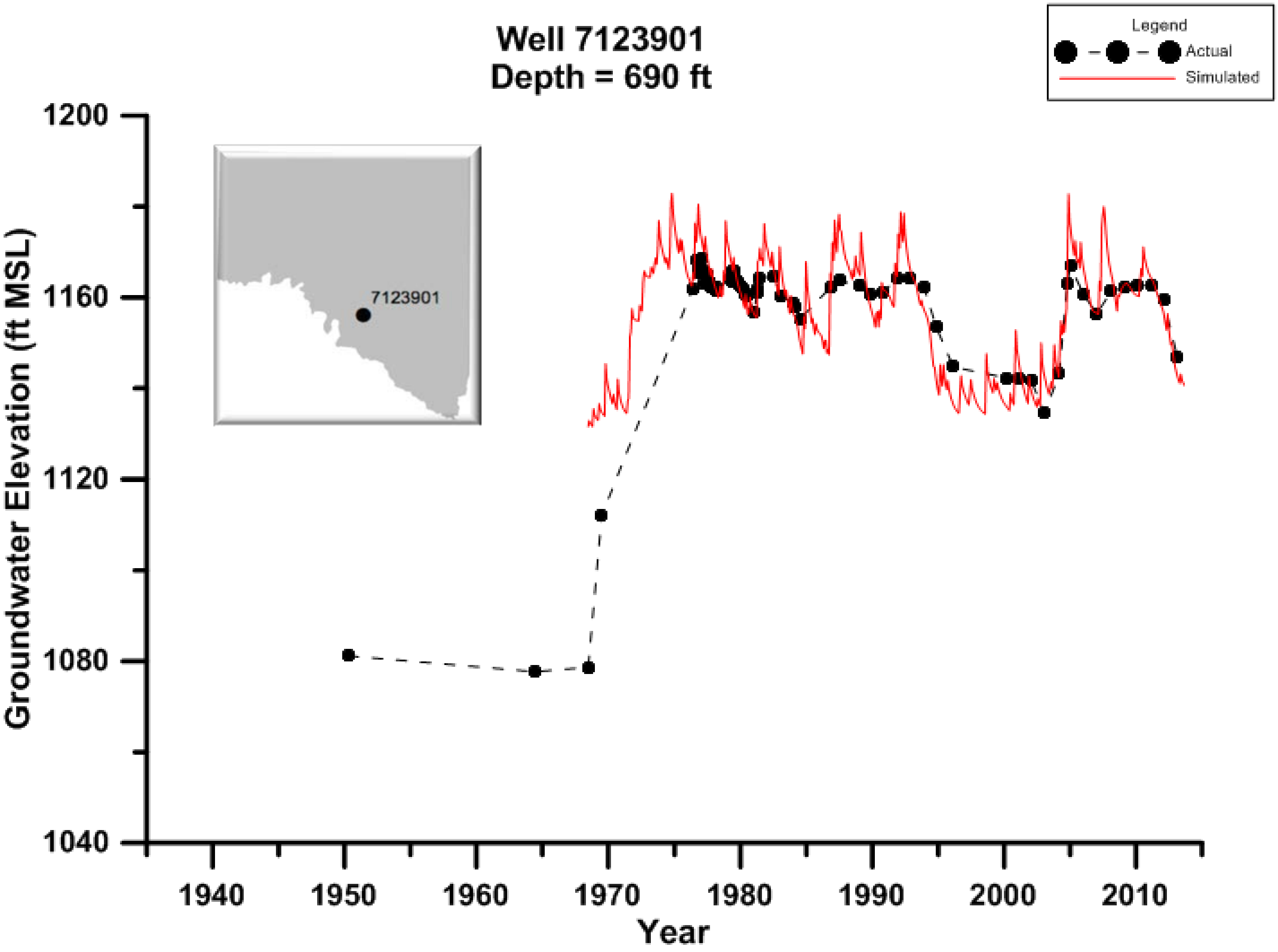

Well 7114702
Depth = 640 ft
Legend
● – ● – ● Actual
Simulated
7114702
Groundwater Elevation (ft MSL)
1160
1140
1120
1100
1080
1060
1940
1950
1960
1970
1980
1990
2000
2010
Year

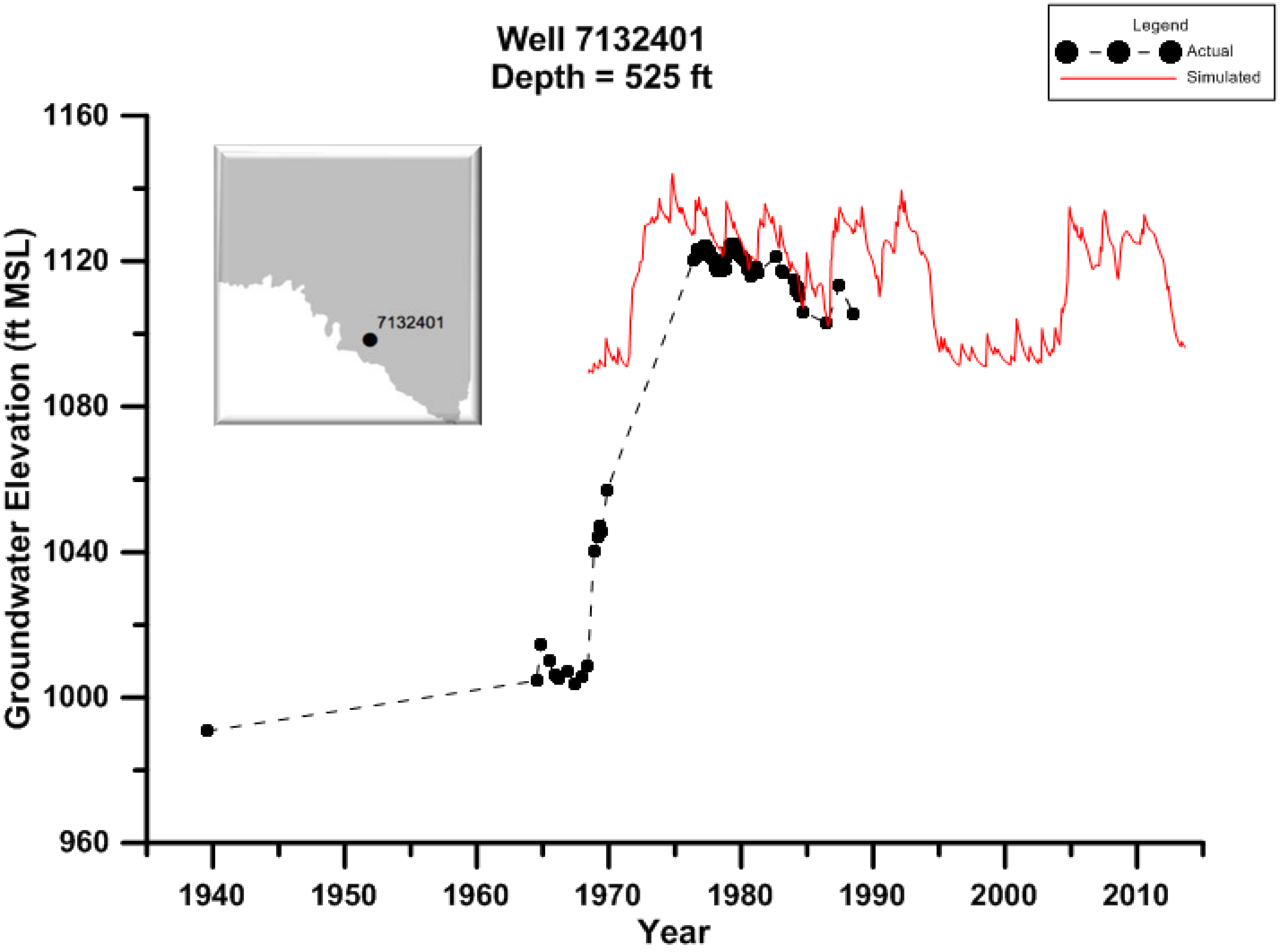

Well 7115501
Depth = 710 ft
Legend
● – ● – ● Actual
Simulated
7115501
Groundwater Elevation (ft MSL)
1360
1340
1320
1300
1280
1940
1950
1960
1970
1980
1990
2000
2010
Year

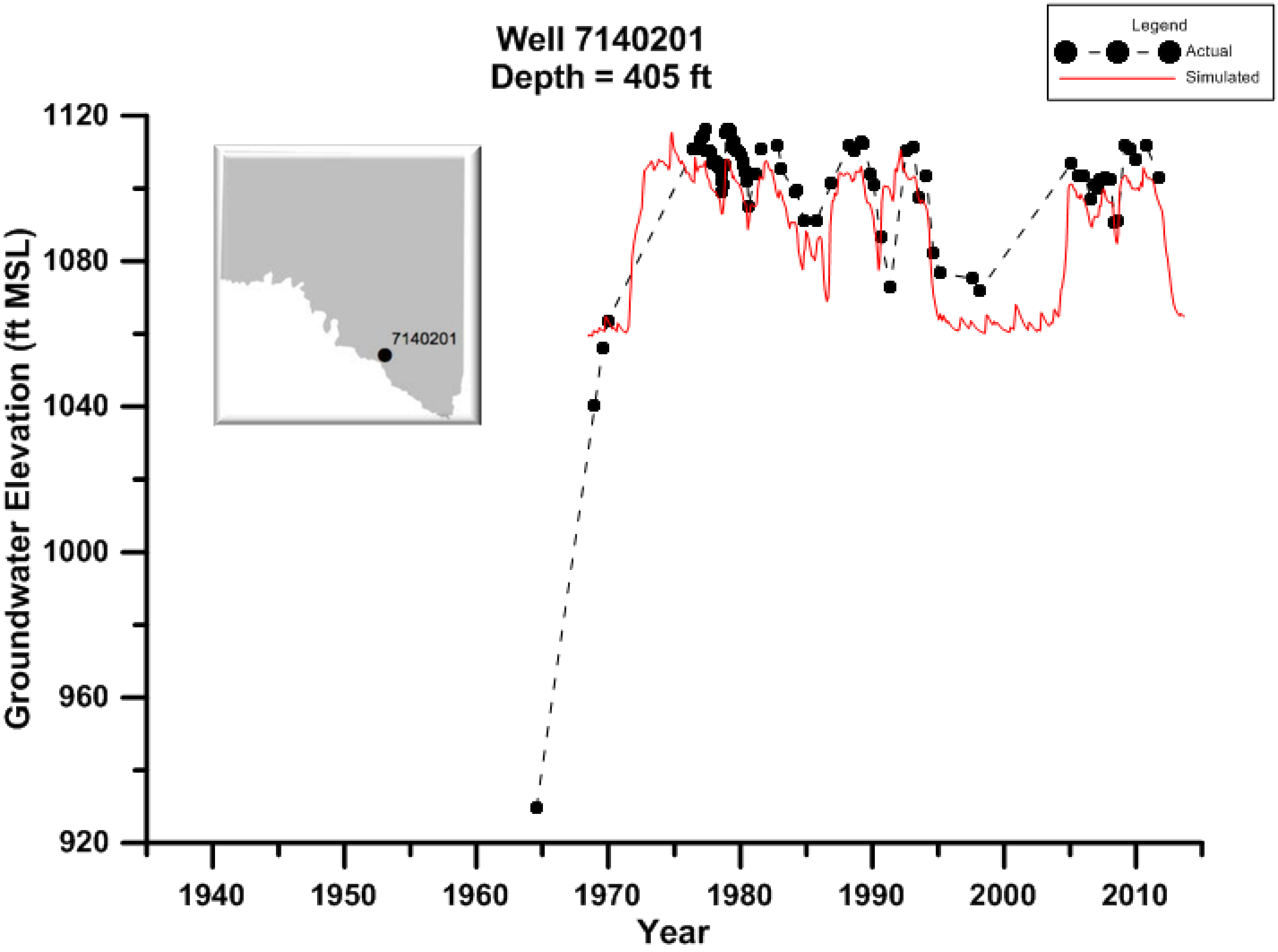

Well 7116402
Depth = 666 ft
Legend
Actual
Simulated
7116402
Groundwater Elevation (ft MSL)
1440
1400
1360
1320
1280
1240
1940
1950
1960
1970
1980
1990
2000
2010
Year

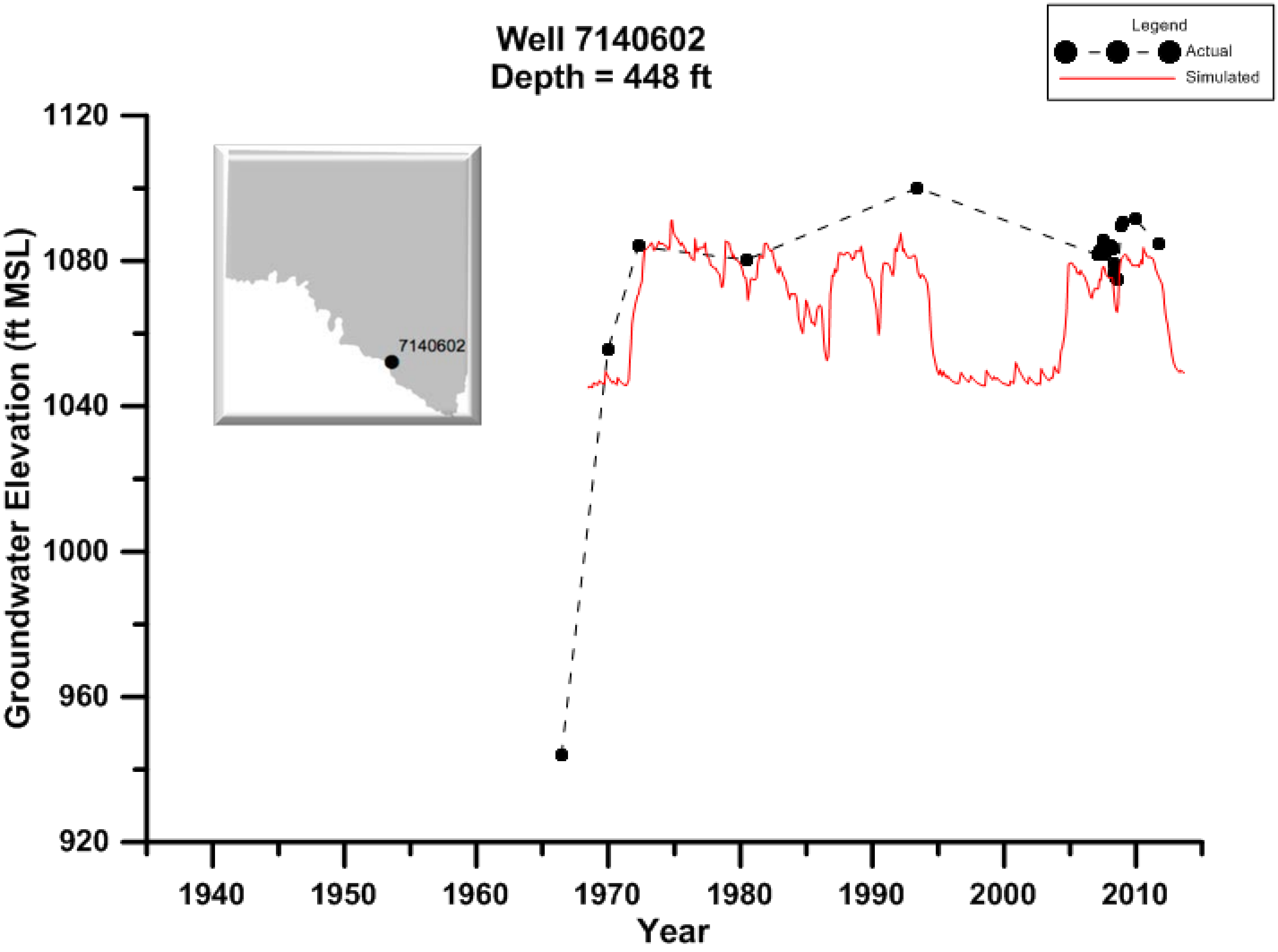

Well 7122801
Depth = 800 ft
Legend
Actual
Simulated
7122801
Groundwater Elevation (ft MSL)
1120
1080
1040
1000
960
1940
1950
1960
1970
1980
1990
2000
2010
Year


Well 7123802
Depth = 830 ft
Legend
Actual
Simulated
7123802
Groundwater Elevation (ft MSL)
1180
1160
1140
1120
1100
1080
1060
1940
1950
1960
1970
1980
1990
2000
2010
Year


Well 7123901
Depth = 690 ft
Legend
● – ● – ● Actual
Simulated
7123901
Groundwater Elevation (ft MSL)
1200
1160
1120
1080
1040
1940
1950
1960
1970
1980
1990
2000
2010
Year


Well 7132401
Depth = 525 ft
Legend
● – ● – ● Actual
Simulated
7132401
Groundwater Elevation (ft MSL)
1160
1120
1080
1040
1000
960
1940
1950
1960
1970
1980
1990
2000
2010
Year


Well 7140201
Depth = 405 ft
Legend
Actual
Simulated
7140201
Groundwater Elevation (ft MSL)
1120
1080
1040
1000
960
920
1940
1950
1960
1970
1980
1990
2000
2010
Year


Well 7140602
Depth = 448 ft
Legend
● - ● - ● Actual
Simulated
7140602
Groundwater Elevation (ft MSL)
1120
1080
1040
1000
960
920
1940
1950
1960
1970
1980
1990
2000
2010
Year