Update of the Groundwater Availability Model for the Edwards-Trinity (Plateau) and Pecos Valley Aquifers of Texas

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Geoscientist Seal

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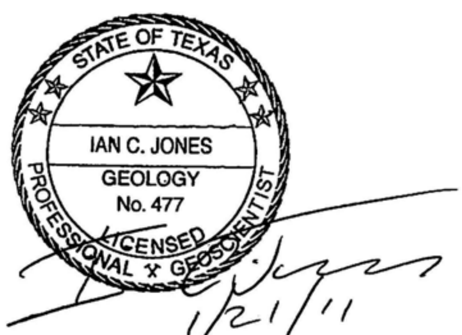

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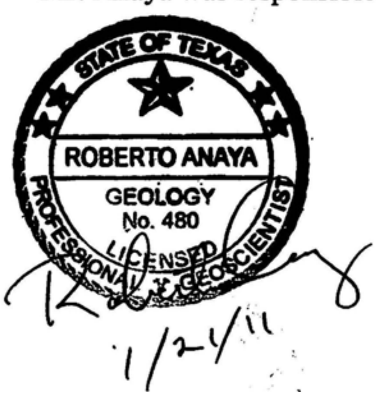

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EXECUTIVE SUMMARY

The groundwater flow model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers was updated with the objective of improving the calibration of the original model (version 1.01). This was achieved by converting the model from a two-layer to a one-layer model and by adjusting many of the input parameters including the model boundaries, model base and top elevations, recharge, hydraulic conductivity, anisotropy, and storage. The updated model was also calibrated for a longer period of time, 1930 through 2005, than the original model which was calibrated for the period 1980 through 2000. The updated model was constructed and run using a newer version of MODFLOW: MODFLOW-2000 versus MODFLOW-96 in the original model. Additionally, calibration was achieved using parameter estimation software, PEST, along with FORTRAN pre-processors.

Calibration of the updated model resulted in improved calibration statistics, with a standard deviation of 70 feet. This was an improvement from the original model which had a standard deviation of 143 feet. The updated model retained fixed transmissivities that were used to address an issue in the original model related to dry cells, especially where pumping rates were higher. Dry cells were an issue in the original version of the model over large parts of Reagan and Glasscock counties; the dry cells in the updated model are now restricted to small areas along the margins of the model area.

1.0 INTRODUCTION AND PURPOSE FOR GROUNDWATER FLOW MODEL

An update of the groundwater flow model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Anaya and Jones, 2009) was developed to improve the calibration of the model. In this updated model (version 2.01), numerous adjustments were made including:

(1) using the MODFLOW-2000 code for model implementation,

(2) converting to a single-layer model,

(3) adjusting the boundaries of the Pecos Valley Aquifer to be more consistent with the aquifer boundary revisions of 2007 (Texas Water Development Board, 2007),

(4) revising the western boundary of the model and including a general-head boundary to simulate groundwater inflow from the west,

(5) revising the base elevation of the aquifer,

(6) extending the model across the Rio Grande into Mexico,

(7) revising the distribution of many hydraulic parameters such as recharge, hydraulic conductivity, anisotropy, and storage, and

(8) changing the calibration period from 1980 through 2000 to 1930 through 2005.

2.0 MODEL OVERVIEW

The original groundwater flow model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Anaya and Jones, 2009) was constructed using MODFLOW-96 (Harbaugh and McDonald, 1996). The updated model was constructed using MODFLOW-2000 (Harbaugh and others, 2000) and used the Geometric Multigrid (GMG) solver (Wilson and Naff, 2004). The Basic, Discretization, Layer-Property Flow, Well, Drain, Recharge, General-Head Boundary, and River packages were used for the updated model. A combination of trial-and-error and parameter estimation software (PEST, Water Numerical Computing, 2004) were used to calibrate the model.

2.1 Model Packages

The MODFLOW-2000 packages used to calibrate the model and their input filenames are listed in Table 2-1. MODFLOW output files and their names are listed in Table 2-2.

Table 2-1. Summary of model input packages and filenames.

MODFLOW 2000	**Input Filename**
Basic (BAS)	etppv4.bas
Name (NAM)	etppv4.nam
Discretization (DIS)	etppv4.dis
Layer-Property Flow (LPF)	etppv4.lpf
Well (WEL)	etppv4.wel
Drain (DRN)	etppv4.drn
Recharge (RCH)	etppv4.rch
General-Head Boundary (GHB)	etppv4.ghb
River (RIV)	etppv4.riv
Output Control (OC)	etppv4.oc
Geometric Multigrid Solver (GMG)	etppv4.gmg
Starting Heads	oetppv4.hds

Table 2-2. Summary of model output files and their names.

MODFLOW-2000	**Output Filename**
Global output	etppv4.glo
List output	etppv4.lst
Cell-by-cell output data for the Layer-Property Flow Package	etppv4.cbb
Cell-by-cell output data for Well Package	etppv4.cbw
Cell-by-cell output data for Recharge Package	etppv4.crc
Head output	etppv4.hds
Drawdown output	etppv4.ddn

2.1.1 Basic Package

The Basic Package specifies the status of each cell (active or inactive), the assigned head for inactive cells (9999), and specifications of starting heads (Harbaugh and others, 2000). The Basic Package also reads the name file which contains the input and output files that will be invoked during a simulation using MODFLOW-2000 (Harbaugh and others, 2000). The model boundaries in the updated model are slightly different than the original model by Anaya and Jones (2009), especially for the footprint of the Pecos Valley Aquifer in Texas and New Mexico (Figure 2-1). Additionally, the updated model now extends into Mexico along the southern extent instead of ending at the Rio Grande. Figure 2-2 shows the starting heads used in the simulation.

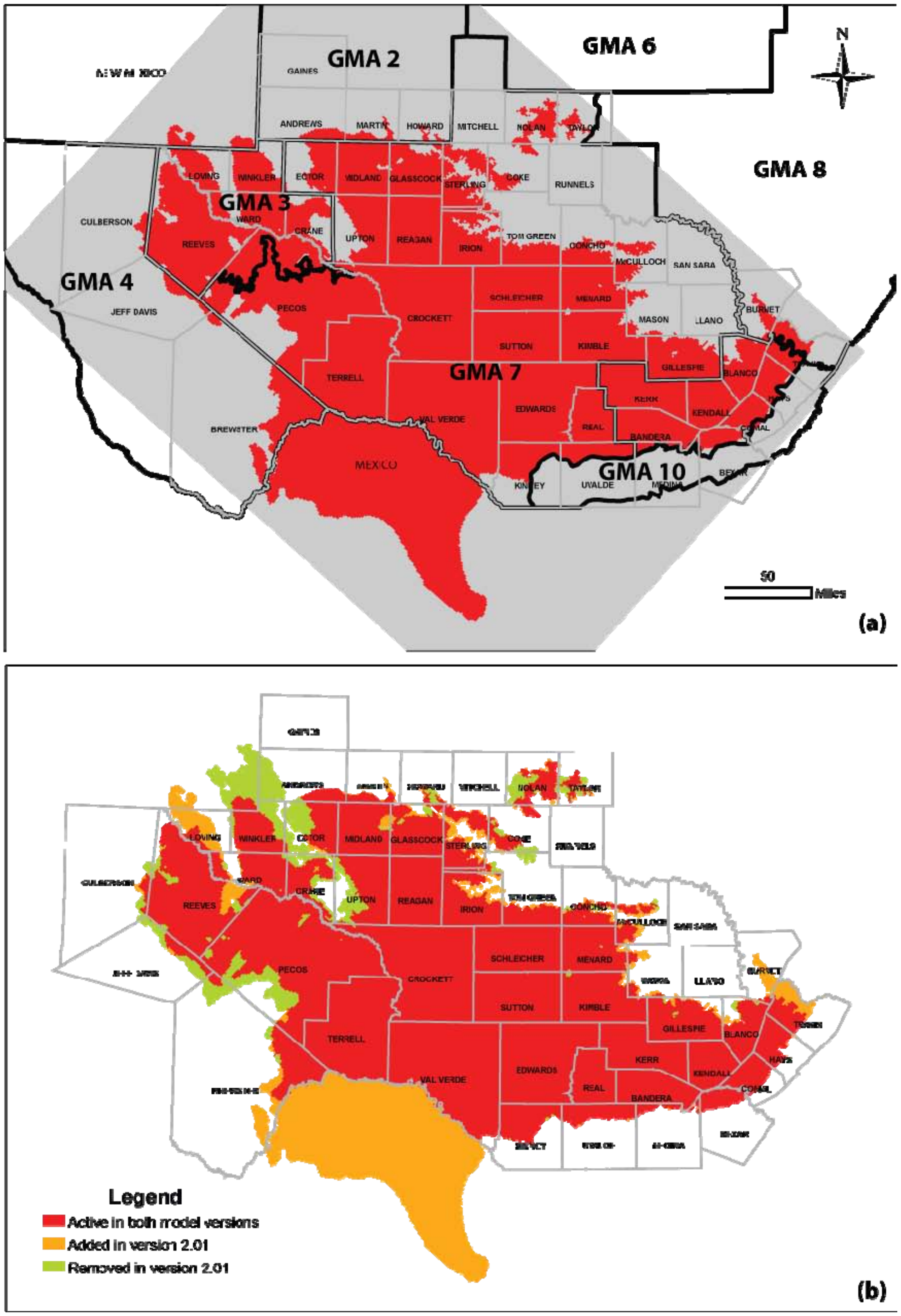


Figure 2-1. (a) Active model cells and (b) comparison of the extents of the model domains in original and updated models. The model mostly coincides with Groundwater Management Areas (GMA) 3 and 7.

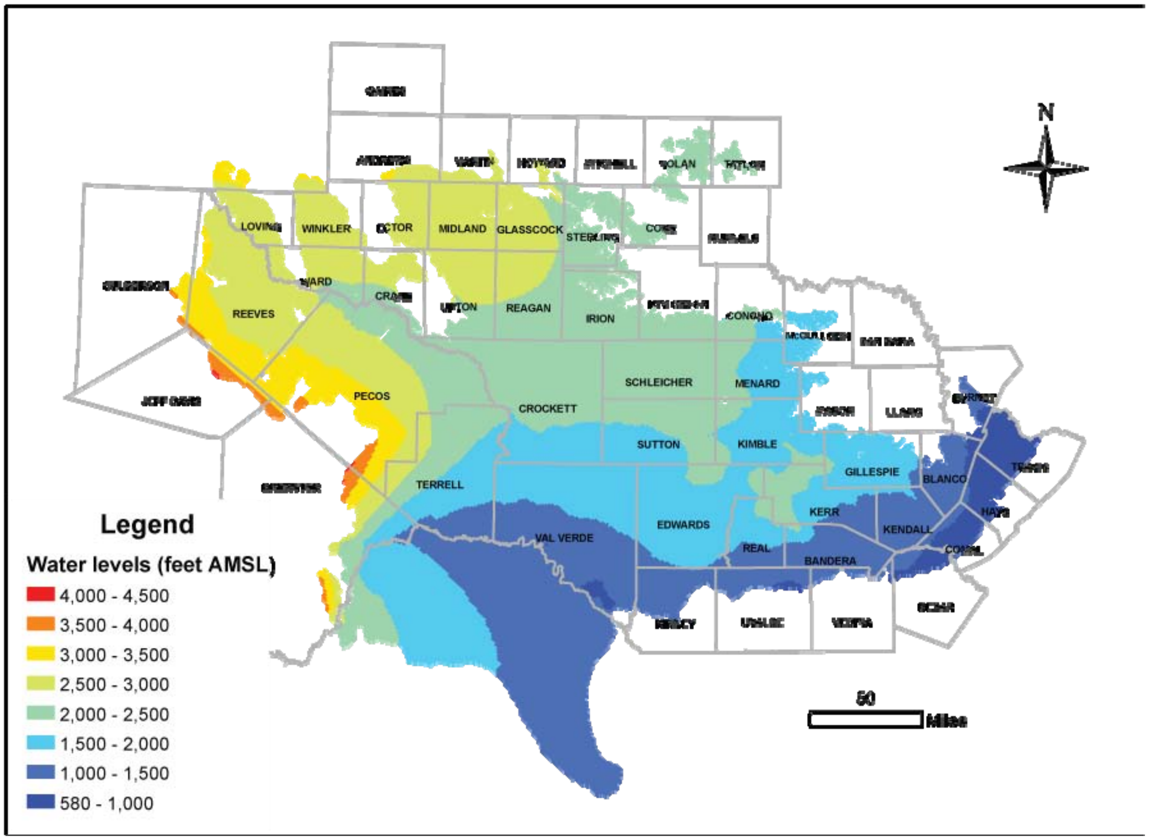


Figure 2-2. Starting heads within the model domain for the groundwater flow model for the Pecos Valley and Edwards-Trinity (Plateau) aquifers.

2.1.2 Discretization Package

The Discretization Package specifies the spatial and temporal discretization of the model (Harbaugh and others, 2000). The model consists of a single layer with 300 rows and 400 columns. The cell length is 5,280 feet and the cell width is 5,280 feet (one mile by one mile). The time period and distance units for the model are days and feet, respectively. The combined steady-state/transient model has 76 stress periods. The first stress period is specified as steady-state and was used to provide a stable head distribution at the start of the transient calibration period, and is not intended to represent true “pre-development” conditions. The following 75 stress periods are transient, each with a length of 365 days (1 year). The stress periods represent 1930 through 2005.

The Discretization Package also contains model top and bottom data. The aquifer top is defined as land surface (Figure 2-3). The aquifer base, the combined base of the Pecos Valley and Edwards-Trinity (Plateau) aquifers, generally dips towards the Rio Grande in the south and the Balcones Fault Zone to the east (Figure 2-4). The base of the Pecos Valley Aquifer is characterized by two basins, the Pecos Trough centered in Reeves County and the Monument Draw Trough extending through Winkler, Ward and Pecos counties.

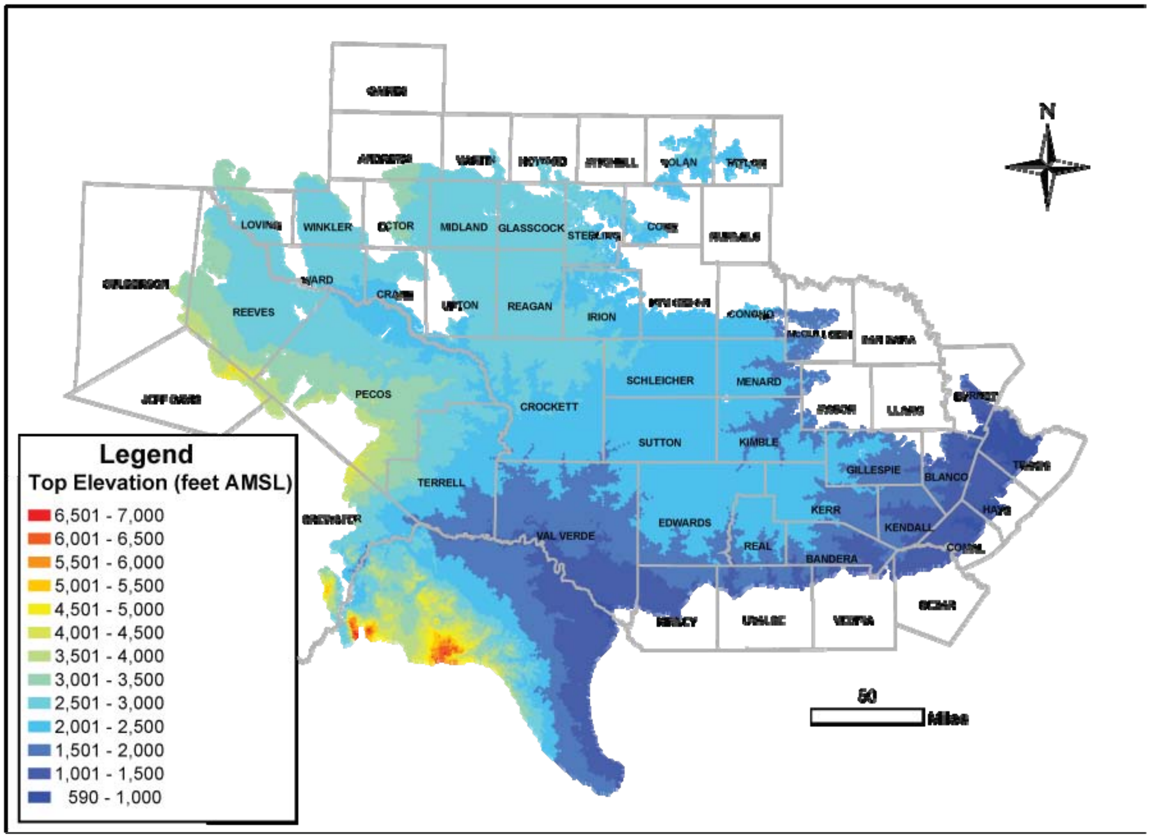


Figure 2-3. The elevation of the aquifer top, expressed in feet.

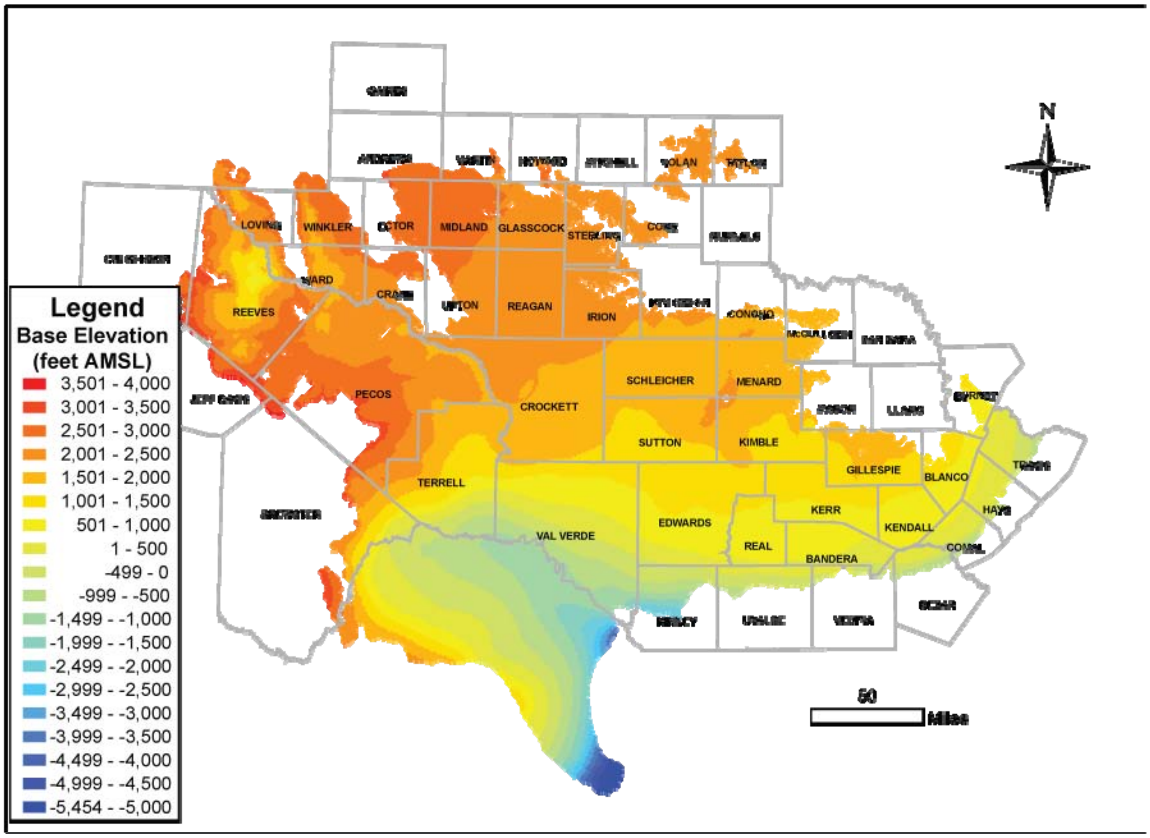


Figure 2-4. The elevation of the aquifer bottom, expressed in feet Mean Sea Level.

2.1.3 Layer-Property Flow Package

The Layer-Property Flow Package specifies the layer type, the method of calculating interblock transmissivity, hydraulic conductivity (in both the x- and y-directions) and the storativity values for each cell in the model domain (Harbaugh and others, 2000).

LAYTYP, the variable that specifies the layer type, was set equal to zero. This assumes confined aquifer conditions and constant transmissivity exist throughout the simulation. Hydraulic conductivity is read and multiplied by the saturated thickness at the beginning of the simulation to estimate aquifer transmissivity. As a result of this specification, the only storage value required is specific storage. By assuming constant transmissivity conditions (LAYTYP = 0), active cells are unable to go dry during the simulation, even if the water level falls below the base of the aquifer.

The variable LAYAVG was set equal to zero, that is interblock transmissivity is based on a harmonic mean and horizontal anisotropy was assigned on a cell-to-cell basis by setting the variable CHANI equal to -1.

In order to facilitate calibration, the Layer-Property Flow Package was created using a pre-processor program (*lpf.exe*) written in FORTRAN. The *lpf.exe* pre-processor reads a file of aquifer parameter zone numbers (*kszone2.dat*) and three database files−one for hydraulic conductivity and specific storage (*ksdb.dat*), one for 1930 (initial) hydraulic heads, and one for aquifer base elevation (*bot.dat*)−and writes a new Layer-Property Flow data file that can be read by MODFLOW-2000.

The hydraulic conductivity file (*ksdb.dat*) contains estimates for hydraulic conductivity in the x- and y-directions. The hydraulic conductivity in the x-direction is used for the MODFLOW-2000 variable HK (hydraulic conductivity in the x-direction). The hydraulic conductivity in the y-direction is used in the pre-processor to calculate the MODFLOW-2000 variable HANI (ratio of hydraulic conductivity along columns to hydraulic conductivity along rows). Although the Layer Property Flow package pre-processor generates values for vertical hydraulic conductivity and the MODFLOW-2000 input file requires specification of the vertical hydraulic conductivity, these values have no meaning in a one-layer model. The pre-processor program also uses the aquifer parameter zonation file (*kszone2.dat*) with the specific storage data from the database file (*ksdb.dat*) to write specific storage estimates for each cell.

The hydraulic conductivity zonation used in the updated model is far more complex than the generalized zones used in the original model (Anaya and Jones, 2009). The zones are based on geologic facies of the Pecos Valley and Edwards-Trinity (Plateau) aquifers. In the original model, there were five zones spread over two layers with hydraulic conductivity values ranging from 2.5 to 15 feet per day. In the updated model, there are a total of thirty-eight zones with hydraulic conductivity values ranging from 0.9 to 80 feet per day (Figure 2-5). The hydraulic conductivity values shown in Figure 2-5 represent hydraulic conductivity along rows (K_x). The aquifers are assumed to be anisotropic, consequently, hydraulic conductivity values along columns (K_y) are different and are determined by anisotropy values shown in Figure 2-6. This anisotropic assumption differs from the original model where hydraulic conductivity was assumed to be isotropic, in other words equal in the x- and y-directions.

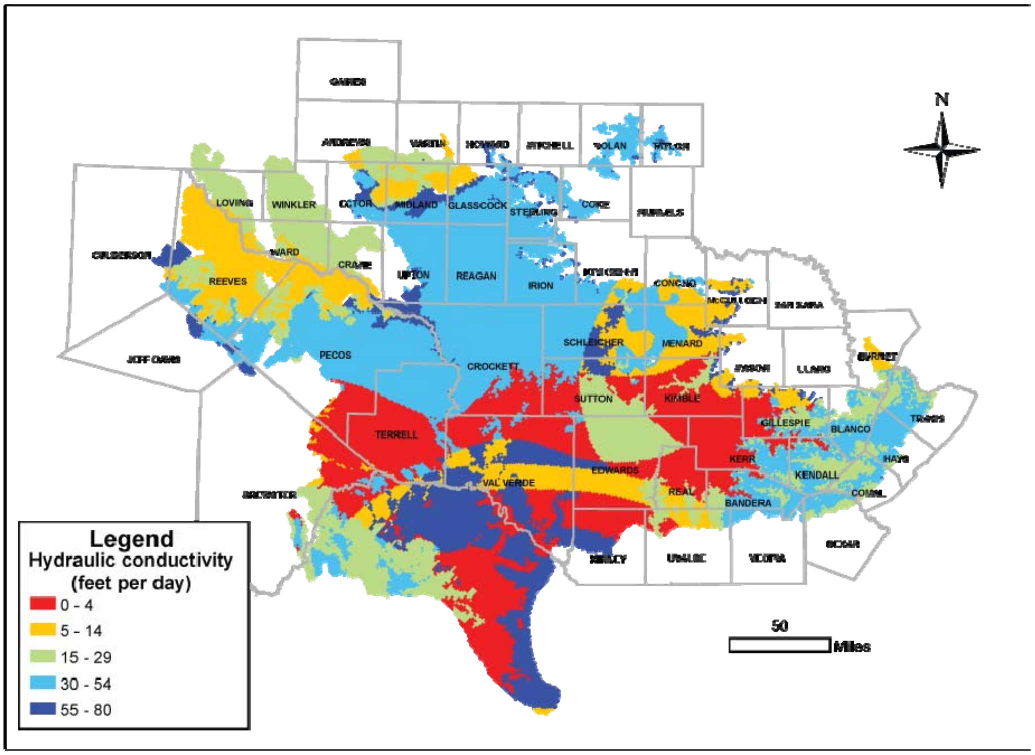


Figure 2-5. Map showing the hydraulic conductivity reported in feet per day along rows (K_x) in the model domain. Hydraulic conductivity along columns is determined by the horizontal anisotropy.

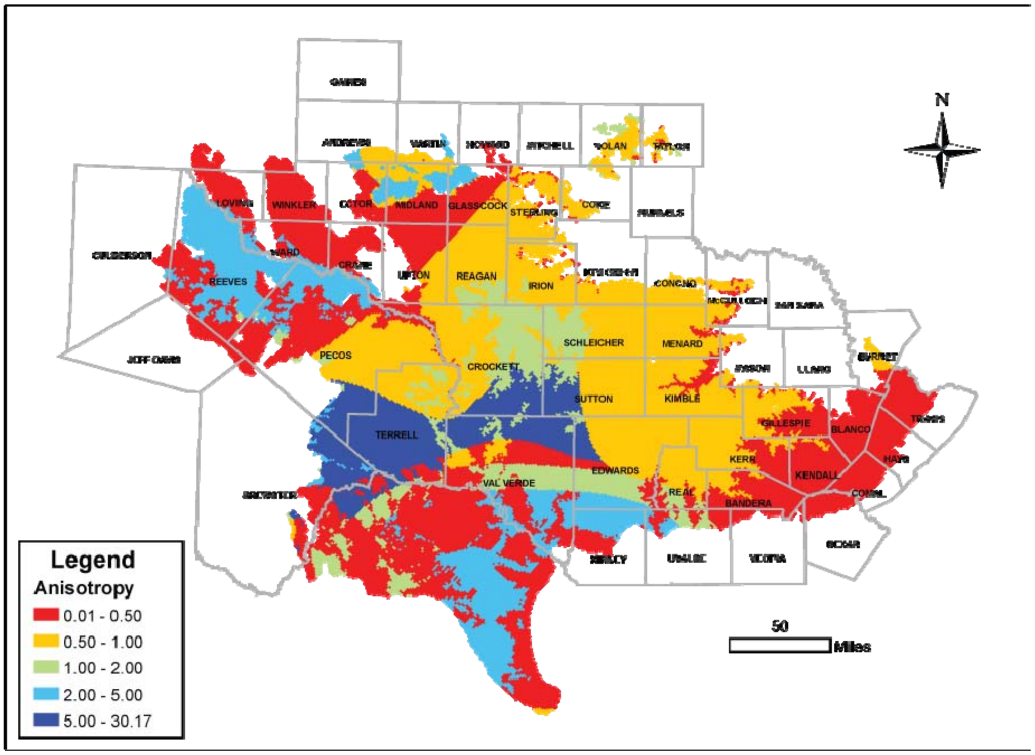


Figure 2-6. Horizontal anisotropy, the ratio of hydraulic conductivity along columns (K_y) to hydraulic conductivity along rows (K_x).

2.1.4 Well Package

The Well Package was used to simulate pumping from the respective aquifers (Harbaugh and others, 2000). Figure 2-7 shows the spatial distribution of pumpage across the model domain in 1964 and 2005. Pumping in the model area, mostly for irrigation, started in the 1930s, reached a maximum around 1964 before declining through the late 1960s, 1970s, and 1980s (Figure 2-8). In the model, it was assumed that pumpage in the New Mexico and Mexico portions of the model area is not significant. The highest pumping rates occur mostly in Reeves, Pecos, Glasscock, Reagan, and Kinney counties (Figure 2-7).

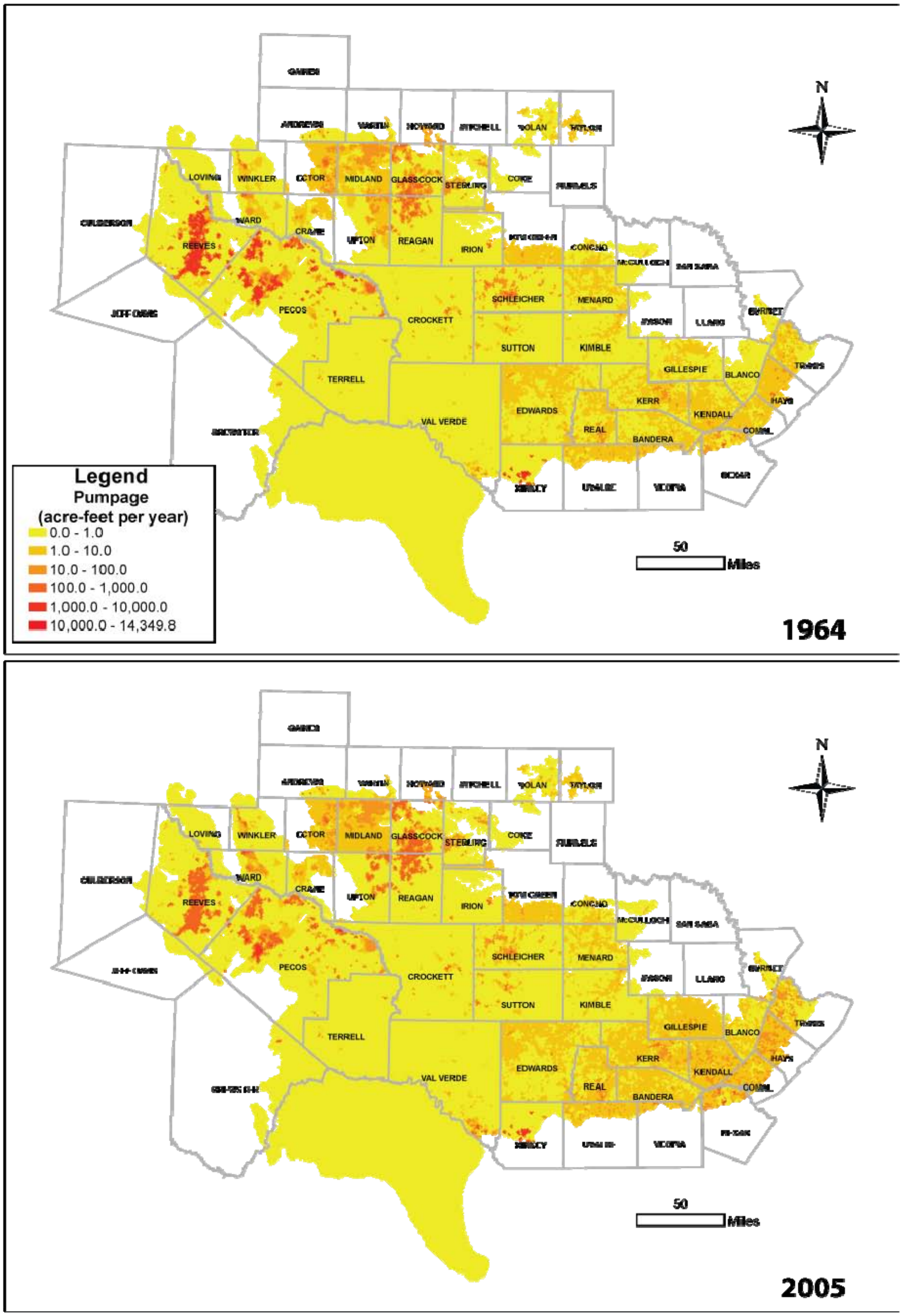


Figure 2-7. The distribution of pumpage in the years 1964 and 2005.

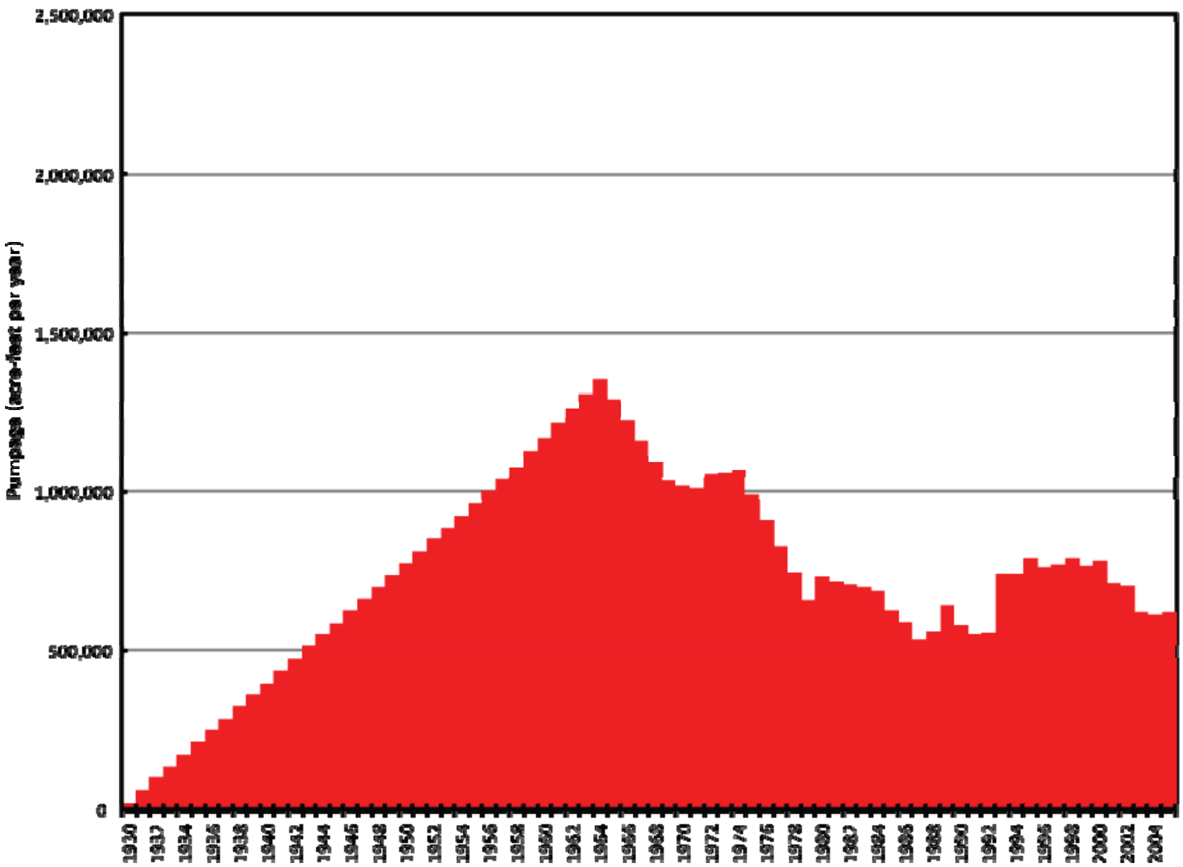


Figure 2-8. Total pumpage from the model domain for the period 1930 through 2005.

In order to facilitate spatial and temporal distribution of pumpage, we used FORTRAN pre-processors, *bigcototal.exe*, *excototal.exe*, and *combinewell.exe*. The pre-processor *bigcototal.exe* calculates and distributes non-exempt pumpage, the high pumpage users such as for irrigation, municipal, and industrial users. Non-exempt pumpage is distributed using input files *bigfac.dat* and *newbigwells.dat* which contain the distribution factors, and pumpage from high pumpage model cells. The results generated are written to a MODFLOW well file, *bigtran.wel*, containing non-exempt pumpage. The pre-processor, *excototal.exe*, is used to distribute the exempt pumpage using exempt pumpage data, *exemptwells.dat*, and pumpage factors, *exemptfactors.dat* and *excofac.dat*. The results are written to a MODFLOW well file, *tranexempt.wel*. The pre-processor, *combinewell.exe*, combines the exempt and non-exempt pumpage well files (see Figure A-1 in Appendix A).

2.1.5 Drain Package

The Drain Package was used to simulate discharge from the numerous springs that occur throughout the model domain and especially along the edge of the Edwards Group outcrop (Figure 2-9). Drain conductance was varied during model calibration. The conductance values in the new calibrated model vary from about 2.3×10^6 to 6.6×10^6 square feet per day.

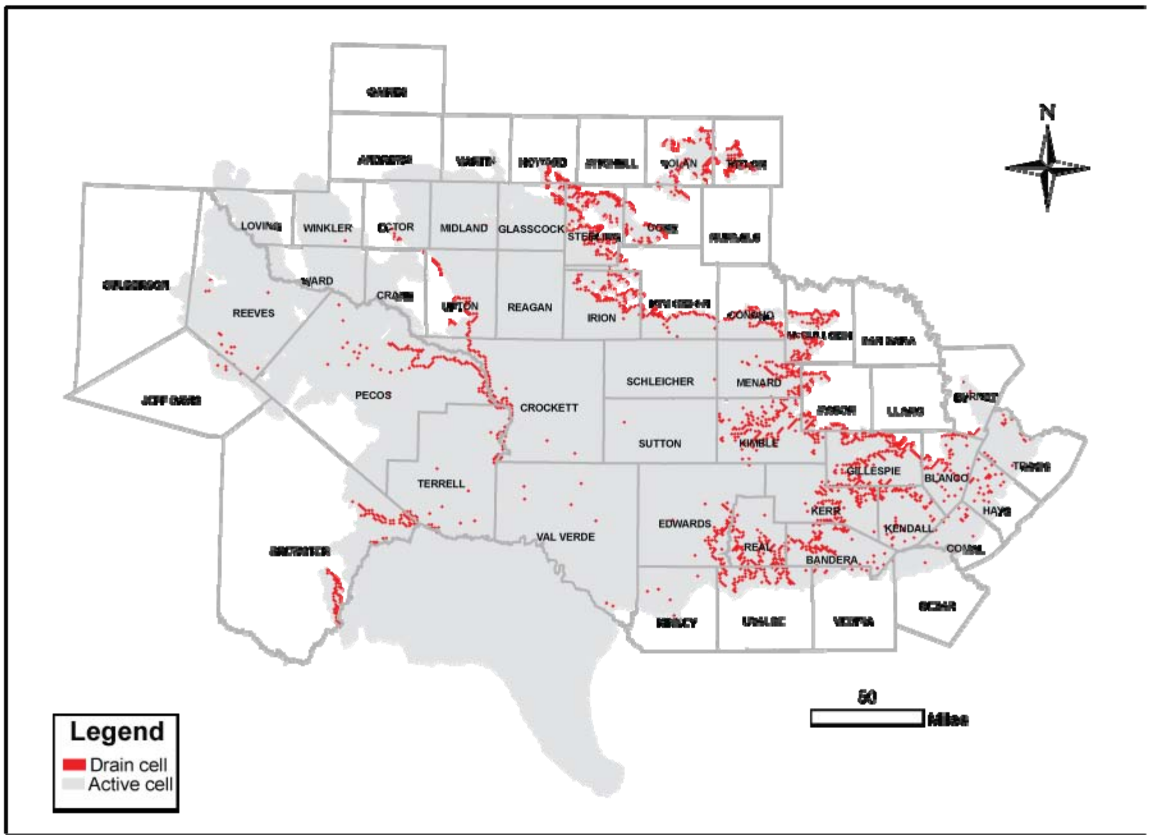


Figure 2-9. Drain cells in the model domain.

2.1.6 Recharge Package

The Recharge Package is used to simulate annual variations of recharge to the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Harbaugh and others, 2000). The 9 recharge zones in the updated groundwater flow model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers roughly correlate to stratigraphic facies of the surface geology within the model domain (Figure 2-10). Recharge is spatially distributed using a FORTRAN pre-processor *rech.exe*. The recharge pre-processor requires the following input files *rechzone2.dat*, *rechparam.dat*, *cellavg.dat*, and *annprecip.dat*. The input file *rechzone2.dat* is a matrix file containing the recharge zones in the model grid. The input file *rechparam.dat* contains the recharge factors for each recharge zone along with the overall dampening factor, and decadal dampening factors. The overall and decadal dampening factors controls the interannual and decadal variation of recharge, respectively. Dampening factors vary can be varied between 0 and 1. A dampening factor of 0 indicates that recharge varies directly with rainfall, as a fixed fraction of annual rainfall. On the other hand, a dampening factor of 1 means that recharge is fixed as an average value. The file *cellavg.dat* is a matrix file containing average annual precipitation across the model domain. The file *annprecip.dat* contains annual precipitation and a precipitation factor for each stress period (Table 2-3). The recharge pre-processor: (1) reads the input files, (2) converts average annual precipitation units from inches per year to feet per day, (3) calculates rain (Equation 2.1), (4) calculates recharge (Equation 2.2), and (5) writes a MODFLOW recharge package file.

$$\text{Rain} = \text{AAP} \times (\text{pfac} + ((1 - \text{pfac}) \times \text{damp})) \tag{2.1}$$

where:

Rain = Annual precipitation for specific stress period
AAP = Average annual precipitation
pfac = Precipitation factor
damp = Overall dampening factor (0.580738).

$$\text{Recharge} = \text{Rain} \times \text{rfac} \times \text{df} \tag{2.2}$$

where:

Recharge = Recharge expressed in feet per day
Rain = Annual precipitation for specific stress period
rfac = Recharge factor
df = Decadal dampening factor (1.0 for all decades).

The precipitation factor indicates annual precipitation relative to average annual precipitation. The recharge factor indicates the fraction of annual precipitation that recharges the aquifer. Figure 2-11 presents an example of the results for the year 1930.

Independent of this study, an investigation by the Southwest Research Institute estimated recharge in some of the counties in the model area (Green and Bertetti, 2010). The results of the Southwest Research Institute study are similar to those in the model simulation (Table 2-4).

Table 2-3. Annual precipitation and the precipitation factor for each stress period in the model (*annprecip.dat*).

Year	Annual Precipitation (inches)	Precipitation Factor	Recharge (inches)
1930	17.51	0.98	0.60
1931	19.80	1.10	0.67
1932	24.82	1.38	0.84
1933	13.06	0.73	0.44
1934	13.15	0.73	0.45
1935	21.94	1.22	0.75
1936	19.31	1.08	0.66
1937	16.72	0.93	0.57
1938	15.73	0.88	0.53
1939	15.50	0.86	0.53
1940	19.95	1.11	0.68
1941	28.84	1.61	0.98
1942	18.17	1.01	0.62
1943	14.97	0.83	0.51
1944	21.39	1.19	0.73
1945	16.83	0.94	0.57
1946	18.30	1.02	0.62
1947	15.16	0.84	0.52
1948	13.71	0.76	0.47
1949	22.46	1.25	0.76
1950	15.73	0.88	0.53
1951	11.21	0.62	0.38
1952	12.81	0.71	0.44
1953	12.18	0.68	0.41
1954	11.69	0.65	0.40
1955	14.24	0.79	0.48
1956	8.18	0.46	0.28
1957	22.70	1.26	0.77
1958	24.35	1.36	0.83
1959	19.17	1.07	0.65
1960	19.02	1.06	0.65
1961	16.94	0.94	0.58
1962	14.05	0.78	0.48
1963	13.75	0.77	0.47
1964	15.54	0.87	0.53
1965	17.00	0.95	0.58

Table 2-3 (continued).

Year	Annual Precipitation (inches)	Precipitation Factor	Recharge (inches)
1966	16.41	0.91	0.56
1967	16.04	0.89	0.55
1968	21.74	1.21	0.74
1969	21.64	1.20	0.74
1970	16.03	0.89	0.54
1971	19.53	1.09	0.66
1972	17.87	0.99	0.61
1973	19.59	1.09	0.67
1974	21.71	1.21	0.74
1975	19.00	1.06	0.65
1976	21.61	1.20	0.73
1977	14.53	0.81	0.49
1978	20.46	1.14	0.70
1979	17.25	0.96	0.59
1980	18.41	1.03	0.63
1981	22.16	1.23	0.75
1982	16.79	0.94	0.57
1983	14.97	0.83	0.51
1984	17.50	0.97	0.60
1985	20.59	1.15	0.70
1986	24.55	1.37	0.83
1987	21.30	1.19	0.72
1988	14.67	0.82	0.50
1989	14.04	0.78	0.48
1990	22.44	1.25	0.76
1991	24.02	1.34	0.82
1992	24.54	1.37	0.83
1993	15.20	0.85	0.52
1994	16.82	0.94	0.57
1995	15.70	0.87	0.53
1996	15.45	0.86	0.53
1997	21.01	1.17	0.71
1998	14.81	0.82	0.50
1999	14.51	0.81	0.49
2000	16.23	0.90	0.55
2001	14.79	0.82	0.50
2002	17.53	0.98	0.60
2003	17.71	0.99	0.60
2004	32.23	1.79	1.10
2005	17.60	0.98	0.60

Table 2-4. Comparison of calculated recharge from the model and recharge estimates by Green and Bertetti (2010) for selected counties.

County	Precipitation Recharge (inches per year)	River Recharge (inches per year)	Sum (inches per year)	Recharge Estimate (Green and Bertetti, 2010) (inches per year)
Crockett	0.49	0.11	0.60	0.34
Edwards	0.46	2.64	3.10	1.30
Kimble	0.72	0.19	0.91	1.50
Menard	0.47	0.03	0.50	0.50
Real	0.87	0.57	1.44	2.14
Schleicher	0.31	0.28	0.59	0.80
Sutton	0.40	0.42	0.82	1.00
Val Verde	0.39	2.35	2.74	0.63

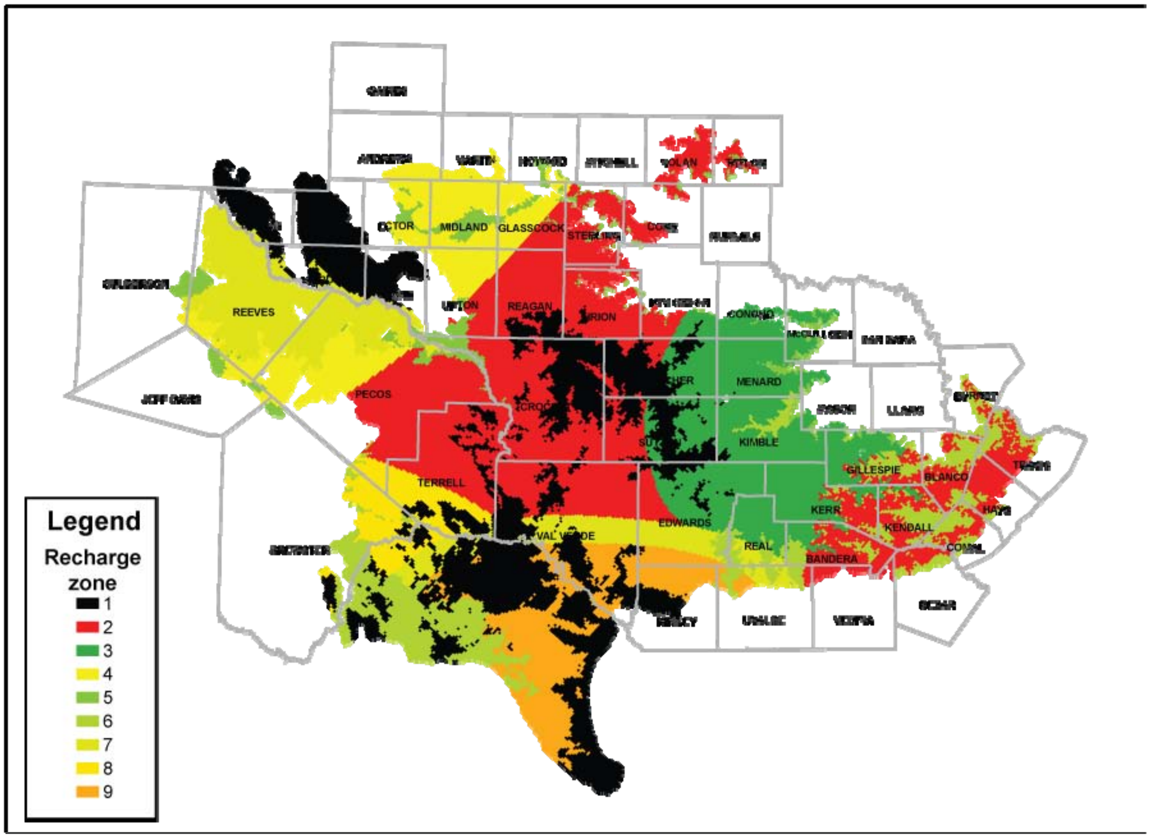


Figure 2-10. The recharge zones used to distribute recharge to the model domain.

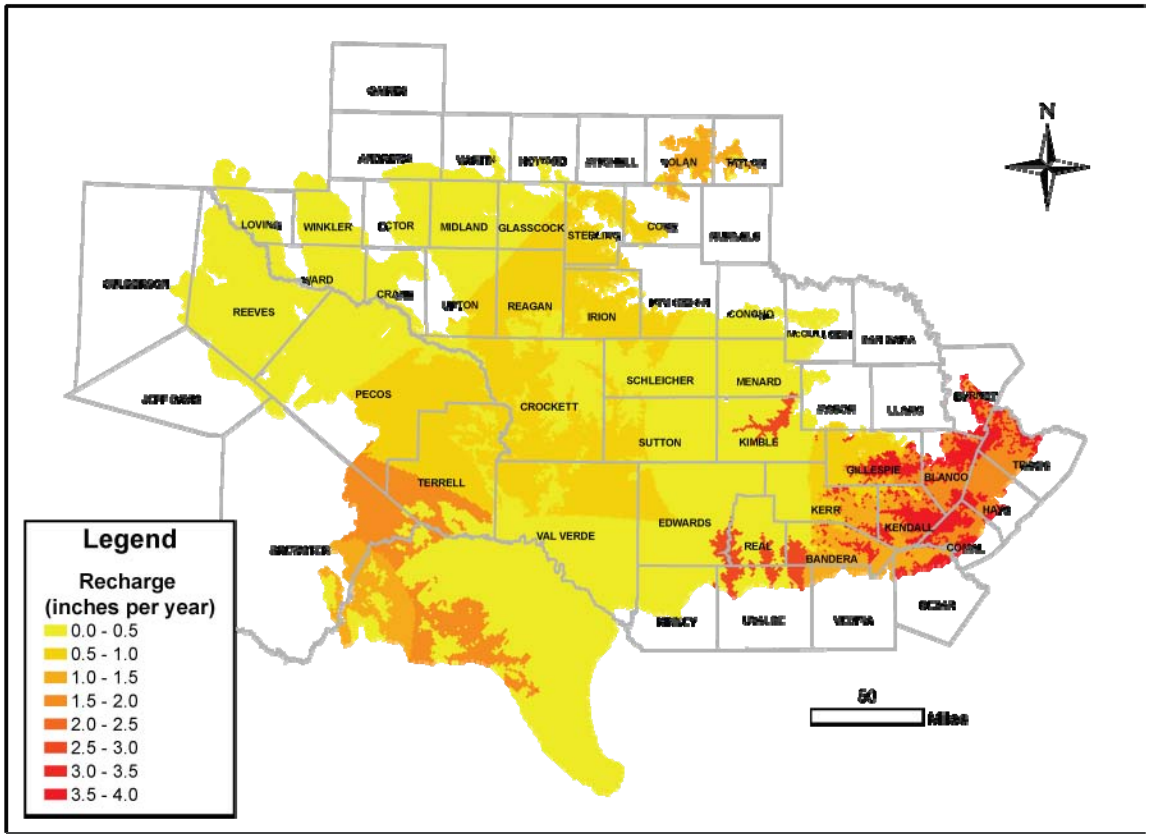


Figure 2-11. The spatial distribution of recharge for the year 1930. Recharge is expressed in inches per year.

2.1.7 General-Head Boundary Package

The General-Head Boundary Package is used to simulate groundwater flow between aquifers adjacent to the model domain and the aquifers inside the model domain. Three distinct areas are simulated: (1) groundwater flow across the western margin of the model domain, (2) the overlying Ogallala Aquifer in the north central portion of the model, and (3) the Edwards (Balcones Fault Zone) Aquifer along the southeastern portion of the model domain (Figure 2-12). The spatial distribution of general-head boundaries in the updated model differs from original model with the addition of general-head boundaries along the western margin of the model domain and refinements to the boundary where the Ogallala Aquifer overlies the Edwards-Trinity (Plateau) Aquifer.

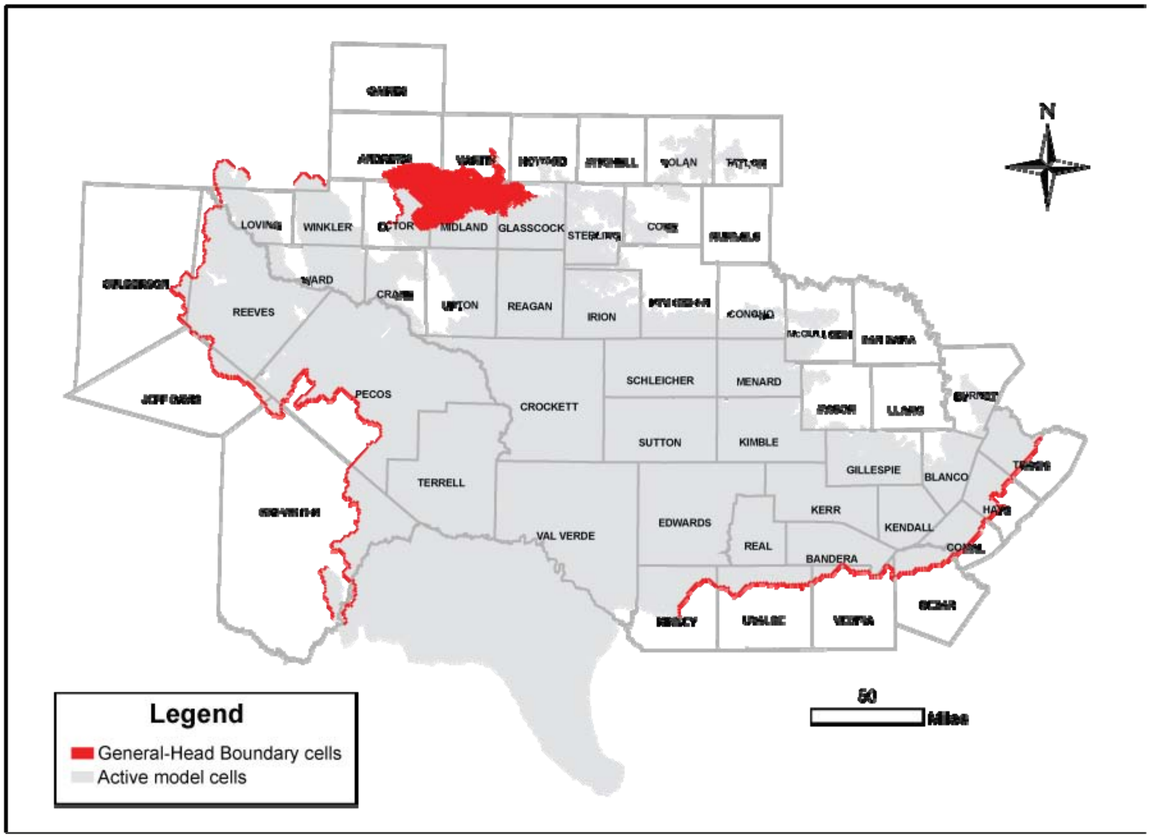


Figure 2-12. The general-head boundary cells in the model domain are indicated in red.

2.1.8 River Package

The River Package is used to simulate interaction between the Pecos Valley and Edwards-Trinity (Plateau) aquifers and overlying rivers and reservoirs (Harbaugh and others, 2000) (Figure 2-13). In the original model (Anaya and Jones, 2009), rivers and reservoirs were simulated using the Streamflow-Routing Package (Prudic, 1989) and constant-head cells, respectively. Using the River Package to simulate reservoirs has the advantage over constant-head cells of allowing reservoir stage fluctuations during the model period. Changes in reservoir stage are important especially when simulating the filling of the respective reservoirs after construction. Of the five reservoirs in the model domain−Canyon Lake, Lake Austin, Lake Travis, Medina Lake, and Lake Amistad−only Medina Lake pre-dates the 1930 through 2005 calibration period. The other reservoirs−Canyon Lake, Lake Austin, Lake Travis, and Lake Amistad−were constructed in 1965, 1940, 1943, and 1970, respectively. River stage is varied during the simulation to pre- and post-construction water-level fluctuations.

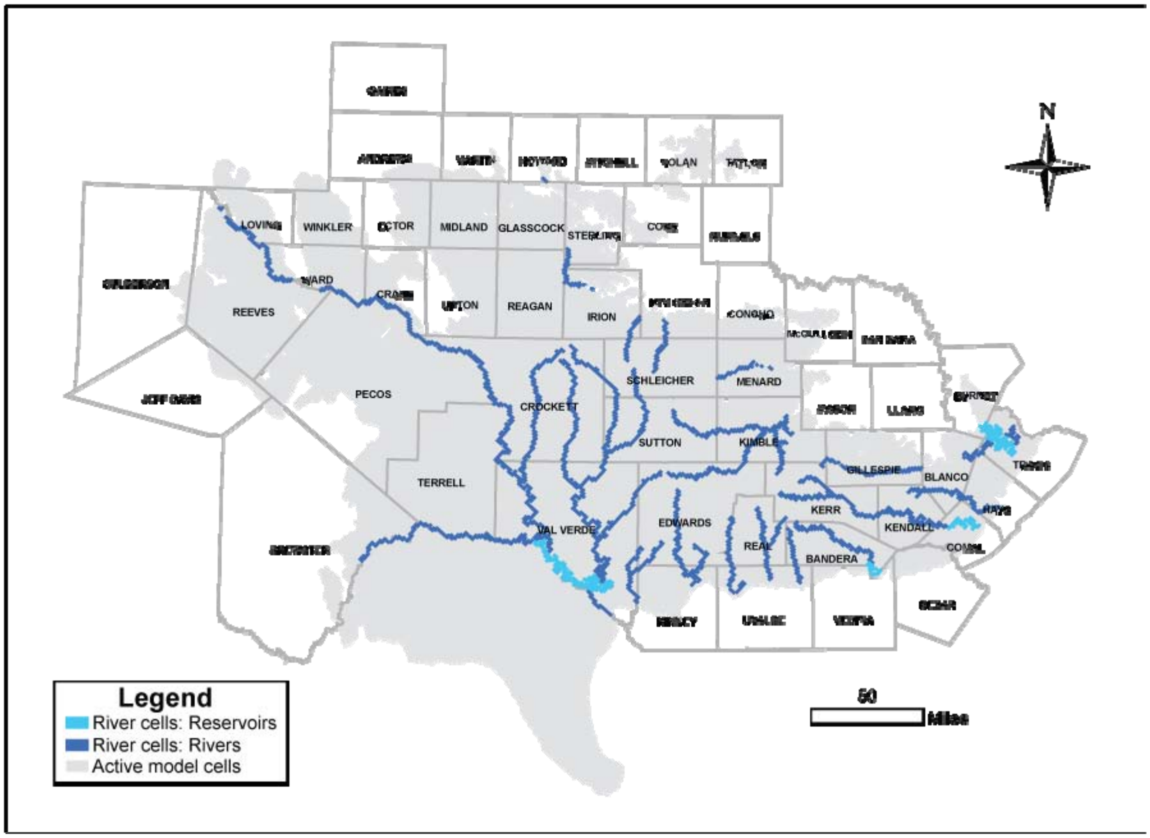


Figure 2-13. River cells in the model domain.

2.1.9 Output Control Package

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

2.1.10 Geometric Multigrid Solver

The Geometric Multigrid Solver (Wilson and Naff, 2004) contains specifications for the chosen solver package. Note that in this particular implementation the head change convergence criterion is 10.0, and the residual convergence criterion is 10.0. The head change and residual convergence criterion are maximum changes between iterations for model convergence to occur.

3.0 MODEL CALIBRATION AND RESULTS

The model was calibrated using a combination of trial-and-error and automated adjustments using PEST, an industry-standard inverse modeling software package (Watermark Numerical Computing, 2004). Calibration of the model was primarily based on the match between simulated and measured groundwater elevations. Calibration was accomplished by adjusting various parameters until simulated discharges and groundwater elevations were in reasonable agreement with groundwater elevations and to a lesser degree, estimated or measured natural discharges. The target calibration statistic was a ratio of standard deviation to elevation range of less than ten percent. Parameter adjustments generally focused on hydraulic conductivity in the x- and y-directions, specific storage, drain and general-head boundary conductance, and recharge.

The calibration period was 1930 through 2005 (76 stress periods), with a steady-state stress period (stress period 1) preceding the transient simulation. The steady-state stress period provided a stable initial head solution that was used to initialize the transient simulation, and was not intended to represent an accurate “pre-development” condition.

The model was calibrated with data from 1,639 target wells. Water level data from Texas were obtained from the Texas Water Development Board groundwater database. Water-level data from the New Mexico portion of model domain were obtained from U.S. Geological Survey (U.S. Geological Survey, 2010) website, while water-level data from Mexico was obtained from Comisión Nacional del Agua publications (Elizondo, 1977; Leal, 1992). These target wells had at least one groundwater elevation measurement during the calibration period and 368 of the 1,639 wells had 10 or more measurements. The locations of the target wells that were used in the calibration are shown in Figure 3-1. The total number of groundwater elevation measurements used to calibrate the model was 9,957.

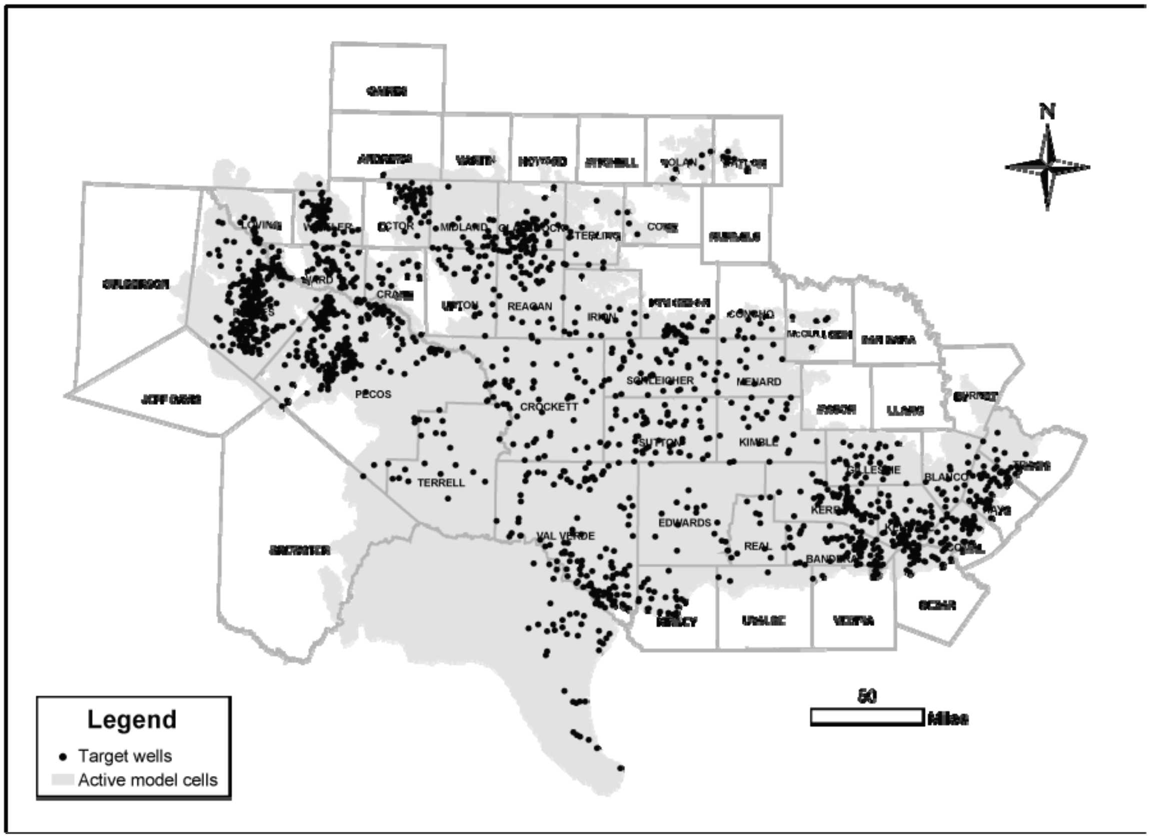


Figure 3-1. Locations of the target wells used to calibrate the model.

Figure 3-2 shows simulated water levels for 1930, 1964, and 2005 for the Pecos Valley and Edwards-Trinity (Plateau) aquifers. In each case, simulated water levels indicate groundwater flow converging on and therefore likely discharging to the Pecos River and Rio Grande. Overall, water levels are similar in the respective time periods. However, Figure 3-3 (a) shows simulated drawdown for 1964 and 2005 relative to 1930 water levels. This figure shows (1) the development of the cones of depression and partial recovery in Reeves and Pecos counties due to irrigation pumpage that peaked in the mid 1960s, (2) the development of a cone of depression in Glasscock and Reagan counties due to increasing irrigation pumpage since the 1960s, and (3) water-level declines in Ward and Winkler counties attributable to increasing municipal and industrial pumpage since the 1960s from the Monument Draw portion of the Pecos Valley Aquifer (Jones, 2004). Figure 3-3 (b) shows the effects of more recent pumping, changes in water levels between 1964 and 2005. The partial recovery in Reeves and Pecos counties is more apparent in the figure as well as the more recent drawdown in Glasscock, Reagan, Ward, and Winkler counties.

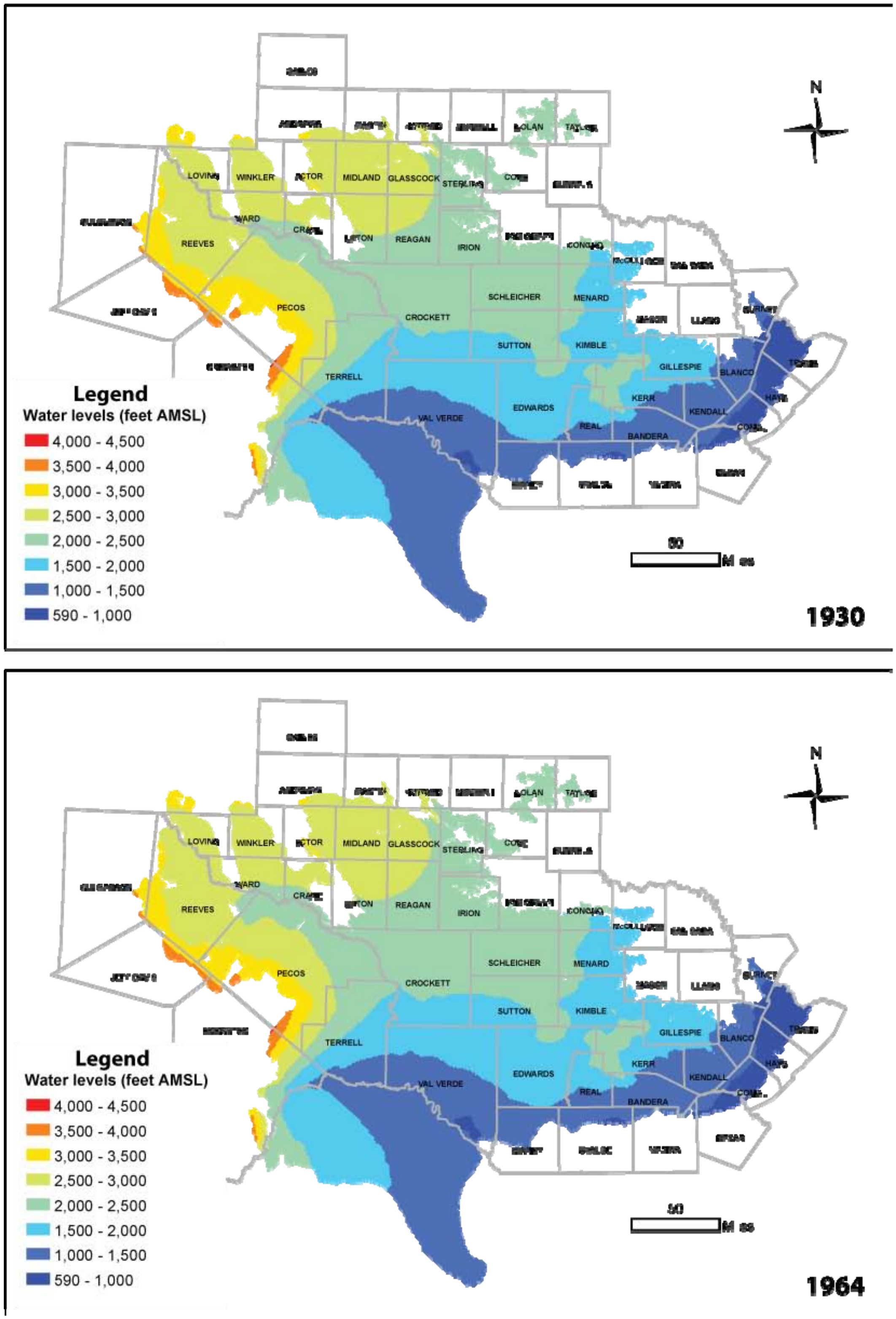


Figure 3-2. Simulated water levels for the years 1930, 1964, and 2005. The year 1964 is the year with the highest pumping rates from the Pecos Valley and Edwards-Trinity (Plateau) aquifers.

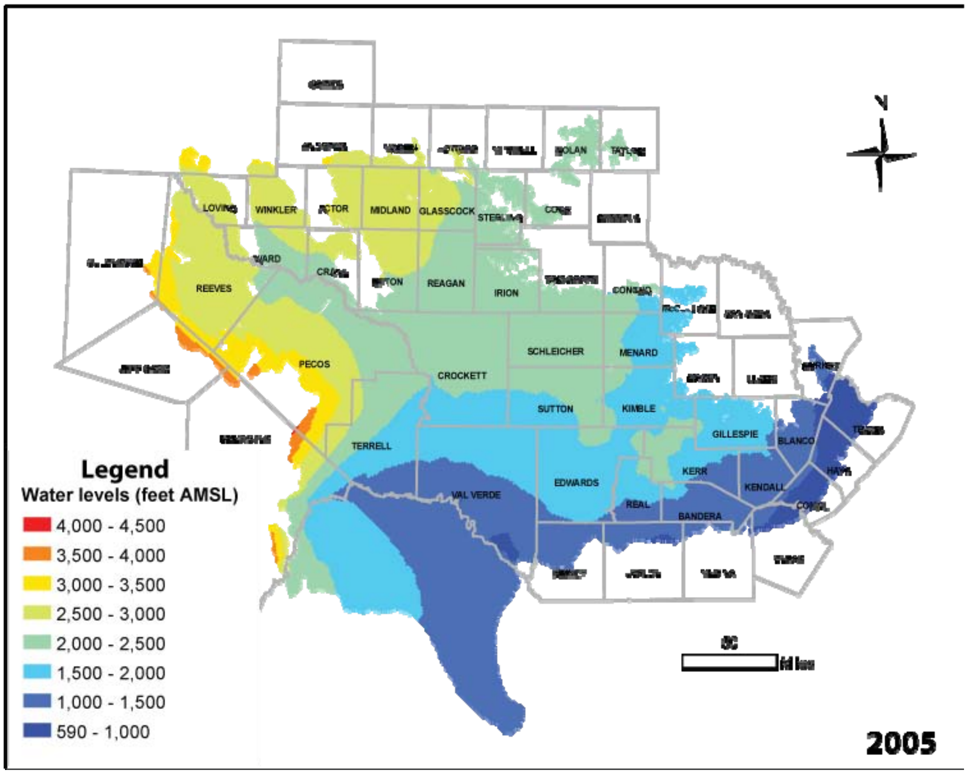


Figure 3-2 (continued).

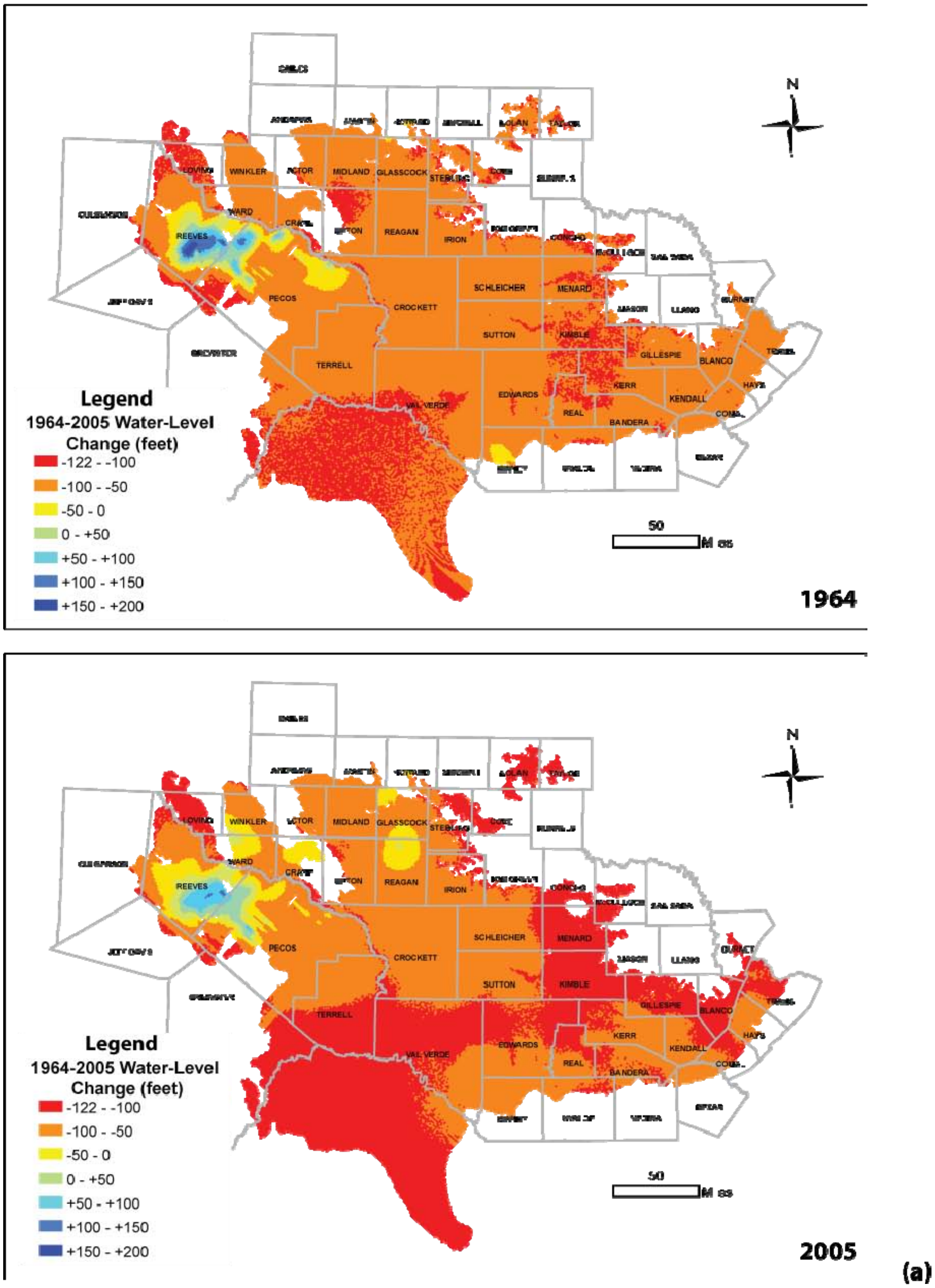
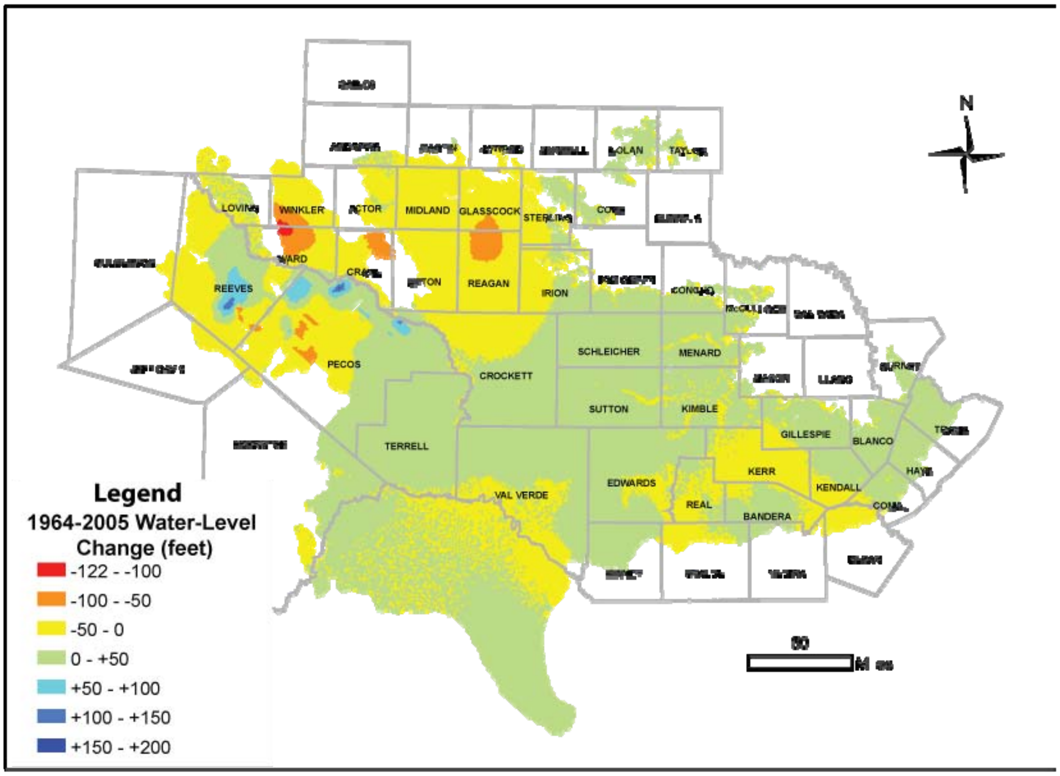


Figure 3-3. (a) Drawdown in the years 1964 and 2005 relative to 1930 water levels. (b) Water-level changes since the peak pumpage in the mid-1960s. Negative values indicate slightly increase in water levels or no change to water levels.



(b)

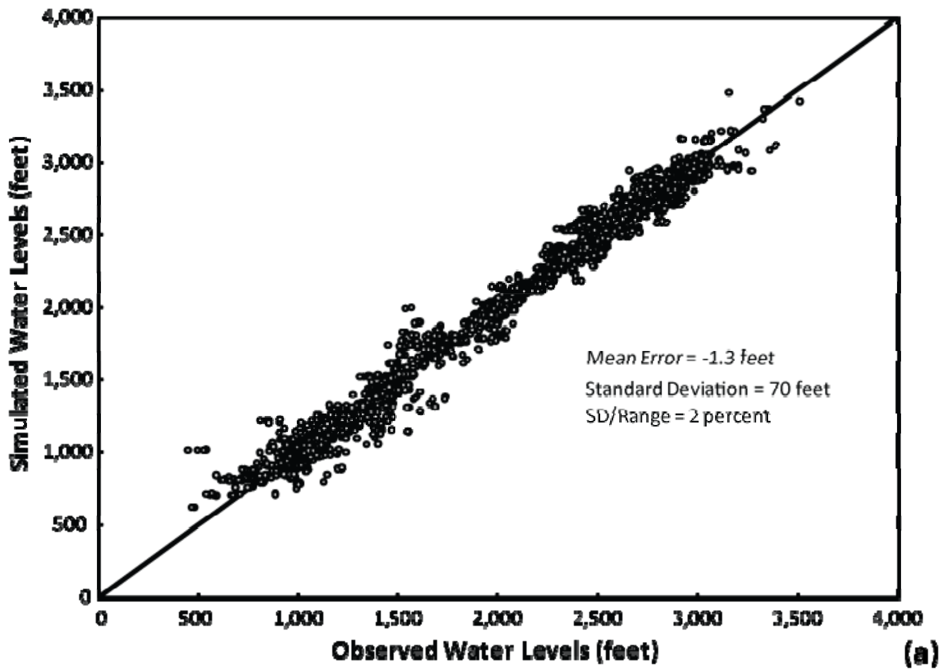
Figure 3-3 (continued).

3.1 Measured Groundwater Elevations versus Model Simulated Groundwater Elevations

A statistical summary of the minimum residual, maximum residual, and the absolute residual mean are presented in Table 3-1. The residual is the difference between measured and simulated groundwater elevations. If the residual is positive, the measured groundwater elevation is higher than the simulated groundwater elevation (the model underestimated groundwater level). If the residual is negative, the measured groundwater elevation is lower than the simulated groundwater elevation (the model overestimated groundwater level). The standard deviation of the residuals and the range of measured groundwater elevations are also provided in Table 3-1. The standard deviation of the residuals divided by the range of measured groundwater elevations for the updated model is 0.023. The summary in Table 3-1 also includes the value of the sum of squared residuals, which was used as the objective function during parameter estimation. Finally, the summary table includes the frequency distribution of residuals within 10, 25, and 50 feet. About 32 percent of the simulated groundwater elevations are within ± 10 feet of the measured groundwater elevations, 54 percent are within ± 25 feet, while 77 percent are within ± 50 feet. A graphical summary showing a plot between measured and simulated groundwater elevations and a histogram of the residuals is shown in Figure 3-4. For the most part, simulated groundwater elevations favorably match measured groundwater elevations and the residuals show a fairly normal distribution (Figure 3-4). Figure 3-5 shows the spatial distribution of residuals in the model domain to be fairly random and evenly distributed.

Table 3-1. Statistical summary of simulated groundwater elevations in the updated model.

Calibration Statistic	Calibrated Model Value
Minimum Residual (feet)	-571
Maximum Residual (feet)	414
Absolute Residual Mean (feet)	48.45
Standard Deviation of Residuals	70.33
Range of Measured Groundwater Elevations (feet)	3,058
Standard Deviation/Range	0.023
Absolute Residual Mean/Range*100	1.58%
Sum of Squared Residuals	4.93×10^7
Percent of residuals within:	
± 10 feet	32
± 25 feet	54
± 50 feet	77



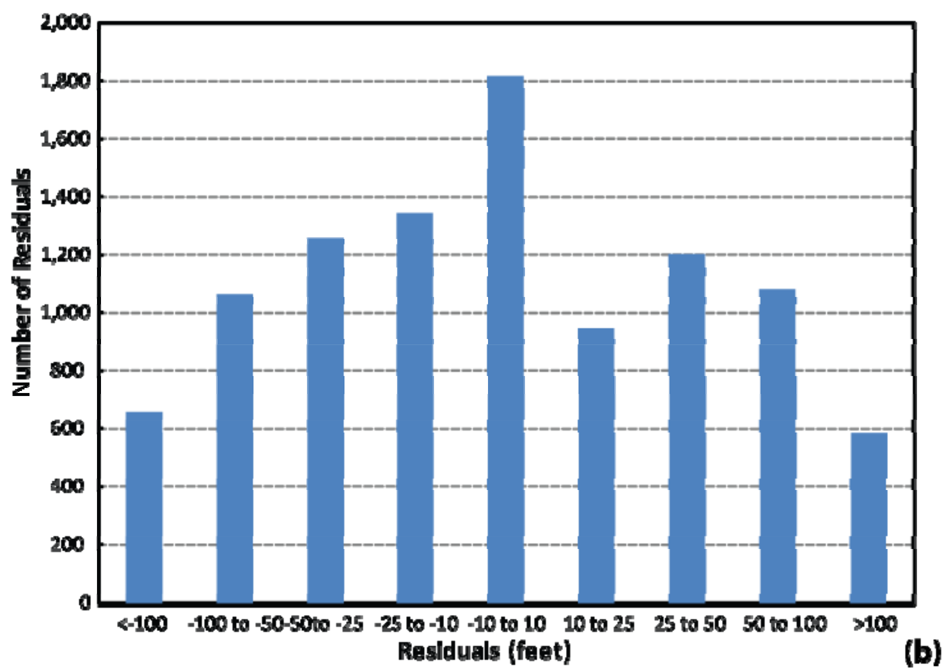


Figure 3-4. A graphical summary of measured groundwater elevations versus simulated groundwater elevations from the updated model (a) and a histogram of residuals (b).

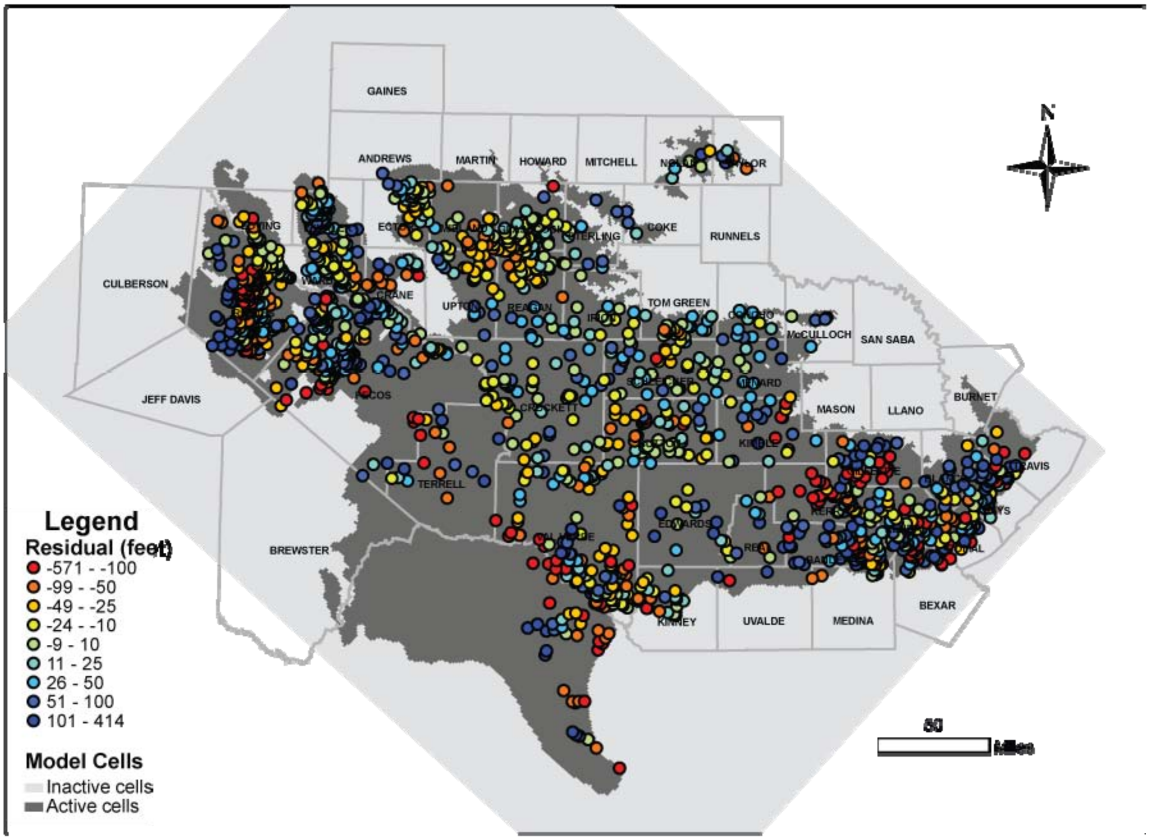


Figure 3-5. The spatial distribution of residuals over the model domain.

Figure B-2, in Appendix B, shows hydrographs for selected wells in the model area. In most cases, there is agreement between measured and simulated water levels.

3.2 Water Budget

Groundwater budgets, or groundwater inventories, are developed by quantifying all inflows to and outflows from, and the storage change of a groundwater flow system over a specified period of time.

A groundwater flow system in near steady-state (or near equilibrium) prior to development (such as groundwater pumping) is shown in Figure 3-6. In this condition, groundwater inflow equals groundwater outflow and no long-term change in storage occurs. This assumes that seasonal and interannual variations in inflow (such as recharge) are negligible.

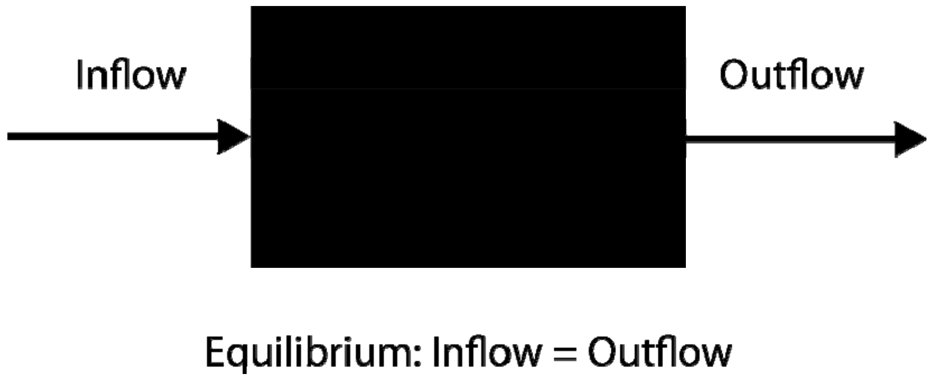


Figure 3-6. Groundwater system prior to development (after Alley and others, 1999).

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 flow (generally manifested by increased inflow from streams and adjacent aquifers, and 3) reduced natural outflow (generally manifested in decreased springflow).

The initial response to pumping is a lowering of the groundwater level or formation of 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 flow toward the well thereby increasing the inflow to the area around the well.

The cone of depression can also cause a decrease of natural groundwater outflow from the area adjacent to the well by “capturing” this natural outflow. If the cone of depression causes water levels to decline in an area of shallow groundwater, discharge through evapotranspiration is reduced and the pumping is said to capture the evapotranspiration. 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 3-7 illustrates the case of a groundwater system after pumping begins. Note that the groundwater storage is decreased, inflow is increased, and outflow is decreased relative to that shown in Figure 3-6 in response to the pumping. Initially, the inflow does not equal the total outflow (natural outflow plus pumping). The system is not in equilibrium and groundwater storage is decreasing.

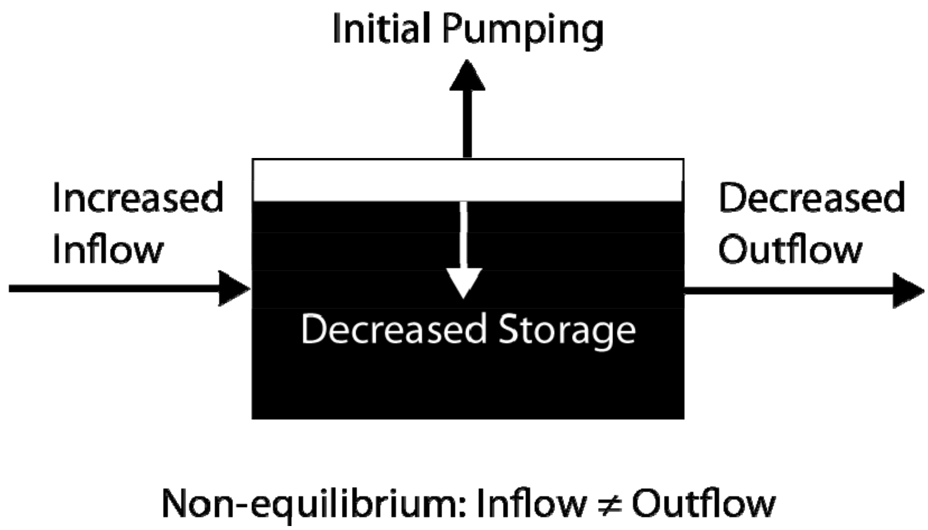


Figure 3-7. Groundwater system after initial pumping (after Alley and others, 1999).

If the hydraulic conductivity is sufficiently large and the 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 3-8 presents a diagram of this new near steady-state or new equilibrium condition.

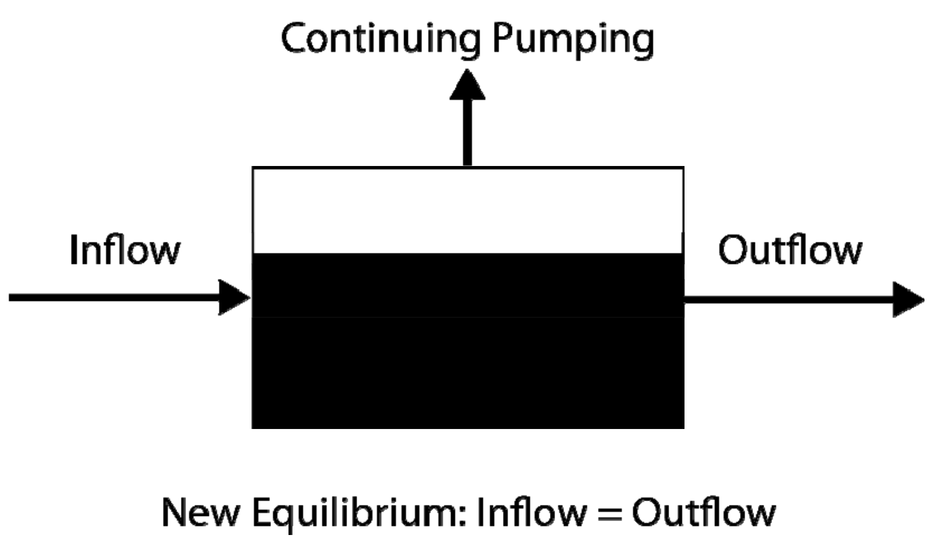


Figure 3-8. Groundwater system under continued pumping with new equilibrium condition (after Alley and others, 1999).

If pumping were to increase after 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 3-9 depicts this condition.

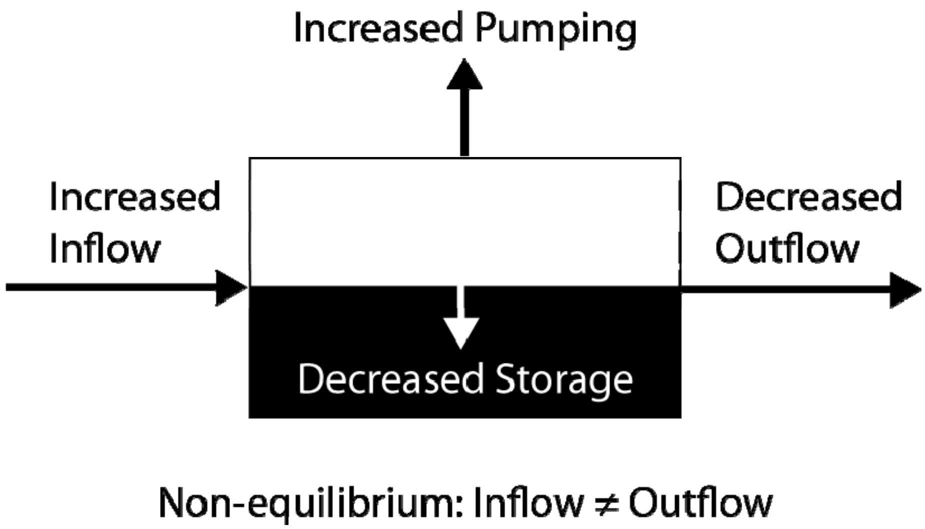


Figure 3-9. Groundwater system under an additional increment of increased pumping (after Alley and others, 1999).

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 all natural outflow is captured. From an outflow perspective, this condition would be reached once the water table has declined to the point that all springs cease flowing (no more springflow to “capture”) and groundwater evapotranspiration ceases.

In summary, groundwater pumping dynamically alters the direction and magnitude of hydraulic gradients, induces inflow, decreases natural discharge from the groundwater flow system, and affects fluxes between hydraulically connected aquifer systems. Bredehoeft (2002) noted that understanding the dynamic response of a groundwater flow 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 inflow and the change in discharge caused by pumping. A calibrated numerical groundwater model of a region is an ideal tool to meet the objective of understanding capture. Output from the model includes estimates of the various components of the water budget.

There are four main components to the water budget in the updated groundwater flow model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers: (1) discharge to springs and rivers, (2) recharge, (3) pumpage, and (4) inter-aquifer flow (Figure 3-10; Table 3-2). Discharge to springs and rivers is the combined discharge from the aquifer into rivers, springs, and reservoirs. Recharge refers to infiltration of precipitation that recharges the aquifer. Pumpage refers to both domestic (rural) and non-domestic (agricultural, municipal, and industrial) groundwater well withdrawals. Inter-aquifer flow refers to groundwater flow between the model domain and adjacent Ogallala and Edwards (Balcones Fault Zone) aquifers. Inter-aquifer flow also includes inflow along the western margin of the model. This inflow is largely derived from the Davis, Guadalupe, and Delaware mountains, located to the west of the model area. Natural discharge to springs and rivers is the primary component of discharge from the Pecos Valley and Edwards-Trinity (Plateau) aquifers, accounting for about 70 percent of the total natural discharge (Figure 3-10). Pumpage from wells is a relatively minor component of discharge from the modeled aquifers, accounting for about 15 percent of total discharge. Storage change refers to the difference between inflows and outflows. Negative values indicate water is being removed from storage, whereas positive values indicate water is being added to storage. On a decadal basis, net storage change from the Pecos Valley and Edwards-Trinity (Plateau) aquifers is always positive (Table 3-2).

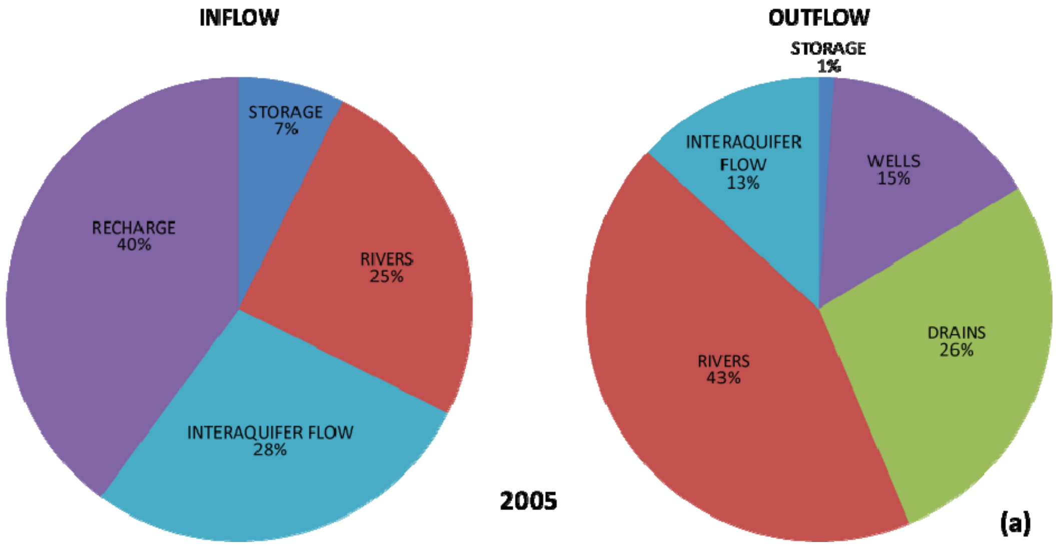


Figure 3-10. Components of the water budget of the groundwater flow model for the Pecos Valley and Edwards-Trinity (Plateau) aquifers for (a) 2005 and (b) the entire calibration period (1930 through 2005).

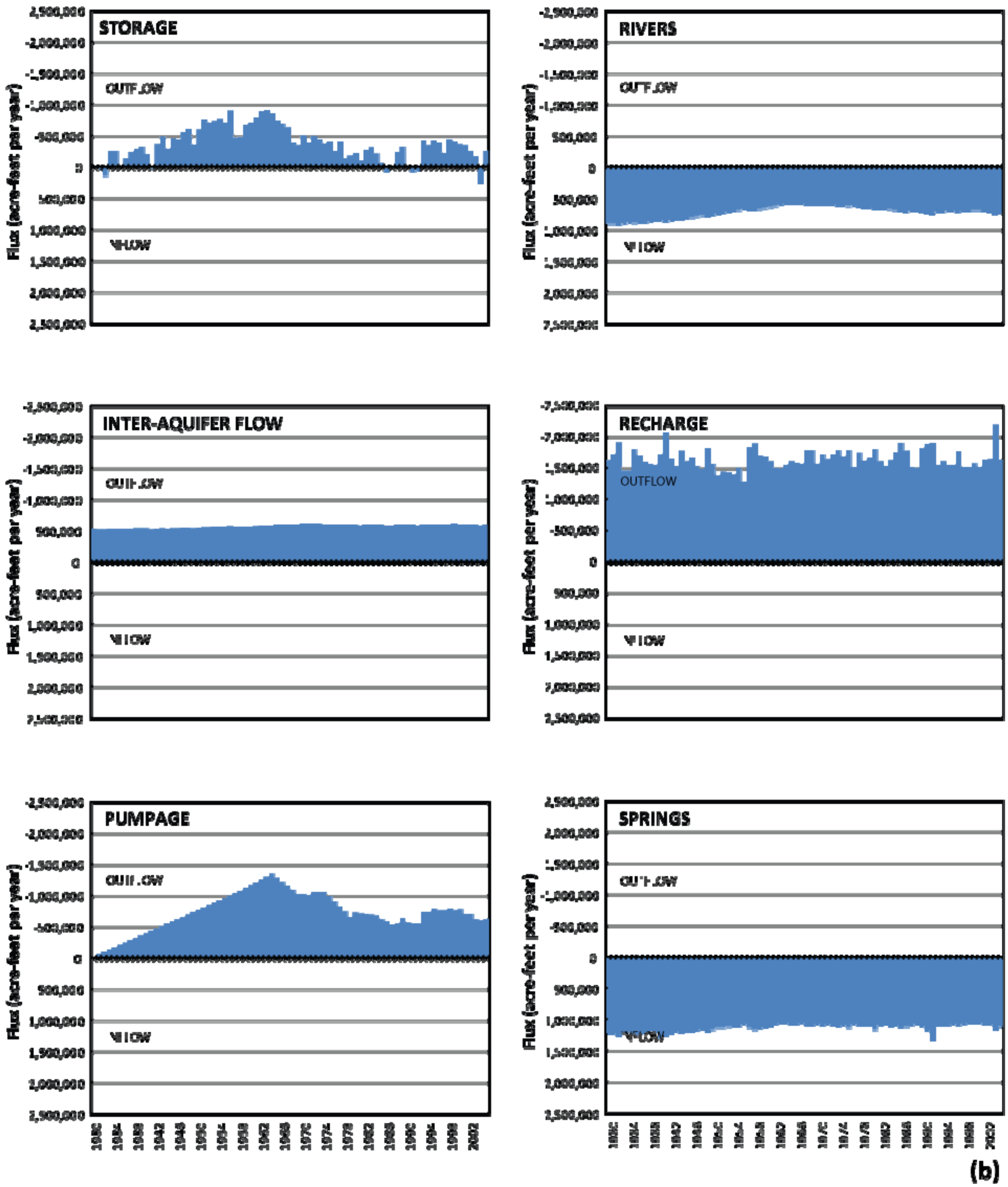


Figure 3-10 (continued).

Table 3-2. Annual average groundwater budget for eight decadal time periods. All values are in acre-feet per year.

	Water Budget 1930-1939 (acre-feet per year)	Water Budget 1940-1949 (acre-feet per year)	Water Budget 1950-1959 (acre-feet per year)	Water Budget 1960-1969 (acre-feet per year)	Water Budget 1970-1979 (acre-feet per year)	Water Budget 1980-1989 (acre-feet per year)	Water Budget 1990-1999 (acre-feet per year)	Water Budget 2000-2005 (acre-feet per year)
Inflow								
Rivers	993,229	1,009,160	1,054,950	1,107,275	1,092,402	1,048,220	1,033,690	1,033,726
Inter-aquifer Flow	1,095,795	1,100,269	1,112,419	1,123,952	1,135,663	1,131,445	1,137,506	1,136,281
Recharge	1,641,803	1,688,928	1,545,021	1,621,125	1,680,625	1,671,631	1,669,556	1,703,227
Total Inflow	3,730,827	3,798,357	3,712,390	3,852,352	3,908,690	3,851,296	3,840,752	3,873,234
Outflow								
Pumpage	-194,233	-570,080	-947,024	-1,210,949	-935,718	-651,331	-706,359	-677,860
Springs	-1,216,432	-1,210,615	-1,129,334	-1,082,433	-1,092,612	-1,101,266	-1,120,187	-1,093,636
Rivers	-1,893,959	-1,841,710	-1,767,816	-1,722,471	-1,715,415	-1,741,168	-1,756,911	-1,755,300
Inter-aquifer Flow	-560,262	-557,538	-546,381	-532,124	-526,554	-531,894	-533,580	-535,091
Total Outflow	-3,864,885	-4,179,943	-4,390,555	-4,547,978	-4,270,298	-4,025,658	-4,117,038	-4,061,887
In-Out	-134,058	-381,585	-678,165	-695,626	-361,608	-174,362	-276,286	-188,653
Storage Change	-133,865	-372,190	-678,034	-695,534	-358,631	-166,175	-250,497	-188,648
Model Error	-194	-9,395	-131	-92	-2,977	-8,187	-25,789	-5
Model Error (Percent)	-0.01	-0.25	0.00	0.00	-0.08	-0.21	-0.67	0.00

4.0 MODEL LIMITATIONS

Numerical groundwater flow models are approximate representations of aquifer systems (Anderson and Woessner, 2002). Similar to analytical models, numerical models require some assumptions and have some limitations. These limitations are usually associated with (1) the purpose for the groundwater flow model, (2) the extent of our understanding of the aquifer(s), (3) the quantity and quality of data used to constrain parameters in the groundwater flow model, and (4) assumptions made during model development.

Several input parameter data sets for the model are based on limited information. These include geologic framework, recharge, water level and streamflow data, hydraulic conductivity, specific storage, and specific yield. There is a paucity of information on the geologic framework of the model area along the western margin of the Edwards-Trinity (Plateau) Aquifer and in Mexico. Consequently, the elevations of the aquifer tops and bottoms in these areas of the model are less reliable than the geologic framework information in the other parts of the model.

There is model uncertainty associated with using annual stress periods in the model. The use of annual stress periods results in the model not simulating seasonal effects of recharge and pumping. However, attempting to simulate seasonal effects would be impractical due to the paucity of wells and frequent water level measurements needed for calibration and the fact that seasonal fluctuations may be too small to simulate with certainty at the regional scale. This updated model lumps together the two layers in the original model and thus potentially introduces uncertainty related to head differences between the Trinity and Edwards Groups.

There is uncertainty with simulating base flow and spring discharge at the spatial and temporal scale of this model. Actual discharge to streams occurs within small areas averaging 50 feet wide, compared to the 1 square mile of the model cells, and base flow is more variable within the annual time steps of the model. Therefore, uncertainty occurs because modeled discharge to streams is averaged over a 1-year stress period and 1 square-mile cell.

Available transmissivity and hydraulic conductivity data for the Edwards-Trinity (Plateau) and Pecos Valley aquifers is derived primarily from specific-capacity data obtained from wells scattered throughout the model area. However, these data are not located close enough to indicate more localized heterogeneity within the zones used in the model. The same is true in the assignment of specific storage and specific yield values for the model. The scarcity of measured specific storage and yield values is addressed by calibrating the model based on observed water level responses to wells with time series measurements of annual water levels.

Several assumptions were made in constructing this model. The most important assumptions were that (1) groundwater flow between the model domain of the Edwards-Trinity (Plateau) and Pecos Valley aquifers, and the underlying Rustler, Capitan Reef Complex, Dockum, and Ellenberger-San Saba aquifers is insignificant; (2) some components of recharge are modeled by stream-aquifer interactions; (3) the General-Head Boundary package of MODFLOW can be used to simulate cross-formational flow between the model domain and adjacent units, such as the Ogallala and Edwards (Balcones Fault Zone) aquifers; and (4) transmissivity is fixed for this model and not allowed to vary according to saturated thickness.

Groundwater flow between the Edwards-Trinity (Plateau) and Pecos Valley aquifers and the underlying aquifers is assumed to be negligible. This assumption is based partially on successfully calibrating the model without the need to factor in flows to or from the underlying aquifers. It was difficult for us to consider this inter-aquifer groundwater flow because of the paucity of water level and hydraulic property data to constrain such flow. Additionally, groundwater geochemistry studies in the Pecos Valley Aquifer, which would potentially be impacted the most by groundwater interaction with underlying aquifers, indicate only minor amounts of groundwater flow from underlying saline aquifers (Jones, 2004).

Recharge generally takes the form of diffuse infiltration from precipitation through aquifer material exposed at land surface. This recharge differs from direct recharge, such as streamflow losses from rivers and reservoirs or along other specific discrete recharge features. However, these alternative mechanisms are simulated in MODFLOW using the River package.

Because transmissivity in the model is fixed and not allowed to change with changes in water levels, it is important to note that model cells will not go dry when simulated water levels fall below the base of the aquifer, consequently, saturated thickness must be carefully monitored to determine where the model cells may go dry. Additionally, it should be noted that the assumption of fixed transmissivity values is not valid in cases of extreme drawdown. Saturated thickness data from this model must be used carefully where saturated thickness is less than the root mean square error of the model. This often results in negative calculated saturated thickness because the simulated water levels lie below the base of the aquifer. Negative saturated thickness was a greater issue in the original version of the model (Anaya and Jones, 2009). However, in the updated model, negative saturated thicknesses are restricted to small areas along the margins of the model area.

The limitations described earlier and the nature of regional groundwater flow models affect the scale of application of the model. This model is most accurate in assessing larger regional-scale groundwater issues, such as predicting aquifer-wide water level changes and trends over the next 50 years that may result from different proposed water management strategies. Accuracy and applicability of the model decreases when using it to address more local-scale issues because of limitations of the information used in model construction and the model cell size that determines spatial resolution of the model. Consequently, this model is not likely to accurately predict water level declines associated with a single well or spring because (1) these water level declines depend on site-specific hydrologic properties not included in detail in regional-scale models, and (2) the cell size used in the model is too large to resolve changes in water levels that occur over relatively short distances. Addressing local-scale issues requires a more detailed model, with local estimates of hydrologic properties, or an analytical model. This model is more useful in determining the impacts of groups of wells distributed over many square miles. The model predicts changes in ambient water levels rather than actual water level changes at specific locations, such as an individual well.

5.0 SUMMARY AND CONCLUSIONS

An updated groundwater flow model for the Pecos Valley and Edwards-Trinity (Plateau) aquifers calibrated from 1930 through 2005 was developed to improve the calibration of the original model (Anaya and Jones, 2009). This was achieved with a one-layer model. The calibration statistics in the updated model are better than in the original model with standard deviation values of 70 feet and 143 feet, respectively. Additionally, the issue of water levels below the base of the aquifer is significantly reduced in the updated model.

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7.0 APPENDIX

APPENDIX A

ESTIMATED COUNTY PUMPAGE

1930 to 2005

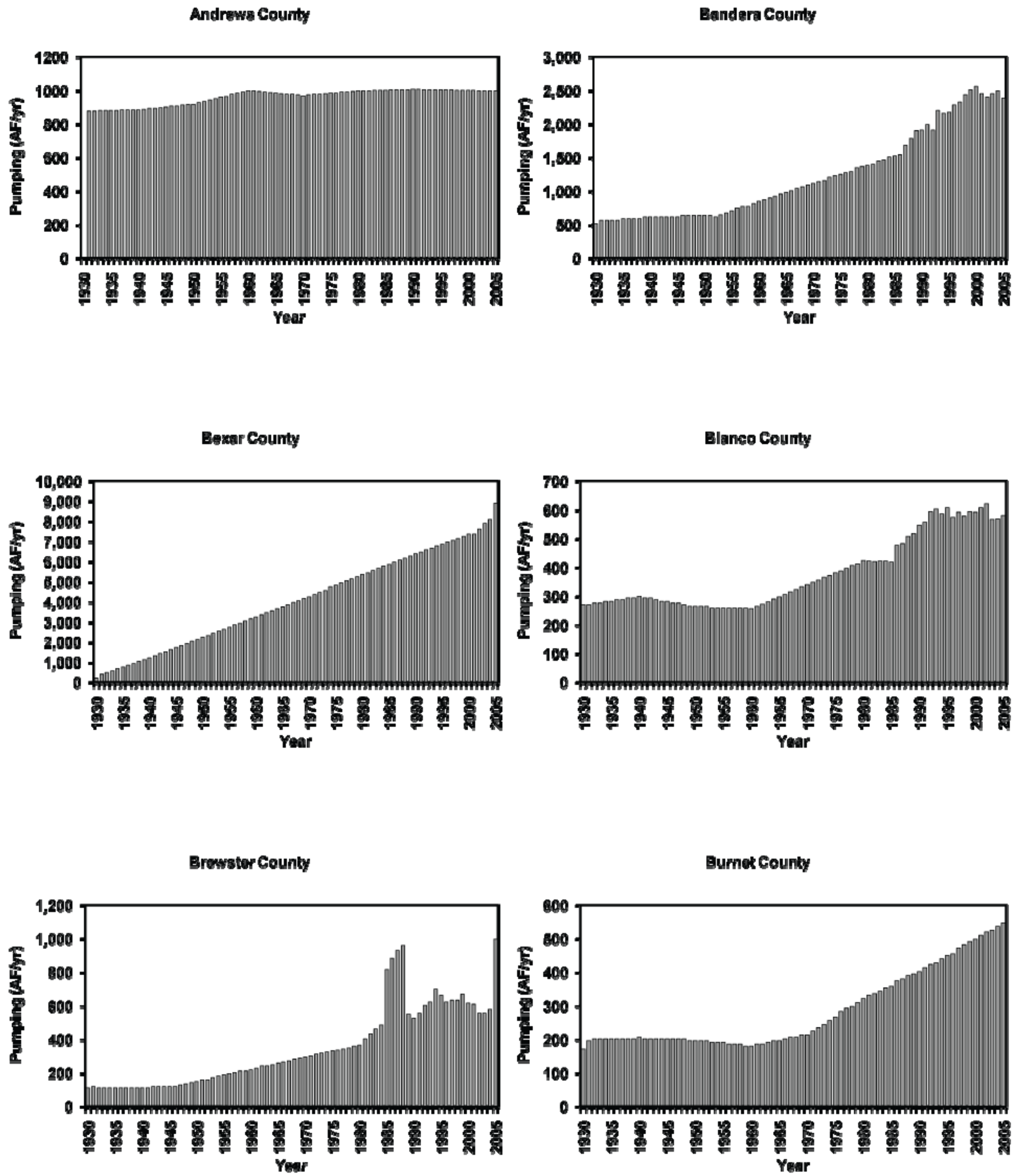


Figure A-1. County pumpage for the calibration period 1930 through 2005.

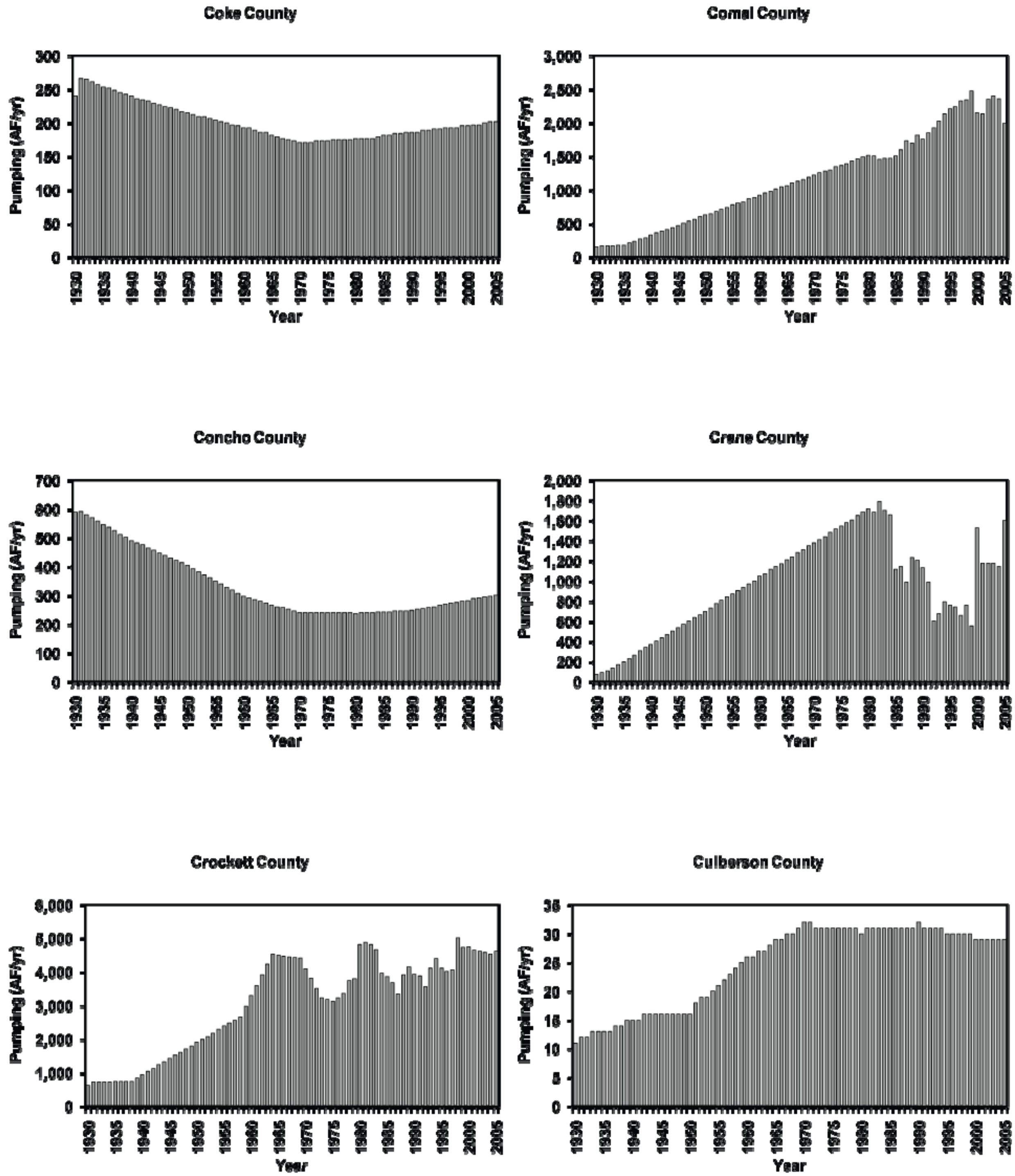
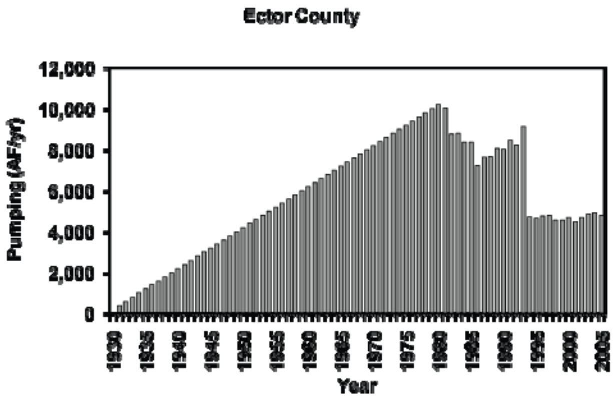
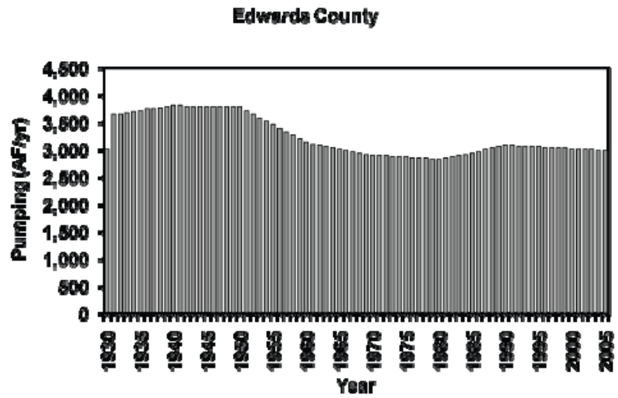
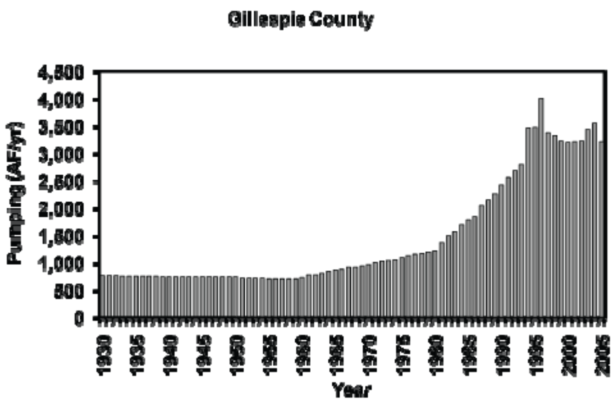
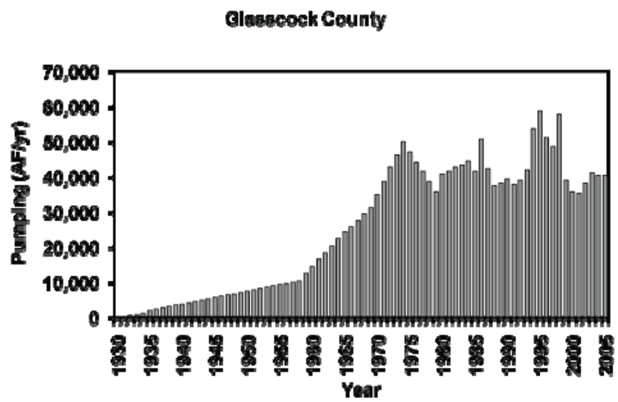


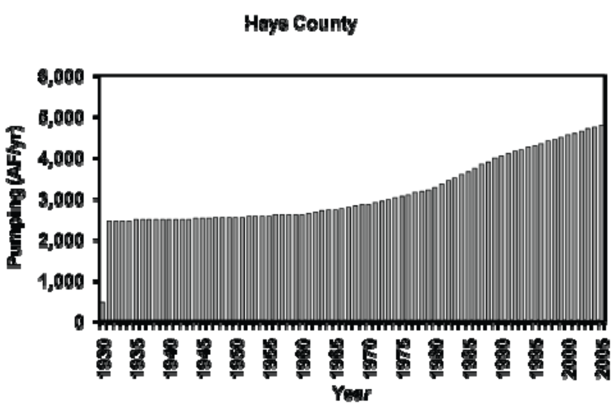
Figure A-1 (continued).











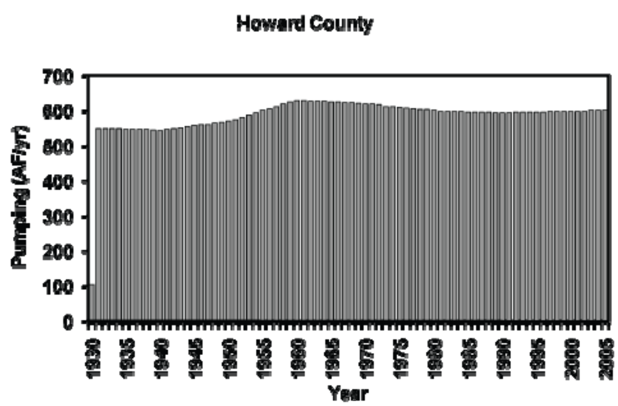


Figure A-1 (continued).

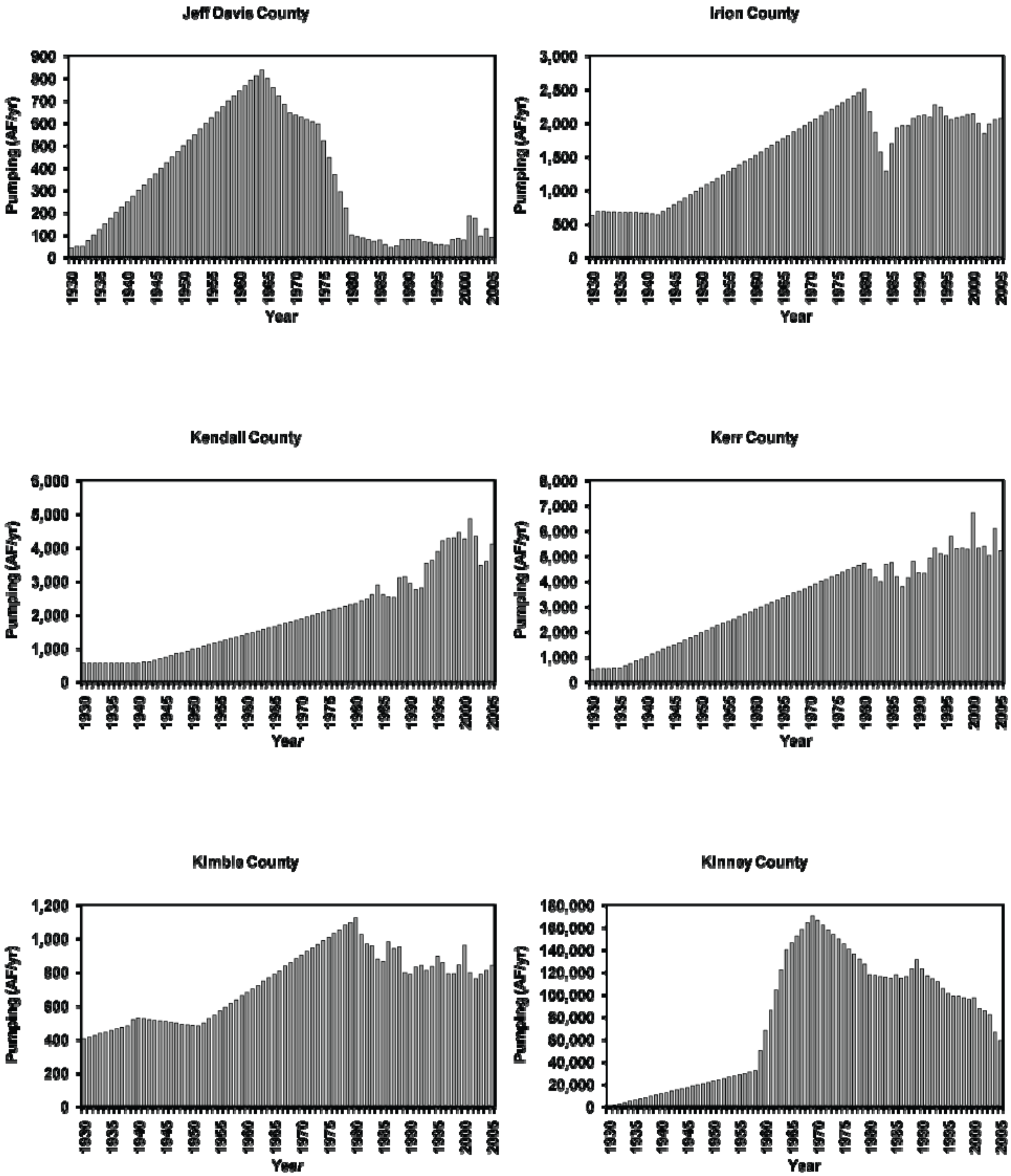


Figure A-1 (continued).

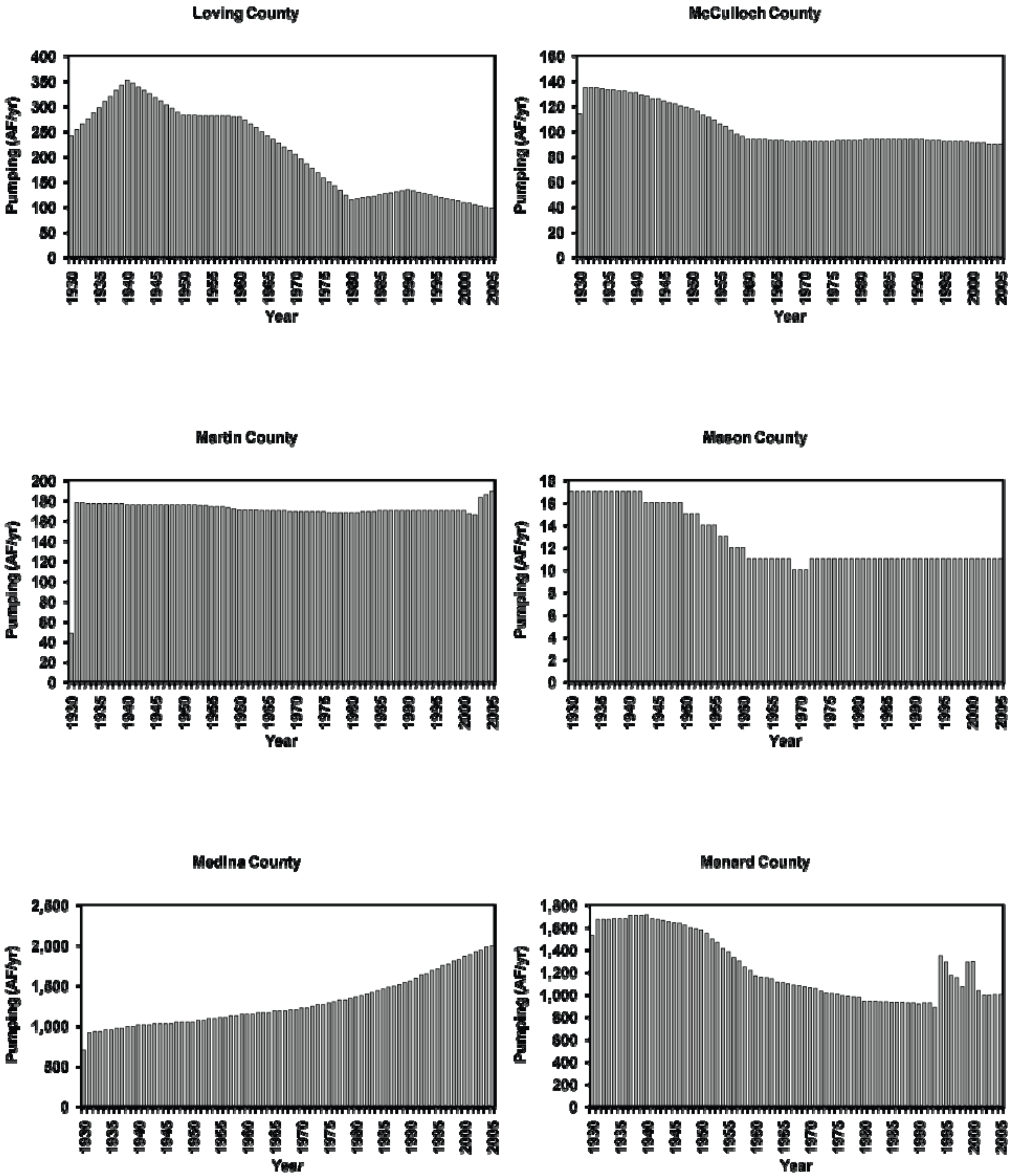


Figure A-1 (continued).

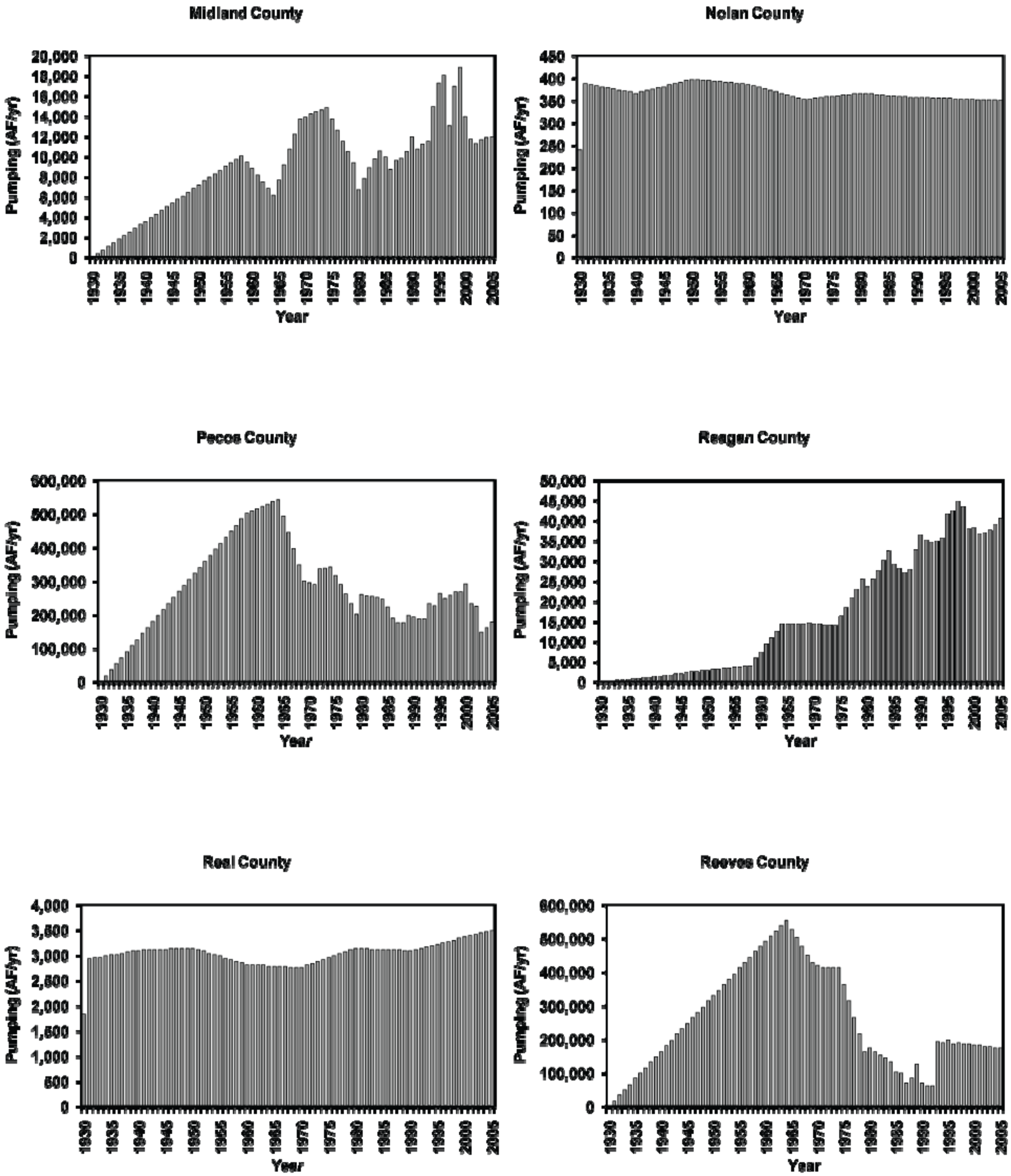


Figure A-1 (continued).

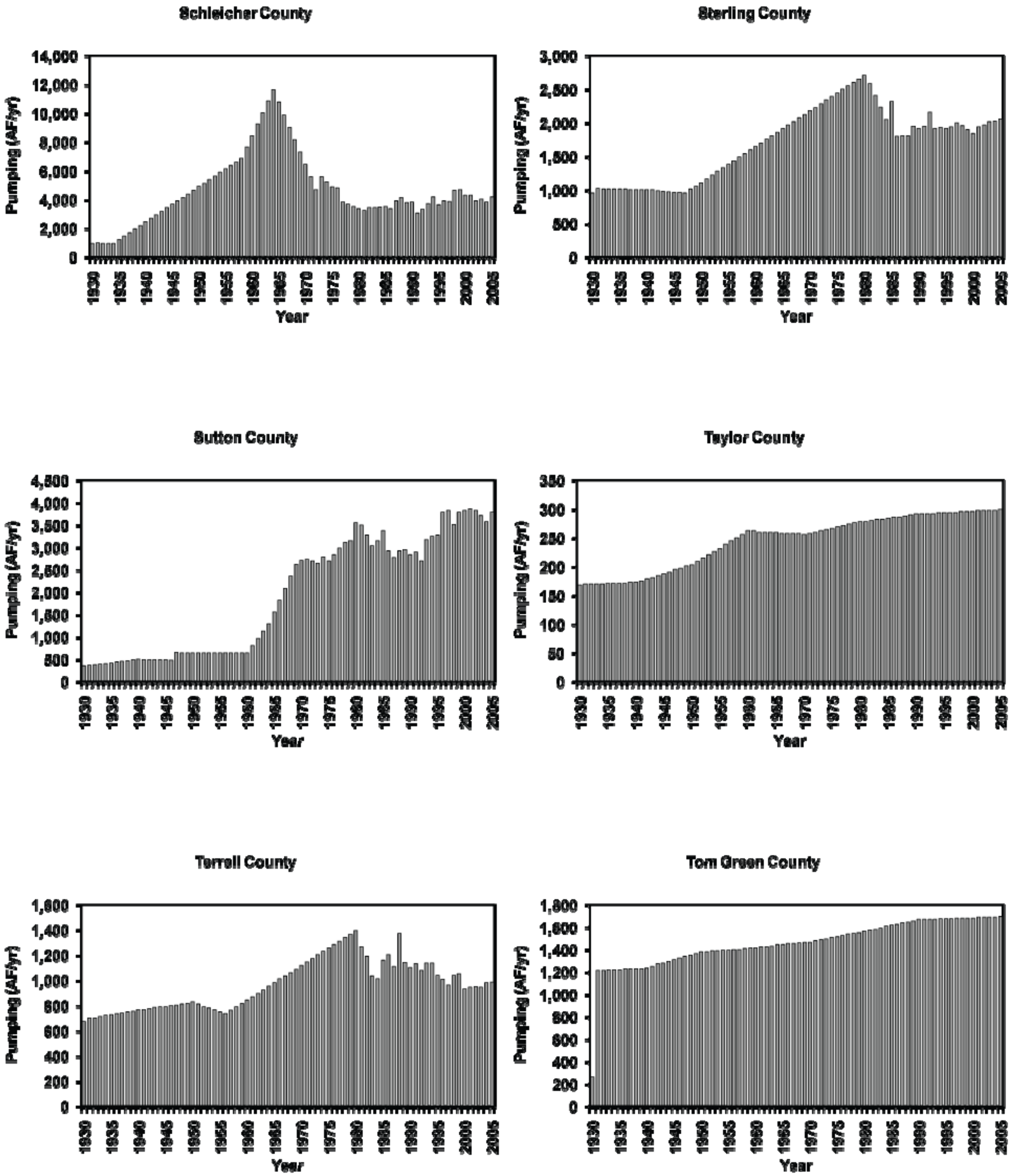


Figure A-1 (continued).

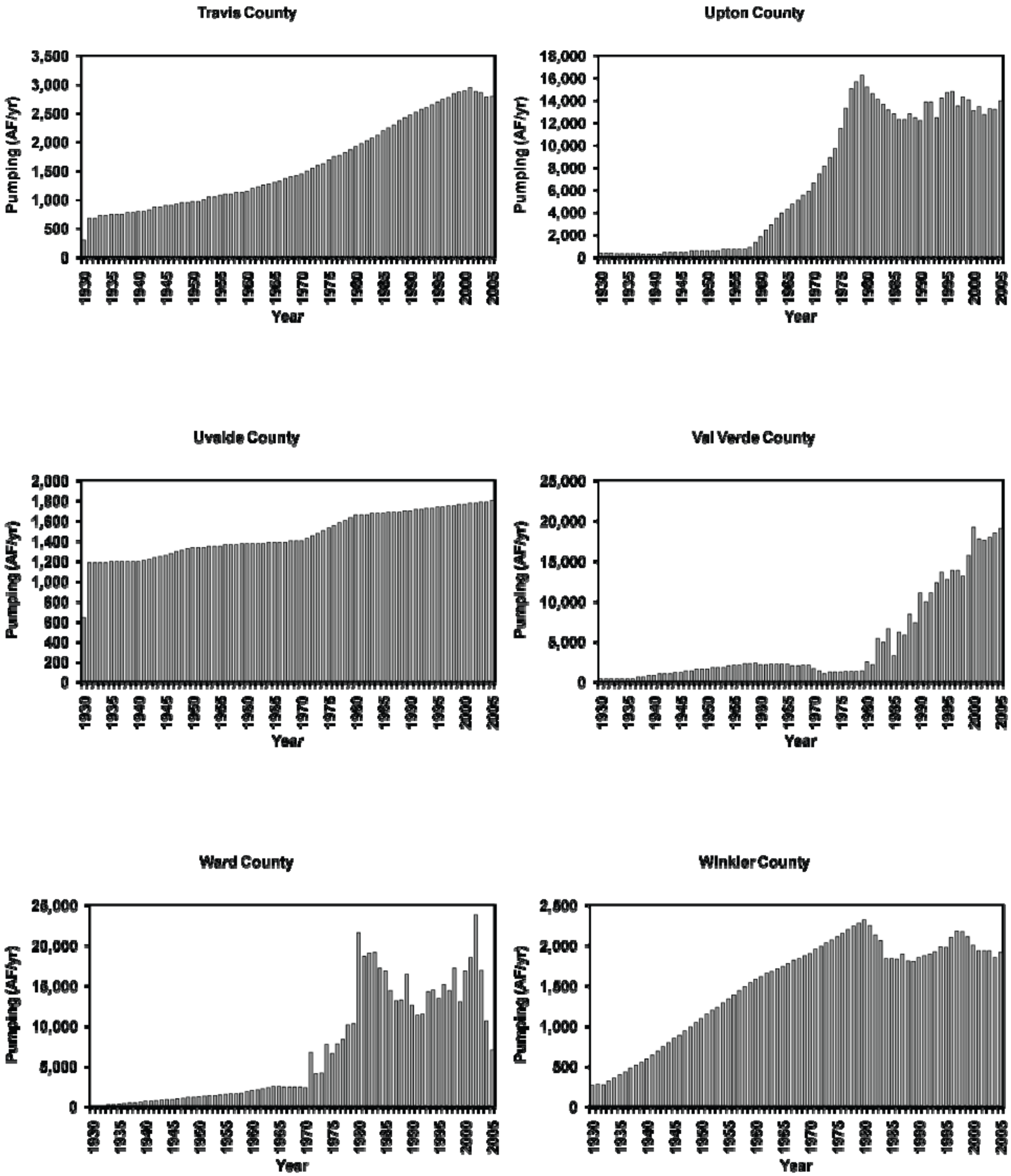


Figure A-1 (continued).

APPENDIX B

GROUNDWATER HYDROGRAPHS

AT SELECTED WELLS

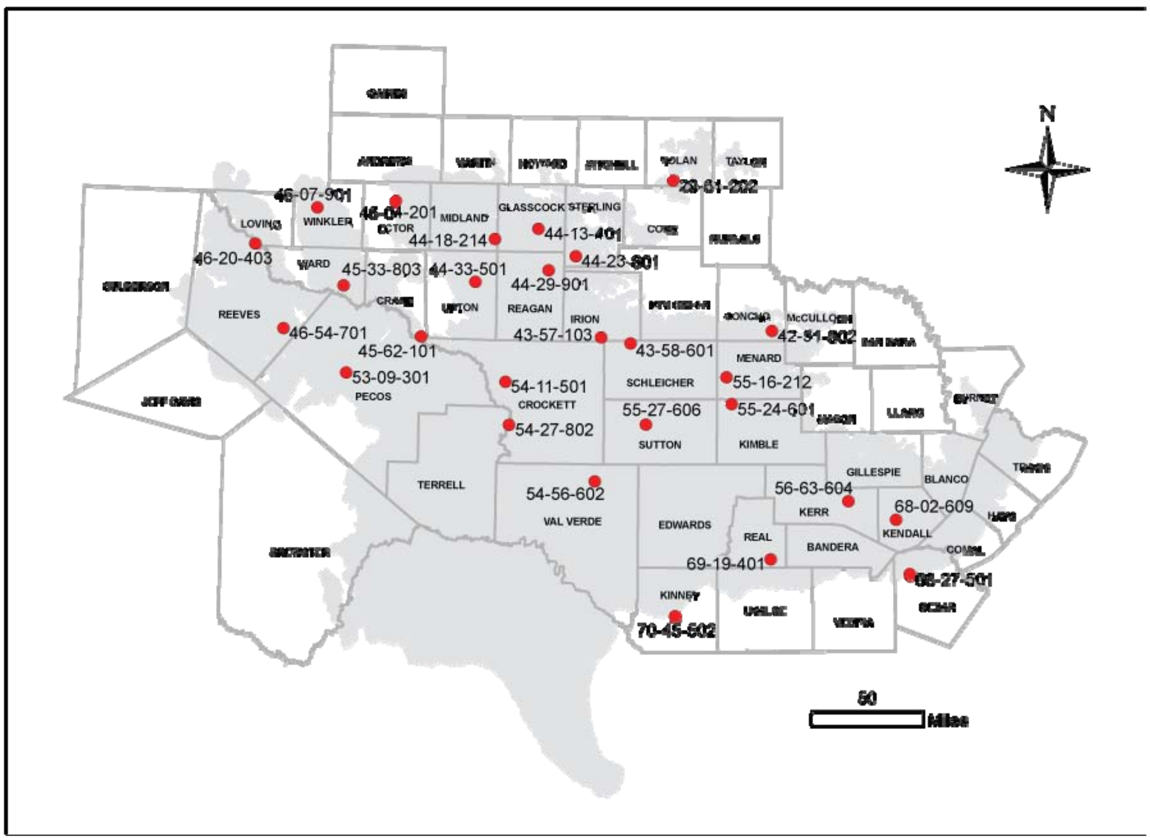


Figure B-1. Locations of the hydrograph wells in the model area.

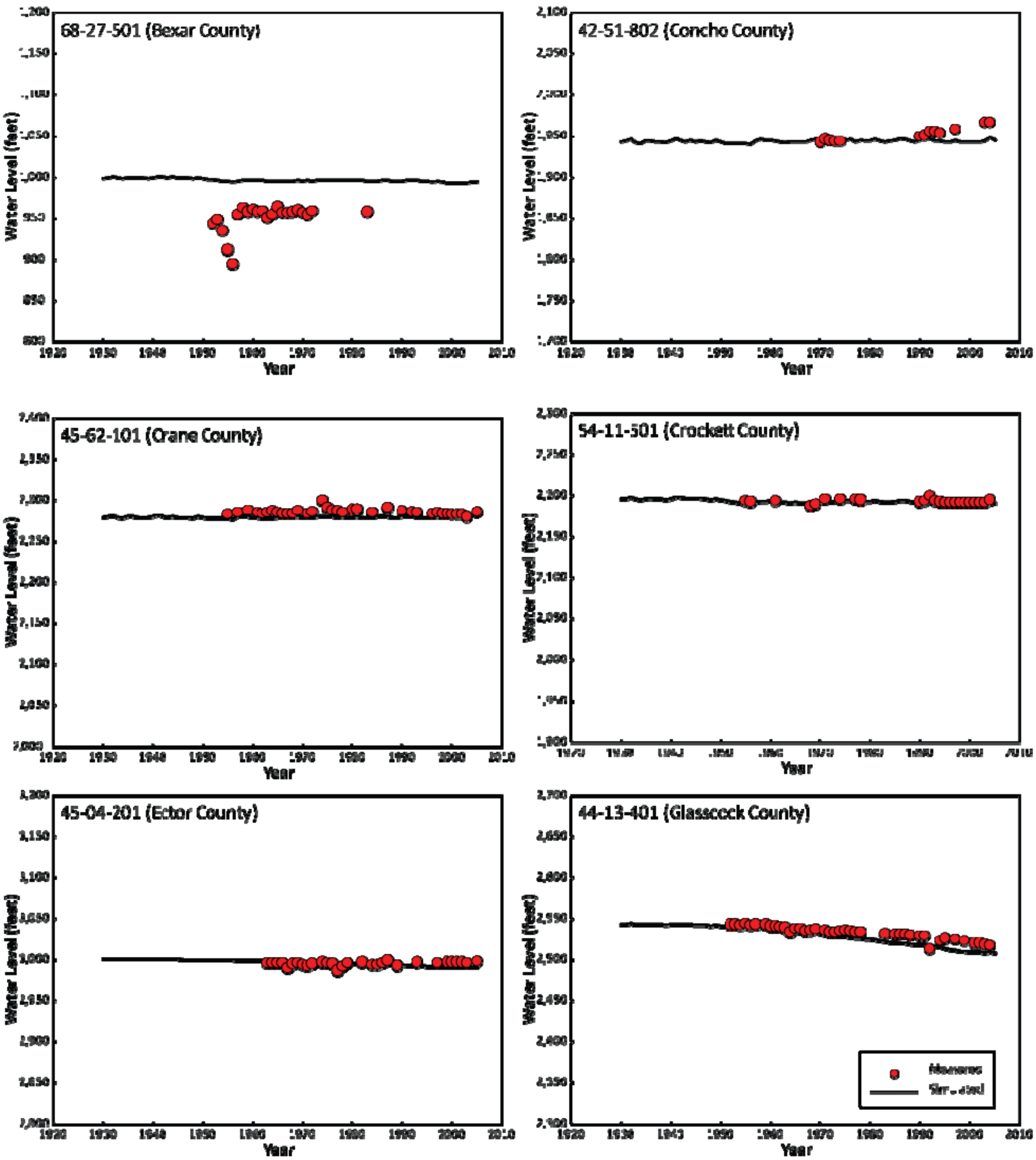


Figure B-2. Hydrographs for selected wells in the model area.

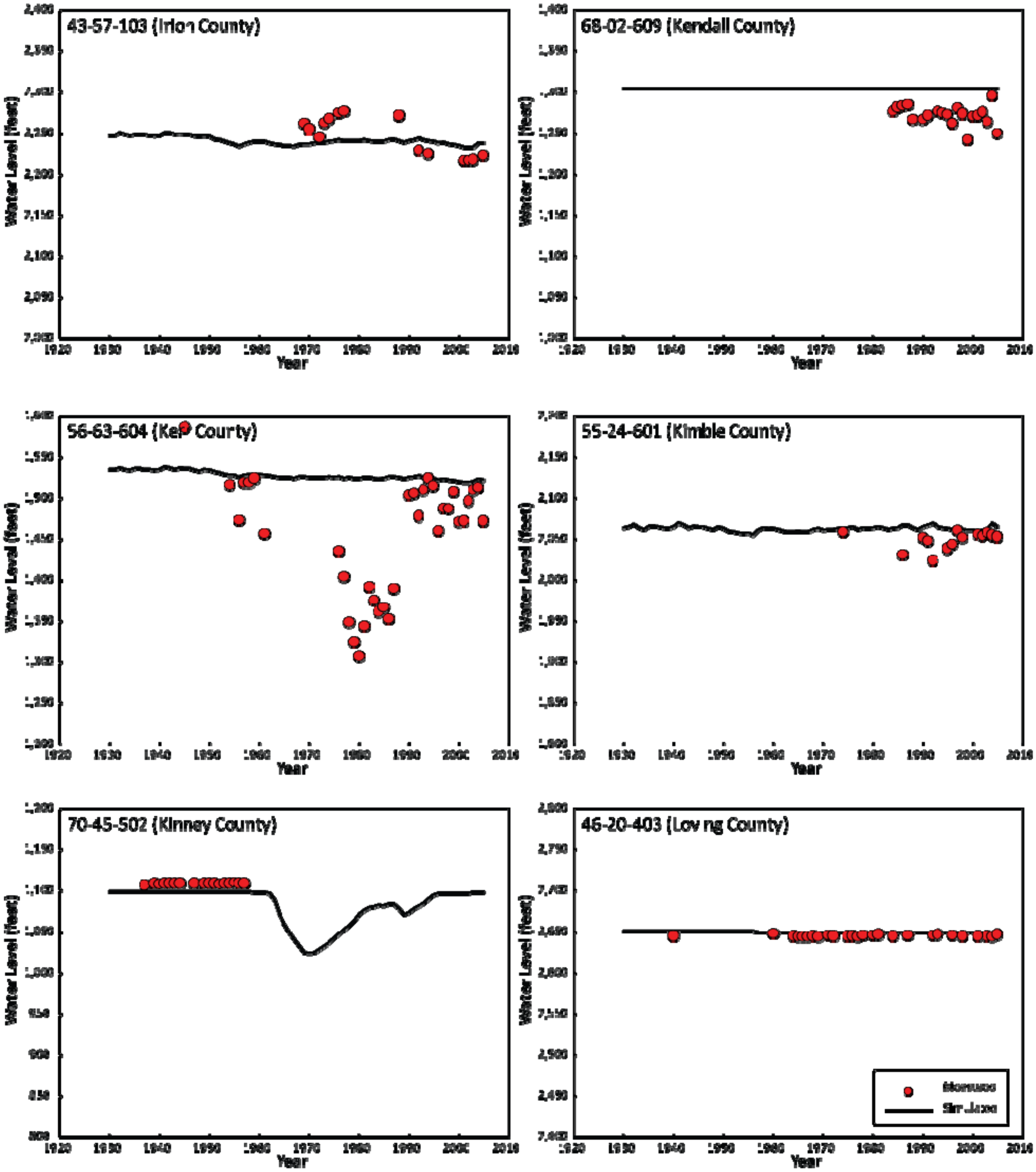


Figure B-2 (continued).

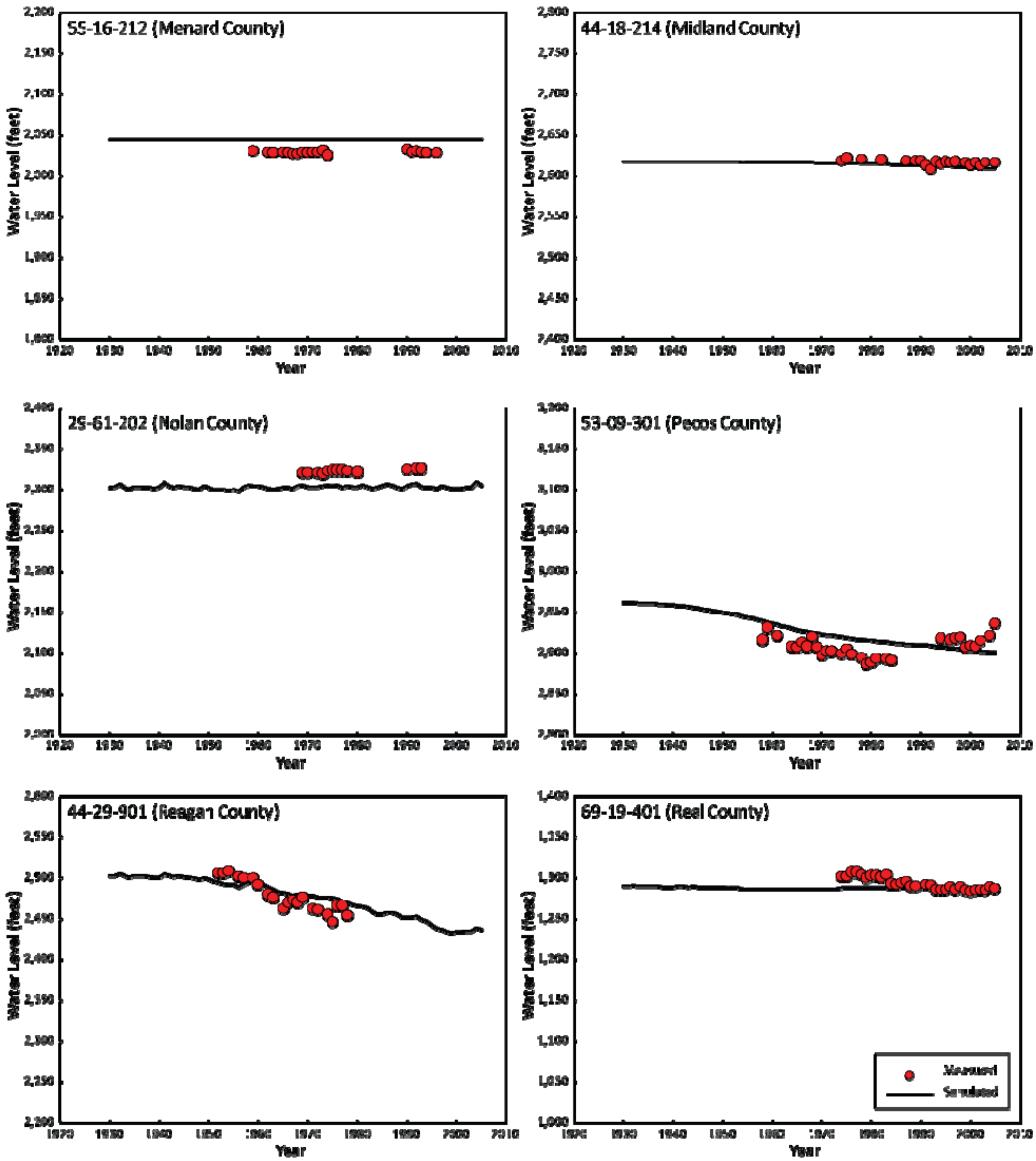


Figure B-2 (continued).

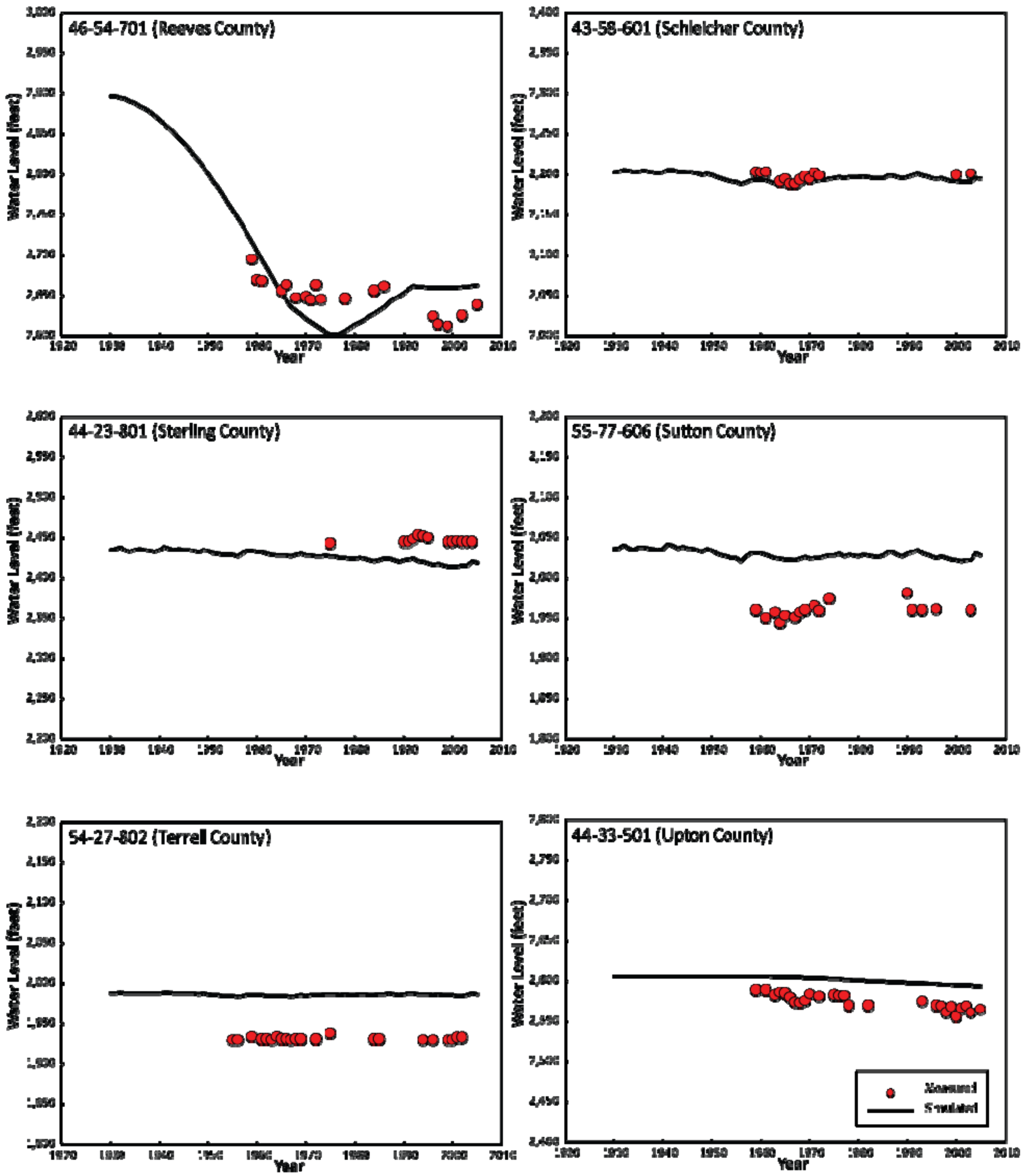


Figure B-2 (continued).

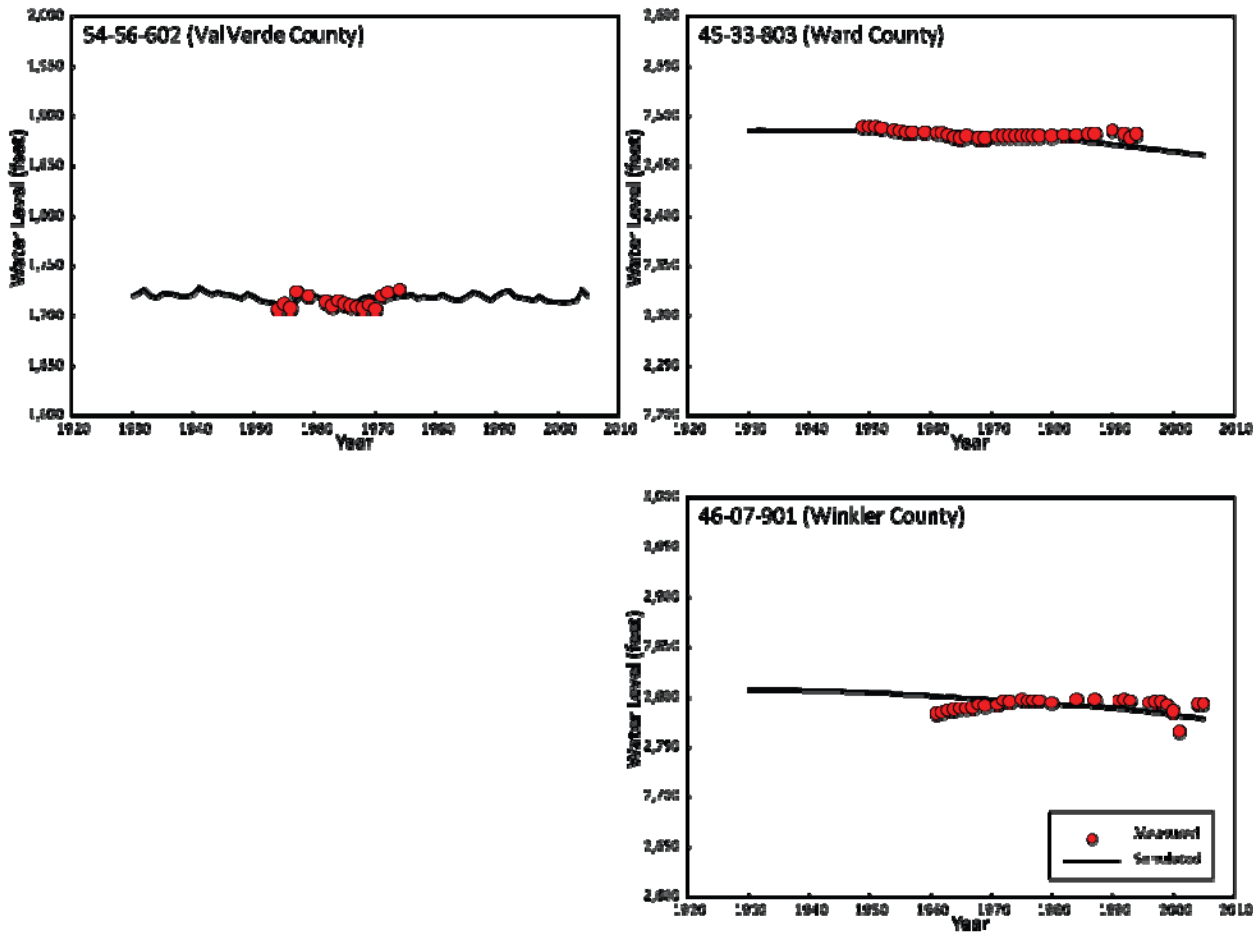


Figure B-2 (continued).

Update of the Groundwater Availability Model for the Edwards-Trinity (Plateau) and Pecos Valley Aquifers of Texas

Erratum

Page 3. The updated model is referred to as "version 2.01" on this page. Because the updated model is not an officially-recognized Groundwater Availability Model but an alternative version of the model–the original model is version 1.01–the correct reference should be "alternative version 2011".