Report: Recalibration of the Edwards (Balcones Fault Zone) Aquifer –Barton Springs Segment–Groundwater Flow Model

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Texas Water Development Board

June 2011

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EXECUTIVE SUMMARY

Groundwater Management Area 10 requested model runs associated with alternative Barton Springs flow conditions under drought conditions. Specifically, the request sought the amount of pumping that would result in specified springflows of 11, 9, 7, 5, and 3 cubic-feet per second under drought-of-record conditions. The existing groundwater availability model for the Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer (Scanlon and others, 2001) was calibrated based on data from 1989 to 1998. Thus, the calibration did not include the historic drought-of-record that lasted from 1950 through 1956, when the estimated minimum discharges of 11 cubic-feet per second (Slade and others, 1986) occurred for Barton Springs. Because the request focused on drought-of-record conditions, the confidence in the results from the existing model would be lower than results from a model that had been calibrated during the drought-of-record period. In order to develop results that would be more useful, the Scanlon and others (2001) model for the Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer was recalibrated for the period January 1943 to December 2004.

The updated model was calibrated using 744 estimated or measured discharges for Barton Springs (Slade and others, 1986) provided by the Barton Springs/Edwards Aquifer Groundwater Conservation District. Additionally, 152 target wells from the Texas Water Development Board's groundwater database

were used. These target wells had at least one groundwater elevation measurement during the calibration period. The total number of groundwater elevation measurements was 2,246. Simulated discharges at Barton Springs, using the updated model, include satisfactory agreement with the minimum estimated discharges of 11 cubic-feet per second that occurred in July and August of 1956 during the historic drought-of-record.

1.0 INTRODUCTION AND PURPOSE FOR GROUNDWATER FLOW MODEL

Groundwater Management Area 10 requested model runs associated with alternative Barton Springs flow conditions under a drought-of-record recurrence. Specifically, the request sought the amount of pumping that would result in specified springflows of 11, 9, 7, 5, and 3 cubic-feet per second under drought-of-record conditions. The existing groundwater availability model for the Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer (Scanlon and others, 2001) was calibrated based on data from 1989 to 1998. Thus, the calibration did not include the historic drought-of-record that lasted from 1950 through 1956, when the estimated minimum discharges of 11 cubic-feet per second occurred for Barton Springs. Because the request focused on drought-of-record conditions, the confidence in the results from the existing model would be lower than results from a model that had been calibrated during the drought-of-record period. In order to develop results that would be more useful, the Scanlon and others (2001) model for the Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer was recalibrated for the period January 1943 to December 2004.

The existing MODFLOW-96 (Harbaugh and McDonald, 1996) packages used by Scanlon and others (2001) were converted to MODFLOW-2000 (Harbaugh and others, 2000). MODFLOW-2000 was used with the Geometric Multigrid (GMG) solver (Wilson and Naff, 2004). The updated model included the Basic, Discretization, Layer-Property Flow, Well, Drain, Horizontal Flow Barrier, and Recharge packages. As with Scanlon and others (2001), this model consists of a single layer and conceptualized equivalent porous medium continuum. This conceptualization treats the matrix and conduit network as one continuum, thereby simulating the bulk hydraulic properties for the matrix and conduit network. Conduit networks are traditionally incorporated into equivalent continua models by assigning high hydraulic conductivity values to model cells at suspected conduit locations.

Conversely, conduits are explicitly incorporated into dual-porosity groundwater flow models where they are known to exist. Moreover, dual-porosity models use groundwater flow simulators that handle flow through the matrix and conduit networks separately. For example, the U.S. Geological Survey MODFLOW-2005 Conduit Flow Process, when operated in Mode 1, uses the Darcy-Weisbach equation to simulate turbulent flow in the conduit network and the Hagen-Poiseuille equation to simulate laminar flow in the conduit network, which differs from the governing groundwater flow equation used to simulate laminar flow in the rock matrix.

Additionally, fluid exchange between the matrix and conduit network is considered with an iterative head-dependent flux between the conduit network and rock matrix (Shoemaker and others, 2008). Application of dual-porosity models with the MODFLOW-2005 Conduit Flow Process operated in Mode 1 introduces new model parameters that require extensive characterization beyond that typically required for laminar equivalent continua models used with MODFLOW-2000.

In a previous comparison between the performances of a laminar-turbulent, dual-porosity model with a comparable laminar equivalent continuum model in a multi-porosity karst aquifer, improvements (12 to 40%) in the overall average match between simulated and measured discharges were observed by accounting for fluid exchange between the matrix and conduit network coupled with changes in hydraulic conductivity values. However, it was observed that during drought conditions, or low recharge periods, both the equivalent continuum model and the dual-porosity model underestimated discharges at a first magnitude spring. It was noted that the performance of both models during drought conditions may have improved had antecedent rainfall conditions been accounted for in the recharge estimates (Hill and others, 2010).

2.0 MODEL OVERVIEW

The existing MODFLOW-96 (Harbaugh and McDonald, 1996) packages used by Scanlon and others (2001) were converted to MODFLOW-2000 (Harbaugh and others, 2000). MODFLOW-2000 was used with the Geometric Multigrid (GMG) solver (Wilson and Naff, 2004). The updated model included the Basic, Discretization, Layer-Property Flow, Well, Drain, Horizontal Flow Barrier, and Recharge packages.

2.1 Model Packages

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

2.11 Basic Package

The Basic Package specifies the status of each cell (active or inactive), the assigned head for inactive cells (999), and specifications of starting heads. 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).

TABLE 1. SUMMARY OF MODEL INPUT PACKAGES AND FILENAMES.

MODFLOW-2000	**Input Filename**
Basic (BAS)	bseacd.bas
Name (NAM)	bseacd.nam
Discretization (DIS)	bseacd.dis
Zone Array File (ZONE)	bseacd.zone
Layer-Property FLOW (LPF)	bseacd.lpf
Well (WEL)	bseacd.wel
Drain (DRN)	bseacd.drn
Recharge (RCH)	bseacd.rch
Horizontal Flow Barrier (HFB)	bseacd.hfb
Output Control (OC)	bseacd.oc
Geometric Multigrid Solver (GMG)	bseacd.gmg

TABLE 2. SUMMARY OF MODEL OUTPUT FILES AND THEIR NAMES.

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

2.12 Discretization Package

The Discretization Package specifies the spatial and temporal discretization of the model. The model consists of a single layer with 120 rows and 120 columns. The cell length is 1,000 feet and the cell width is 500 feet. The time period for the model is days, and the distance unit for the model is feet. The combined steady-state/transient model defines 745 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. The next 744 stress periods are transient, each with a length of 30 days (1 month). The transient stress periods represent January 1943 through December 2004.

The same active model domain and model boundaries used by Scanlon and others (2001), as shown in Figure 1, was used in the updated model. Two previous dye-trace studies conducted in the eastern and confined portions of the aquifer during different flow conditions indicate that the groundwater divide separating the Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer may fluctuate according to hydraulic head conditions (Hunt and others, 2006). The use of an alternate boundary condition along this portion of the study area is an item that may be addressed in future updates to the model. Similar to Scanlon and others (2001), the updated model does not account for flows from the Trinity Aquifer.

Minor corrections were made to the hydrogeologic framework (top and bottom elevations of the aquifer) used by Scanlon and others (2001). Elevations for the top and bottom of the Edwards (Balcones Fault Zone) Aquifer used in the updated model are shown in Figure 2.

2.13 Zone Array File

The zone array file is used to specify the cells in a layer variable that are associated with a parameter (Harbaugh and others, 2000). Zones for hydraulic conductivity, storativity, and recharge can be specified in the zone array file.

2.14 Layer-Property Flow Package

The Layer-Property Flow Package specifies the 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 was set equal to zero, which assumes a constant transmissivity condition throughout the simulation. As a result of this specification, the only storage value required is specific storage. That is, MODFLOW-2000 will not read them (item 14; specific yield), even if written to the Layer Property Flow Package, when LAYTYP=0 (Harbaugh and others, 2000). By assuming a constant transmissivity condition, (LAYTYP=0) there is no occurrence of cells converting to dry during the simulation. LAYAVG was set equal to zero (interblock transmissivity is based on a harmonic mean) and CHANI equal to -1, which means that horizontal anisotropy is assigned on a cell-to-cell basis. Hydraulic conductivity is read and multiplied by the saturated thickness at the beginning of the simulation to estimate aquifer transmissivity.

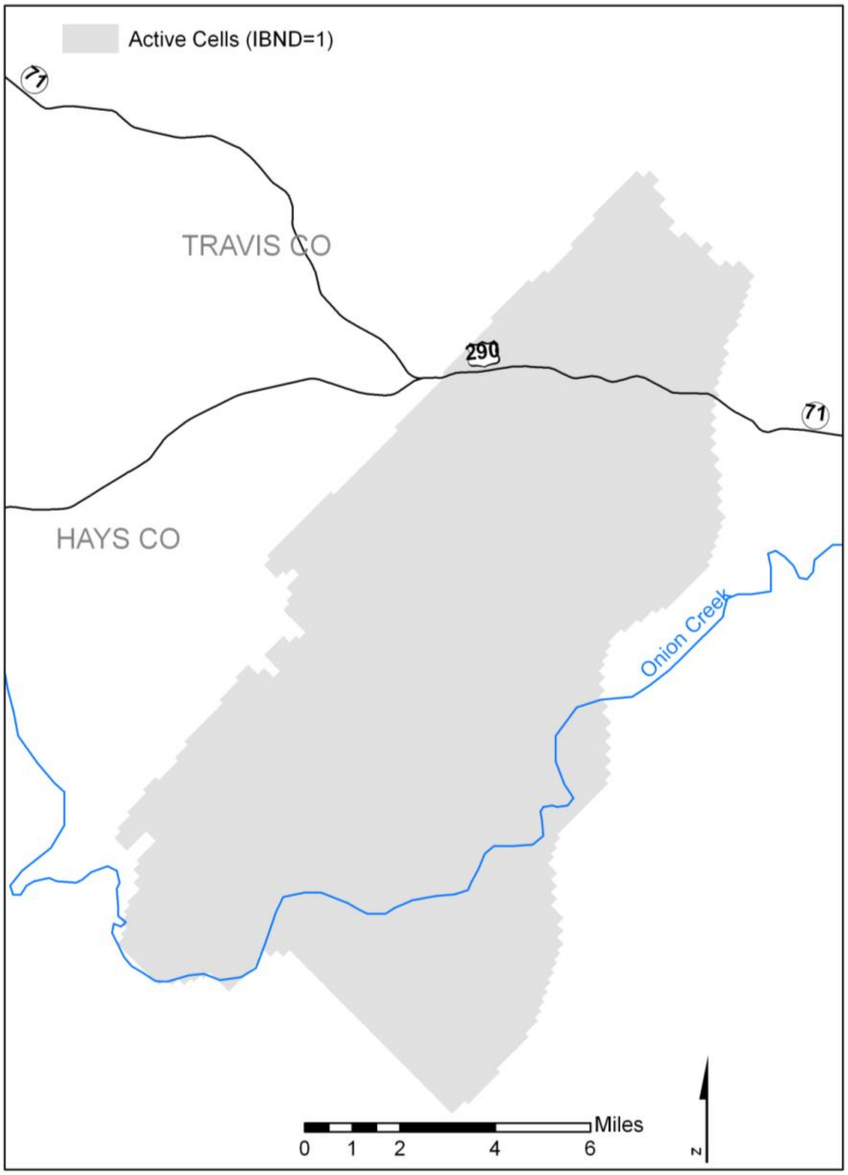
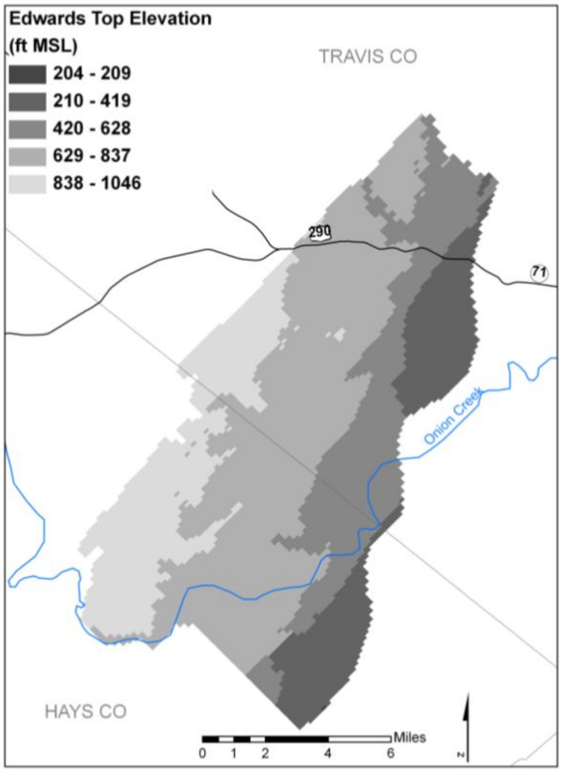


FIGURE 1. ACTIVE MODEL CELLS WITHIN THE MODEL DOMAIN FOR THE EDWARDS (BALCONES FAULT ZONE)—BARTON SPRINGS SEGMENT—GROUNDWATER AVAILABILITY MODEL (FROM SCANLON AND OTHERS, 2001).



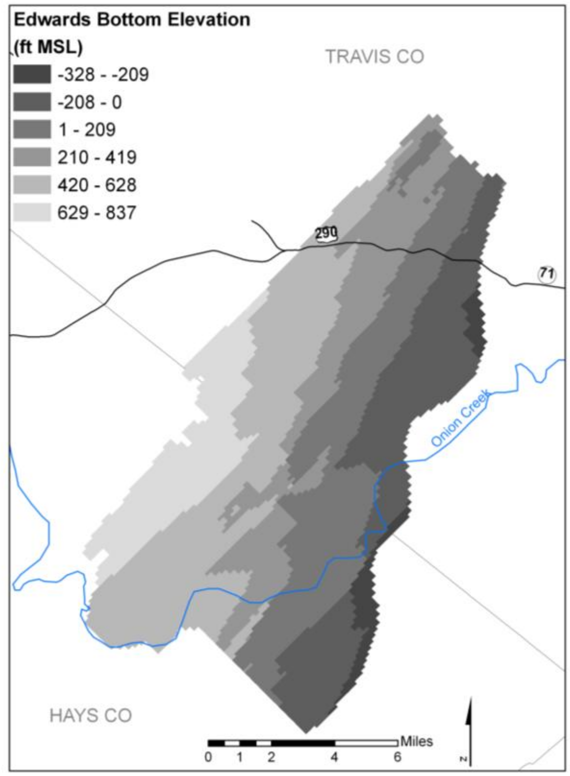


FIGURE 2. TOP AND BOTTOM ELEVATIONS FOR THE EDWARDS (BALCONES FAULT ZONE) AQUIFER IN THE UPDATED MODEL.

In order to facilitate calibration, the Layer-Property Flow Package was written using a pre-processor program (*lpf.exe*) written in FORTRAN. In summary, the *lpf.exe* pre-processor reads a file of aquifer parameter zone numbers (*kszone.dat*) and two database files, one for hydraulic conductivity (*kdb.dat*) and one for specific storage (*sdb.dat*), and writes a new Layer-Property Flow data file that can be read by MODFLOW-2000.

The hydraulic conductivity file (*kdb.dat*) contains estimates for hydraulic conductivity in the x-, y-, and z-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 hydraulic conductivity database contains a value for vertical hydraulic conductivity and the MODFLOW-2000 input file requires specification of the vertical hydraulic conductivity, these values have no meaning since this is a one-layer model. The pre-processor program also uses the aquifer parameter zonation file (*kszone.dat*) with the specific storage database file (*sdb.dat*) to write specific storage estimates for each cell.

The same hydraulic conductivity zonation used by Scanlon and others (2001) was used in the updated model. The nine hydraulic conductivity zones (1, 3, 4, 5, 6, 7, 8, 9, and 10) in the active area of the model domain are shown in Figure 3. Zone 2 represents the inactive area of the model domain, and therefore is not shown in Figure 3.

Figure 4 is a bar graph with hydraulic conductivity values from the updated model and those from the Scanlon and others (2001) model. One apparent difference is that in the previous model, hydraulic conductivity is isotropic, whereas in the new model hydraulic conductivity is anisotropic. Table 3 summarizes the model zones, hydraulic conductivity values in the x- and y-directions, and the anisotropy ratios. Hydraulic conductivity values for each zone in the Scanlon and others (2001) model are provided for comparison. Table 4 lists the specific storage values for each zone in the active model domain.

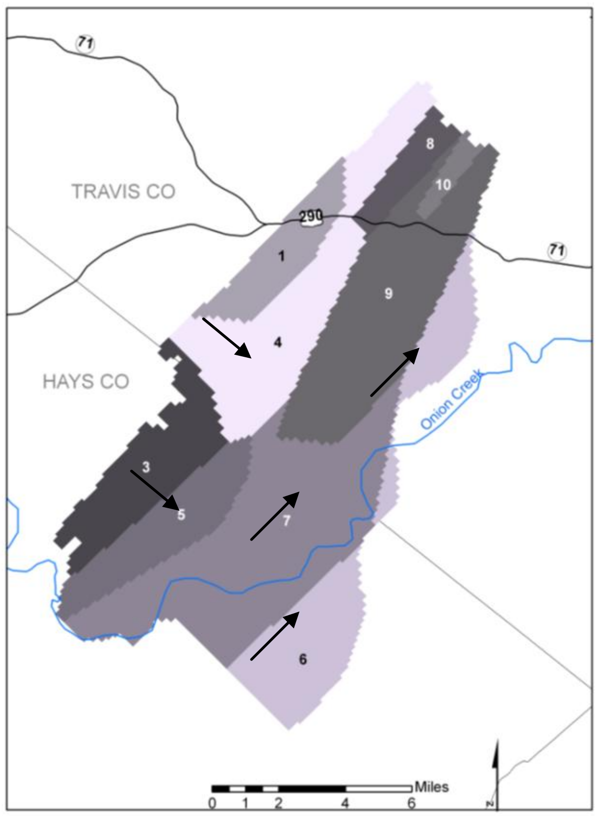


FIGURE 3. HYDRAULIC CONDUCTIVITY ZONES (FROM SCANLON AND OTHERS, 2001). ARROWS SHOW THE GENERAL TREND IN ANISOTROPY. ZONE 2 IS NOT LISTED AS IT REPRESENTS THE INACTIVE AREAS OF THE MODEL.

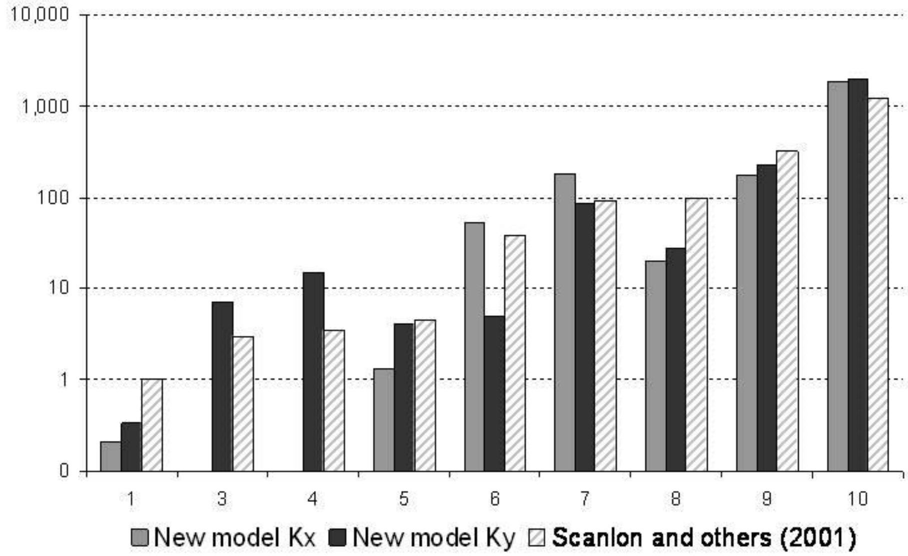


FIGURE 4. BAR GRAPH OF HYDRAULIC CONDUCTIVITY VALUES IN THE UPDATED MODEL AND THOSE USED BY SCANLON AND OTHERS (2001). HYDRAULIC CONDUCTIVITY IS ANISOTROPIC IN THE UPDATED MODEL AND ISOTROPIC IN THE SCANLON AND OTHERS (2001) MODEL. ZONE 2 IS NOT LISTED AS IT REPRESENTS THE INACTIVE AREAS OF THE MODEL. HYDRAULIC CONDUCTIVITY VALUES IN THE X-DIRECTION FOR ZONES 3 AND 4 IN THE UPDATED MODEL ARE 0.1 FT/DAY (SEE TABLE 3) AND THEREFORE, ARE NOT VISIBLE IN FIGURE 4.

TABLE 3. HYDRAULIC CONDUCTIVITY VALUES IN THE UPDATED MODEL (ANISOTROPIC) COMPARED TO THOSE USED BY SCANLON AND OTHERS (2001) WHICH ARE ISOTROPIC. ZONE 2 IS NOT LISTED AS IT REPRESENTS THE INACTIVE AREAS OF THE MODEL.

Zone	New Model			Scanlon and others (2001)
	Kx (feet/day)	Ky (feet/day)	Kx/Ky	Kx=Ky (feet/day)
1	0.2	0.3	0.7	1
3	0.1	7.2	0.01	3
4	0.1	15.0	0.01	3.5
5	1.3	4.1	0.3	4.5
6	52.2	5.0	10	39
7	176.0	85.8	2	93
8	20.0	27.3	0.7	100
9	172.0	227.0	0.8	320
10	1,855.9	2,000.0	0.9	1,236

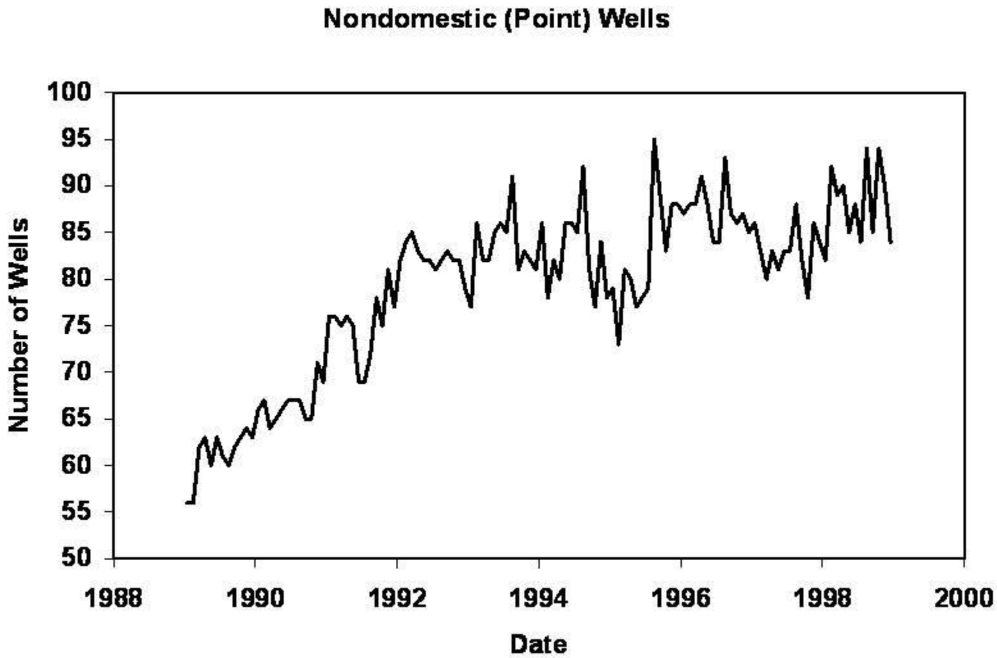
TABLE 4. SPECIFIC STORAGE VALUES FOR EACH ZONE IN THE ACTIVE AREA OF THE UPDATED MODEL. ZONE 2 IS NOT LISTED AS IT REPRESENTS THE INACTIVE AREAS OF THE MODEL.

Zone	Ss(feet^{-1})
1	1.7×10^{-5}
3	7.2×10^{-5}
4	3.2×10^{-6}
5	1.3×10^{-5}
6	2.2×10^{-7}
7	1.1×10^{-5}
8	1.7×10^{-4}
9	8.7×10^{-8}
10	1.2×10^{-3}

2.15 Well Package

The Well Package was used to simulate pumping from domestic (rural) and non-domestic or point withdrawals. For the updated transient model, monthly groundwater withdrawal estimates from 1947 through 2004 were provided by the Barton Springs/Edwards Aquifer Conservation District. Groundwater withdrawal quantities from 1943 through 1946 were assumed to be comparable to 1947 withdrawal quantities. Domestic (rural) pumpage quantities were distributed uniformly throughout the active model domain. Non-domestic, or point withdrawals, were distributed using the same monthly distributions applied in the Scanlon and others (2001) Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer groundwater availability model. Domestic (rural) and non-domestic (point) withdrawal quantities were extrapolated backward (1943 through 1988) and forward (1999 through 2004). The extrapolations involved separating out the number of non-domestic or point wells and the percent of domestic or rural pumping. Figure 5 shows the number of non-domestic or point wells in the Scanlon and others (2001) model and the percent of non-domestic or rural pumping.

Twelve regression models were developed using the percentage of domestic pumping in the Scanlon and others (2001) model with year and precipitation as the independent variables for the months of January through December. Figure 6 shows an example of the percent of rural pumping in the Scanlon and others (2001) model with the regression model developed for the month of June. The intercepts, coefficients, and coefficients of determination are listed in Table A-1 of Appendix A for the twelve regression models.



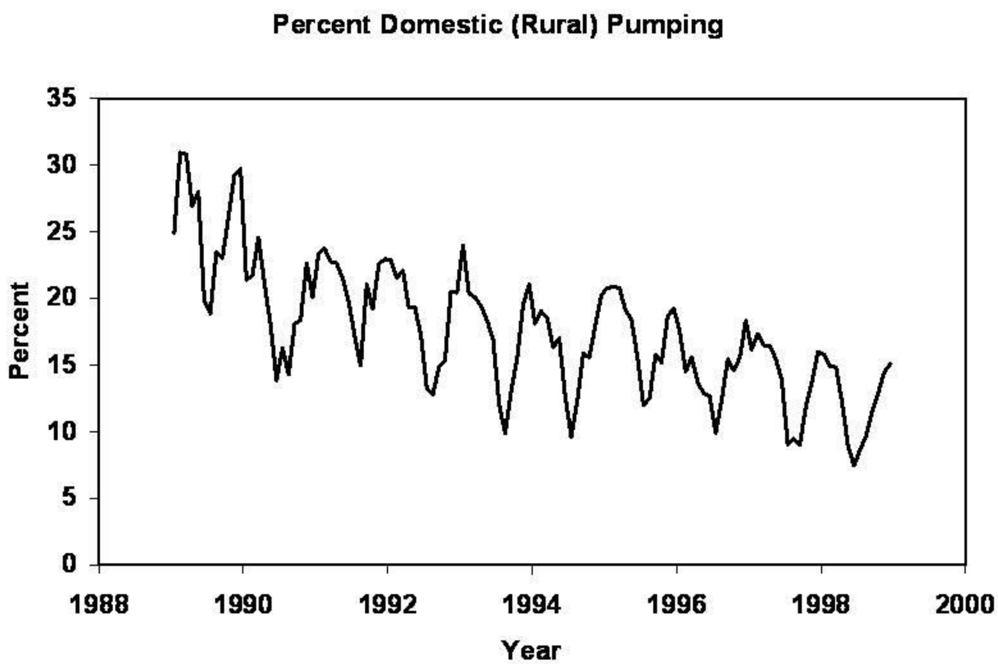


FIGURE 5. NUMBER OF NON-DOMESTIC OR POINT WELLS IN SCANLON AND OTHERS (2001) MODEL (TOP) AND PERCENT OF DOMESTIC OR RURAL PUMPING IN SCANLON AND OTHERS (2001) MODEL (BOTTOM). THE TOTAL NUMBER OF WELLS (NON-DOMESTIC PLUS DOMESTIC) IS 7,037.

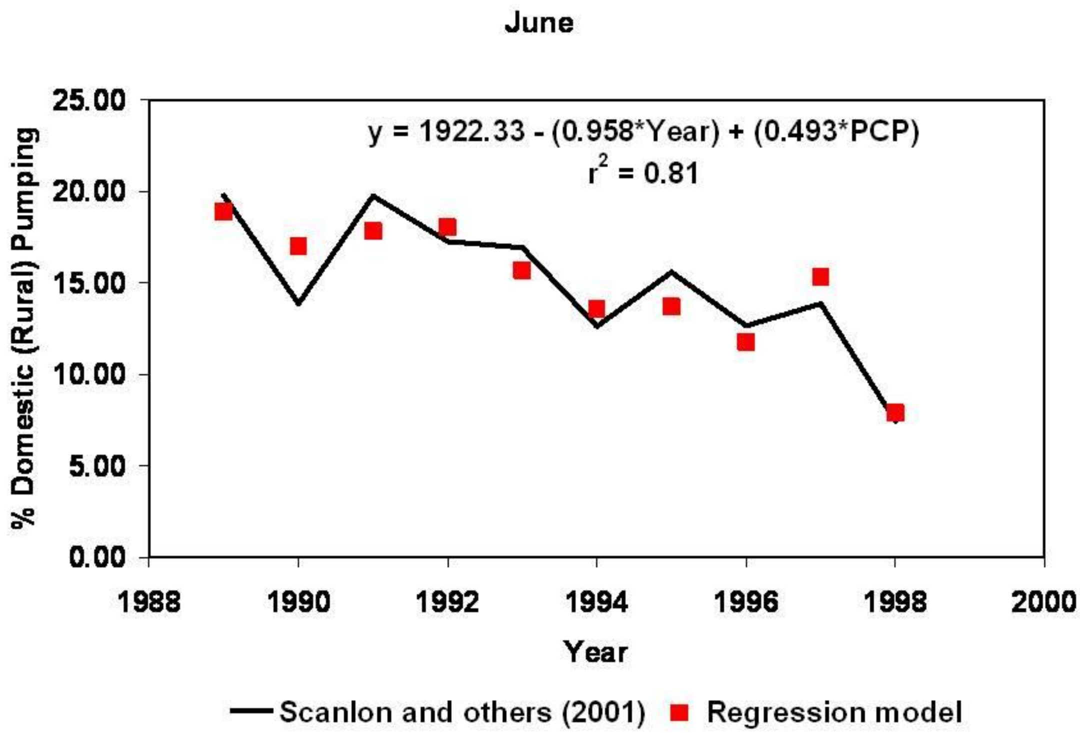


FIGURE 6. PERCENT OF RURAL PUMPING FOR THE MONTH OF JUNE BASED ON THE REGRESSION MODEL RELATIVE TO THAT IN THE SCANLON AND OTHERS (2001) MODEL.

A pre-processor program (*pumping.exe*) written in FORTRAN was used to develop the well package and to facilitate calibration. In summary, *pumping.exe* reads an input file (*kszone.dat)* and several database files (*pcpindex.dat*, *begpumpaf.dat*, *pumpcoef.dat*, *begwel.dat*, *minmaxpumpyear.dat*, *welcount.dat*, *pumpfac.dat, pump43to04.dat*) and writes a new well file (*newpump.wel*) that is read by MODFLOW-2000 and one summary file (*newpumpsum.dat*).

The pumping zonation in the new model honors the zonation used for aquifer properties (shown in Figure 3). The pre-processor reads the zones from *kszone.dat*. *Begpumpaf.dat* contains the domestic and non-domestic pumping quantities separately, as well as the composite of the two quantities in acre-feet per month that were used by Scanlon and others (2001). The database file *pumpcoef.dat* contains the intercepts, and coefficients for the year and precipitation variables for the twelve regression equations. *Begwel.dat* contains the well file from the Scanlon and others (2001) model, whereas *minmaxpumpyear.dat* contains the minimum and maximum pumping year for the months of January through December in the Scanlon and others (2001) model. *Welcount.dat* contains the number of point or non-domestic wells for each of the monthly stress periods in the Scanlon and others (2001) model. *Pumpfac.dat* contains the decadal pumping factors (or for the subset of years for periods that did not span the full decade, as is the case for 1943 through 1949 and 2000 through 2004) for each zone. *Pump43to04.dat* contains the monthly pumping from 1943 to 2004 based on the extrapolations.

Annual average pumping per zone in the new model is summarized in Table 5. A comparison of annual average pumping in the updated model and pumping estimates provided by the Barton Springs/Edwards Aquifer Conservation District is summarized in Table 6.

TABLE 5. SUMMARY OF ANNUAL AVERAGE PUMPING FOR EACH MODEL ZONE DURING THE RESPECTIVE TIME FRAME. ALL PUMPING QUANTITIES REPORTED ARE IN ACRE-FEET PER YEAR.

Zone	Pumping 1943-1949	Pumping 1950-1959	Pumping 1960-1969	Pumping 1970-1979	Pumping 1980-1989	Pumping 1990-1999	Pumping 2000-2004
1	0.69	24.24	43.26	63.14	44.45	52.22	50.55
3	0.01	45.88	105.40	110.69	109.74	49.19	67.58
4	2.33	81.41	172.39	147.88	299.80	178.09	214.48
5	4.73	38.60	43.22	94.61	81.05	49.91	89.11
6	19.19	228.83	591.32	850.66	1,281.18	1,271.09	2,214.33
7	3.53	368.66	430.27	673.81	1,839.55	1,435.77	2,058.36
8	2.38	15.31	25.72	20.25	33.70	15.59	13.07
9	13.26	131.67	312.97	203.26	397.90	459.68	529.11
10	1.10	6.20	14.01	8.75	13.71	10.17	6.82
Average annual pumping (acre-feet per year)	47.22	940.79	1,738.56	2,173.04	4,101.10	3,521.71	5,243.42

TABLE 6. ANNUAL AVERAGE PUMPING IN THE UPDATED MODEL VERSUS PUMPAGE ESTIMATES PROVIDED BY THE BARTON SPRINGS/EDWARDS AQUIFER CONSERVATION DISTRICT. ALL PUMPING QUANTITIES REPORTED ARE IN ACRE-FEET PER YEAR.

Period	Pumping Updated Model (acre-feet per year)	Barton Springs/ Edwards Aquifer Conservation District* Estimates (acre-feet per year)
1943-1949	47.22	74.10**
1950-1959	940.79	363.61
1960-1969	1,738.56	1,299.32
1970-1979	2,173.04	2,265.78
1980-1989	4,101.10	3,214.64
1990-1999	3,521.71	3,963.70
2000-2004	5,243.42	5,810.44

* Estimates provided by Barton Springs/Edwards Aquifer Conservation District range from January 1947 through December 2004.
** 1947 through 1949

Figure 7 shows a graphical summary of monthly pumping and annual average pumping in the updated model relative to estimates provided by the Barton Springs/Edwards Aquifer Conservation District. Figure 8 shows the monthly pumping (domestic and non-domestic) quantities with the monthly individual non-domestic and domestic pumping quantities in the updated model.

Pumpage estimates provided by the Barton Springs/Edwards Aquifer Conservation District were used to loosely constrain pumpage quantities in the groundwater flow model. During model calibration, pumpage was adjusted by decade (for the 1950’s, 1960’s, 1970’s, 1980’s, and 1990’s), or for the subset of years for periods that did not span the full decade, as is the case for 1943 through 1949 and 2000 through 2004.

The largest differences between pumpage quantities used in the updated model and the estimates provided by the Barton Springs/Edwards Aquifer Conservation District occur during the simulated historic drought of record (1950s) and the 1980’s (Table 6 and Figure 7). During the simulated historic drought of record, pumpage quantities in the updated model are generally higher than pumpage estimates provided by the Barton Springs/Edwards Aquifer Conservation District by a factor of 2.6. During the 1980’s, the pumpage quantities in the updated model are generally higher than pumpage estimates provided by the Barton Springs/Edwards Aquifer Conservation District by a factor of 1.3.

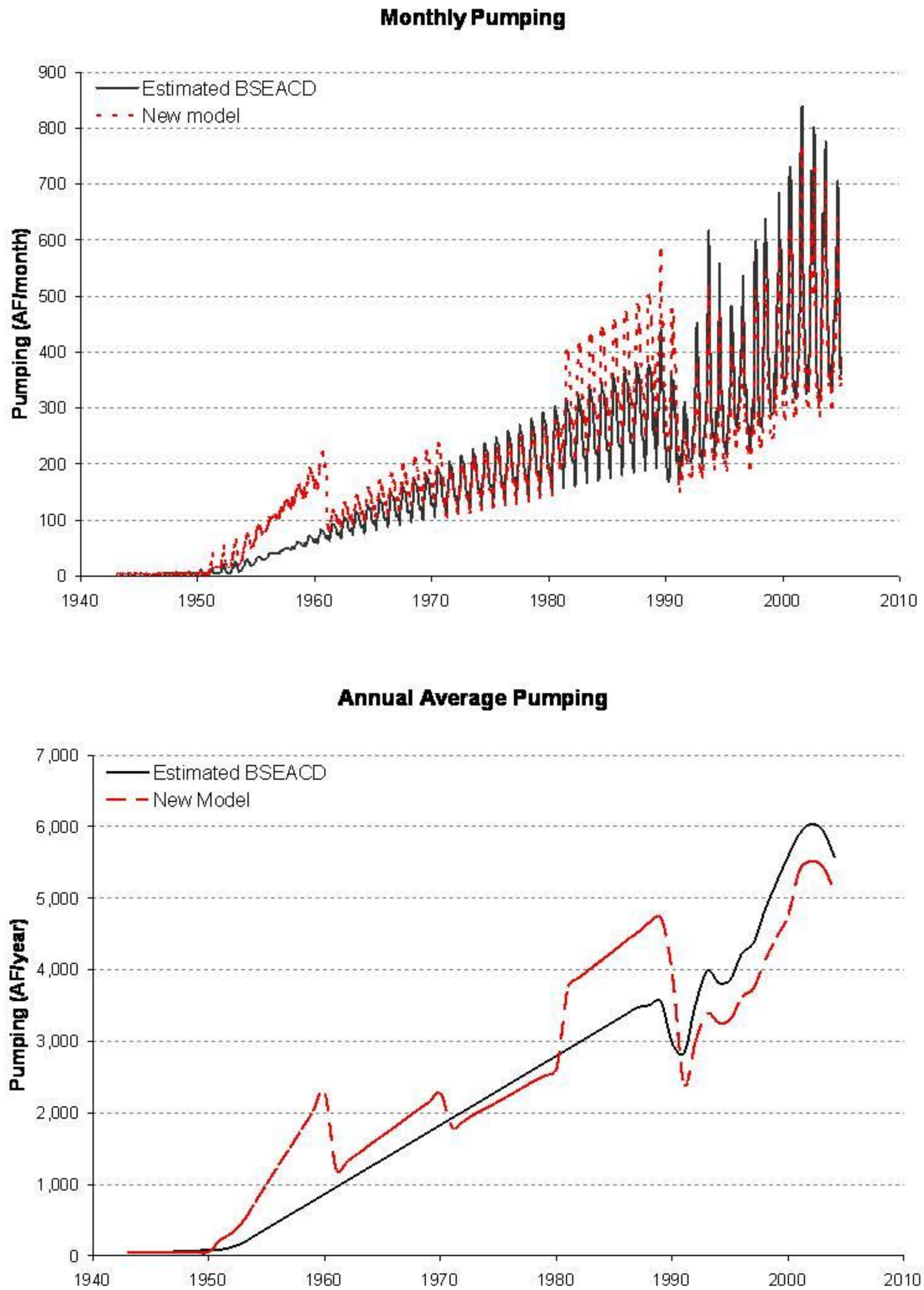


FIGURE 7. PLOT WITH MONTHLY PUMPING ESTIMATES PROVIDED BY THE BARTON SPRINGS/EDWARDS AQUIFER CONSERVATION DISTRICT (BSEACD) VERSUS MONTHLY PUMPING IN THE UPDATED MODEL (TOP) AND ANNUAL AVERAGE PUMPING ESTIMATES PROVIDED BY THE BARTON SPRINGS/EDWARDS AQUIFER CONSERVATION DISTRICT (BSEACD) VERSUS ANNUAL AVERAGE PUMPING IN THE UPDATED MODEL (BOTTOM).

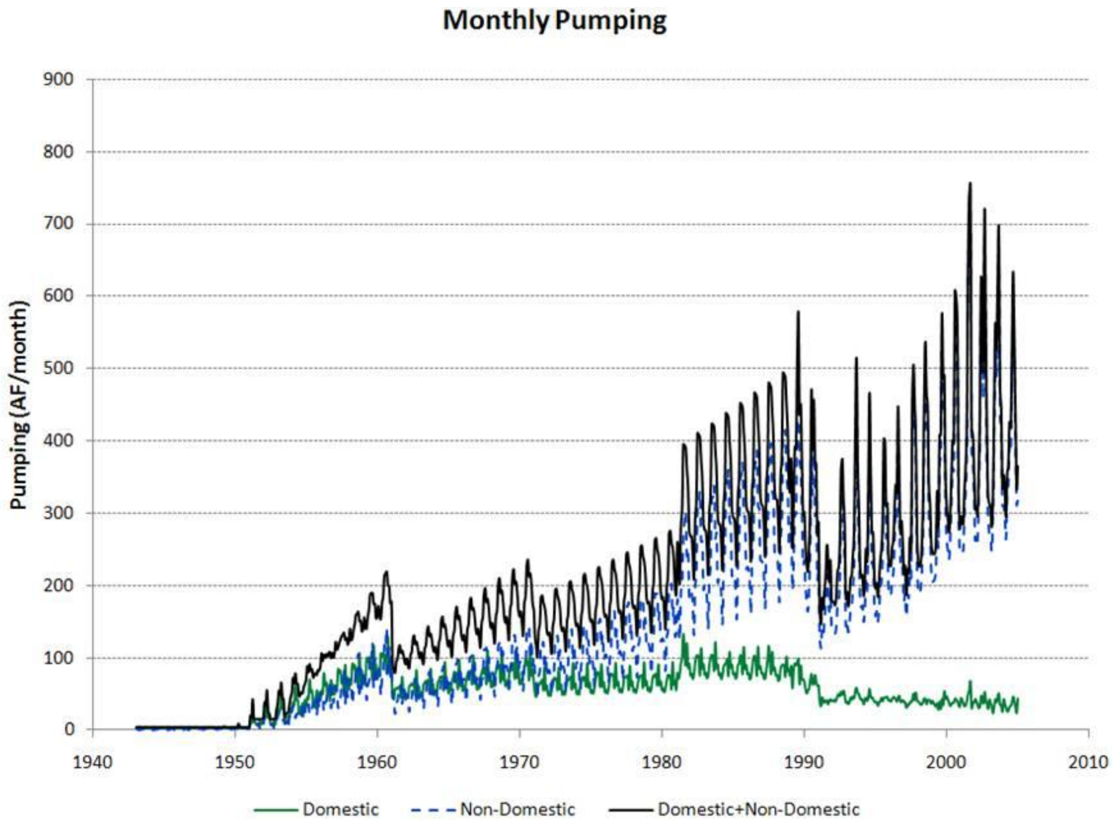


FIGURE 8. MONTHLY PUMPING (DOMESTIC PLUS NON-DOMESTIC) QUANTITIES WITH MONTHLY INDIVIDUAL NON-DOMESTIC AND DOMESTIC QUANTITIES IN THE UPDATED MODEL.

2.16 Drain Package

The Drain Package was used to simulate discharge from Barton and Cold springs. Drain conductances were varied during model calibration. The conductance values in the new calibrated model (3×10^6 feet-squared per day for Barton and 1×10^6 feet-squared per day for Cold Springs) are comparable to those used in the Scanlon and others (2001) model (1×10^6 feet-squared per day for Barton and Cold Springs).

2.17 Recharge Package

The seven (7) recharge zones applied in the Scanlon and others (2001) model which roughly correlate to the various sub watersheds that occur where the Edwards (Balcones Fault Zone) Aquifer is exposed at land surface were also used in the updated model. These zones include both focused recharge at karst features along Onion, Little Bear, Bear, Slaughter, Williamson, and Barton Creeks, in addition to distributed rainfall falling on the outcrop area (Figure 9).

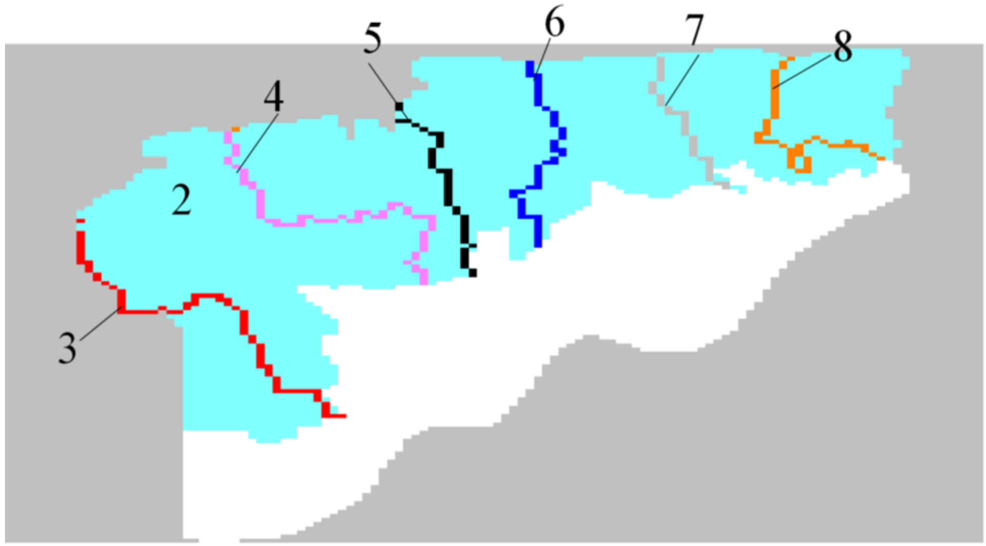


FIGURE 9. SEVEN RECHARGE ZONES. ZONES 2 THROUGH 8 ARE SHOWN. ZONE 1 IS THE CONFINED AREA OF THE EDWARDS (BALCONES FAULT ZONE) AQUIFER (WHITE) ZONE. DISTRIBUTED OUTCROP AREA (2), ONION CREEK (3), LITTLE BEAR CREEK (4), BEAR CREEK (5), SLAUGHTER CREEK (6), WILLIAMSON CREEK (7) AND BARTON CREEK (8).

Recharge estimates for the updated model were extrapolated as follows: 84 regression relationships were developed for each month (12 total) and recharge zone (7 total) using the recharge for each zone in the Scanlon and others (2001) model and a precipitation index. The precipitation index accounts for antecedent rainfall and was developed by taking the average monthly rainfall recorded at San Marcos and Austin Airport rainfall gages for the month of interest, plus half of the previous month of interest, plus one fourth of the month prior to the previous month of interest as shown in equation 1:

$$PI = m_i + \frac{1}{2} m_{i-1} + \frac{1}{4} m_{i-2} \qquad \text{(equation 1)}$$

where:

PI = precipitation index,

m_i = month of interest,

Figure 10 provides an example of the regression model developed using the precipitation index versus recharge for zone 3 (Onion Creek) in the Scanlon and others (2001) model for the month of October. The coefficients, constants, and the coefficients of determination for the eighty-four regression models developed for each month and zone are summarized in Table B-1 of Appendix B.

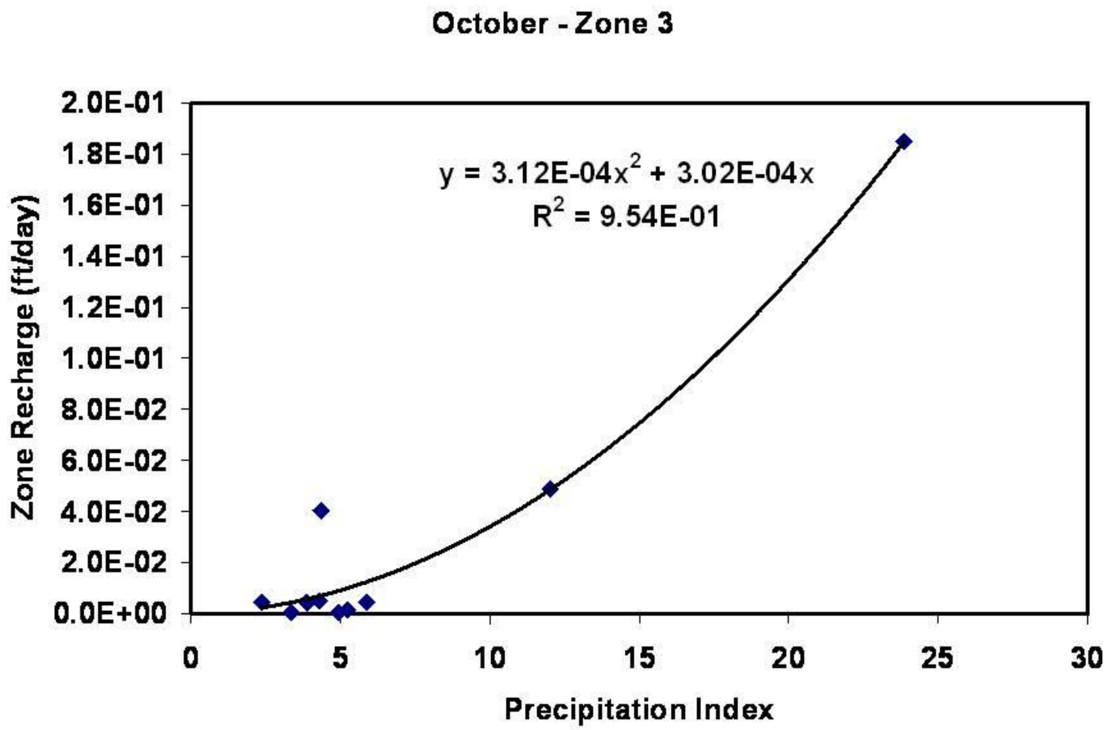


FIGURE 10. REGRESSION MODEL DEVELOPED USING THE PRECIPITATION INDICES FOR THE MONTH OF OCTOBER AND THE RECHARGE QUANTITIES IN ZONE 3 (ONION CREEK) FROM THE SCANLON AND OTHERS MODEL (2001).

Figure 11 summarizes the results of applying the regression approach to estimate recharge for the entire calibration period. Please note that strict application of this approach yielded two anomalies (circled areas in Figure 11) where recharge appears unacceptably high. In an effort to avoid this type of condition during model calibration, such as that shown in Figure 11, the maximum recharge rate was capped for each zone.

During model calibration the following adjustments were made to the regression-based estimates: 1) the maximum recharge rate by zone, 2) wet threshold and wet factor by month, 3) dry threshold and dry factor by month, and 4) decadal adjustments for the 1950’s, 1960’s, 1970’s, 1980’s, and 1990’s, or for the subset of years for periods that did not span the full decade, as is the case for 1943 through 1949 and 2000 through 2004. Decadal adjustments to recharge were tested to account for reported changes in recharge resulting from urbanization (Sharp and others, 2009), but proved to be insensitive. Maximum recharge rates for the calibrated model are listed in Table 7. Dry month thresholds and factors, wet month thresholds and factors, and the decadal factors are listed in Tables 8 and 9.

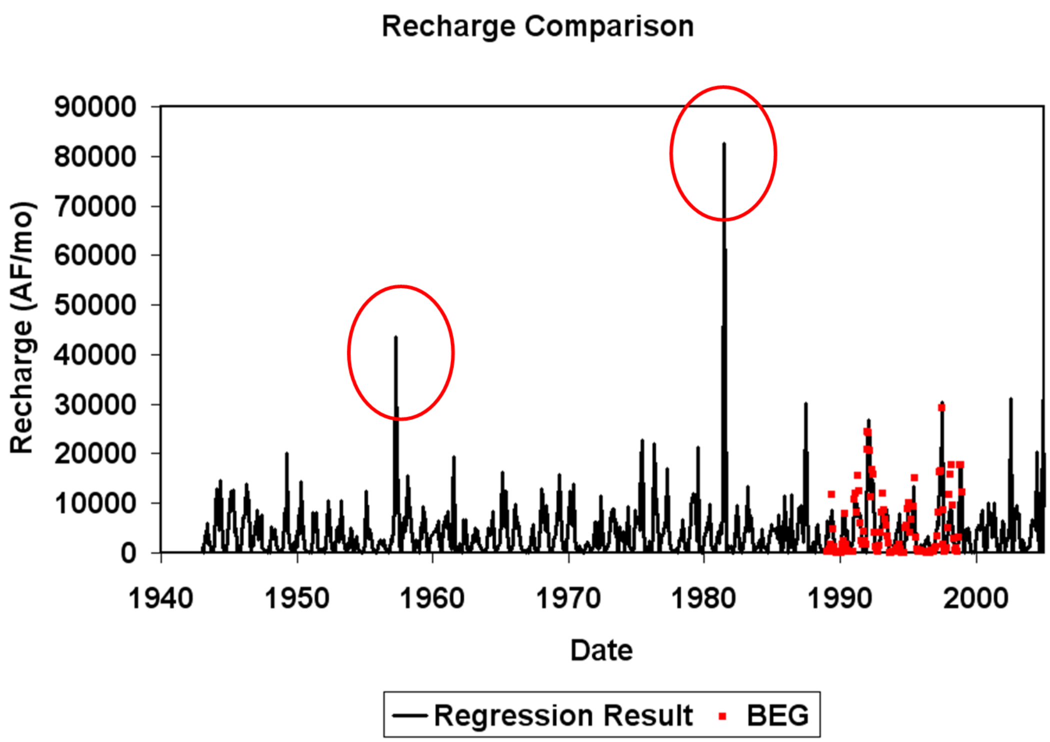


FIGURE 11. A COMPARISON OF MONTHLY RECHARGE BASED ON THE REGRESSION MODELS WITH THAT USED IN THE SCANLON AND OTHERS (2001) MODEL (NOTED AS "BEG" IN THE LEGEND). TWO ANOMALIES (CIRCLED) ARE APPARENT.

TABLE 7. MAXIMUM RECHARGE RATES PER ZONE IN THE UPDATED MODEL.

Zone	Maximum Recharge Rate (feet/day)
2	2.00×10^{-3}
3	2.00×10^{-1}
4	5.00×10^{-2}
5	1.97×10^{-1}
6	6.26×10^{-2}
7	3.01×10^{-2}
8	1.80×10^{-1}

TABLE 8. DRY THRESHOLDS, DRY FACTORS, WET THRESHOLDS, AND WET FACTORS FOR MONTHS 1 THROUGH 12 IN THE UPDATED MODEL.

Month	Dry Threshold	Factor	Wet Threshold	Factor
1	4	0.143	6	9.500
2	4	0.100	7	0.700
3	4	0.100	8	0.700
4	5	0.100	6	6.700
5	4	0.100	9	6.500
6	6	0.100	8	0.700
7	4	0.100	7	4.500
8	4	0.100	6	9.000
9	4	0.100	8	10.500
10	7	0.100	7	8.500
11	6	0.100	9	10.500
12	5	0.100	9	2.500

TABLE 9. DECADAL RECHARGE FACTORS IN THE UPDATED MODEL. THESE QUANTITIES WERE USED TO ACCOUNT FOR URBAN RECHARGE (SHARP AND OTHERS, 2009).

Decade	Factor
1943-1950	0.50
1950-1960	0.65
1961-1970	0.99
1971-1980	1.10
1981-1990	1.13
1991-2000	1.14
2001-2004	1.15

To summarize, the precipitation index was calculated using equation 1 for each month of the transient calibration (744 total). Recharge was then estimated by substituting the precipitation index into the (x) variable from the regression models developed for each month and recharge zone. Once an initial estimate for monthly recharge was obtained additional conditions were applied as follows. If the recharge zone equaled 2 and the estimated recharge was less than 0, then recharge was set equal to the minimum recharge. If the zone number was greater than 2 (zones 3-8;

creeks) and the estimated recharge was less for a given month than that for zone 2, then the recharge was set equal to that for zone 2. Additionally, wet thresholds and wet factors were set for each month (12 total). Similarly, dry thresholds and dry factors were set for each month (12 total). If the estimated recharge for a given month exceeded the wet threshold then the estimated recharge was multiplied by the wet factor. If the estimated recharge for a given month was less than the dry threshold, then the estimated recharge was multiplied by the dry factor. An additional factor was also added to the recharge estimates to account for urban recharge. Lastly, if the estimated recharge for a given month exceeded the maximum recharge, then the recharge was set to the maximum recharge.

As previously stated, the maximum recharge rate was capped, however values below the set capped value were determined for each zone during calibration. Similarly, values for the wet threshold, wet factor, dry threshold, dry factor, and the urban recharge factors were determined during calibration.

In order to facilitate calibration, the Recharge Package was written using a pre-processor program (*rech.exe*) written in FORTRAN. In summary, the *rech.exe* pre-processor reads an input file with the number of cells in each recharge zone (*rzcount.dat*) and several database files that contain the lowermost bounds for the maximum recharge rates for the months of January through December (*minmaxrech.dat*), the precipitation indices (see equation 1) for each stress period in the new model (*pcpindex.dat*), the coefficients based on the 84 regression relationships (*rechcoeff.dat*), the dry threshold, dry factors, wet threshold, and wet factors (*rechfactors.dat*), and the recharge decadal factors (*rechdecfac.dat*). The pre-processor then writes a new recharge file that can be read by MODFLOW-2000.

2.18 Horizontal Flow Barrier Package

The Horizontal Flow Barrier Package was used to simulate faults that are inferred restrictions to horizontal groundwater flow. The Horizontal Flow Barrier Package used in the Scanlon and others (2001) model was applied in the updated model without modification.

2.19 Output Control 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.

2.20 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 closure criterion is 1.0×10^{-3}, and the residual closure criterion is 1.00.

3.0 MODEL CALIBRATION AND RESULTS

The model was calibrated using a combination of automated adjustments using PEST, an industry-standard inverse modeling software package (Watermark Numerical Computing, 2004) and trial-and-error. Calibration of the model was primarily evaluated based on the match between simulated and estimated or measured discharges for Barton Springs and secondly, 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 estimated or measured discharges and groundwater elevations. Parameter adjustments generally focused on wet and dry factors, wet and dry precipitation triggers (i.e. what constitutes a “wet” month or a “dry” month), maximum recharge rates, and decadal recharge factors. Decadal adjustments were also made to pumpage. Additionally, hydraulic conductivity in the x- and y-directions, specific storage, and drain conductances were varied.

The calibration period was January 1943 through December 2004 (744 monthly stress periods), with a steady-state stress period (stress period 1) preceding the transient simulation for a total of 745 stress periods. The steady-state stress period was useful in that it provided a stable initial head solution that was used to initialize the transient simulation.

The model was calibrated with 744 estimated or measured discharges for Barton Springs provided by the Barton Springs/Edwards Aquifer Conservation District. Additionally, data from 152 target wells from the Texas Water Development Board’s groundwater database were used. These target wells had at least one groundwater elevation measurement during the calibration period and thirty-five of the 152 wells had 5 or more measurements. The location for Barton Springs and the 152 wells that were used in the calibration are shown in Figure 12.

The total number of monthly discharge measurements was 744 and the total number of groundwater elevation measurements was 2,246. Because estimated or measured discharges for Barton Springs were used, as well as measured groundwater elevations for targets, target discharges were divided by 10,000 in the PEST control file in order to numerically weight the residuals of each type of target value. Using this approach, equal numerical weight was applied to both the target discharges and the target groundwater elevations. The 744 estimated or measured discharges for Barton Springs, along with the simulated discharges for Barton Spring are listed in Table C-1 of Appendix C. Table D-1 of Appendix D summarizes the number of groundwater elevation measurements, the highest and lowest measured groundwater elevations, and the decimal years for the earliest and latest measurements.

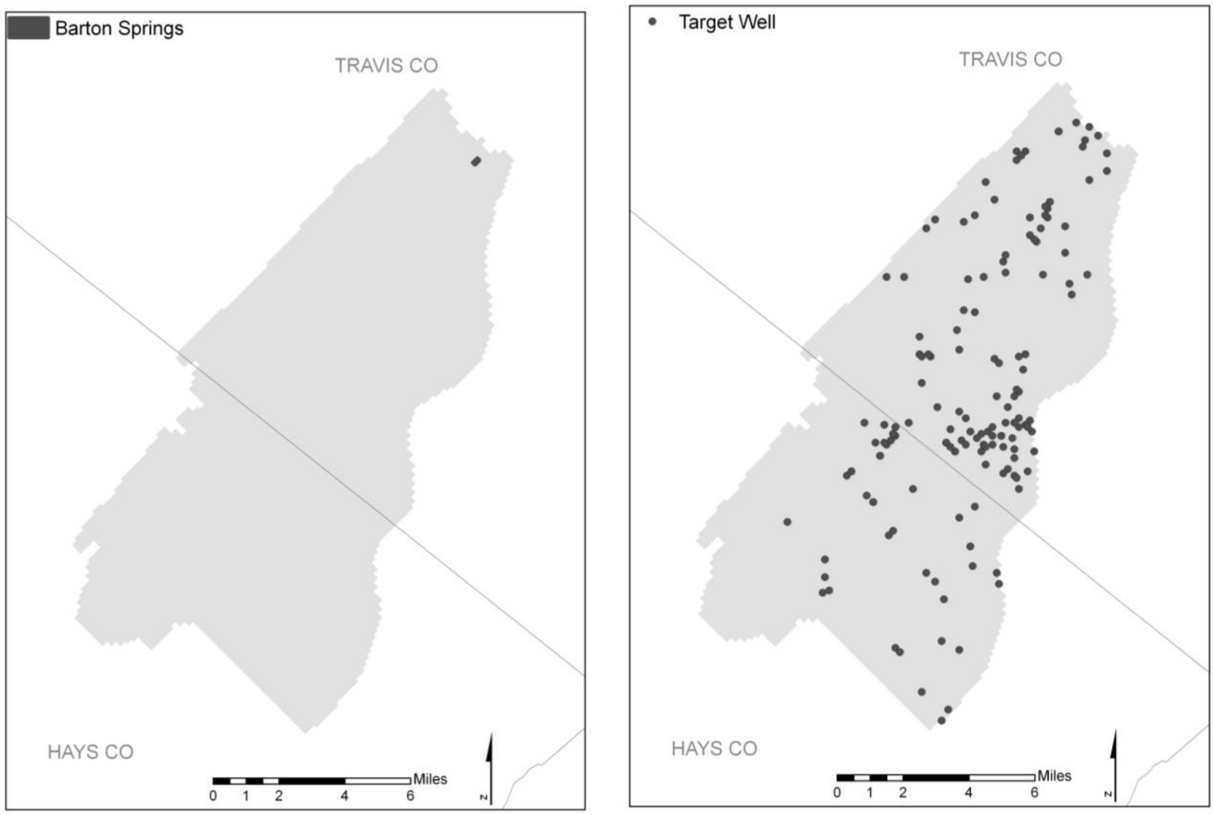


FIGURE 12. LOCATION OF BARTON SPRINGS (LEFT) AND THE LOCATION OF THE 152 TARGET WELLS (RIGHT) USED TO CALIBRATE THE GROUNDWATER FLOW MODEL.

3.1 Model Simulated Discharges at Barton Springs versus Estimated or Measured Discharges

As previously stated, calibration of the model was primarily evaluated based on the match between simulated and estimated or measured discharges from Barton Springs. Particular emphasis was placed on the match between simulated and estimated or measured discharges during the historic drought-of-record, which lasted from 1950 through 1956. Slade and others (1986) estimate that a minimum average monthly discharge of 11 cubic-feet per second occurred at Barton Springs during July and August of 1956. The estimated monthly discharge values for 1917 through February 1978 were estimated using: 1) discrete discharge measurements, and 2) rainfall quantities, which were used to estimate discharge between discrete measurements. Since March 1978, monthly mean discharges have been based on gauged values of daily mean discharge (Slade and others, 1986).

Given the collective effect of potential errors in discharge estimates and/or other model parameters, the updated model satisfactorily simulates the minimum estimated discharges of 11 cubic-feet per second that occurred during the historic drought-of-record in July and August of 1956 (Figure 13). Discharge hydrographs with estimated or measured discharges for Barton Springs versus simulated discharges using the Scanlon and others (2001) model and the updated model during the same time frame are shown in Figure 14.

A statistical summary of the minimum residual, maximum residual, and the absolute residual mean for simulated discharges in the updated model are presented in Table 10. The residual is the difference between estimated or measured discharges and simulated discharges. If the residual is positive, the estimated or measured discharge is higher than the simulated discharge. If the residual is negative, the estimated or measured discharge is lower than the simulated discharge. The standard deviation of the residuals and the range of estimated or measured discharges are also provided in Table 10. A common statistical test to examine calibration is the standard deviation of the residuals (the difference between measured and simulated values) divided by the range of measured values. Rumbaugh (2004) suggests that a good calibration yields a value less than 10 to 15 percent or (0.10 to 0.15). The standard deviation of the residuals divided by the range of measured discharges for the updated model is 0.136.

The summary also includes the value of the sum of squared residuals, which was used as the objective function during parameter estimation. Finally, the summary includes the frequency of residuals within 10, 25, and 50 cubic-feet per second. A graphical summary showing the match between measured and simulated discharges and a histogram of the residuals is shown in Figure 15. Fifty percent of the simulated discharges are within ± 10 cubic-feet per second of the estimated or measured discharges, 85 percent are within ± 25 cubic-feet per second, while 99 percent are within ± 50 cubic-feet per second.

The temporal calibration fit for simulated discharges at Barton Springs is shown in Figure 16, which presents a plot of year versus residual. This plot is useful for identifying any obvious bias in specific years relative to other years.

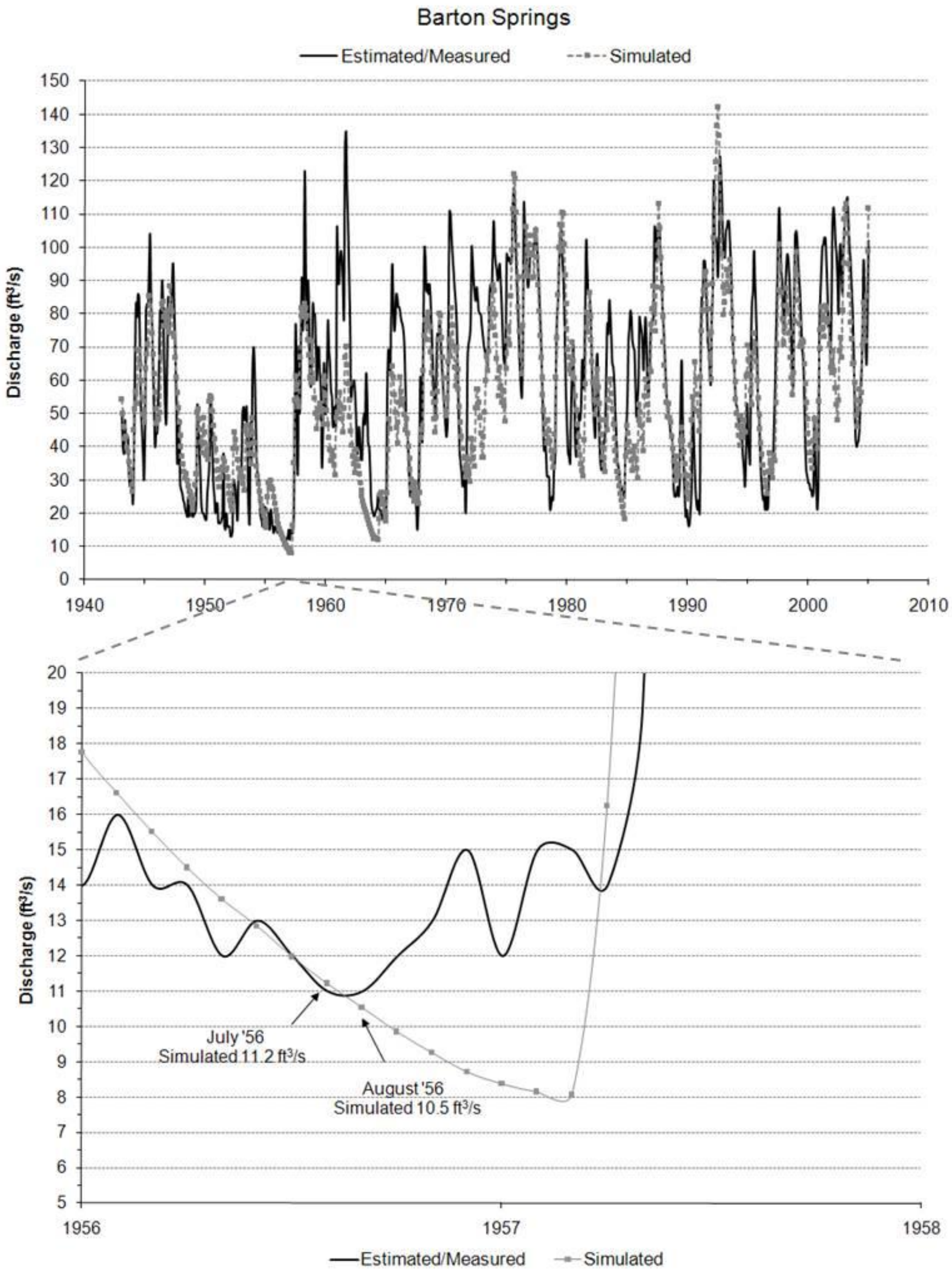


FIGURE 13. ESTIMATED/MEASURED DISCHARGES AT BARTON SPRINGS VERSUS SIMULATED DISCHARGES FROM JANUARY 1943 TO DECEMBER 2004 USING THE UPDATED MODEL (TOP). BOTTOM PLOT RESCALED TO HIGHLIGHT SIMULATED DISCHARGES DURING THE HISTORIC DROUGHT OF RECORD WHEN THE ESTIMATED MINIMUM DISCHARGES OF 11 FT^3/S OCCURRED IN JULY AND AUGUST OF 1956 (SLADE AND OTHERS, 1986).

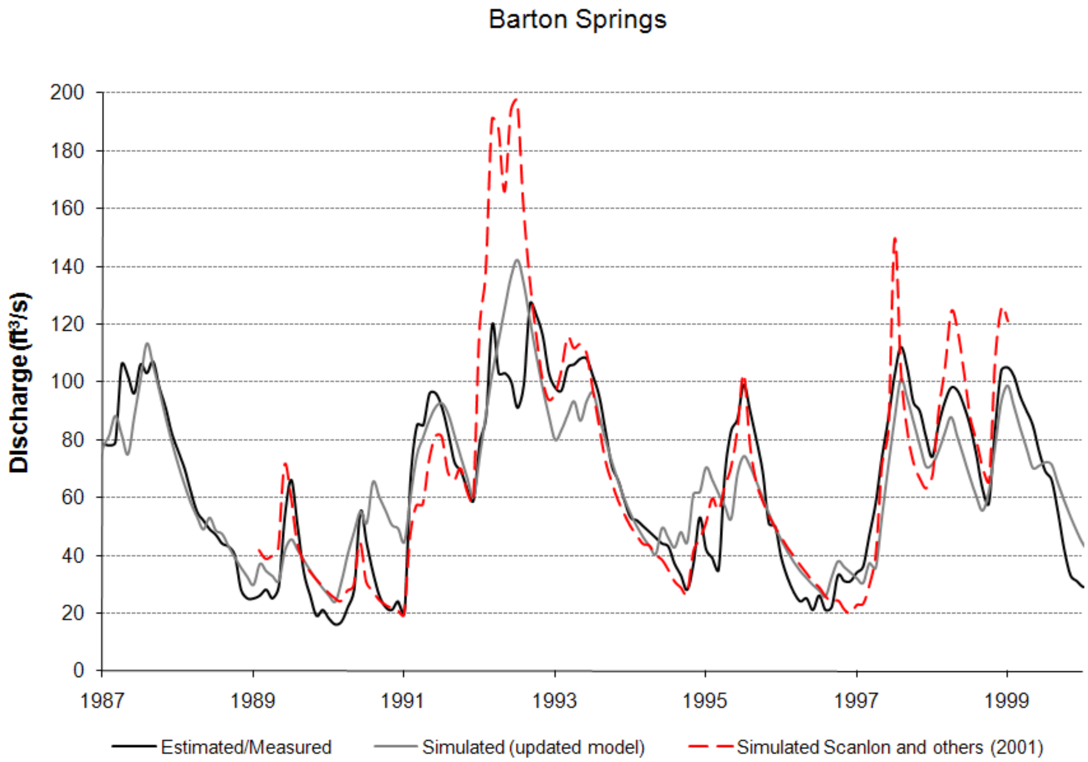


FIGURE 14. DISCHARGE HYDROGRAPHS FOR BARTON SPRINGS SHOWING ESTIMATED OR MEASURED DISCHARGES FOR BARTON SPRINGS (SLADE AND OTHERS, 1986) AND SIMULATED DISCHARGES USING THE SCANLON AND OTHERS (2001) MODEL AND THE UPDATED MODEL.

TABLE 10. STATISTICAL SUMMARY OF SIMULATED DISCHARGES FOR BARTON SPRINGS IN THE UPDATED MODEL.

Calibration Statistic	Calibrated Model Value
Minimum Residual (feet^3/second)	-51.08
Maximum Residual (feet^3/second)	64.83
Absolute Residual Mean (feet^3/second)	13.39
Standard Deviation of Residuals	16.85
Range of Measured Groundwater Discharge (feet^3/second)	124
Standard Deviation/Range	0.136
Absolute Residual Mean/Range*100	11
Sum of Squared Residuals	2.29×10^5
Percent of residuals within:	
± 10 feet^3/second	50
± 25 feet^3/second	85
± 50 feet^3/second	99

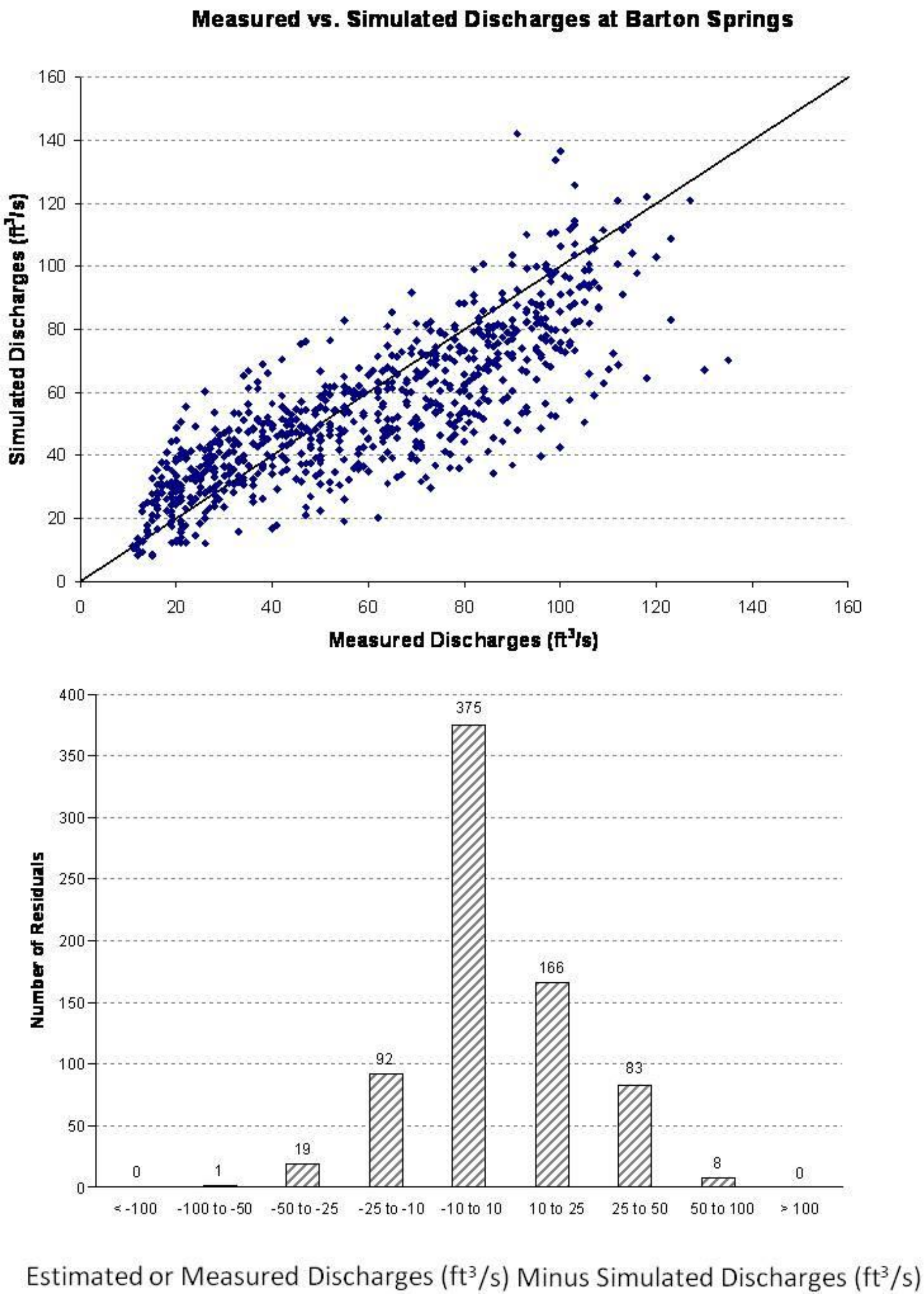


FIGURE 15 GRAPHICAL SUMMARY OF ESTIMATED OR MEASURED DISCHARGES VERSUS SIMULATED DISCHARGES USING THE UPDATED MODEL (TOP) AND A HISTOGRAM OF RESIDUALS WITHIN EACH BIN (BOTTOM).

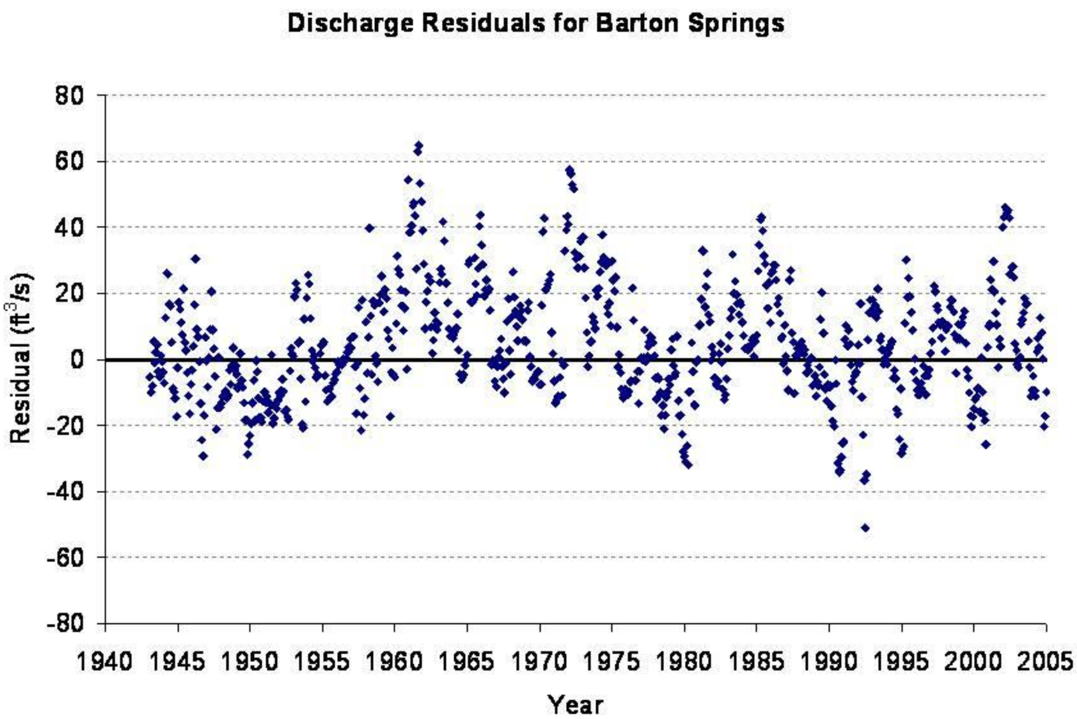


FIGURE 16. TIME VERSUS DISCHARGE RESIDUALS, WHICH WERE CALCULATED USING MEASURED DISCHARGES MINUS SIMULATED DISCHARGES (BOTTOM).

3.2 Model Simulated Groundwater Elevations versus Measured Groundwater Elevations

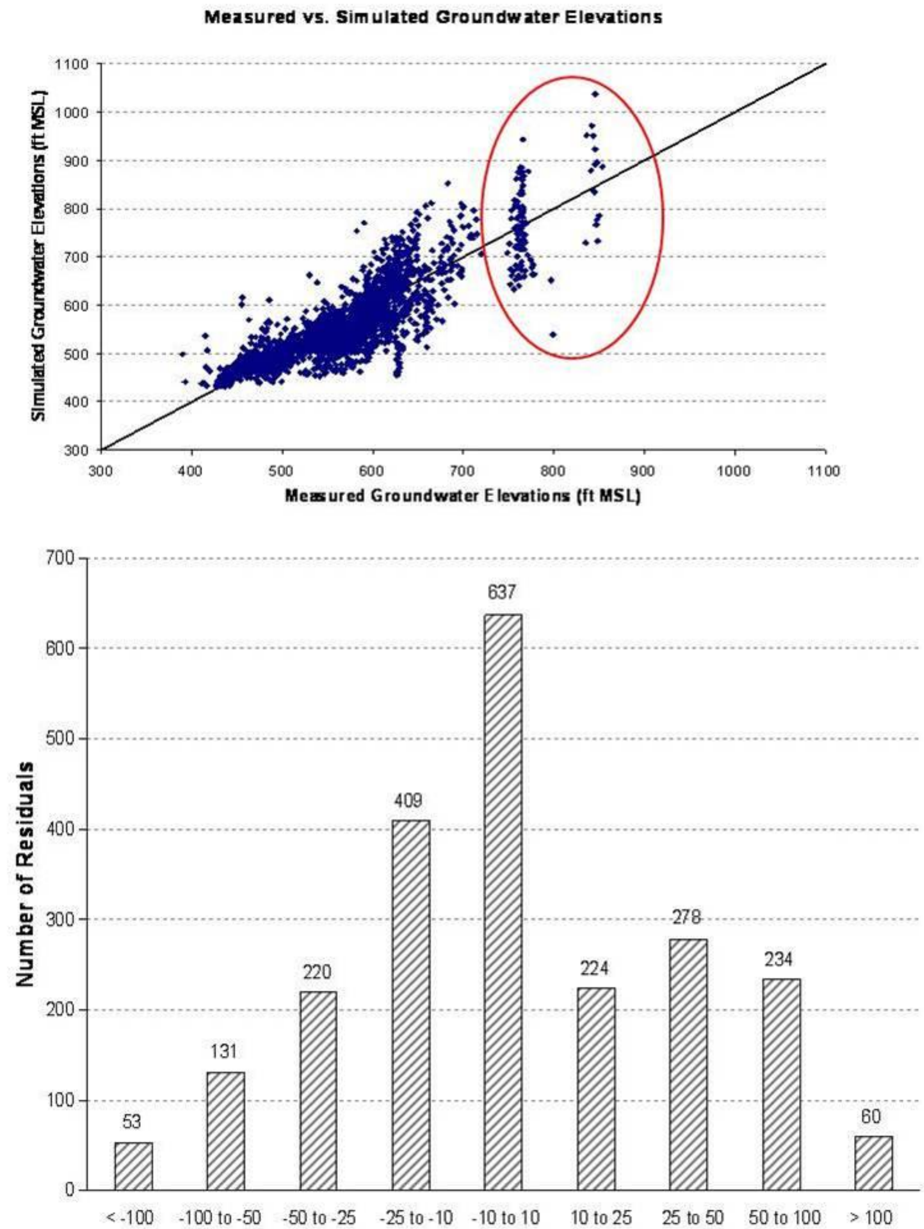
Calibration of the model was also evaluated in terms of the match between measured and simulated groundwater elevations from 152 wells. A statistical summary of the minimum residual, maximum residual, and the absolute residual mean are presented in Table 11. The residual is the difference between measured groundwater elevations and simulated groundwater elevations. If the residual is positive, the measured groundwater elevation is higher than the simulated groundwater elevation. If the residual is negative, the measured groundwater elevation is lower than the simulated groundwater elevation. The standard deviation of the residuals and the range of measured groundwater elevations are also provided in Table 11. The standard deviation of the residuals divided by the range of measured groundwater elevations for the updated model is 0.096.

TABLE 11. STATISTICAL SUMMARY OF SIMULATED GROUNDWATER ELEVATIONS IN THE UPDATED MODEL.

Calibration Statistic	Calibrated Model Value
Minimum Residual (feet)	-191.74
Maximum Residual (feet)	259.21
Absolute Residual Mean (feet)	31.48
Standard Deviation of Residuals	44.69
Range of Measured Groundwater Elevations (feet)	464.20
Standard Deviation/Range	0.096
Absolute Residual Mean/Range*100	7%
Sum of Squared Residuals	4.51×10^{6}
Percent of residuals within:	
± 10 ft	28
± 25 ft	57
± 50 ft	79

The summary also includes the value of the sum of squared residuals, which was used as the objective function during parameter estimation. Finally, the summary includes the frequency of residuals within 10, 25, and 50 feet. A graphical summary showing the match between measured and simulated groundwater elevations and a histogram of the residuals is shown in Figure 17. Twenty-eight percent of the simulated groundwater elevations are within ± 10 feet of the measured groundwater elevations, fifty-seven percent are within ± 25 feet, while seventy-nine percent are within ± 50 feet.

Figure 17 shows that for the most part, simulated groundwater elevations favorably match measured groundwater elevations. A departure in the match between simulated and measured groundwater elevations however is visible (circled area in Figure 17). The locations for these wells with a relatively poor match between simulated and measured groundwater elevations are shown in Figure 18. These 3 wells are located in the outcrop area. The less favorable match between simulated and measured groundwater elevations in this area of the model is likely associated with our assumption of confined conditions (LAYTYP=0) which utilizes specific storage rather than specific yield values. The performance of the model in the outcrop area shown in Figure 18 indicates that the updated model may be an inappropriate tool if used for purposes other than that described in section *1.0 Introduction and Purpose for Groundwater Flow Model* of this report.



Measured Groundwater Elevation (ft MSL) Minus Simulated Groundwater Elevation (ft MSL)

FIGURE 17. GRAPHICAL SUMMARY OF MEASURED GROUNDWATER ELEVATIONS VERSUS SIMULATED GROUNDWATER ELEVATIONS USING THE UPDATED MODEL (TOP) AND HISTOGRAM OF RESIDUALS WITHIN EACH BIN (BOTTOM).

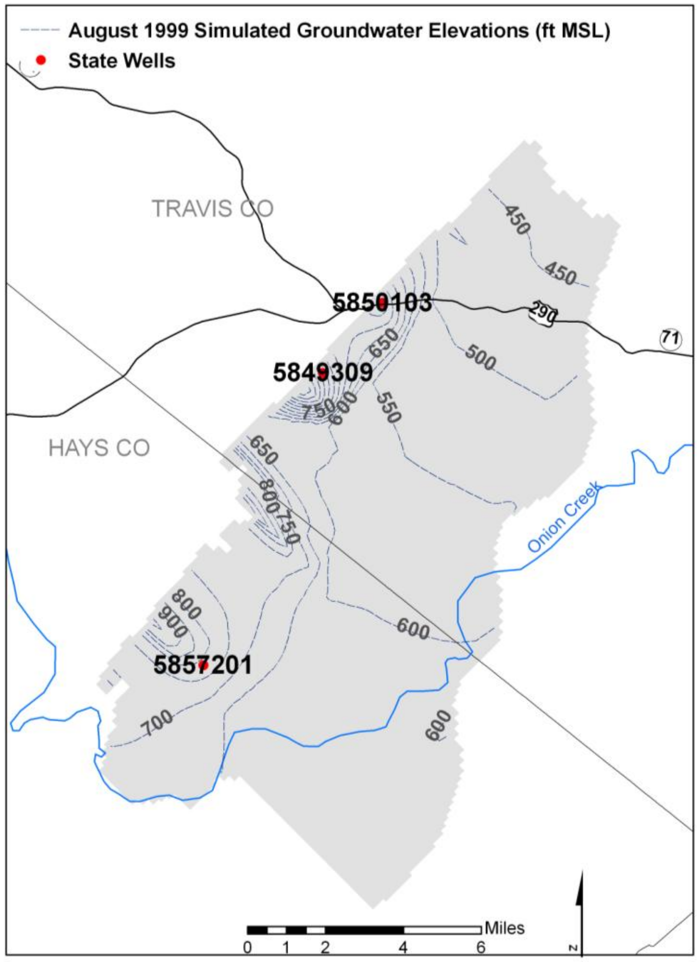


FIGURE 18. LOCATION OF WELLS WITH A RELATIVELY POOR MATCH BETWEEN SIMULATED AND MEASURED GROUNDWATER ELEVATIONS.

Figure 19 is a graphical summary of measured and simulated groundwater elevations minus the three wells with a relatively poor match shown in Figure 17. The removal of the three wells from the graphical summary shows simulated groundwater elevations for the remaining 149 target wells agree favorably for the most part with measured groundwater elevations.

The calibration fit for the updated model spatially and temporally in Figures 20 and 21, which show the residuals for the simulated groundwater elevations versus the model rows and layers. These plots permit inspection of potential spatial trends in residuals northwest (low model row number) to the southeast (high model row number) as well as southwest (low column number) to the northeast (high column number).

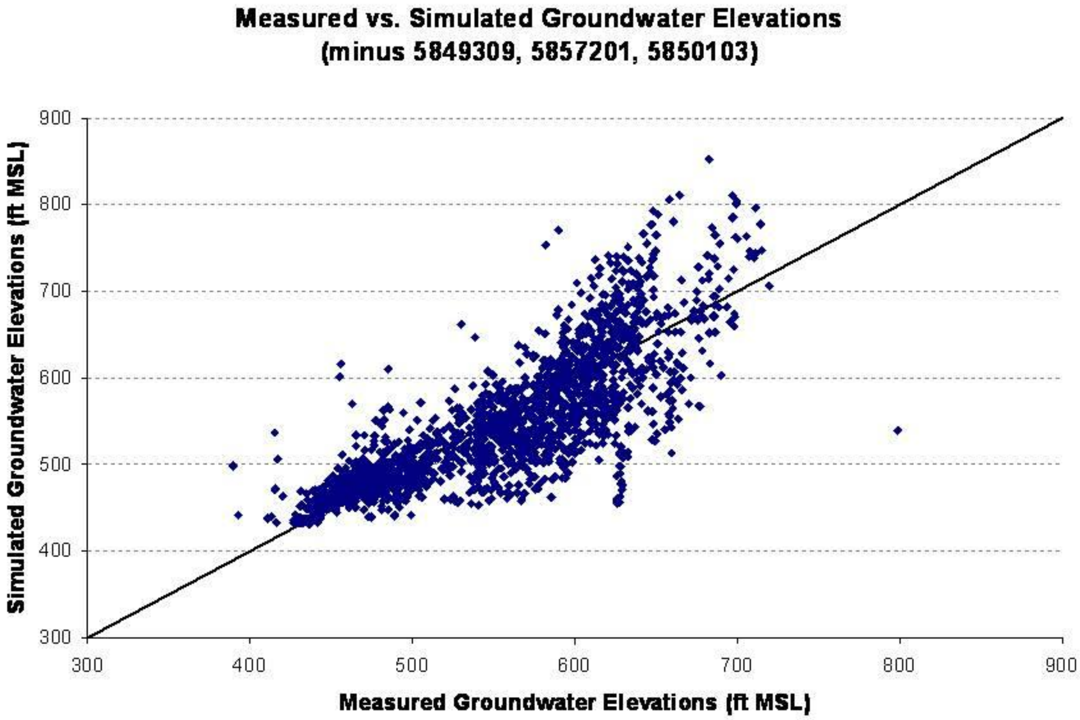


FIGURE 19. GRAPHICAL SUMMARY OF MEASURED AND SIMULATED GROUNDWATER ELEVATIONS USING THE UPDATED MODEL MINUS THE 3 TARGET WELLS WITH A RELATIVELY POOR MATCH SHOWN IN FIGURE 17.

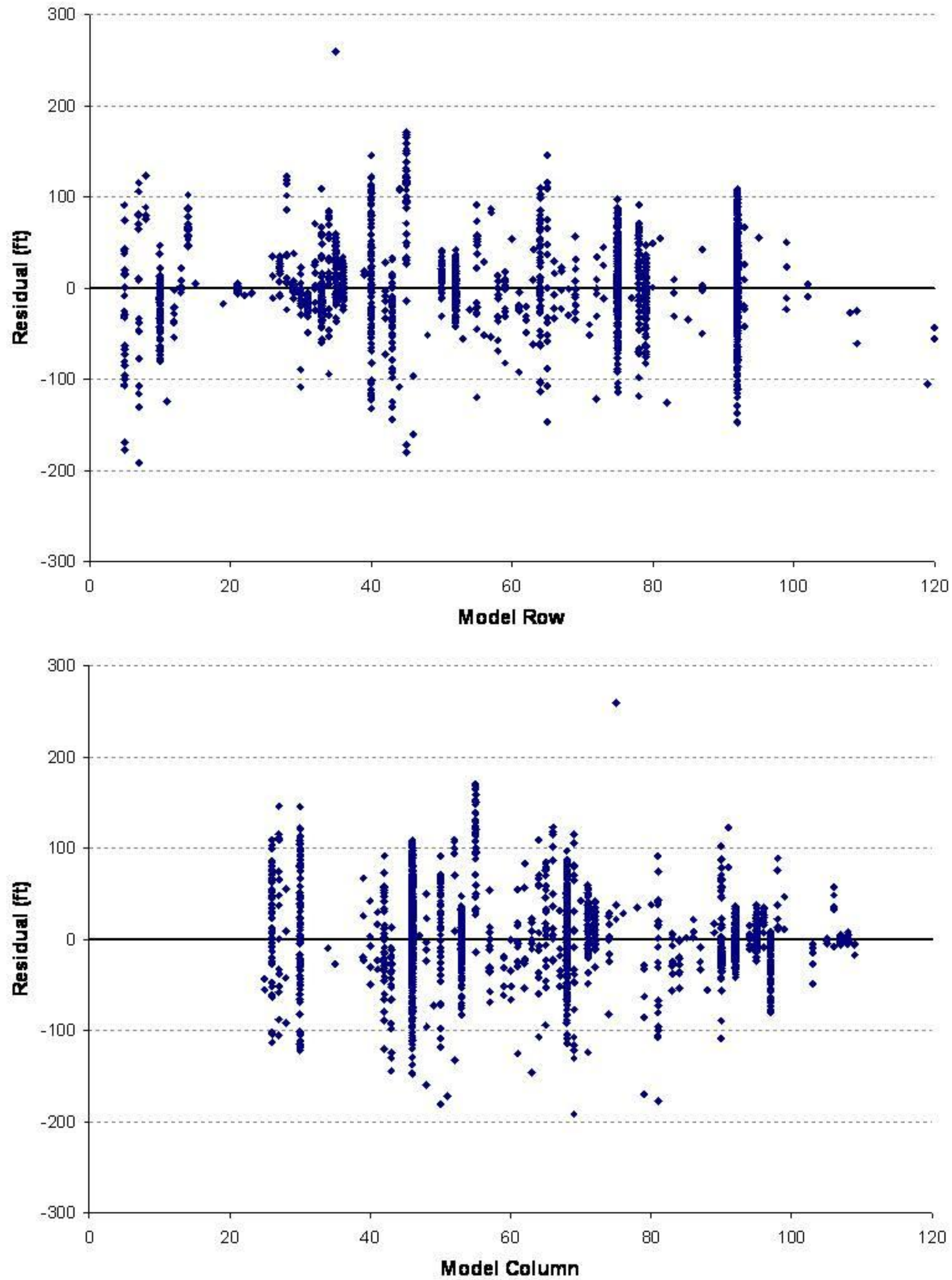


FIGURE 20. MODEL ROW VERSUS THE RESIDUALS FOR THE 152 TARGET GROUNDWATER ELEVATIONS (TOP) AND MODEL COLUMN VERSUS RESIDUALS FOR THE 152 TARGET GROUNDWATER ELEVATIONS (BOTTOM).

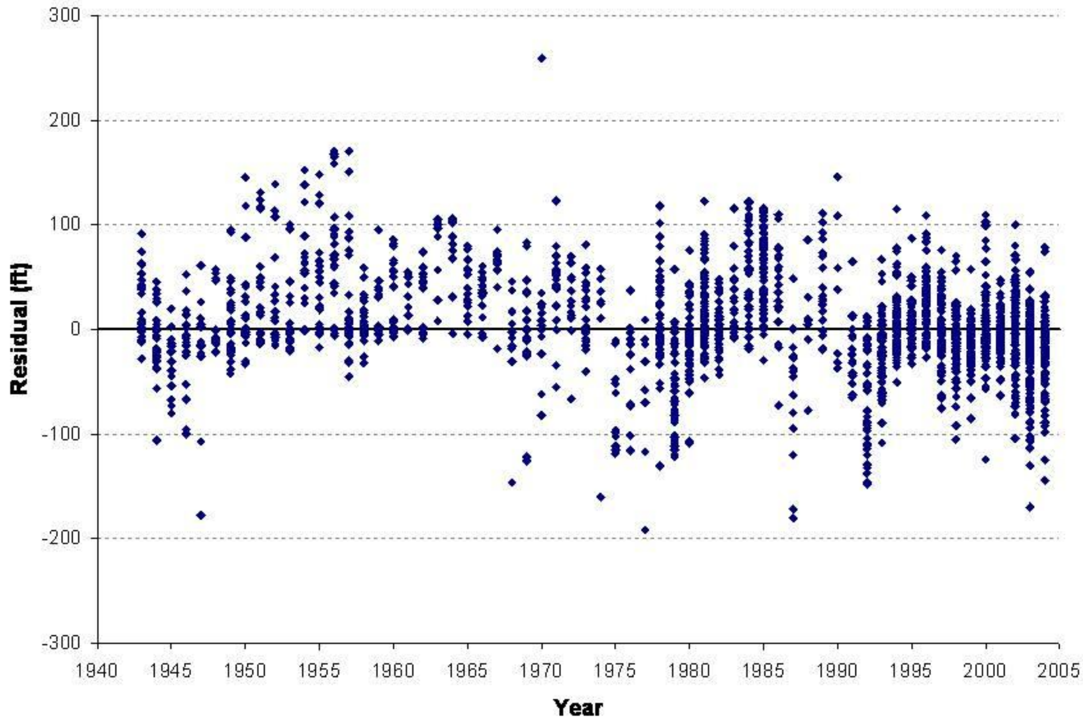


FIGURE 21. TEMPORAL DISTRIBUTION OF RESIDUALS FOR 152 TARGET WELLS USED TO CALIBRATE THE UPDATED GROUNDWATER FLOW MODEL. POSITIVE RESIDUALS INDICATE THAT THE MEASURED GROUNDWATER ELEVATION IS HIGHER THAN THE SIMULATED GROUNDWATER ELEVATION. NEGATIVE RESIDUALS INDICATE THAT THE MEASURED GROUNDWATER ELEVATION IS LOWER THAN THE SIMULATED GROUNDWATER ELEVATION.

The temporal calibration fit shown in Figure 21 presents a plot of year versus residual. This plot is useful for identifying any obvious bias in specific years relative to other years. Figure 21 shows that from the late-1940s through the mid-1960s groundwater elevations are generally underestimated.

Hydrographs showing the match between measured and simulated groundwater elevations for thirty-five of the 152 target wells are provided in Figure E-1 of Appendix E. These thirty-five wells have 5 or more groundwater elevation measurements that were used to calibrate the groundwater flow model.

In summary, the comparison between estimated or measured discharges and simulated discharges for Barton Springs, coupled with the residual analysis for simulated and measured groundwater elevations, suggests that the calibration is satisfactory for the purposes of this updated groundwater flow model.

3.3 Water Budget

Groundwater budgets, or groundwater inventories, are developed by quantifying all inflows to a system, all outflows from a system, and the storage change of the system over a specified period of time. Literature on the development of groundwater budgets dates back to at least the 1930s with the work of Meinzer (1932). Tolman (1937) noted that, at the time, methods to develop groundwater 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 hydraulic conditions.

Bredehoeft (2002) reviewed the evolution of analysis of groundwater systems. The earliest methods in the 1940s and 1950s revolved around the analysis of flow to a single well. Understanding groundwater 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 groundwater flow. By 1980, Bredehoeft (2002) reported that numerical models had replaced analog models in the investigations of aquifer dynamics. The principle objective of such models is to understand the impacts of pumping on the system.

A groundwater system in near steady-state (or near equilibrium) prior to development (prior to groundwater pumping for irrigation or other human use) is shown in Figure 22. In this condition, groundwater inflow equals groundwater outflow and no change in storage occurs over time. For the updated Barton Springs model, inflows include recharge and outflows include discharge from springs and pumping.

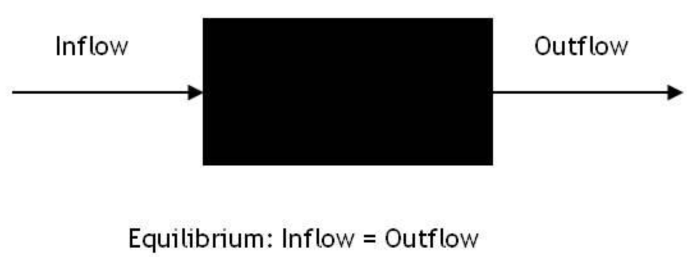


FIGURE 22. GROUNDWATER SYSTEM PRIOR TO DEVELOPMENT (AFTER ALLEY AND OTHERS, 1999).

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 surface water recharge, and 3) captured natural outflow (generally manifested in decreased springflows).

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.

The cone of depression can also cause a decrease of natural groundwater outflow from the area adjacent to the well and acts to “capture” this natural outflow. If the cone of depression causes water levels to decline in an area of shallow groundwater, 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 23 illustrates the case of a groundwater system after 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.

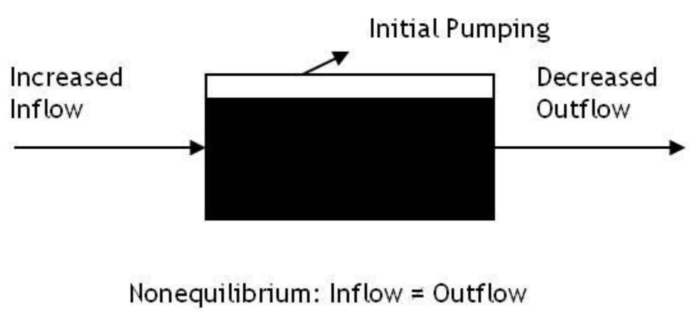


FIGURE 23. GROUNDWATER SYSTEM AFTER INITIAL PUMPING (AFTER ALLEY AND OTHERS, 1999).

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 24 presents a diagram of this new near steady-state or new equilibrium condition.

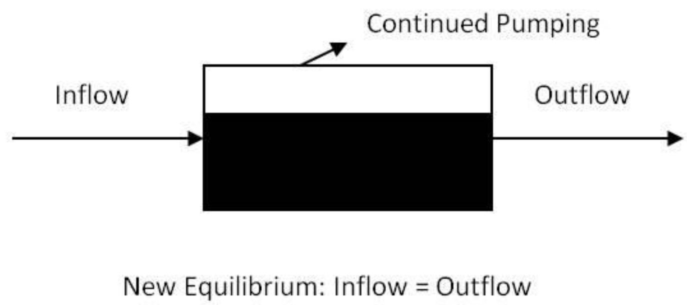


FIGURE 24. GROUNDWATER SYSTEM UNDER CONTINUED PUMPING-NEW EQUILIBRIUM CONDITION (AFTER ALLEY AND OTHERS, 1999).

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 25 depicts this condition.

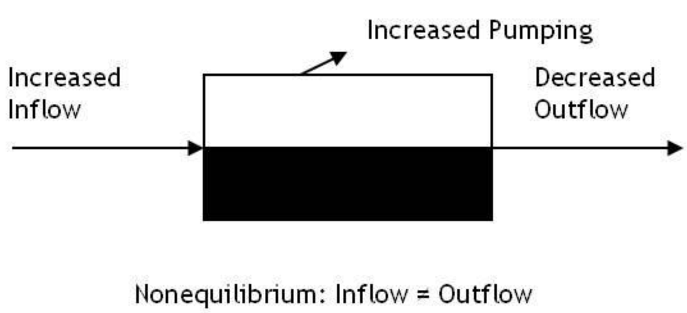


FIGURE 25. GROUNDWATER SYSTEM UNDER ADDITIONAL INCREMENT OF INCREASED PUMPING (AFTER ALLEY AND OTHERS, 1999).

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 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 springflow 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 springflows, evapotranspiration) and affects fluxes between hydraulically connected aquifer systems. Bredehoeft (2002) noted that understanding the dynamic response of a groundwater 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 pumping. A calibrated numerical groundwater model of a region is an ideal tool in meeting 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 Barton Springs model: recharge, pumpage, discharge to springs, and storage change. Recharge (inflows) includes both focused recharge at karst features along Onion, Little Bear, Bear, Slaughter, Williamson, and Barton creeks, in addition to distributed rainfall falling on the outcrop area (see Figure 9). Pumpage (outflows) refers to both domestic (rural) and non-domestic (point) groundwater well withdrawals. Discharge (outflows) refers to springflows at Barton and Cold springs. In the updated model, discharge is the larger component of outflows relative to pumpage. Storage change refers to the difference between inflows (recharge) and outflows (pumpage and discharge). Negative values indicate water is being removed from storage, whereas positive values indicate water is being added to storage. Recharge is the largest component of the water budget, followed by discharge (springflows), pumpage, and storage change in descending order. The annual average groundwater budget for the updated model is summarized for seven time periods in Table 12.

TABLE 12. ANNUAL AVERAGE GROUNDWATER BUDGET FOR SEVEN TIME PERIODS. ALL VALUES ARE IN ACRE-FEET PER YEAR.

	1943-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2004
Inflow							
Recharge	35,969	29,933	32,899	55,064	37,373	54,957	65,367
Outflow							
Pumping	47	941	1,739	2,173	4,101	3,522	5,243
Discharge	38,537	28,226	31,369	50,235	37,688	49,609	50,507
Total Outflow	38,584	29,167	33,107	52,408	41,789	53,130	55,750
In-Out	-2,615	766	-209	2,656	-4,416	1,826	9,617
Storage Change	-2,509	852	-129	2,811	-4,313	1,976	9,800

4.0 MODEL LIMITATIONS

Numerical groundwater flow models are approximations 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 the purpose for the groundwater flow model, our extent of understanding the aquifer(s), the quantity and quality of data needed to constrain parameters in the groundwater flow model, and assumptions made during model development.

As previously stated, the purpose for this modeling effort was to fulfill a specific request by Groundwater Management Area 10 for model runs that included specified springflows of 11, 9, 7, 5, and 3 cubic-feet per second under a drought-of-record recurrence using a groundwater flow model calibrated to the historic 1950 through 1956 drought-of-record. Because the purpose for this updated groundwater flow model is narrow in scope, it may not be an appropriate tool for other applications.

5.0 REFERENCES

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of groundwater resources, U.S. Geological Survey Circular 1186, 79 p.

Anderson, M.P. and Woessner, W.W., 2002, Applied groundwater modeling simulation of flow and advective transport, Academic Press, Inc., 381 p.

Bredehoeft, J. and Durbin, T., 2009, Ground water development-the time to full capture problem: *Ground Water*, vol. 47, no. 4, p. 506-514.

Bredehoeft, J.D., 2002, The water budget myth revisited: why hydrogeologists model: *Ground Water*: vol. 40, no. 4, p. 340-345.

Brune, G. and Duffin, G.L., 1983, Occurrence, availability, and quality of ground water in Travis, County, Texas, Texas Department of Water Resources, Report 276, 103 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model-user guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Harbaugh, A.W. and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Groundwater Flow Model, U.S. Geological Survey Open-File Report 96-485, 56 p.

Hill, M.E., Stewart, M.T., and Martin, A., 2010, Evaluation of the MODFLOW-2005 Conduit Flow Process: *Ground Water*, vol. 48, no. 4, p. 549-559.

Holland, K., 2010, Written communication, September 1, Austin, Texas.

Hunt, B.B., Smith, B.A., and Beery, J., 2006, Summary of the 2005 Groundwater dye tracing, Barton Springs segment of the Edwards Aquifer, Hays and Travis Counties, Central Texas, BSEACD Report of Investigations 2006-0530, 19 p.

Meinzer, O.E., 1932, Outline of methods for estimating ground-water supplies, U.S. Geological Survey Water-Supply Paper 638-C, p. 99-144.

Rumbaugh, J.O. and Rumbaugh, D.B., 2004, Guide to using Groundwater Vistas version 4, Environmental Simulations, Inc., 358 p.

Scanlon, B.R., Mace, R.E., Smith, B., Hovorka, S., Dutton, A.R., and Reedy, R., 2001, Groundwater availability of the Barton Springs segment of the Edwards aquifer, Texas: Numerical simulations through 2050: Bureau of Economic Geology, 36 p.

Sharp, J.M. Jr., Llado, L.E., and Budge, T.J., 2009, Urbanization-induced trends in spring discharge from a karstic aquifer-Barton Springs, Austin, Texas, USA, Proceedings of the 15th International Congress of Speleology, vol.2, p. 1211-1216.

Shoemaker, W.B., Kuniansky, E.L., Birk, S., Bauer, S., and Swain, E.D., 2008, Documentation of a Conduit Flow Process (CFP) for MODFLOW-2005, U.S. Geological Survey Techniques and Methods, Book 6, Chapter A24, 50 p.

Slade, R.M. Jr., Dorsey, M.E., and Stewart, S.L., 1986, Hydrology and water quality of the Edwards Aquifer associated with Barton Springs in the Austin area, Texas, U.S. Geological Survey Water-Resources Investigations Report 86-4036, 117 p.

Tolman, C.F., 1937, Ground Water, McGraw-Hill, New York, 593 p.

Watermark Numerical Computing, 2004, PEST Model-Independent Parameter Estimation User Manual: 5th Edition, variously p.

Wilson, J.D. and Naff, R.L., 2004, The U.S. Geological Survey modular ground-water model-GMG linear equation solver package documentation: U.S. Geological Survey Open-File Report 2004-1261, 47 p.

APPENDICES

APPENDIX A: Regression Models Developed for the Percent of Rural Pumping

TABLE A-1. INTERCEPTS, COEFFICIENTS, AND COEFFICIENTS OF DETERMINATION FOR THE TWELVE REGRESSION MODELS DEVELOPED FOR THE PERCENT OF RURAL PUMPING USING YEAR AND PRECIPITATION AS VARIABLES.

Month	Intercept	Coefficient_1	Coefficient_2	R^2
January	1788.168	-0.887	0.222	0.82
February	1845.853	-0.916	0.161	0.77
March	2977.460	-1.483	-0.083	0.86
April	2484.771	-1.238	0.436	0.85
May	2575.147	-1.284	0.470	0.82
June	1922.330	-0.959	0.493	0.81
July	2232.493	-1.114	0.086	0.88
August	1507.182	-0.751	0.438	0.85
September	3060.417	-1.529	0.617	0.84
October	1704.724	-0.847	0.059	0.83
November	2421.622	-1.205	0.050	0.95
December	1541.247	-0.764	0.090	0.77

APPENDIX B:Regression Models Using Precipitation Indices and Recharge Zones

TABLE B-1. COEFFICIENTS, CONSTANTS, AND COEFFICIENTS OF DETERMINATION FOR THE 84 REGRESSION MODELS DEVELOPED USING THE QUANTITIES FOR EACH RECHARGE ZONE IN THE SCANLON AND OTHERS (2001) MODEL WITH THE PRECIPITATION INDICES.

Month	Zone	x^4	x^3	x^2	X	c	R^2
1	2	0.00E+00	2.59E-06	-5.58E-05	4.96E-04	-6.87E-04	8.02E-01
1	3	0.00E+00	4.53E-04	-1.03E-02	8.66E-02	-1.17E-01	7.13E-01
1	4	0.00E+00	8.31E-05	-1.47E-03	1.31E-02	-1.88E-02	8.44E-01
1	5	0.00E+00	1.22E-04	-2.15E-03	1.91E-02	-2.75E-02	8.43E-01
1	6	0.00E+00	3.31E-05	-5.85E-04	8.48E-03	-1.37E-02	8.93E-01
1	7	0.00E+00	-4.89E-05	1.21E-03	-4.02E-03	3.24E-03	9.94E-01
1	8	0.00E+00	3.60E-04	-8.05E-03	7.12E-02	-9.69E-02	7.95E-01
2	2	0.00E+00	0.00E+00	-2.99E-06	2.78E-04	-4.90E-04	7.85E-01
2	3	0.00E+00	0.00E+00	-1.98E-03	5.42E-02	-8.94E-02	6.38E-01
2	4	0.00E+00	0.00E+00	3.37E-04	6.12E-03	-1.37E-02	8.30E-01
2	5	0.00E+00	0.00E+00	4.99E-04	8.93E-03	-2.01E-02	8.29E-01
2	6	0.00E+00	0.00E+00	-1.56E-04	1.01E-02	-1.99E-02	6.34E-01
2	7	0.00E+00	0.00E+00	2.71E-05	4.63E-03	-1.05E-02	8.75E-01
2	8	0.00E+00	0.00E+00	7.60E-04	2.44E-02	-4.05E-02	8.90E-01
3	2	0.00E+00	0.00E+00	8.54E-06	1.23E-04	0.00E+00	6.09E-01
3	3	0.00E+00	0.00E+00	4.14E-04	2.37E-02	0.00E+00	5.00E-01
3	4	0.00E+00	0.00E+00	7.25E-04	1.37E-03	0.00E+00	7.03E-01
3	5	0.00E+00	0.00E+00	1.06E-03	1.99E-03	0.00E+00	7.03E-01
3	6	0.00E+00	0.00E+00	2.16E-04	3.20E-03	0.00E+00	3.66E-01
3	7	0.00E+00	0.00E+00	4.26E-04	-1.60E-04	0.00E+00	7.77E-01
3	8	0.00E+00	0.00E+00	1.07E-03	1.80E-02	0.00E+00	6.88E-01

Table B-1 continued.

Month	Zone	x^4	x^3	x^2	X	c	R^2
4	2	0.00E+00	9.14E-07	7.49E-06	8.33E-05	0.00E+00	4.96E-01
4	3	0.00E+00	1.82E-04	1.25E-04	1.82E-02	0.00E+00	3.96E-01
4	4	0.00E+00	-1.27E-04	2.38E-03	-3.97E-03	0.00E+00	5.08E-01
4	5	0.00E+00	-1.87E-04	3.50E-03	-5.88E-03	0.00E+00	5.08E-01
4	6	0.00E+00	0.00E+00	5.52E-04	8.14E-04	0.00E+00	3.27E-01
4	7	0.00E+00	0.00E+00	2.22E-04	6.22E-04	0.00E+00	2.10E-01
4	8	0.00E+00	7.33E-04	-6.20E-03	2.98E-02	0.00E+00	6.37E-01
5	2	0.00E+00	-2.03E-07	7.89E-06	6.83E-05	0.00E+00	5.70E-01
5	3	0.00E+00	-1.55E-04	2.15E-03	1.03E-02	0.00E+00	3.72E-01
5	4	0.00E+00	1.31E-05	1.88E-04	1.30E-03	0.00E+00	7.04E-01
5	5	0.00E+00	0.00E+00	6.00E-04	6.00E-04	0.00E+00	7.04E-01
5	6	0.00E+00	5.73E-05	-2.03E-04	1.17E-03	0.00E+00	7.60E-01
5	7	0.00E+00	0.00E+00	3.85E-05	1.86E-03	0.00E+00	3.14E-01
5	8	0.00E+00	0.00E+00	9.78E-04	9.33E-03	0.00E+00	6.70E-01
6	2	0.00E+00	0.00E+00	1.62E-05	-3.32E-05	0.00E+00	8.70E-01
6	3	0.00E+00	0.00E+00	1.01E-03	5.37E-03	0.00E+00	7.02E-01
6	4	0.00E+00	8.25E-05	-4.70E-04	1.02E-03	0.00E+00	9.57E-01
6	5	0.00E+00	1.24E-04	-7.17E-04	1.58E-03	0.00E+00	9.58E-01
6	6	0.00E+00	-1.69E-05	1.01E-03	-3.58E-03	0.00E+00	6.39E-01
6	7	0.00E+00	0.00E+00	1.28E-04	2.27E-04	0.00E+00	6.81E-01
6	8	0.00E+00	0.00E+00	2.32E-03	-4.26E-03	0.00E+00	8.96E-01

Table B-1 continued.

Month	**Zone**	**x^4**	**x^3**	**x^2**	**X**	**c**	**R^2**
7	2	0.00E+00	2.57E-06	-2.12E-05	7.87E-05	0.00E+00	4.76E-01
7	3	0.00E+00	5.65E-04	-4.91E-03	1.64E-02	0.00E+00	4.78E-01
7	4	0.00E+00	1.08E-04	-1.02E-03	3.02E-03	0.00E+00	4.34E-01
7	5	0.00E+00	1.59E-04	-1.50E-03	4.43E-03	0.00E+00	4.34E-01
7	6	0.00E+00	8.80E-05	-8.08E-04	2.26E-03	0.00E+00	3.92E-01
7	7	0.00E+00	0.00E+00	7.47E-05	-1.32E-04	0.00E+00	3.93E-01
7	8	0.00E+00	4.22E-05	3.19E-04	3.97E-03	0.00E+00	4.57E-01
8	2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.96E-05	
8	3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.01E-02	
8	4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.88E-04	
8	5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.43E-03	
8	6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.20E-03	
8	7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.50E-04	
8	8	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.48E-03	
*9	2	3.29E-07	-5.45E-06	2.73E-05	-3.70E-05	1.79E-05	9.73E-01
9	3	1.44E-04	-2.59E-03	1.46E-02	-2.61E-02	1.32E-02	9.61E-01
9	4	0.00E+00	-2.47E-06	4.59E-05	-1.57E-04	1.93E-04	2.48E-01
9	5	0.00E+00	-2.44E-06	3.97E-05	-5.54E-05	0.00E+00	2.12E-01
9	6	0.00E+00	0.00E+00	-8.59E-07	2.91E-05	0.00E+00	5.58E-01
9	7	0.00E+00	2.56E-06	-4.40E-05	2.30E+05	0.00E+00	2.13E-01
9	8	0.00E+00	2.33E-06	-9.81E-06	6.53E-04	0.00E+00	2.88E-01

Table B-1 continued.

Month	Zone	x^4	x^3	x^2	X	c	R^2
10	2	0.00E+00	0.00E+00	3.13E-06	-1.33E-06	0.00E+00	9.81E-01
10	3	0.00E+00	0.00E+00	3.12E-04	3.02E-04	0.00E+00	9.54E-01
10	4	0.00E+00	0.00E+00	2.85E-04	-1.47E-03	0.00E+00	9.91E-01
10	5	0.00E+00	0.00E+00	4.21E-04	-2.18E-03	0.00E+00	9.91E-01
10	6	0.00E+00	0.00E+00	-1.57E-05	1.08E-03	0.00E+00	4.28E-01
10	7	0.00E+00	0.00E+00	1.46E-05	2.79E-04	0.00E+00	8.88E-01
10	8	0.00E+00	0.00E+00	3.10E-04	1.50E-03	0.00E+00	9.53E-01
11	2	0.00E+00	0.00E+00	9.84E-06	-2.45E-05	0.00E+00	9.44E-01
11	3	0.00E+00	0.00E+00	1.43E-03	-3.39E-03	0.00E+00	9.44E-01
11	4	0.00E+00	0.00E+00	4.77E-04	-1.99E-03	0.00E+00	9.83E-01
11	5	0.00E+00	0.00E+00	7.03E-04	-2.94E-03	0.00E+00	9.83E-01
11	6	0.00E+00	0.00E+00	3.78E-04	-1.16E-03	0.00E+00	8.94E-01
11	7	0.00E+00	0.00E+00	8.29E-05	-1.74E-04	0.00E+00	9.25E-01
11	8	0.00E+00	0.00E+00	9.38E-04	-2.18E-04	0.00E+00	8.71E-01
12	2	0.00E+00	0.00E+00	7.65E-06	3.68E-05	0.00E+00	9.43E-01
12	3	0.00E+00	0.00E+00	-5.11E-04	1.82E-02	0.00E+00	4.98E-01
12	4	0.00E+00	9.62E-05	-8.78E-04	5.31E-03	-8.29E-03	9.97E-01
12	5	0.00E+00	1.42E-04	-1.31E-03	7.88E-03	-1.32E-02	9.97E-01
12	6	0.00E+00	0.00E+00	2.45E-04	4.16E-04	0.00E+00	8.14E-01
12	7	0.00E+00	4.12E-06	7.35E-05	-1.69E-04	0.00E+00	9.75E-01
12	8	0.00E+00	-8.75E-05	2.59E-03	-1.97E-03	0.00E+00	9.66E-01

*no September 1991

APPENDIX C: Estimated or Measured Discharges Versus Simulated Discharges at Barton Springs

TABLE C-1. MONTHLY ESTIMATED OR MEASURED DISCHARGES FOR BARTON SPRINGS PROVIDED BY THE BARTON SPRINGS/EDWARDS AQUIFER CONSERVATION DISTRICT, WITH SIMULATED DISCHARGES FOR BARTON SPRINGS USING THE NEW MODEL DURING THE TRANSIENT SIMULATION. RESIDUALS ARE CALCULATED USING THE ESTIMATED OR MEASURED DISCHARGES MINUS THE SIMULATED DISCHARGES.

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1943.08	49	54.320	-5.320
1943.17	40	49.935	-9.935
1943.25	38	46.032	-8.032
1943.33	48	42.440	5.560
1943.42	42	43.031	-1.031
1943.50	42	39.735	2.265
1943.58	43	38.510	4.490
1943.67	32	35.588	-3.588
1943.75	28	33.136	-5.136
1943.83	32	30.760	1.240
1943.92	28	28.620	-0.620
1944.00	23	26.711	-3.711
1944.08	38	45.045	-7.045
1944.17	64	51.341	12.659
1944.25	83	56.746	26.254
1944.33	79	53.142	25.858
1944.42	86	69.280	16.720
1944.50	85	68.828	16.172
1944.58	70	64.821	5.179
1944.67	51	59.807	-8.807

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1944.75	45	54.717	-9.717
1944.83	38	49.869	-11.869
1944.92	30	47.248	-17.248
1945.00	45	47.474	-2.474
1945.08	81	63.680	17.320
1945.17	83	67.811	15.189
1945.25	82	70.763	11.237
1945.33	93	85.462	7.538
1945.42	104	82.493	21.507
1945.50	85	79.767	5.233
1945.58	77	74.241	2.759
1945.67	64	67.993	-3.993
1945.75	51	61.977	-10.977
1945.83	40	56.467	-16.467
1945.92	44	51.474	-7.474
1946.00	44	47.122	-3.122
1946.08	52	48.002	3.998
1946.17	65	48.422	16.578
1946.25	81	50.538	30.462
1946.33	76	66.919	9.081
1946.42	90	83.096	6.904
1946.50	83	83.641	-0.641

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1946.58	66	79.268	-13.268
1946.67	52	76.449	-24.449
1946.75	47	76.227	-29.227
1946.83	64	80.980	-16.980
1946.92	85	78.214	6.786
1947.00	74	74.439	-0.439
1947.08	80	88.342	-8.342
1947.17	83	82.352	0.648
1947.25	90	80.839	9.161
1947.33	95	74.315	20.685
1947.42	82	73.075	8.925
1947.50	70	66.757	3.243
1947.58	56	61.055	-5.055
1947.67	35	56.215	-21.215
1947.75	37	51.579	-14.579
1947.83	48	47.342	0.658
1947.92	29	43.544	-14.544
1948.00	27	40.193	-13.193
1948.08	26	37.166	-11.166
1948.17	24	34.784	-10.784
1948.25	23	32.612	-9.612
1948.33	21	30.626	-9.626
1948.42	20	31.758	-11.758

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1948.50	19	29.832	-10.832
1948.58	25	28.104	-3.104
1948.67	19	26.435	-7.435
1948.75	23	24.847	-1.847
1948.83	27	23.419	3.581
1948.92	19	22.089	-3.089
1949.00	19	20.908	-1.908
1949.08	20	24.433	-4.433
1949.17	20	28.658	-8.658
1949.25	24	31.901	-7.901
1949.33	52	50.231	1.769
1949.42	45	51.295	-6.295
1949.50	40	48.461	-8.461
1949.58	32	45.011	-13.011
1949.67	23	41.428	-18.428
1949.75	20	38.143	-18.143
1949.83	20	48.813	-28.813
1949.92	19	44.508	-25.508
1950.00	18	40.987	-22.987
1950.08	18	37.592	-19.592
1950.17	26	39.126	-13.126
1950.25	30	36.264	-6.264
1950.33	35	53.604	-18.604

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1950.42	55	55.358	-0.358
1950.50	51	54.722	-3.722
1950.58	39	50.579	-11.579
1950.67	29	46.444	-17.444
1950.75	25	42.614	-17.614
1950.83	20	38.998	-18.998
1950.92	23	35.705	-12.705
1951.00	23	32.750	-9.750
1951.08	17	30.108	-13.108
1951.17	17	28.066	-11.066
1951.25	17	33.041	-16.041
1951.33	18	30.988	-12.988
1951.42	20	33.776	-13.776
1951.50	38	36.625	1.375
1951.58	16	35.386	-19.386
1951.67	15	32.760	-17.760
1951.75	20	33.626	-13.626
1951.83	16	30.790	-14.790
1951.92	16	28.310	-12.310
1952.00	16	26.041	-10.041
1952.08	13	23.968	-10.968
1952.17	13	22.229	-9.229
1952.25	15	21.010	-6.010

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1952.33	30	39.643	-9.643
1952.42	29	44.580	-15.580
1952.50	27	42.229	-15.229
1952.58	22	39.345	-17.345
1952.67	18	36.233	-18.233
1952.75	30	33.440	-3.440
1952.83	34	30.597	3.403
1952.92	33	31.413	1.587
1953.00	34	32.945	1.055
1953.08	50	31.017	18.983
1953.17	52	28.876	23.124
1953.25	48	26.903	21.097
1953.33	50	44.933	5.067
1953.42	52	46.552	5.448
1953.50	38	43.819	-5.819
1953.58	21	40.604	-19.604
1953.67	17	37.776	-20.776
1953.75	47	34.745	12.255
1953.83	36	48.669	-12.669
1953.92	63	44.346	18.654
1954.00	70	44.426	25.574
1954.08	64	41.078	22.922
1954.17	50	37.507	12.493

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1954.25	37	34.195	2.805
1954.33	31	31.370	-0.370
1954.42	30	28.889	1.111
1954.50	24	26.452	-2.452
1954.58	19	24.320	-5.320
1954.67	18	22.435	-4.435
1954.75	16	20.699	-4.699
1954.83	21	19.179	1.821
1954.92	22	17.786	4.214
1955.00	21	16.551	4.449
1955.08	21	15.602	5.398
1955.17	20	24.879	-4.879
1955.25	20	29.240	-9.240
1955.33	15	27.687	-12.687
1955.42	21	29.852	-8.852
1955.50	19	27.920	-8.920
1955.58	16	27.352	-11.352
1955.67	14	25.109	-11.109
1955.75	16	23.006	-7.006
1955.83	15	21.074	-6.074
1955.92	15	19.309	-4.309
1956.00	14	17.763	-3.763
1956.08	16	16.612	-0.612

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1956.17	14	15.519	-1.519
1956.25	14	14.503	-0.503
1956.33	12	13.604	-1.604
1956.42	13	12.847	0.153
1956.50	12	11.981	0.019
1956.58	11	11.221	-0.221
1956.67	11	10.542	0.458
1956.75	12	9.854	2.146
1956.83	13	9.259	3.741
1956.92	15	8.718	6.282
1957.00	12	8.377	3.623
1957.08	15	8.154	6.846
1957.17	15	8.084	6.916
1957.25	14	16.256	-2.256
1957.33	19	35.291	-16.291
1957.42	53	54.162	-1.162
1957.50	77	61.200	15.800
1957.58	50	58.641	-8.641
1957.67	32	53.491	-21.491
1957.33	19	35.291	-16.291
1957.42	53	54.162	-1.162
1957.50	77	61.200	15.800
1957.58	50	58.641	-8.641

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1957.67	32	53.491	-21.491
1957.75	70	52.062	17.938
1957.83	50	66.858	-16.858
1957.92	70	81.911	-11.911
1958.00	91	79.617	11.383
1958.08	75	79.122	-4.122
1958.17	88	81.206	6.794
1958.25	123	83.141	39.859
1958.33	95	81.734	13.266
1958.42	75	79.516	-4.516
1958.50	90	72.292	17.708
1958.58	84	67.598	16.402
1958.67	62	60.946	1.054
1958.75	58	59.251	-1.251
1958.83	65	71.699	-6.699
1958.92	83	65.808	17.192
1959.00	80	60.304	19.696
1959.08	80	54.780	25.220
1959.17	70	50.035	19.965
1959.25	60	45.542	14.458
1959.33	70	48.640	21.360
1959.42	70	51.392	18.608
1959.50	62	53.140	8.860

Decimal Year	Estimated/Measured Discharge for Barton Springs ($feet^3$/second)	Simulated Discharge for Barton Springs ($feet^3$/second)	Residual ($feet^3$/second)
1959.58	57	50.699	6.301
1959.67	34	51.248	-17.248
1959.75	43	46.829	-3.829
1959.83	65	61.426	3.574
1959.92	55	59.707	-4.707
1960.00	50	55.280	-5.280
1960.08	62	51.019	10.981
1960.17	78	46.712	31.288
1960.25	70	42.758	27.242
1960.33	65	39.263	25.737
1960.42	57	35.907	21.093
1960.50	55	38.762	16.238
1960.58	46	37.170	8.830
1960.67	50	34.474	15.526
1960.75	52	31.466	20.534
1960.83	46	48.873	-2.873
1960.92	105	50.516	54.484
1961.00	92	53.549	38.451
1961.08	89	50.373	38.627
1961.17	97	56.458	40.542
1961.25	99	52.477	46.523
1961.33	96	48.533	47.467
1961.42	88	44.432	43.568

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1961.50	79	51.549	27.451
1961.58	130	66.993	63.007
1961.67	135	70.169	64.831
1961.75	118	64.628	53.372
1961.83	107	59.139	47.861
1961.92	93	53.863	39.137
1962.00	78	48.963	29.037
1962.08	54	44.631	9.369
1962.17	58	40.543	17.457
1962.25	58	37.295	20.705
1962.33	60	34.821	25.179
1962.42	56	32.255	23.745
1962.50	49	39.188	9.812
1962.58	38	36.093	1.907
1962.67	40	34.135	5.865
1962.75	46	31.741	14.259
1962.83	41	29.319	11.681
1962.92	36	27.016	8.984
1963.00	36	25.208	10.792
1963.08	47	23.646	23.354
1963.17	50	22.461	27.539
1963.25	47	21.148	25.852

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1963.33	62	20.225	41.775
1963.42	55	19.072	35.928
1963.50	41	17.921	23.079
1963.58	40	16.804	23.196
1963.67	33	15.776	17.224
1963.75	24	14.735	9.265
1963.83	21	13.851	7.149
1963.92	20	13.050	6.950
1964.00	19	12.401	6.599
1964.08	20	12.638	7.362
1964.17	21	12.403	8.597
1964.25	22	12.366	9.634
1964.33	26	12.165	13.835
1964.42	21	18.193	2.807
1964.50	21	25.481	-4.481
1964.58	20	26.161	-6.161
1964.67	19	24.221	-5.221
1964.75	18	22.587	-4.587
1964.83	19	20.770	-1.770
1964.92	19	19.121	-0.121
1965.00	19	17.567	1.433
1965.08	55	26.112	28.888
1965.17	69	39.090	29.910

Decimal Year	Estimated/Measured Discharge for Barton Springs ($feet^3$/second)	Simulated Discharge for Barton Springs ($feet^3$/second)	Residual ($feet^3$/second)
1965.25	66	48.544	17.456
1965.33	63	45.521	17.479
1965.42	80	61.951	18.049
1965.50	95	64.238	30.762
1965.58	84	61.075	22.925
1965.67	75	55.557	19.443
1965.75	78	50.455	27.545
1965.83	86	45.622	40.378
1965.92	85	41.284	43.716
1966.00	82	47.337	34.663
1966.08	82	53.228	28.772
1966.17	80	60.917	19.083
1966.25	78	56.805	21.195
1966.33	77	52.835	24.165
1966.42	75	54.445	20.555
1966.50	71	49.684	21.316
1966.58	60	45.194	14.806
1966.67	47	48.517	-1.517
1966.75	44	44.182	-0.182
1966.83	39	40.235	-1.235
1966.92	30	36.513	-6.513
1967.00	25	33.153	-8.153
1967.08	28	30.115	-2.115

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1967.17	28	27.454	0.546
1967.25	28	25.331	2.669
1967.33	30	23.704	6.296
1967.42	27	29.252	-2.252
1967.50	21	26.939	-5.939
1967.58	15	24.983	-9.983
1967.67	22	23.073	-1.073
1967.75	38	26.368	11.632
1967.83	61	42.673	18.327
1967.92	48	45.202	2.798
1968.00	42	46.535	-4.535
1968.08	76	63.088	12.912
1968.17	100	73.390	26.610
1968.25	97	78.068	18.932
1968.33	87	72.300	14.700
1968.42	89	78.937	10.063
1968.50	86	80.329	5.671
1968.58	89	76.033	12.967
1968.67	85	68.679	16.321
1968.75	77	62.145	14.855
1968.83	68	56.000	12.000
1968.92	59	53.389	5.611
1969.00	54	48.486	5.514

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1969.08	50	44.561	5.439
1969.17	64	49.056	14.944
1969.25	74	56.666	17.334
1969.33	73	72.203	0.797
1969.42	78	80.153	-2.153
1969.50	73	79.495	-6.495
1969.58	67	72.824	-5.824
1969.67	61	67.005	-6.005
1969.75	56	60.526	-4.526
1969.83	51	54.725	-3.725
1969.92	46	49.472	-3.472
1970.00	43	50.656	-7.656
1970.08	47	54.451	-7.451
1970.17	82	65.533	16.467
1970.25	111	72.225	38.775
1970.33	110	67.264	42.736
1970.42	103	81.849	21.151
1970.50	98	76.396	21.604
1970.58	93	70.311	22.689
1970.67	88	63.983	24.017
1970.75	84	58.203	25.797
1970.83	78	69.752	8.248
1970.92	65	63.201	1.799

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1971.00	51	57.475	-6.475
1971.08	39	52.153	-13.153
1971.17	35	47.304	-12.304
1971.25	32	43.148	-11.148
1971.33	28	39.598	-11.598
1971.42	31	36.426	-5.426
1971.50	33	33.451	-0.451
1971.58	20	30.778	-10.778
1971.67	35	36.730	-1.730
1971.75	67	34.067	32.933
1971.83	71	31.735	39.265
1971.92	73	29.520	43.480
1972.00	77	36.027	40.973
1972.08	100	42.546	57.454
1972.17	96	39.686	56.314
1972.25	90	36.955	53.045
1972.33	86	34.313	51.687
1972.42	84	51.590	32.410
1972.50	88	57.457	30.543
1972.58	85	57.205	27.795
1972.67	81	53.332	27.668
1972.75	80	48.595	31.405

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1972.83	80	44.258	35.742
1972.92	77	40.350	36.650
1973.00	74	36.806	37.194
1973.08	71	43.233	27.767
1973.17	69	50.340	18.660
1973.25	68	59.873	8.127
1973.33	65	67.136	-2.136
1973.42	64	62.902	1.098
1973.50	74	68.745	5.255
1973.58	87	81.544	5.456
1973.67	89	76.061	12.939
1973.75	87	75.755	11.245
1973.83	98	88.663	9.337
1973.92	108	86.981	21.019
1974.00	99	79.864	19.136
1974.08	95	73.498	21.502
1974.17	93	66.548	26.453
1974.25	90	60.569	29.431
1974.33	93	55.202	37.798
1974.42	95	64.034	30.966
1974.50	89	58.396	30.604
1974.58	82	53.436	28.564
1974.67	73	57.073	15.927

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1974.75	66	52.223	13.777
1974.83	65	47.818	17.182
1974.92	74	63.682	10.318
1975.00	98	68.172	29.828
1975.08	96	71.910	24.090
1975.17	97	76.260	20.740
1975.25	96	71.007	24.993
1975.33	95	85.269	9.731
1975.42	97	99.289	-2.289
1975.50	113	111.514	1.486
1975.58	118	122.054	-4.054
1975.67	112	120.905	-8.905
1975.75	99	110.646	-11.646
1975.83	90	100.576	-10.576
1975.92	82	90.922	-8.922
1976.00	73	82.264	-9.264
1976.08	64	74.708	-10.708
1976.17	58	67.661	-9.661
1976.25	55	61.936	-6.936
1976.33	70	76.423	-6.423
1976.42	113	91.220	21.780
1976.50	106	94.072	11.928
1976.58	100	106.348	-6.348

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1976.67	93	99.351	-6.351
1976.75	88	91.512	-3.512
1976.83	90	103.414	-13.414
1976.92	97	100.565	-3.565
1977.00	98	97.491	0.509
1977.08	98	98.127	-0.127
1977.17	99	98.400	0.600
1977.25	100	91.105	8.895
1977.33	103	103.498	-0.498
1977.42	106	105.084	0.916
1977.50	101	96.980	4.020
1977.58	94	88.744	5.256
1977.67	88	80.843	7.157
1977.75	80	73.440	6.560
1977.83	72	66.798	5.202
1977.92	62	60.902	1.098
1978.00	50	55.657	-5.657
1978.08	39	50.979	-11.979
1978.17	42	47.141	-5.141
1978.25	38	43.912	-5.912
1978.33	31	41.019	-10.019
1978.42	31	47.910	-16.910
1978.50	31	44.863	-13.863

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1978.58	21	41.904	-20.904
1978.67	22	38.936	-16.936
1978.75	25	36.440	-11.440
1978.83	24	33.841	-9.841
1978.92	33	38.855	-5.855
1979.00	36	43.642	-7.642
1979.08	64	61.007	2.993
1979.17	79	72.760	6.240
1979.25	84	85.850	-1.850
1979.33	95	99.929	-4.929
1979.42	103	107.040	-4.040
1979.50	106	98.921	7.079
1979.58	98	110.456	-12.456
1979.67	93	110.097	-17.097
1979.75	84	100.777	-16.777
1979.83	69	91.628	-22.628
1979.92	55	82.981	-27.981
1980.00	46	75.350	-29.350
1980.08	38	69.060	-31.060
1980.17	37	63.254	-26.254
1980.25	35	66.856	-31.856

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1980.33	52	61.793	-9.793
1980.42	62	71.554	-9.554
1980.50	71	65.833	5.167
1980.58	57	60.554	-3.554
1980.67	42	55.465	-13.465
1980.75	37	51.037	-14.037
1980.83	46	46.727	-0.727
1980.92	43	43.061	-0.061
1981.00	50	39.714	10.286
1981.08	48	37.443	10.557
1981.17	53	34.764	18.236
1981.25	66	33.005	32.995
1981.33	64	31.124	32.876
1981.42	58	42.103	15.897
1981.50	81	58.947	22.053
1981.58	102	75.879	26.121
1981.67	94	80.407	13.593
1981.75	86	74.660	11.340
1981.83	86	86.417	-0.417
1981.92	83	79.154	3.846
1982.00	74	72.280	1.720
1982.08	60	65.511	-5.511
1982.17	52	59.262	-7.262

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1982.25	46	53.996	-7.996
1982.33	43	49.722	-6.722
1982.42	62	60.205	1.795
1982.50	68	63.213	4.787
1982.58	57	57.923	-0.923
1982.67	44	52.967	-8.967
1982.75	36	48.107	-12.107
1982.83	33	43.724	-10.724
1982.92	34	39.879	-5.879
1983.00	40	36.676	3.324
1983.08	42	34.637	7.363
1983.17	45	32.519	12.481
1983.25	63	47.943	15.057
1983.33	77	45.190	31.810
1983.42	74	53.892	20.108
1983.50	84	60.249	23.751
1983.58	80	60.397	19.603
1983.67	73	56.037	16.963
1983.75	65	51.336	13.664
1983.83	64	46.689	17.311
1983.92	59	42.504	16.496
1984.00	50	38.663	11.337
1984.08	43	35.696	7.304

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1984.17	36	32.612	3.388
1984.25	34	30.545	3.455
1984.33	32	28.265	3.735
1984.42	29	26.092	2.908
1984.50	28	23.871	4.129
1984.58	26	21.910	4.090
1984.67	26	20.142	5.858
1984.75	25	18.438	6.562
1984.83	38	37.064	0.936
1984.92	46	40.547	5.453
1985.00	54	46.507	7.493
1985.08	71	44.158	26.842
1985.17	76	41.381	34.619
1985.25	81	38.642	42.358
1985.33	79	35.883	43.117
1985.42	72	33.022	38.978
1985.50	70	38.545	31.455
1985.58	69	40.131	28.869
1985.67	59	36.470	22.530
1985.75	49	33.490	15.510
1985.83	54	30.626	23.374
1985.92	59	47.909	11.091
1986.00	79	52.861	26.139

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1986.08	77	50.276	26.724
1986.17	75	46.335	28.665
1986.25	71	42.526	28.474
1986.33	63	38.895	24.105
1986.42	72	55.239	16.761
1986.50	79	60.339	18.661
1986.58	72	57.988	14.012
1986.67	59	52.726	6.274
1986.75	55	47.962	7.038
1986.83	62	63.179	-1.179
1986.92	73	62.566	10.434
1987.00	78	76.948	1.052
1987.08	78	81.345	-3.345
1987.17	79	88.283	-9.283
1987.25	106	81.835	24.165
1987.33	102	74.997	27.003
1987.42	96	87.925	8.075
1987.50	106	100.730	5.270
1987.58	103	113.271	-10.271
1987.67	107	105.801	1.199
1987.75	98	96.934	1.066
1987.83	91	87.713	3.287

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1987.92	82	79.142	2.858
1988.00	76	71.415	4.585
1988.08	70	64.522	5.478
1988.17	62	58.233	3.767
1988.25	55	53.376	1.624
1988.33	52	49.062	2.938
1988.42	49	53.109	-4.109
1988.50	47	48.628	-1.628
1988.58	44	47.488	-3.488
1988.67	43	43.226	-0.226
1988.75	40	39.333	0.667
1988.83	28	35.822	-7.822
1988.92	25	32.661	-7.661
1989.00	25	29.906	-4.906
1989.08	26	37.150	-11.150
1989.17	28	34.646	-6.646
1989.25	25	32.935	-7.935
1989.33	29	31.202	-2.202
1989.42	54	41.874	12.126
1989.50	66	45.646	20.354
1989.58	50	41.959	8.041
1989.67	34	38.418	-4.418

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1989.75	26	34.837	-8.837
1989.83	19	31.623	-12.623
1989.92	21	28.748	-7.748
1990.00	18	26.192	-8.192
1990.08	16	24.122	-8.122
1990.17	17	31.154	-14.154
1990.25	22	40.595	-18.595
1990.33	28	48.224	-20.224
1990.42	55	55.163	-0.163
1990.50	44	51.304	-7.304
1990.58	34	65.423	-31.423
1990.67	26	60.195	-34.195
1990.75	22	55.528	-33.528
1990.83	21	50.585	-29.585
1990.92	24	49.344	-25.344
1991.00	20	44.825	-24.825
1991.08	67	60.821	6.179
1991.17	85	74.816	10.184
1991.25	85	80.998	4.002
1991.33	96	87.052	8.948
1991.42	96	91.369	4.631
1991.50	91	92.584	-1.584
1991.58	82	88.728	-6.728

Decimal Year	**Estimated/Measured Discharge for Barton Springs (feet^3/second)**	**Simulated Discharge for Barton Springs (feet^3/second)**	**Residual (feet^3/second)**
1991.67	72	81.315	-9.315
1991.75	69	73.885	-4.885
1991.83	63	66.790	-3.790
1991.92	59	60.303	-1.303
1992.00	79	74.586	4.414
1992.08	88	89.193	-1.193
1992.17	120	103.032	16.968
1992.25	103	114.453	-11.453
1992.33	103	125.834	-22.834
1992.42	100	136.560	-36.560
1992.50	91	142.079	-51.079
1992.58	99	133.786	-34.786
1992.67	127	121.013	5.987
1992.75	123	108.928	14.072
1992.83	116	97.881	18.119
1992.92	103	88.211	14.789
1993.00	98	79.950	18.050
1993.08	97	83.434	13.566
1993.17	105	88.677	16.323
1993.25	106	93.292	12.708
1993.33	108	86.590	21.410
1993.42	108	93.286	14.714

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1993.50	102	96.254	5.746
1993.58	95	87.952	7.048
1993.67	83	79.992	3.008
1993.75	71	72.440	-1.440
1993.83	66	65.689	0.311
1993.92	59	59.664	-0.664
1994.00	53	54.411	-1.411
1994.08	52	50.036	1.964
1994.17	50	46.317	3.683
1994.25	48	43.311	4.689
1994.33	46	40.545	5.455
1994.42	44	49.524	-5.524
1994.50	43	46.167	-3.167
1994.58	37	42.795	-5.795
1994.67	33	48.132	-15.132
1994.75	28	44.582	-16.582
1994.83	37	61.183	-24.183
1994.92	53	61.888	-8.888
1995.00	42	70.430	-28.430
1995.08	39	66.126	-27.126
1995.17	35	61.371	-26.371
1995.25	68	56.973	11.027

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1995.33	83	52.780	30.220
1995.42	87	68.213	18.787
1995.50	99	74.318	24.682
1995.58	90	70.817	19.183
1995.67	80	65.619	14.381
1995.75	69	60.086	8.914
1995.83	51	54.555	-3.555
1995.92	50	49.683	0.317
1996.00	39	45.270	-6.270
1996.08	32	41.273	-9.273
1996.17	27	37.709	-10.709
1996.25	24	34.670	-10.670
1996.33	25	32.238	-7.238
1996.42	21	29.877	-8.877
1996.50	26	28.003	-2.003
1996.58	21	25.872	-4.872
1996.67	22	32.572	-10.572
1996.75	33	38.027	-5.027
1996.83	31	36.009	-5.009
1996.92	31	34.123	-3.123
1997.00	34	32.160	1.840
1997.08	36	30.548	5.452
1997.17	47	37.410	9.590

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1997.25	58	35.762	22.238
1997.33	74	53.466	20.534
1997.42	87	70.752	16.248
1997.50	102	87.053	14.947
1997.58	112	100.788	11.212
1997.67	105	94.464	10.536
1997.75	93	86.381	6.619
1997.83	90	78.319	11.681
1997.92	81	70.805	10.195
1998.00	74	71.494	2.506
1998.08	85	76.030	8.970
1998.17	93	82.386	10.614
1998.25	98	87.855	10.145
1998.33	97	81.053	15.947
1998.42	92	74.081	17.919
1998.50	85	67.025	17.975
1998.58	75	60.566	14.434
1998.67	63	55.516	7.484
1998.75	58	62.147	-4.147
1998.83	84	77.752	6.248
1998.92	104	93.301	10.699
1999.00	105	98.733	6.267
1999.08	102	91.686	10.314

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
1999.17	95	84.034	10.966
1999.25	90	77.127	12.873
1999.33	85	70.336	14.664
1999.42	76	71.039	4.961
1999.50	69	72.214	-3.214
1999.58	66	71.448	-5.448
1999.67	55	64.946	-9.946
1999.75	42	58.962	-16.962
1999.83	33	53.433	-20.433
1999.92	31	48.417	-17.417
2000.00	29	43.998	-14.998
2000.08	29	41.019	-12.019
2000.17	27	38.228	-11.228
2000.25	27	35.891	-8.891
2000.33	25	33.642	-8.642
2000.42	26	41.759	-15.759
2000.50	49	48.350	0.650
2000.58	38	47.673	-9.673
2000.67	27	43.498	-16.498
2000.75	21	39.469	-18.469
2000.83	28	53.769	-25.769
2000.92	73	69.401	3.599
2001.00	85	75.019	9.981

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
2001.08	93	82.110	10.890
2001.17	100	75.788	24.212
2001.25	101	79.804	21.196
2001.33	103	73.246	29.754
2001.42	103	82.463	20.537
2001.50	96	81.823	14.177
2001.58	88	77.460	10.540
2001.67	76	78.363	-2.363
2001.75	77	70.852	6.148
2001.83	68	64.033	3.967
2001.92	80	62.362	17.638
2002.00	106	65.950	40.050
2002.08	112	68.734	43.266
2002.17	109	62.827	46.173
2002.25	102	57.626	44.374
2002.33	98	52.743	45.257
2002.42	91	48.031	42.969
2002.50	80	54.136	25.864
2002.58	97	68.999	28.001
2002.67	101	72.792	28.208
2002.75	92	67.056	24.944
2002.83	86	81.171	4.829
2002.92	98	95.220	2.780

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
2003.00	107	108.504	-1.504
2003.08	109	111.446	-2.446
2003.17	114	113.267	0.733
2003.25	115	104.232	10.768
2003.33	107	94.991	12.009
2003.42	100	85.699	14.301
2003.50	96	77.397	18.603
2003.58	89	72.376	16.624
2003.67	82	64.908	17.092
2003.75	71	65.398	5.602
2003.83	57	59.340	-2.340
2003.92	43	54.166	-11.166
2004.00	40	49.365	-9.365
2004.08	41	46.059	-5.059
2004.17	42	51.487	-9.487
2004.25	46	57.159	-11.159
2004.33	56	53.638	2.362
2004.42	63	56.469	6.531
2004.50	74	70.455	3.545
2004.58	96	83.315	12.685
2004.67	86	77.852	8.148
2004.75	72	71.726	0.274
2004.83	65	85.385	-20.385

Decimal Year	Estimated/Measured Discharge for Barton Springs (feet^3/second)	Simulated Discharge for Barton Springs (feet^3/second)	Residual (feet^3/second)
2004.92	82	99.074	-17.074
2005.00	102	111.875	-9.875

APPENDIX D: Wells Used for Measured Groundwater Elevations

TABLE D-1. STATE WELL NUMBERS, MODEL ROW, MODEL COLUMN, NUMBER OF MEASUREMENTS, HIGHEST MEASURED GROUNDWATER ELEVATION, LOWEST MEASURED GROUNDWATER ELEVATION, DECIMAL YEAR OF EARLIEST MEASUREMENT, AND DECIMAL YEAR OF LATEST MEASUREMENT FOR THE 152 TARGET WELLS USED TO CALIBRATE THE GROUNDWATER FLOW MODEL.

State Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (feet MSL)	Lowest Groundwater Elevation (feet MSL)	Decimal Year of Earliest Measurement	Decimal Year of Latest Measurement
5858101	92	46	429	664.50	551.80	1943.33	2005.00
5850801	75	68	290	630.10	504.25	1943.33	2005.00
5850301	52	92	281	528.65	431.00	1949.58	2005.00
5842911	21	107	120	443.20	426.73	1944.00	1981.08
5858123	79	53	113	648.24	536.17	1985.17	2005.00
5850212	33	90	84	510.18	415.75	1978.42	2005.00
5857201	40	30	83	797.00	748.40	1951.00	2004.17
5842819	10	97	78	494.23	420.00	1982.25	2005.00
5850216	36	95	66	505.58	435.33	1978.75	2005.00
5850205	31	92	48	475.60	430.88	1943.33	1950.00
5857509	64	26	42	699.89	656.85	1988.67	2004.83
5858104	78	50	42	635.26	553.94	1943.33	1997.00
5850411	35	71	39	561.11	539.66	1978.50	2002.17
5842903	29	108	37	441.50	427.36	1949.08	1960.42
5850702	45	55	36	660.10	624.41	1949.58	1960.00
5850501	50	72	27	568.62	477.40	1949.67	1958.58
5850413	34	65	24	603.70	559.26	1980.50	2004.25
5849925	43	43	21	648.29	636.07	1995.25	2005.00
5849926	43	42	21	697.20	671.95	1995.25	2005.00
5850103	5	81	21	765.23	763.81	1943.17	1947.25
5849309	7	69	17	853.70	835.17	1969.25	1992.17
5857602	65	27	17	707.86	652.67	1975.83	1998.17
5850211	14	90	15	580.49	523.50	1971.92	2004.58

State Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (feet MSL)	Lowest Groundwater Elevation (feet MSL)	Decimal Year of Earliest Measurement	Decimal Year of Latest Measurement
5850215	30	90	11	517.80	389.50	1985.92	2003.42
5850217	27	96	10	497.93	475.30	1981.08	2004.58
5850704	58	57	10	585.24	514.29	1968.17	2001.50
5857303	55	42	10	660.70	613.39	1978.08	1998.33
5842915	31	103	9	443.70	392.69	1993.33	2003.42
5850204	33	83	9	475.66	465.05	1943.33	1944.58
5850412	28	66	9	657.53	647.57	1978.50	1994.33
5850805	59	68	9	569.01	499.69	1943.33	1947.50
5850104	12	84	7	541.43	526.82	1943.33	1946.25
5850408	33	64	7	614.80	590.60	1981.08	2003.42
5850417	32	74	6	545.67	524.75	2000.50	2004.58
5850123	5	79	5	715.00	682.70	1998.67	2003.42
5842928	33	106	4	499.00	472.76	1979.25	2004.50
5842931	23	109	4	430.62	428.97	1997.25	2004.67
5849935	40	52	4	675.80	530.00	1993.00	2003.42
5850201	42	92	4	521.83	457.55	1981.08	2003.42
5850855	69	67	4	592.75	538.80	1998.67	2003.42
5857307	66	41	4	634.78	592.00	1985.08	2001.50
5857311	55	42	4	655.35	627.00	1993.42	2003.42
5858423	93	39	4	650.21	614.00	1998.67	2003.42
5858508	99	48	4	618.06	593.82	1985.92	2001.50
5842814	13	105	3	439.10	435.40	1978.25	1989.42
5842821	10	98	3	499.10	477.80	1982.17	2004.67
5842913	22	106	3	431.04	426.80	1981.08	2003.58
5850122	13	86	3	545.72	539.34	1998.67	2004.67
5850214	42	87	3	462.30	448.76	1978.33	1981.08

State Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (feet MSL)	Lowest Groundwater Elevation (feet MSL)	Decimal Year of Earliest Measurement	Decimal Year of Latest Measurement
5850226	30	94	3	488.61	465.00	1985.42	1993.58
5850227	29	94	3	487.08	450.00	1985.42	1993.58
5850836	73	68	3	623.10	542.70	1973.33	2004.67
5850837	69	68	3	589.00	505.20	1973.67	1986.17
5858427	87	40	3	654.45	615.80	2002.17	2004.58
5842812	10	99	2	489.00	461.00	1948.75	1978.67
5842815	8	91	2	585.50	552.74	1971.83	1978.25
5842817	8	98	2	547.00	543.90	1978.50	1980.08
5842825	10	98	2	495.82	494.77	2002.42	2003.42
5850206	26	92	2	476.00	471.50	1969.50	1981.08
5850207	30	84	2	475.60	460.24	1971.33	1978.33
5850228	28	95	2	485.00	484.45	1985.42	1993.42
5850229	27	95	2	470.00	467.64	1985.42	1993.58
5850231	50	89	2	510.50	510.20	2003.67	2004.50
5850402	40	69	2	536.10	516.90	1969.17	1981.08
5850506	59	74	2	554.10	485.00	1970.50	1973.33
5850517	55	75	2	583.00	520.10	1973.50	1981.08
5850701	61	59	2	519.20	515.45	1949.58	1949.92
5850703	58	57	2	583.50	535.10	1973.33	1978.33
5850705	61	61	2	555.50	520.00	1965.92	1969.67
5850710	39	61	2	555.30	554.60	1949.58	1978.25
5850714	57	62	2	645.00	549.50	1969.75	1979.17
5850730	64	61	2	565.80	551.42	1998.58	2003.67
5850810	80	66	2	605.00	575.60	1969.58	1981.08
5850811	69	62	2	537.00	506.70	1963.42	1978.33
5850817	67	63	2	539.20	500.00	1955.92	1981.08

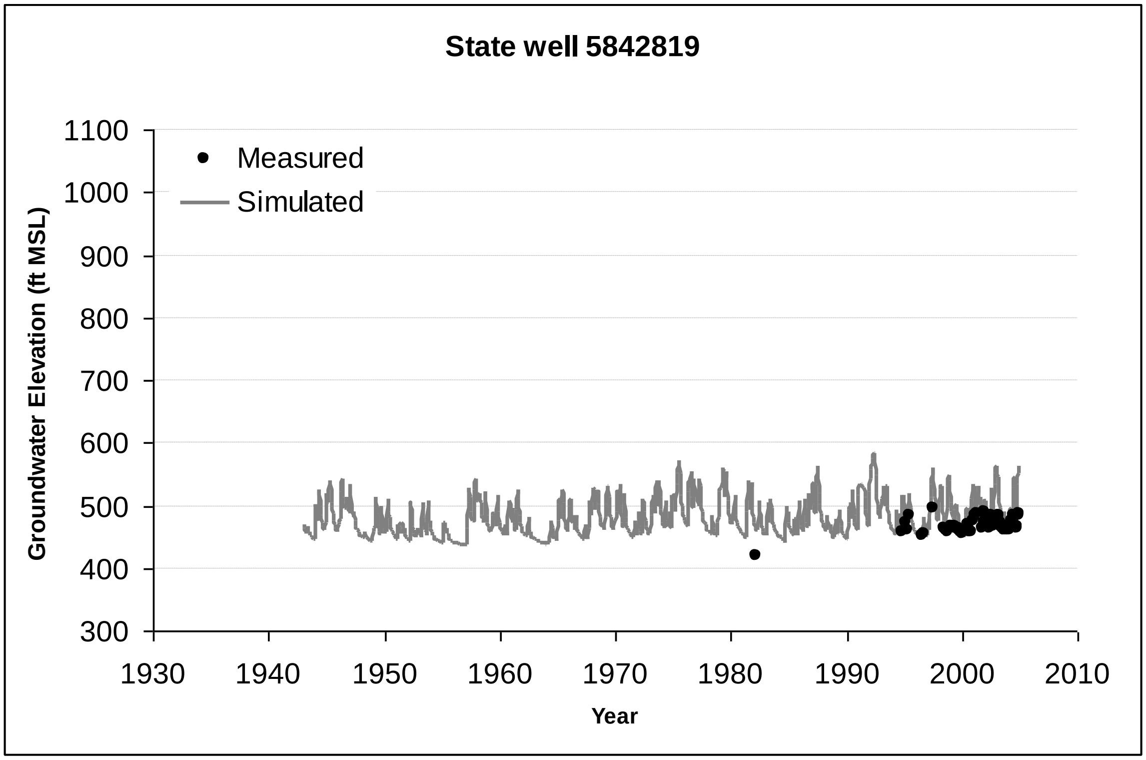
State Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (feet MSL)	Lowest Groundwater Elevation (feet MSL)	Decimal Year of Earliest Measurement	Decimal Year of Latest Measurement
5850822	64	68	2	559.50	524.05	1970.17	1981.08
5850827	71	67	2	555.30	476.20	1973.67	1978.33
5850838	72	65	2	610.80	524.60	1973.67	1978.33
5850852	62	71	2	514.89	502.80	1998.67	2003.67
5857606	93	28	2	639.71	625.00	2003.67	2004.58
5858202	83	63	2	605.30	563.30	1969.67	1998.67
5858711	120	25	2	604.77	592.64	2003.42	2004.67
5858712	109	26	2	595.69	569.50	2003.67	2004.58
5842813	13	105	1	432.10	432.10	1981.08	1981.08
5842901	19	109	1	416.20	416.20	1955.25	1955.25
5842912	15	108	1	436.30	436.30	1955.25	1955.25
5849910	46	48	1	456.00	456.00	1974.50	1974.50
5849911	46	48	1	629.00	629.00	1975.42	1975.42
5849916	45	50	1	590.00	590.00	1987.58	1987.58
5849917	45	51	1	582.00	582.00	1987.58	1987.58
5849918	44	50	1	538.50	538.50	1980.58	1980.58
5849919	42	49	1	565.00	565.00	1986.58	1986.58
5849922	45	52	1	595.00	595.00	1984.42	1984.42
5849923	44	52	1	594.00	594.00	1984.75	1984.75
5849924	44	52	1	592.00	592.00	1984.75	1984.75
5849931	43	53	1	545.00	545.00	1990.33	1990.33
5849933	43	53	1	545.00	545.00	1990.33	1990.33
5849938	43	43	1	719.60	719.60	2004.50	2004.50
5849939	35	50	1	711.20	711.20	2004.67	2004.67
5850108	29	80	1	530.00	530.00	1949.58	1949.58
5850112	26	78	1	567.20	567.20	1970.83	1970.83

State Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (feet MSL)	Lowest Groundwater Elevation (feet MSL)	Decimal Year of Earliest Measurement	Decimal Year of Latest Measurement
5850124	11	71	1	612.48	612.48	2000.25	2000.25
5850208	29	85	1	463.00	463.00	1955.17	1955.17
5850218	27	96	1	441.00	441.00	1978.58	1978.58
5850230	32	90	1	501.90	501.90	2003.42	2003.42
5850403	35	65	1	650.00	650.00	1968.50	1968.50
5850405	35	75	1	798.80	798.80	1970.83	1970.83
5850407	32	64	1	605.00	605.00	1971.25	1971.25
5850505	56	76	1	500.00	500.00	1963.17	1963.17
5850515	52	72	1	495.00	495.00	1953.58	1953.58
5850602	53	88	1	415.20	415.20	1971.42	1971.42
5850706	67	61	1	495.00	495.00	1962.92	1962.92
5850708	65	63	1	455.00	455.00	1968.50	1968.50
5850713	54	62	1	558.20	558.20	1970.83	1970.83
5850717	68	60	1	590.00	590.00	1970.33	1970.33
5850718	63	59	1	526.00	526.00	1970.83	1970.83
5850724	64	62	1	552.15	552.15	2003.67	2003.67
5850734	62	57	1	544.00	544.00	1980.58	1980.58
5850735	62	57	1	540.00	540.00	1978.00	1978.00
5850737	68	61	1	548.62	548.62	2003.67	2003.67
5850738	60	57	1	559.00	559.00	1985.83	1985.83
5850743	48	60	1	565.88	565.88	2003.42	2003.42
5850745	56	59	1	574.38	574.38	2004.58	2004.58
5850746	72	59	1	585.84	585.84	2004.67	2004.67
5850803	72	68	1	562.00	562.00	1943.33	1943.33
5850809	69	64	1	535.00	535.00	1966.50	1966.50
5850812	69	64	1	540.00	540.00	1965.83	1965.83

State Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (feet MSL)	Lowest Groundwater Elevation (feet MSL)	Decimal Year of Earliest Measurement	Decimal Year of Latest Measurement
5850819	75	64	1	498.00	498.00	1949.58	1949.58
5850826	67	66	1	515.00	515.00	1969.92	1969.92
5850828	72	63	1	555.00	555.00	1972.42	1972.42
5850829	63	70	1	545.00	545.00	1971.67	1971.67
5850830	63	71	1	510.00	510.00	1971.67	1971.67
5850835	72	69	1	415.00	415.00	1969.17	1969.17
5850846	77	63	1	620.40	620.40	2003.42	2003.42
5850861	65	64	1	462.70	462.70	2003.67	2003.67
5857210	57	30	1	690.00	690.00	1995.33	1995.33
5857314	52	42	1	633.98	633.98	2002.42	2002.42
5857315	66	40	1	607.99	607.99	2003.67	2003.67
5857609	61	28	1	630.00	630.00	1998.17	1998.17
5857610	95	28	1	666.60	666.60	2003.67	2003.67
5858122	87	48	1	602.55	602.55	2003.67	2003.67
5858127	61	48	1	558.00	558.00	1990.42	1990.42
5858203	81	61	1	578.10	578.10	1981.17	1981.17
5858204	78	61	1	498.00	498.00	1962.83	1962.83
5858207	82	61	1	485.00	485.00	1969.33	1969.33
5858208	85	60	1	480.00	480.00	1971.58	1971.58
5858215	78	60	1	505.00	505.00	1972.50	1972.50
5858416	102	34	1	653.00	653.00	1977.67	1977.67
5858425	108	35	1	603.40	603.40	1999.50	1999.50
5858426	83	40	1	603.14	603.14	2003.58	2003.58
5858509	102	47	1	592.80	592.80	2003.67	2003.67
5858710	119	27	1	610.00	610.00	1999.00	1999.00

APPENDIX E: Hydrographs for Target Wells

FIGURE E-1. HYDROGRAPHS FOR 35 OF THE 152 TARGET WELLS USED TO CALIBRATE THE GROUNDWATER FLOW MODEL. HYDROGRAPHS SHOWN ARE FOR WELLS WITH 5 OR MORE DATA POINTS.



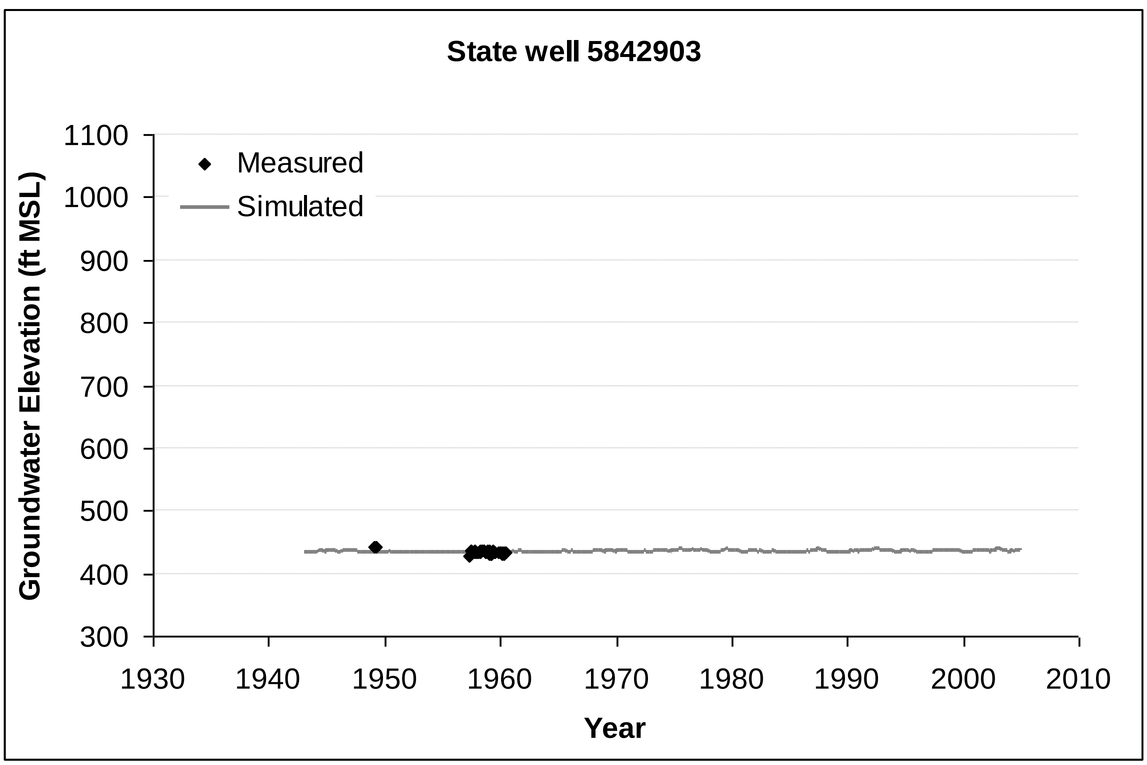
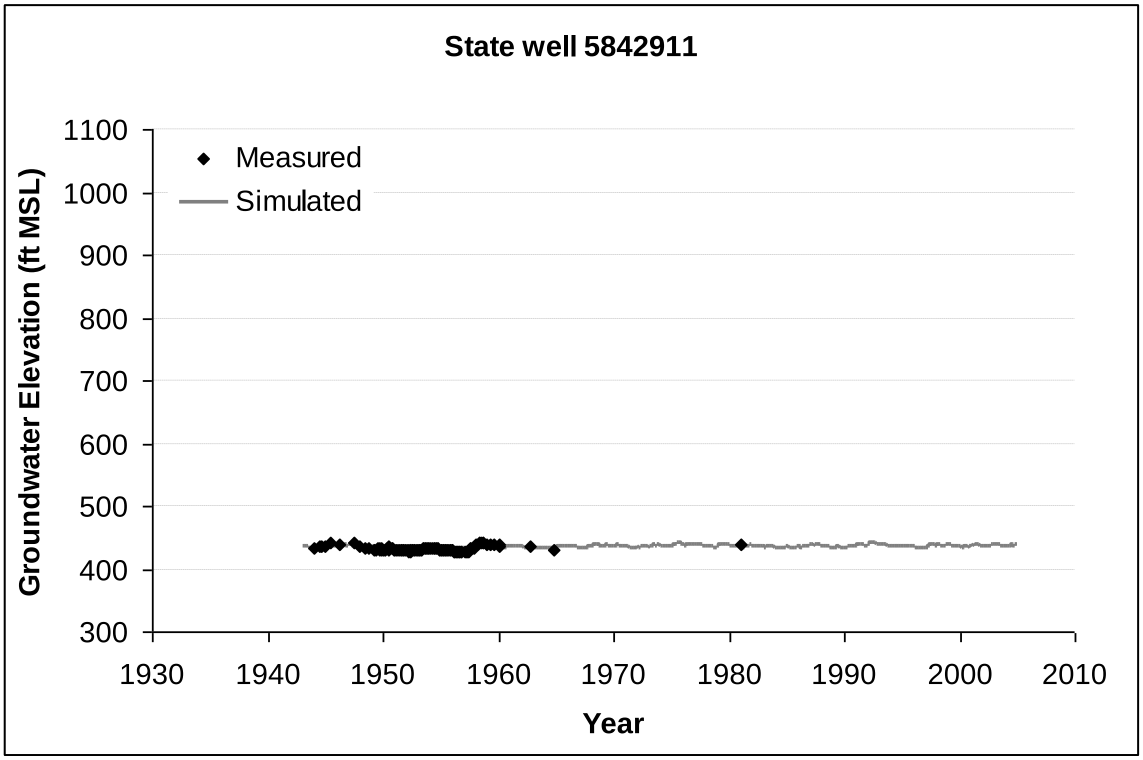


Figure E-1 continued



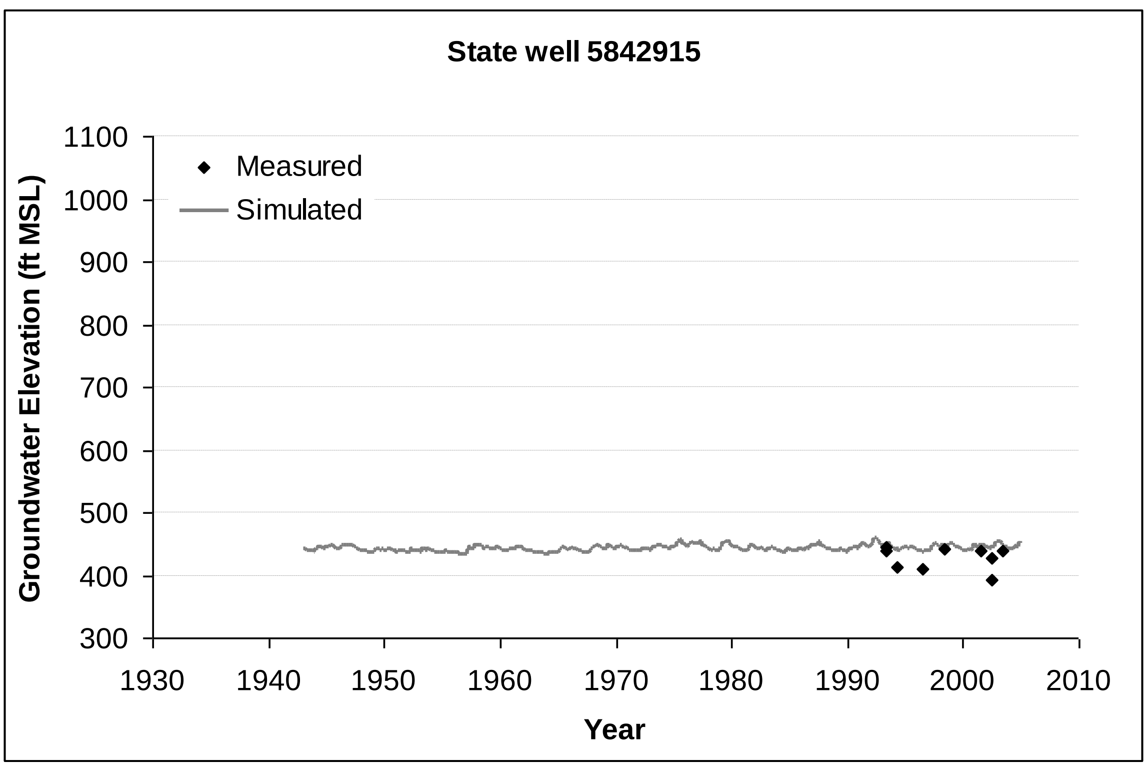
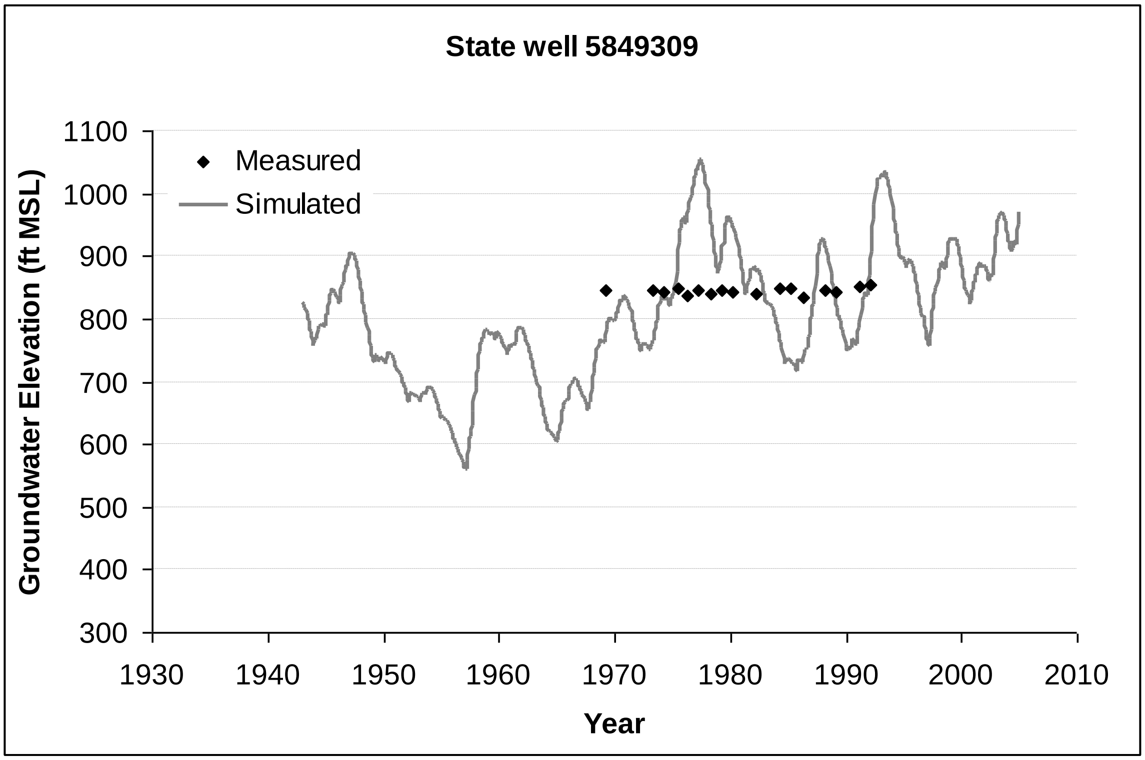
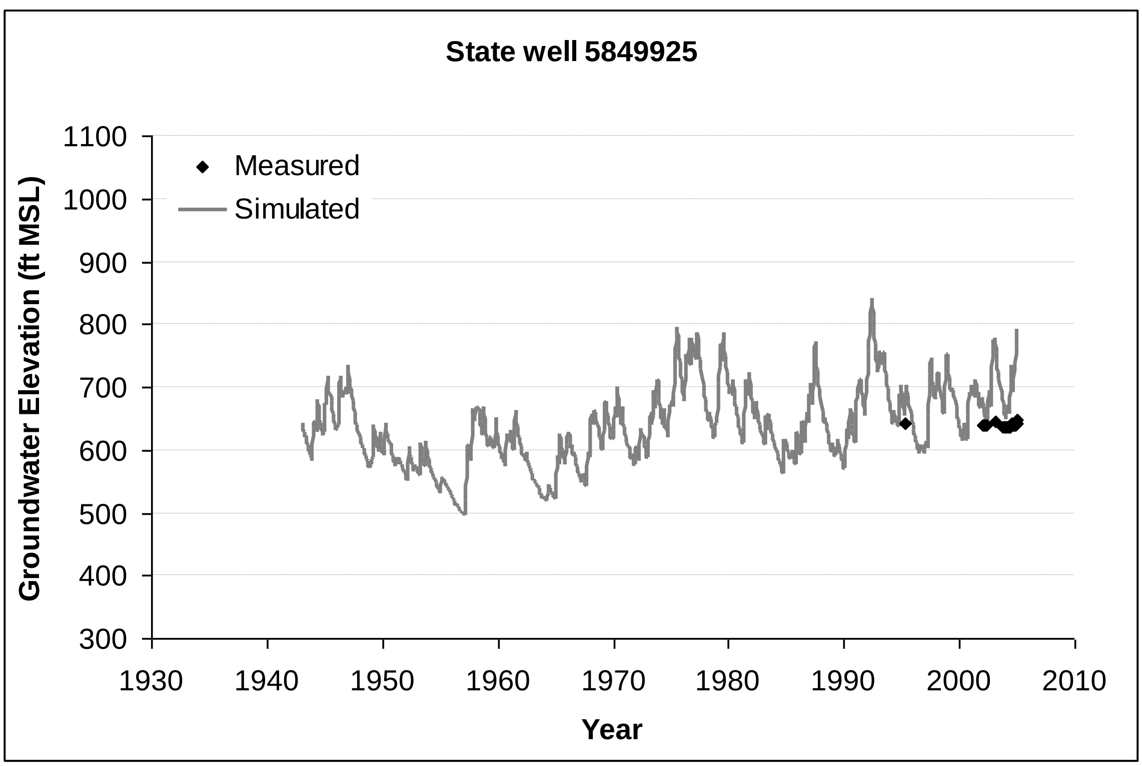


Figure E-1 continued.





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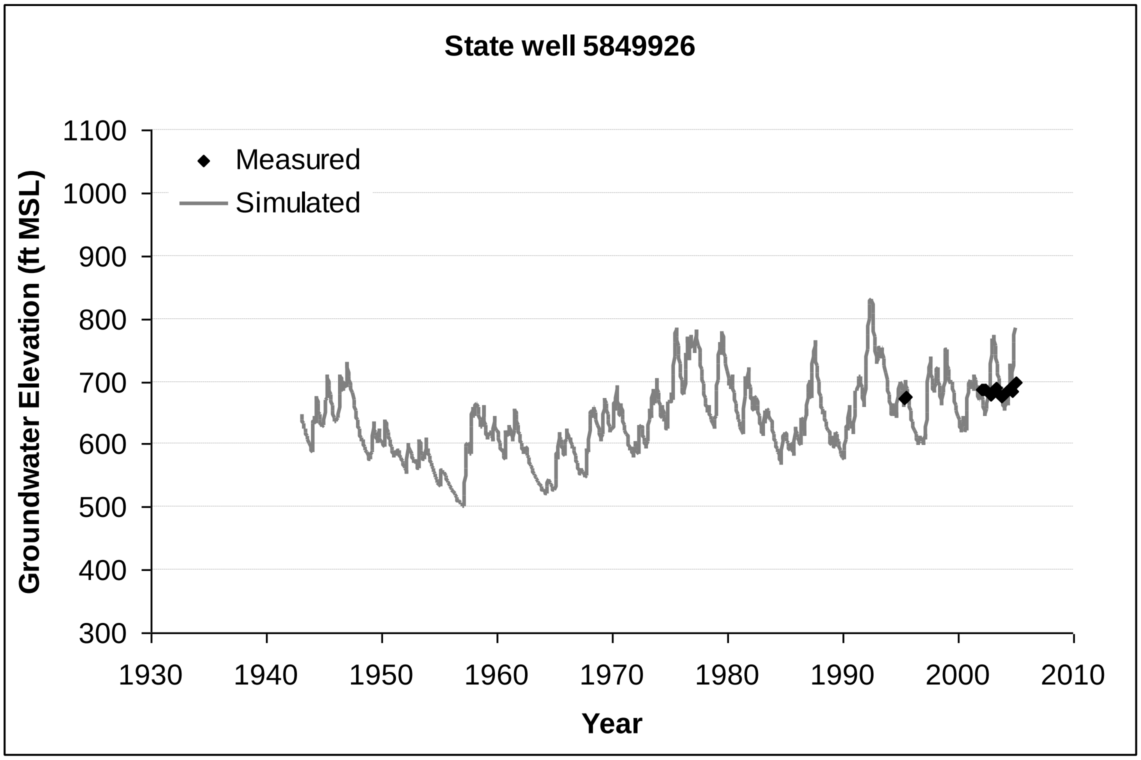

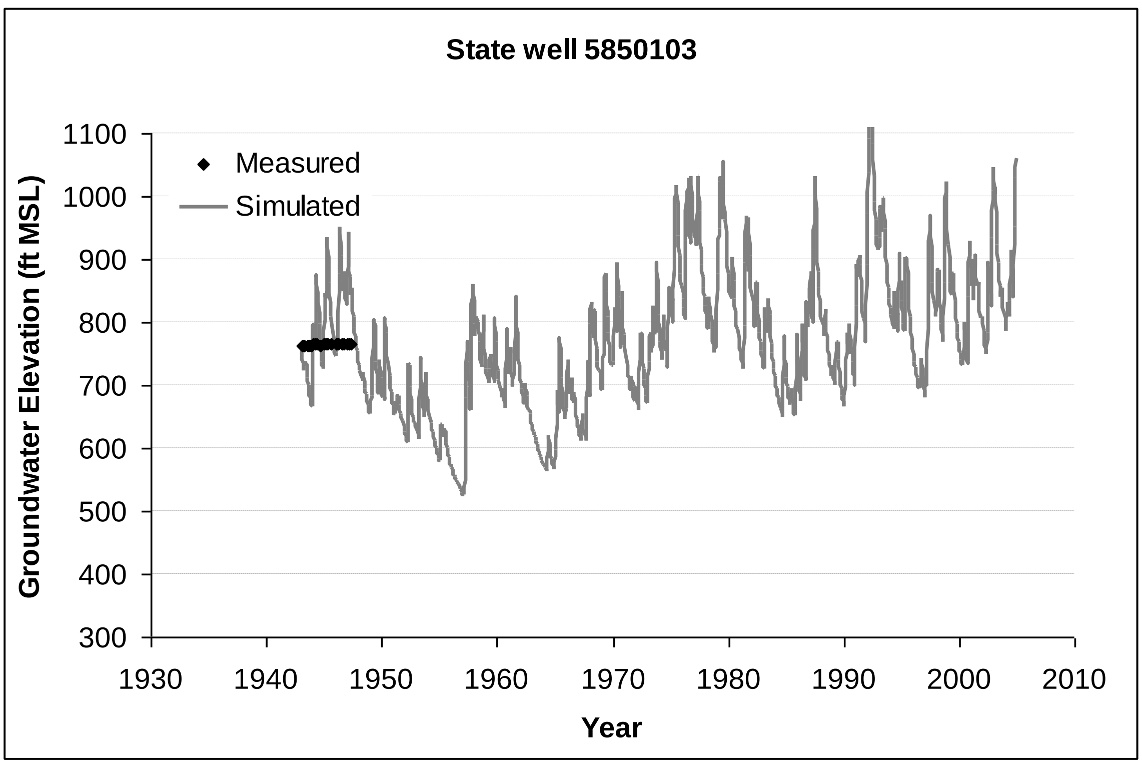

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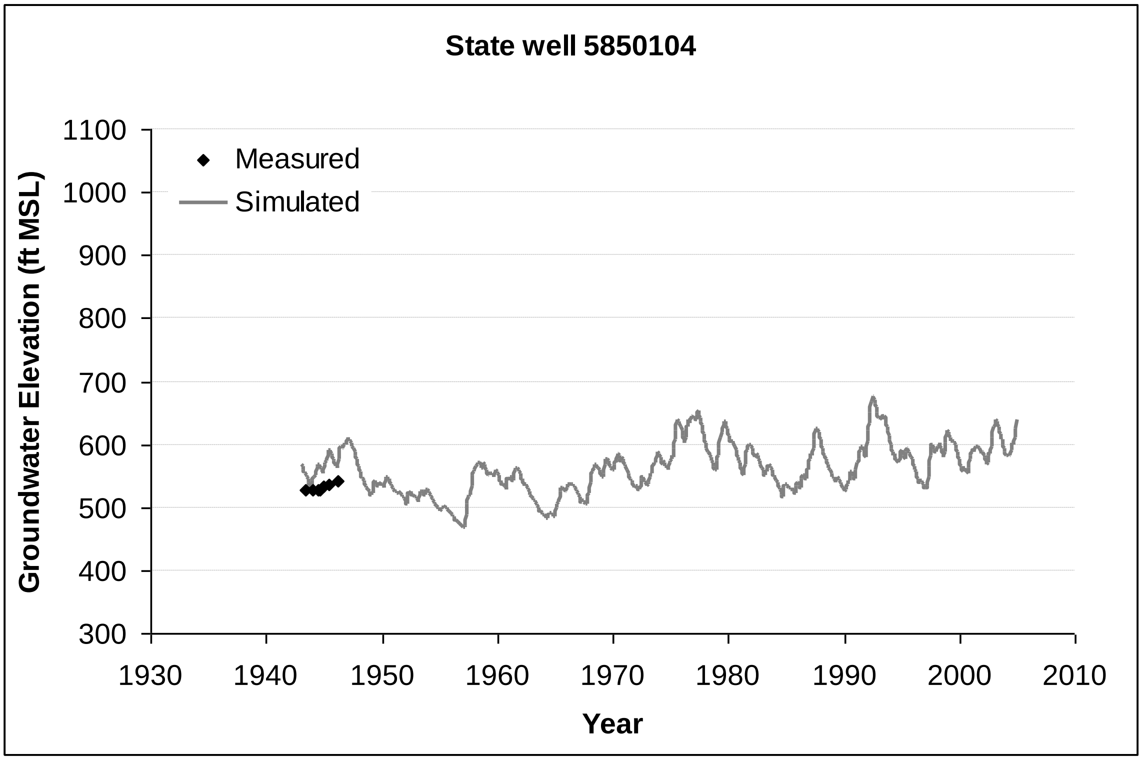

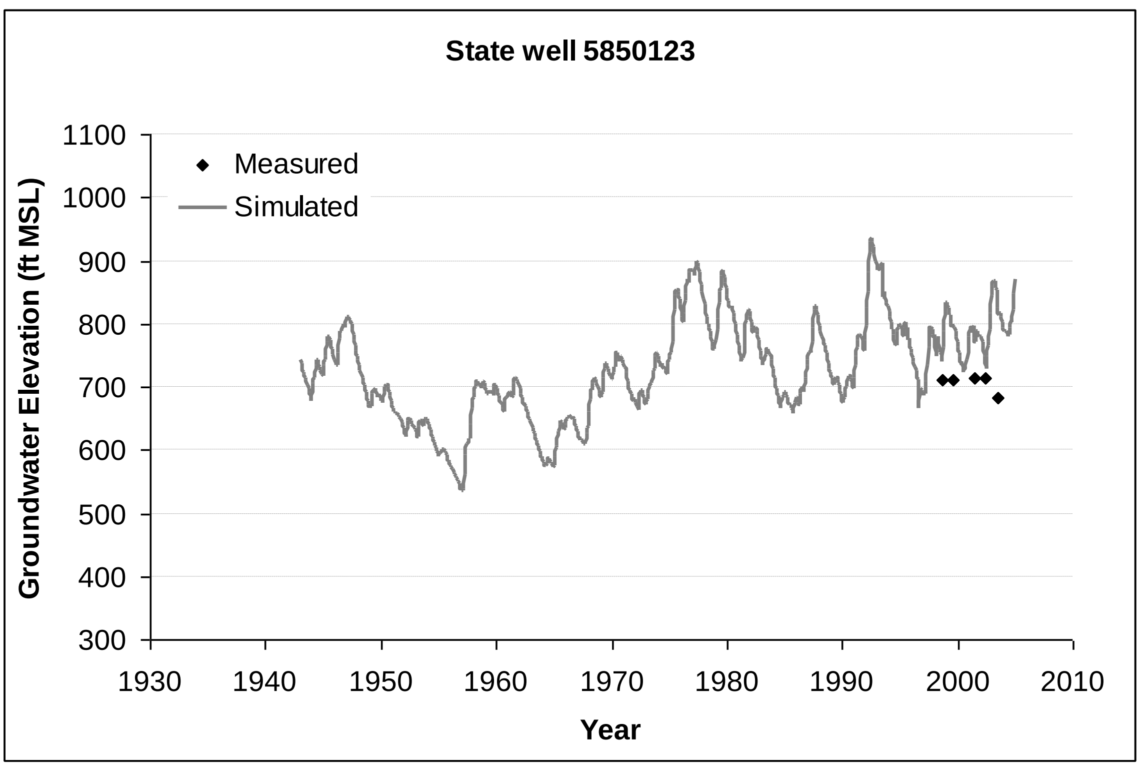

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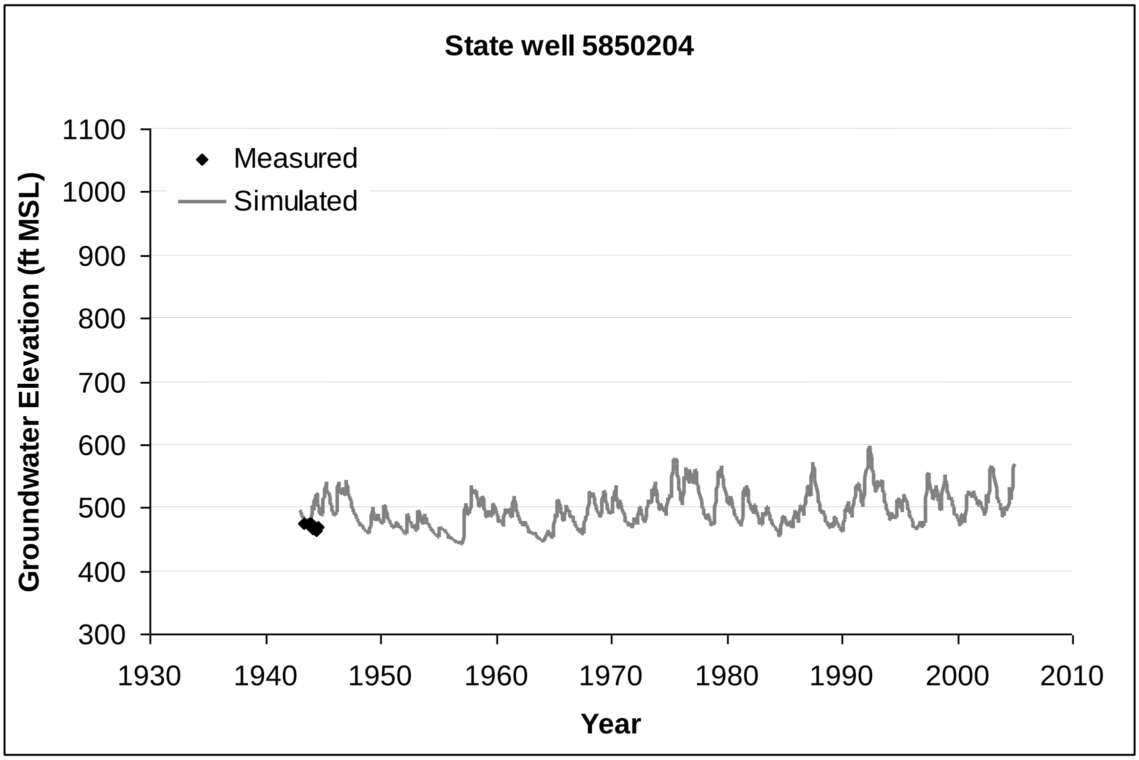

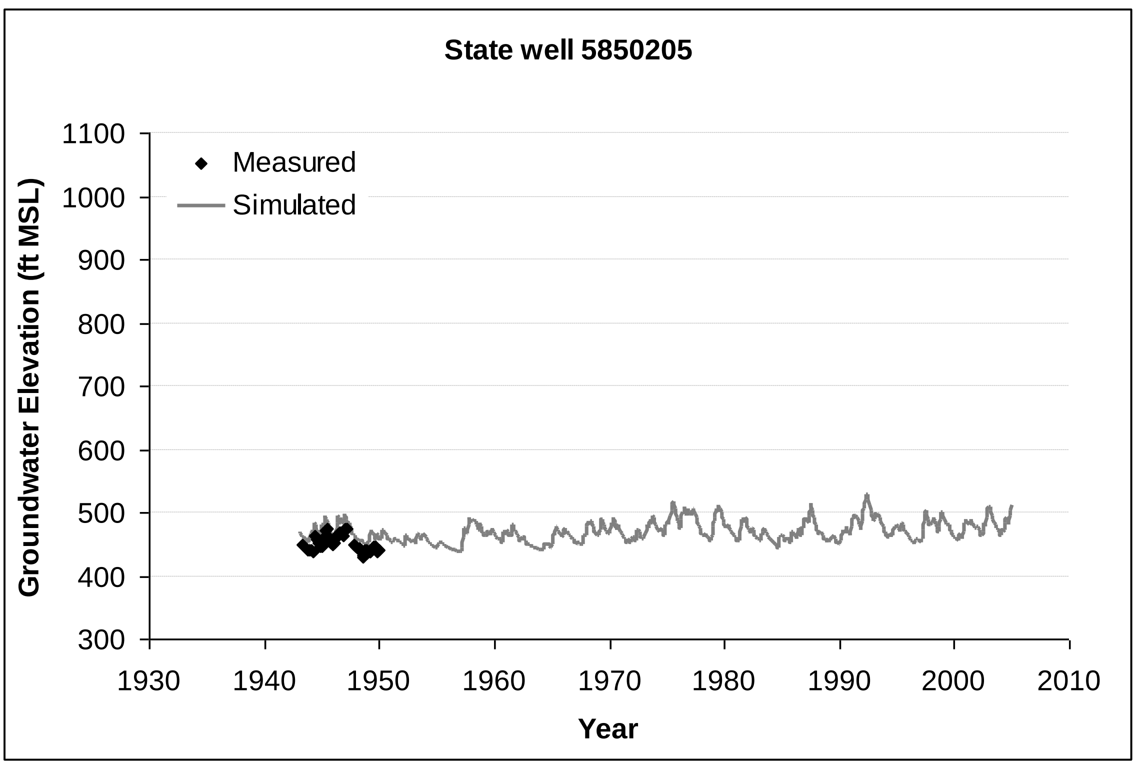

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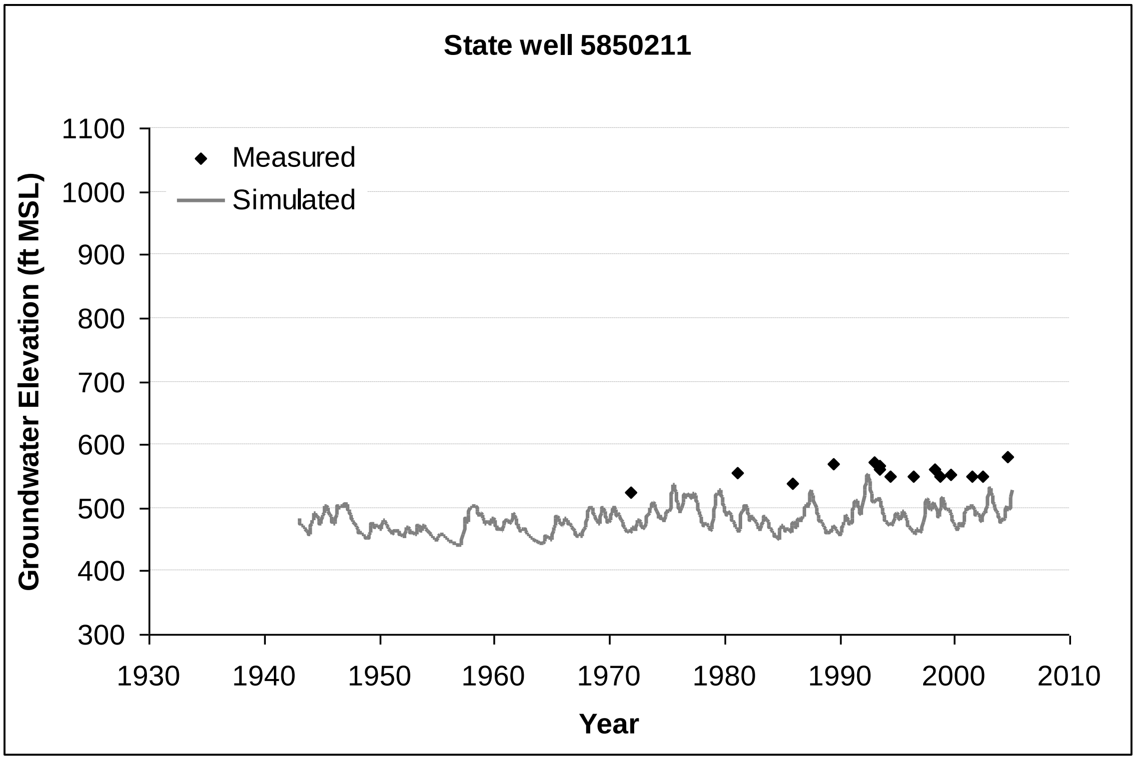

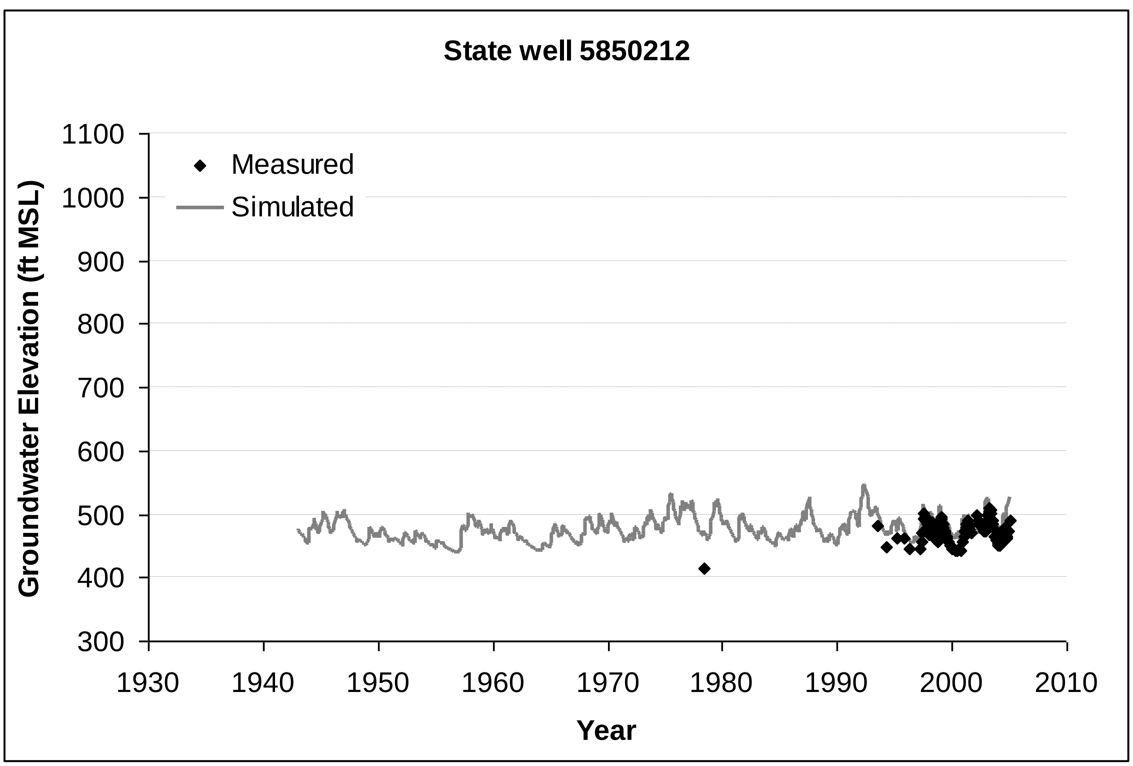

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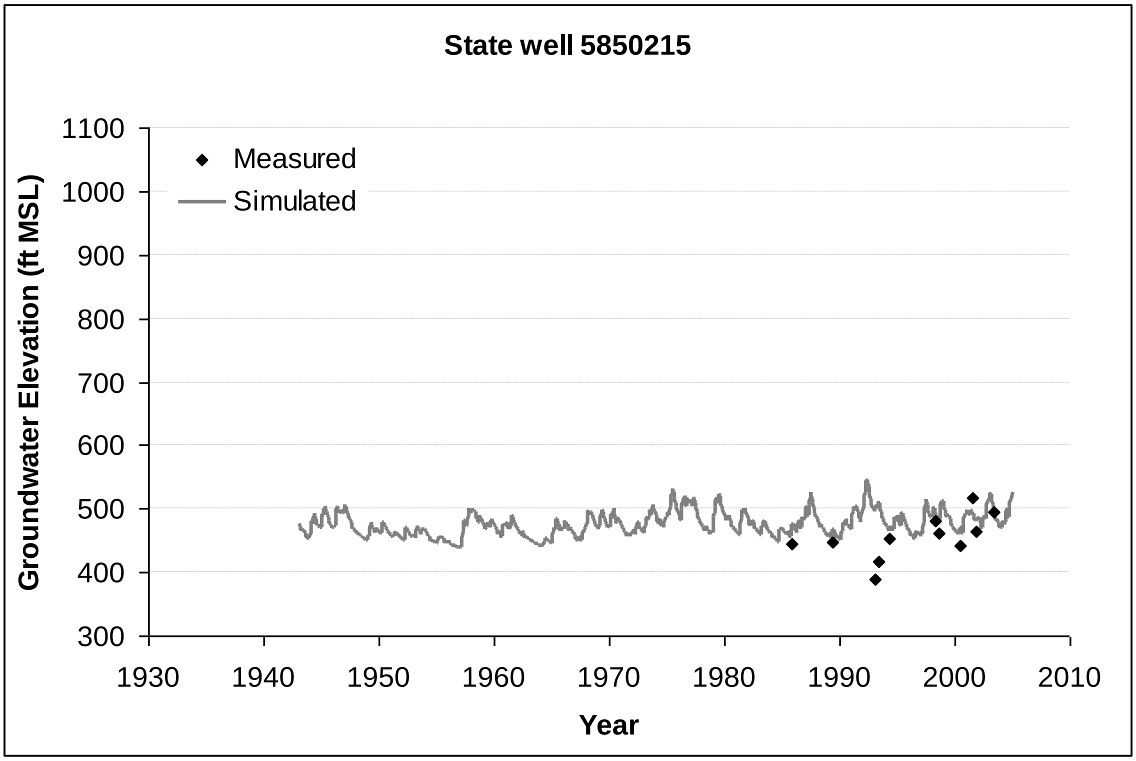

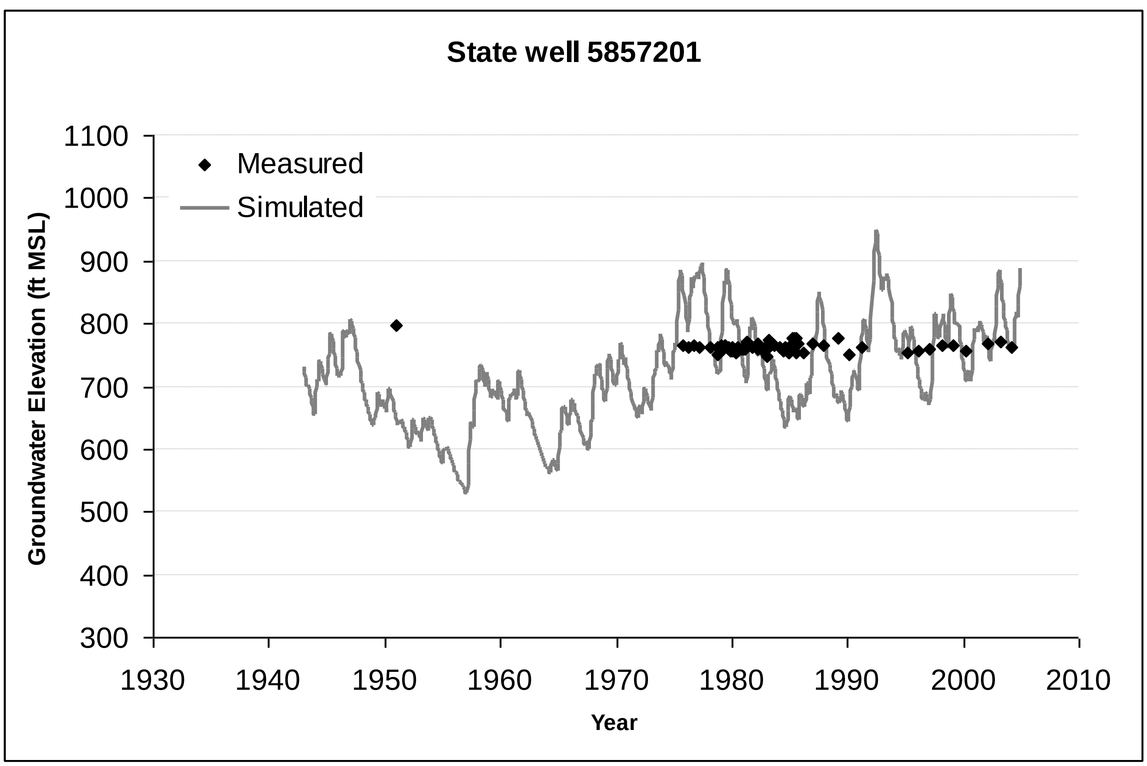

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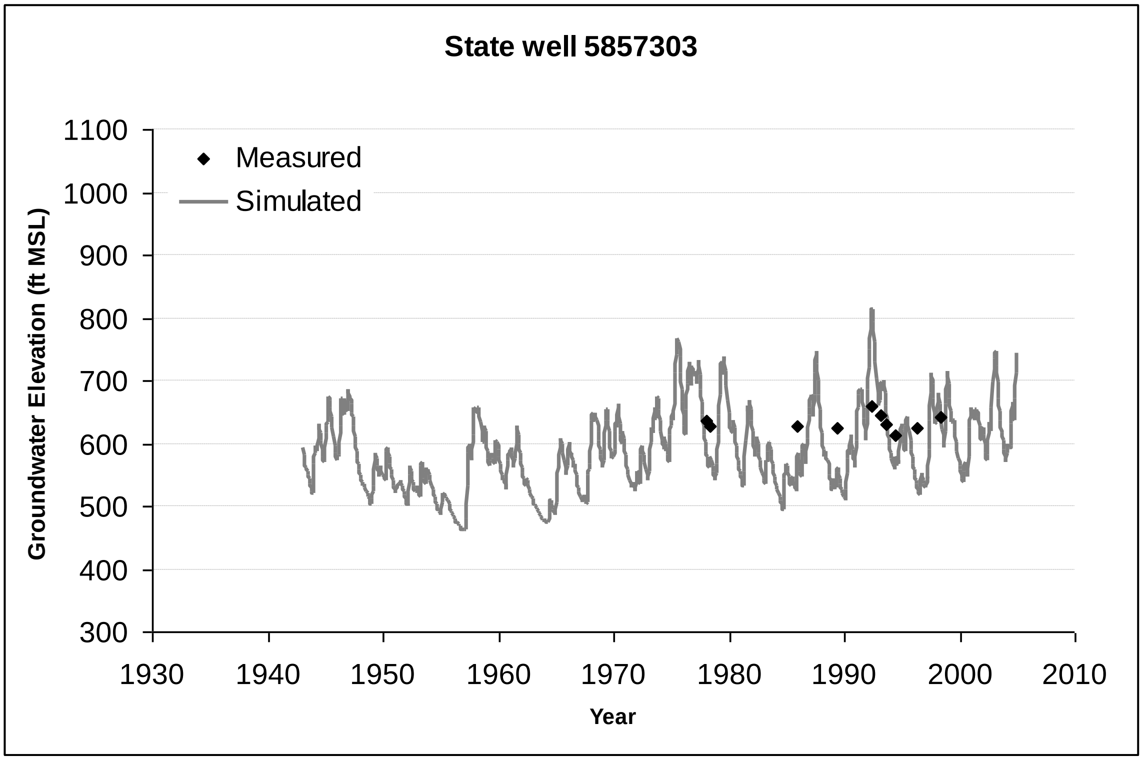

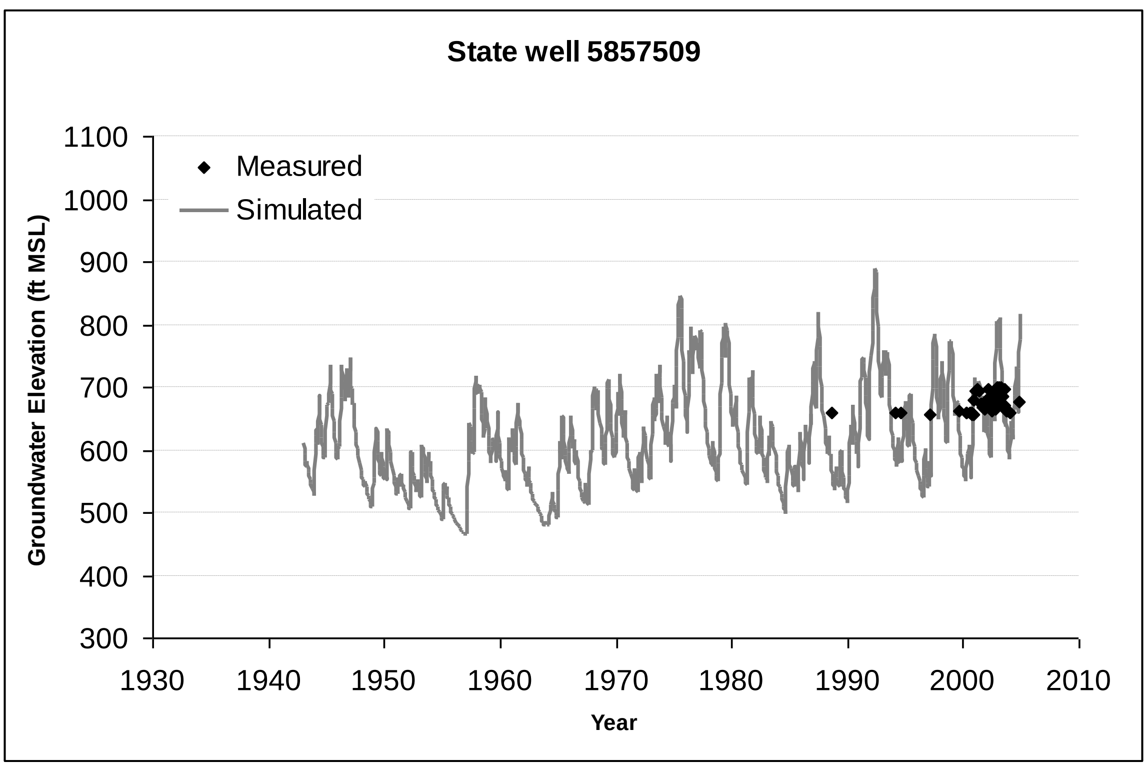

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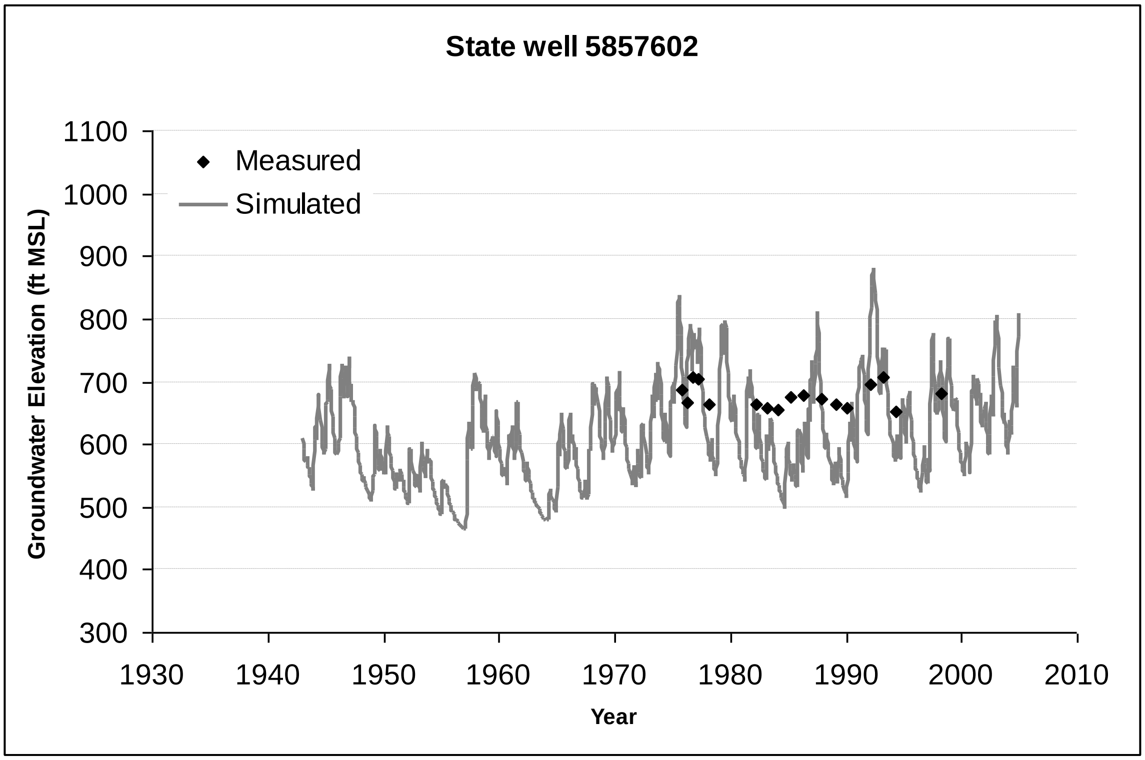

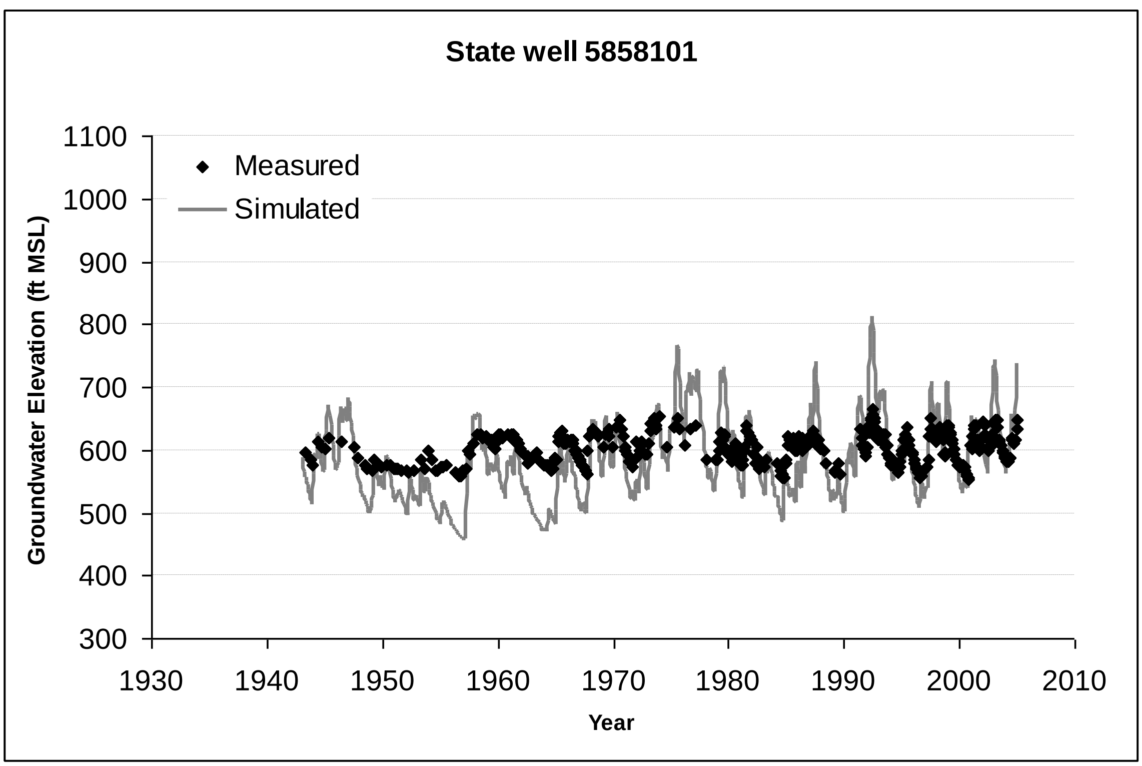

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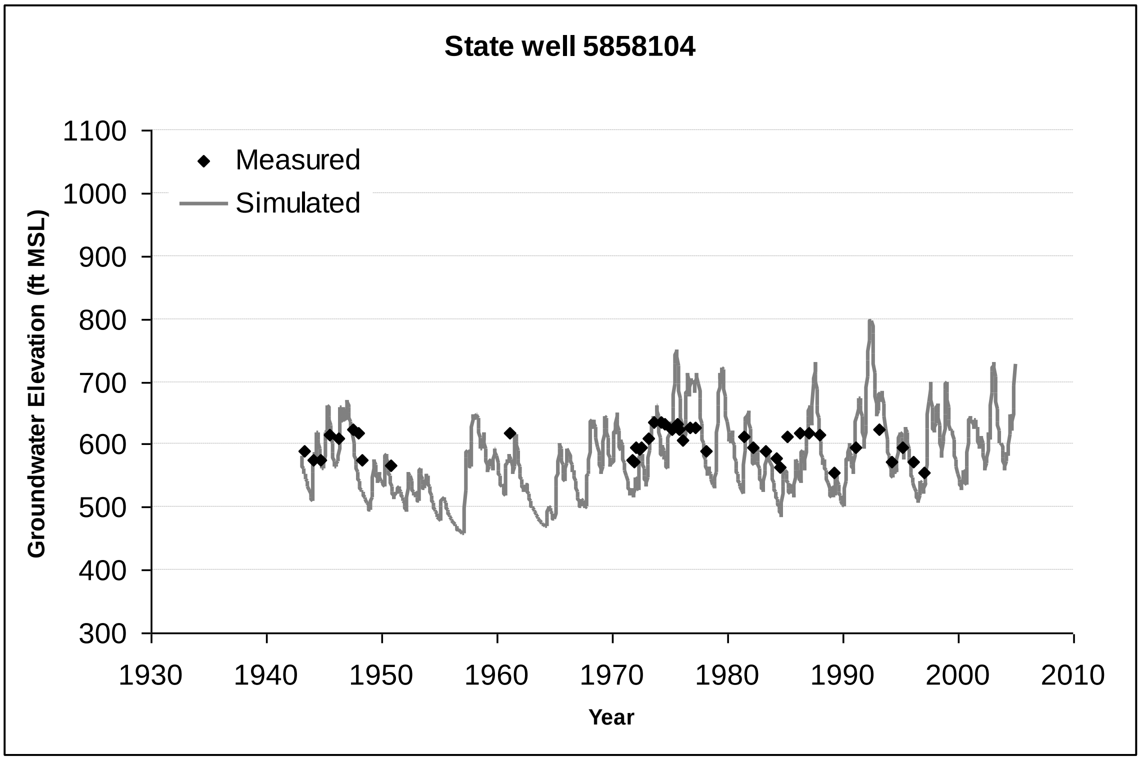

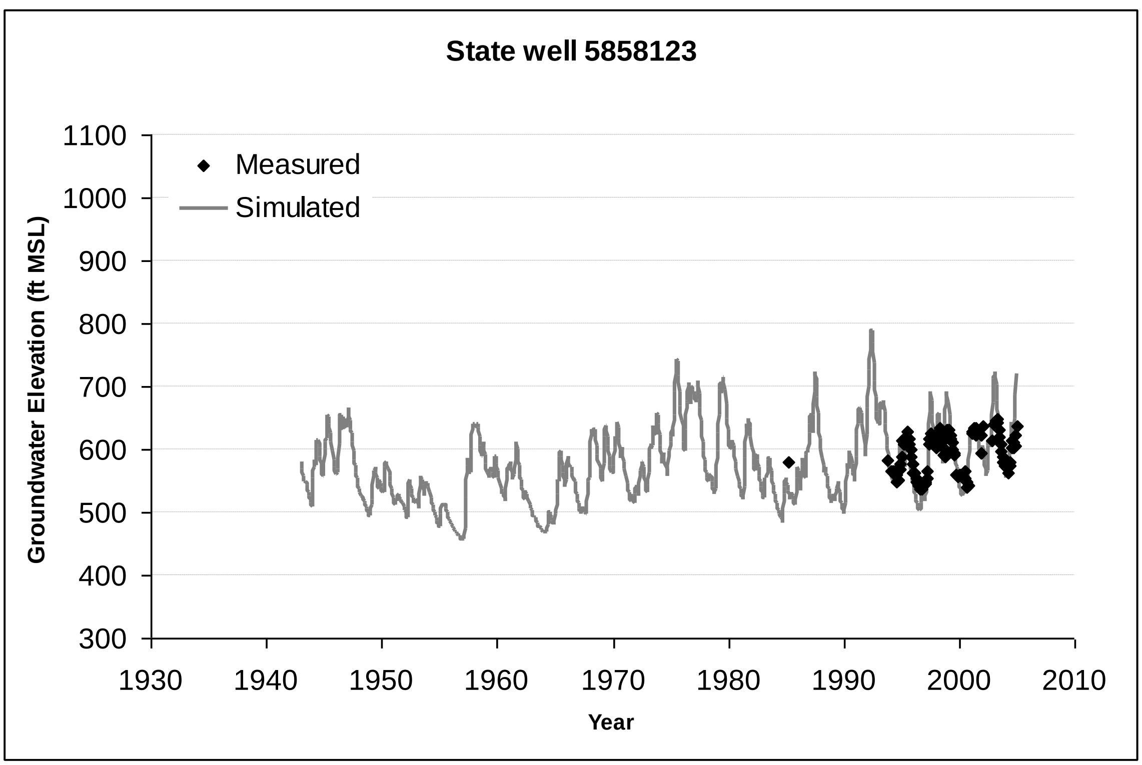

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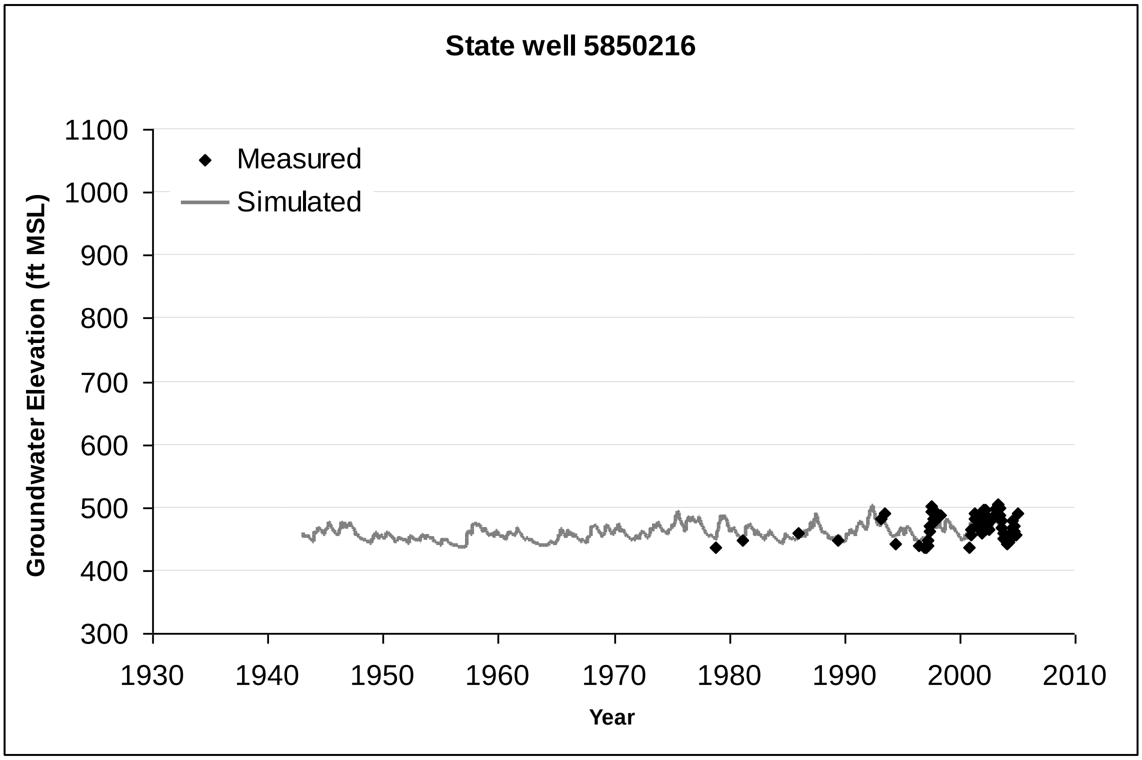

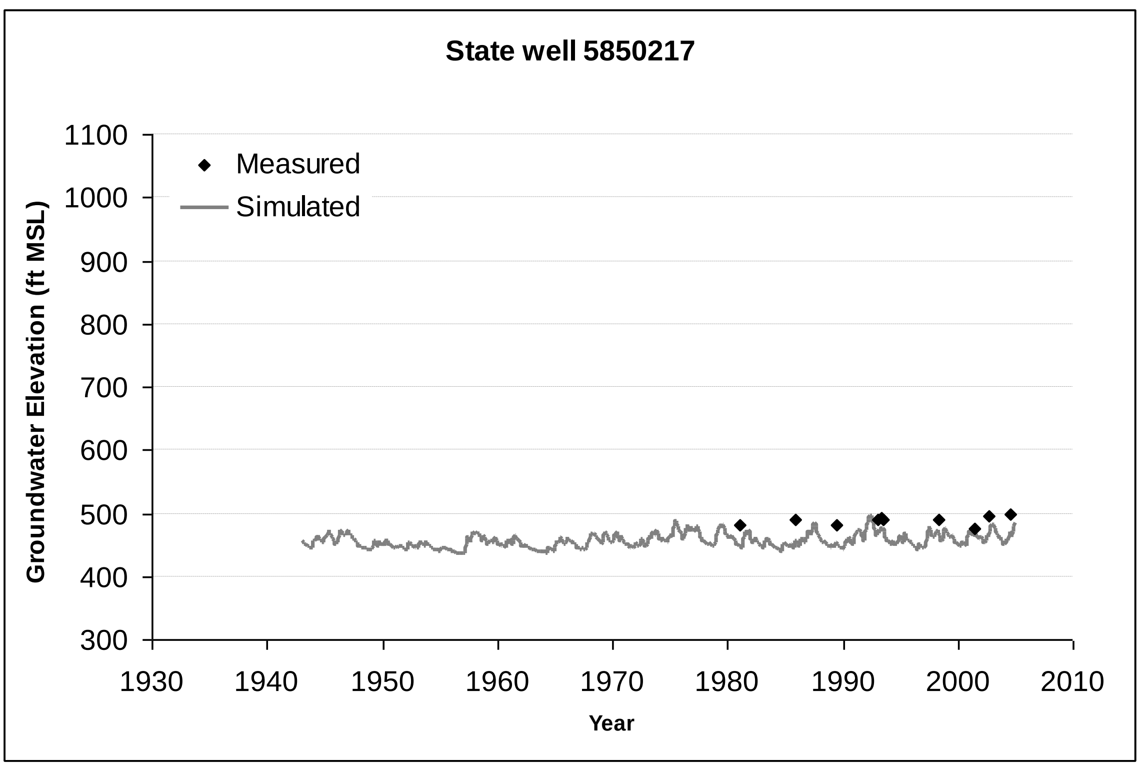

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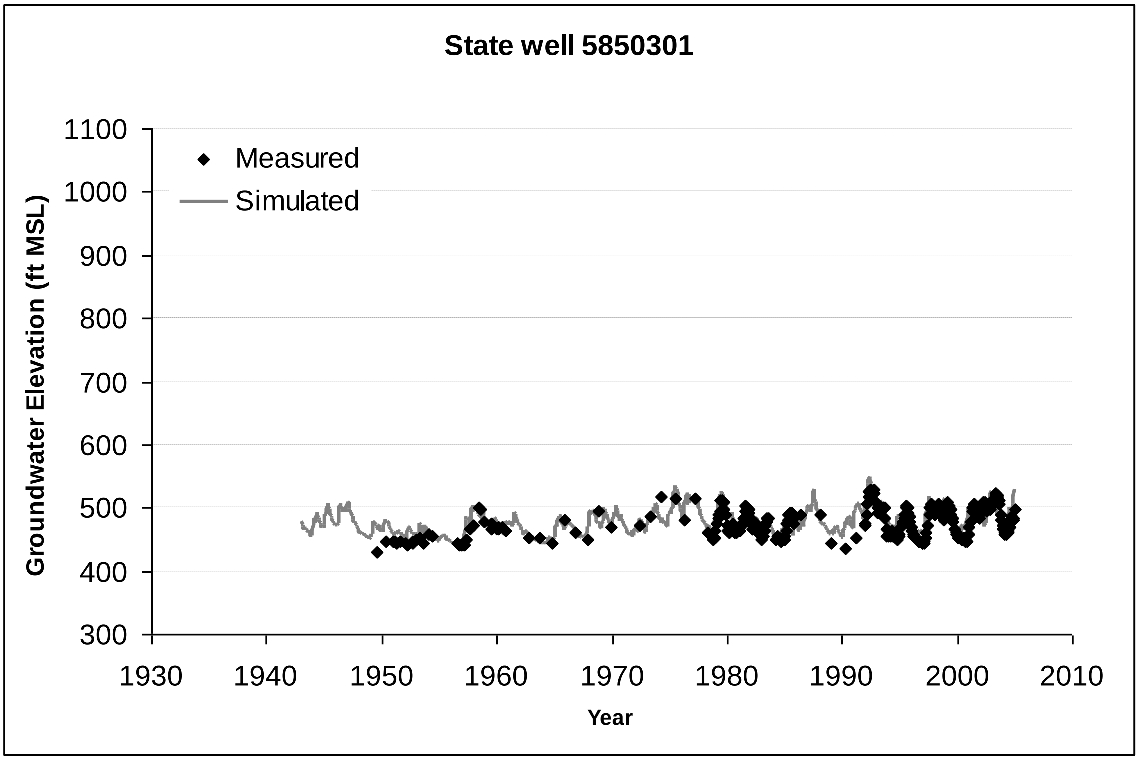

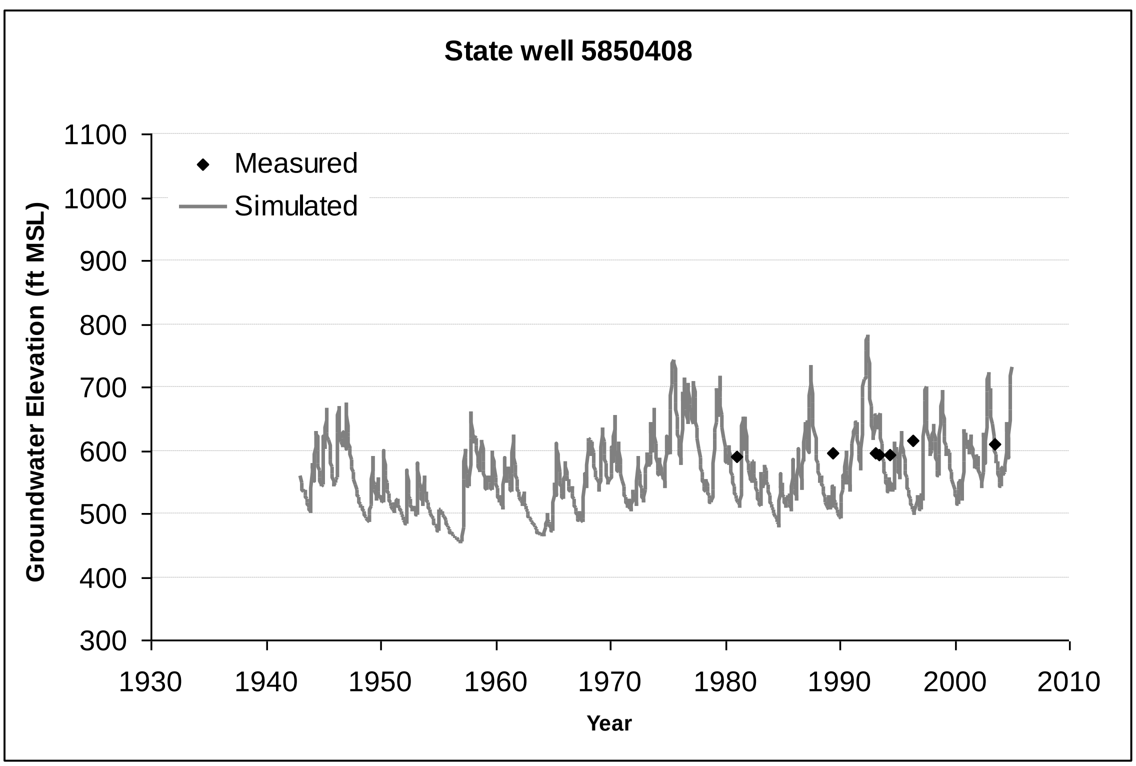

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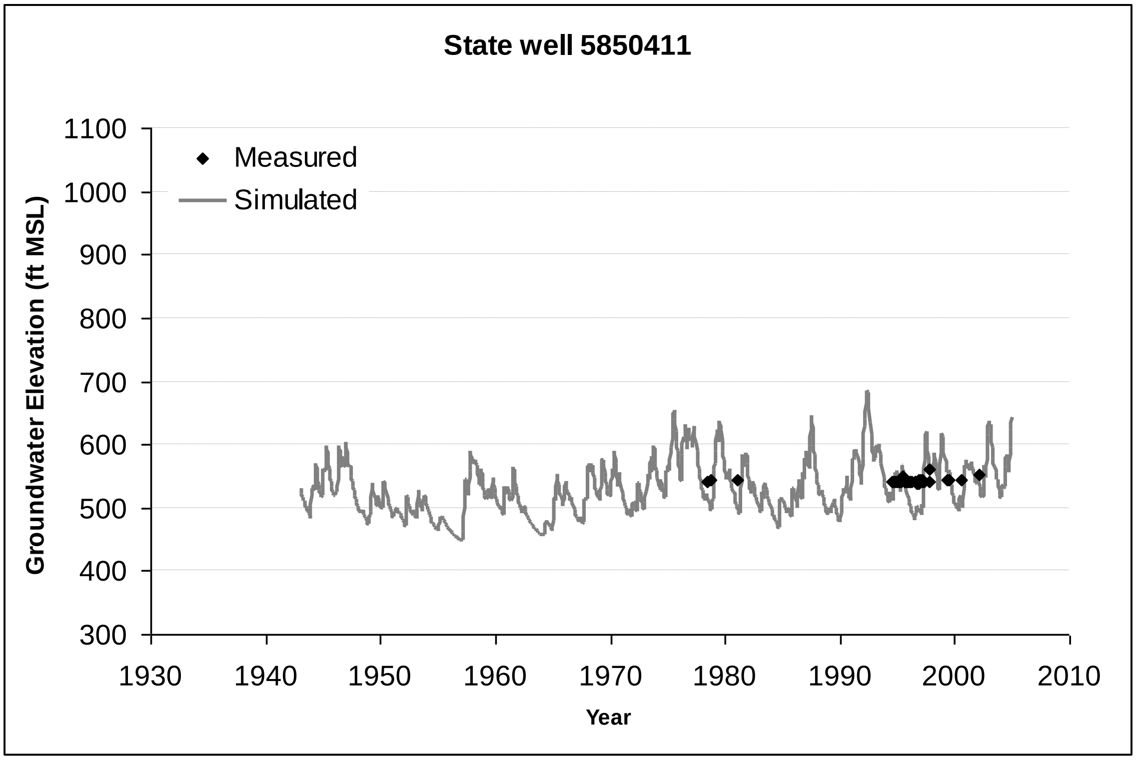

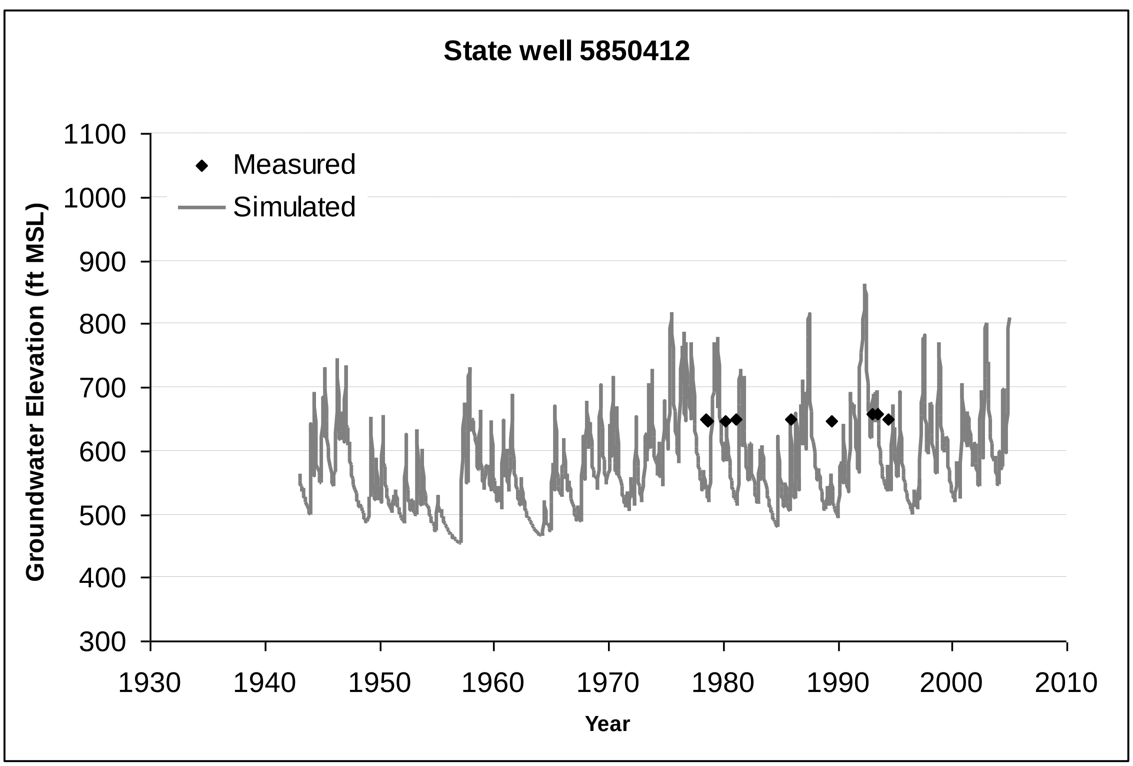

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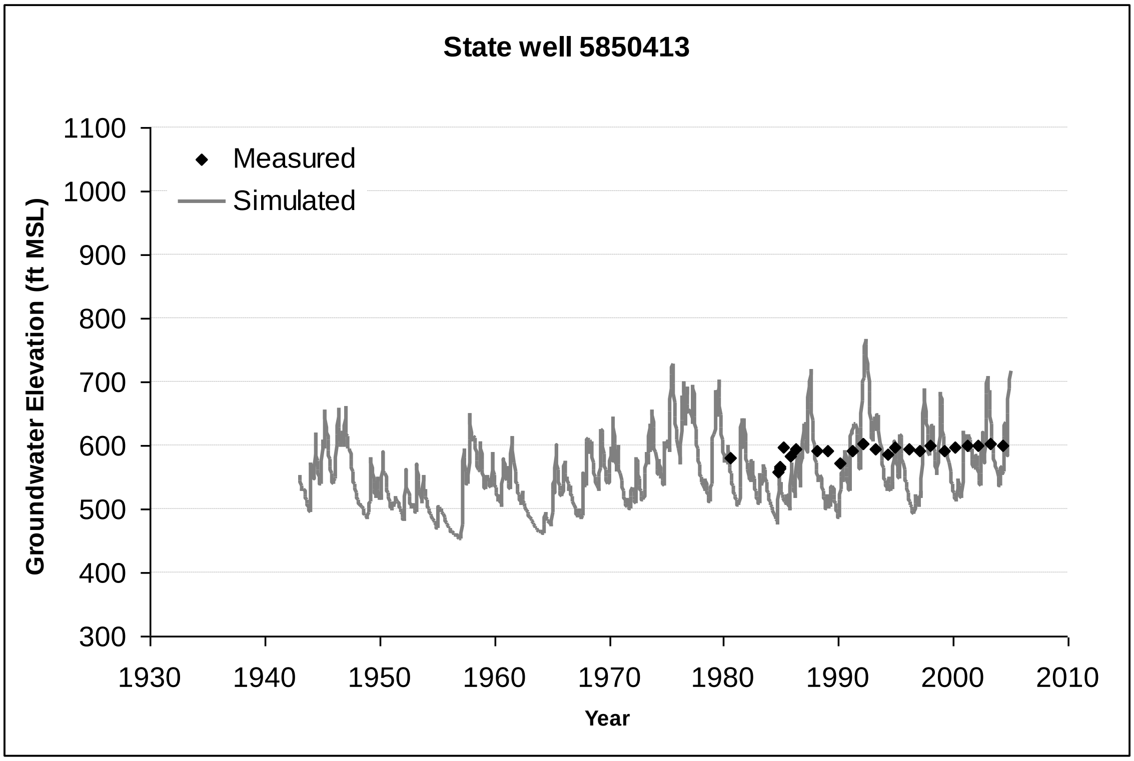

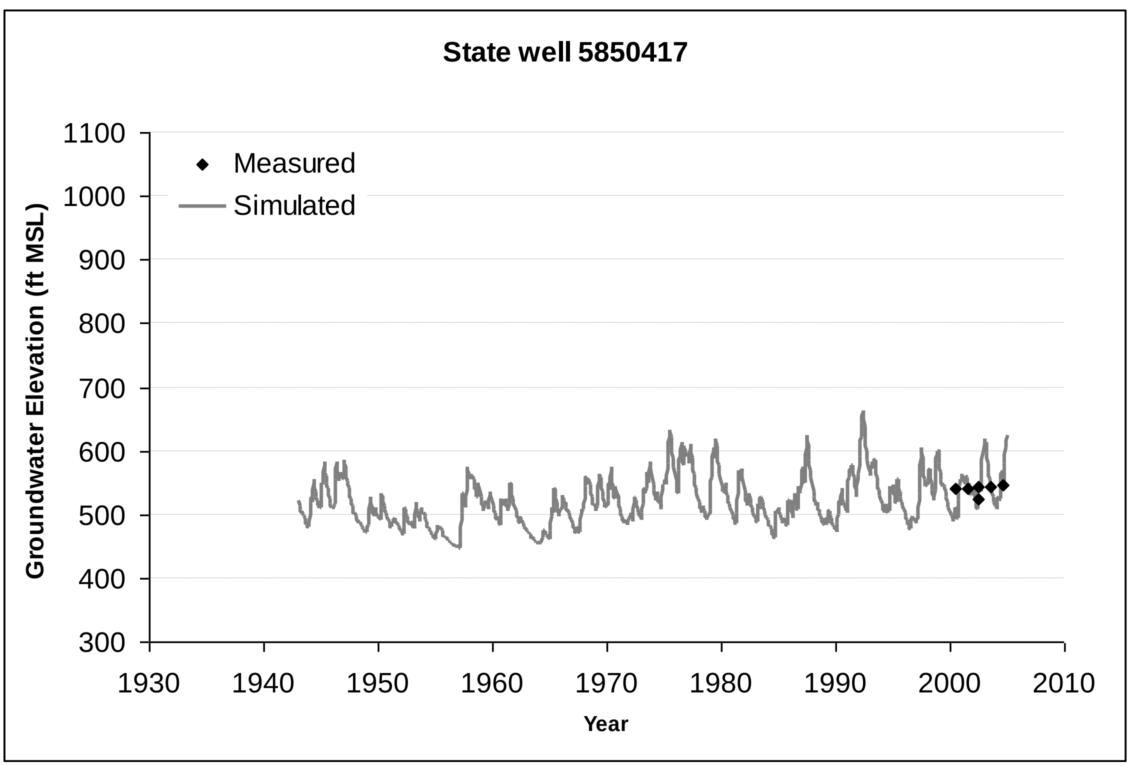

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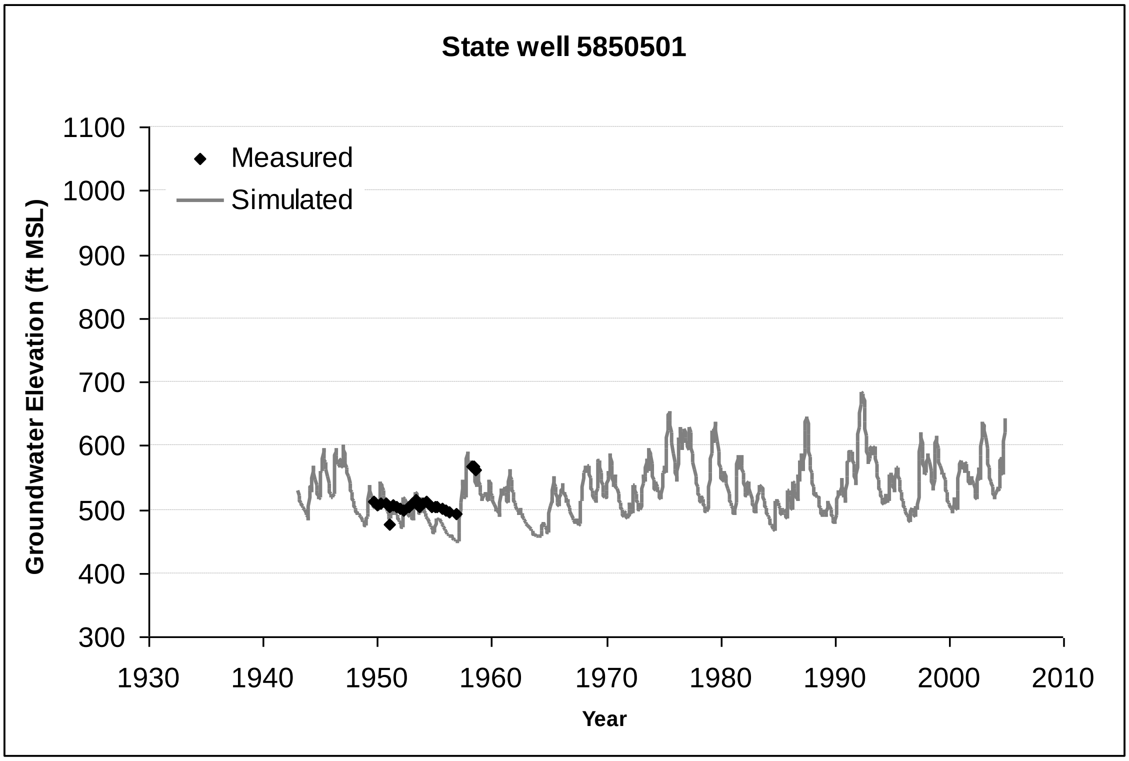

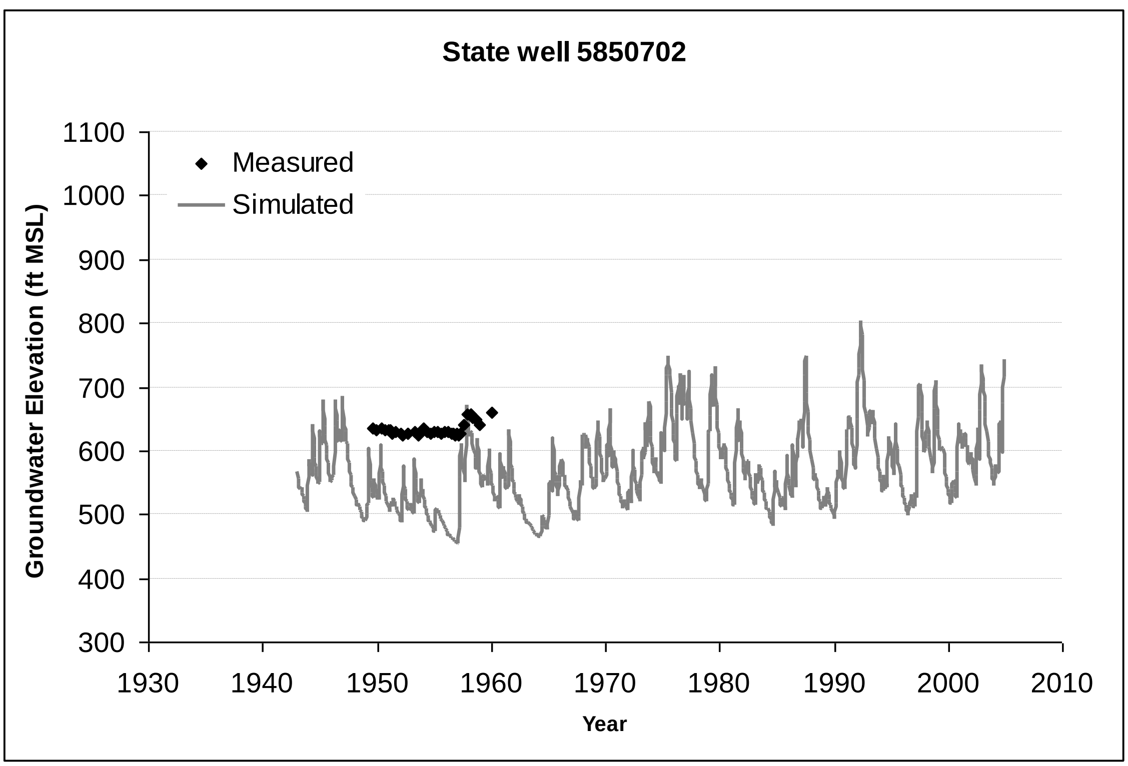

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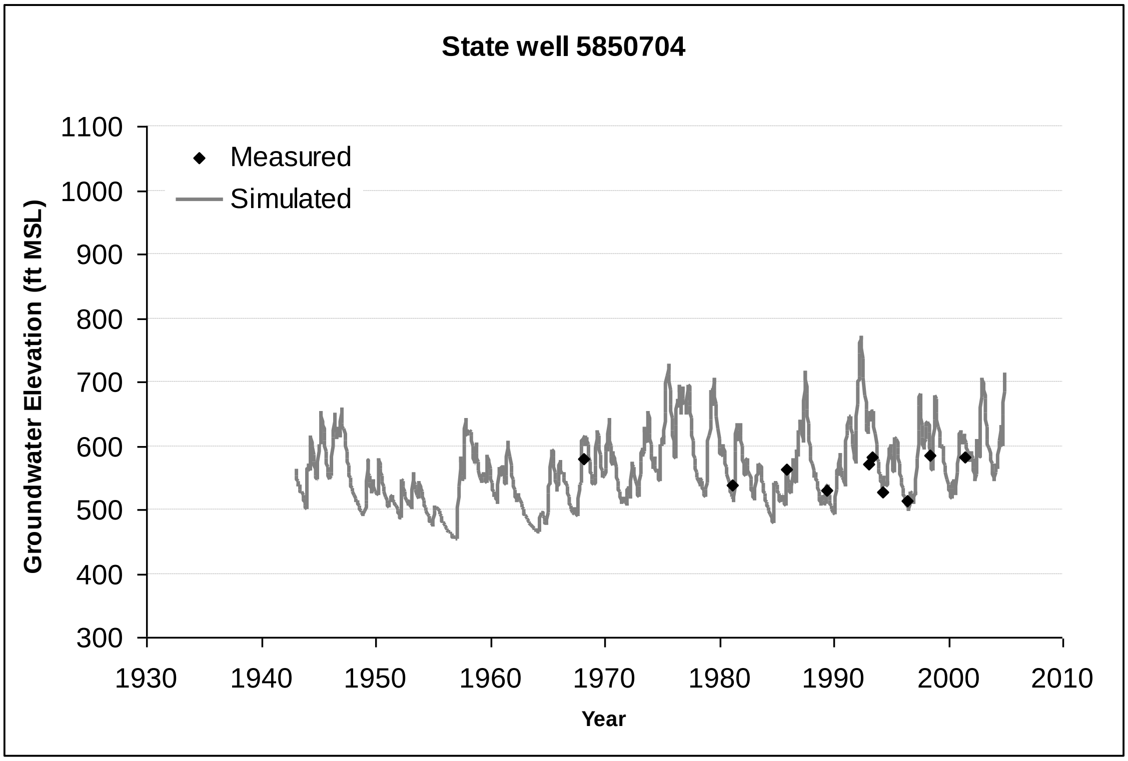

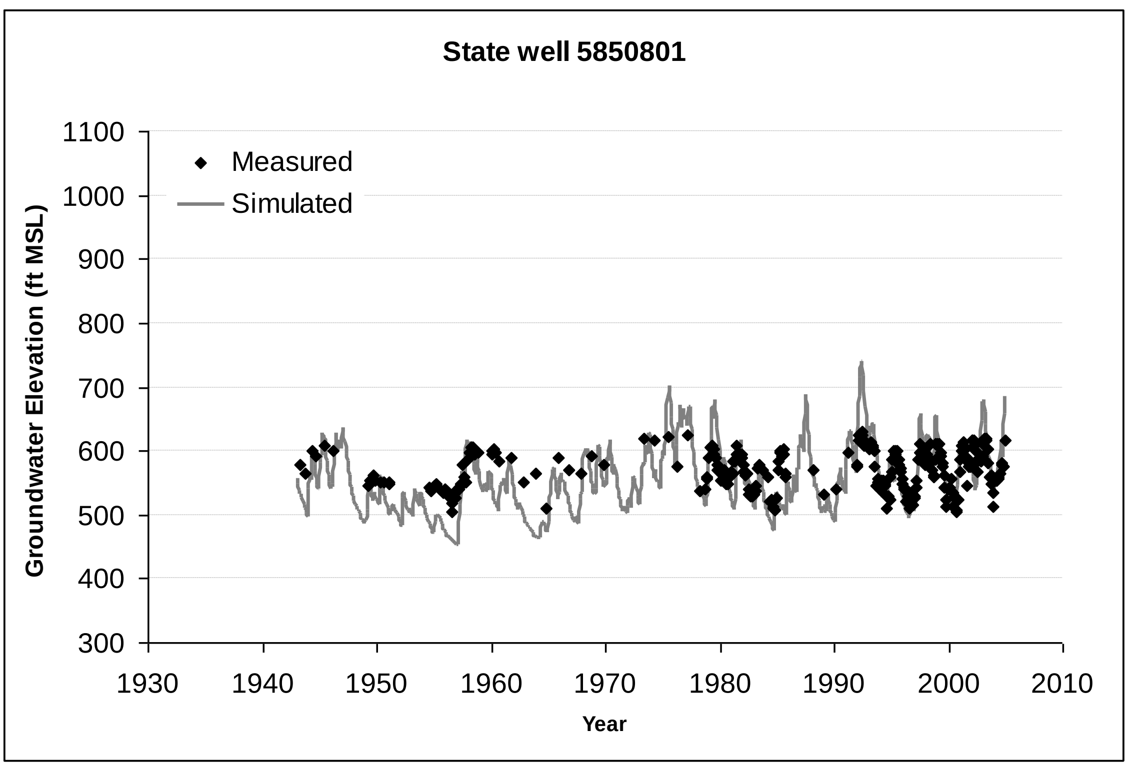

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