Groundwater Availability Model of the Blossom Aquifer

Shirley C. Wade, Ph.D., P.G.
Texas Water Development Board
January 2022

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EXECUTIVE SUMMARY

As part of the Texas Water Development Board's Groundwater Availability Modeling Program we have completed a groundwater flow model of the Blossom Aquifer. The model will provide a groundwater management tool for potential groundwater users in Red River, Lamar, and Bowie counties as well as Groundwater Management Area 8 and the Northeast Texas Regional Water Planning Group.

We developed the model using the U.S. Geological Survey code MODFLOW-NWT. The model includes three layers of quarter mile grid cells representing three units (from top to bottom): (1) Red River Alluvium and terrace deposits, (2) the Brownstown confining unit, and (3) the Blossom Sand. Recharge to the aquifer is modeled using the MODFLOW Recharge package based on a recharge model from an earlier recharge study. During model calibration the recharge values were adjusted based on spatial zones and a temporal dampening factor was used to account for travel time in the unsaturated zone. Interaction with the Red River, Pecan Bayou, and riparian evapotranspiration are modeled using the MODFLOW River package. We used the general-head boundary package for the top of the confining layer 2 and the downdip extent of layer 3. The remainder of the lateral model boundaries are assumed to be no-flow representing possible groundwater divides.

We used the MODFLOW Well package to model groundwater withdrawal for municipal, domestic, irrigation, and livestock use. We compiled groundwater use estimates for distributed and point sources. During calibration, parameters for recharge, hydraulic properties, and boundary conditions were adjusted to match over 400 water level targets collected from 1957 through 2012. Calibration was assisted using PEST: a model-independent, industry-standard, parameter estimation code. The Root Mean Squared Error (RMSE) is 29.4 feet or 6.3 percent of the range in head elevations.

In the model, groundwater enters the aquifer system from two sources: recharge due to precipitation and the general-head boundaries on the confining portion of layer 2.

Groundwater leaves the system primarily through net leakage to rivers and the downdip general-head boundary in layer 3. The model suggests groundwater flow in layer one is principally toward Pecan Bayou and the Red River. In layer three the groundwater flows from the outcrop southward to the downdip boundary with a slight convergence towards the pumping center in Red River County.

Sensitivity analysis results indicate that the model is most sensitive to recharge and horizontal hydraulic conductivity. It is moderately sensitive to general-head boundaries, and slightly sensitive to pumping wells and vertical hydraulic conductivity of layer 2 confining units.

Model users should consider limitations when using this model. This model is most accurate in assessing subregional-scale groundwater issues, such as predicting aquifer-wide water level changes and trends over the next 50 years that may result from different proposed water management strategies. Accuracy and applicability of the model decreases when using it to address more local-scale issues because of limitations of the information used in model construction and the model cell size that determines spatial resolution of the model. Another limitation to consider is the lack of independent measures of groundwater velocity or discharge rates. Calibration data consisted primarily of water level measurements. Future improvements to the model would benefit from groundwater age and discharge data.

1.0 INTRODUCTION AND PURPOSE FOR GROUNDWATER FLOW MODEL

The Blossom Aquifer is an important source of drinking water for the City of Clarksville in Red River County (TWDB water use survey, 2018). The aquifer is also a source of water for domestic use, livestock, and irrigation in Lamar, Red River, and Bowie counties. Stakeholders in Lamar, Red River and Bowie counties, Groundwater Management Area 8, and the Northeast Texas Regional Water Planning Group (Figures 1 and 2) will all benefit from having a modeling tool to help them evaluate the groundwater resources of the area. Groundwater models are useful tools for understanding aquifers and for predicting the effects of future water management strategies. As part of the Texas Water Development Board's Groundwater Availability Modeling Program, we have developed a groundwater availability model for the Blossom Aquifer. The purpose of the program is to provide reliable and timely information on groundwater availability to the citizens of Texas to ensure adequate supplies or recognize inadequate supplies over a 50-year planning period. Our process includes stakeholder input and results in standardized, thoroughly documented and publicly available numerical groundwater flow models and support information.

Following standard modeling protocols (Anderson and Woessner, 1992), we first developed a conceptual model of the groundwater system by gathering data on the hydrology and geology of the study area and identifying hydrostratigraphic units and model boundaries for the groundwater flow system. Data from two water level data field projects in 1982 and 1983 (McLaurin, 1988) and 2006 were combined with water level data from other time periods. In addition, information from previous hydrogeology and water resource studies was reviewed to help define the water balance components such as recharge, evapotranspiration, spring discharge, groundwater pumping, and surface water-groundwater interactions. A geochemical study (Chowdhury, 2010) and a recharge study (Kirk and others, 2012) also provided information about groundwater recharge in the study area. Groundwater flow properties derived from aquifer tests and other hydrologic and modeling studies of the area were also analyzed. Finally, historical water levels, spring flow, and estimated stream baseflows were compiled to potentially use as calibration targets. A final report summarizing the conceptual model was released in 2022 (Wade and others, 2022). This report documents the final phase of the project; to construct and calibrate a numerical groundwater flow model based on the conceptual model and hydrogeology data.

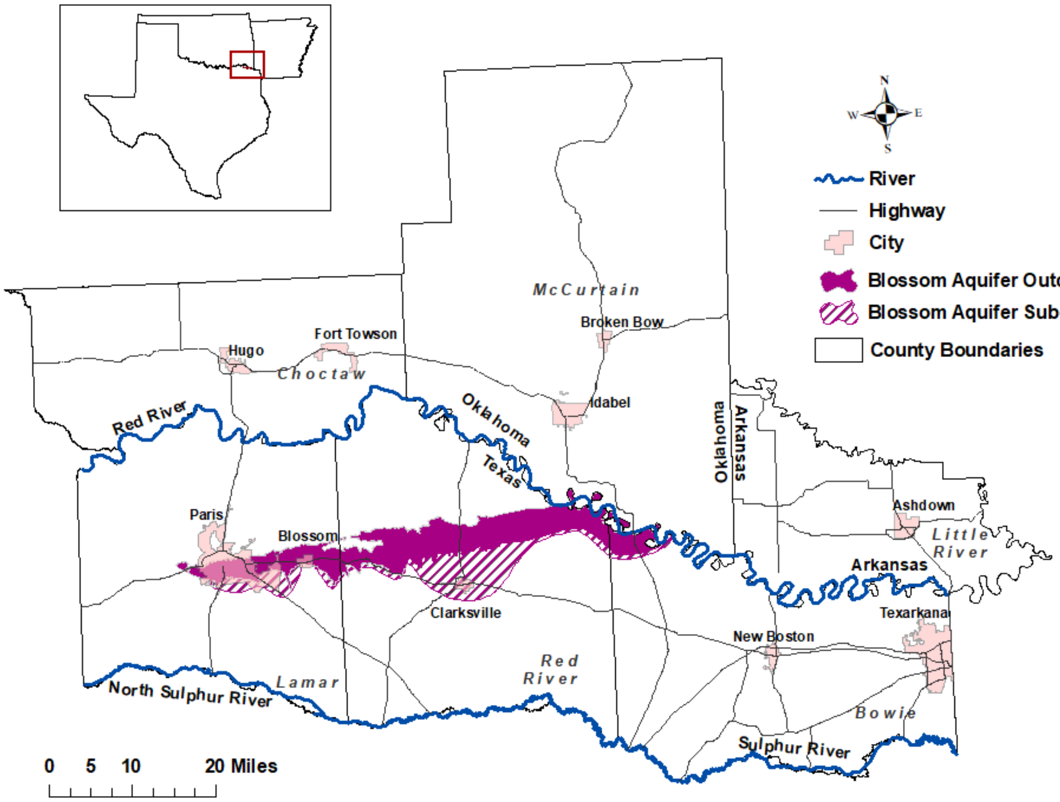

FIGURE 1 STUDY AREA[1].

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[1] County locations are from the U.S. Census Bureau (2013). City locations are from Arkansas GIS Office (2013a), Oklahoma Center for Geospatial Information (2003b), and TWDB (2013). Roads are from Arkansas GIS Office (2013b), Oklahoma Center for Geospatial Information (2003a), and Texas Department of Transportation (2006).

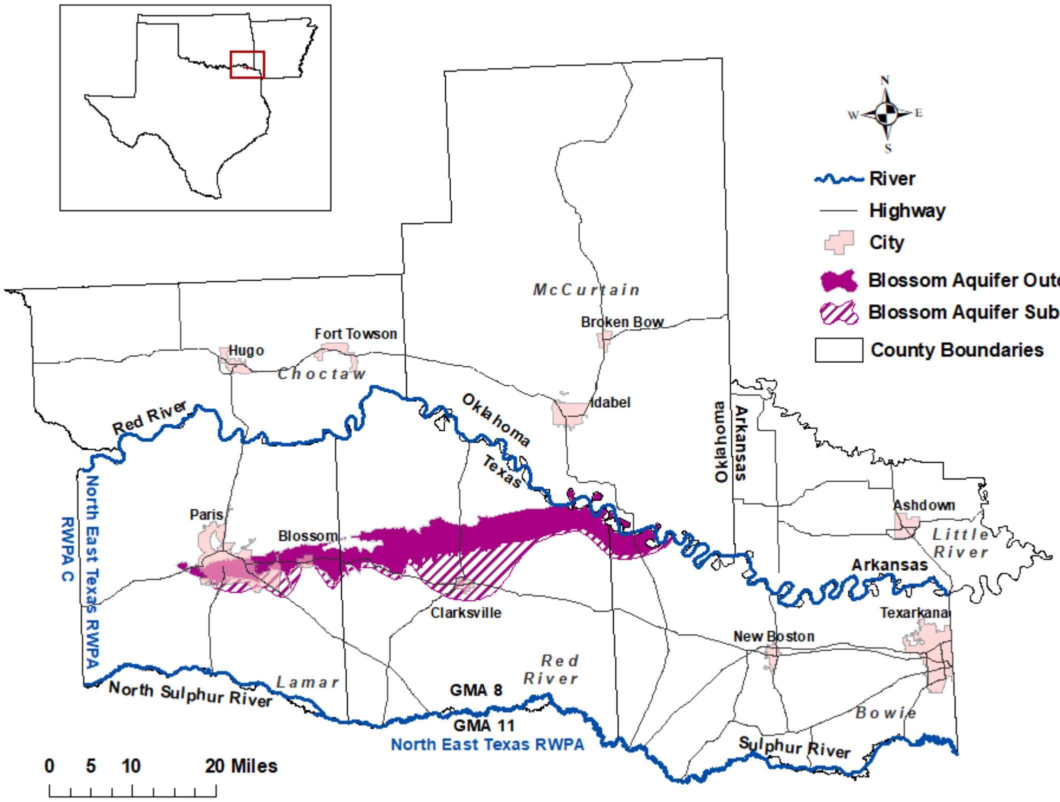

FIGURE 2 REGIONAL WATER PLANNING AREAS (RWPA) AND GROUNDWATER MANAGEMENT AREAS (GMA) IN STUDY AREA[2].

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[2] County locations are from the U.S. Census Bureau (2013). City locations are from Arkansas GIS Office (2013a), Oklahoma Center for Geospatial Information (2003b), and TWDB (2013). Roads are from Arkansas GIS Office (2013b), Oklahoma Center for Geospatial Information (2003a), and Texas Department of Transportation (2006).

2.0 MODEL OVERVIEW AND PACKAGES

Geologic units included in our groundwater availability model for the Blossom Aquifer include the Red River Alluvium and adjacent terrace deposits, the Brownstown confining unit and the Blossom Sand (Figure 3; Wade and others, 2022). Recharge enters the aquifer in the outcrop and moves slowly downdip eventually discharging through seepage into other formations in the subsurface, particularly along the Luling Mexia-Talco fault system. Geochemistry data suggest the groundwater is older than 10,000 years in the deeper portions of the aquifer. Estimates of annual recharge range from zero, for a dry year, to 4 inches, for a wet year. The estimated recharge for an average year is about 1 inch per year (Wade and others, 2022).

Groundwater leaves the Blossom Aquifer through natural processes in the outcrop such as evapotranspiration and leakage to streams and through groundwater pumping in the outcrop and subcrop. The Blossom Aquifer also discharges to other formations downdip especially along the Luling-Mexia-Talco fault system (Wade and others, 2022). The majority of groundwater pumping from the Blossom Aquifer is for municipal supply in Red River County. The municipal pumping amounts range from about 300 acre-feet per year to about 1,000 acre-feet per year for the years 1957 to 2012. Lesser amounts are produced for domestic supply and livestock use. Water is also produced for irrigation from the Red River Alluvium in the study area (Wade and others, 2022).

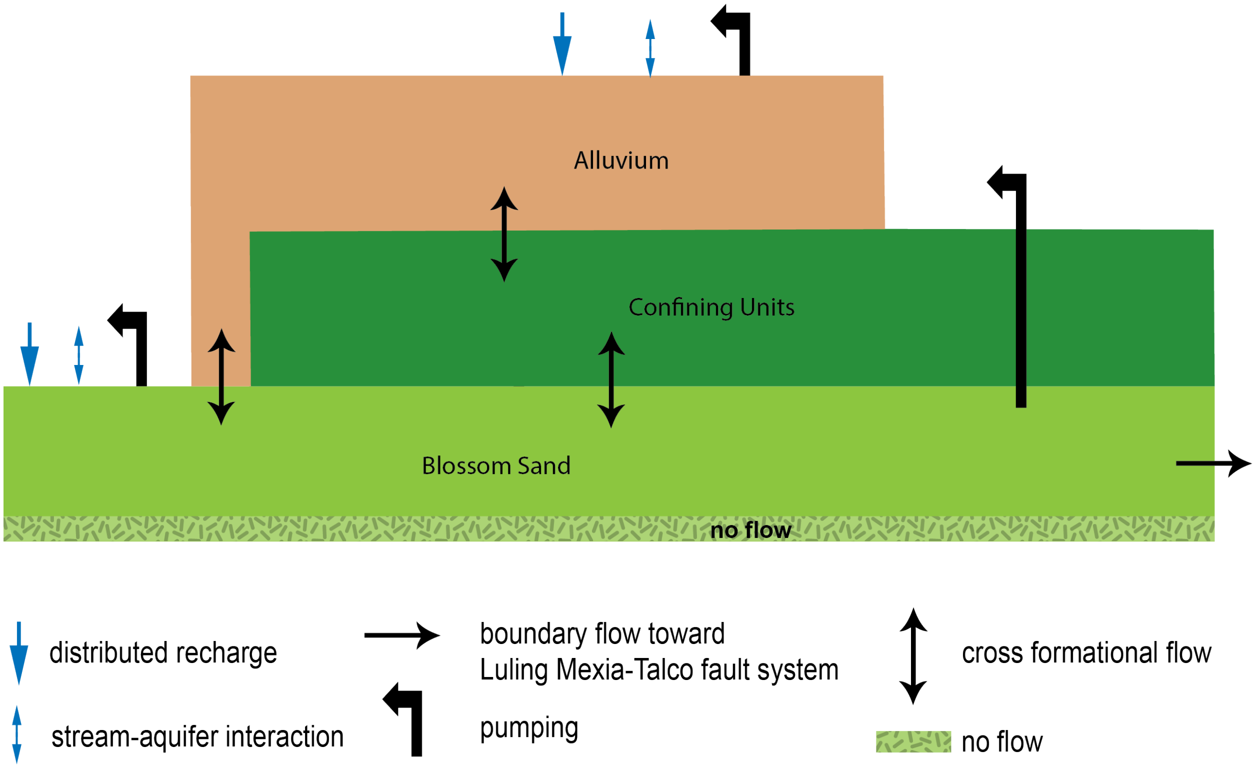

FIGURE 3 CONCEPTUAL MODEL DIAGRAM (FROM WADE AND OTHERS, 2022).

We developed a three-layer model of the Blossom Aquifer using MODFLOW-NWT (Niswonger and others, 2011) with three layers of quarter mile grid cells (Figure 4). The top model layer represents the Red River Alluvium and terrace deposits. The second layer consists of the Brownstown Confining unit, and the bottom layer represents the Blossom Sand and the Tokio Formation. Where layer 3 is active north of the updip extent of the Blossom Aquifer footprint (Figure 4) layer 3 represents the Tokio Formation (hydrostratigraphically equivalent to the Blossom Sand in Oklahoma). Approximately half of the alluvium in the model area is in direct contact with the Blossom Sand outcrop, so beneath this area layer 2 model cells are 20 feet thick and represent the Blossom Sand. The grid has 80 rows and 280 columns and is rotated 12 degrees counter-clockwise so that the model columns generally correspond to the principal groundwater flow direction. The model coordinate system is based on an Albers Equal Area projection with parameters shown in Table 1. The x and y coordinates of the centroid of the upper leftmost grid cell in Row 1, Column 1 are 6,214,127.3246 feet and 20,607,634.031 feet respectively.

The northern model boundary is a no-flow and coincides with the up-dip limit of the Blossom Sand and Tokio Formation (in Oklahoma). The western boundary was based on the estimated location where the transmissivity of the Blossom Sand is greatly reduced because it thins out and the clay content increases. In layer 3, most of the southeast boundary is a general-head boundary to allow downdip flow out of the model area. In layer

2 the southeast boundary is no-flow. The eastern boundary is also a no-flow boundary and was chosen to be far away enough from the area of interest so that uncertainty about the boundary would have minimal effect on the model results in the primary area of interest.

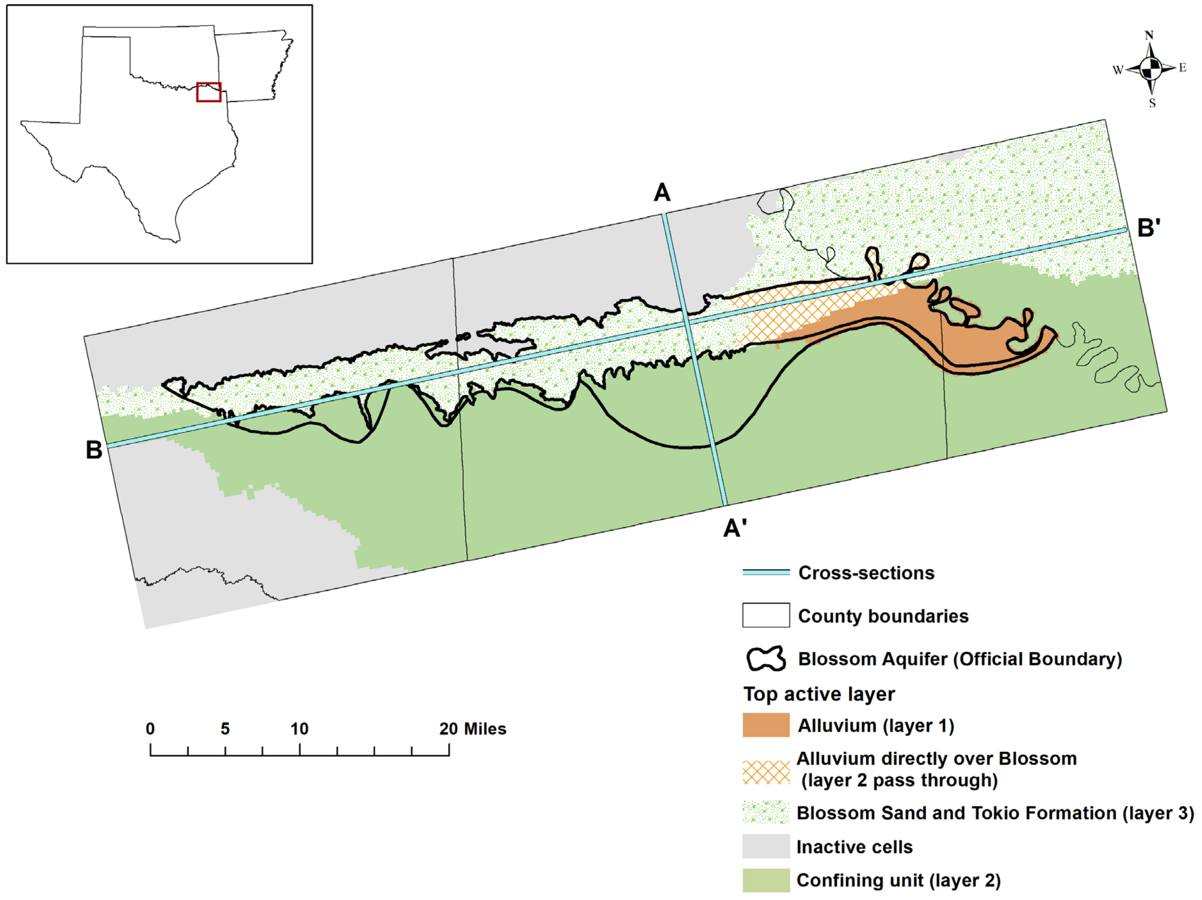

FIGURE 4 MODEL GRID, HYDROGEOLOGIC UNITS, INACTIVE AREAS, AND LOCATIONS OF CROSS-SECTIONS.

TABLE 1 MODEL COORDINATE SYSTEM AND PARAMETERS.

Projection	Albers equal area conic
Datum	North American datum 1983
Spheroid	Geodetic reference system 1980
Longitude of origin	-100.00 degrees west
Latitude of origin	31.25 degrees north
Lower standard parallel	27.50 degrees north
Upper standard parallel	35.00 degrees north
False easting	4,921,250.00000 feet
False northing	19,685,000.00000 feet
Unit of linear measure	U.S. survey feet

The Blossom Aquifer groundwater availability model input (Table 2) and output packages (Table 3) are included in a name file (blsm.nam). The MODFLOW-NWT code initiates a model run by calling this name file.

TABLE 2 SUMMARY OF MODEL INPUT PACKAGES.

Packages	**Input Files**
Basic (BAS6)	blsm.bas
Discretization (DIS)	blsm.dis
Upstream weighting (LPF)	blsm.upw
Zone File	blsm.zone
Well (WEL)	blsm.wel
Drain (DRN)	blsm.drn
River (RIV)	blsm.riv
General-head (GHB)	blsm.ghb
Recharge (RCH)	blsm.rch
Output Control (OC)	blsm.oc
Newton Solver (NWT)	blsm.nwt

TABLE 3 SUMMARY OF MODEL OUTPUT FILES.

Packages	Output Files
LIST (LST)	blsm.lst
Cell-by-Cell Budgets (CBB)	blsm.cbb
Heads (HDS)	blsm.hds
Drawdown (DDN)	blsm.ddn

2.1 Basic (BAS6) Package

The MODFLOW Basic package specifies the status of each cell (active or inactive), the assigned head for inactive cells (-9,999 feet), and specifications of starting heads. Inactive cells were used for areas where a specific hydrogeologic unit was absent in the related numerical model layer (Figure 4). For example, we set model cells of model layer 1 (Figure 4) in much of the model area as inactive because it represents the Red River Alluvium which is only present within about five miles of the Red River. In the outcrop area of the Blossom Sand and Tokio Formation cells in layer 2 are inactive and up-dip (north) of the Blossom Sand outcrop model cells are inactive in layers 2 and 3.

2.2 Discretization (DIS) Package

The Discretization package defines the spatial and temporal discretization of the model, including the numbers of layers, rows, columns, stress periods, horizontal dimensions of model cells, the top elevation of model layer 1, bottom elevations of all model layers, and length and type of each stress period.

The MODFLOW-NWT model for the Blossom Aquifer contains three layers with 80 rows and 280 columns per layer. The row and column spacing is 1,320 feet (one quarter mile). The active model domain covers an area of 1,400 square miles within the Blossom Aquifer located at the center (Figure 4). The three model layers represent, from top to bottom, the Red River Alluvium and terrace deposits, the Brownstown confining unit and overlying

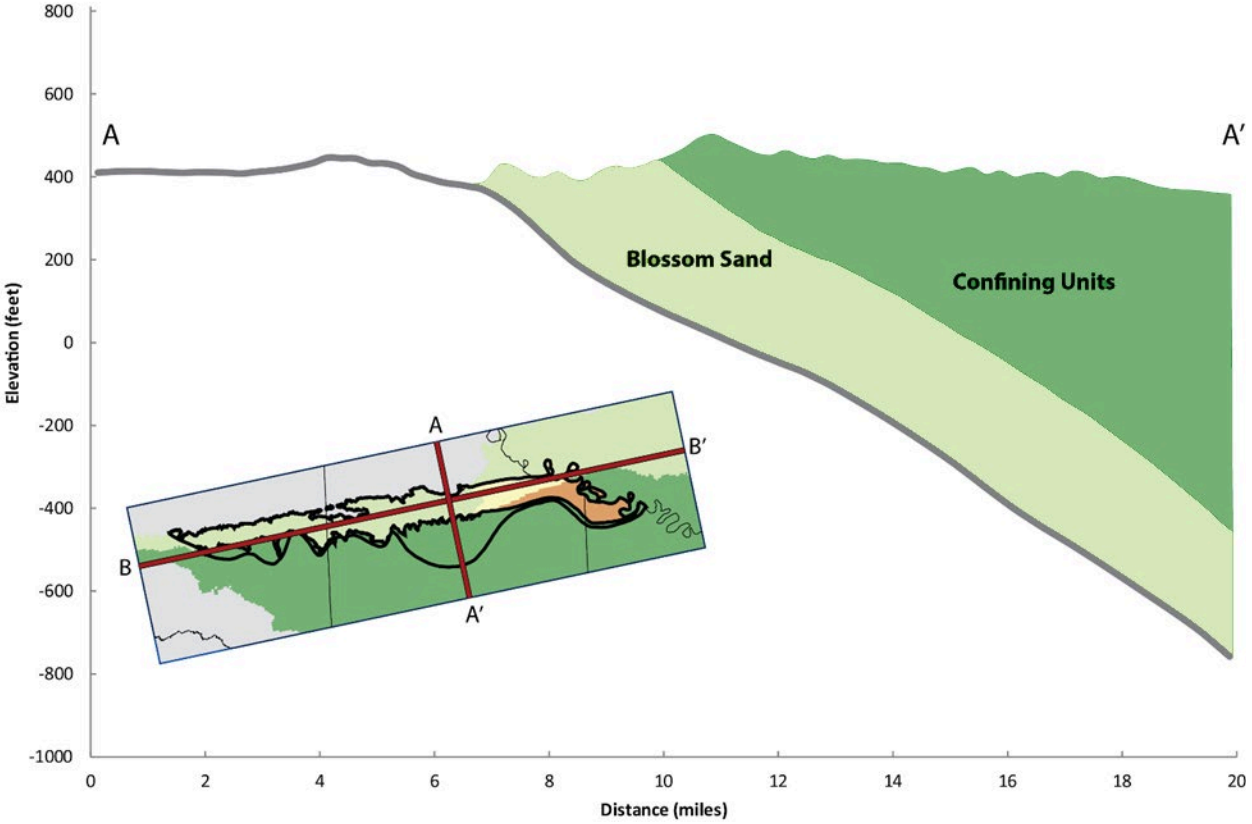

FIGURE 5 NORTH-SOUTH CROSS-SECTION OF THE MODEL LAYERS APPROXIMATELY IN THE DIP DIRECTION OF THE GEOLOGIC UNITS.

alluvium deposits, and the Blossom Sand and Tokio Formation (Figures 3, 5, and 6). We defined the layer surfaces based on (1) land surface elevation from a digital elevation model (DEM), (2) estimates of alluvium thickness from driller's logs (3) and McLaurin's (1988) surface maps supplemented with control points from outcrop contracts and additional well control from Baker and others (1963). Details of the data and references for the framework surfaces are provided in Wade and others (2022).

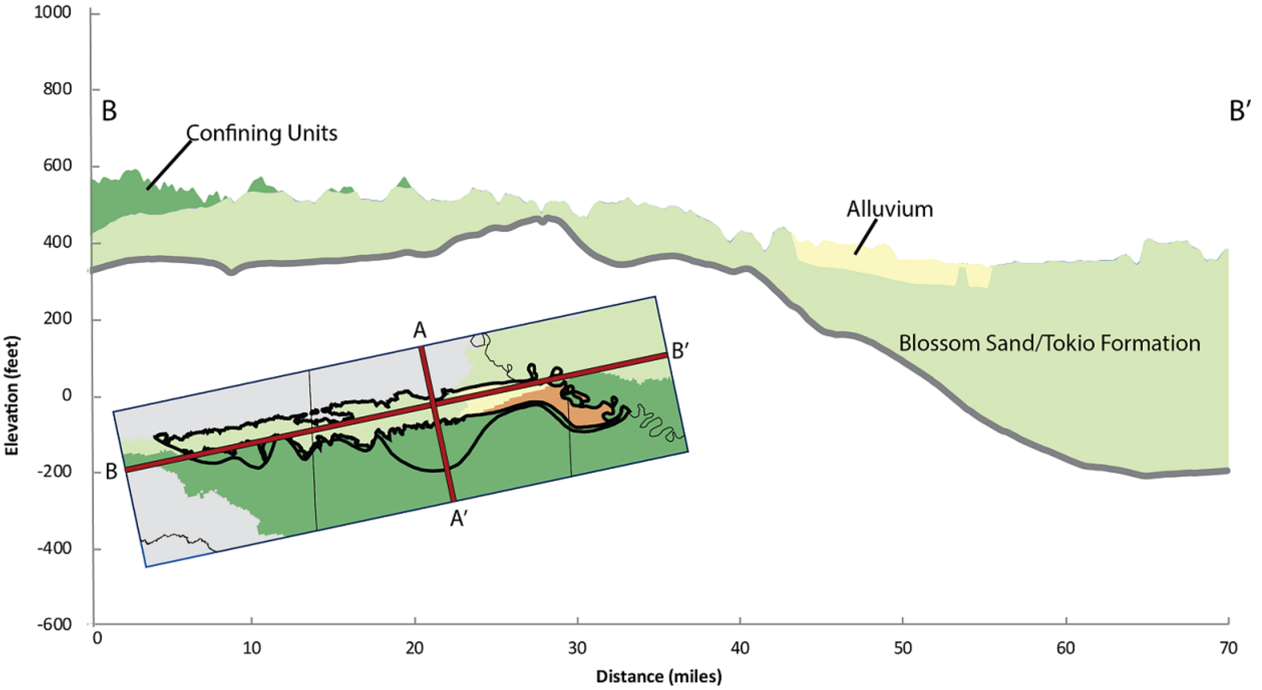

FIGURE 6 EAST-WEST CROSS-SECTION OF THE MODEL LAYERS APPROXIMATELY IN THE STRIKE DIRECTION OF THE GEOLOGIC UNITS.

The temporal discretization (Table 4) includes one steady-state stress period (stress period 1) and fifty-six transient stress periods (stress periods 2 through 57). Stress period one doesn't represent a particular time period, rather it mainly serves the purpose of providing starting conditions for the transient calibration. Stress periods 2 through 57 are annual and represent 1957 through 2012

TABLE 4 STRESS PERIOD LENGTH AND TIME PERIOD.

Stress Period	Time Period	Length (days)	Time Steps
1	Steady-state	365.25	10
2	1957	365.25	1
3	1958	365.25	1
4	1959	365.25	1
5	1960	365.25	1

Stress Period	**Time Period**	**Length (days)**	**Time Steps**
6	1961	365.25	1
7	1962	365.25	1
8	1963	365.25	1
9	1964	365.25	1
10	1965	365.25	1
11	1966	365.25	1
12	1967	365.25	1
13	1968	365.25	1
14	1969	365.25	1
15	1970	365.25	1
16	1971	365.25	1
17	1972	365.25	1
18	1973	365.25	1
19	1974	365.25	1
20	1975	365.25	1
21	1976	365.25	1
22	1977	365.25	1
23	1978	365.25	1
24	1979	365.25	1
25	1980	365.25	1
26	1981	365.25	1
27	1982	365.25	1

Stress Period	**Time Period**	**Length (days)**	**Time Steps**
28	1983	365.25	1
29	1984	365.25	1
30	1985	365.25	1
31	1986	365.25	1
32	1987	365.25	1
33	1988	365.25	1
34	1989	365.25	1
35	1990	365.25	1
36	1991	365.25	1
37	1992	365.25	1
38	1993	365.25	1
39	1994	365.25	1
40	1995	365.25	1
41	1996	365.25	1
42	1997	365.25	1
43	1998	365.25	1
44	1999	365.25	1
45	2000	365.25	1
46	2001	365.25	1
47	2002	365.25	1
48	2003	365.25	1
49	2004	365.25	1

Stress Period	Time Period	Length (days)	Time Steps
50	2005	365.25	1
51	2006	365.25	1
52	2007	365.25	1
53	2008	365.25	1
54	2009	365.25	1
55	2010	365.25	1
56	2011	365.25	1
57	2012	365.25	1

2.3 Upstream Weighting (UPW) Package

The MODFLOW Upstream Weighting package contains the flags of layer type, cell-by-cell flow output, horizontal and vertical hydraulic conductivity, specific storage, and specific yield. The layer type values were all set greater than zero meaning all three layers are convertible between confined and unconfined.

The horizontal hydraulic conductivity is specified as isotropic meaning the hydraulic conductivity is the same in all horizontal directions. We assigned hydraulic conductivity values based on zones (Figures 7 and 8 and Table 5). Layer 1 includes one zone for the Red River Alluvium (Figure 7). Layer 2 includes two zones. One zone represents the Brownstown confining unit (Figure 7, zone 4) and one zone (Figure 7, zone 2) represents the pass-through cells where the Brownstown is not present to allow communication between layer 3 and layer 1. Layer 3 includes five zones (Figure 8). At the beginning of model calibration zones were based on layers and whether that area was confined or unconfined. The preliminary values of horizontal hydraulic conductivity for calibration were assigned based on the median of the data values for the Red River Alluvium and Blossom Sand from the conceptual model report (Wade and others, 2022). The median values of the data are shown with the final calibrated values in Table 5. Additional zones were added during calibration. The additional zones were based on the distribution of water level residuals and with consideration of characteristics of the aquifer that may be different in certain areas. For example, the transmissive properties of the Blossom Aquifer decrease to the west. Specific details about the calibration are provided in the Model

Calibration and Results Section. We also assigned and calibrated specific storage, specific yield and vertical hydraulic conductivity according to the same zones as the horizontal hydraulic conductivity (Table 5).

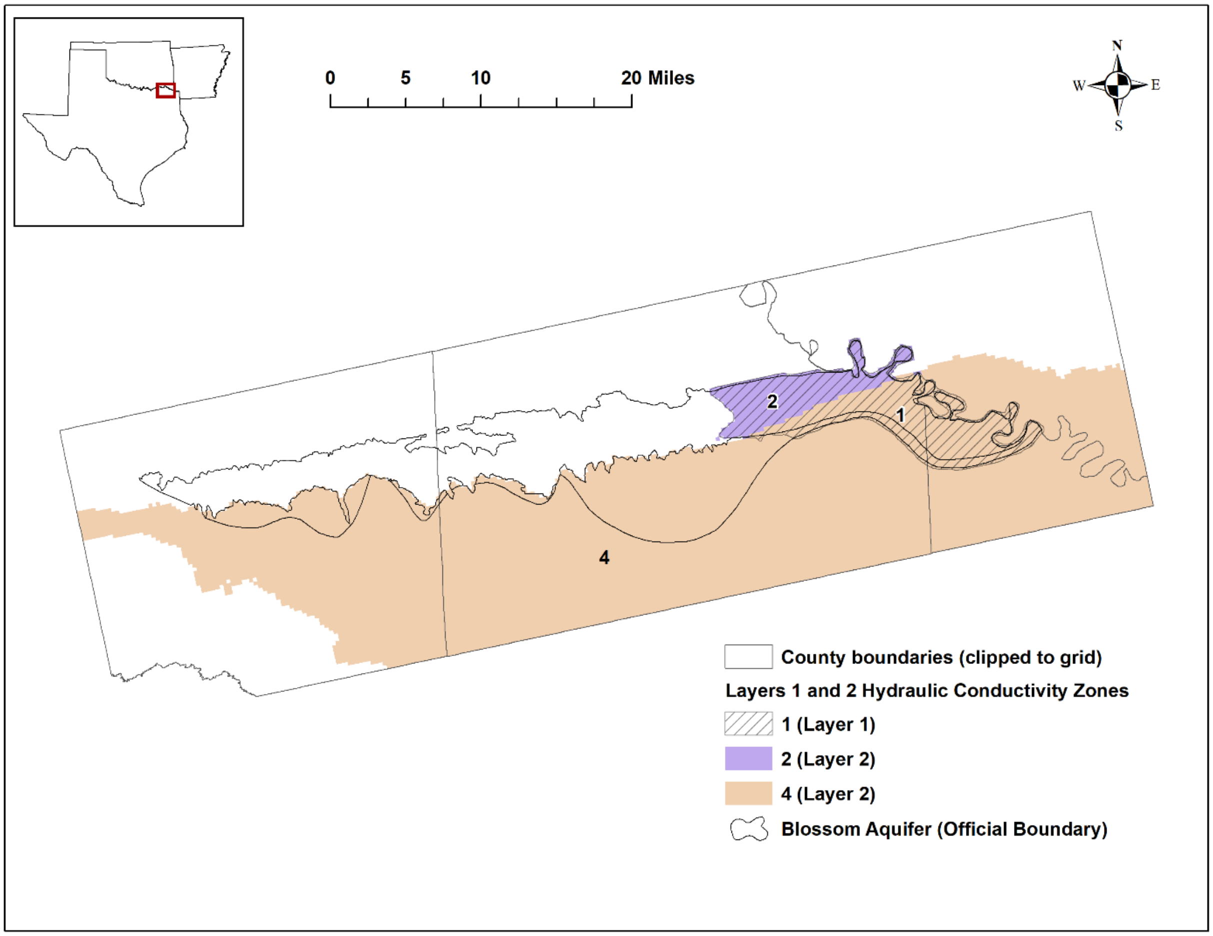

FIGURE 7 LAYERS 1 AND 2 HYDRAULIC PROPERTY ZONES.

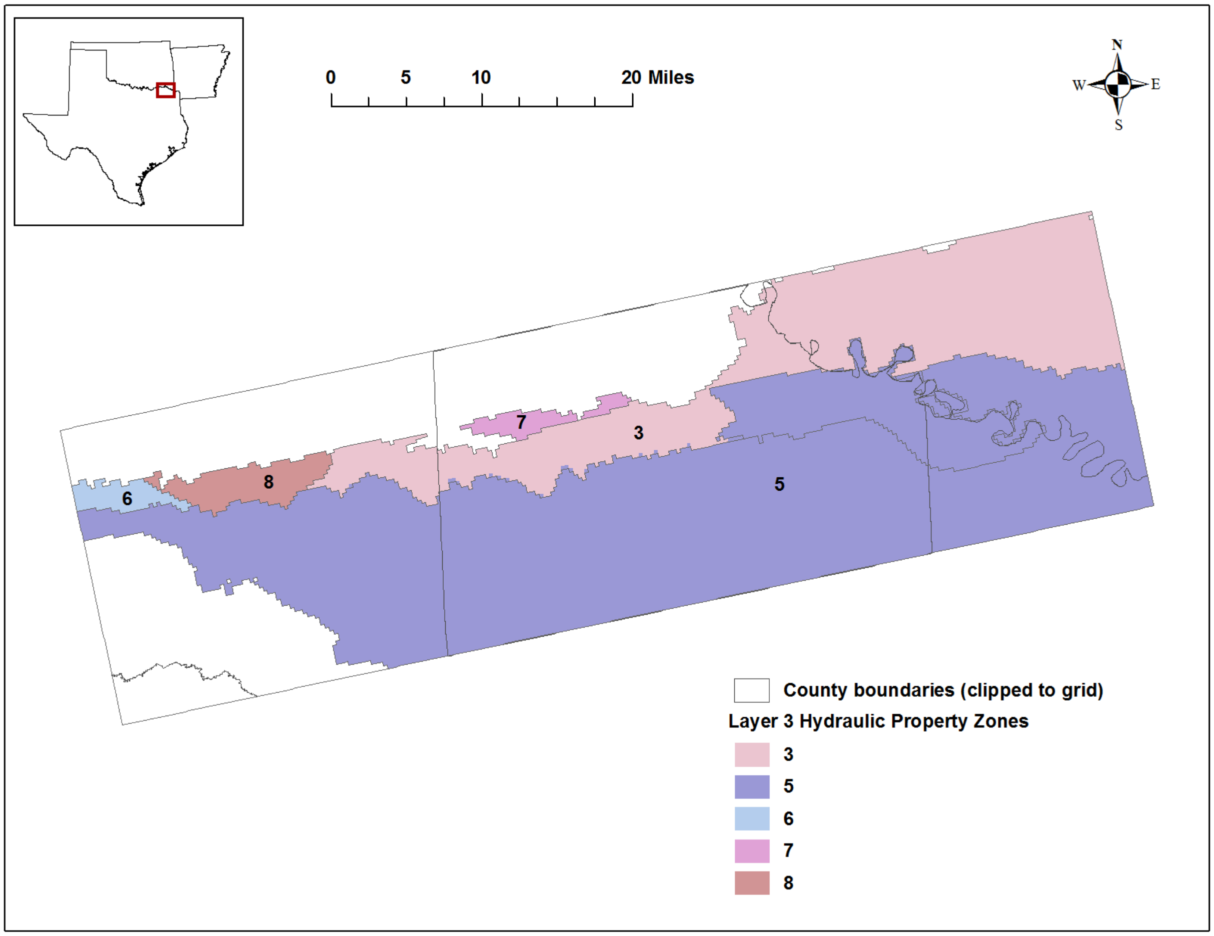

FIGURE 8 LAYER 3 HYDRAULIC PROPERTY ZONES.

TABLE 5 CALIBRATED HYDRAULIC PROPERTY VALUES FOR ZONES 1 THROUGH 8.

Property	Zone	Calibrated Property Value	Median Data Value from conceptual model
Horizontal Hydraulic Conductivity	1	114.2 feet per day	80 feet per day
Horizontal Hydraulic Conductivity	2	103.5 feet per day	80 feet per day
Horizontal Hydraulic Conductivity	3	2.7 feet per day	5.3 feet per day
Horizontal Hydraulic Conductivity	4	0.2 feet per day	5.3 feet per day
Horizontal Hydraulic Conductivity	5	2.8 feet per day	5.3 feet per day

Property	Zone	Calibrated Property Value	Median Data Value from conceptual model
Horizontal Hydraulic Conductivity	6	3.7 feet per day	5.3 feet per day
Horizontal Hydraulic Conductivity	7	20 feet per day	5.3 feet per day
Horizontal Hydraulic Conductivity	8	2.9 feet per day	5.3 feet per day
Vertical Hydraulic Conductivity	1	1.347 feet per day	Not applicable
Vertical Hydraulic Conductivity	2	$7.8 X 10^{-3}$ feet per day	Not applicable
Vertical Hydraulic Conductivity	3	$1.0 X 10^{-3}$ feet per day	Not applicable
Vertical Hydraulic Conductivity	4	$7.0 X 10^{-6}$ feet per day	Not applicable
Vertical Hydraulic Conductivity	5	$8.0 X 10^{-4}$ feet per day	Not applicable
Vertical Hydraulic Conductivity	6	$1.0 X 10^{-3}$ feet per day	Not applicable
Vertical Hydraulic Conductivity	7	$1.0 X 10^{-3}$ feet per day	Not applicable
Vertical Hydraulic Conductivity	8	$1.0 X 10^{-3}$ feet per day	Not applicable
Specific Storage	1	$7.0 x 10^{-4}$ foot $^{-1}$	Not applicable
Specific Storage	2	$8.0 x 10^{-3}$ foot $^{-1}$	Not applicable
Specific Storage	3	$2.0 x 10^{-7}$ foot $^{-1}$	Not applicable
Specific Storage	4	$1.0 x 10^{-7}$ foot $^{-1}$	Not applicable
Specific Storage	5	$2.0 x 10^{-5}$ foot $^{-1}$	Not applicable
Specific Storage	6	$1.0 x 10^{-7}$ foot $^{-1}$	Not applicable
Specific Storage	7	$1.0 x 10^{-7}$ foot $^{-1}$	Not applicable
Specific Storage	8	$8.0 x 10^{-7}$ foot $^{-1}$	Not applicable
Specific Yield	1	0.1176	Not applicable
Specific Yield	2	0.2	Not applicable
Specific Yield	3	$8.0 x 10^{-2}$	Not applicable

Property	**Zone**	**Calibrated Property Value**	**Median Data Value from conceptual model**
Specific Yield	4	1.5×10^{-2}	Not applicable
Specific Yield	5	1.6×10^{-2}	Not applicable
Specific Yield	6	0.1214	Not applicable
Specific Yield	7	0.1079	Not applicable
Specific Yield	8	8.02×10^{-2}	Not applicable

2.4 Well (WEL) Package

The MODFLOW Well package contains groundwater withdrawal information for municipal, domestic, irrigation, and livestock use. We compiled groundwater use estimates in Texas from the TWDB Water Use Survey, as well as historic references (McLaurin, 1988; Baker and others, 1963).

Municipal pumping was assigned to the model based on point well locations from the TWDB groundwater database. (Figures 9 and 10). The well locations were determined based on owner name. The domestic and livestock pumping was assigned to the model grid using all wells in the area identified as domestic supply or livestock supply for the primary, secondary, or tertiary use type. Greater detail on the assumptions and development of the pumping file are given in the conceptual model report for this study (Wade and others, 2022).

Total modeled pumping ranges from approximately 505 acre-feet per year in 1957 to approximately 1,246 acre-feet per year in 1986 (Table 6).

TABLE 6 SUMMARY OF SIMULATED PUMPING RATES IN ACRE-FEET PER YEAR.

Year	Domestic and Livestock	Municipal	Irrigation	Total estimated pumping rate for model
Steady-State	0	0	0	0
1957	103	310	91	505
1958	123	370	91	585
1959	115	345	91	551
1960	110	330	91	531
1961	108	325	91	525
1962	123	370	91	585
1963	170	495	91	756
1964	154	448	91	693
1965	178	520	91	789
1966	180	525	91	796

Year	Domestic and Livestock	Municipal	Irrigation	Total estimated pumping rate for model
1967	148	430	91	669
1968	153	445	91	689
1969	69	605	91	765
1970	83	730	91	904
1971	83	730	91	904
1972	90	799	91	981
1973	84	739	91	914
1974	93	824	91	1,008
1975	90	799	91	981
1976	79	699	91	870
1977	86	764	91	942
1978	100	884	91	1,075
1979	91	809	91	992
1980	93	823	38	953
1981	89	792	91	973
1982	91	813	91	996
1983	98	874	91	1,063
1984	100	888	100	1,088
1985	94	835	90	1,020
1986	113	1,000	134	1,246
1987	86	757	110	952
1988	79	696	104	879
1989	65	567	57	688
1990	64	563	68	695
1991	66	578	0	644

Year	Domestic and Livestock	Municipal	Irrigation	Total estimated pumping rate for model
1992	63	551	0	614
1993	54	470	31	555
1994	57	499	0	556
1995	64	565	0	629
1996	68	596	0	664
1997	67	587	0	653
1998	82	720	0	801
1999	85	745	0	830
2000	87	770	0	857
2001	87	766	0	853
2002	77	695	0	772
2003	76	688	0	764
2004	76	688	251	1,015
2005	77	694	236	1,007
2006	108	970	5	1,083
2007	57	514	55	625
2008	69	624	70	763
2009	71	643	449	1,163
2010	63	567	445	1,075
2011	66	596	274	936
2012	63	569	497	1,129

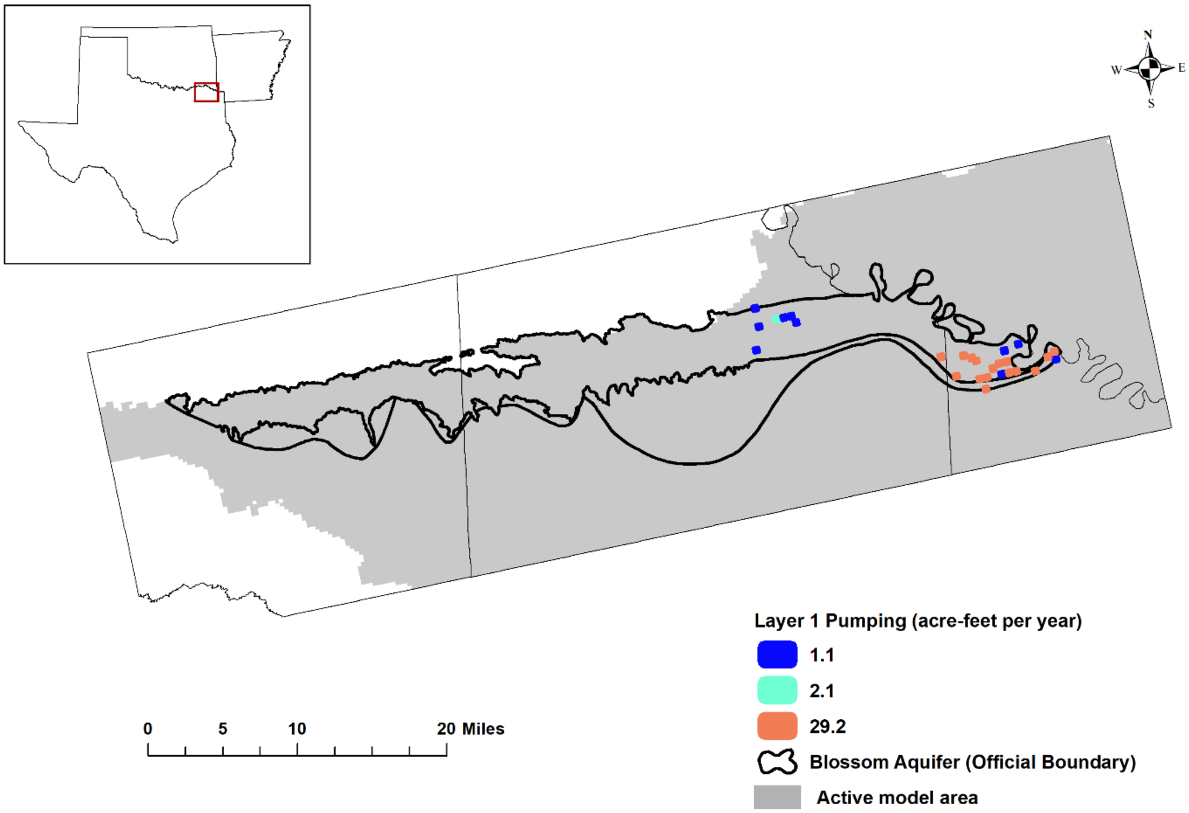

FIGURE 9 PUMPING LOCATIONS FOR LAYER 1 IN 2012 (STRESS PERIOD 57).

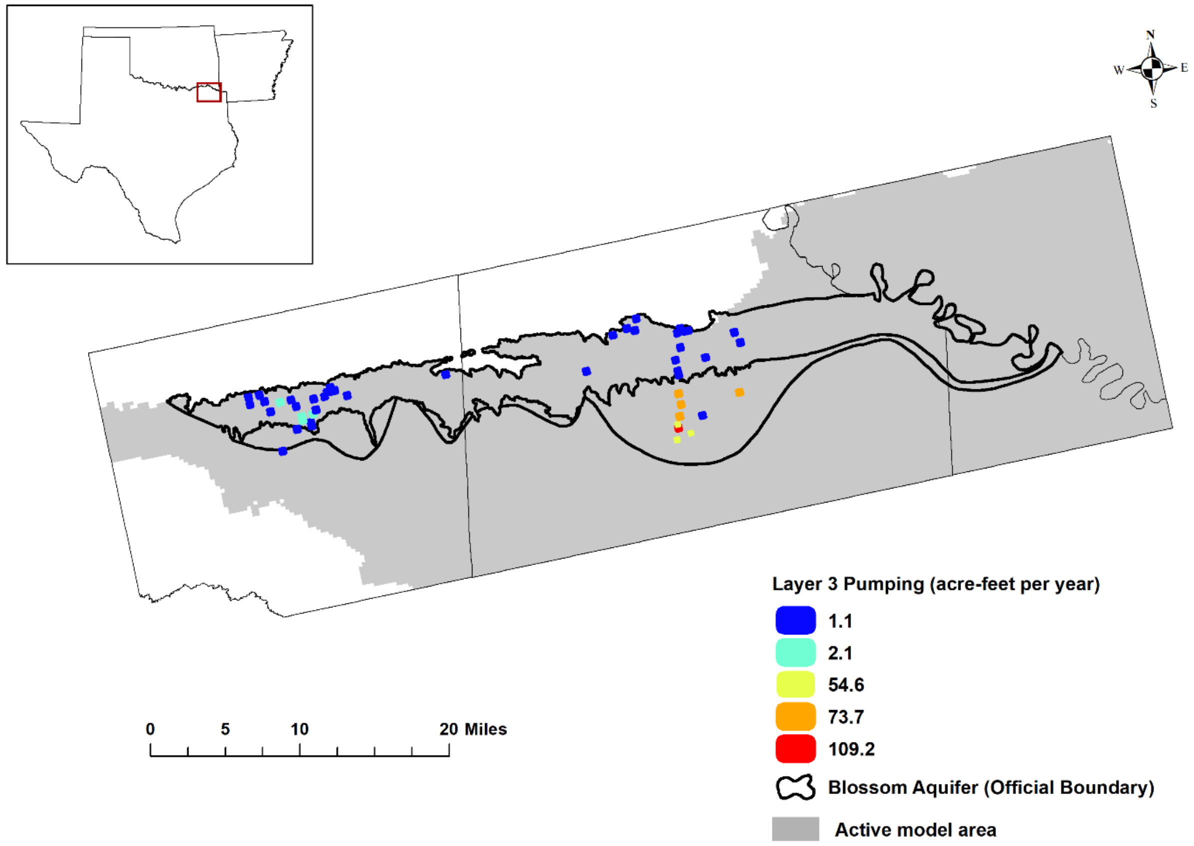

FIGURE 10 PUMPING LOCATIONS FOR LAYER 3 IN 2012 (STRESS PERIOD 57).

2.5 Drain (DRN) Package

The MODFLOW Drain package was used to drain water from sixteen cells to reduce excessive ponding of water in a shallow isolated portion of the outcrop (Figure 11). The drain elevation for the drain cells were selected as land surface elevation. The conductance values of the drain cells were adjusted to 11.4 feet^2 per day during the model calibration.

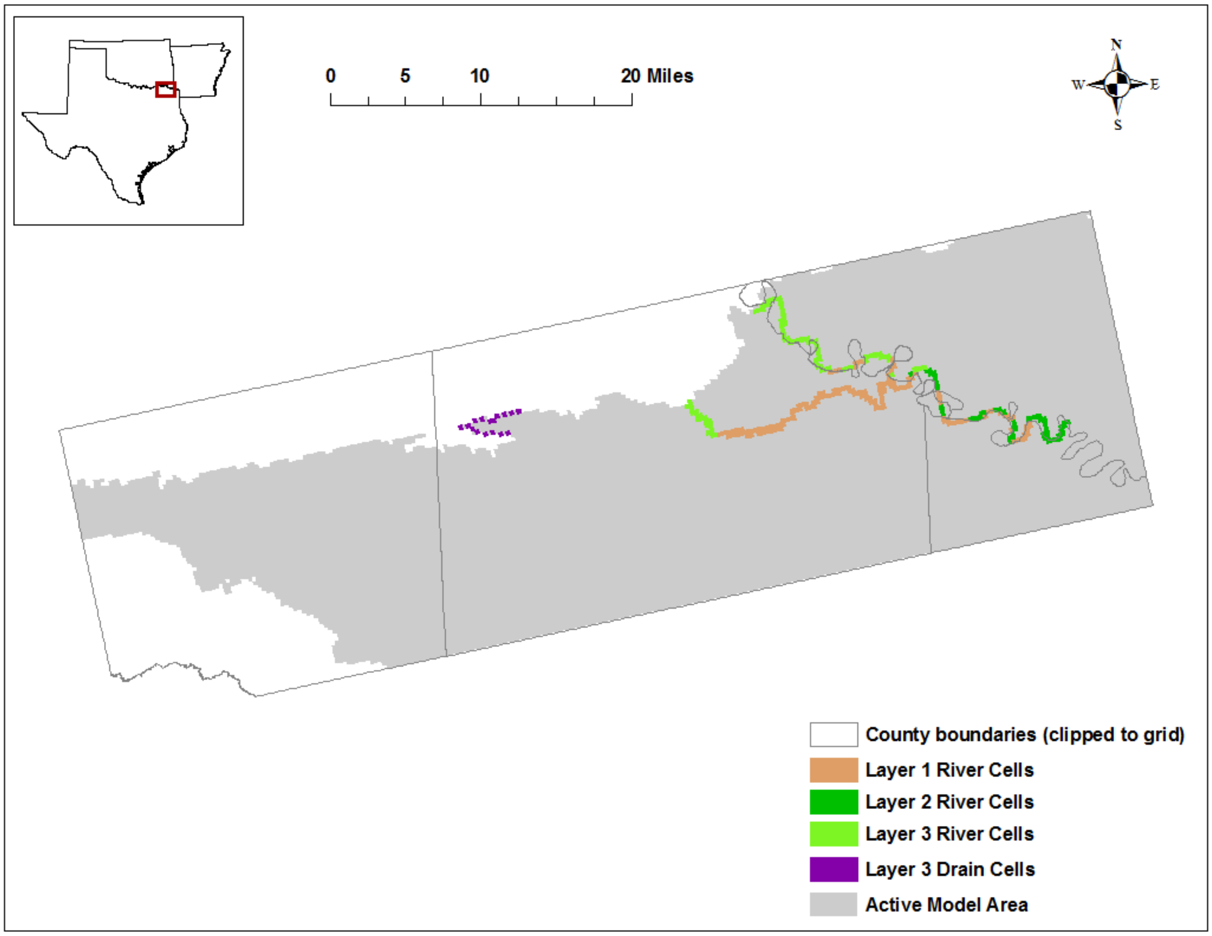

FIGURE 11 LOCATION OF DRAIN AND RIVER CELLS.

2.6 River (RIV) Package

The MODFLOW River package was used to simulate the interaction of groundwater with the Pecan Bayou and the Red River (Figure 11). The MODFLOW River package was also used to simulate the riparian groundwater evapotranspiration discharge.

River cell locations were first digitized using the National Hydrography Dataset (NHD; U.S. Geological Survey, 2015). Other properties for the MODFLOW River package were derived from the U.S. Environmental Protection Agency river reach file (U.S. Environmental Protection Agency, 1994) and the U.S. Geological Survey digital elevation model (DEM; U.S. Geological Survey, 2014). Properties required for the MODFLOW River package include river head, riverbed hydraulic conductance, and the elevation of the base of the riverbed sediments. The river head for the cells was calculated from the elevation of the river bottom plus the river stage (Table 7). The elevation of the river bottom for each river cell was set based on the digital elevation model (DEM) and slope information from the U.S. Environmental Protection Agency river reach file (U.S. Environmental Protection Agency, 1994). The elevation of the base of river bed sediments was calculated as the river bottom elevation minus an assumed bed thickness of 5 feet for the Red River sediments and an assumed thickness of 1 foot for the Pecan Bayou sediments. The riverbed conductance (by reach) was estimated during model calibration.

TABLE 7 SUMMARY OF RIVER BOUNDARY VALUES.

Reach	Conductance ($feet^2$ per day)	Bed Thickness (feet)	Stage[1] (feet)
Red River (upstream)	10,000	5	3.38
Red River (downstream)	10,000	5	4.29
Pecan Bayou	796.35	1	0.61

1. From U.S. EPA Reach File (RF1)

2.7 General-Head Boundary (GHB) Package

The General-Head Boundary (GHB) package is used in two locations in the model. There is a general-head boundary on the top of layer two representing the water table in overlying formations and alluvium (Figure 12). The head value assigned to the boundary is set at 10 feet below the mean elevation from the 30-meter resolution DEM (U.S. Geological Survey, 2014). The boundary conductance value was set at 420 $feet^2$ per day during initial trial and error manual calibration. However, the conductance was not used as a parameter in the automated calibration (PEST; Watermark Numerical Computing, 2004) because model convergence was very sensitive to the boundary conductance values.

The second general-head boundary is along the downdip boundary of layer 3 to allow groundwater to flow downdip out of the model (Figure 12). The head values along this boundary were determined during automated calibration and were estimated as 53.12 feet at the western most active cell and 3.12 feet at the southeast corner. The head boundary values decrease linearly between the two cells. The conductance was estimated as 10,000 feet^2 per day through manual calibration. Again, as with layer 2, the conductance was not used as a parameter in the automated calibration (PEST; Watermark Numerical Computing, 2004) because model convergence was very sensitive to the boundary conductance values.

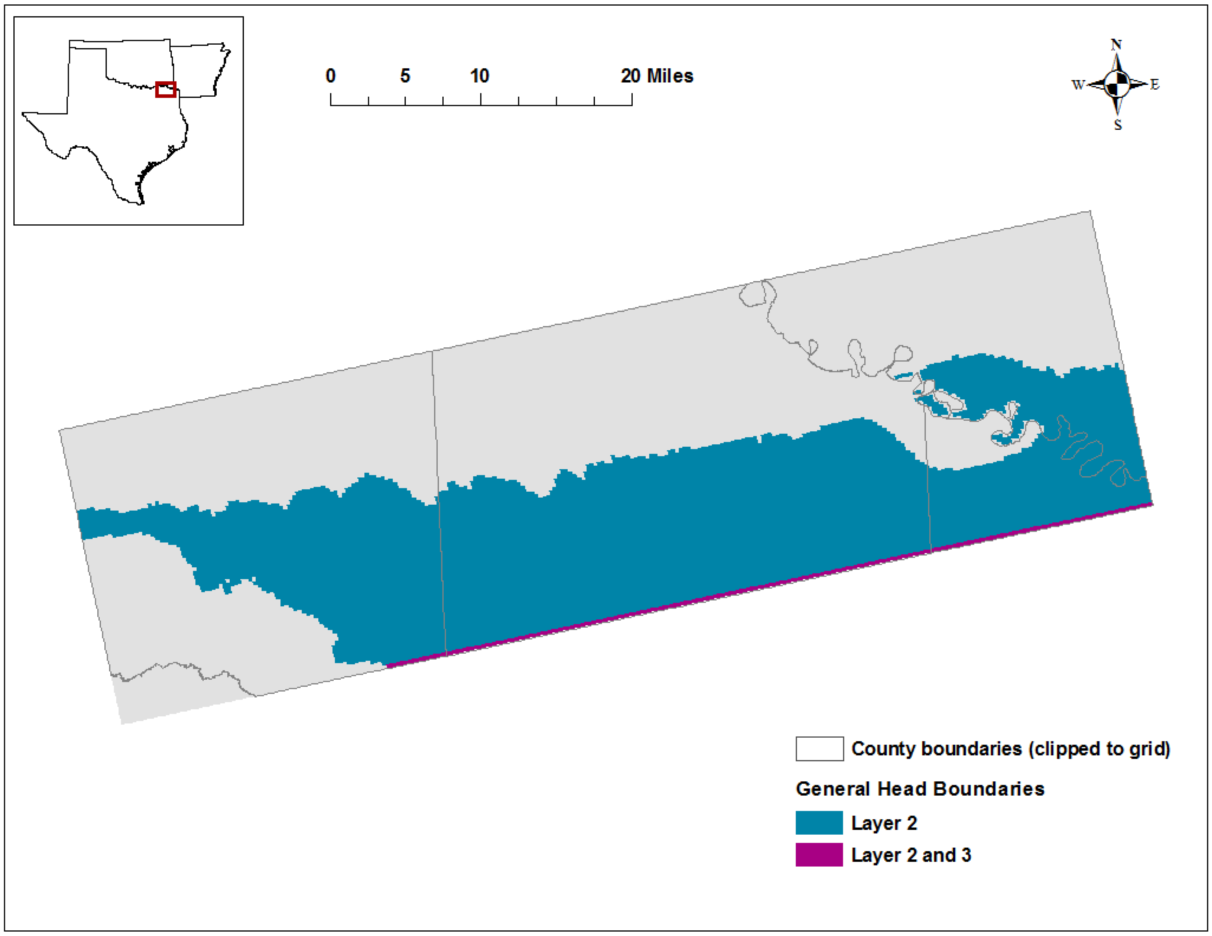

FIGURE 12 LOCATION OF GENERAL-HEAD BOUNDARIES.

2.8 Recharge (RCH) Package

The MODFLOW Recharge package was used to simulate inflow to groundwater due to precipitation on the outcrop areas. The Recharge Package contains recharge rates (feet per day) on a cell-by-cell basis which are applied to the uppermost active cells during simulations.

The MODFLOW Recharge package was constructed based on the recharge approach described in the conceptual model (Wade and others, 2022). Kirk and others (2012) developed a model of recharge from precipitation, watershed discharge, and evapotranspiration from satellite data. The recharge model consisted of recharge rasters for each year from 1960 to 2009. Recharge zones (Figure 13 and Table 10) were used to generalize the high-resolution recharge from Kirk and others (2012) for the groundwater model. Zones 1, 3, 5, 6, and 7 correspond to portions of the Blossom Sand outcrop and Tokio Formation outcrop. Zone 2 is the confined portion of the model and Zone 4 is the inactive portion of the model. The recharge model values were generalized by calculating zonal averages of the recharge rasters for each zone by year. The zonal average recharge for each year was then assigned to all model cells in each zone. The recharge was further adjusted during calibration by adjusting the recharge for each zone by a factor and applying a temporal dampening factor. A pre-processor written in Perl, a scripting language, was used to implement this algorithm. The pre-processor reads in cell-by-cell zone numbers, average recharge values for each zone per stress period, a recharge adjustment factor for each zone, and a dampening factor. The pre-processor then (1) calculates dampened recharge (Equation 2.1), (2) calculates adjusted recharge (Equation 2.2), and (3) writes a MODFLOW Recharge package file.

$$\text{Recharge} = (\text{AAR} \times \text{damp}) + (1 - \text{damp}) \text{ x } \text{RYR} \qquad (2.1)$$

where:

Recharge = adjusted annual recharge for specific stress period
AAR = average annual recharge
RYR = original estimated annual recharge amount
damp = overall dampening factor

$$\text{R} = R_o \text{ x factor} \qquad (2.2)$$

where:

R = adjusted zonal recharge in feet per day
R_o = original zonal average recharge estimated from Kirk and others (2012)
factor = recharge adjustment factor for calibration

The dampening factor accounts for lag time associated with travel time in the unsaturated zone. A dampening factor of one applies average recharge every stress period and a dampening factor of zero results in no adjustment to annual recharge amounts. The dampening factor (damp) and the recharge adjustment factor were adjusted during calibration (Table 8).

TABLE 8 SUMMARY OF CALIBRATED RECHARGE PARAMETERS.

Parameter	Factor Value
Recharge factor zone 1	1.035
Recharge factor zone 2	NA[1]
Recharge factor zone 3	0.623
Recharge factor zone 4	NA[1]
Recharge factor zone 5	0.480
Recharge factor zone 6	0.378
Recharge factor zone 7	0.338
Dampening factor	0.628

1. NA: Not applicable

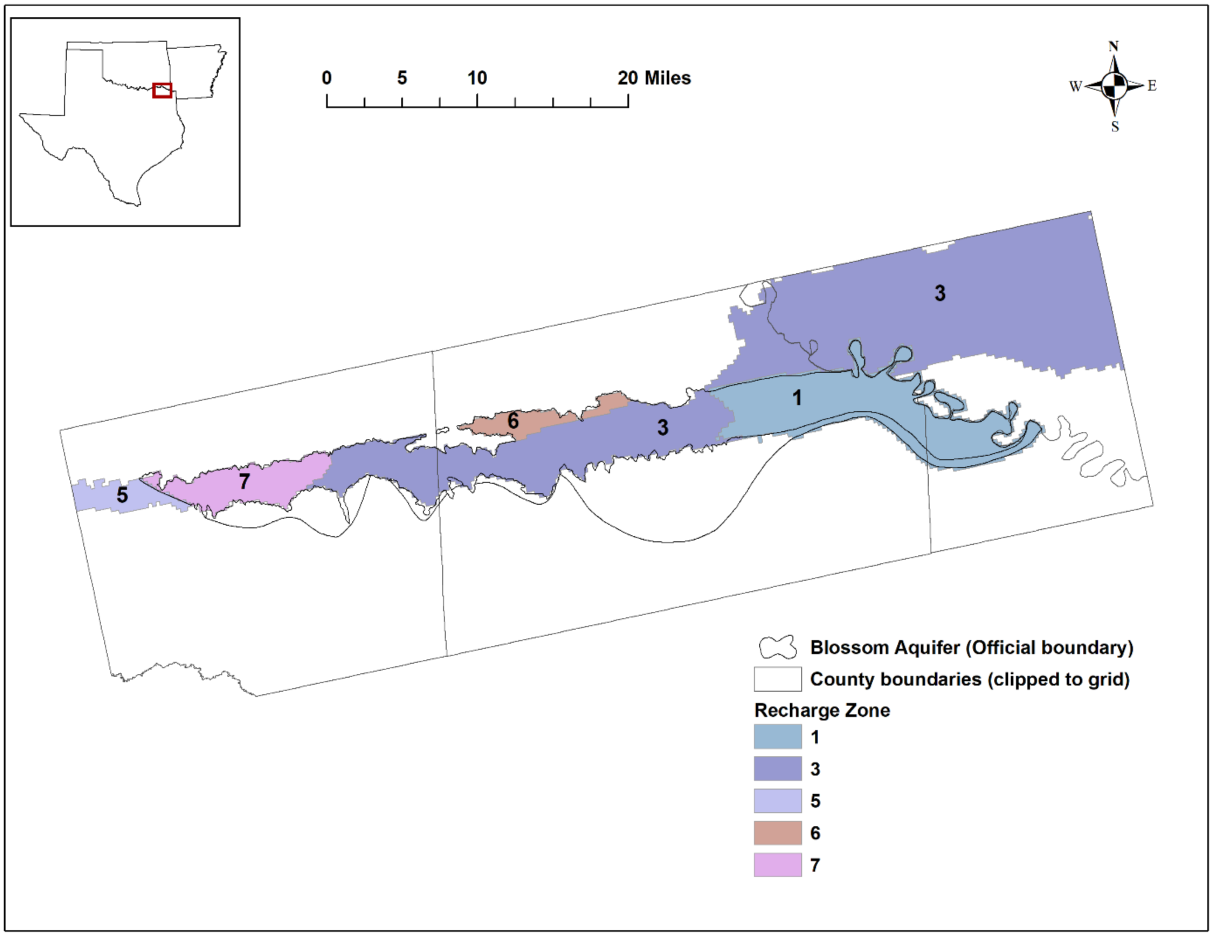

FIGURE 13 RECHARGE ZONES. ZONES 2 AND 4 ARE NOT IN THE OUTCROP.

2.9 Output Control (OC) Package

The MODFLOW Output Control package specifies when to save head, drawdown, and water budget output during the model run. It is a standard file required for all MODFLOW models. The output control file for this model was set up to write head, drawdown, and budget information at the end of each stress period.

2.10 Newton (NWT) Solver Package

We are using the Newton (NWT) solver (Niswonger and others, 2011) to solve the finite difference equations that simulate groundwater flow in the model. For the NWT solver convergence criteria we used a head tolerance of 0.005 feet and a flux tolerance of 200 cubic feet per day between outer iterations. We set the maximum number of outer iterations at 200. Evaluation of mass balance for each stress period and cumulative discrepancy between total inflows and outflows indicated negligible numerical errors with this solver setup.

The variable, PHIRAMP, is used with the NWT solver and the upstream weighting package to reduce cell dewatering. PHIRAMP is specified in the well package input file and is a fraction of the cell thickness below which pumping rates are smoothly adjusted to zero to minimize dry cells. We set phiramp equal to 30 percent for the Blossom Aquifer model.

3.0 MODEL CALIBRATION AND RESULTS

The calibration of a groundwater model involves adjusting hydraulic properties and boundary conditions in the model, within a reasonable range, to match the simulated water levels and flows to measured water levels and flows. A calibrated groundwater flow model is a tool that can be used to test or predict future pumping and recharge conditions. A model which is calibrated over a range of historical conditions can improve reliability of the prediction.

3.1 Calibration Procedure

We calibrated the Blossom Aquifer groundwater availability model primarily to measured water levels at wells. Groundwater discharge was estimated from the gauge data on Pecan Bayou (Wade and others, 2022); however, those estimates are fairly uncertain and represent areas mostly outside the model area. We adjusted hydraulic conductivity, specific storage, specific yield, recharge, and boundary conditions (both head and conductance) using parameter estimation (PEST), an industry-standard inverse modeling software package (Watermark Numerical Computing, 2004), and by trial-and-error.

Our calibration data set consisted of 438 water level targets at 153 wells (Figures 14 through 16). There are 321 targets at 114 wells specifically in the Blossom Sand (Figure 16).

For model calibration we used pre- and post-processor programs to create model input files and convert model output files to compare with target water levels and discharge estimates. During the automated model calibration, PEST adjusted the following parameters: hydraulic conductivity by zone, specific storage and specific yield by zone, drain conductance, river conductance by reach, head values at either end of the layer 3 downdip general-head boundary, and recharge parameters. PEST selects the parameter combination which produces the best fit to the target values. The fit is determined by the value of the objective function φ. The objective function, φ, is the sum of squared deviations between model-generated observations and measured (or estimated) field observations. The lower the value of φ, the better the model fits the data (Watermark Numerical Computing, 2004).

The parameter values and model results achieved through PEST runs were first inspected to determine if they were reasonable. In cases where unreasonable results were found, a trial-and-error method was used to determine a more appropriate range of possible parameter values to produce more reasonable results. This process was repeated until the model matched the measured or calculated values and generated reasonable flow fields consistent with the conceptual understanding of the regional groundwater flows.

The final set of estimated parameters included a value of specific yield for zone 5 (Layer 3 confined portion) equal to 0.0036 which is unreasonably low. A new value was calculated by multiplying the estimated specific storage by the maximum aquifer thickness in zone 5. The new estimate was set at 0.016. The model results were very similar to the final PEST run results.

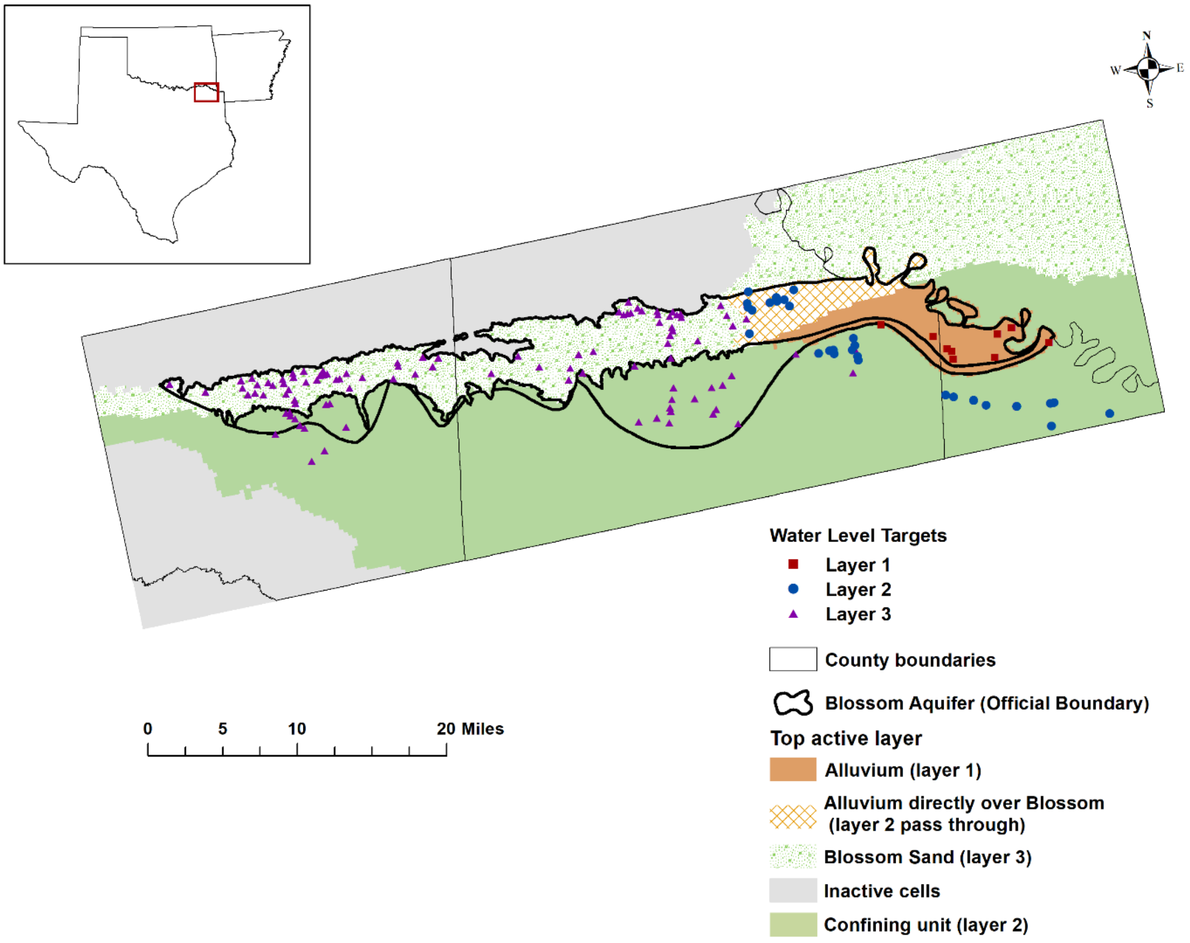

FIGURE 14 LOCATION OF WATER LEVEL MEASUREMENTS USED FOR CALIBRATING THE GROUNDWATER MODEL OF THE BLOSSOM AQUIFER[3].

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[3] Water level data were extracted from the TWDB Groundwater database (TWDB, 2015).

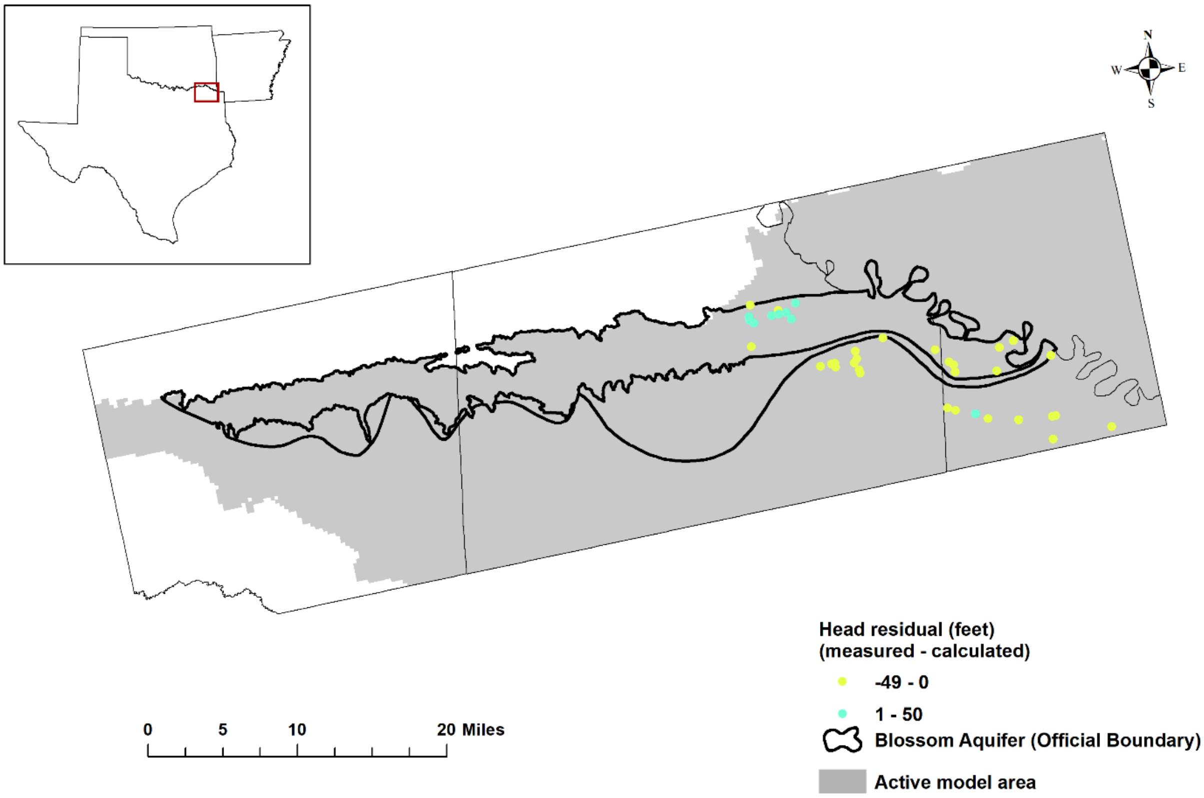

FIGURE 15 HEAD RESIDUALS BETWEEN MEASURED AND SIMULATED WATER LEVELS FOR THE ENTIRE CALIBRATION PERIOD IN LAYERS 1 AND 2.

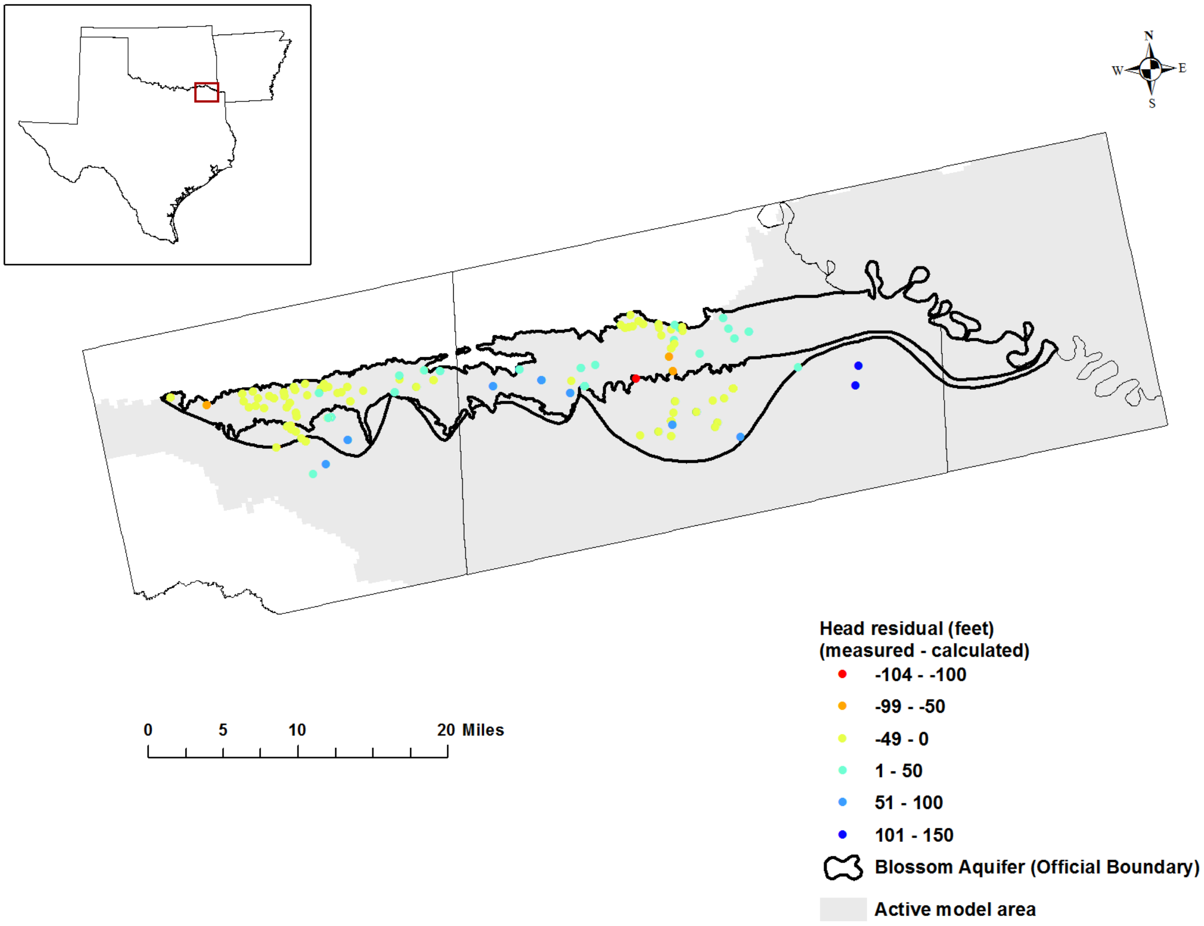

FIGURE 16 HEAD RESIDUALS BETWEEN MEASURED AND SIMULATED WATER LEVELS FOR THE ENTIRE CALIBRATION PERIOD IN LAYER 3.

3.2 Model Calibration Results

Water Level Targets

The measured water levels plotted versus the modeled water levels generally plot along a line with a slope of one (Figure 17). Some tailing occurs at about 200 feet which is probably mostly due to the model not reproducing the large variation in heads at one target, state well number (SWN) 1732201 (Figure 21). The root mean squared error for all layers for the final model calibration is 29.4 feet, which is 6.0 percent of the range in heads (Table 9). The mean head residual for all targets is -5.6 feet. The root mean squared error for layer 3, the Blossom Aquifer, is 33.4 feet, which is 6.8 percent of the range in heads (Table 10). The mean head residual for layer 3 targets is -4.4 feet. The calibration statistics for targets in all layers and for the targets in just layer 3 (Tables 9 and 10) meet the goal of a root mean squared of no greater than 10 percent of the range in heads. The calibration statistics for layers one and two exceed ten percent (39.5 and 21.3 respectively). However, the range in heads for layer 1 and 2 targets is less than 50 feet which would require a root mean squared of five feet or less and the primary focus of the model is the Blossom Aquifer.

The water level residuals range from -100 feet to 150 feet (Figures 18 and 19). The residual distribution is approximately symmetric and centered around zero (Figure 19) with most of the residuals between 26 and -26 feet. The measured water levels, model estimates, and residuals for each target are listed in Appendix A (Table A.1).

TABLE 9 FINAL CALIBRATION STATISTICS OVERALL

Parameter	**Value**
Head φ	3.77×10^5
Root Mean Squared Error (RMSE)	29.4 feet
Mean head residual	-5.6 feet
Root Mean Squared Error/Range in heads	6.0 percent

TABLE 10 FINAL CALIBRATION STATISTICS BY LAYER.

Layer	**Mean Residual (feet)**	**Root Mean Squared Error (RMSE)**	**Range (feet)**	**RMSE/Range (percent)**
1	-15.6	17.4	44.1	39.5
2	-5.3	9.6	45.4	21.3
3	-4.4	33.4	490.1	6.8
Overall	-5.6	29.4	490.1	6.0

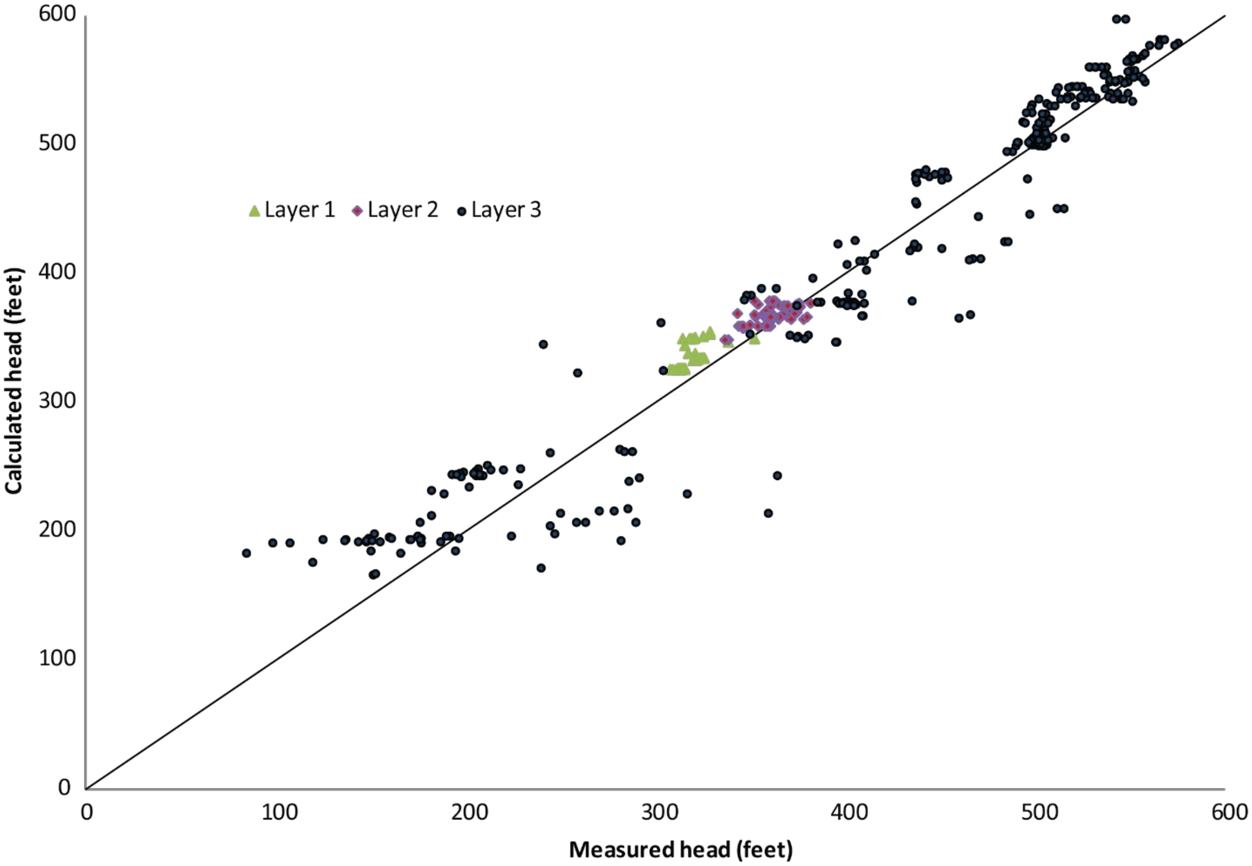

FIGURE 17 MEASURED VERSUS MODEL CALCULATED WATER LEVELS.

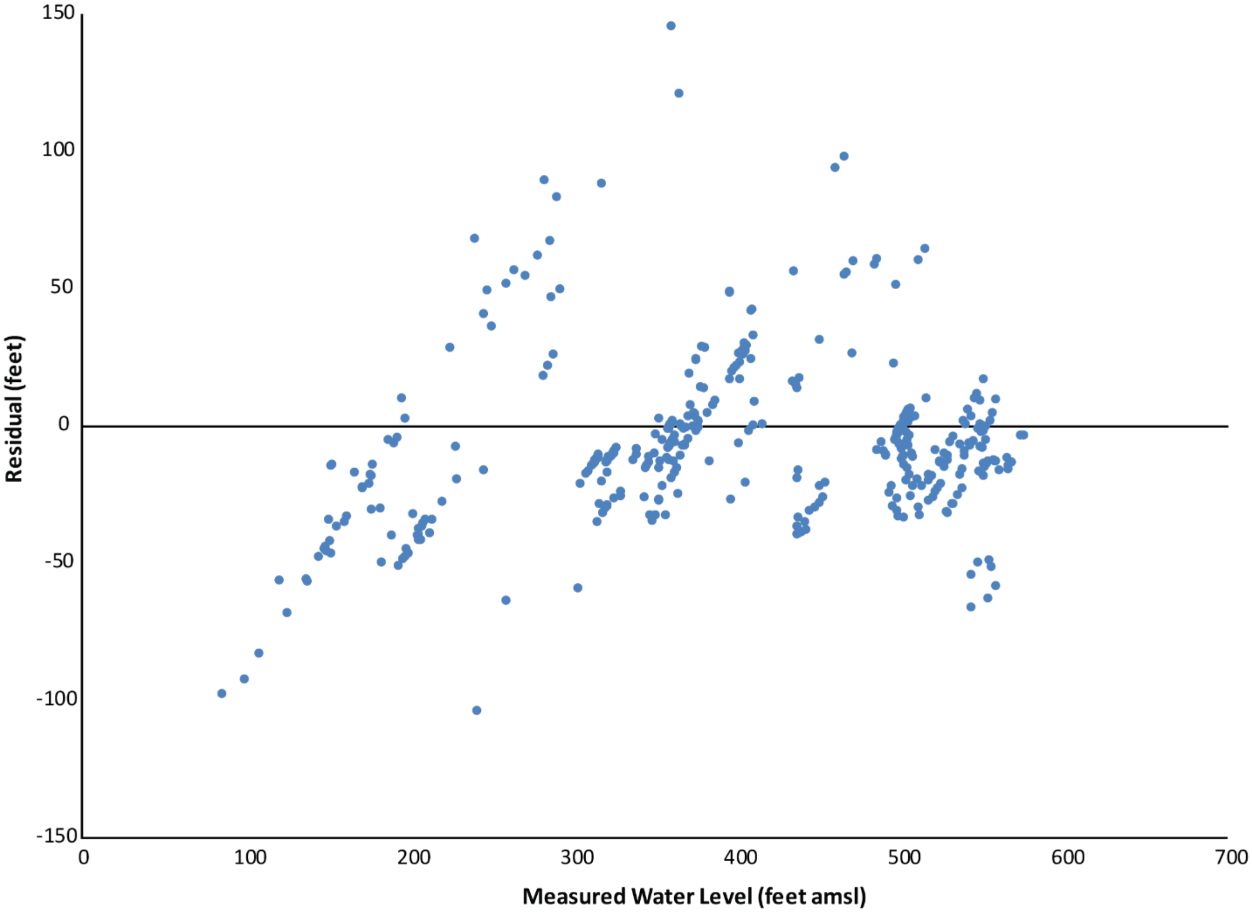

FIGURE 18 MEASURED WATER LEVELS VERSUS MODEL RESIDUALS.

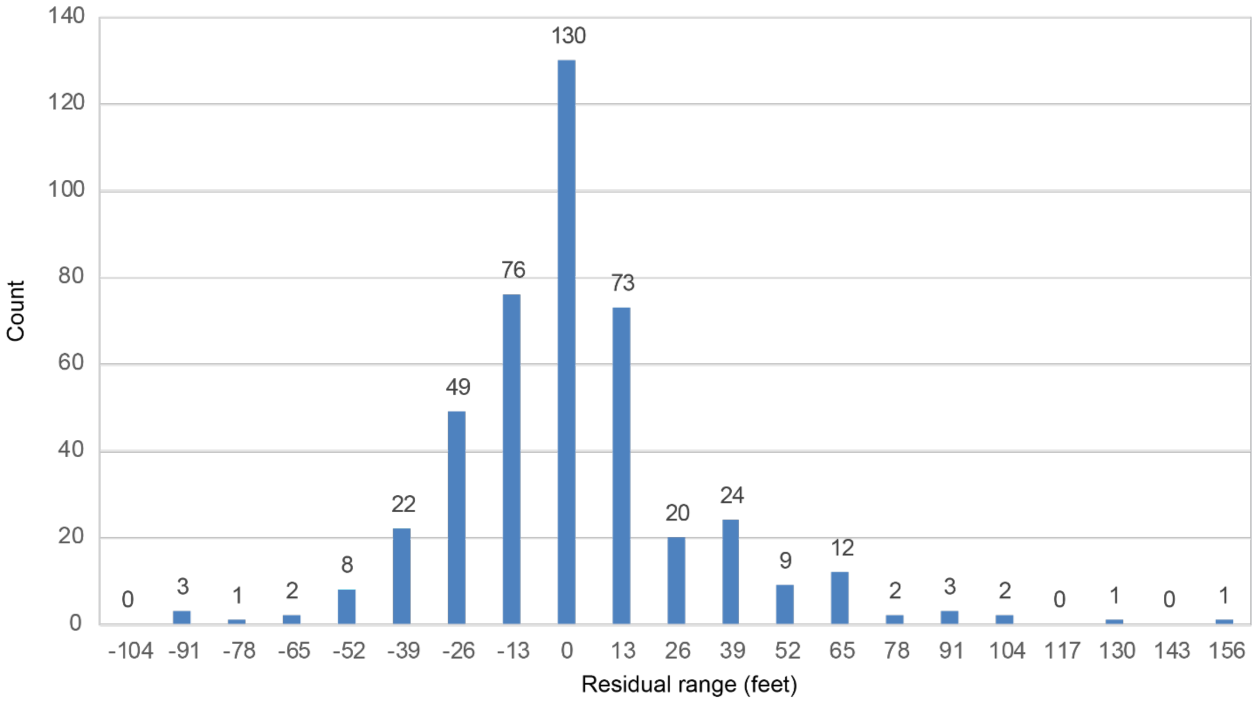

FIGURE 19 HISTOGRAM OF MODEL RESIDUALS.

Hydrographs

Ten wells in the study area include multiple water level measurements through time. We extracted and compared modeled water levels at those ten wells to evaluate how well the model responds to changing recharge and pumping through time (Figures 20 through 22).

For two subcrop wells in Lamar County the model calculated water levels match the measured values fairly well and are mostly within about 10 feet (Figure 20). However, modeled water levels at an outcrop well are about 60 to 70 feet too high. Modeled water levels at three subcrop wells in Red River County generally match the trends of the observations, but the model does not reproduce the amount of fluctuation seen in the data (Figure 21). Regional models with large grid cells will not necessarily be able to reproduce the fluctuations seen at pumping centers. Water levels through time at four wells in Bowie County are relatively level through time and the modeled water levels reproduce the flat trend and are within about fifteen feet of the observed water levels (Figure 22).

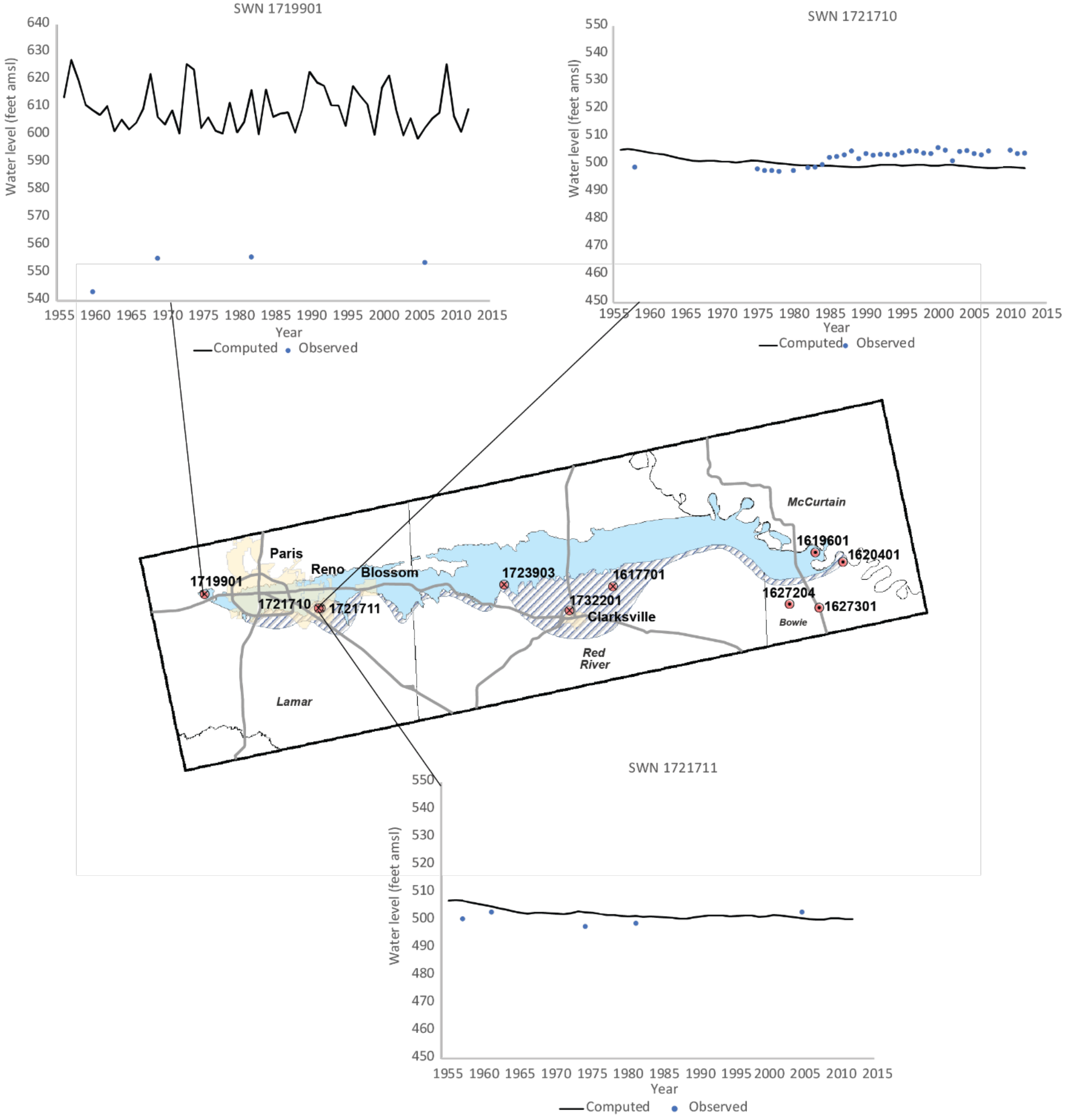

FIGURE 20 COMPARISON OF MODELED TO MEASURED HYDROGRAPHS FOR THREE WELLS IN LAMAR COUNTY.[4]

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[4] Observed water levels were extracted from the TWDB Groundwater database (TWDB, 2015).

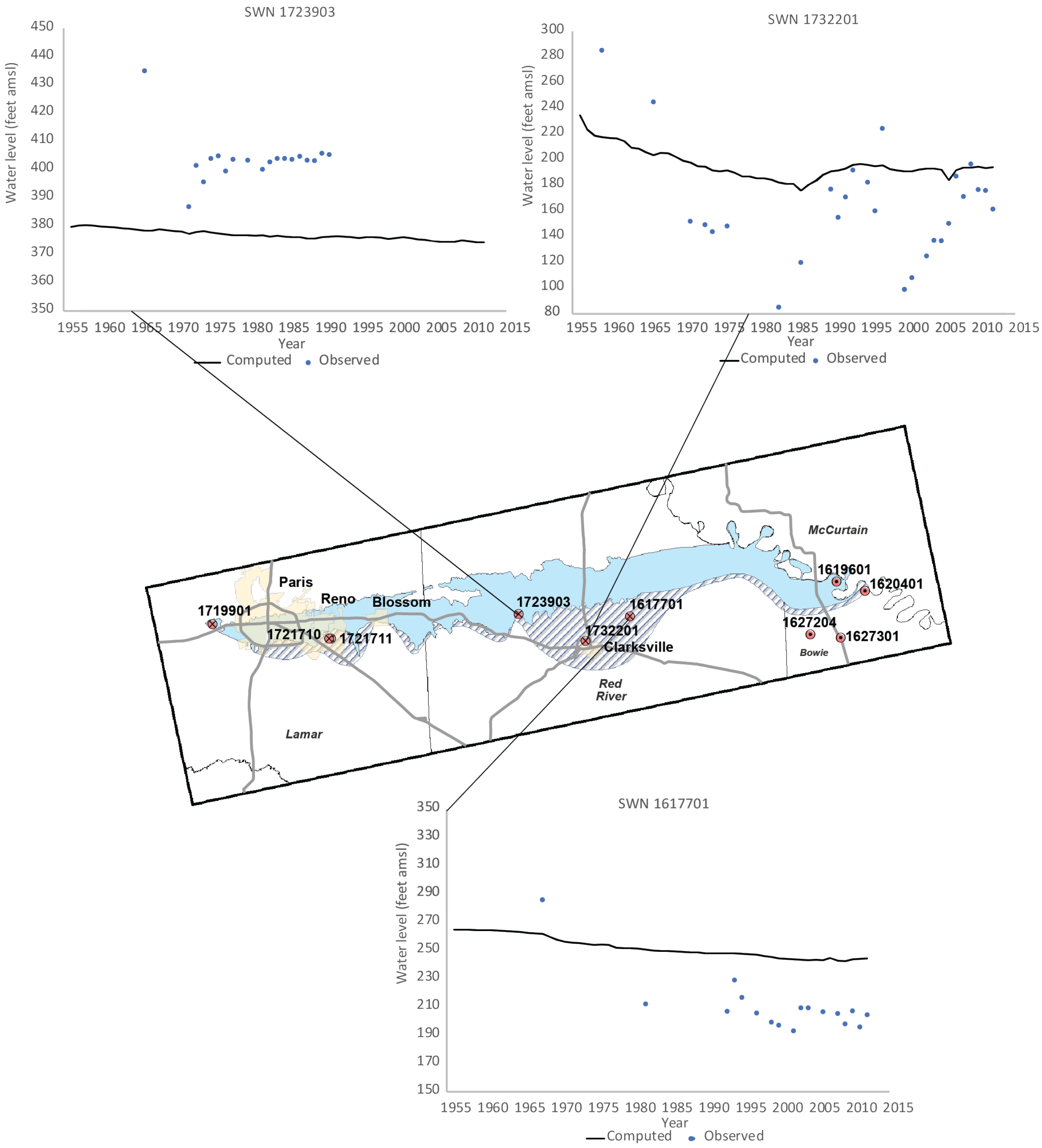

FIGURE 21 COMPARISON OF MODELED TO MEASURED HYDROGRAPHS FOR THREE WELLS IN RED RIVER COUNTY[5].

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[5] Observed water levels were extracted from the TWDB Groundwater database (TWDB, 2015).

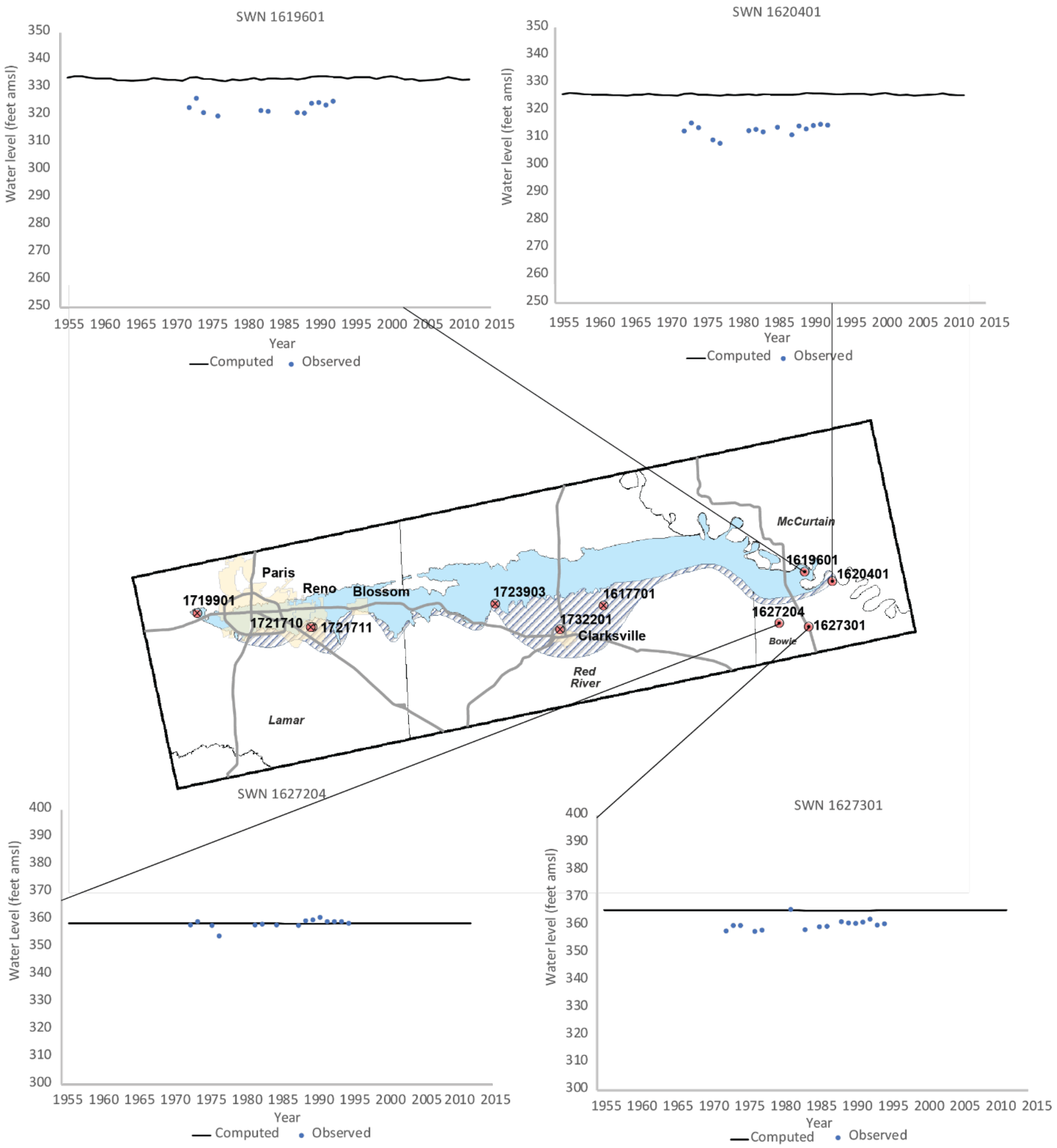

FIGURE 22 COMPARISON OF MODELED TO MEASURED HYDROGRAPHS IN FOR FOUR WELLS BOWIE COUNTY[6].

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[6] Observed water levels were extracted from the TWDB Groundwater database (TWDB, 2015).

Groundwater Levels and Flow Direction

To compare the modeled groundwater flow directions to our conceptual understanding of the flow system (Wade and others, 2022) we plotted maps of simulated groundwater levels and flow directions in 1982 (Figures 23 and 24) and for 2012 the last year of the calibration (Figures 25 and 26). The flow directions were derived from the cell-by-cell flow output from MODFLOW using Groundwater Vistas Version 7 (Rumbaugh and Rumbaugh, 2017). The simulated flow directions in the Red River alluvium (layer 1; Figures 23 and 25) suggest the Red River is gaining in the model area.

In layer 1 the groundwater flow is principally toward Pecan Bayou and the Red River (Figures 23 and 25). In layer 3 (Figures 24 and 26) the simulated groundwater flows from the outcrop southward to the downdip boundary. In central Red River County, the groundwater flow is slightly diverted toward the pumping center (Figures 24 and 26).

3.3 Model Simulated Water Budgets

Evaluation of the simulated water budget helps to verify that the model is consistent with our conceptual understanding of the regional groundwater flow and regional recharge and discharge. For a groundwater system near equilibrium prior to development (prior to groundwater pumping for irrigation or other human use) groundwater inflow equals groundwater outflow and little change in storage occurs over time.

Introduction of pumping wells can result in 1) storage decline (lowered groundwater levels), 2) induced flow such as increased surface water recharge, and/or 3) captured natural outflow such as decreased springflow, river baseflow, or evapotranspiration. Bredehoeft (2002) noted that understanding the dynamic response of a groundwater system under pumping stress comes 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 can be used to help understand capture. Output from the model includes estimates of the various components of the water budget. The numerical model can be used to investigate the effects of increased future development on the regional water budget. It is important to note though that predictions outside the range of historical stresses are more uncertain and that models should also be updated to reflect new data as it becomes available.

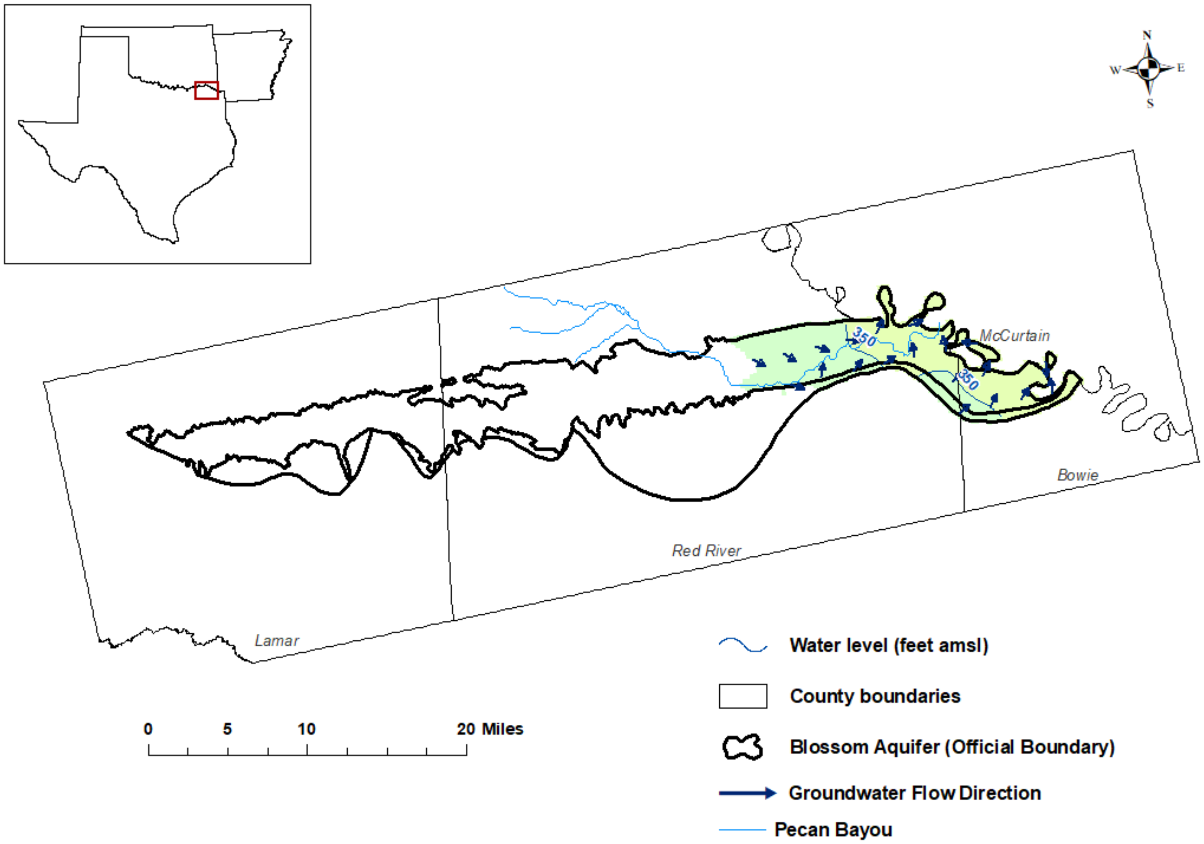

FIGURE 23 SIMULATED GROUNDWATER FLOW DIRECTIONS AND POTENTIOMETRIC ELEVATIONS IN LAYER 1 IN 1982.

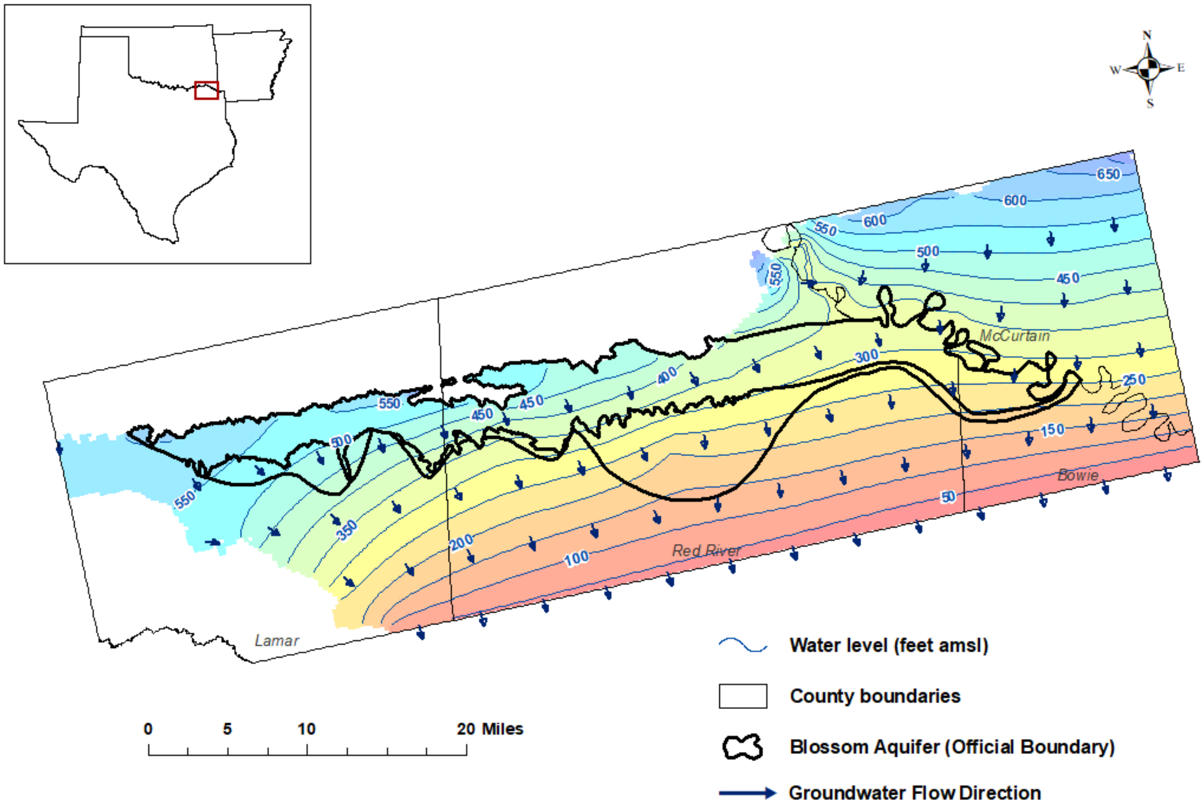

FIGURE 24 SIMULATED GROUNDWATER FLOW DIRECTIONS AND POTENTIOMETRIC ELEVATIONS IN LAYER 3 IN 1982.

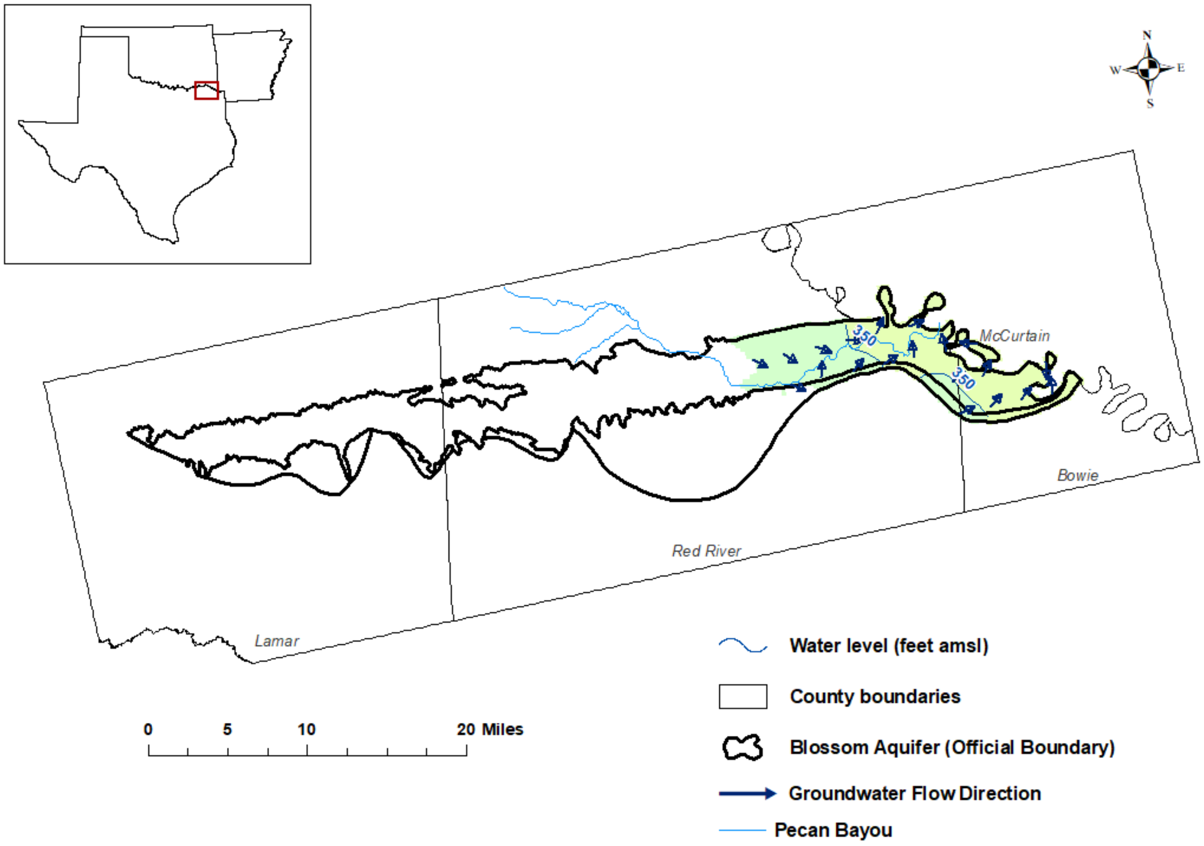

FIGURE 25 SIMULATED GROUNDWATER FLOW DIRECTIONS AND POTENTIOMETRIC ELEVATIONS IN LAYER 1 IN 2012.

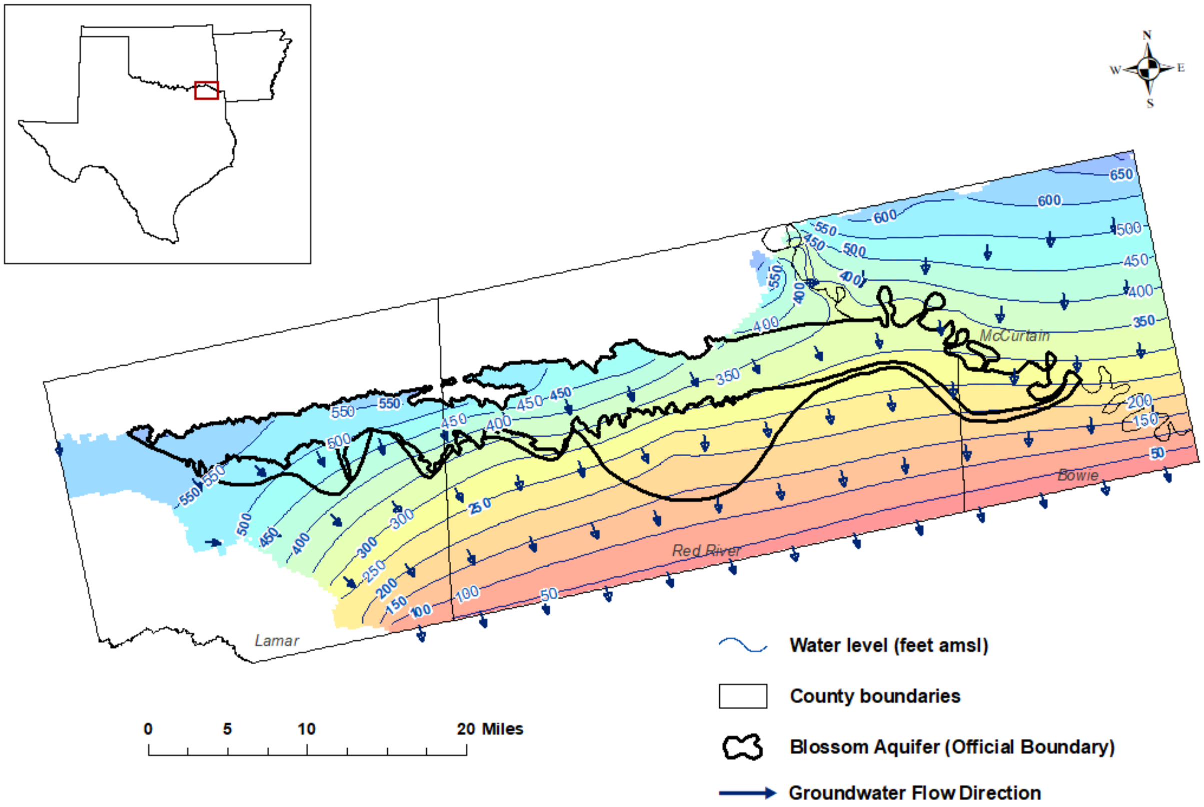

FIGURE 26 SIMULATED GROUNDWATER FLOW DIRECTIONS AND POTENTIOMETRIC ELEVATIONS IN LAYER 3 IN 2012.

We extracted the overall and county water budgets (Tables 11 and 12) from the groundwater model cell-by-cell output with ZONEBUDGET Version 3.01 (Harbaugh, 2009). The budgets include the following components: recharge, general-head boundaries, rivers, drains, pumping, and storage change. The county budgets also include lateral flow to and from other counties. Inflow and outflow components contribute groundwater to or take groundwater away from the aquifers in the model domain, respectively. The groundwater inflow (Tables 11 and 12) is mostly from recharge due to precipitation and the general-head boundary in Layer 2. Note the rainfall hydrographs for Paris and Clarksville indicate that 1957 was a very wet year in the model area (Wade and others, 2022). The outflow components include (in descending order of flow magnitude): general-head boundary discharge in Layers 2 and 3, discharge to rivers, pumping, and discharge to drains. The relatively large increase in storage for 1957 indicates a water level rise resulting from greater than average recharge for 1957. The relatively small average change in storage from 1957 to 2012 indicates insignificant net change in overall water levels over the time period.

TABLE 11 SUMMARY OF OVERALL ANNUAL GROUNDWATER BUDGET FOR THE MODEL IN ACRE-FEET PER YEAR. POSITIVE STORAGE CHANGE INDICATES WATER LEVEL RISE AND NEGATIVE STORAGE CHANGE INDICATES WATER LEVEL DECLINE.

Flow components	1957	1982	2012	Average 1957 through 2012
Recharge Inflow	40,948	34,587	28,218	26,639
River Leakage Inflow	2,530	2,579	2,593	2,581
General-head Boundary (ghb) Inflow	26,991	27,025	27,031	27,018
Total Inflow	**70,469**	**64,191**	**57,842**	**56,238**
Wells	498	985	1,094	805
Drain Outflow	33	20	19	20
River Discharge Outflow	19,194	16,033	14,787	15,213
General-head Boundary (ghb) Outflow	41,496	41,029	40,965	41,122
Total Outflow	**61,221**	**58,067**	**56,865**	**57,160**
Total Inflow - Total Outflow	9,248	6,124	977	-922
Storage change	9,245	6,123	979	-923

TABLE 12 SUMMARY OF AVERAGE 1975 THROUGH 2012 GROUNDWATER BUDGET IN ACRE-FEET PER YEAR. POSITIVE STORAGE CHANGE INDICATES WATER LEVEL RISE AND NEGATIVE STORAGE CHANGE INDICATES WATER LEVEL DECLINE.

Flow components	Bowie County	Lamar County	Red River County	Oklahoma
Recharge	3,287	1,723	12,529	9,072
River Leakage Inflow	444	0	155	1,983
Inflow from general-head boundary (layer 2)	3,601	6,169	16,859	390
Inflow from surrounding counties	9,811	130	4,562	8,260
Total Inflow	**17,143**	**8,022**	**34,105**	**19,705**
Wells	89	52	679	0
Drain Outflow	0	0	20	0
River Discharge Outflow	2,944	0	7,031	5,219
Outflow to General-head Boundary (layer 2)	3,721	6,069	15,946	2,553
Outflow to General-head Boundary (Layer 3)	4,871	950	7,006	0
Outflow to surrounding counties	5,554	1,091	4,099	12,020
Total Outflow	**17,179**	**8,162**	**34,781**	**19,792**
Total Inflow - Total Outflow	-36	-140	-676	-87
Storage change	-37	-139	-675	-88

The modeled recharge inflow fluctuates through time and is based on the annual variation of precipitation (Figure 27). The model responds to increasing recharge with inflow to storage (water levels rise) and increased discharge to the rivers and general-head boundaries. Pumping to wells varies somewhat through time based on historical use information. Net inflow from the general-head boundaries shows little variation through time (Figure 27).

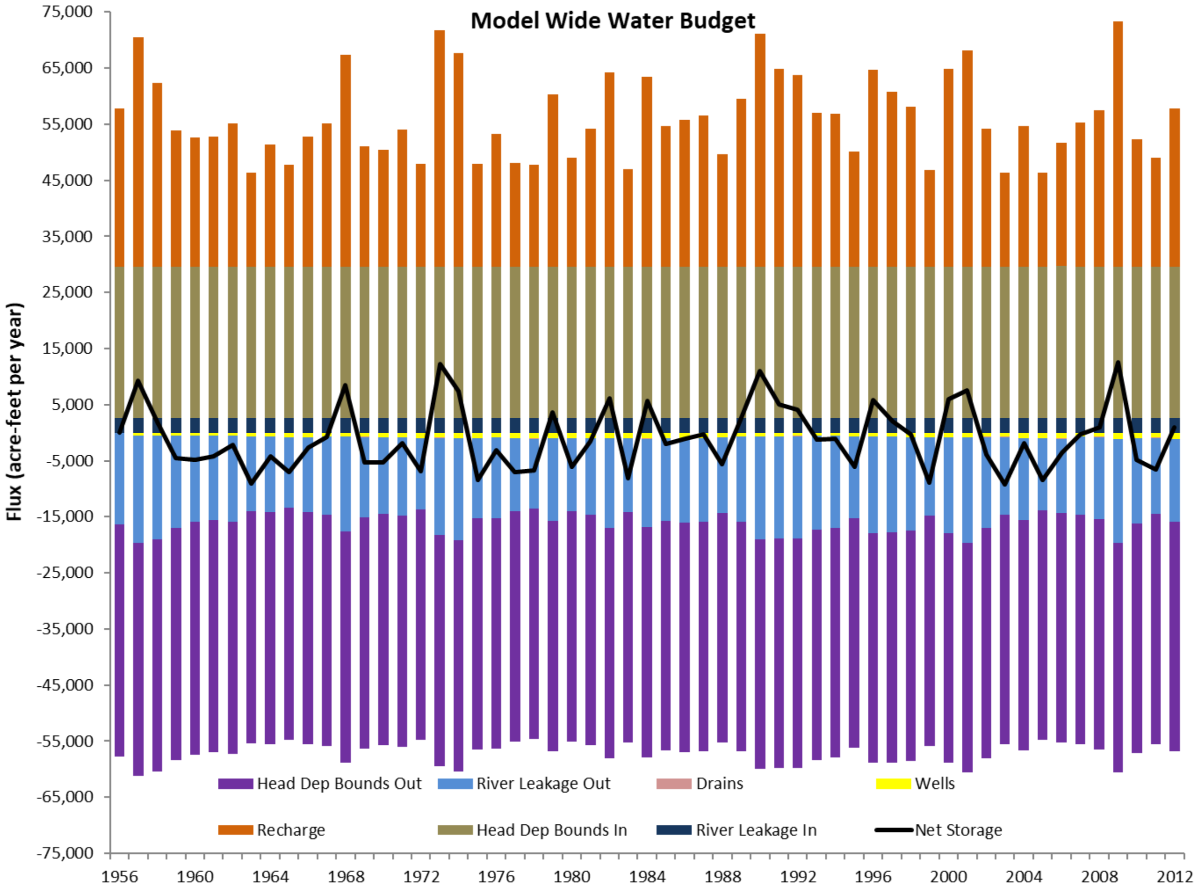

FIGURE 27 OVERALL MODEL WIDE GROUNDWATER BUDGET BY YEAR FOR THE MODEL IN ACRE-FEET PER YEAR.[7]

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[7] For display purposes the sign for net storage change for the water budget charts and tables have been reversed, so that positive storage change in the chart indicates rising water levels. Positive storage change in ZONEBUDGET output indicates declining water levels.

4.0 SENSITIVITY ANALYSIS

Sensitivity analyses are useful for comparing the relative uncertainty in model predictions caused by uncertainty in various model parameters. Parameter values are usually varied one at a time within a specified range. The results of the sensitivity analysis can be reported as the effect of the parameter change on either all water levels in the model or on water levels at the calibration targets. It is important to note that in addition to uncertainty in model parameter values there is also uncertainty in model design (Freeze and others, 1990). Model geometry, and stratigraphy and sources of recharge and discharge all have associated uncertainty.

4.1 Sensitivity Analysis Procedure

For the sensitivity analysis we adjusted 17 parameters over either one or two orders of magnitude (Table 13) while all other model parameters were held at their calibrated values. For all 17 sensitivity analyses we ran the model then calculated and plotted the average change in head values for all targets using equation 4.1 (Figures 28 and 29).

Change in head (feet) = Sensitivity Run Target Head – Calibrated Model Target Head (4.1)

Horizontal and vertical hydraulic conductivity were adjusted at four levels over two orders of magnitude (Table 13 and Figure 28). Initially model-wide hydraulic conductivity values were adjusted to 10, 50, 200, and 1,000 percent of their calibrated values. All other model parameters were held at their calibrated values. However, for the horizontal hydraulic conductivity of Layer 3, the model runs set at 200 and 1,000 percent of their calibrated values would not converge. Scaling factors were reduced to get a range (120 and 150 percent) over which all model runs would converge (Table 13 and Figure 28).

Storage properties, recharge, river conductance, general-head boundary head and conductance, and pumping were adjusted to 20, 50, 80, 120, 150, and 200 percent of their calibrated value while all other model parameters were held at their calibrated value (Table 13 and Figure 29).

4.2 Results of Sensitivity Analysis

The sensitivity analysis results indicate that the model is most sensitive to horizontal hydraulic conductivity of layer 3, recharge, and downdip general-head boundary (Figures 28 and 29). The model is slightly sensitive to vertical hydraulic conductivity of layer 2, pumping, and specific yield of layer 3. The other parameters are relatively insensitive (Figures 28 and 29).

When recharge was adjusted to 20 percent and 80 percent of the calibrated value the model runs would not converge; therefore, the sensitivity plot for recharge is asymmetric and is shown with a dashed line below 100 percent (Figure 29).

TABLE 13 PARAMETER ADJUSTMENT FACTORS FOR SENSITIVITY ANALYSES.

Sensitivity	Layer	Parameter	Zones	Run1	Run2	Run3	Run4	Run5	Run6	Run7
1	1	Kx1	1	na	0.1	0.5	1	2	10	na
2	2	Kx2	2, 4	na	0.1	0.5	1	2	10	na
3	3	Kx3	3, 5, 6, 7, 8	na	0.1	0.5	1	1.2	1.5	na
4	1	Kz1	1	na	0.1	0.5	1	2	10	na
5	2	Kz2	2, 4	na	0.1	0.5	1	2	10	na
6	3	Kz3	3, 5, 6, 7, 8	na	0.1	0.5	1	2	10	na
7	1	Ss1	1	0.2	0.5	0.8	1	1.2	1.5	2
8	2	Ss2	2, 4	0.2	0.5	0.8	1	1.2	1.5	2
9	3	Ss3	3, 5, 6, 7, 8	0.2	0.5	0.8	1	1.2	1.5	2
10	1	Sy1	1	0.2	0.5	0.8	1	1.2	1.5	2
11	2	Sy2	2, 4	0.2	0.5	0.8	1	1.2	1.5	2
12	3	Sy3	3, 5, 6, 7, 8	0.2	0.5	0.8	1	1.2	1.5	2
13	all	recharge	na	0.2	0.5	0.8	1	1.2	1.5	2
14	all	river conductance	na	0.2	0.5	0.8	1	1.2	1.5	2
15	all	ghb head	na	0.2	0.5	0.8	1	1.2	1.5	2
16	all	ghb conductance	na	0.2	0.5	0.8	1	1.2	1.5	2
17	all	pumping	na	0.2	0.5	0.8	1	1.2	1.5	2

na: not applicable
Kx: horizontal hydraulic conductivity
Kz: vertical hydraulic conductivity
Ss: specific storage
Sy: specific yield
ghb: general-head boundary

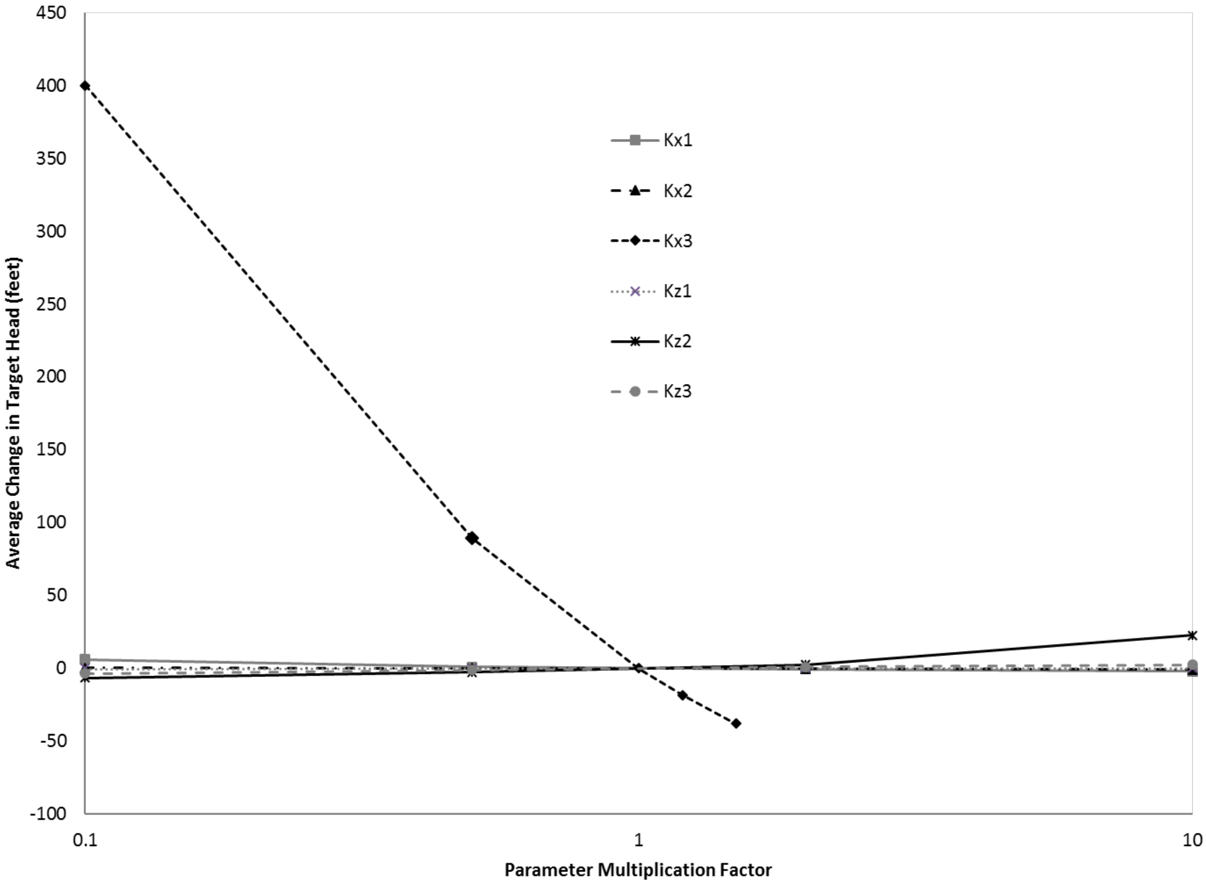

FIGURE 28 AVERAGE CHANGE IN TARGET HEAD (COMPARED WITH CALIBRATED MODEL) AS A FUNCTION OF VARIATION OF HYDRAULIC CONDUCTIVITY VALUES (SENSITIVITY ANALYSIS).

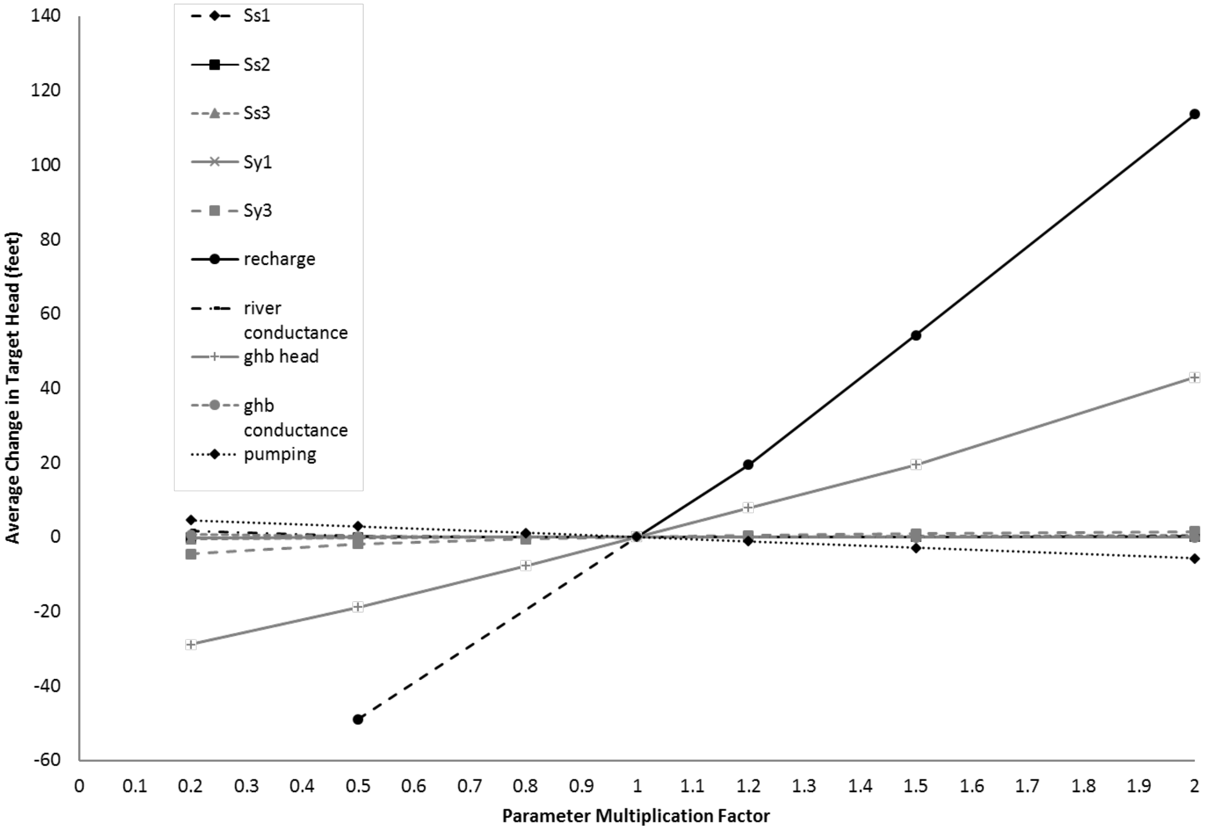

FIGURE 29 AVERAGE CHANGE IN TARGET HEAD (COMPARED WITH CALIBRATED MODEL) AS A FUNCTION OF VARIATION OF STORAGE AND OTHER PARAMETER VALUES (SENSITIVITY ANALYSIS).

5.0 PREDICTIVE SCENARIOS

One of the primary objectives of the groundwater availability model for the Blossom Aquifer is to estimate groundwater availability based on predictive pumping scenarios. In order to further test the Blossom Aquifer model, we simulated four predictive pumping scenarios. The first scenario extends 2012 pumping rates (1,100 acre-feet per year total) through 2070. The second scenario doubles pumping rates (2,200 acre-feet per year total) from 2013 through 2070. The second scenario pumping rate is approximately equal to the modeled available groundwater from the first round (2010) of joint groundwater planning (Bradley, 2011). The third and fourth scenarios triple and quadruple pumping rates respectively. For scenarios 2, 3, and 4 the pumping was scaled up at existing pumping locations. In all scenarios the pumping was uniformly scaled upward from 2013 through 2070 and average recharge was used from 2013 to 2070.

As expected, water level drawdowns from 2012 through 2070 for scenario 1 are minimal (Figure 30) because the predictive pumping rates were equal to the 2012 pumping rates. Scenario 2 (2,200 acre-feet per year) produces up to more than 40 feet of drawdown in the Blossom Aquifer in central Red River County after 58 years (Figure 31). Scenario 3 (3,300 acre-feet per year) produces drawdowns in the Blossom Aquifer of up to more than 80 feet (Figure 32) and Scenario 4 (4,400 acre-feet per year) produces drawdowns in the Blossom Aquifer of up to more than 140 feet (Figure 33) after 58 years in central Red River County. In Lamar and Bowie counties drawdowns in all scenarios are minimal (Figures 30 through 33).

Average drawdowns for each scenario are summarized for the entire layer 3 active model area in Table 14 and average drawdowns based on the official aquifer boundary are summarized for each county by confined and outcrop areas in Table 15.

For Scenario 1 the predictive water budget shows almost no variation through time (Figure 34) because average recharge is used in the scenario and the predictive pumping is equal to 2012 pumping rates. For Scenario 4, net water coming out of storage declines from 2013 through 2070 and groundwater discharge to rivers and the general-head boundary also decline over the same period (Figure 35). The water budget results suggest that initially the increased pumping (400 percent increase from 2012 to 2013) comes from storage, but through time that source is replaced by capturing water that previously discharged to surface water and downdip flow.

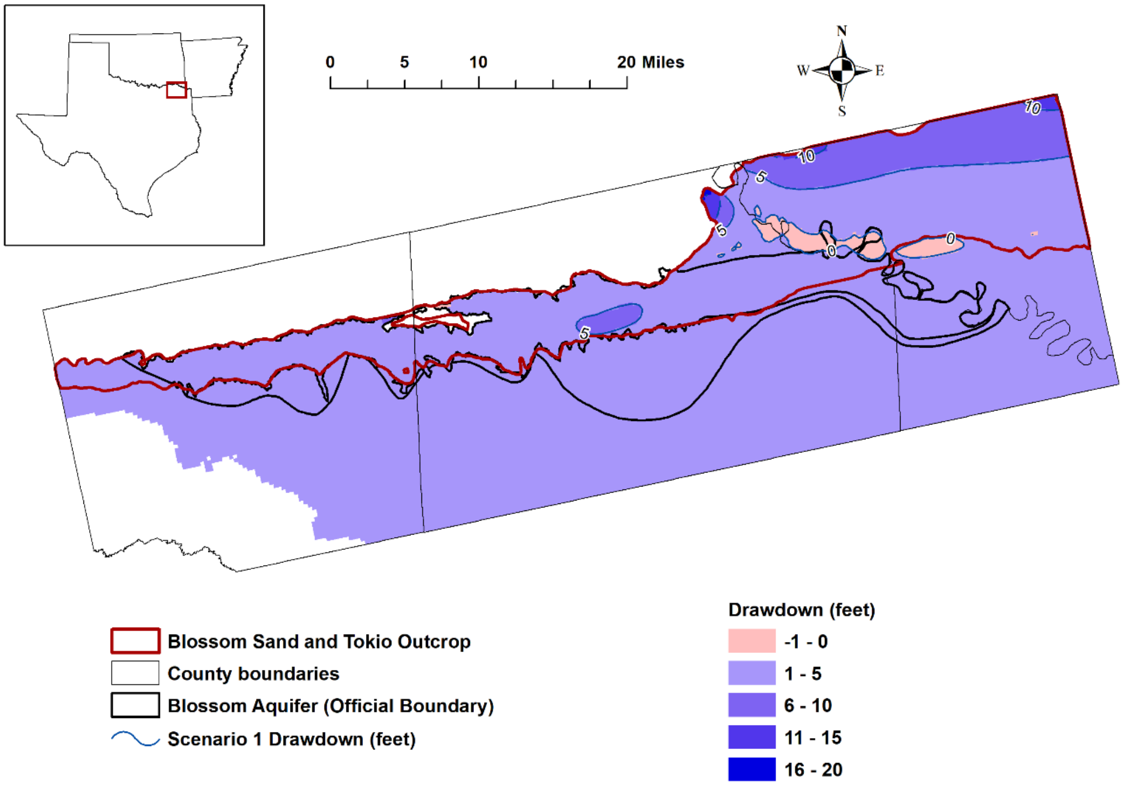

FIGURE 30 WATER LEVEL DRAWDOWN FOR LAYER 3 FROM 2012 THROUGH 2070 FOR SCENARIO 1 PUMPING SIMULATION.

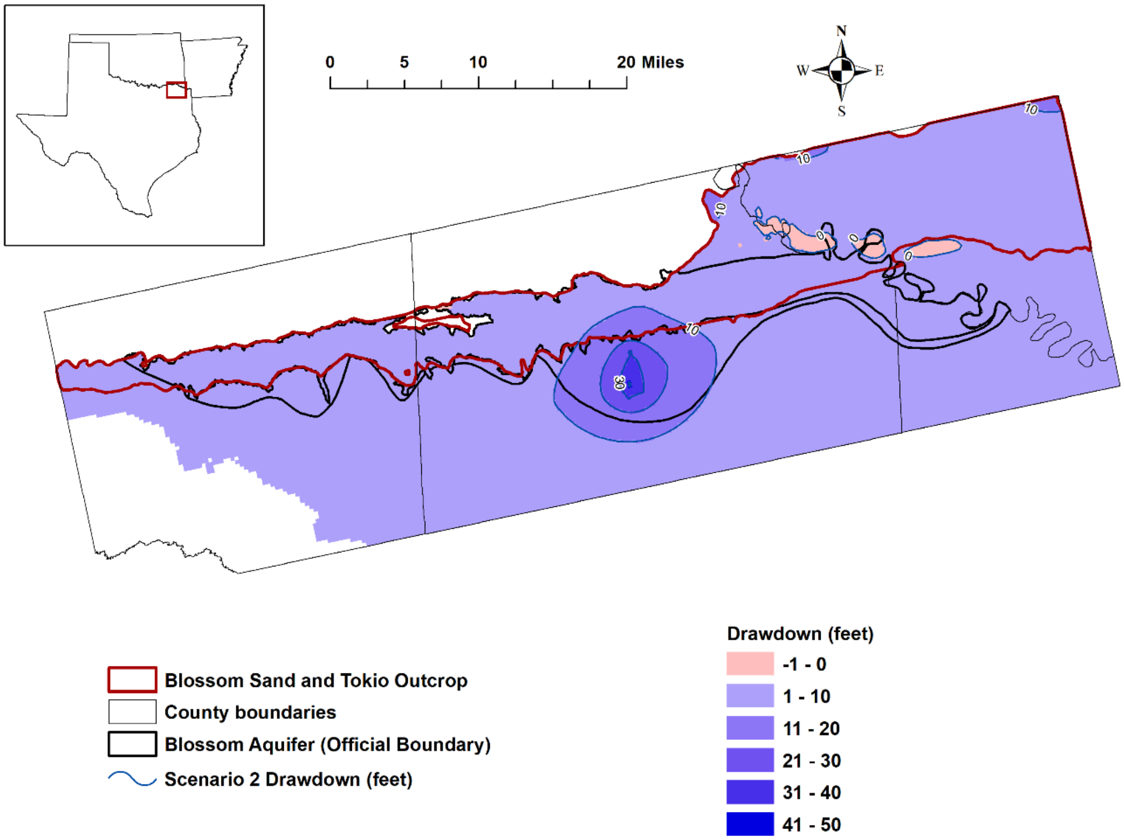

FIGURE 31 WATER LEVEL DRAWDOWN FOR LAYER 3 FROM 2012 THROUGH 2070 FOR SCENARIO 2 PUMPING SIMULATION.

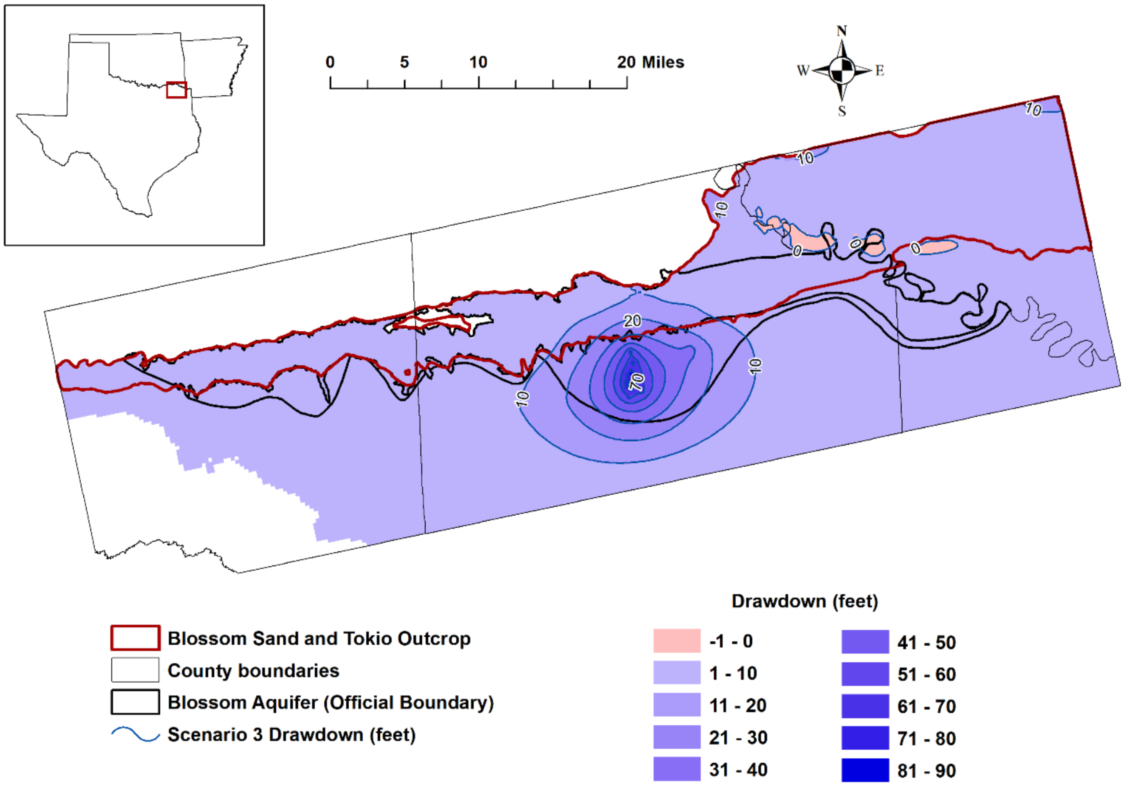

FIGURE 32 WATER LEVEL DRAWDOWN FOR LAYER 3 FROM 2012 THROUGH 2070 FOR SCENARIO 3 PUMPING SIMULATION.

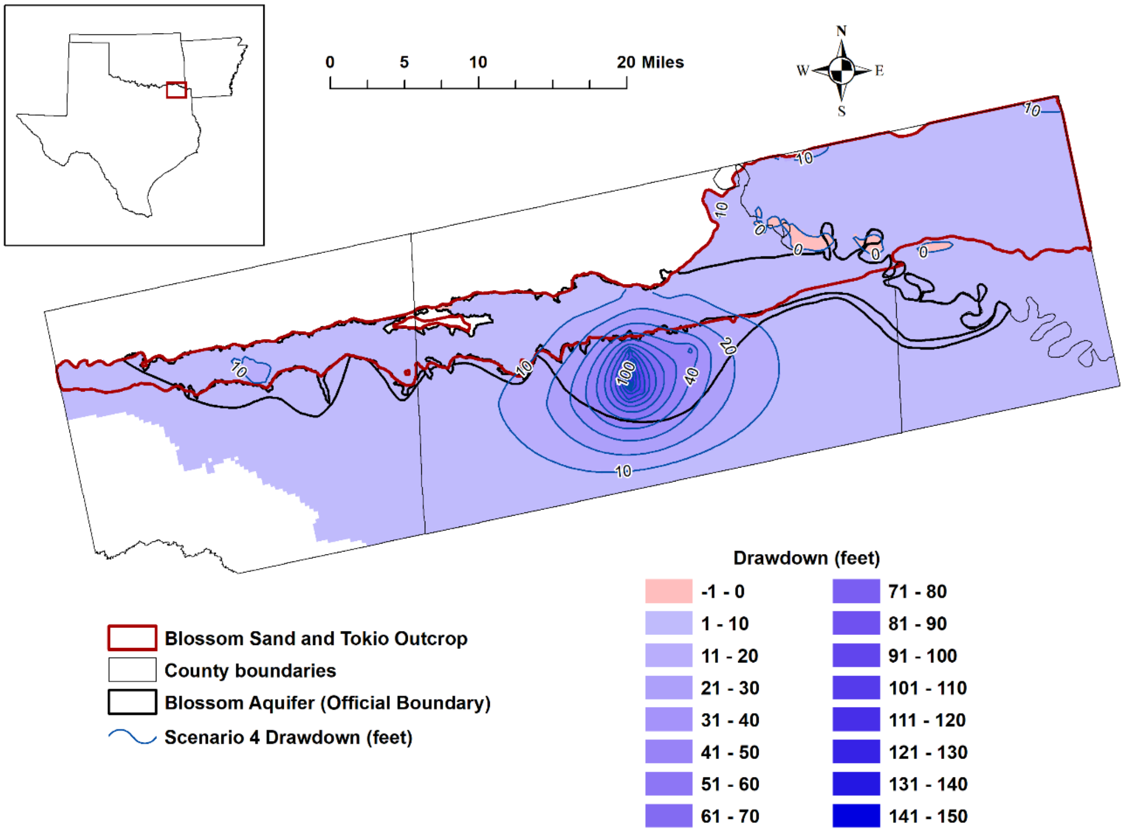

FIGURE 33 WATER LEVEL DRAWDOWN FOR LAYER 3 FROM 2012 THROUGH 2070 FOR SCENARIO 4 PUMPING SIMULATION.

TABLE 14 LAYER 3 AVERAGE DRAWDOWN IN FEET BY COUNTY AND BLOSSOM AQUIFER MODEL EXTENT OUTCROP AND CONFINED CONDITIONS.

County	Outcrop or confined	Area	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Bowie	Confined	90.4	0.7	0.8	0.9	0.9
Bowie	Outcrop[8]	14.9	1.0	1.1	1.3	1.5
Lamar	Confined	160.2	2.2	3.1	4.0	4.8
Lamar	Outcrop	58.1	2.5	3.5	4.4	5.3
Red River	Confined	340.6	1.3	5.9	10.6	15.3
Red River	Outcrop	128.9	2.3	3.9	5.4	6.7

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[8] Because the outcrop area in Bowie County is defined based on the official TWDB aquifer boundary and the Blossom Sand (layer 3) is actually completely confined in Bowie County, the areas for Bowie outcrop for both official aquifer boundary and model extent are the same.

TABLE 15 LAYER 3 AVERAGE DRAWDOWN IN FEET BY COUNTY AND BLOSSOM AQUIFER (OFFCIAL BOUNDARY ONLY) OUTCROP AND CONFINED CONDITIONS.

County	Outcrop or confined	Area	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Bowie	Confined	4.4	1.1	1.2	1.3	1.5
Bowie	Outcrop[9]	14.9	1.0	1.1	1.3	1.5
Lamar	Confined	20.1	2.8	4.1	5.4	6.7
Lamar	Outcrop	48.1	2.6	3.7	4.8	5.8
Red River	Confined	70.5	2.2	14.8	27.6	40.6
Red River	Outcrop	116.9	2.1	3.9	5.5	7.0

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[9] Because the outcrop area in Bowie County is defined based on the official TWDB aquifer boundary and the Blossom Sand (layer 3) is actually completely confined in Bowie County, the areas for Bowie outcrop for both official aquifer boundary and model extent are the same.

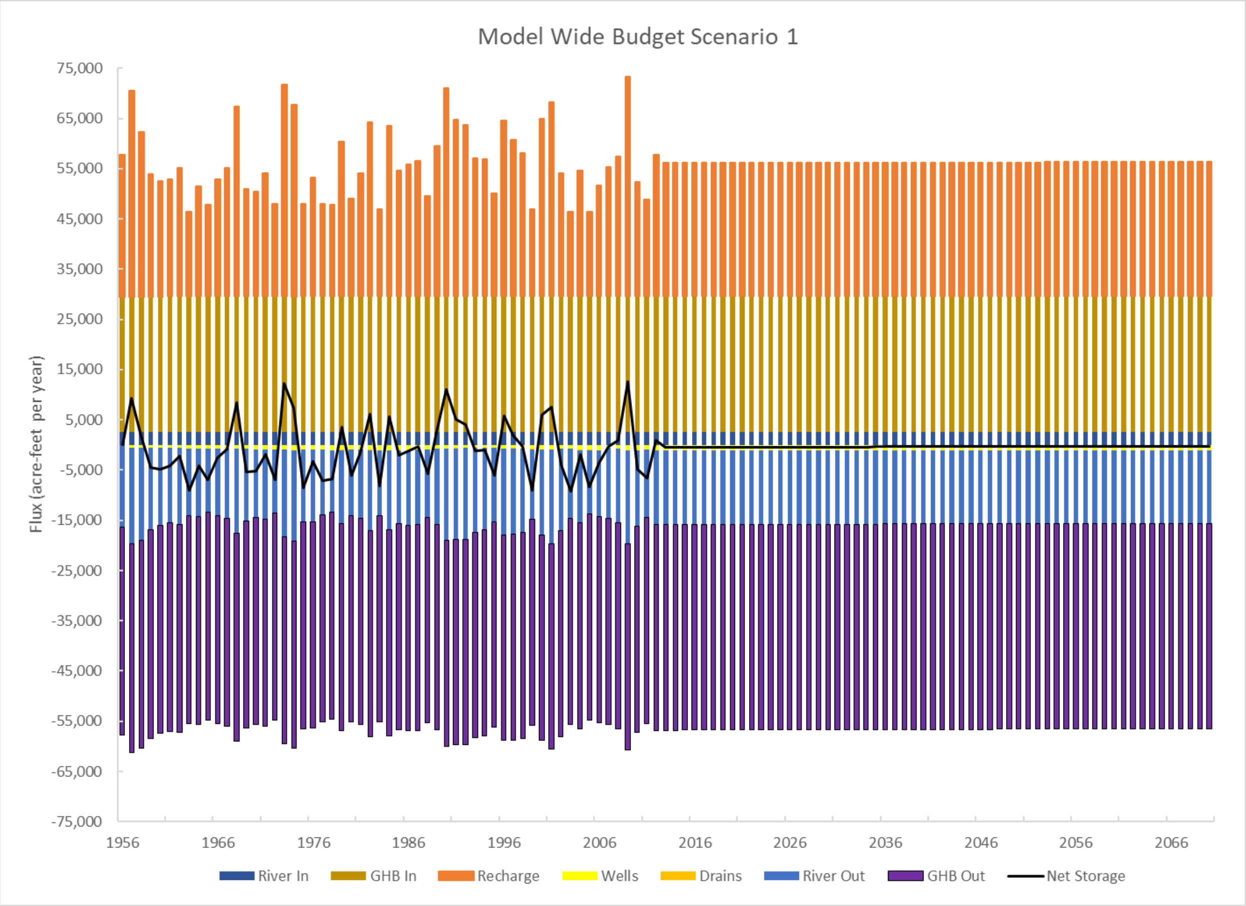

FIGURE 34 MODEL WIDE WATER BUDGET FOR PREDICTIVE SCENARIO 1.[10]

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[10] For display purposes the sign for net storage change for the water budget chart has been reversed, so that positive storage change in the chart indicates rising water levels.

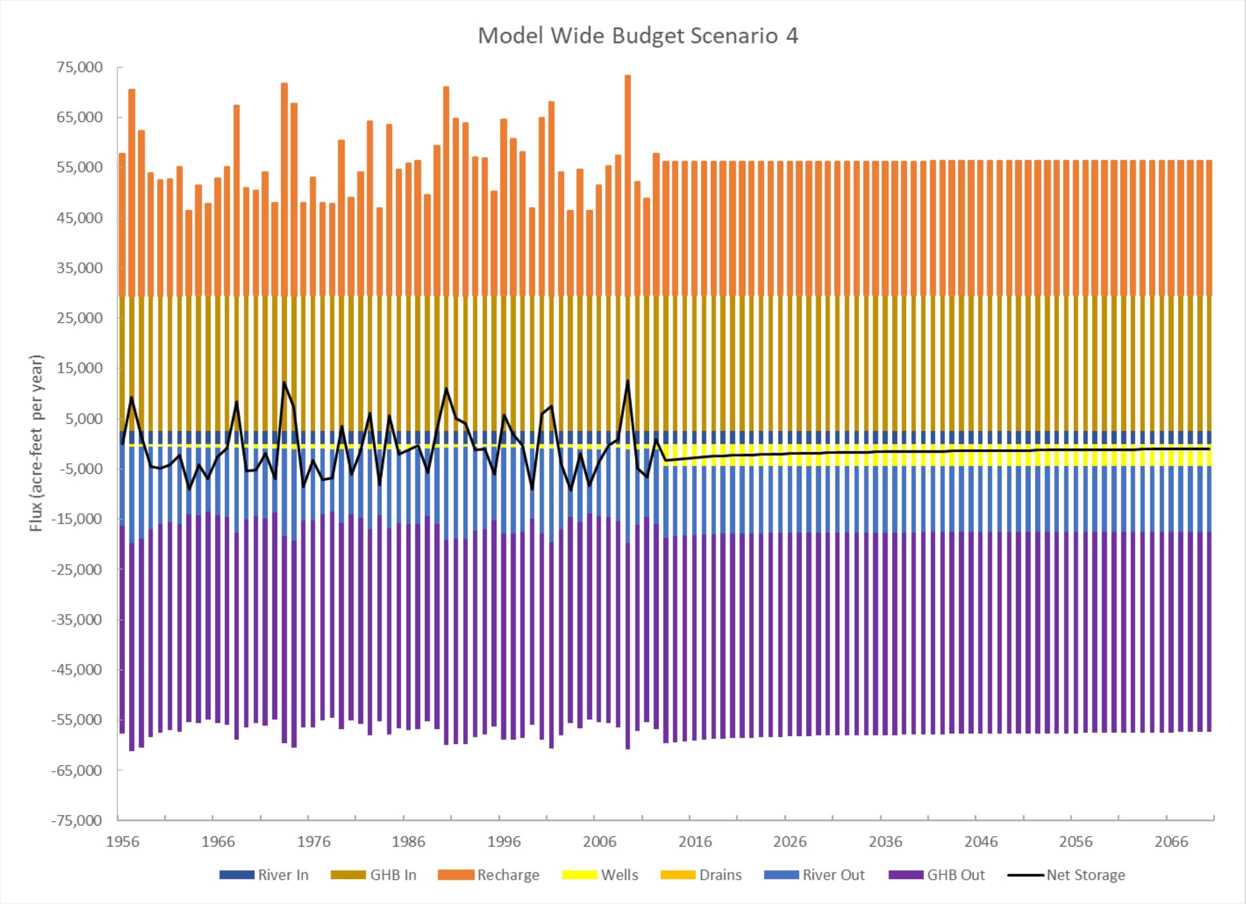

FIGURE 35 MODEL WIDE WATER BUDGET FOR PREDICTIVE SCENARIO 4.[11]

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[11] For display purposes the sign for net storage change for the water budget chart has been reversed, so that positive storage change in the chart indicates rising water levels.

6.0 MODEL LIMITATIONS

Numerical groundwater flow models are approximate representations of aquifer systems (Anderson and Woessner, 1992), and as such have limitations. These limitations are usually associated with (1) the purpose for the groundwater flow model, (2) the extent of the understanding of the aquifer(s), (3) the quantity and quality of data used to constrain parameters in the groundwater flow model, and (4) assumptions made during model development. Models are best viewed as tools to help form decisions rather than as machines to generate truth or make decisions. The National Research Council (2007) concluded that scientific advances will never make it possible to build a perfect model that accounts for every aspect of reality or be able to prove that a given model is correct in all respects for a particular application.

The nature of regional groundwater flow models affects the scale of application of the model. This model is most accurate in assessing subregional-scale groundwater issues, such as predicting aquifer-wide water level changes and trends over the next 50 years that may result from different proposed water management strategies. Accuracy and applicability of the model decreases when using it to address more local-scale issues because of limitations of the information used in model construction and the model cell size that determines spatial resolution of the model. Consequently, this model is not likely to accurately predict water level declines associated with a single well because (1) these water level declines depend on site-specific hydrologic properties not included in detail in regional- and subregional-scale models, and (2) the cell size used in the model is too large to resolve changes in water levels that occur over relatively short distances. Addressing local-scale issues requires a more detailed model, with local estimates of hydrologic properties, or an analytical model. This model is more useful in determining the impacts of groups of wells distributed over many square miles. The model predicts changes in ambient water levels rather than actual water level changes at specific locations, such as an individual well. These scale limitations are especially true in the outcrop portion of the Blossom Aquifer model because the fit to hydrographs in the outcrop is not as good as the fit in the subcrop portions of the model. In addition, some outcrop grid cells are flooded in the calibrated model. These two issues suggest the model will not do as good a job at predicting water levels in the outcrop.

A key aspect of using the groundwater model to evaluate historical groundwater flow conditions includes the assumptions about the location in the aquifer where historical pumping was placed. In addition, assumptions regarding precipitation, recharge, and streamflow are specific to a particular historical time period. Actual streamflow responds swiftly to events and this model uses annual stress periods; therefore, high frequency short-time period stream interactions will not be captured by the model. The surface water groundwater interactions represented by the model are based on annual average conditions.

It is important to continue to monitor groundwater pumping and overall conditions of the aquifer. Because of the limitations of the groundwater model and the assumptions in this analysis, it is important that local groundwater managers and water utilities in Lamar, Red River, and Bowie counties work with the TWDB to refine this analysis in the future given the reality of how the aquifer responds to the actual amount and location of pumping now and in the future. Historical precipitation patterns also need to be placed in context as future climatic conditions, such as dry and wet year precipitation patterns, may differ and affect groundwater flow conditions.

7.0 FUTURE IMPROVEMENTS

The primary data used to calibrate the groundwater availability model for the Blossom Aquifer consisted of 438 water level measurements. Ideally, groundwater flow models should also be calibrated using independent measurements or estimates of groundwater discharge and/or groundwater flow velocity or age. This additional data would increase confidence in the model calibrated estimates for hydraulic conductivity and recharge because calibrated estimates based solely on water level data are strongly correlated. If possible future updates to the model should include groundwater age data or discharge estimates to better constrain recharge and hydraulic conductivity estimates.

Our analysis of hydraulic properties for the conceptual model was based on eight aquifer pumping tests and 24 specific capacity tests. However, the distribution of the hydraulic property estimates is not uniform and some areas of the aquifer outcrop and subcrop have no measurements (Wade and others, 2022; Figure 44) Additional aquifer tests, particularly multi-well tests, in areas with no data could reduce the uncertainty in the overall estimates of hydraulic properties and further constrain the model results.

In November of 2017 a contracted study was completed to identify potential brackish groundwater production areas for the Blossom Aquifer. Part of that study consisted of reviewing geophysical logs and delineating the top surface and bottom surface of the Blossom Aquifer (LBG-Guyton Associates, 2017). In 2019, the TWDB Brackish Resources Aquifer Characterization System group completed additional research to identify brackish groundwater production zones in or near the Blossom Aquifer (Andrews and Croskrey, 2019). Future updates to the Blossom Aquifer groundwater model should incorporate the information from these two studies.

8.0 ACKNOWLEDGEMENTS

This project would not have been possible without the support of several individuals and organizations. We are very grateful for the ongoing support of our TWDB Groundwater Division management, Cindy Ridgeway and Larry French. We also appreciate the expertise of Jerry Shi, Roberto Anaya, and Radu Boghici for their help with modeling and data analysis as well as report editing. This project has benefited from previous unpublished TWDB studies by Ali Chowdhury, Scott Hamlin, and Cindy Ridgeway (Chowdhury, 2010 and Ridgeway and Hamlin, 2005). We greatly appreciate the information their work provided for this report. We would also like to thank Wendell Davis of the Red River Water Supply Corporation for providing us with very helpful background information for the project. We appreciate Texas Parks and Wildlife Department staff at Daingerfield State Park for allowing us to use their meeting facilities for our first stakeholder advisory forum.

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Appendix A:
Simulated Heads and Measured Heads at Wells

TABLE A.1 WATER LEVEL TARGETS, SIMULATED VALUES AND RESIDUALS. AMSL=ABOVE MEAN SEA LEVEL.

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1617101	2	29	177	1959	4	381.80	376.98	4.82
1617102	2	26	178	1973	18	376.00	376.42	-0.42
1617102	2	26	178	2006	51	374.63	376.18	-1.55
1617103	2	30	177	1978	23	376.10	374.09	2.01
1617103	2	30	177	2006	51	376.07	374.34	1.73
1617104	3	28	170	1978	23	401.80	384.62	17.18
1617104	3	28	170	2006	51	408.85	384.14	24.71
1617105	2	31	178	1973	18	373.00	372.90	0.10
1617201	2	30	183	1973	18	374.00	370.26	3.74
1617201	2	30	183	1978	23	374.40	369.82	4.58
1617204	2	29	185	1978	23	368.60	368.80	-0.20
1617205	2	30	187	1978	23	369.90	366.26	3.64
1617206	2	30	185	1971	16	357.00	368.53	-11.53
1617206	2	30	185	1978	23	367.40	368.13	-0.73
1617206	2	30	185	2006	51	373.55	368.49	5.06
1617208	2	32	188	1989	34	378.00	363.84	14.16
1617208	2	32	188	2006	51	371.80	364.20	7.60
1617303	2	28	190	1978	23	365.10	364.28	0.82
1617401	3	31	171	1978	23	409.20	366.74	42.46
1617401	3	31	171	1982	27	408.60	366.54	42.06
1617402	3	34	172	1965	10	350.00	352.89	-2.89
1617402	3	34	172	1982	27	380.30	351.52	28.78

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1617402	3	34	172	1982	27	370.70	351.52	19.18
1617403	3	33	176	1973	18	375.00	350.77	24.23
1617403	3	33	176	1978	23	374.60	349.86	24.74
1617403	3	33	176	1982	27	378.50	349.58	28.92
1617404	2	37	176	2003	48	380.00	366.11	13.89
1617404	2	37	176	2006	51	353.18	365.70	-12.52
1617601	2	46	193	1979	24	367.00	373.77	-6.77
1617601	2	46	193	1982	27	360.90	373.77	-12.87
1617602	3	45	187	1982	27	281.50	263.04	18.46
1617701	3	47	169	1968	13	288.00	261.91	26.09
1617701	3	47	169	1968	13	284.00	261.91	22.09
1617701	3	47	169	1982	27	212.00	250.94	-38.94
1617701	3	47	169	1993	38	207.00	248.15	-41.15
1617701	3	47	169	1994	39	229.00	248.15	-19.15
1617701	3	47	169	1995	40	220.00	247.62	-27.62
1617701	3	47	169	1995	40	213.50	247.62	-34.12
1617701	3	47	169	1997	42	205.55	247.01	-41.46
1617701	3	47	169	1999	44	199.12	245.47	-46.35
1617701	3	47	169	2000	45	197.00	244.52	-47.52
1617701	3	47	169	2002	47	193.00	243.78	-50.78
1617701	3	47	169	2003	48	209.45	243.45	-34.00
1617701	3	47	169	2004	49	209.35	243.20	-33.85
1617701	3	47	169	2006	51	205.65	243.11	-37.46
1617701	3	47	169	2006	51	207.80	243.11	-35.31

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1617701	3	47	169	2007	52	205.38	244.82	-39.44
1617701	3	47	169	2009	54	197.90	242.58	-44.68
1617701	3	47	169	2010	55	207.24	243.71	-36.47
1617701	3	47	169	2011	56	195.75	244.16	-48.41
1617701	3	47	169	2012	57	204.55	244.36	-39.81
1617702	3	49	166	1982	27	286.10	238.89	47.21
1617702	3	49	166	2006	51	201.95	233.81	-31.86
1618402	2	44	203	1973	18	354.00	375.67	-21.67
1618403	2	47	202	1978	23	368.20	374.87	-6.67
1618404	2	46	203	1978	23	365.00	375.65	-10.65
1618405	2	46	197	1971	16	360.00	378.74	-18.74
1618405	2	46	197	1978	23	363.40	378.74	-15.34
1618406	2	46	196	1973	18	352.00	378.40	-26.40
1618406	2	46	196	1978	23	361.70	378.40	-16.70
1618407	2	47	197	2000	45	352.00	378.82	-26.82
1618407	2	47	197	2006	51	362.11	378.82	-16.71
1618501	1	42	211	1998	43	352.00	349.03	2.97
1618501	1	42	211	2006	51	338.59	346.75	-8.16
1618601	1	48	224	2006	51	314.50	349.45	-34.95
1618701	3	53	201	1959	4	359.80	213.97	145.83
1618702	3	48	203	1978	23	364.60	243.42	121.18
1618703	2	50	203	1978	23	368.10	374.88	-6.78
1618704	2	49	203	1978	23	370.00	374.62	-4.62
1619501	1	51	241	1970	15	321.00	337.89	-16.89

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1619501	1	51	241	2006	51	317.50	337.51	-20.01
1619601	1	50	245	1973	18	322.67	333.57	-10.90
1619601	1	50	245	1974	19	326.08	333.95	-7.87
1619601	1	50	245	1975	20	320.92	333.17	-12.25
1619601	1	50	245	1977	22	319.66	332.70	-13.04
1619601	1	50	245	1983	28	321.66	332.82	-11.16
1619601	1	50	245	1984	29	321.36	333.29	-11.93
1619601	1	50	245	1988	33	320.78	332.93	-12.15
1619601	1	50	245	1989	34	320.76	333.34	-12.58
1619601	1	50	245	1990	35	324.16	334.11	-9.95
1619601	1	50	245	1991	36	324.47	334.16	-9.69
1619601	1	50	245	1992	37	323.68	334.18	-10.50
1619601	1	50	245	1993	38	324.99	333.90	-8.91
1619701	1	55	228	2002	47	329.00	354.25	-25.25
1619701	1	55	228	2006	51	320.80	350.02	-29.22
1619702	1	53	228	2002	47	329.00	352.90	-23.90
1619702	1	53	228	2006	51	319.21	348.94	-29.73
1619703	1	52	227	2006	51	320.60	349.08	-28.48
1619704	1	52	227	1999	44	325.00	351.30	-26.30
1619803	1	57	239	2001	46	318.00	349.47	-31.47
1619803	1	57	239	2006	51	315.68	343.83	-28.15
1620401	1	56	254	1973	18	312.46	326.08	-13.62
1620401	1	56	254	1974	19	315.40	326.22	-10.82
1620401	1	56	254	1975	20	315.45	325.66	-10.21

State Well Number	**Layer**	**Row**	**Column**	**Year**	**Stress Period**	**Measured head (feet, amsl)**	**Simulated head (feet, amsl)**	**Residual (measured head - simulated head, feet)**
1620401	1	56	254	1975	20	311.90	325.66	-13.76
1620401	1	56	254	1977	22	309.21	325.43	-16.22
1620401	1	56	254	1978	23	307.93	325.32	-17.39
1620401	1	56	254	1982	27	312.60	325.99	-13.39
1620401	1	56	254	1983	28	313.10	325.51	-12.41
1620401	1	56	254	1985	30	312.18	325.79	-13.61
1620401	1	56	254	1986	31	313.83	325.75	-11.92
1620401	1	56	254	1988	33	311.06	325.58	-14.52
1620401	1	56	254	1989	34	314.26	325.89	-11.63
1620401	1	56	254	1990	35	313.13	326.35	-13.22
1620401	1	56	254	1991	36	314.43	326.31	-11.88
1620401	1	56	254	1992	37	314.92	326.28	-11.36
1620401	1	56	254	1993	38	314.63	326.07	-11.44
1625101	3	60	168	1960	5	240.00	171.61	68.39
1627101	2	65	226	1978	23	343.20	369.02	-25.82
1627102	2	64	224	1970	15	362.00	367.83	-5.83
1627102	2	64	224	1982	27	352.57	367.83	-15.26
1627201	2	69	234	1960	5	358.24	370.36	-12.12
1627204	2	67	231	1973	18	358.09	358.75	-0.66
1627204	2	67	231	1974	19	359.29	358.75	0.54
1627204	2	67	231	1976	21	357.90	358.75	-0.85
1627204	2	67	231	1977	22	354.05	358.75	-4.70
1627204	2	67	231	1982	27	358.09	358.75	-0.66
1627204	2	67	231	1983	28	358.46	358.75	-0.29

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1627204	2	67	231	1985	30	358.12	358.75	-0.63
1627204	2	67	231	1988	33	358.12	358.75	-0.63
1627204	2	67	231	1988	33	357.91	358.75	-0.84
1627204	2	67	231	1989	34	359.68	358.75	0.93
1627204	2	67	231	1990	35	360.00	358.75	1.25
1627204	2	67	231	1991	36	360.79	358.75	2.04
1627204	2	67	231	1992	37	359.34	358.75	0.59
1627204	2	67	231	1993	38	359.39	358.75	0.64
1627204	2	67	231	1994	39	359.35	358.75	0.60
1627204	2	67	231	1995	40	358.75	358.75	0.00
1627301	2	71	242	1973	18	357.98	365.67	-7.69
1627301	2	71	242	1974	19	359.91	365.67	-5.76
1627301	2	71	242	1975	20	360.54	365.67	-5.13
1627301	2	71	242	1975	20	359.33	365.67	-6.34
1627301	2	71	242	1977	22	357.73	365.67	-7.94
1627301	2	71	242	1978	23	358.20	365.67	-7.47
1627301	2	71	242	1982	27	365.72	365.67	0.05
1627301	2	71	242	1984	29	358.45	365.67	-7.22
1627301	2	71	242	1986	31	359.50	365.67	-6.17
1627301	2	71	242	1988	33	360.30	365.67	-5.37
1627301	2	71	242	1988	33	359.04	365.67	-6.63
1627301	2	71	242	1989	34	361.36	365.67	-4.31
1627301	2	71	242	1990	35	360.94	365.67	-4.73
1627301	2	71	242	1991	36	360.76	365.67	-4.91

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1627301	2	71	242	1992	37	361.10	365.67	-4.57
1627301	2	71	242	1993	38	362.21	365.67	-3.46
1627301	2	71	242	1994	39	360.05	365.67	-5.62
1627301	2	71	242	1995	40	360.52	365.67	-5.15
1628102	2	72	251	1960	5	349.73	359.45	-9.72
1628103	2	72	252	1960	5	346.14	357.05	-10.91
1628104	2	78	250	1973	18	344.00	359.17	-15.17
1628104	2	78	250	1974	19	345.02	359.17	-14.15
1628104	2	78	250	1982	27	346.20	359.17	-12.97
1628202	2	78	266	1982	27	338.50	348.56	-10.06
1628202	2	78	266	1982	27	336.40	348.56	-12.16
1719901	3	18	21	1960	5	543.18	609.03	-65.85
1719901	3	18	21	1969	14	555.40	606.58	-51.18
1719901	3	18	21	1982	27	558.20	616.41	-58.21
1719901	3	18	21	1982	27	553.60	616.41	-62.81
1719901	3	18	21	2006	51	553.81	602.73	-48.92
1720501	3	21	43	1982	27	575.10	578.17	-3.07
1720501	3	21	43	2006	51	573.40	576.84	-3.44
1720601	3	22	54	1982	27	554.50	552.44	2.06
1720601	3	22	54	1982	27	550.80	552.44	-1.64
1720601	3	22	54	2006	51	549.40	551.45	-2.05
1720701	3	22	30	1982	27	547.50	597.11	-49.61
1720701	3	22	30	1982	27	543.00	597.11	-54.11
1720801	3	21	40	1982	27	565.60	581.27	-15.67

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1720801	3	21	40	1982	27	565.80	581.27	-15.47
1720801	3	21	40	2006	51	566.04	580.42	-14.38
1720802	3	21	40	1982	27	568.20	581.27	-13.07
1720802	3	21	40	1982	27	568.20	581.27	-13.07
1720803	3	25	41	1982	27	556.60	568.78	-12.18
1720803	3	25	41	1982	27	550.90	568.78	-17.88
1720804	3	23	40	1982	27	564.80	576.33	-11.53
1720804	3	23	40	1982	27	560.20	576.33	-16.13
1720805	3	25	43	1982	27	553.60	566.20	-12.60
1720805	3	25	43	1982	27	549.50	566.20	-16.70
1720805	3	25	43	2006	51	550.40	564.05	-13.65
1720806	3	23	44	1982	27	558.00	570.66	-12.66
1720806	3	23	44	1982	27	557.80	570.66	-12.86
1720901	3	32	50	1959	4	498.20	530.83	-32.63
1720902	3	34	52	1959	4	493.30	517.28	-23.98
1720902	3	34	52	1982	27	501.20	512.32	-11.12
1720903	3	26	52	1982	27	522.60	545.28	-22.68
1720903	3	26	52	1982	27	519.50	545.28	-25.78
1720904	3	26	52	1982	27	524.60	545.28	-20.68
1720904	3	26	52	1982	27	521.50	545.28	-23.78
1720905	3	23	51	1982	27	552.30	557.32	-5.02
1720905	3	23	51	1982	27	549.70	557.32	-7.62
1720905	3	23	51	2006	51	548.70	556.17	-7.47
1720906	3	24	51	1982	27	538.00	553.52	-15.52

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1720906	3	24	51	1982	27	536.10	553.52	-17.42
1720907	3	23	47	1982	27	552.80	566.44	-13.64
1720907	3	23	47	1982	27	551.70	566.44	-14.74
1720907	3	23	47	2006	51	548.09	564.32	-16.23
1720908	3	24	48	1982	27	537.60	560.28	-22.68
1720908	3	24	48	1982	27	535.20	560.28	-25.08
1720909	3	24	48	1982	27	531.90	560.28	-28.38
1720909	3	24	48	1982	27	528.80	560.28	-31.48
1720910	3	33	51	1982	27	507.80	518.96	-11.16
1720910	3	33	51	1982	27	503.80	518.96	-15.16
1720910	3	33	51	2006	51	506.85	516.65	-9.80
1720911	3	32	51	1982	27	505.70	523.17	-17.47
1720911	3	32	51	1982	27	503.60	523.17	-19.57
1720912	3	26	45	1982	27	531.30	559.49	-28.19
1720912	3	26	45	1982	27	528.20	559.49	-31.29
1720913	3	27	51	1982	27	517.30	544.31	-27.01
1720913	3	27	51	1982	27	511.90	544.31	-32.41
1720913	3	27	51	2006	51	510.99	540.46	-29.47
1721401	3	24	63	1959	4	526.60	541.34	-14.74
1721402	3	24	62	1959	4	528.60	540.96	-12.36
1721402	3	24	62	1982	27	526.70	536.36	-9.66
1721402	3	24	62	1982	27	523.70	536.36	-12.66
1721403	3	23	62	1982	27	528.70	539.46	-10.76
1721403	3	23	62	1982	27	526.00	539.46	-13.46

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1721404	3	24	61	1982	27	523.90	536.88	-12.98
1721404	3	24	61	1982	27	518.90	536.88	-17.98
1721404	3	24	61	2006	51	516.97	536.46	-19.49
1721405	3	22	57	1982	27	541.90	548.03	-6.13
1721405	3	22	57	1982	27	539.00	548.03	-9.03
1721501	3	25	68	1982	27	531.90	535.75	-3.85
1721501	3	25	68	1982	27	529.90	535.75	-5.85
1721602	3	26	82	1960	5	502.10	535.23	-33.13
1721603	3	25	82	1982	27	543.10	539.26	3.84
1721603	3	25	82	1982	27	540.00	539.26	0.74
1721701	3	25	57	1960	5	536.50	542.92	-6.42
1721702	3	25	60	1960	5	548.50	539.24	9.26
1721702	3	25	60	1982	27	545.10	534.73	10.37
1721702	3	25	60	1982	27	546.60	534.73	11.87
1721710	3	32	62	1958	3	499.00	505.41	-6.41
1721710	3	32	62	1975	20	499.47	501.30	-1.83
1721710	3	32	62	1975	20	498.66	501.30	-2.64
1721710	3	32	62	1975	20	497.20	501.30	-4.10
1721710	3	32	62	1976	21	497.76	501.08	-3.32
1721710	3	32	62	1977	22	497.74	500.74	-3.00
1721710	3	32	62	1978	23	497.57	500.35	-2.78
1721710	3	32	62	1980	25	497.74	499.97	-2.23
1721710	3	32	62	1982	27	499.20	499.86	-0.66
1721710	3	32	62	1982	27	498.50	499.86	-1.36

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1721710	3	32	62	1983	28	499.11	499.62	-0.51
1721710	3	32	62	1984	29	500.00	499.70	0.30
1721710	3	32	62	1985	30	502.52	499.60	2.92
1721710	3	32	62	1986	31	502.90	499.46	3.44
1721710	3	32	62	1987	32	503.56	499.35	4.21
1721710	3	32	62	1988	33	504.92	499.08	5.84
1721710	3	32	62	1989	34	502.17	499.01	3.16
1721710	3	32	62	1990	35	503.95	499.35	4.60
1721710	3	32	62	1991	36	503.40	499.67	3.73
1721710	3	32	62	1992	37	503.60	499.93	3.67
1721710	3	32	62	1993	38	503.60	499.97	3.63
1721710	3	32	62	1994	39	503.38	499.95	3.43
1721710	3	32	62	1995	40	504.54	499.71	4.83
1721710	3	32	62	1995	40	503.85	499.71	4.14
1721710	3	32	62	1996	41	504.80	499.83	4.97
1721710	3	32	62	1997	42	504.80	499.95	4.85
1721710	3	32	62	1998	43	504.12	499.95	4.17
1721710	3	32	62	1999	44	503.98	499.65	4.33
1721710	3	32	62	2000	45	506.17	499.72	6.45
1721710	3	32	62	2001	46	505.25	500.03	5.22
1721710	3	32	62	2002	47	501.35	500.02	1.33
1721710	3	32	62	2003	48	504.72	499.70	5.02
1721710	3	32	62	2004	49	505.00	499.49	5.51
1721710	3	32	62	2005	50	503.89	499.14	4.75

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1721710	3	32	62	2006	51	503.55	498.85	4.70
1721710	3	32	62	2007	52	504.84	498.71	6.13
1721710	3	32	62	2010	55	505.11	499.06	6.05
1721710	3	32	62	2011	56	503.93	498.80	5.13
1721710	3	32	62	2012	57	504.05	498.73	5.32
1721711	3	32	61	1958	3	500.50	507.19	-6.69
1721711	3	32	61	1962	7	503.00	505.24	-2.24
1721711	3	32	61	1975	20	497.80	503.06	-5.26
1721711	3	32	61	1982	27	496.60	501.63	-5.03
1721711	3	32	61	1982	27	501.50	501.63	-0.13
1721711	3	32	61	2006	51	502.98	500.55	2.43
1721712	3	23	54	1982	27	544.80	550.04	-5.24
1721712	3	23	54	1982	27	539.30	550.04	-10.74
1721712	3	23	54	2006	51	542.25	549.01	-6.76
1721713	3	29	53	2002	47	506.00	531.39	-25.39
1721714	3	29	53	2006	51	497.70	528.33	-30.63
1721715	3	30	53	2006	51	498.06	524.28	-26.22
1721716	3	30	53	2006	51	495.26	524.28	-29.02
1721801	3	26	65	1957	2	513.00	534.81	-21.81
1721802	3	26	66	1960	5	516.90	534.70	-17.80
1721803	3	27	72	1960	5	521.08	529.52	-8.44
1721805	3	29	68	1982	27	502.30	512.77	-10.47
1721805	3	29	68	1982	27	500.90	512.77	-11.87
1721805	3	29	68	2006	51	504.70	511.60	-6.90

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1721806	3	26	66	1982	27	507.70	529.44	-21.74
1721806	3	26	66	1982	27	510.40	529.44	-19.04
1721901	3	29	80	1983	28	509.00	505.22	3.78
1721902	3	29	80	1983	28	515.50	505.22	10.28
1722402	3	25	89	1960	5	552.00	551.79	0.21
1722402	3	25	89	1982	27	558.00	548.16	9.84
1722402	3	25	89	1982	27	548.80	548.16	0.64
1722403	3	28	91	1982	27	504.20	508.94	-4.74
1722403	3	28	91	1982	27	505.60	508.94	-3.34
1722403	3	28	91	2006	51	500.60	508.91	-8.31
1722405	3	25	89	1985	30	547.00	547.89	-0.89
1722405	3	25	89	1992	37	556.30	551.21	5.09
1722502	3	26	93	1960	5	538.60	536.63	1.97
1722502	3	26	93	1982	27	551.00	533.62	17.38
1722502	3	26	93	2006	51	541.15	534.83	6.32
1722701	3	29	86	1982	27	504.90	503.38	1.52
1722701	3	29	86	1982	27	506.60	503.38	3.22
1722701	3	29	86	2006	51	501.72	502.86	-1.14
1722903	3	33	106	1977	22	484.10	424.91	59.19
1722903	3	33	106	1982	27	485.50	424.38	61.12
1723402	3	30	114	1982	27	496.00	472.91	23.09
1723601	3	33	130	1982	27	438.00	420.46	17.54
1723601	3	33	130	1982	27	435.80	420.46	15.34
1723601	3	33	130	2006	51	450.72	419.01	31.71

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1723602	3	33	134	1982	27	433.70	417.32	16.38
1723701	3	34	119	1982	27	471.00	410.81	60.19
1723701	3	34	119	1982	27	466.80	410.81	55.99
1723701	3	34	119	2006	51	465.50	410.00	55.50
1723802	3	36	127	1972	17	383.00	395.86	-12.86
1723803	3	39	126	1982	27	465.90	367.41	98.49
1723803	3	39	126	2006	51	459.78	365.40	94.38
1723903	3	38	130	1966	11	435.00	378.48	56.52
1723903	3	38	130	1972	17	386.88	377.42	9.46
1723903	3	38	130	1973	18	401.54	378.06	23.48
1723903	3	38	130	1974	19	395.64	378.37	17.27
1723903	3	38	130	1975	20	403.93	377.79	26.14
1723903	3	38	130	1976	21	404.83	377.55	27.28
1723903	3	38	130	1977	22	399.44	377.13	22.31
1723903	3	38	130	1978	23	403.61	376.73	26.88
1723903	3	38	130	1980	25	403.27	376.68	26.59
1723903	3	38	130	1982	27	403.27	376.82	26.45
1723903	3	38	130	1982	27	396.80	376.82	19.98
1723903	3	38	130	1983	28	402.78	376.30	26.48
1723903	3	38	130	1984	29	403.92	376.60	27.32
1723903	3	38	130	1985	30	403.90	376.34	27.56
1723903	3	38	130	1986	31	403.57	376.21	27.36
1723903	3	38	130	1987	32	404.70	376.08	28.62
1723903	3	38	130	1988	33	403.31	375.66	27.65

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1723903	3	38	130	1989	34	403.25	375.67	27.58
1723903	3	38	130	1990	35	405.80	376.18	29.62
1723903	3	38	130	1991	36	405.40	376.35	29.05
1723904	3	38	130	1976	21	385.50	377.55	7.95
1723904	3	38	130	1982	27	410.20	376.82	33.38
1723904	3	38	130	2006	51	374.60	374.52	0.08
1723905	3	38	130	1982	27	398.30	376.82	21.48
1723905	3	38	130	2006	51	404.75	374.52	30.23
1723906	3	38	130	2006	51	401.18	374.52	26.66
1724102	3	25	146	1967	12	437.00	476.33	-39.33
1724102	3	25	146	1982	27	439.30	477.94	-38.64
1724103	3	24	143	1978	23	444.00	474.87	-30.87
1724103	3	24	143	1982	27	447.50	476.93	-29.43
1724104	3	24	148	1982	27	452.70	478.66	-25.96
1724104	3	24	148	1982	27	450.70	478.66	-27.96
1724104	3	24	148	2006	51	450.71	472.44	-21.73
1724105	3	25	149	1982	27	438.40	477.45	-39.05
1724105	3	25	149	2006	51	437.60	470.66	-33.06
1724106	3	25	144	1982	27	441.70	476.43	-34.73
1724106	3	25	144	2006	51	436.90	473.26	-36.36
1724107	3	25	145	1997	42	442.35	480.19	-37.84
1724109	3	22	146	2006	51	453.70	474.27	-20.57
1724202	3	26	153	1959	4	437.64	453.64	-16.00
1724203	3	27	153	1958	3	436.80	455.77	-18.97

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1724204	3	28	156	1959	4	396.00	422.62	-26.62
1724205	3	28	158	1960	5	415.50	414.72	0.78
1724206	3	29	159	1960	5	401.00	407.05	-6.05
1724207	3	28	159	1982	27	409.70	409.07	0.63
1724207	3	28	159	1982	27	407.40	409.07	-1.67
1724208	3	27	157	1982	27	436.40	422.31	14.09
1724501	3	31	156	1960	5	410.90	402.04	8.86
1724503	3	33	155	1982	27	350.40	382.59	-32.19
1724503	3	33	155	1982	27	348.10	382.59	-34.49
1724503	3	33	155	2006	51	346.85	379.14	-32.29
1724504	3	29	153	1978	23	405.00	425.34	-20.34
1724505	3	32	156	1982	27	363.70	388.31	-24.61
1724505	3	32	156	1982	27	356.10	388.31	-32.21
1724506	3	35	154	2006	51	303.00	362.04	-59.04
1724507	3	39	154	1999	44	304.00	324.74	-20.74
1724507	3	39	154	2006	51	259.17	322.52	-63.35
1724601	3	36	162	1982	27	395.50	346.53	48.97
1724601	3	36	162	1982	27	395.20	346.53	48.67
1724701	3	39	144	1982	27	240.90	344.49	-103.59
1724801	3	47	153	1968	13	245.00	260.84	-15.84
1724801	3	47	153	1982	27	291.70	241.66	50.04
1724801	3	47	153	2006	51	182.45	231.84	-49.39
1724803	3	50	152	1969	14	189.00	228.70	-39.70
1724901	3	51	158	1966	11	317.00	228.46	88.54

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1724901	3	51	158	1982	27	278.10	215.69	62.41
1724901	3	51	158	1982	27	270.60	215.69	54.91
1724901	3	51	158	2006	51	182.20	212.22	-30.02
1724903	3	49	163	1986	31	228.00	235.54	-7.54
1728301	3	37	46	1982	27	502.10	516.17	-14.07
1728301	3	37	46	1982	27	494.40	516.17	-21.77
1729101	3	37	54	1959	4	489.80	498.86	-9.06
1729101	3	37	54	1982	27	488.20	493.98	-5.78
1729101	3	37	54	1982	27	485.20	493.98	-8.78
1729102	3	44	58	1956	1	497.00	445.48	51.52
1729104	3	36	53	1982	27	490.80	501.18	-10.38
1729104	3	36	53	1982	27	490.70	501.18	-10.48
1729105	3	46	54	2006	51	470.20	443.55	26.65
1729201	3	39	65	1982	27	515.10	450.53	64.57
1729201	3	39	65	1982	27	511.20	450.53	60.67
1732101	3	54	142	1982	27	176.20	206.57	-30.37
1732201	3	52	151	1959	4	285.40	217.72	67.68
1732201	3	52	151	1966	11	245.00	203.92	41.08
1732201	3	52	151	1971	16	152.00	198.07	-46.07
1732201	3	52	151	1973	18	149.25	194.55	-45.30
1732201	3	52	151	1974	19	143.98	191.57	-47.59
1732201	3	52	151	1976	21	148.20	191.89	-43.69
1732201	3	52	151	1983	28	85.00	182.61	-97.61
1732201	3	52	151	1986	31	120.00	175.95	-55.95

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1732201	3	52	151	1990	35	177.00	190.87	-13.87
1732201	3	52	151	1991	36	155.00	191.63	-36.63
1732201	3	52	151	1992	37	171.00	193.26	-22.26
1732201	3	52	151	1993	38	192.00	196.09	-4.09
1732201	3	52	151	1995	40	190.00	196.00	-6.00
1732201	3	52	151	1995	40	175.00	196.00	-21.00
1732201	3	52	151	1996	41	160.00	194.94	-34.94
1732201	3	52	151	1997	42	224.40	195.69	28.71
1732201	3	52	151	2000	45	98.85	191.07	-92.22
1732201	3	52	151	2001	46	108.00	190.89	-82.89
1732201	3	52	151	2003	48	125.10	193.27	-68.17
1732201	3	52	151	2004	49	137.11	193.45	-56.34
1732201	3	52	151	2005	50	136.70	192.35	-55.65
1732201	3	52	151	2006	51	150.28	184.21	-33.93
1732201	3	52	151	2007	52	187.12	191.87	-4.75
1732201	3	52	151	2008	53	171.21	193.88	-22.67
1732201	3	52	151	2009	54	196.80	194.06	2.74
1732201	3	52	151	2010	55	176.79	194.62	-17.83
1732201	3	52	151	2011	56	176.10	193.67	-17.57
1732201	3	52	151	2012	57	161.51	194.15	-32.64
1732202	3	53	151	1960	5	263.50	206.52	56.98
1732203	3	53	151	1960	5	258.67	206.52	52.15
1732205	3	56	150	1957	2	247.00	197.50	49.50
1732205	3	56	150	1982	27	151.70	165.92	-14.22

State Well Number	Layer	Row	Column	Year	Stress Period	Measured head (feet, amsl)	Simulated head (feet, amsl)	Residual (measured head - simulated head, feet)
1732205	3	56	150	2006	51	152.74	166.63	-13.89
1732206	3	54	147	1960	5	250.00	213.46	36.54
1732207	3	54	147	1982	27	282.00	192.45	89.55
1732207	3	54	147	1982	27	147.90	192.45	-44.55
1732301	3	55	163	1959	4	290.00	206.45	83.55
1732301	3	55	163	1982	27	150.90	192.71	-41.81
1732302	3	56	162	1995	40	195.00	184.62	10.38
1732302	3	56	162	2006	51	166.11	182.73	-16.62

Appendix B:
Responses to Stakeholder Comments

No comments have been received on the numerical model report as of January 5, 2022.