Texas Water Development Board
Contract Number # 1648302063

Appendix C Report: Draft Numerical Model for the Groundwater Availability Model for the Northern Portion of the Queen City, Sparta, and Carrizo-Wilcox Aquifers

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Table of Contents

List of Figures

List of Tables

Appendices

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Executive Summary

This report presents a draft groundwater numerical model which serves as the basis for the final calibration of the groundwater availability model for the northern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers, in northeast Texas. The final groundwater model is presented in the main report to which this appendix report is attached; the main report is entitled Numerical Model Report: Groundwater Availability Model for the Northern Portions of the Queen City, Sparta, and Carrizo-Wilcox Aquifers (Panday and others, 2020).

The draft groundwater availability model for the northern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers was submitted July 16, 2020. Texas Water Development Board (TWDB) submitted comments to the draft report on November 4, 2020. In response, a final groundwater model was developed and calibrated to address three major comments received by TWDB. The draft model and final calibrated model are identical except for changes described below.

1. The draft model layer 2 thickness represents the Younger Units and the Sparta Aquifer while the final model layer 2 thickness represents the Sparta Aquifer only;
2. The hydraulic conductivity of the Carrizo Aquifer was increased from 0.12 feet per day (ft/day) (draft model) to 7.04 ft/day (final model) to better match the observed range; and
3. The draft model contains 8 more target wells in the Queen City Aquifer (model layer 4) than the final calibrated model. In the final model, these wells were moved into the layers above (model layer 2) and below (model layer 6) in order to improve calibration statistics in the Queen City Aquifer.

The draft and final numerical calibrations did not significantly differ in calibration statistics or qualitative match to observed data. Sensitivity evaluations and predictive analyses were performed for the Northern Portions of the Queen City, Sparta, and Carrizo-Wilcox Aquifers using the draft model described here. Results of these sensitivity and predictive simulations are discussed in the Numerical Model Report. The results of the draft model calibration is presented below in Section 3.

1.0 Introduction of Draft Model

The draft groundwater availability model for the northern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers was submitted July 16, 2020. Texas Water Development Board (TWDB) submitted comments to the draft report on November 4, 2020. In response, a final groundwater model was developed and calibrated to address three major comments received by TWDB and is presented in the Numerical Model Report (Panday and others, 2020). The purpose of this appendix report is to present the draft model calibration which differs slightly from the final calibration and which was used for model sensitivity and predictive simulations.

The draft model differs from the final calibrated model as follows:

1. The top elevation of the draft model layer 2 represents the thickness of the Sparta Aquifer and the Younger Units (in the final model, model layer 2 represents only the thickness of the Sparta Aquifer);
2. The draft model hydraulic conductivity of the Carrizo Aquifer is 0.12 feet per day (ft/day) (in the final model, this hydraulic conductivity was increased to 7.04 ft/day to better match the conceptual range); and
3. The draft model contains 8 more target wells in the Queen City Aquifer (model layer 4) than the final calibrated model. (In the final model, these wells were moved into the layers above (model layer 2) and below (model layer 6) in order to improve calibration statistics in the Queen City Aquifer.)

The sensitivity analysis and predictive sensitivities are based on the draft model but deemed applicable to both the draft and final models. Sensitivity and predictive results are presented in the final Numerical Model Report (Panday and others, 2020). The draft model discretization package is presented in Section 2.0 and the draft model calibration is presented in Section 3.0.

2.0 Model Overview and Discretization Package

A conceptual model of the hydrogeologic system of the area of interest in the northern portion of the Queen City Aquifer, Sparta Aquifer, and Carrizo-Wilcox aquifers was developed by Montgomery and Associates (2020) and is the basis of the numerical model described in this report.

Except for the thickness and top elevation of model layer 2, the draft and final model grids are identical. The Discretization (DIS) package of MODFLOW 6 was used and defines the model discretization information for the 3-dimensional groundwater cells. Nine geologic units in the model domain were discretized into 9 numerical layers.

The hydrostratigraphic unit Younger Units was not represented as a separate model layer but was incorporated into model layer 2 which simulates the thickness of the Younger Units and the Sparta Aquifer. Aquifer properties of the Younger Units are not simulated. Spatially, the Younger Units have a limited extent along the southern portion of the model domain and this extent was simulated as a general head boundary within model layer 2.

The top of model layer 2 and the thickness of model layer 2 (representing both the Younger Units and the Sparta Aquifer) are shown on Appendix C Figures 2.4-1 and 2.4-2. Appendix C Figure 2.4-3 shows cross-sections of the numerical model with a north-south cross-section A-A' and northwest to southeast cross-section B-B'.

3.0 Draft Model Calibration and Results

The draft model was constructed and calibrated using MODFLOW 6 (Langevin and others, 2017) and Groundwater Vistas (Rumbaugh and Rumbaugh, 2017) as discussed above and in Sections 2.0 and 3.0 of the Numerical Model Report (Panday and others, 2020). This section presents a summary of the draft hydraulic conductivity calibration and the results of the draft model calibration.

3.1 Calibration Procedures

Calibration of recharge and the general head boundaries were conducted as described in the Numerical Model Report Section 3.0 (Panday and others, 2020). In general, the model was calibrated using an interactive expert approach (manual calibration evaluations) in conjunction with automatic model calibration using the parameter estimation code PEST (Doherty, 2010). Consistency with the conceptual model was also evaluated and adjustments were made to model aquifer parameters or conceptual elements until the model was considered calibrated. Measured groundwater level elevations were used to constrain the simulation results and calibration parameter adjustments.

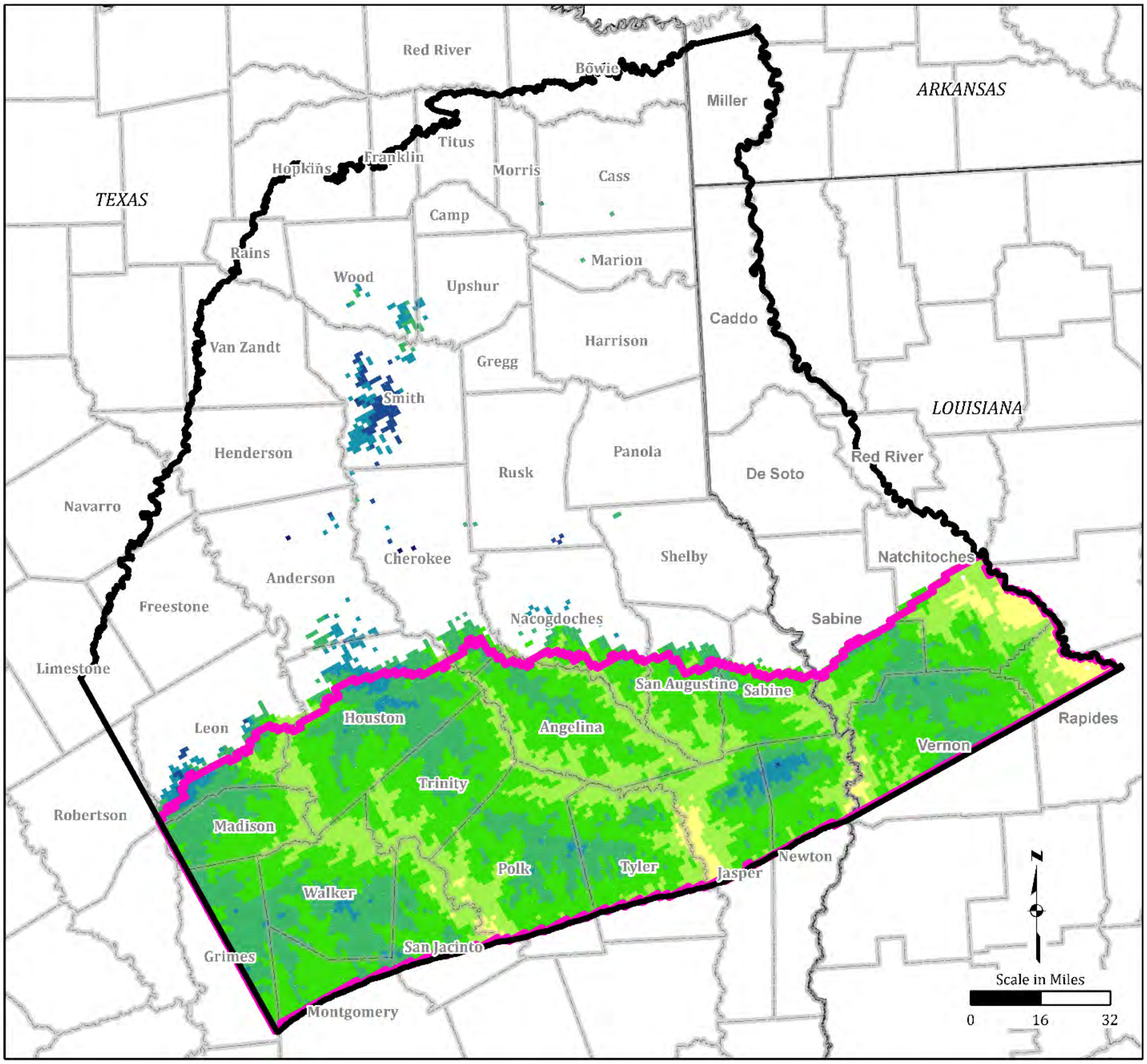
3.1.1 Calibration of Aquifer Parameters

The draft model calibration of hydraulic conductivity was conducted using a two-period steady-state model representing 1980 and 2013 conditions.

As discussed in the Numerical Model Report Section 2.5, the horizontal and vertical hydraulic conductivities were parameterized using two datasets: the sand fraction within each simulated geologic layer, with the remaining fraction assumed to be clay; and hydraulic conductivity estimates for sand and clay in each of layer. Within Groundwater Vistas, each model layer horizontal hydraulic conductivity was calculated using the sand fraction and sand estimated hydraulic conductivity; each layer vertical hydraulic conductivity was calculated using the clay fraction and clay estimated hydraulic conductivity.

The hydraulic conductivity values for sand and clay were calibrated using PEST and adjusted manually to best fit observed groundwater levels. The two-period steady-state model was used for the PEST simulations. Though the 1980 and 2013 periods do not represent steady-state conditions, water levels were relatively stable during these two years, making them useful for estimating hydraulic conductivity. The resulting hydraulic conductivity values were considered reliable as the two-period model represented different stress conditions.

Appendix C Table 3.1-1 shows the draft model horizontal and vertical hydraulic conductivities. These are based on the parameterized hydraulic conductivity values for sand and clay and the layer sand fractions. The horizontal and vertical hydraulic



LEGEND

- Model Boundary
- Extent of General Head Boundary
- County or Parish Boundary

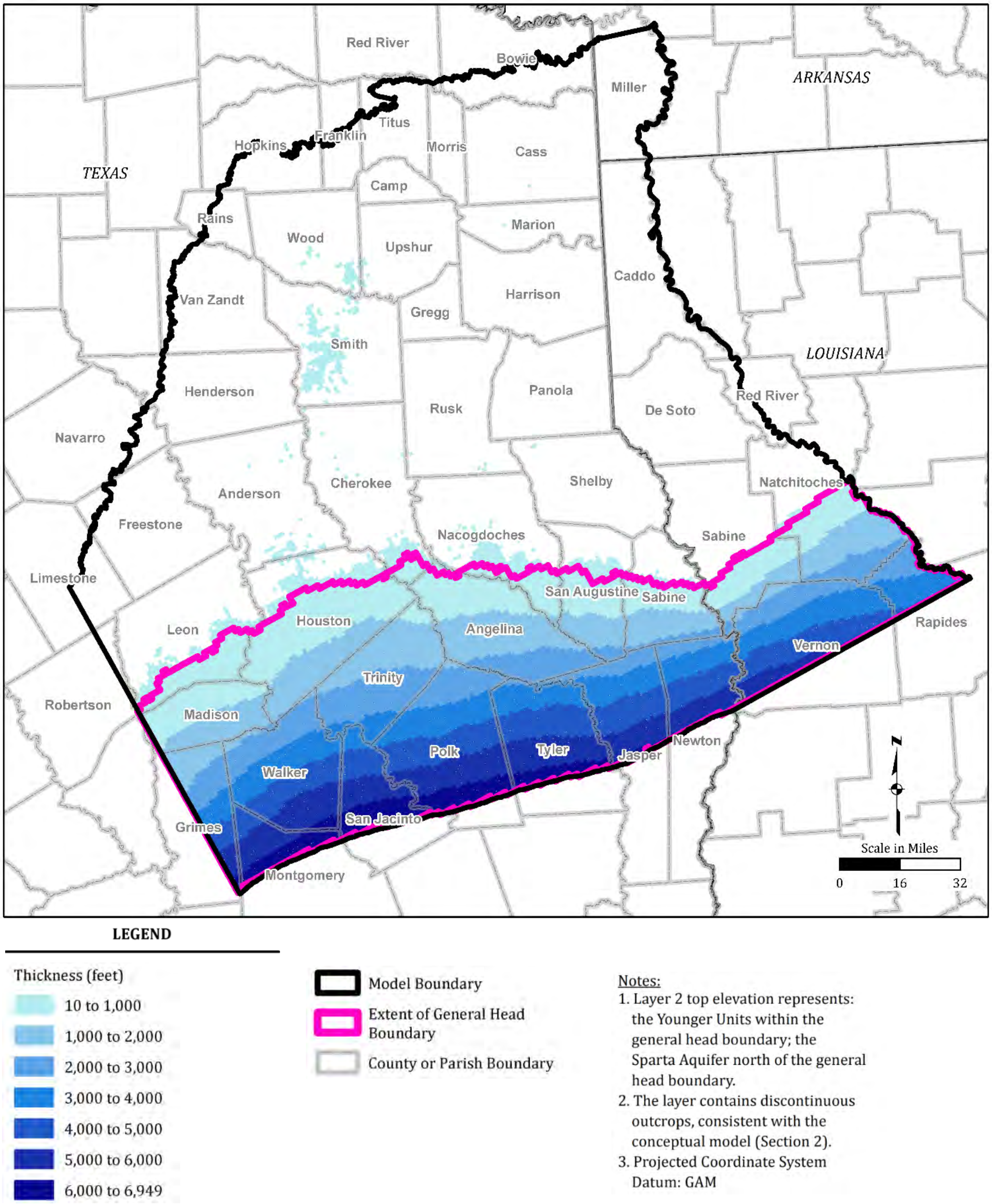
Elevation (feet above mean sea level)

- 22 to 100
- 100 to 200
- 200 to 300
- 300 to 400
- 400 to 500
- 500 to 600
- 600 to 676

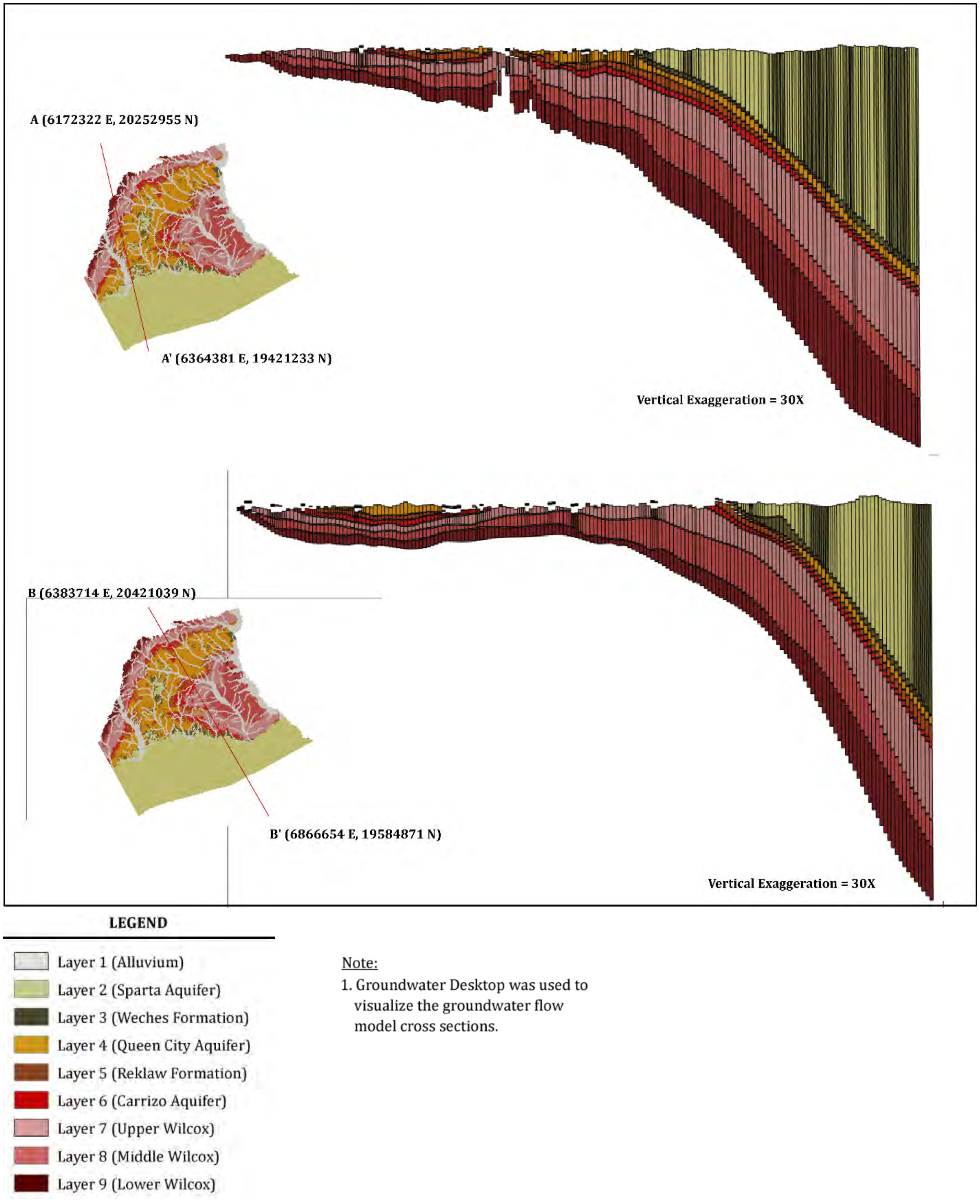
Notes:

1. Layer 2 top elevation represents: the Younger Units within the general head boundary; the Sparta Aquifer north of the general head boundary.
2. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
3. Projected Coordinate System Datum: GAM

Appendix C Figure 2.4-1. Modeled Top Elevation for Sparta Aquifer (Model Layer 2)



Appendix C Figure 2.4-2. Modeled Thickness for Sparta Aquifer (Model Layer 2)



Appendix C Figure 2.4-3. Cross-Sections of Gridded Model Layers in the Groundwater Flow Model

Appendix C Table 3.1-1. Draft Model Calibrated Hydraulic Conductivity

Model Layer	Hydrostratigraphic Unit	Model Sand Fraction	Parameterized Hydraulic Conductivity Values (feet per day)		Calibrated Model Hydraulic Conductivity (feet per day)		Conceptual Model Estimated Hydraulic Conductivity (feet per day)	
			Sand	Clay	Horizontal	Vertical	Range	Geometric Mean
1	Quaternary Alluvium	0.70	7.77	3.73	6.56	5.87	1 - 1000	165
2	Sparta Aquifer	0.05 - 0.95	2.92	7.31E-06	0.15 - 2.78	7.7E-06 - 1.5E-04	1 - 808	14
3	Weches Formation	0.10	60.75	9.70E-05	6.08	1.08E-04	0.2 - 65	5
4	Queen City Aquifer	0.05 - 0.95	2	1	1.05 - 1.95	1.03 - 1.90	0.1 - 451	5
5	Reklaw Formation	0.10	1	7.76E-06	0.10	8.63E-06	0.05 - 385	5
6	Carrizo Aquifer	0.70	0.16	1.33E-02	0.12	3.72E-02	0.3 - 198	6
7	Upper Wilcox	0.05 - 0.95	18.82	3.309378	4.09 - 18.05	3.45 - 15.25	0.06 - 278	4
8	Middle Wilcox	0.05 - 0.95	8.67	4.10E-05	0.43 - 8.24	4.3E-05 - 8.2E-04	0.04 - 671	4
9	Lower Wilcox	0.05 - 0.95	2.31	6.82E-03	0.12 - 2.19	7.2E-03 - 0.13	0.01 - 97	3

Notes:
1. Calibrated horizontal and vertical hydraulic conductivities are based on sand fraction and parameterized hydraulic conductivity values. Equations for calculating horizontal and vertical hydraulic conductivity are discussed in Section 2.5.
2. Estimated hydraulic conductivities are from the Conceptual Model Report (Montgomery and Associates, 2020).

conductivity distributions for model geologic units are shown in Appendix C Figures 3.1-1 through 3.1-10.

The sand fraction within the Quaternary Alluvium (model layer 1) and the Carrizo Aquifer (model layer 6) was assumed to be uniform at 0.7, resulting in calibrated horizontal hydraulic conductivity values of 6.56 feet/day and 0.12 feet/day, respectively, and calibrated vertical hydraulic conductivity values of 5.87 feet/day and 0.04 feet/day, respectively. For the Weches Formation (model layer 3) and the Reklaw Formation (model layer 5), the sand fraction was assumed to be uniform at 0.1, resulting in calibrated horizontal hydraulic conductivity values of 6.08 feet/day and 0.10 feet/day, respectively, and calibrated vertical hydraulic conductivity values of 1.08e-4 feet/day and 8.63e-6 feet/day, respectively.

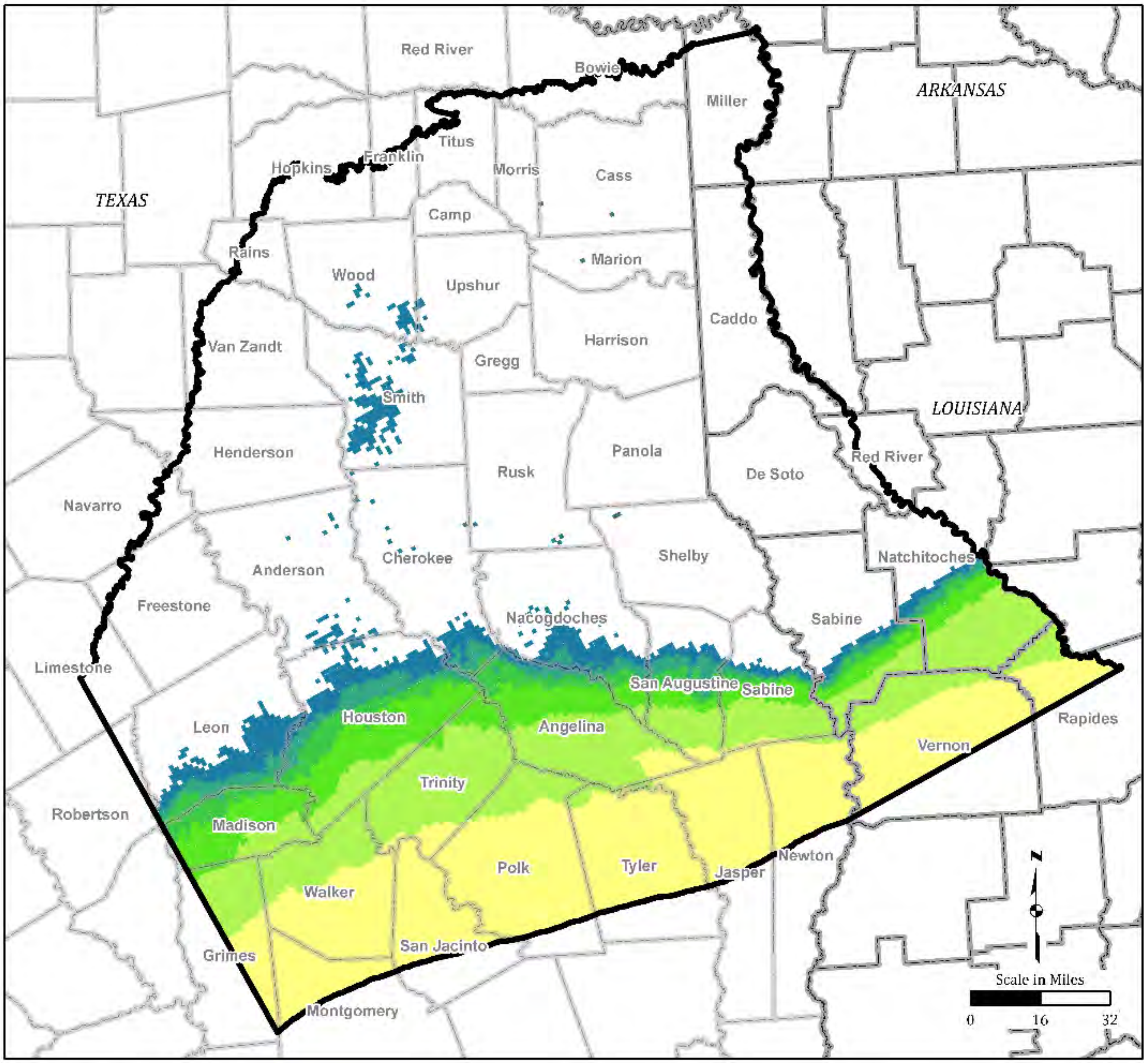
The calibrated horizontal hydraulic conductivity values for the Sparta Aquifer (model layer 2) ranged from 0.15 to 2.78 feet/day and that of the Queen City Aquifer (model layer 4) ranged from 1.05 to 1.95 feet/day. The calibrated vertical hydraulic conductivity values for the Sparta Aquifer (model layer 2) ranged from 7.7e-6 to 1.5e-4 feet/day and that of the Queen City Aquifer (model layer 4) ranged from 1.03 to 1.90 feet/day. The calibrated horizontal hydraulic conductivity units of the Wilcox Aquifer (Upper, Middle, and Lower Wilcox) (model layers 7, 8, and 9) ranged from 0.12 to 18.05 feet/day. The calibrated vertical hydraulic conductivity units of the Wilcox Aquifer (Upper, Middle, and Lower Wilcox) (model layers 7, 8, and 9) ranged from 4.3e-5 to 15.25 feet/day.

The calibrated hydraulic conductivity values were compared to the estimated hydraulic conductivity values and geometric means presented in the Conceptual Model Report in Section 4.5 (Montgomery and Associates, 2020) (Appendix C Table 3.1-1). The calibrated horizontal hydraulic conductivity values are within the range of the estimated values, except for the lower horizontal hydraulic conductivities in the Sparta Aquifer (model layer 2) and Carrizo Aquifer (model layer 6) which are below the estimated range. Calibrated horizontal hydraulic conductivity values in the Weches Formation (model layer 3), and the Upper, Middle, and Lower Wilcox Aquifer (model layers 7, 8, and 9) match the conceptual model geometric mean (Appendix C Table 3.1-1).

3.2 Model Simulated Versus Measured Heads

Groundwater level elevations were used to constrain the model to observed conditions during the simulation period. The development of the water level elevation target data set is discussed in the Numerical Model Report Section 3.2 (Panday and others, 2020).

The draft model dataset is the same target dataset used in the final model (1,797 wells with 18,606 measured water level elevations) but the distribution of target wells across model layers differs (final calibration targets are listed in Appendix B Table 1). The draft model contains 163 target wells with 3,072 measured water level elevations in model layer 4, the Queen City Aquifer. The final model has 8 model layer 4 wells moved to layers 2 or 6 (total of 155 target wells with 1,629 observations in the final layer 4 target dataset). The eight wells in model layer 4 in the draft model are: wells 3446104, 3726804, and 6001204 (in model layer 2 in the final model); wells 3430907, 3505101, 3511202, 3807203, and 3826706 (in model layer 6 in the final model).



LEGEND

Model Boundary
County or Parish Boundary

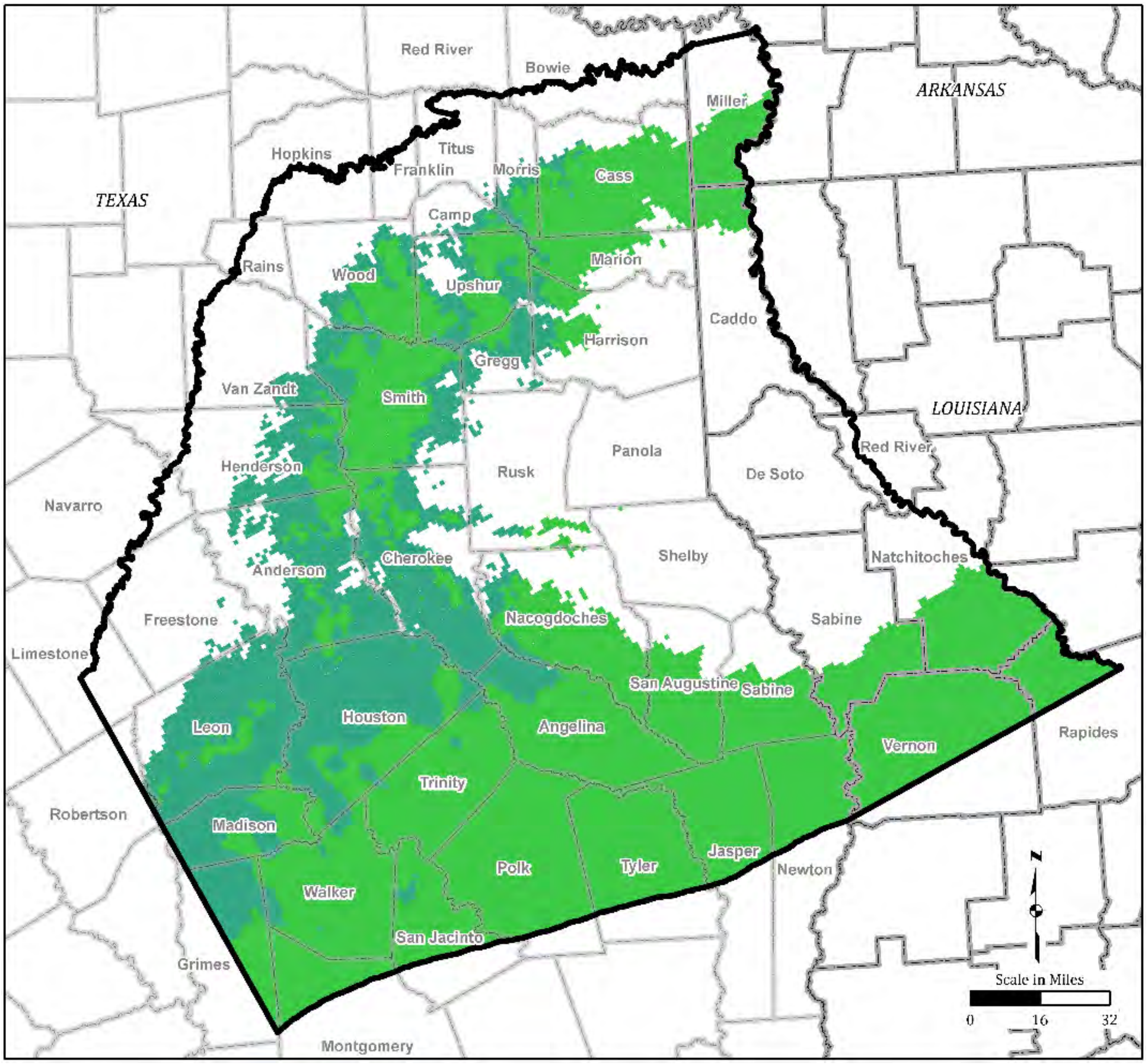
Calculated Hydraulic Conductivity (Feet/Day)

- 0 to 0.1
- 0.1 to 0.5
- 0.5 to 1
- 1 to 1.5
- 1.5 to 2.5
- 2.5 to 5
- 5 to 10
- 10 to 18.05

Notes:

1. Layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM

Appendix C Figure 3.1-1. Calculated Horizontal Hydraulic Conductivity for Sparta Aquifer (Model Layer 2)



LEGEND

- Model Boundary
- County or Parish Boundary

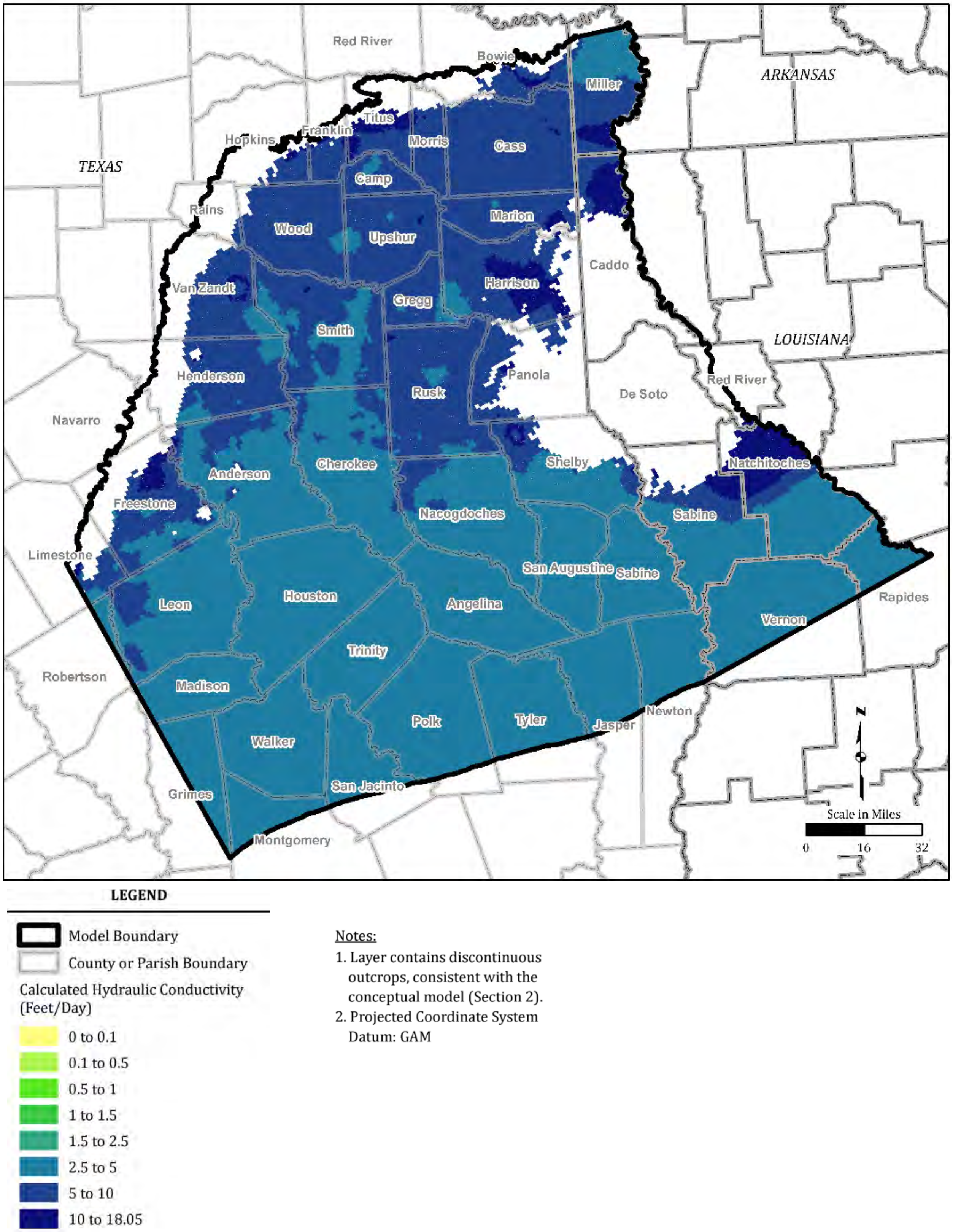
Calculated Hydraulic Conductivity (Feet/Day)

- 0 to 0.1
- 0.1 to 0.5
- 0.5 to 1
- 1 to 1.5
- 1.5 to 2.5
- 2.5 to 5
- 5 to 10
- 10 to 18.05

Notes:

1. Layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM

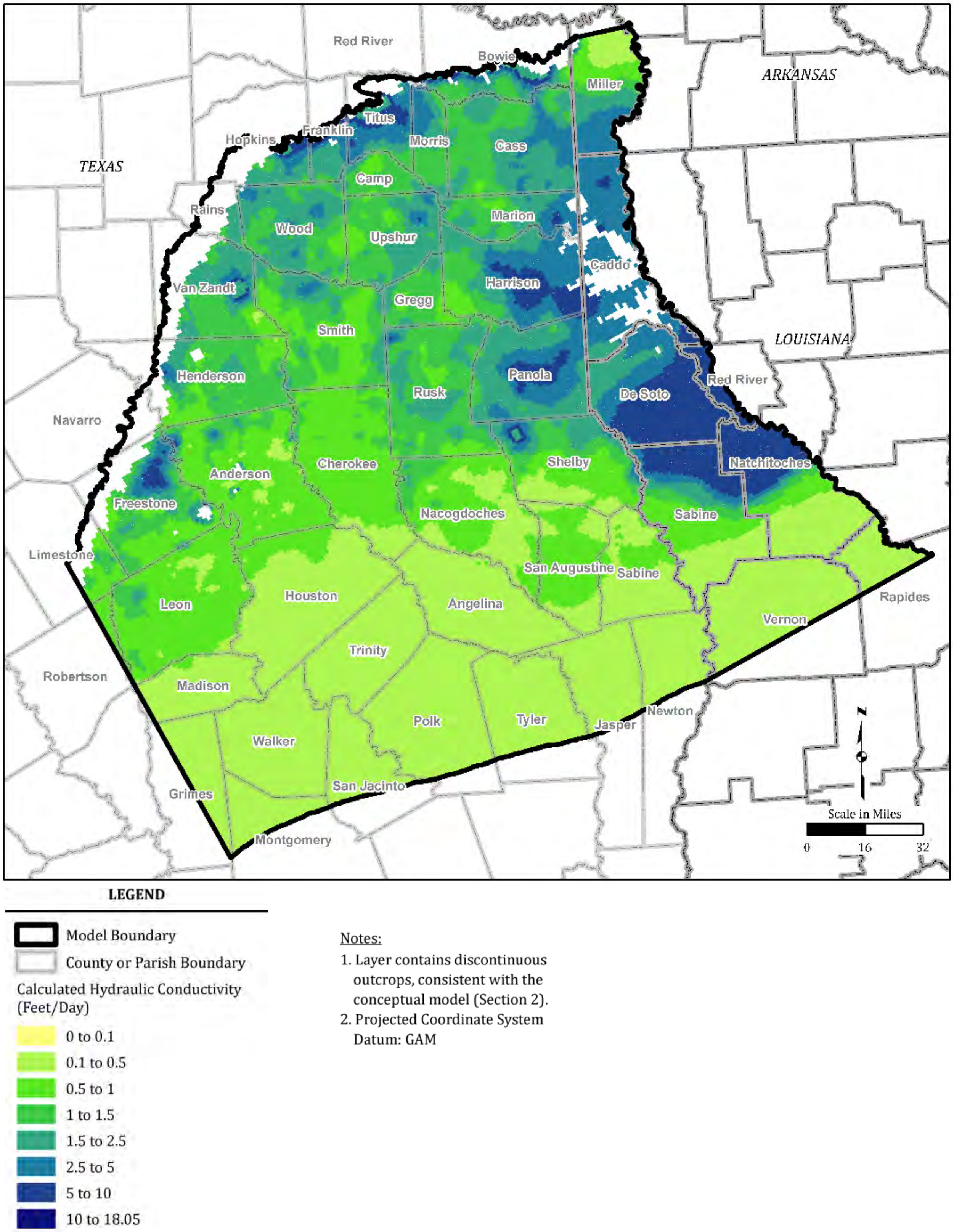
Appendix C Figure 3.1-2. Calculated Horizontal Hydraulic Conductivity for Queen City Aquifer (Model Layer 4)



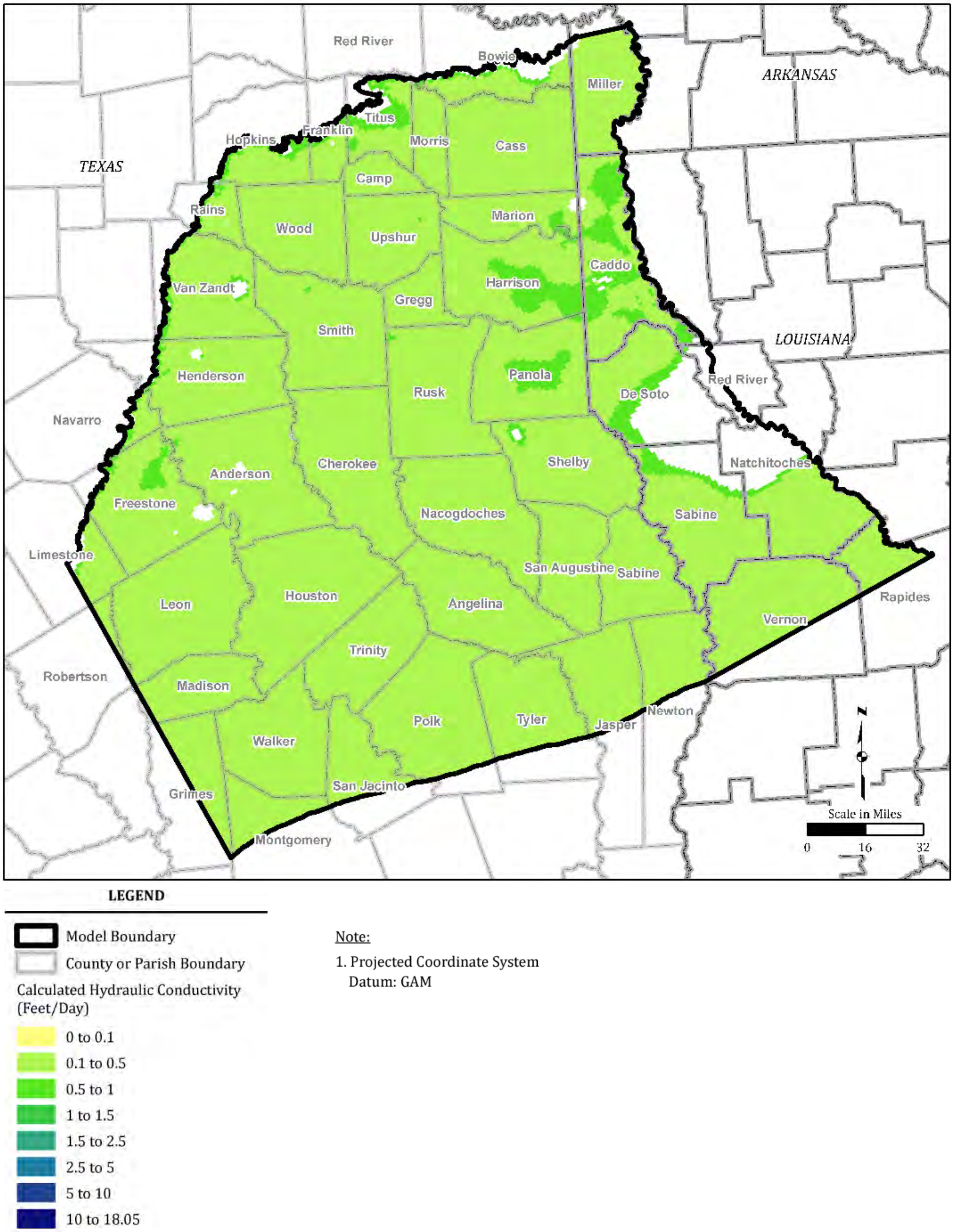
Notes:

1. Layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM

Appendix C Figure 3.1-3. Calculated Horizontal Hydraulic Conductivity for Upper Wilcox (Model Layer 7)



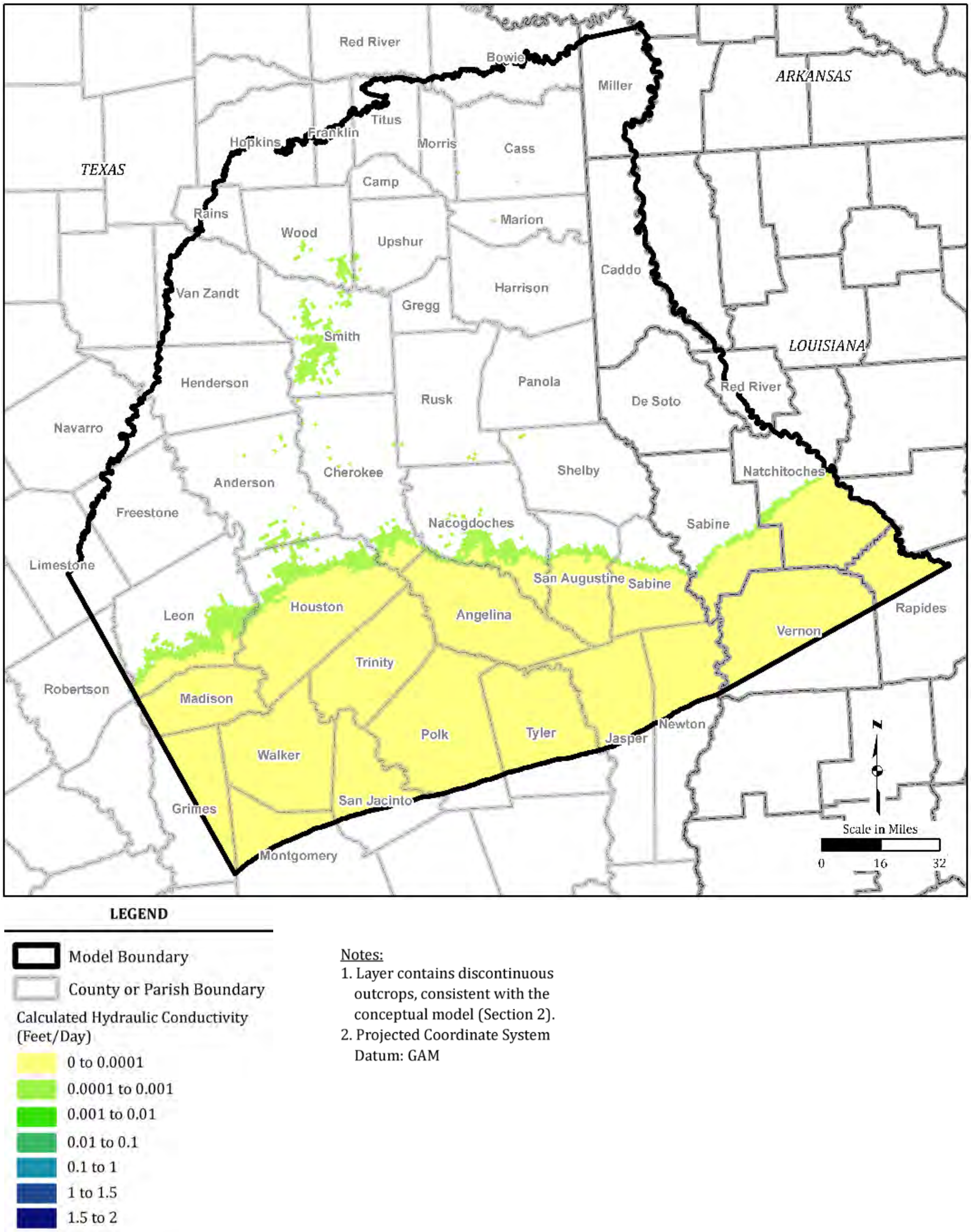
Appendix C Figure 3.1-4. Calculated Horizontal Hydraulic Conductivity for Middle Wilcox (Model Layer 8)



Note:

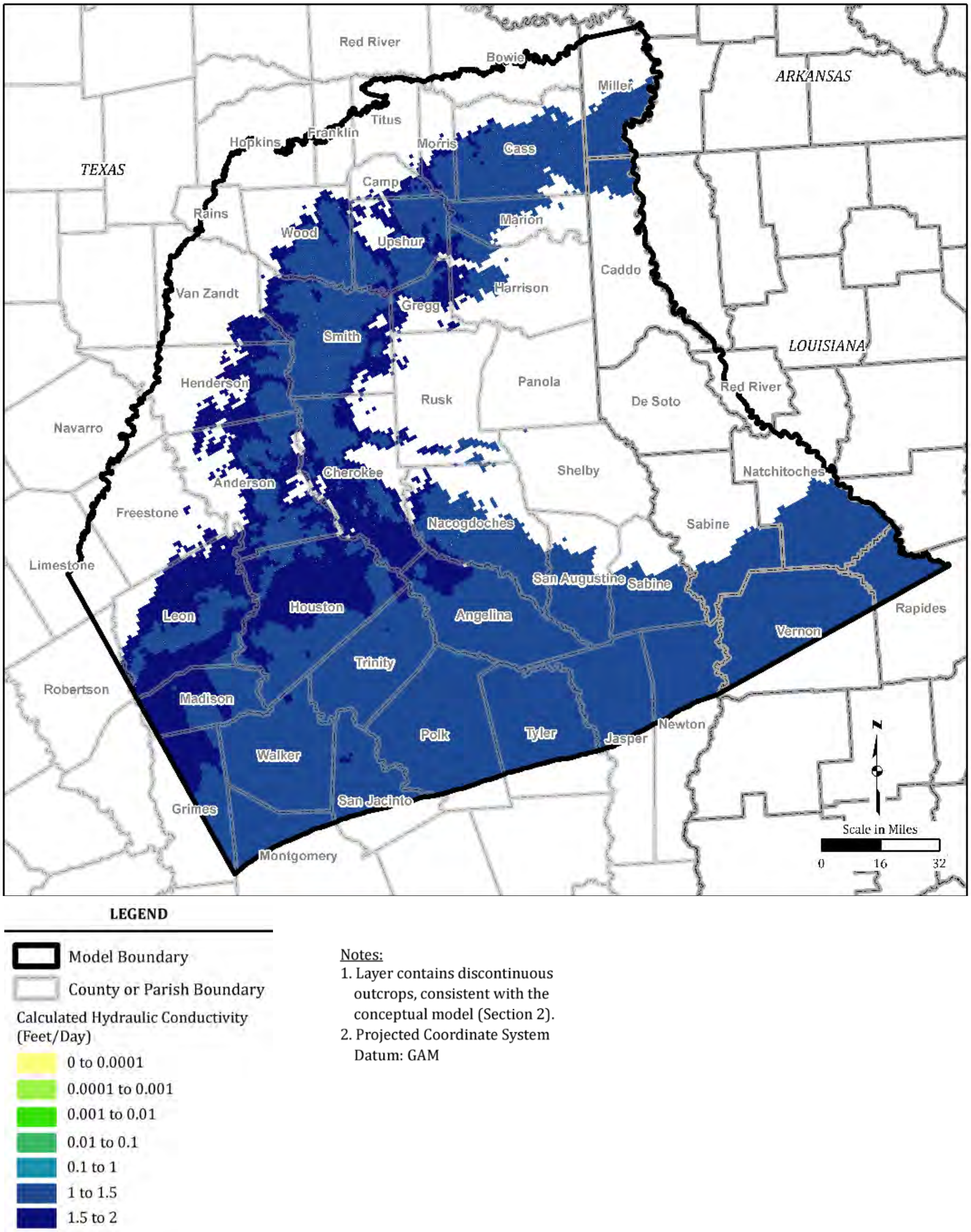
1. Projected Coordinate System
   Datum: GAM

Appendix C Figure 3.1-5. Calculated Horizontal Hydraulic Conductivity for Upper Wilcox (Model Layer 9)

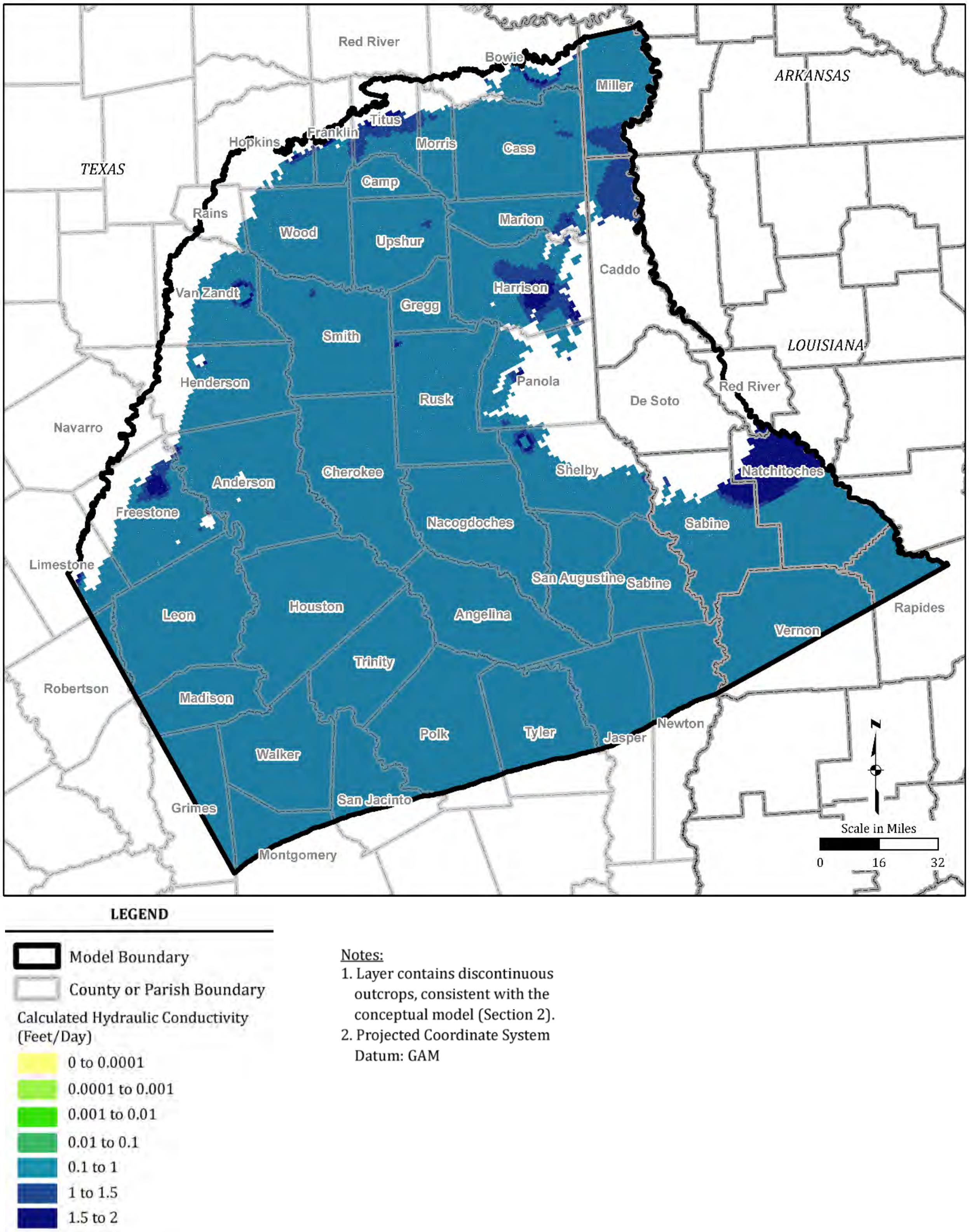


Notes:
1. Layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM

Appendix C Figure 3.1-6. Calculated Vertical Hydraulic Conductivity for Sparta Aquifer (Model Layer 2)



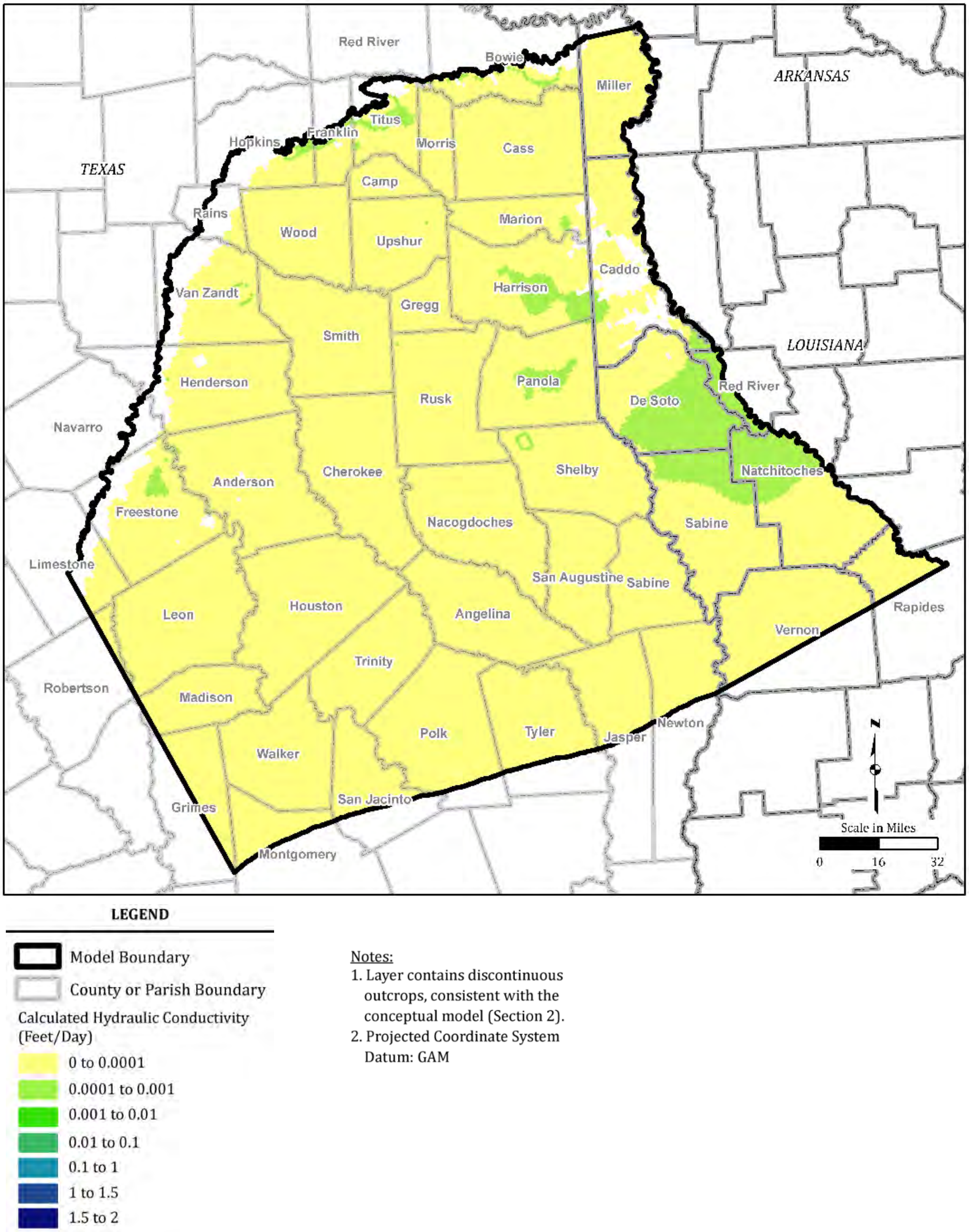
Appendix C Figure 3.1-7. Calculated Vertical Hydraulic Conductivity for Queen City Aquifer (Model Layer 4)



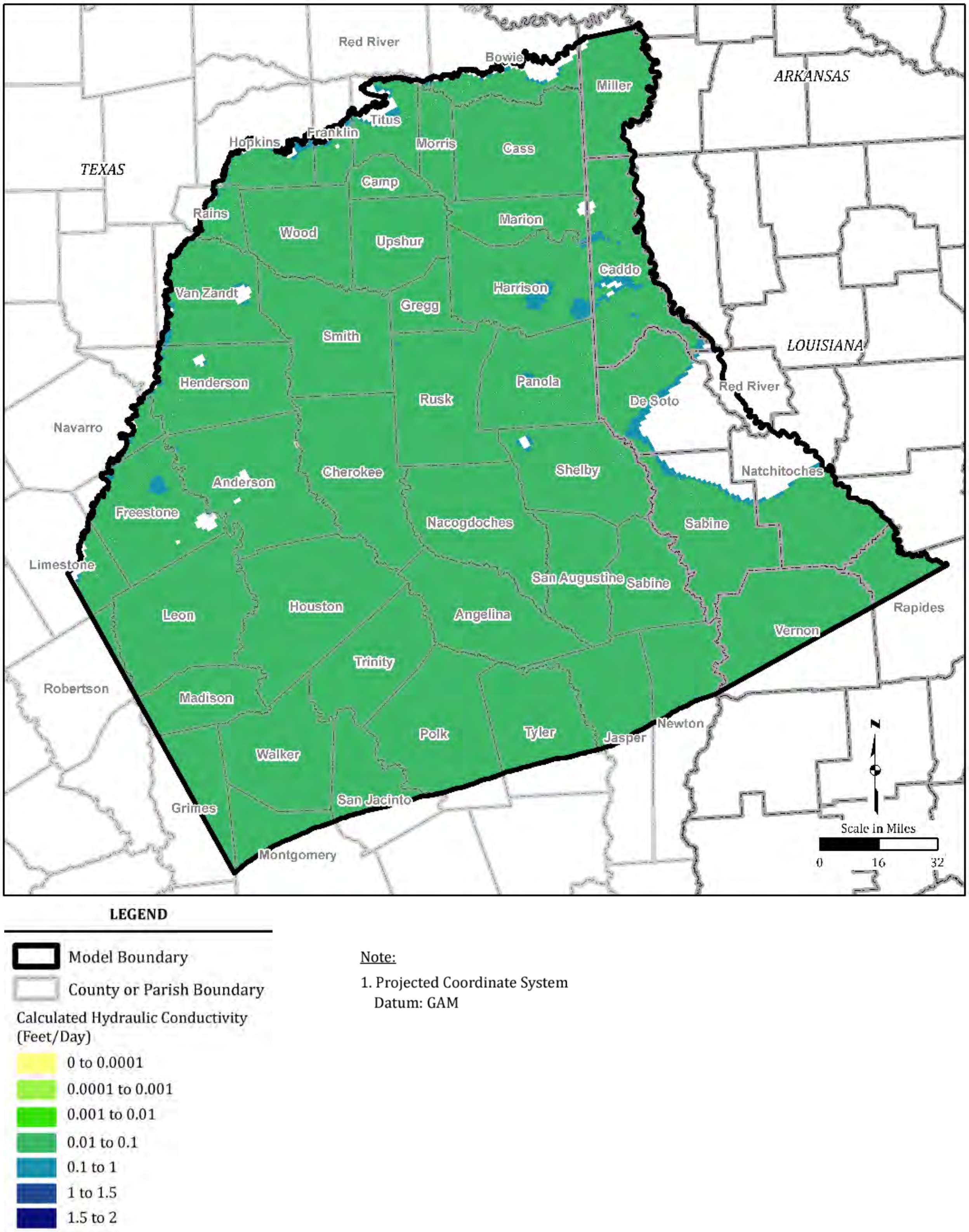
Notes:

1. Layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM

Appendix C Figure 3.1-8. Calculated Vertical Hydraulic Conductivity for Upper Wilcox (Model Layer 7)



Appendix C Figure 3.1-9. Calculated Vertical Hydraulic Conductivity for Middle Wilcox (Model Layer 8)



Note:

1. Projected Coordinate System
   Datum: GAM

Appendix C Figure 3.1-10. Calculated Vertical Hydraulic Conductivity for Lower Wilcox (Model Layer 9)

The distribution of water level elevation data in the draft model layers 2, 4, and 6 are shown on Appendix C Figures 3.2-1, 3.2-2, and 3.2-3.

3.2.1 Simulated Versus Observed Heads

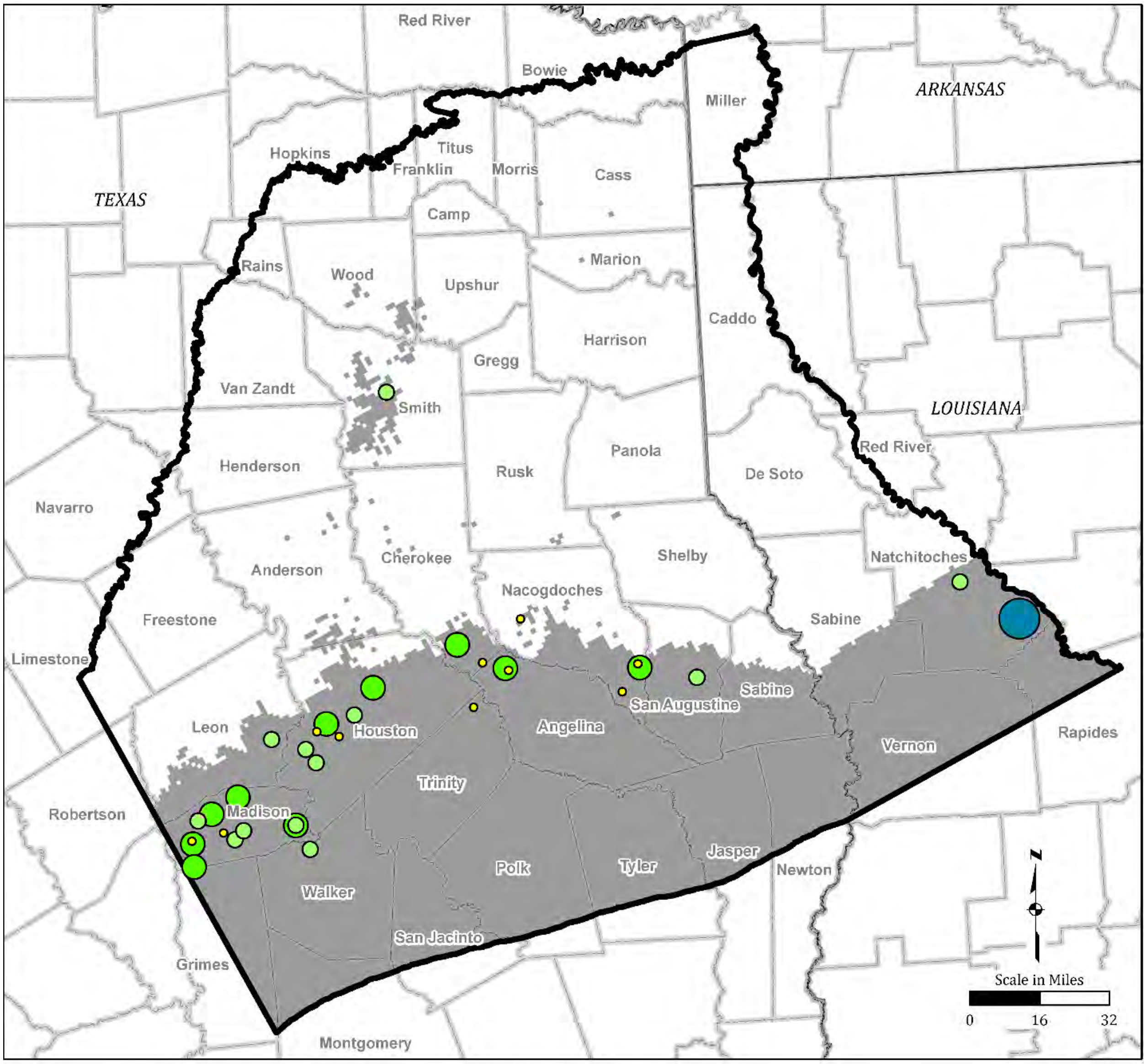
Appendix C Table 3.2-1 shows the summary for weighted head calibration statistics for the two-period steady-state model representing 1980 and 2013 conditions. For the 1980 conditions, the residual mean of 7.20 feet is relatively close to zero, indicating a good calibration and no overall bias in the calibration. The absolute residual mean was 31.71 feet and the root mean squared (RMS) error was 45.78 feet. Appendix C Table 3.2-2 shows the summary for weighted head calibration statistics for the transient simulation period for 1980 through 2013 conditions. The residual mean of -9.10 feet is slightly negative indicating simulated water level elevations are slightly higher than observed overall. However, given the large range of water level elevation measurements of 901.4 feet, the residual mean is relatively close to zero, indicating a good calibration. The absolute residual mean was 47.05 feet and the RMS error was 70.00 feet. The standard deviation of 69.40 feet is less than 10 percent of the range of observed values, indicating a good calibration.

Appendix C Table 3.2-3 shows the summary for the weighted head calibration statistics for the transient simulation period for 1980 through 2013 conditions for each model layer. The Upper, Middle, and Lower Wilcox (model layers 7, 8, and 9) calibration statistics indicate these layers have the best calibration. The Queen City Aquifer (model layer 4) calibration statistics indicate this layer has the worst calibration as simulated water level elevations are higher than observed. The RMS error was 128.00 feet. The Queen City Aquifer is between two aquitard layers.

The steady-state and transient error statistics are less than 10 percent of the range of observations which is generally considered a reasonably good calibration. All residuals are computed as observed minus simulated metrics. Thus, positive residuals indicate that simulated water levels are lower than observed, while negative residuals indicate that simulated water levels are higher than observed.

Appendix C Figure 3.2-4 shows the observed versus simulated water levels for the steady-state 1980 and 2013 conditions while Appendix C Figure 3.2-5 and Figure 3.2-6 show these values based on whether the aquifer is confined or unconfined. The steady-state simulation results tightly surround the best-fit line with no noticeable bias across the range of observations. The regression coefficient (R^2) for the three plots are greater than 0.9, indicating a good match between observed and simulated water levels for both confined and unconfined conditions.

Appendix C Figure 3.2-7 shows the regression plot of observed versus simulated water levels for the transient 1980 through 2013 simulation period. Appendix C Figure 3.2-8 shows the confined water level regression plot and Appendix C Figure 3.2-9 shows the unconfined water level regression plot for the 1980 through 2013 simulation period. The transient simulation results tightly surround the best-fit line with no noticeable bias across the range of observations. The regression coefficient (R^2) for the three plots are greater than 0.9, indicating a good match between observed and simulated water levels of the transient simulation for both confined and unconfined conditions.



LEGEND

Number of Water Level Measurements

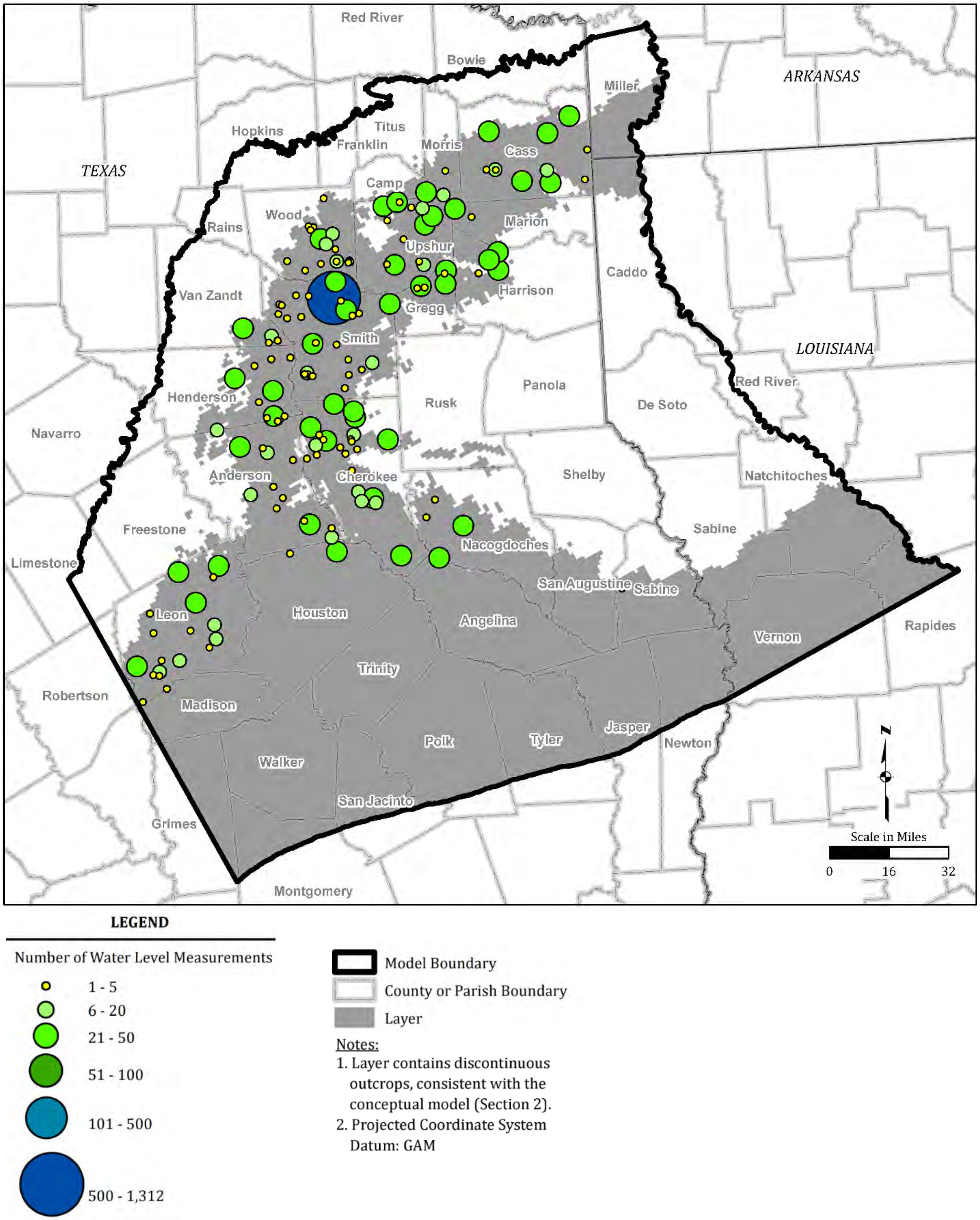
- 1 - 5
- 6 - 20
- 21 - 50
- 51 - 100
- 101 - 500
- 500 - 1,312

- Model Boundary
- County or Parish Boundary
- Layer

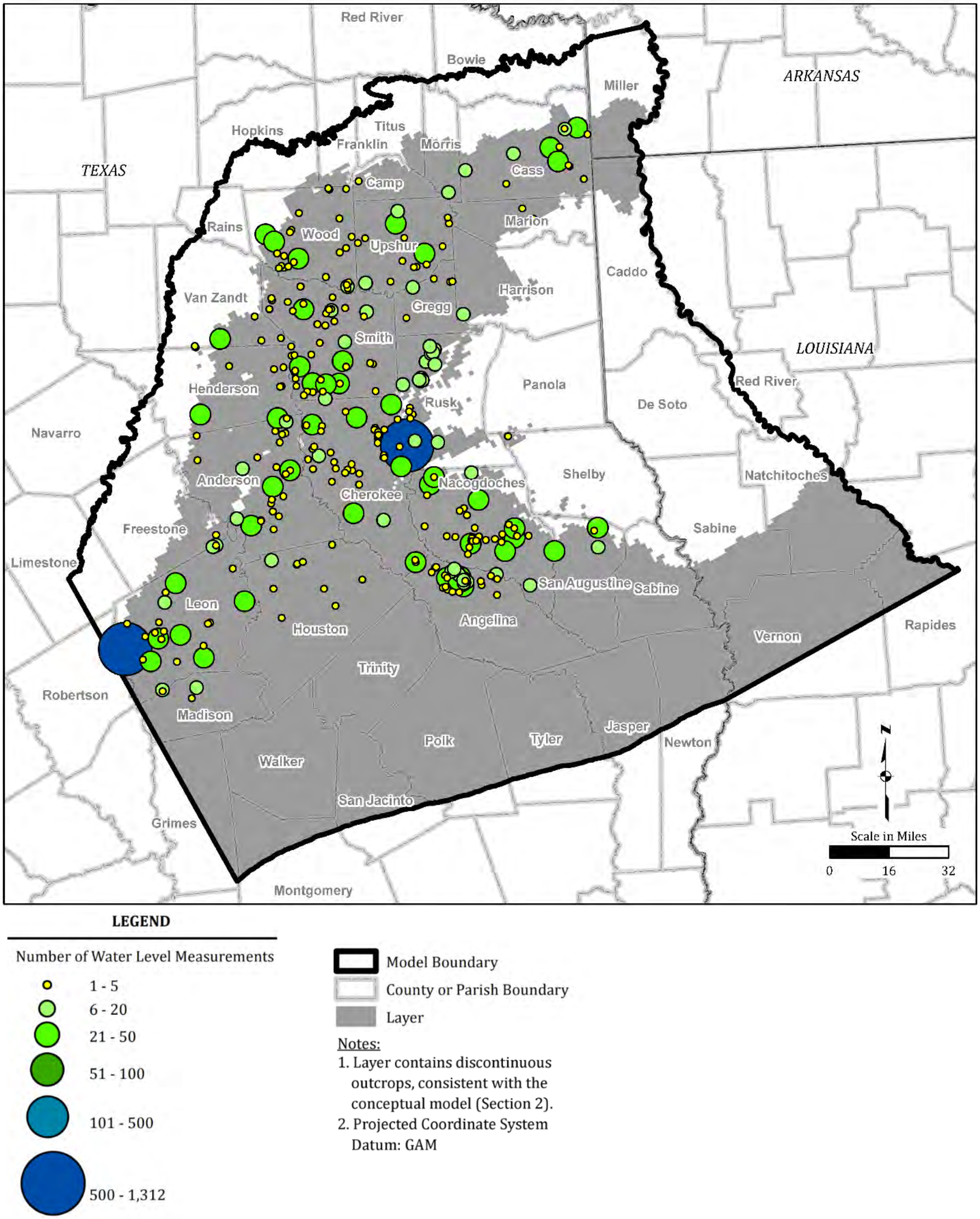
Notes:

1. Layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM

Appendix C Figure 3.2-1. Location of Groundwater Observation Wells and Available Water Level Elevation Data – Sparta Aquifer (Model Layer 2)



Appendix C Figure 3.2-2. Location of Groundwater Observation Wells and Available Water Level Elevation Data – Queen City Aquifer (Model Layer 4)



Appendix C Figure 3.2-3. Location of Groundwater Observation Wells and Available Water Level Elevation Data – Carrizo Aquifer (Model Layer 6)

Appendix C Table 3.2-1. Draft Model Weighted Calibration Statistics for Steady-State 1980 and 2013 Simulation

Statistic	1980 Values	2013 Values
Number of targets	695	386
Number of observations	695	386
Range in observed values	805.78	852.78
Minimum residual	-153.22	-226.25
Maximum residual	233.72	195.10
Sum of squared residuals	1.46E+06	1.46E+06
Root mean square (RMS) error	45.78	61.50
Residual mean	7.20	-6.37
Absolute residual mean	31.71	45.72
Standard deviation	45.24	61.25
Scaled residual mean	0.009	-0.007
Scaled absolute residual mean	0.039	0.054
Scaled standard deviation	0.056	0.072
Scaled RMS error	0.057	0.072

Appendix C Table 3.2-2. Draft Model Weighted Calibration Statistics for the Transient 1980 to 2013 Simulation

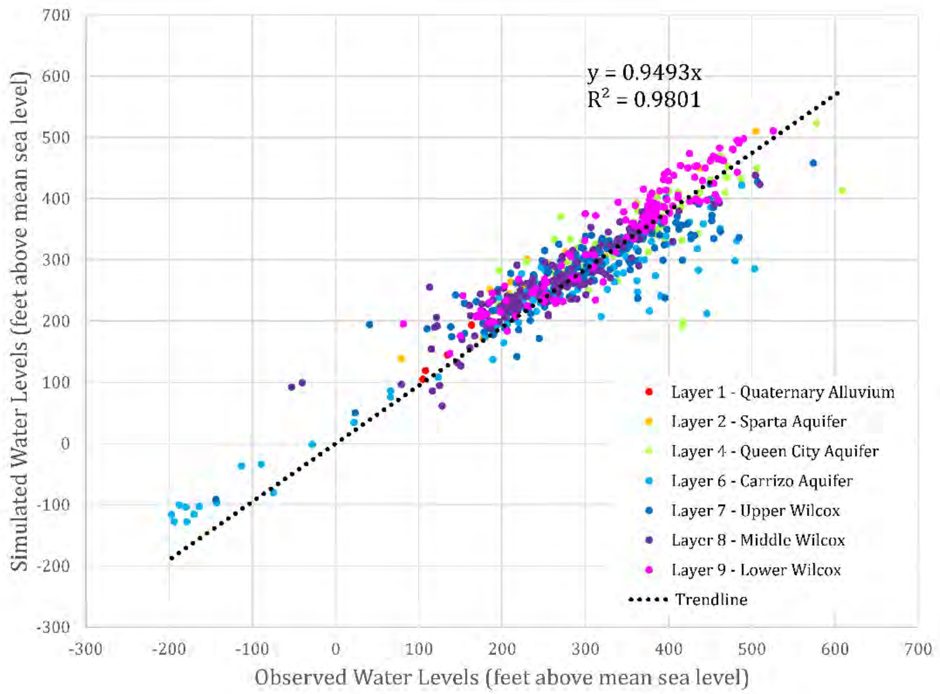
Statistic	All Targets	Confined Targets	Unconfined Targets
Number of targets	1,797	1,326	471
Number of observations	18,421	11,062	7,359
Range in observed values	901.40	901.40	551.10
Minimum residual	-314.43	-314.43	-216.35
Maximum residual	270.80	270.80	176.02
Sum of squared residuals	9.03E+07	3.28E+07	5.74E+07
Root mean square (RMS) error	70.00	54.48	88.33
Residual mean	-9.10	6.20	-32.10
Absolute residual mean	47.05	34.47	33.14
Standard deviation	69.40	54.13	82.30
Scaled residual mean	-0.010	0.007	-0.058
Scaled absolute residual mean	0.052	0.038	0.060
Scaled standard deviation	0.077	0.060	0.149
Scaled RMS error	0.078	0.060	0.160

Appendix C Table 3.2-3. Draft Model Weighted Calibration Statistics by Layer for the Transient 1980 to 2013 Simulation

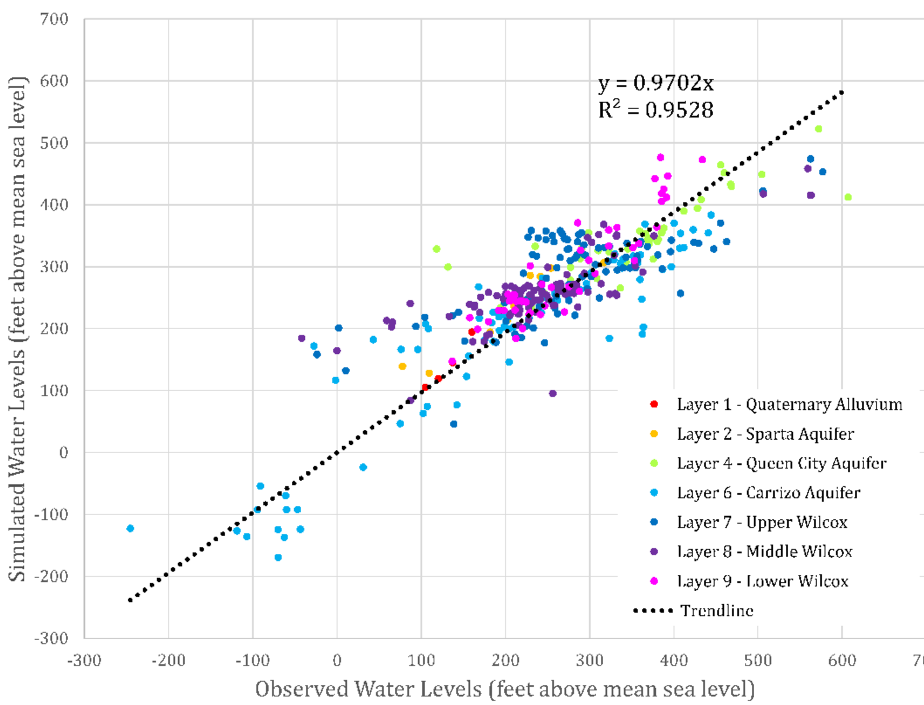
Statistic	Layer 1 (Quaternary Alluvium)	Layer 2 (Sparta Aquifer)	Layer 4 (Queen City Aquifer)	Layer 6 (Carrizo Aquifer)	Layer 7 (Upper Wilcox)	Layer 8 (Middle Wilcox)	Layer 9 (Lower Wilcox)
Number of Targets	707	626	3,072	3,581	3,458	4,147	2,830
Range in Observed Values	77.62	449.07	503.04	897.10	738.15	752.00	616.16
Minimum Residual	-43.30	-100.43	-216.35	-217.97	-242.61	-277.65	-314.43
Maximum Residual	8.25	35.78	225.44	270.80	254.40	212.06	101.13
Sum of Squared Residuals	176,000	1,080,000	50,300,000	13,000,000	12,900,000	9,170,000	3,550,000
Root mean square (RMS) Error	15.79	41.51	128.00	60.25	61.20	47.03	35.42
Residual Mean	-8.73	-31.56	-70.38	26.11	4.87	-6.36	-3.33
Absolute Residual Mean	11.04	36.45	99.21	45.77	47.28	32.12	25.01
Standard Deviation	13.16	26.96	106.91	54.30	61.00	46.60	35.27
Scaled Residual Mean	-0.112	-0.070	-0.140	0.029	0.007	-0.008	-0.005
Scaled Absolute Residual Mean	0.142	0.081	0.197	0.051	0.064	0.043	0.041
Scaled Standard Deviation	0.169	0.060	0.213	0.061	0.083	0.062	0.057
Scaled RMS Error	0.203	0.092	0.254	0.067	0.083	0.063	0.057

Note:
Model layers 3 and 5 (Weches and Reklaw Formations) do not contain water level elevation targets.

1980

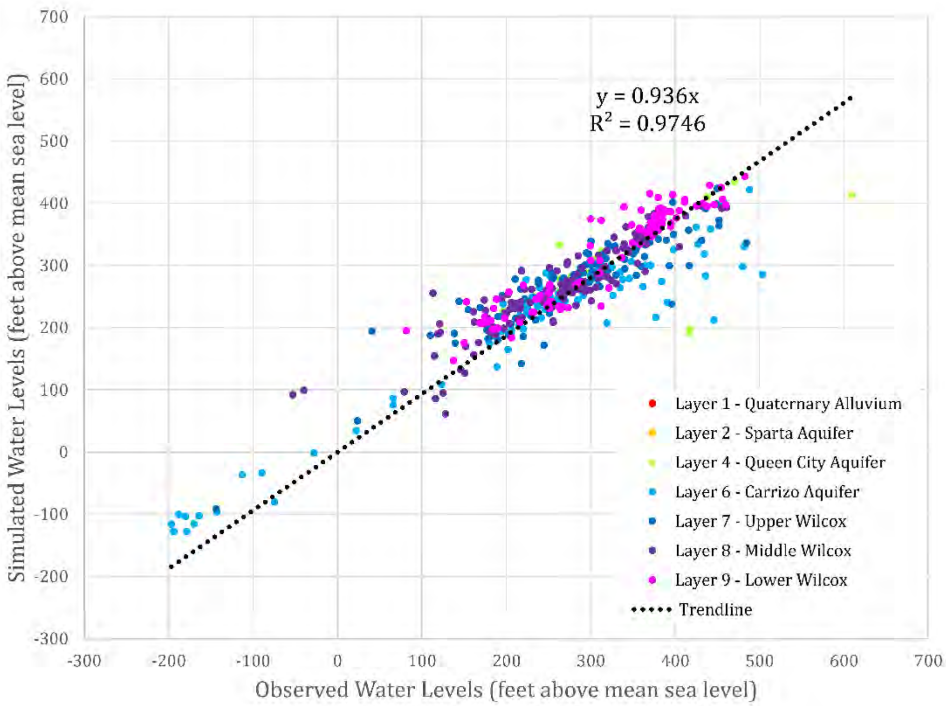


2013

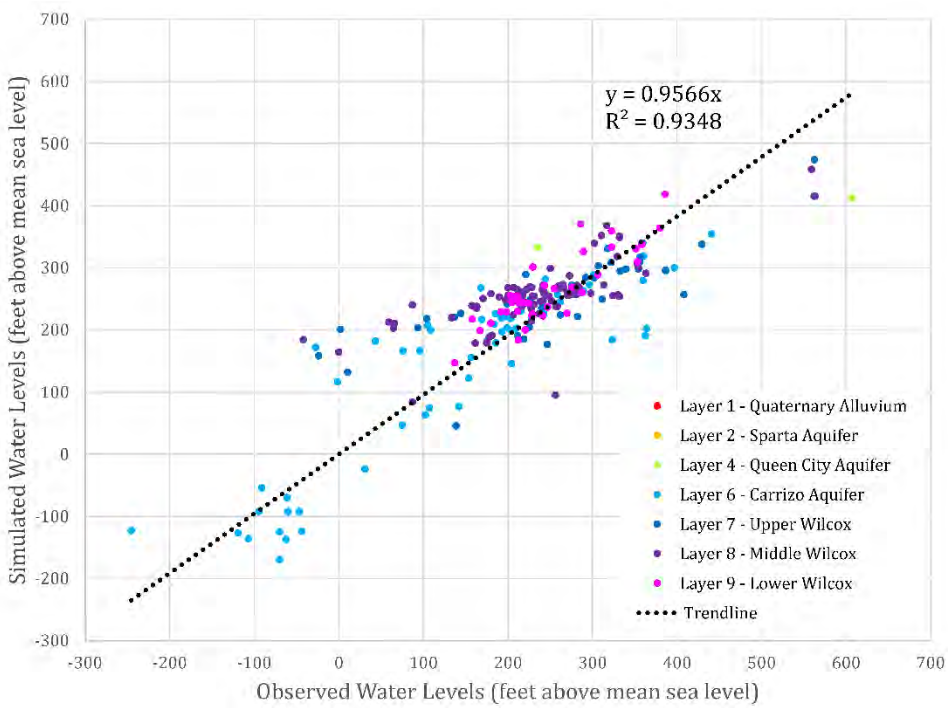


Appendix C Figure 3.2-4. Observed vs. Simulated Water Level Elevations for Calibrated 1980 and 2013 Conditions

1980

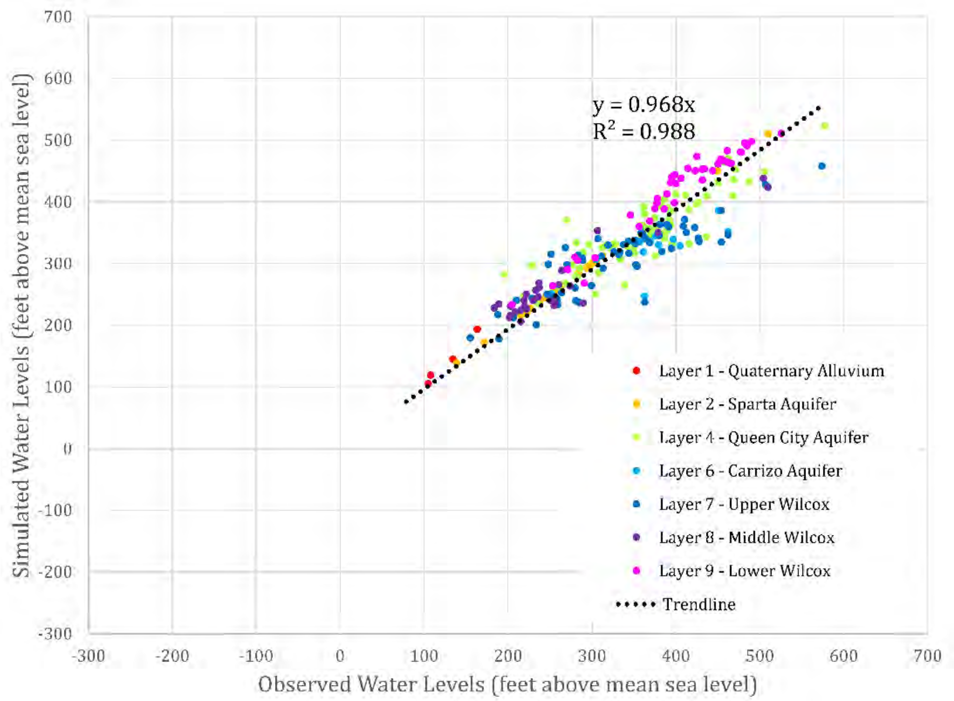


2013

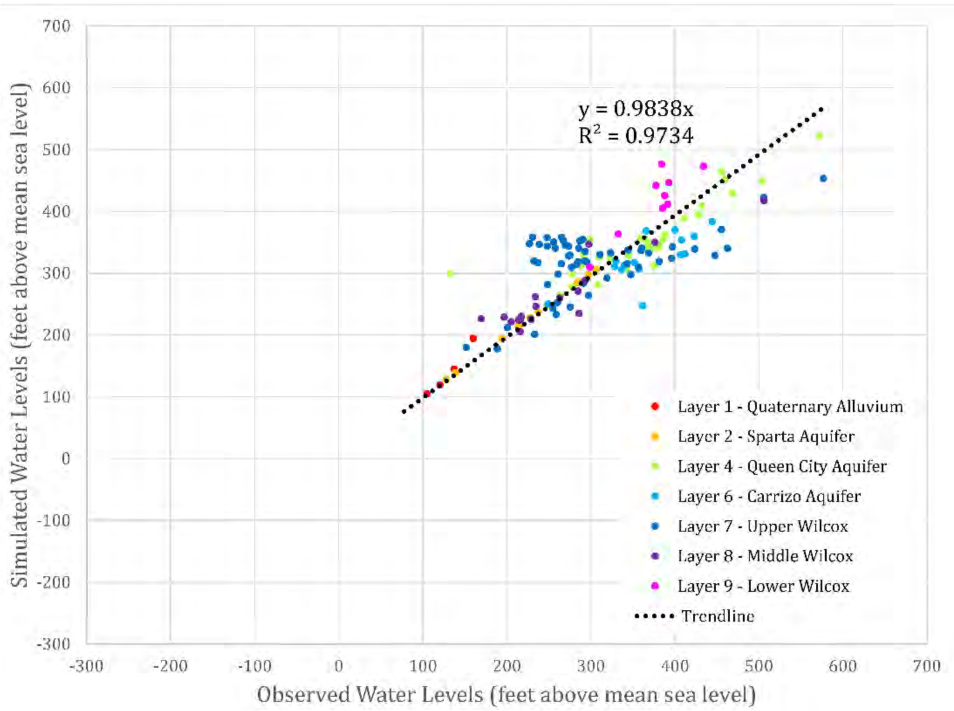


Appendix C Figure 3.2-5. Observed vs. Simulated Confined Water Level Elevations for Calibrated 1980 and 2013 Conditions

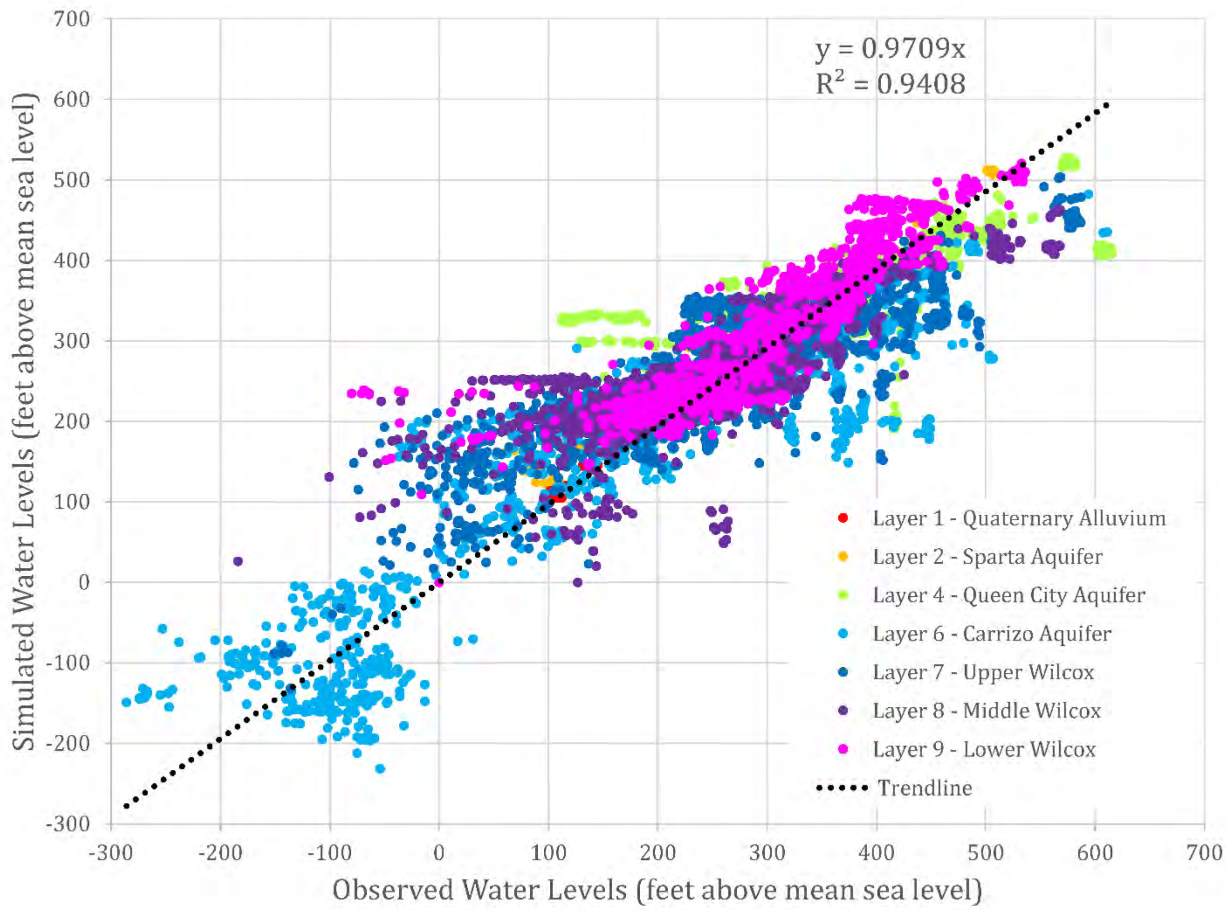
1980



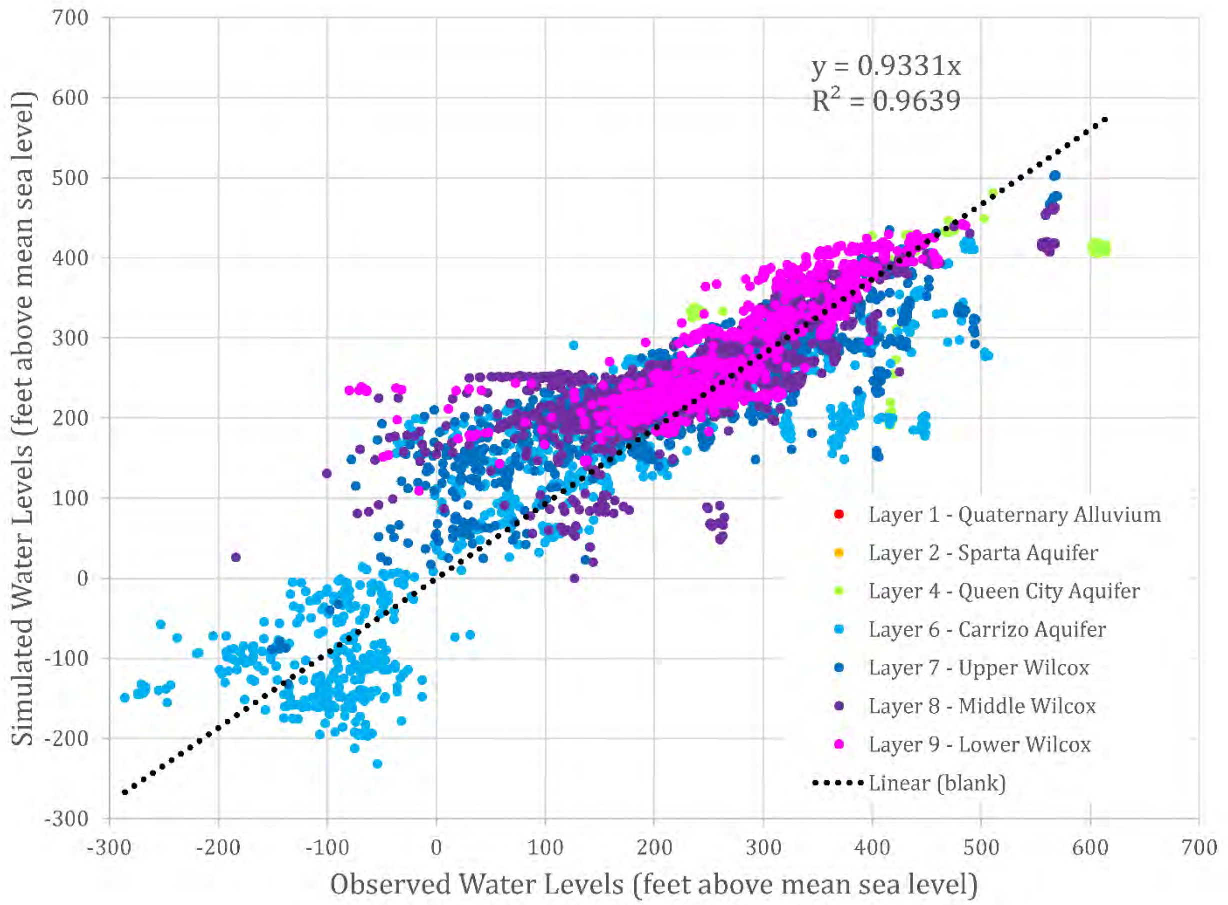
2013



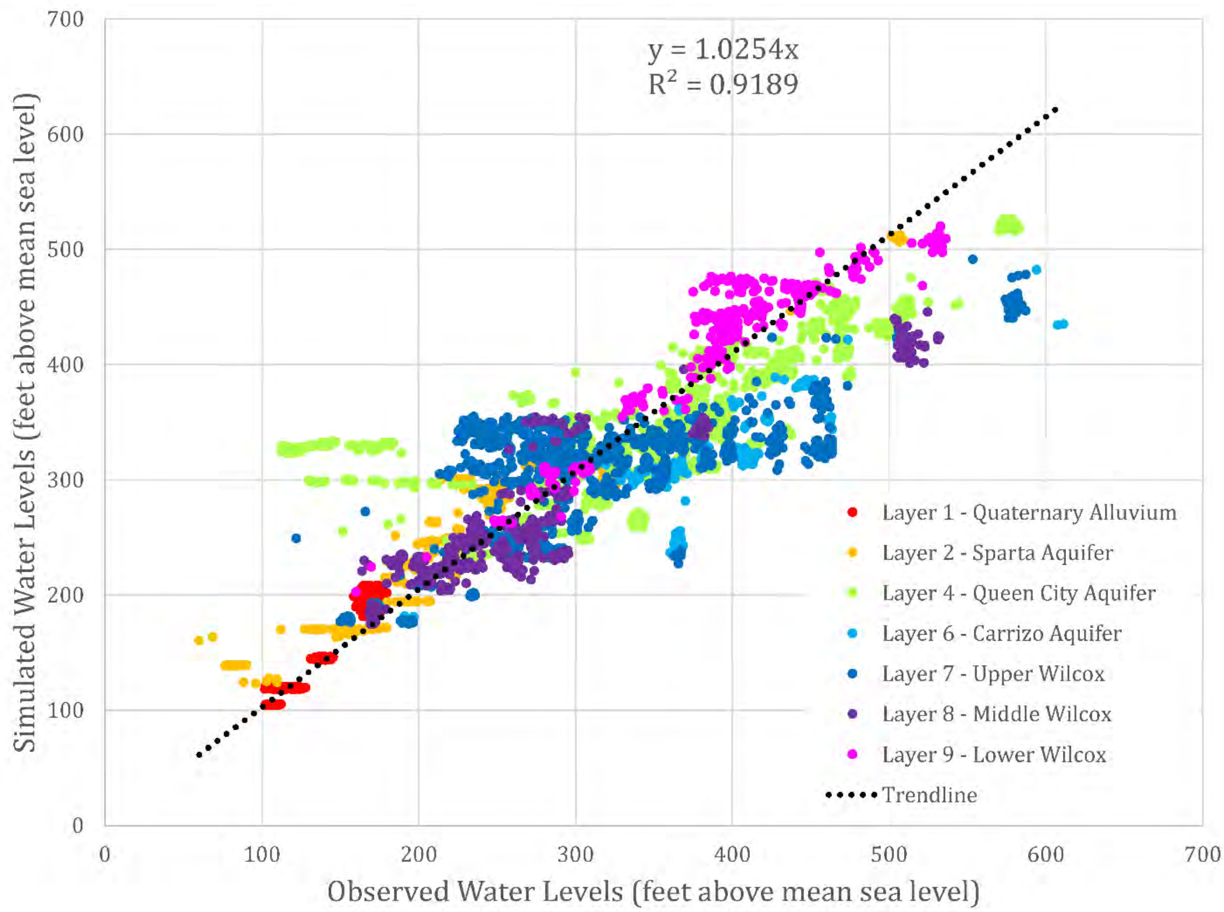
Appendix C Figure 3.2-6. Observed vs. Simulated Unconfined Water Level Elevations for Calibrated 1980 and 2013 Conditions



Appendix C Figure 3.2-7. Observed vs. Simulated Water Level Elevations for the Calibrated 1980 to 2013 Simulation



Appendix C Figure 3.2-8. Observed vs. Simulated Confined Water Level Elevations for the Calibrated 1980 to 2013 Simulation



Appendix C Figure 3.2-9. Observed vs. Simulated Unconfined Water Level Elevations for the Calibrated 1980 to 2013 Simulation

Appendix C Figure 3.2-10 shows the unconfined water level regression plot for the 1980 through 2013 simulation period and plots the subset of unconfined wells which are overlain by the Quaternary Alluvium (model layer 1). There is no bias noted for unconfined targets overlain by Quaternary Alluvium.

Appendix C Figures 3.2-11a through 11c show the observed versus simulated water levels for the 1980 through 2013 simulation period for each aquifer layer. The regression coefficient (R^2) for the plots range from about 0.86 to 0.99, indicating a good match between observed and simulated values in all layers. The Queen City Aquifer (Layer 4) showed the poorest match with a regression coefficient of 0.86 while other aquifer layers had regression coefficients above 0.95.

3.2.2 Spatial Distribution and Frequency of Residuals

The spatial distribution of head residuals for the 1980 through 2013 simulation period is shown for target wells without quality control issues on Appendix C Figure 3.2-12. This figure plots 541 of the 1,797 total targets used for model calibration which had no issues and an average weight of 1.

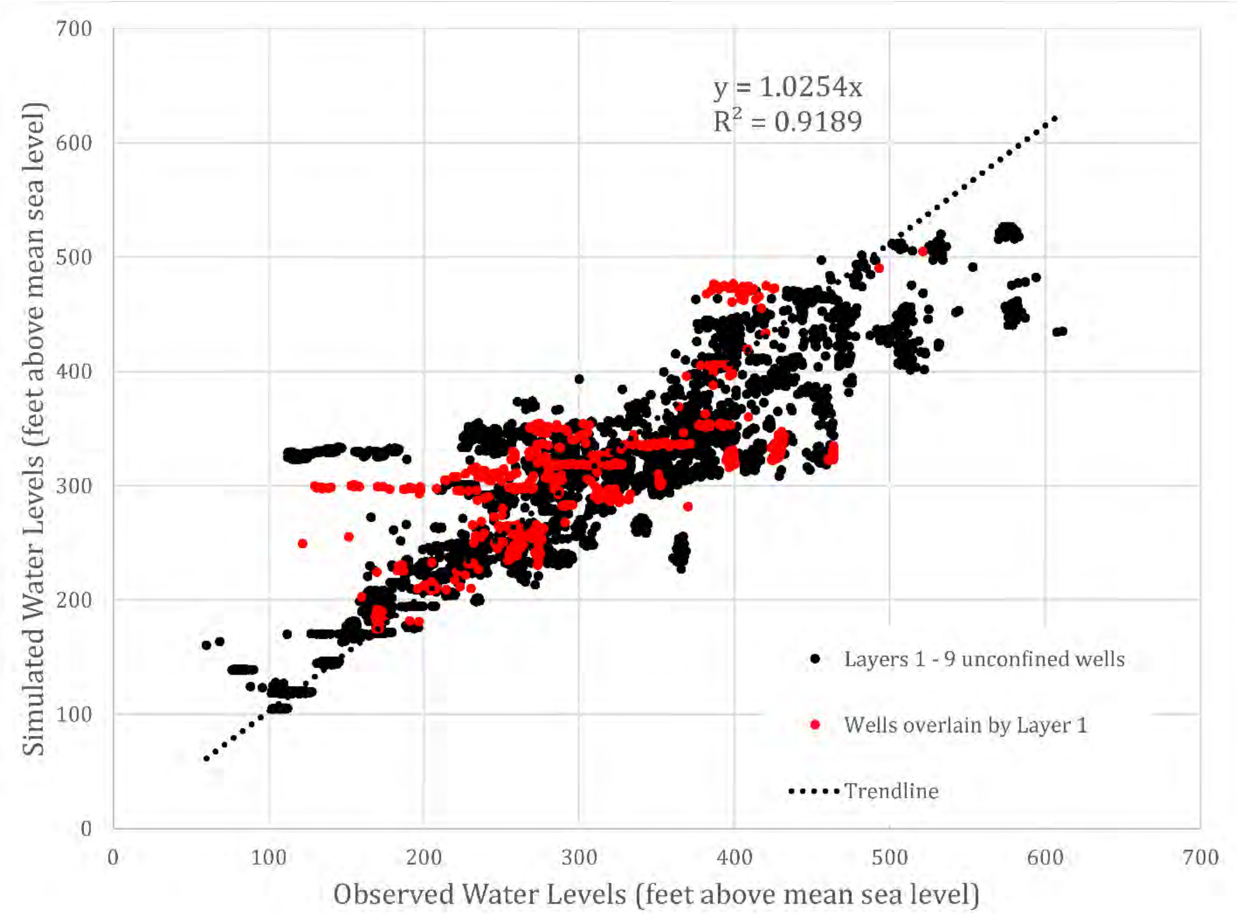
The residual values plotted at each well are an average of all residuals (from 1980 to 2013) at that well. Residuals at these 541 wells range from -249 to 257 feet. Large clusters of residuals occur in Rusk, Smith, and Van Zandt counties. These counties have high pumping rates as shown on the Numerical Model Report Figures 2.7-2 through 2.7-7 (Panday and others, 2020). In general, negative and positive residuals are evenly distributed across the model domain with no noticeable bias.

Appendix C Figures 3.2-13a and 3.2-13b show the frequency of residual values by model aquifer layer (Layers 1, 2, 4, 6, 7, 8, and 9). Residuals cluster around a value of zero except model layer 4 (Queen City Aquifer) where residuals erred both higher and lower, and show only a minimal match to the layer observed water level elevations. The lower model layers (Carrizo Aquifer and Wilcox Aquifer) have more water level elevation data and also showed more spread in residual values but no noticeable bias towards high or low residuals.

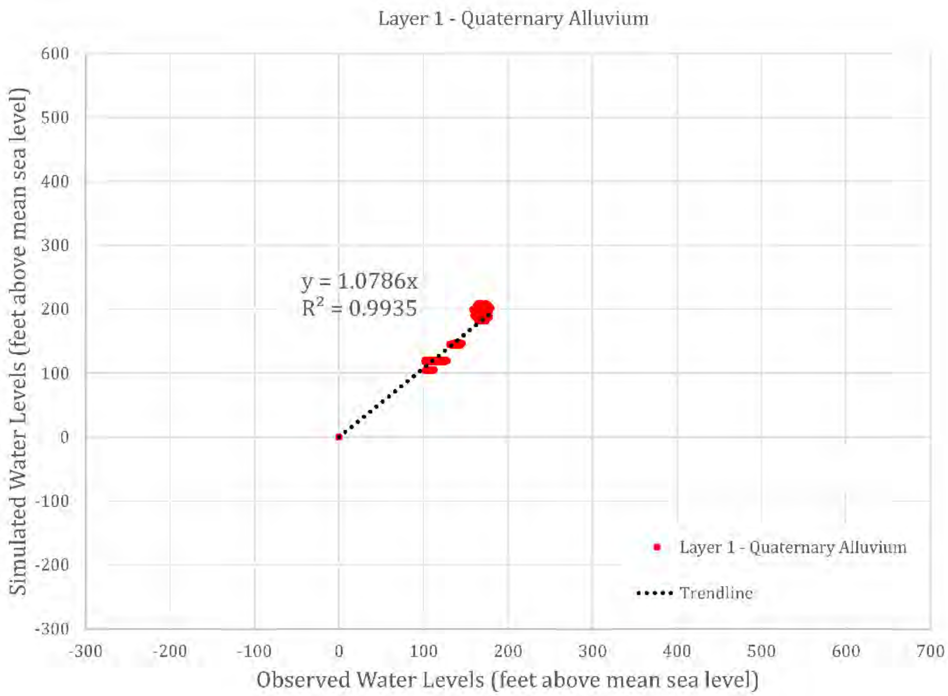
3.2.3 Water Level Hydrographs

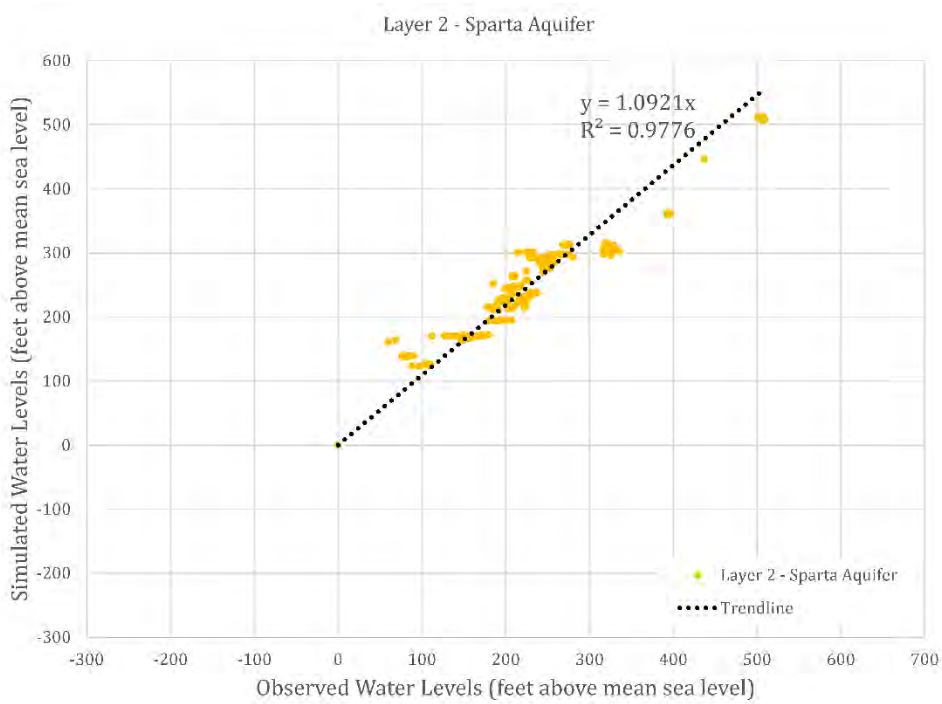
Appendix C Figures 3.2-14 through 3.2-20 show the observed and simulated hydrographs for select wells with observations spanning the simulation period from 1980 through 2013 within the various aquifer units. Observed water level fluctuations are generally similar in frequency and amplitude. Simulated water level elevations match well to observed in the Quaternary Alluvium (model layer 1) except in the northern-most well in Caddo County where simulated water levels are higher than observed, (as shown on Appendix C Figure 3.2-14).

Simulated water level elevations in the Sparta Aquifer (model layer 2) are higher and lower compared to observed, depending on the location (Appendix C Figure 3.2-15). However, fluctuations are of similar magnitude. Simulated water level elevations in the Queen City Aquifer (model layer 4) are generally lower than observed to the north and higher to the south, but general water level trends and fluctuations match observed trends and amplitudes, as shown on Appendix C Figure 3.2-16. Simulated water level elevations in the

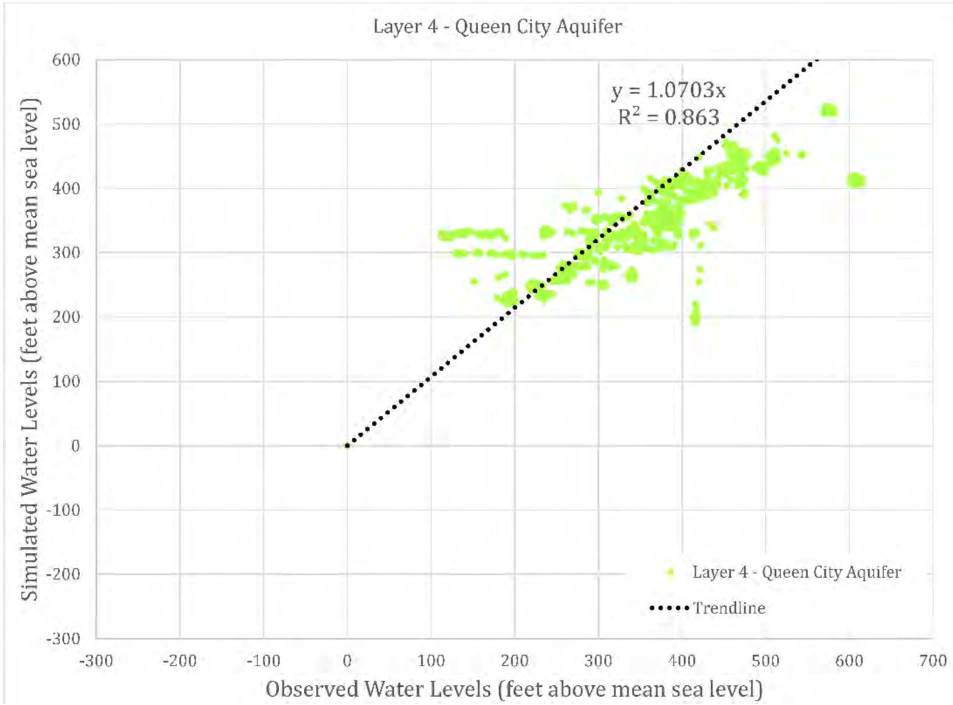


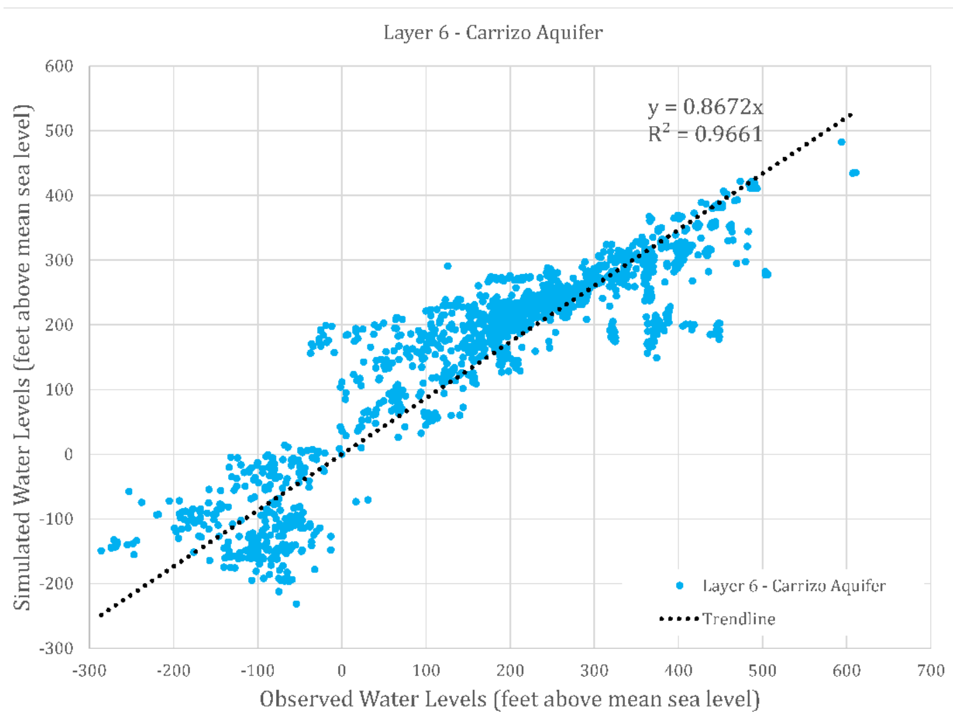
Appendix C Figure 3.2-10. Observed vs. Simulated Unconfined Water Level Elevations for the Calibrated 1980 to 2013 Simulation Showing Wells Overlain by Layer 1



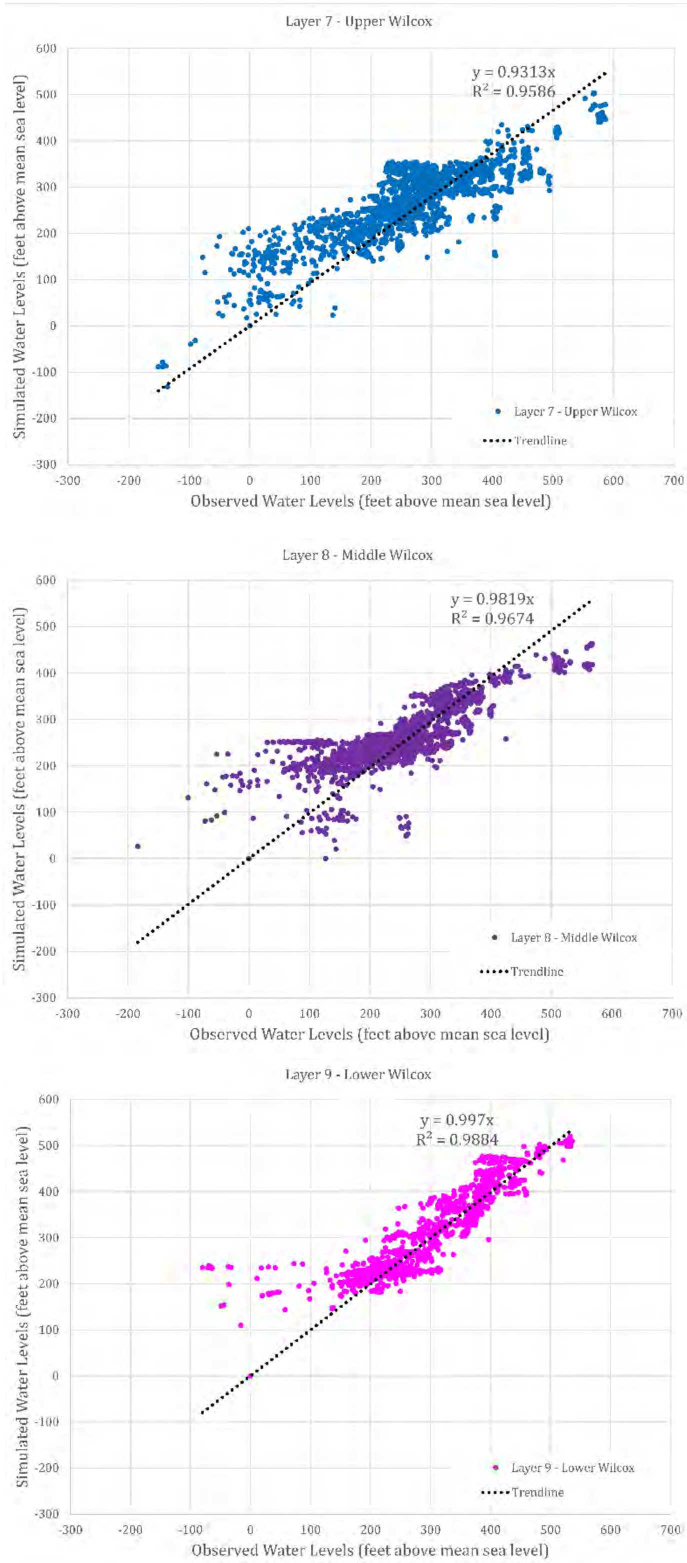


Appendix C Figure 3.2-11a. Observed vs. Simulated Water Level Elevations for the Calibrated 1980 to 2013 Simulation by Layer

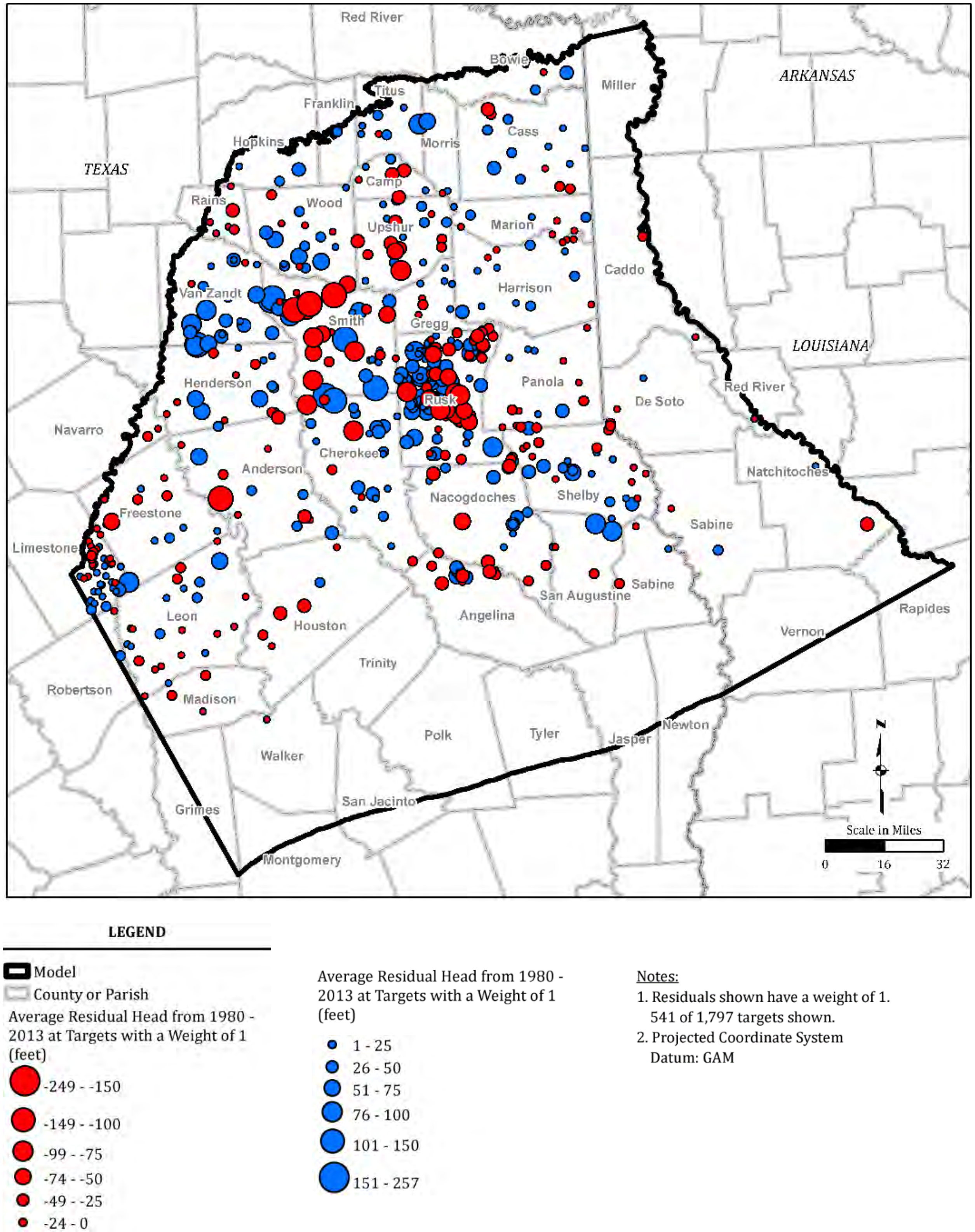




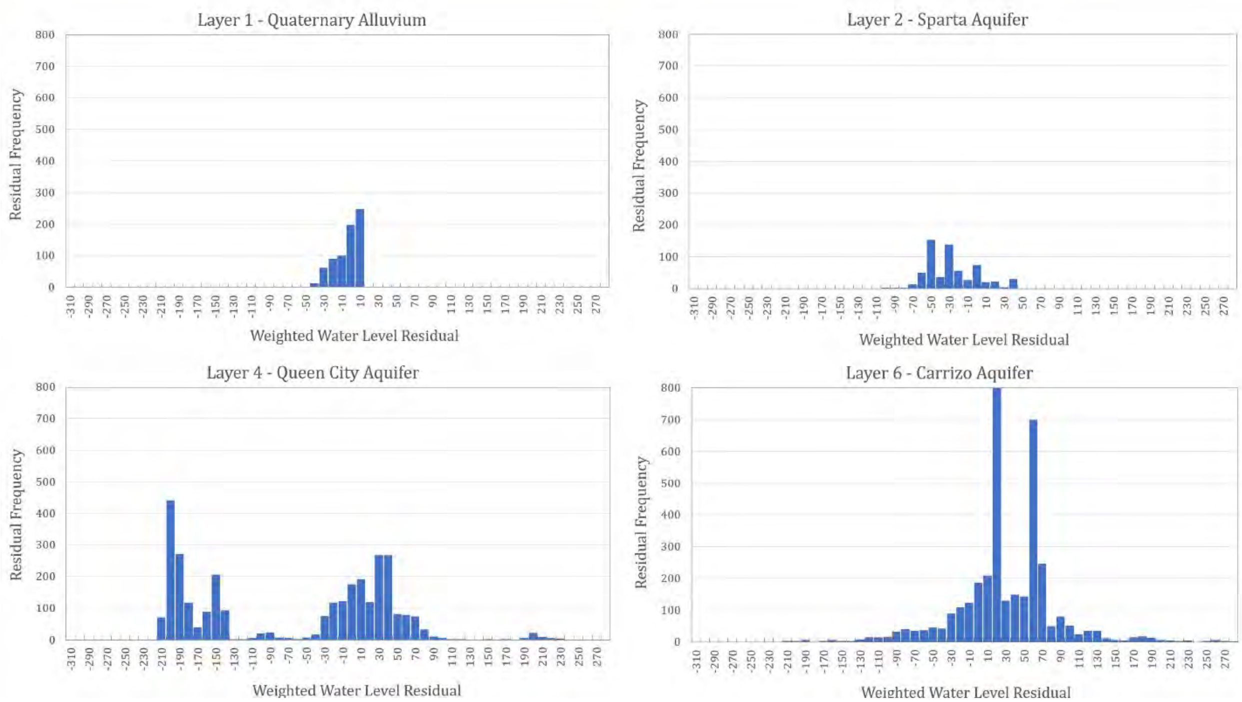
Appendix C Figure 3.2-11b. Observed vs. Simulated Water Level Elevations for the Calibrated 1980 to 2013 Simulation by Layer



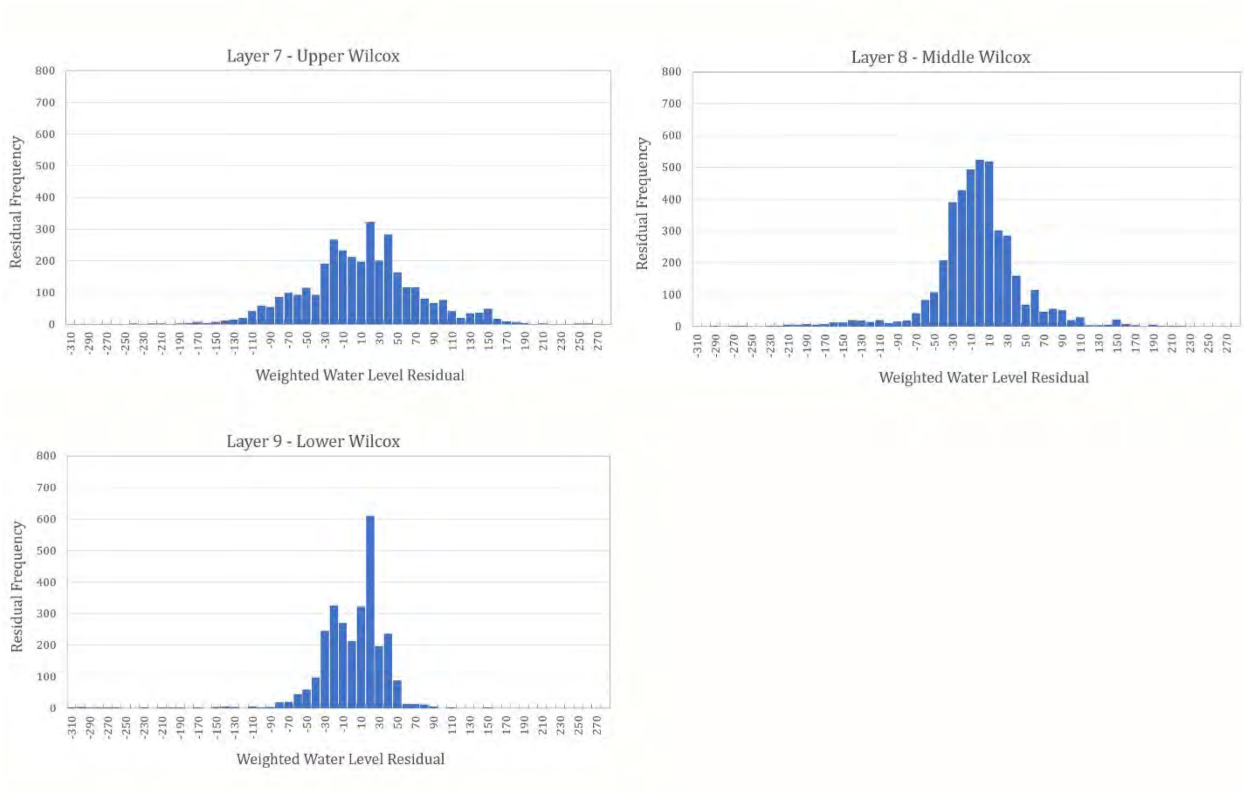
Appendix C Figure 3.2-11c. Observed vs. Simulated Water Level Elevations for the Calibrated 1980 to 2013 Simulation by Layer



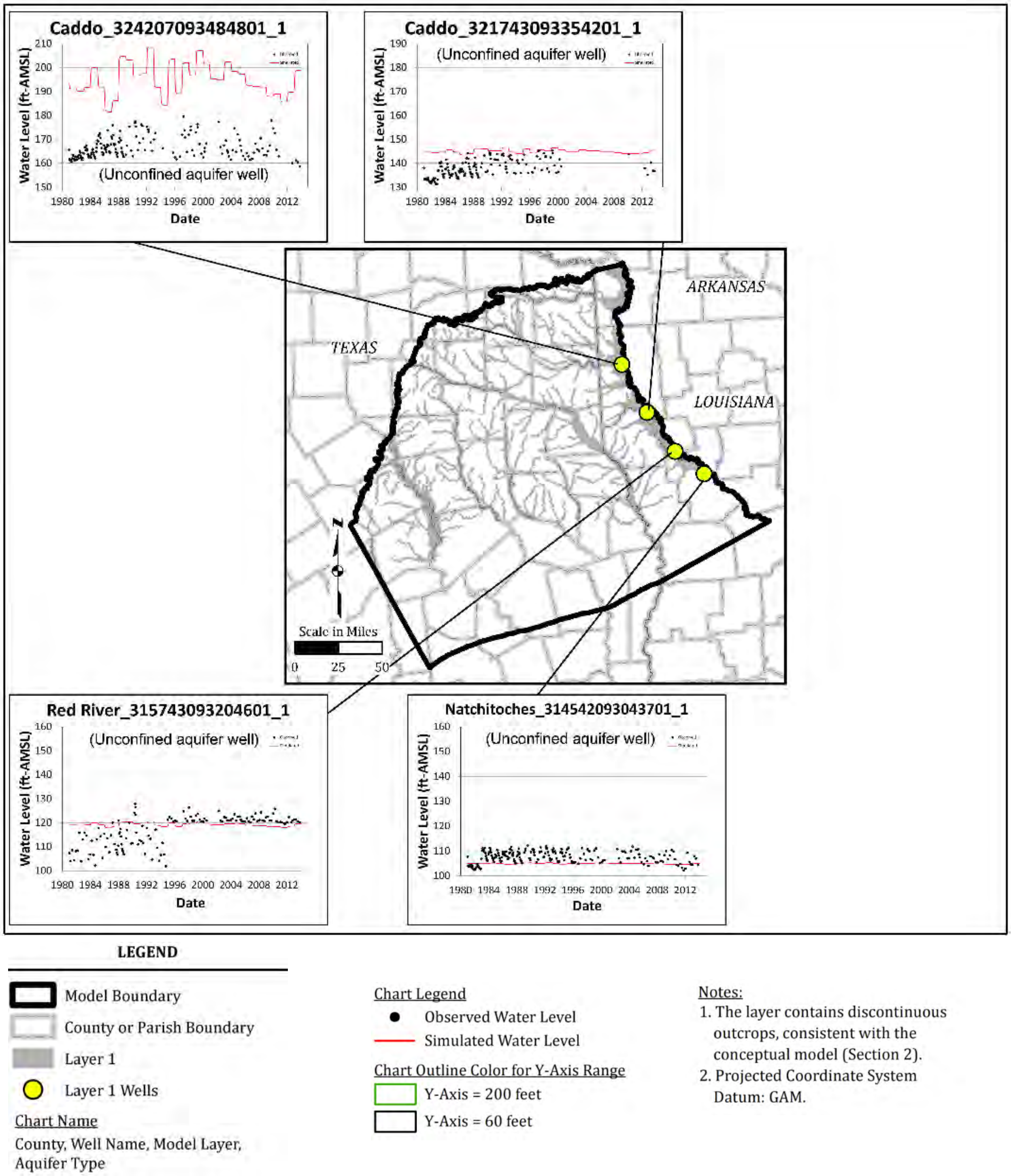
Appendix C Figure 3.2-12. Distribution of Water Level Elevation Errors for the Calibrated 1980 to 2013 Simulation at Weight = 1



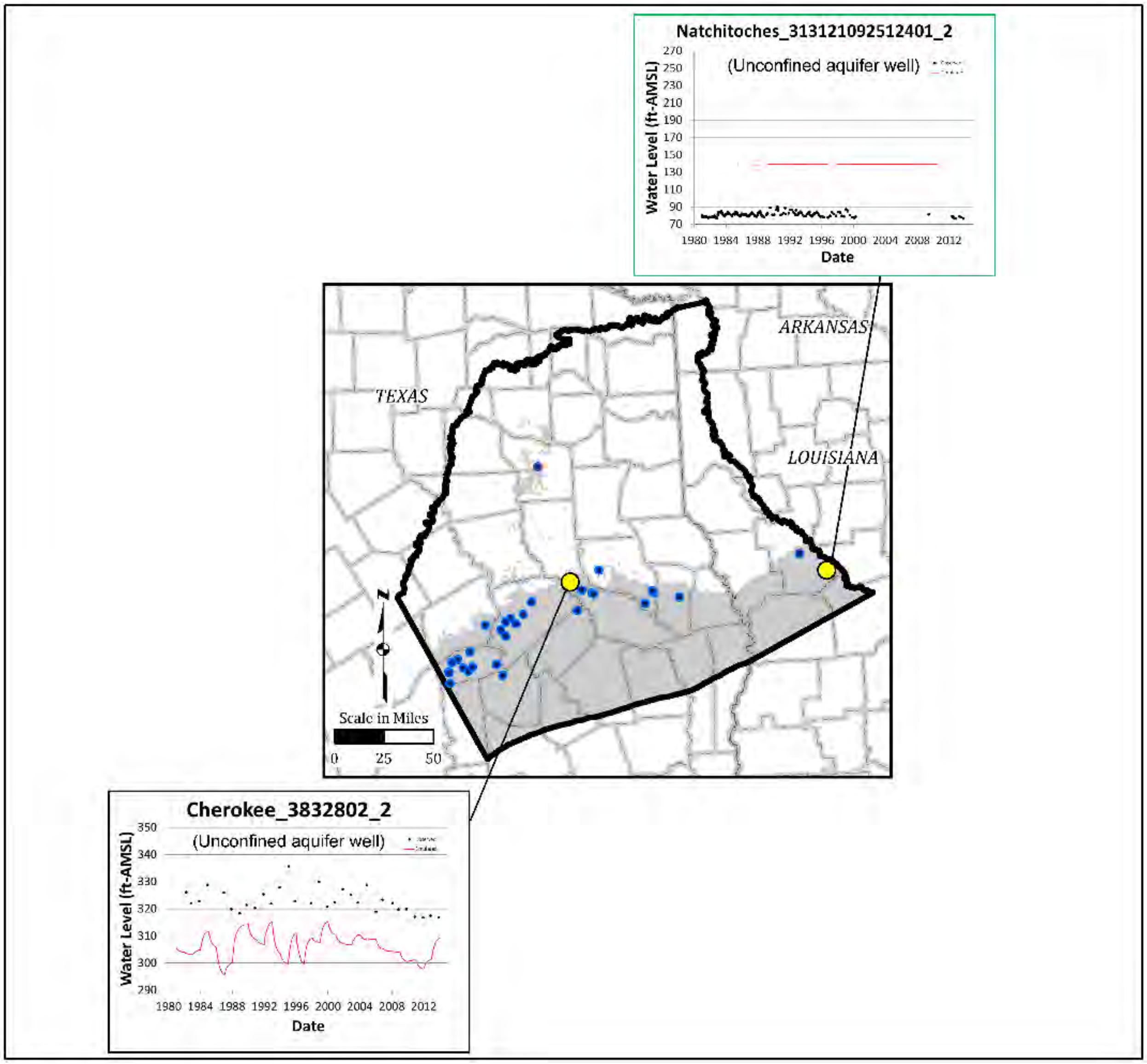
Appendix C Figure 3.2-13a. Histograms of Water Level Elevation Residuals by Layer



Appendix C Figure 3.2-13b. Histograms of Water Level Elevation Residuals by Layer



Appendix C Figure 3.2-14. Measured and Simulated Water Level Elevation Hydrographs for Select Wells – Quaternary Alluvium (Layer 1)



LEGEND

Model
County or Parish Boundary
Layer 2
Select Layer 2
Layer 2

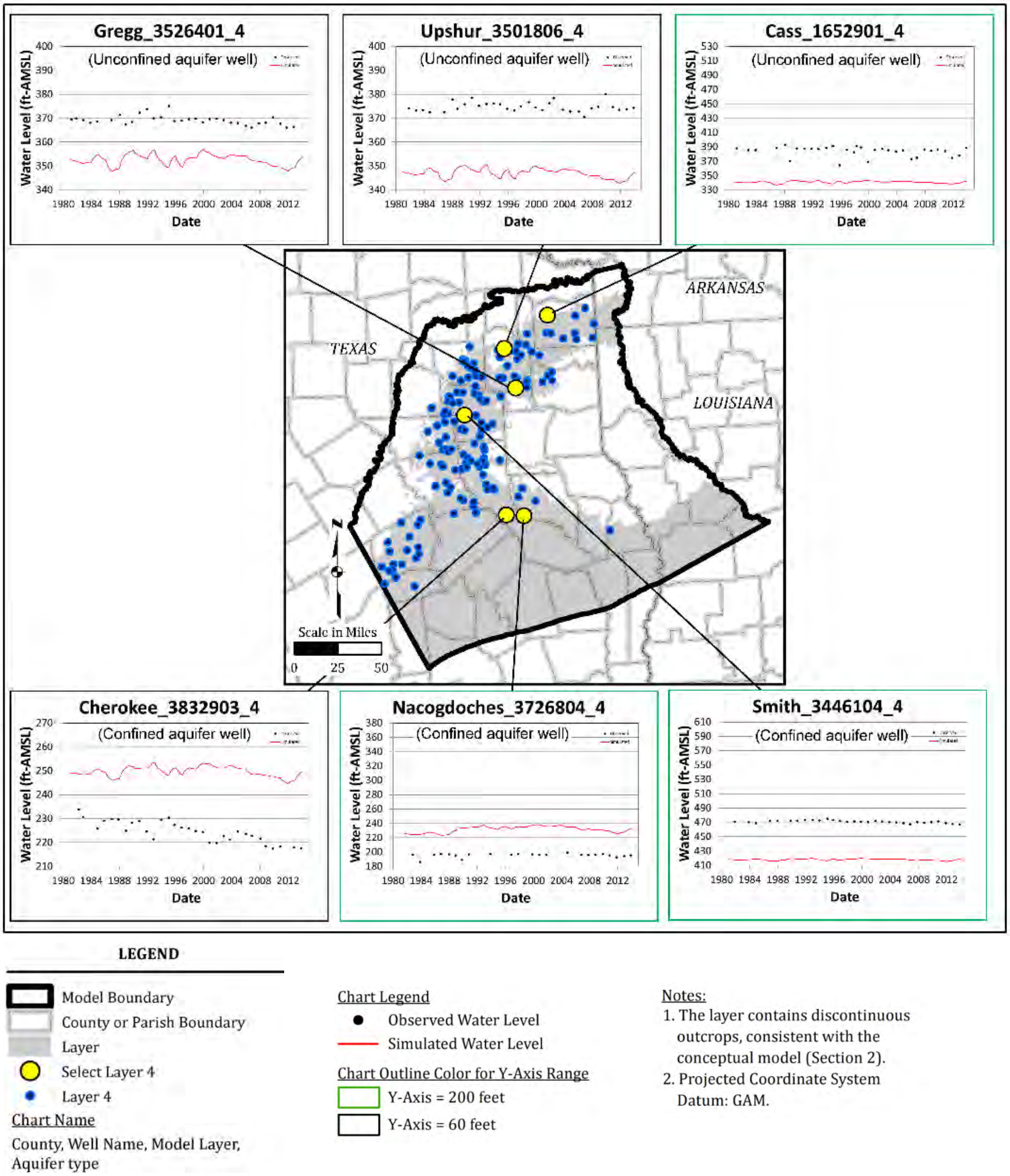
Chart Name
County, Well Name, Model Layer, Aquifer Type

Chart Legend
Observed Water Level
Simulated Water Level

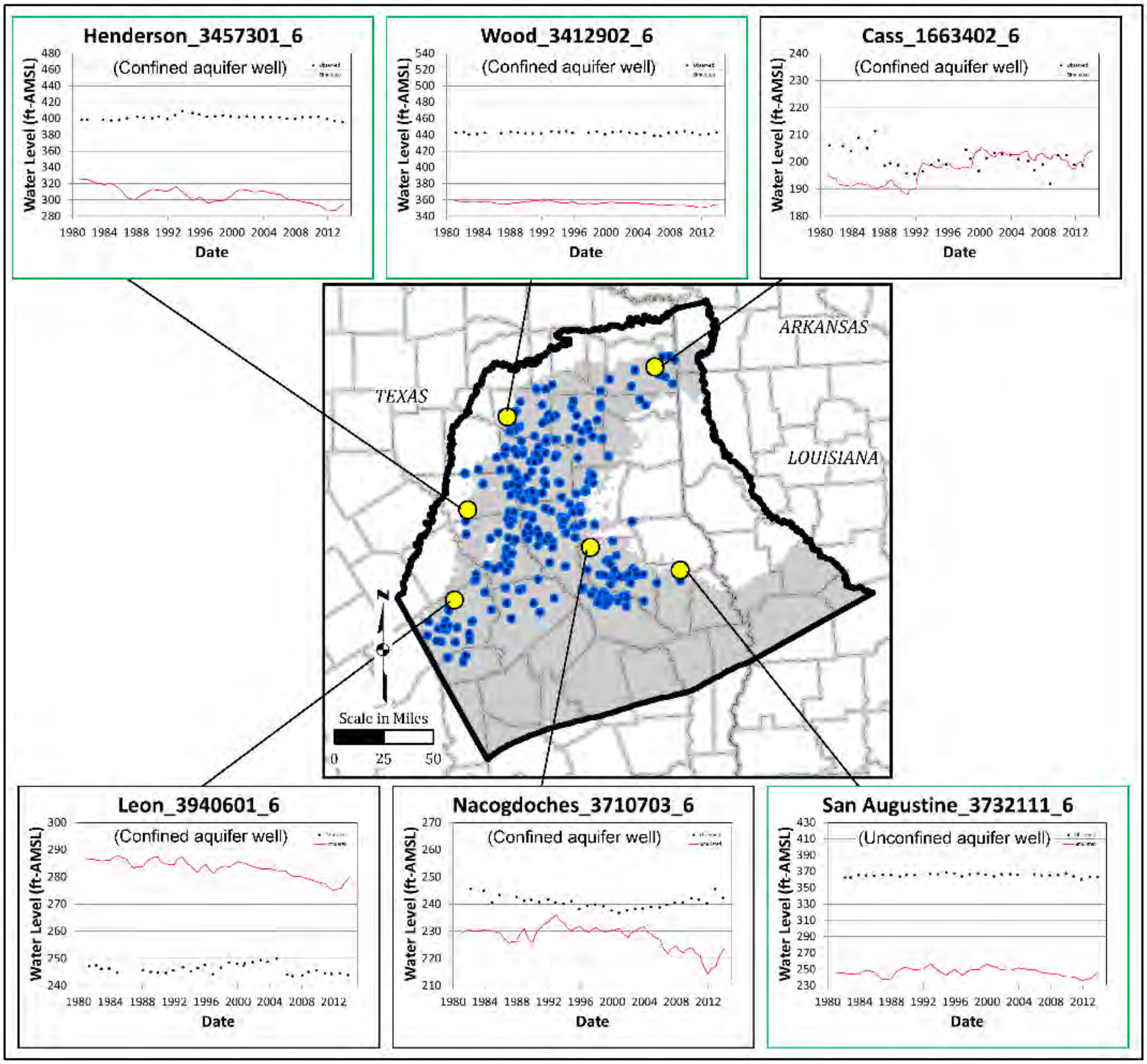
Chart Outline Color for Y-Axis Range
Y-Axis = 200 feet
Y-Axis = 60 feet

Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-15. Measured and Simulated Water Level Elevation Hydrographs for Select Wells – Sparta Aquifer (Layer 2)



Appendix C Figure 3.2-16. Measured and Simulated Water Level Elevation Hydrographs for Select Wells – Queen City Aquifer (Layer 4)



LEGEND

Model

County or Parish Boundary

Layer 6

Select Layer 6

Layer 6

Chart Name

County, Well Name, Model Layer, Aquifer Type

Chart Legend

Observed Water Level

Simulated Water Level

Chart Outline Color for Y-Axis Range

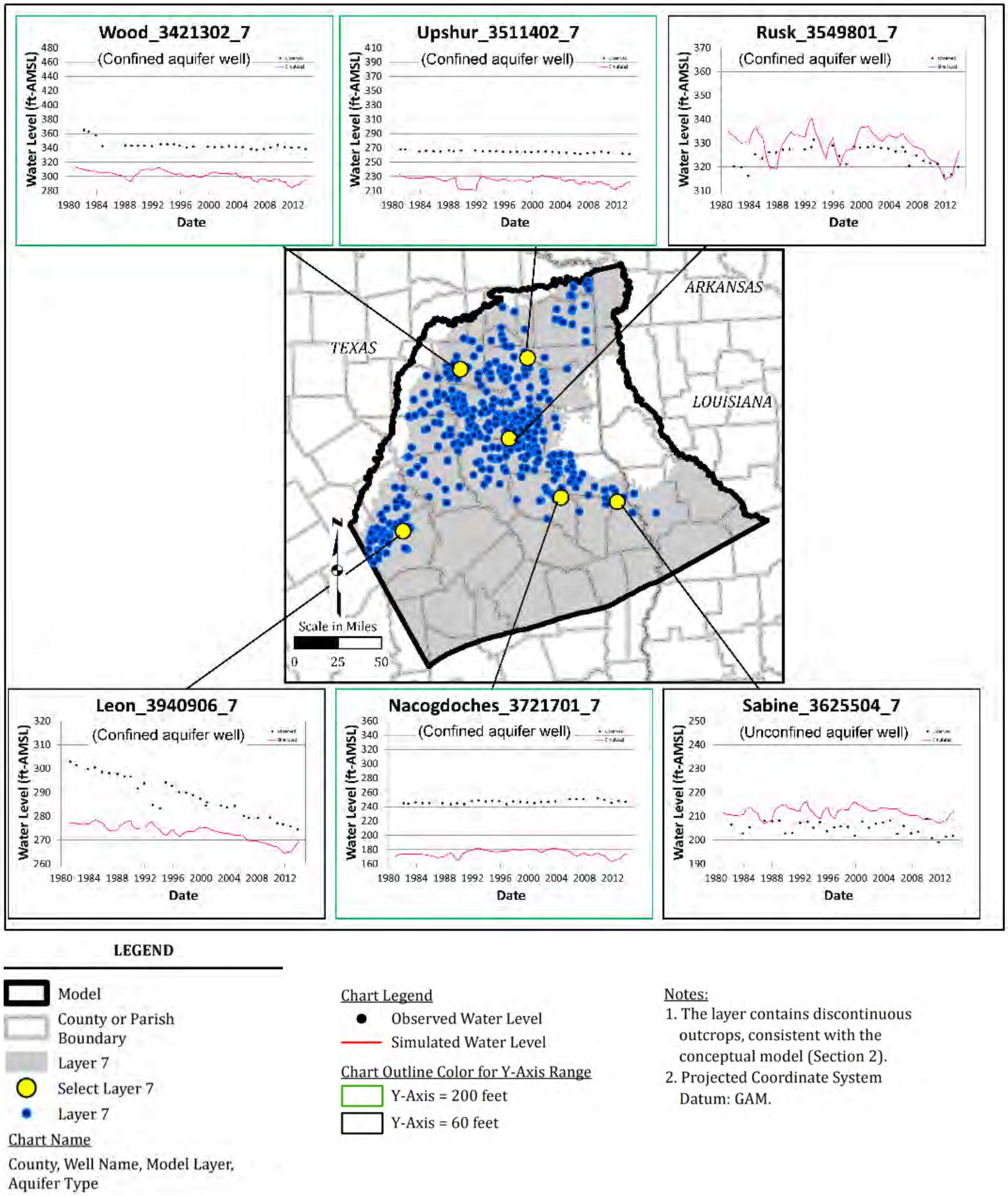
Y-Axis = 200 feet

Y-Axis = 60 feet

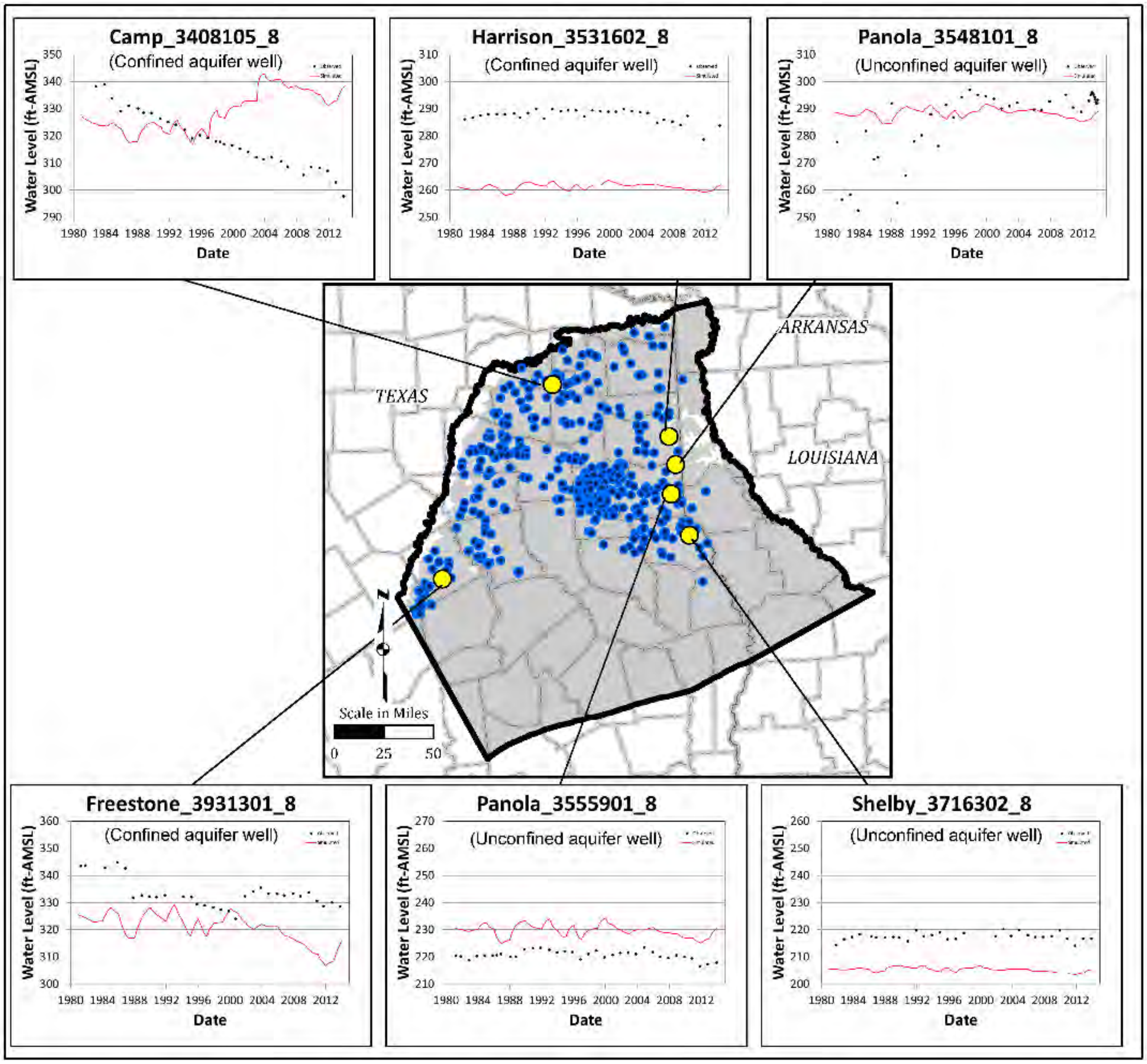
Notes:

1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-17. Measured and Simulated Water Level Elevation Hydrographs for Select Wells – Carrizo Aquifer (Layer 6)



Appendix C Figure 3.2-18. Measured and Simulated Water Level Elevation Hydrographs for Select Wells – Upper Wilcox (Layer 7)



LEGEND

Model
County or Parish Boundary
Layer 8
Select Layer 8
Layer 8

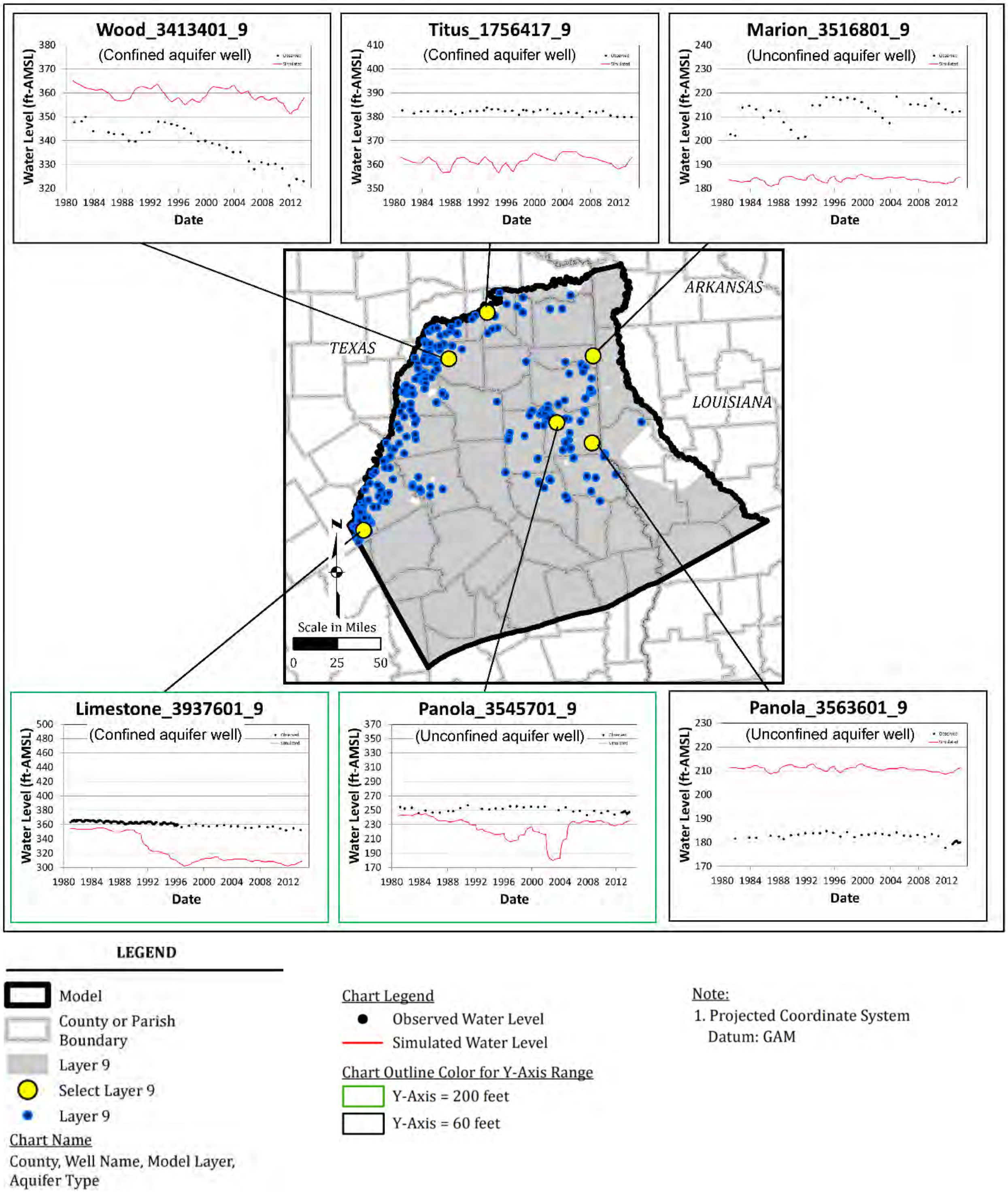
Chart Name
County, Well Name, Model Layer, Aquifer Type

Chart Legend
Observed Water Level
Simulated Water Level

Chart Outline Color for Y-Axis Range
Y-Axis = 200 feet
Y-Axis = 60 feet

Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-19. Measured and Simulated Water Level Elevation Hydrographs for Select Wells – Middle Wilcox (Layer 8)



Appendix C Figure 3.2-20. Measured and Simulated Water Level Elevation Hydrographs for Select Wells – Lower Wilcox (Layer 9)

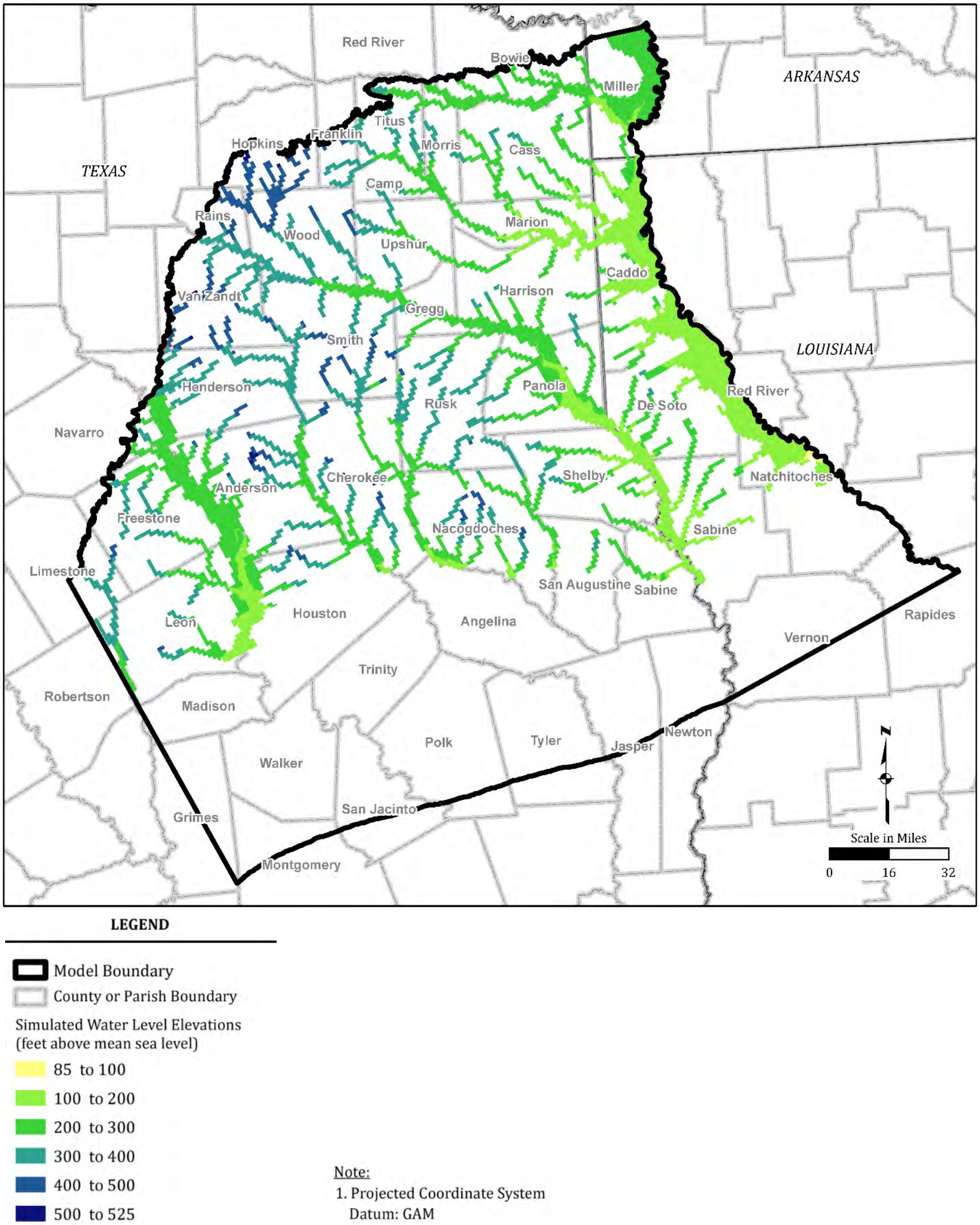
Carrizo Aquifer (model layer 6) are generally lower than observed water level elevations, except for Cass County where simulated and observed water levels match well and Leon county where simulated water levels are greater than observed, as shown on Appendix C Figure 3.2-17.

Simulated water level elevations in the Upper Wilcox (model layer 7) are generally lower than observed water level elevations, except for Sabine and Rusk counties where simulated and observed water levels match well, as shown on Appendix C Figure 3.2-18. Frequency and amplitude of fluctuations are similar at most wells except the well in Leon County where simulated water level declines are smaller than measured. Simulated water level elevations in the Middle Wilcox (model layer 8) generally match well to observed water level elevations, except for Camp county, where the simulated water levels do not follow the observed water level trend, as shown on Appendix C Figure 3.2-19. A better definition of increase in pumping through time in that area would better match the observed decline in water levels during the simulation period. Simulated water level elevations in model layer 9 are higher than observed at some wells and lower in others, as shown on Appendix C Figure 3.2-20. The simulated water level elevations in Panola County show a dip in 2003 that is not shown in the observed data. Appendix A of this report provides water level hydrographs for target wells with no quality control issues (all water level elevations with a calibration target weight of 1) and also containing 30 or more observed water level elevations at the well.

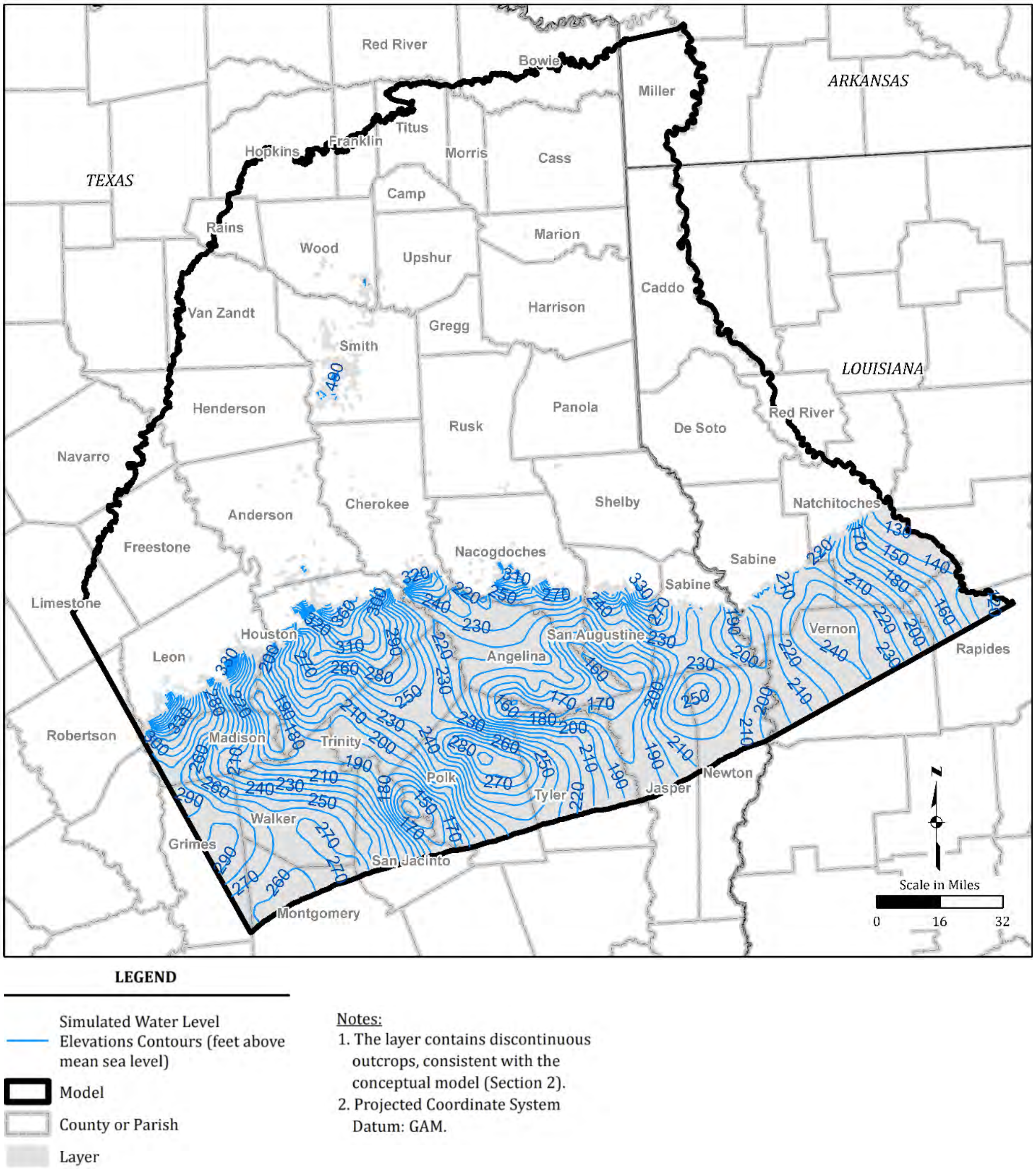
3.2.4 Simulated Water Levels

Appendix C Figures 3.2-21 through 3.2-29 show the simulated water level elevations in the 9 modeled layers, respectively, at the end of the simulation period in 2013. Water level elevations show water flows generally to the southern boundary in all layers. Model layer 1, representing the Quaternary Alluvium, reflects flow in the river channels, as shown on Appendix C Figure 3.2-21. Water level contours in deeper units show drawdown cones at pumping wells. The northern portion of the Queen City Aquifer shows numerous water level nonconformities Appendix C Figure 3.2-24. There is a large simulated cone of depression extending across Angelina and Nacogdoches counties in the Carrizo Aquifer and Wilcox Aquifers (layers 6 through 9), as shown on Appendix C Figure 3.2-26 through 3.2-29. Slightly smaller drawdown cones are noted in Smith County within the Carrizo Sand and Wilcox Aquifers (model layers 6 through 9).

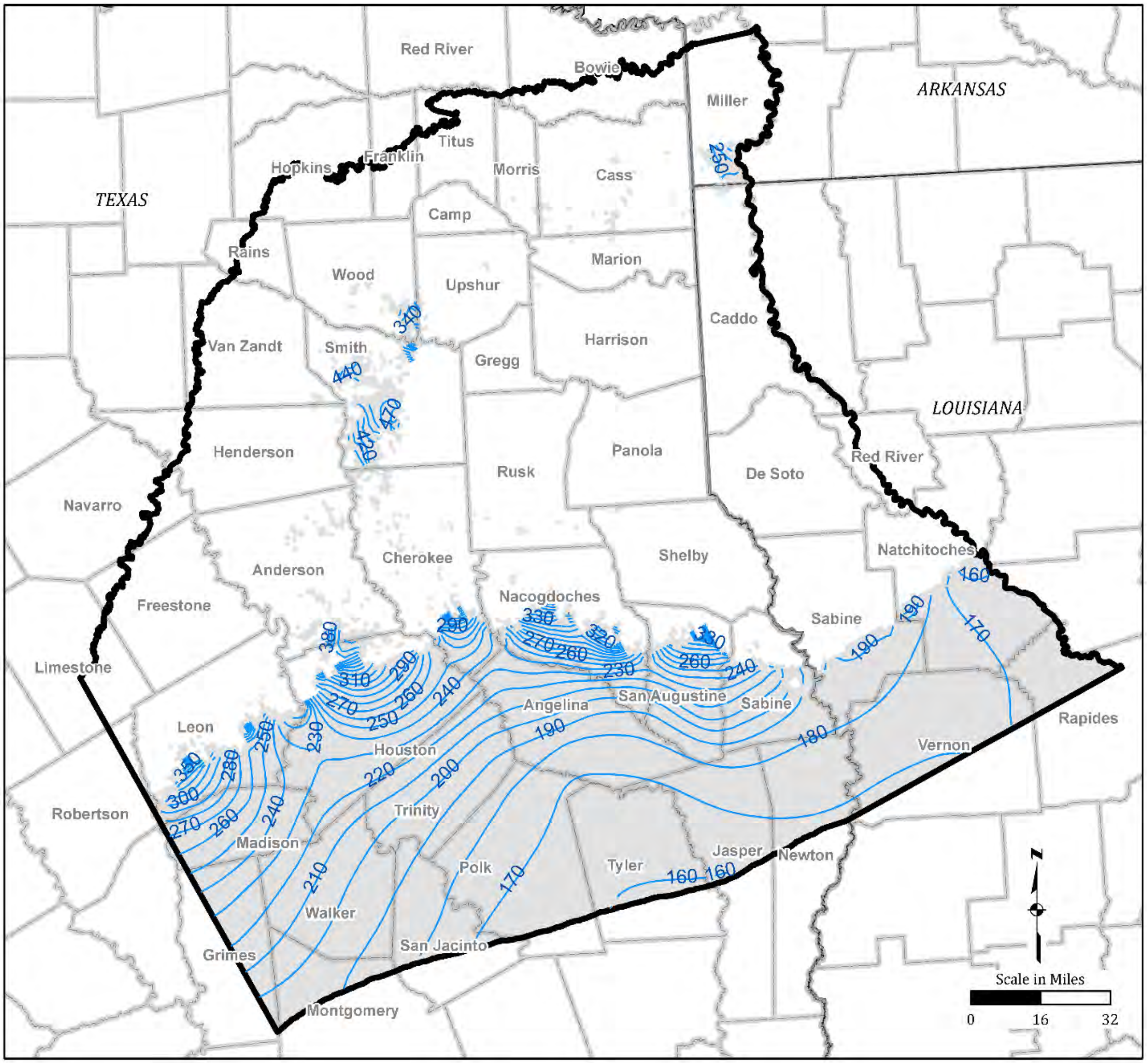
Appendix C Figures 3.2-30 through 3.2-38 show the change in water levels within each layer from 1980 to 2013. Generally, water level changes in the upper four layers, the Quaternary Alluvium (model layer 1) to the Queen City Aquifer (model layer 4), are small with most changes within 10 feet and limited pockets of greater water level change such as in Wood County, as shown on Appendix C Figures 3.2-30 through 3.2-33. Generally, water level changes in the lower five layers, the Reklaw Formation (model layer 5) to the Lower Wilcox (model layer 9), are larger with a large area in the northern portion of the model, centered about Smith County and extending southward, showing groundwater levels decreasing up to 50 feet, as shown on Appendix C Figures 3.2-34 through 3.2-38.



Appendix C Figure 3.2-21. Simulated Water Level Elevations in Quaternary Alluvium (Layer 1) for 2013



Appendix C Figure 3.2-22. Simulated Water Level Elevation Contours in Sparta Aquifer (Layer 2) for 2013



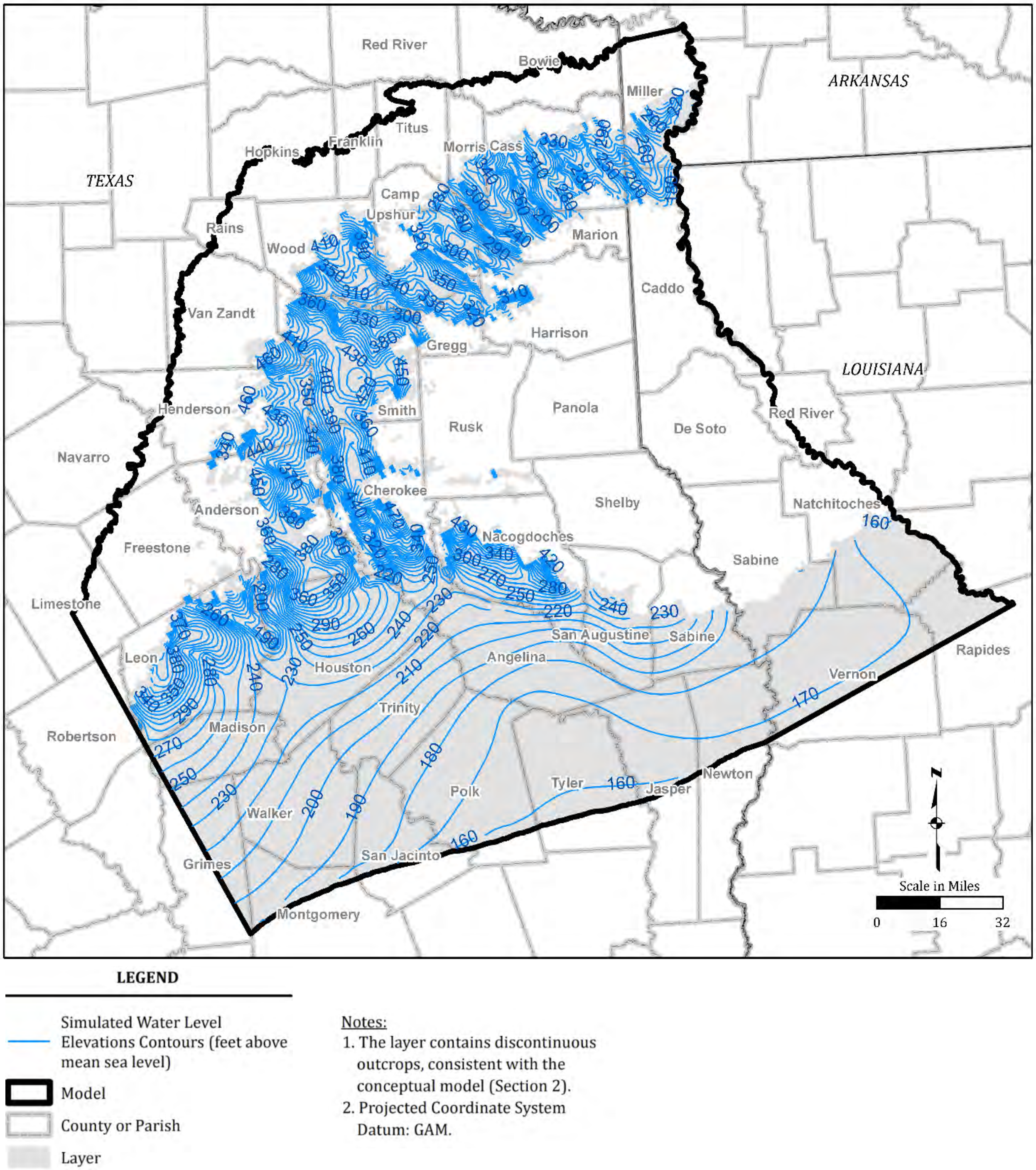
LEGEND

- Simulated Water Level Elevations Contours (feet above mean sea level)
- Model
- County or Parish
- Layer

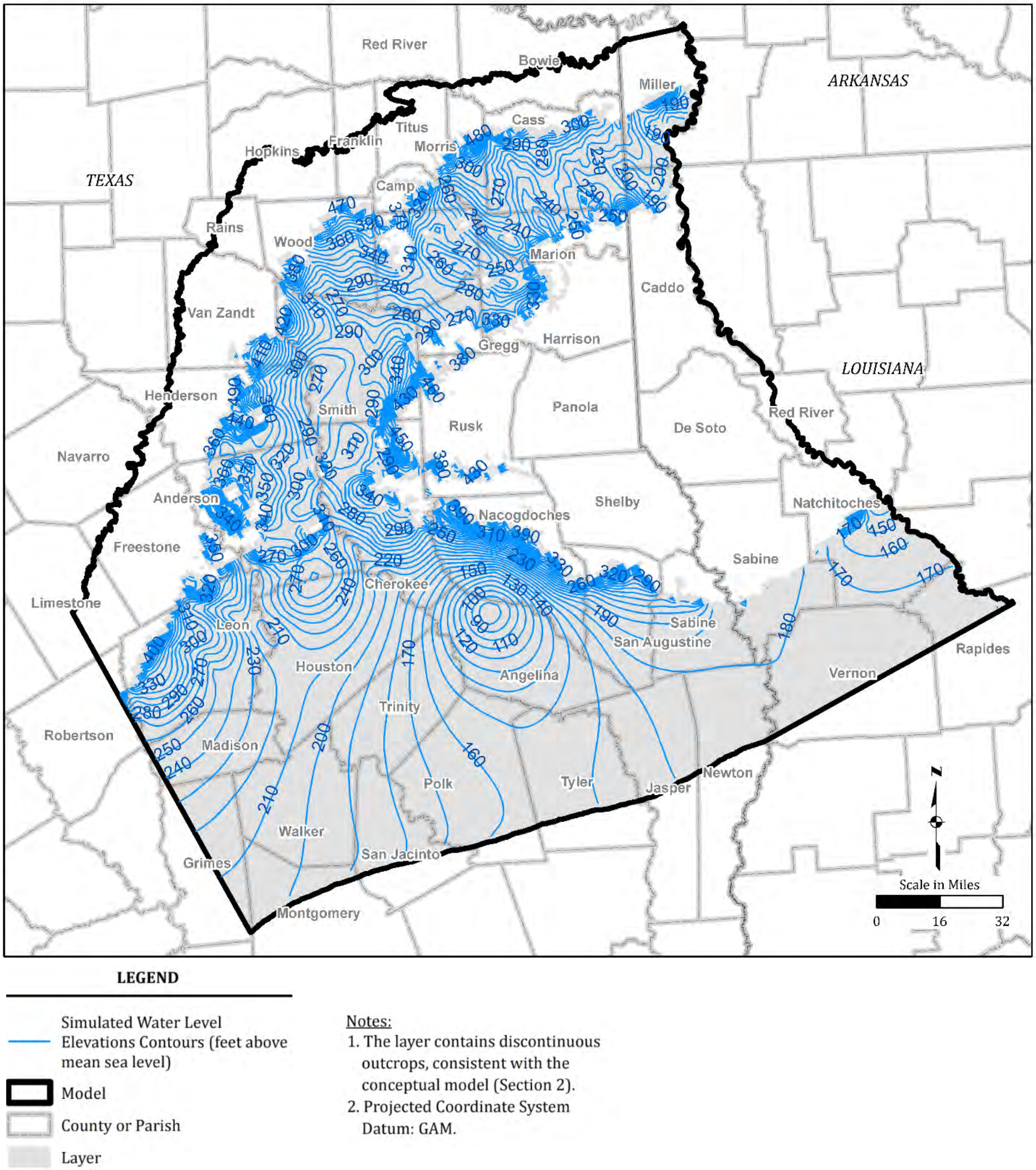
Notes:

1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

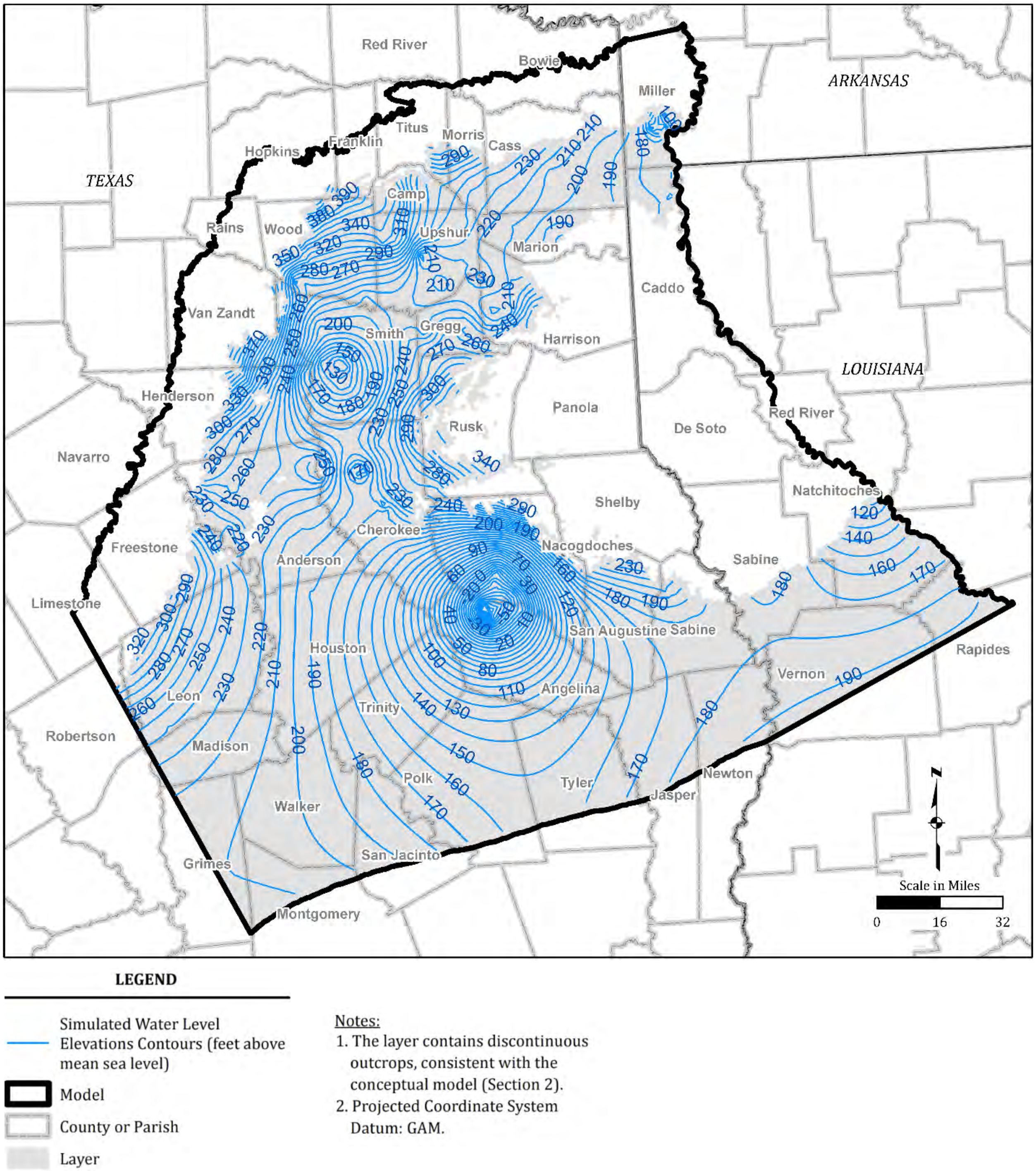
Appendix C Figure 3.2-23. Simulated Water Level Elevation Contours in Weches Formation (Layer 3) for 2013



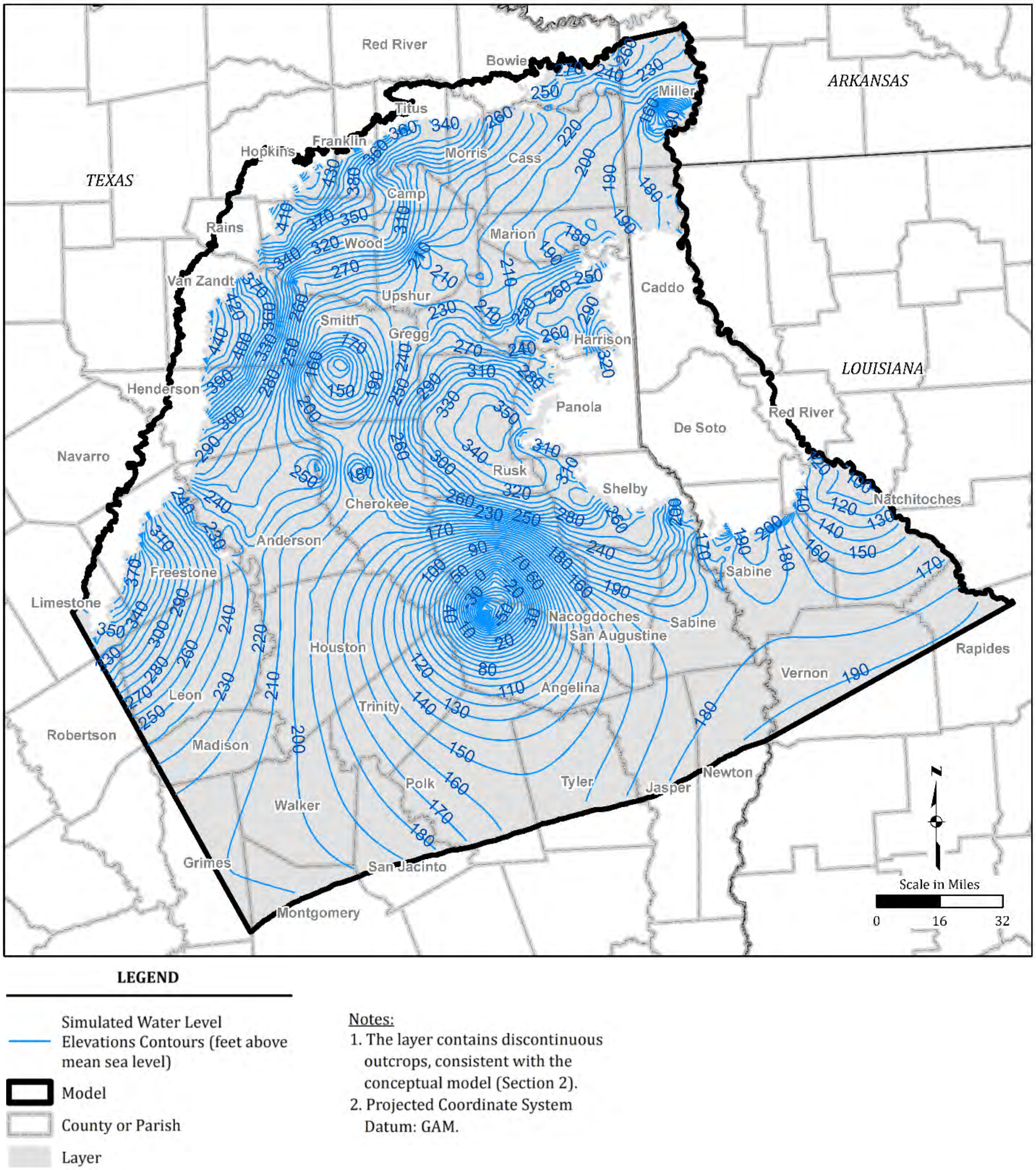
Appendix C Figure 3.2-24. Simulated Water Level Elevation Contours in Queen City Aquifer (Layer 4) for 2013



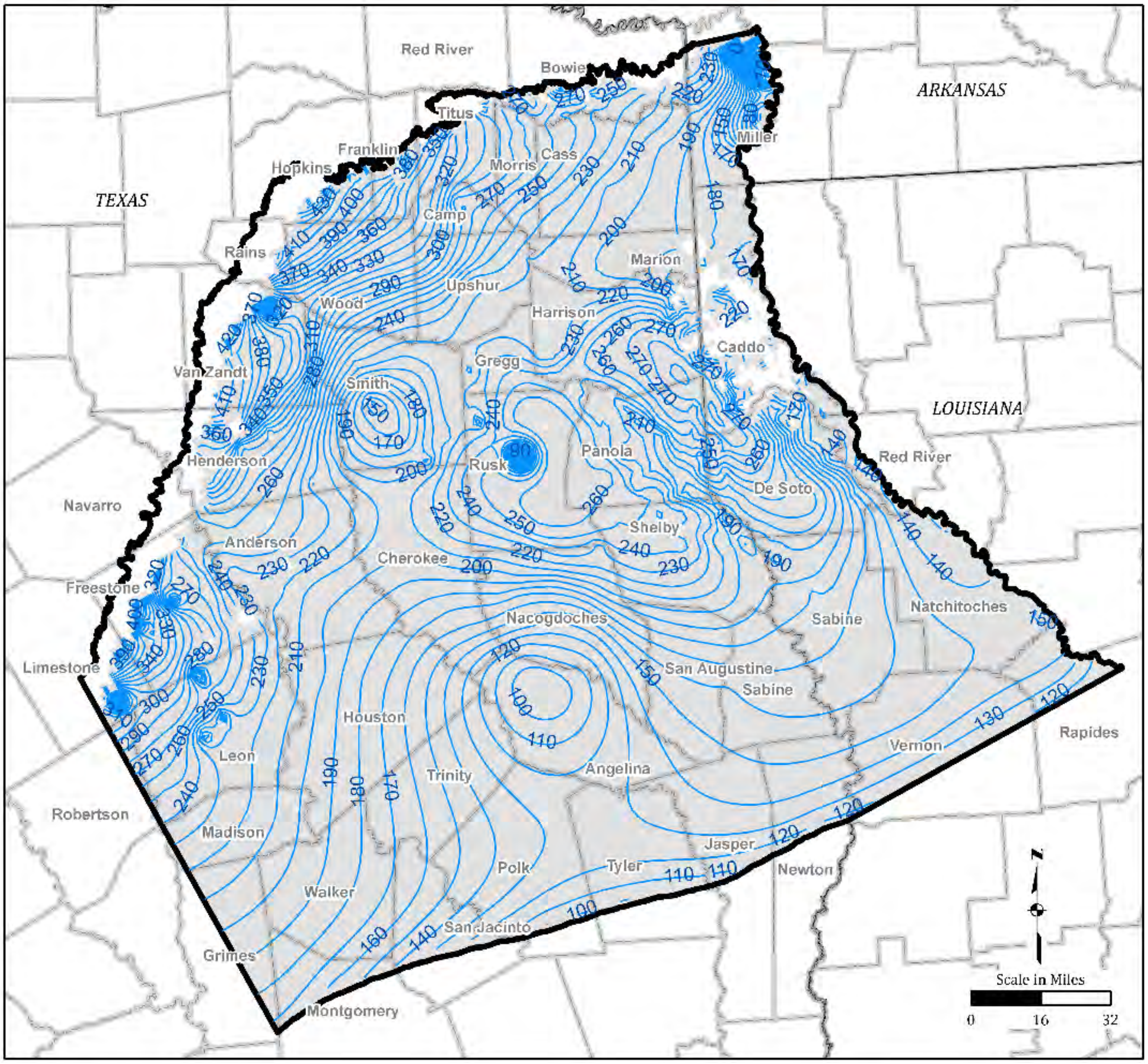
Appendix C Figure 3.2-25. Simulated Water Level Elevation Contours in Reklaw Formation (Layer 5) for 2013



Appendix C Figure 3.2-26. Simulated Water Level Elevation Contours in Carrizo Aquifer (Layer 6) for 2013



Appendix C Figure 3.2-27. Simulated Water Level Elevation Contours in Upper Wilcox (Layer 7) for 2013



LEGEND

Simulated Water Level Elevations Contours (feet above mean sea level)

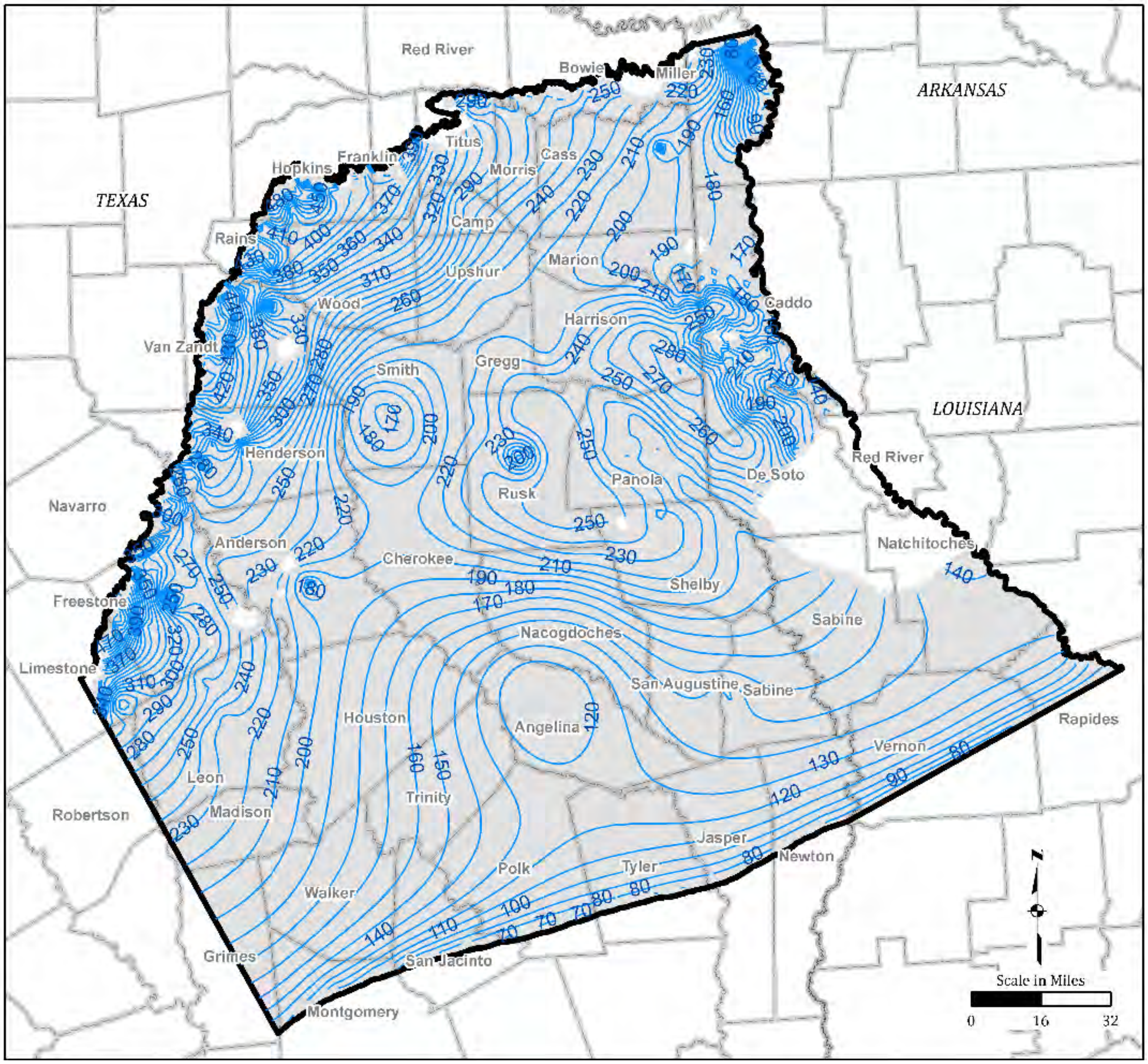
Model

County or Parish

Layer

Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-28. Simulated Water Level Elevation Contours in Middle Wilcox (Layer 8) for 2013



LEGEND

Simulated Water Level Elevations Contours (feet above mean sea level)

Model

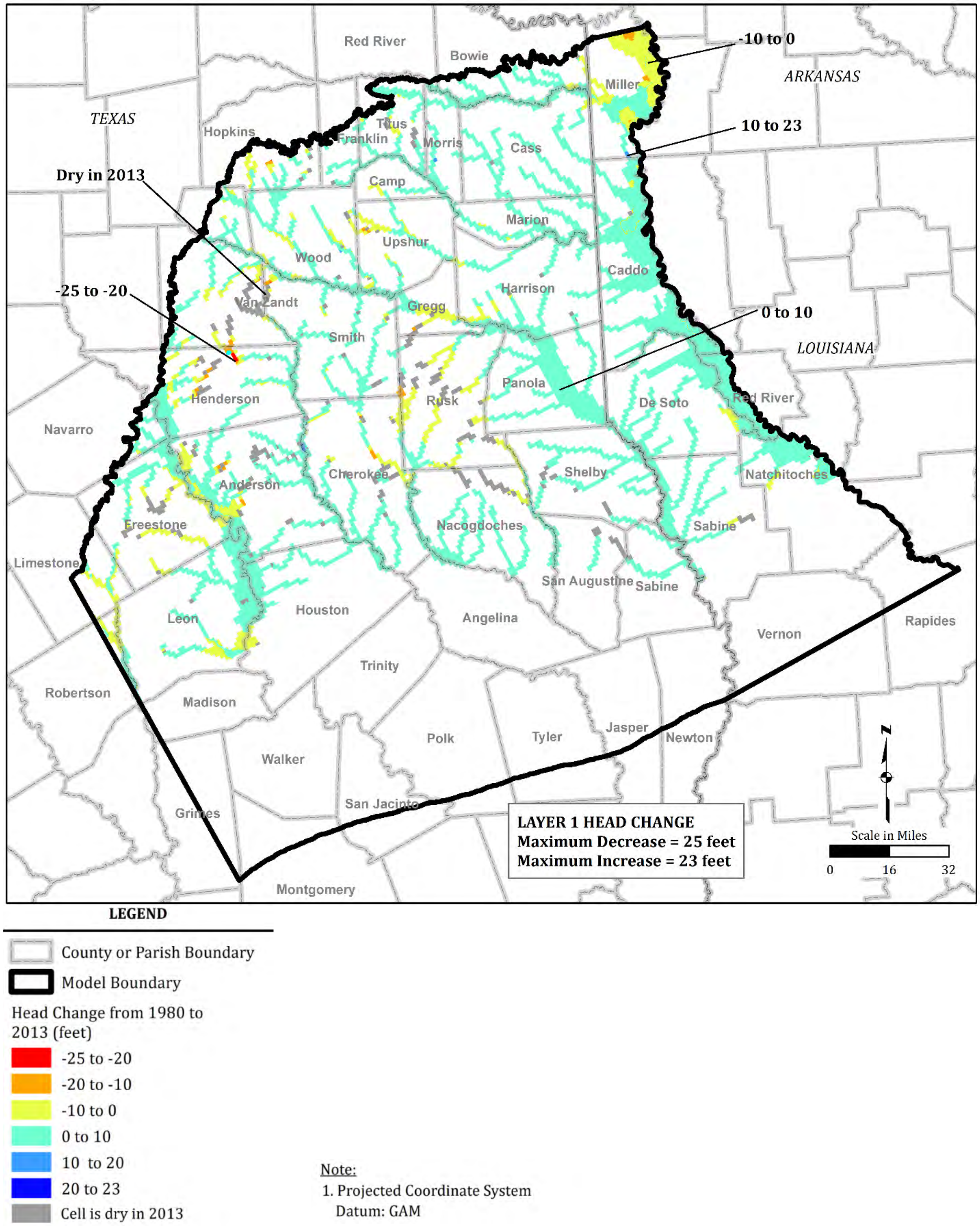
County or Parish

Layer

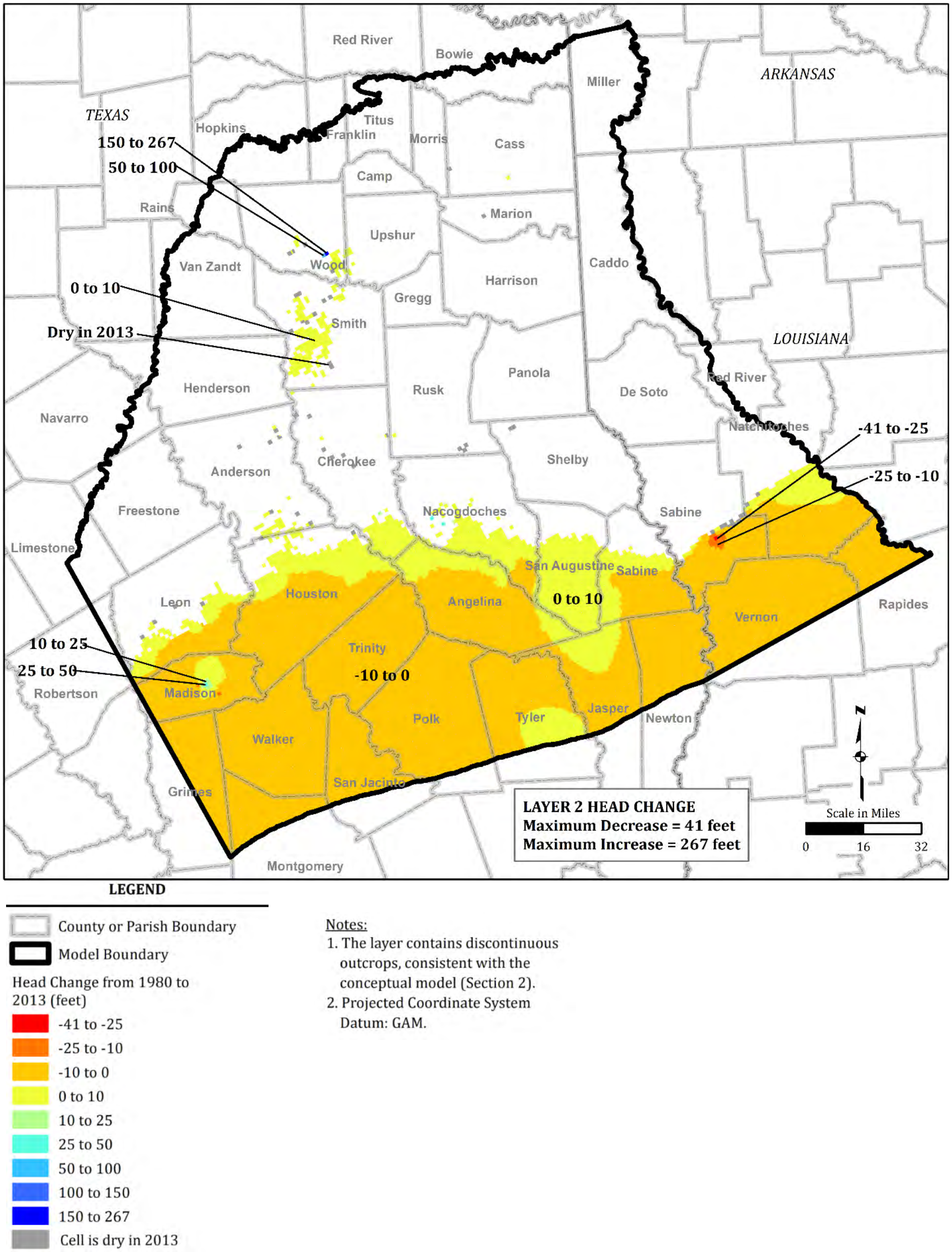
Note:

1. Projected Coordinate System
   Datum: GAM

Appendix C Figure 3.2-29. Simulated Water Level Elevation Contours in Lower Wilcox (Layer 9) for 2013

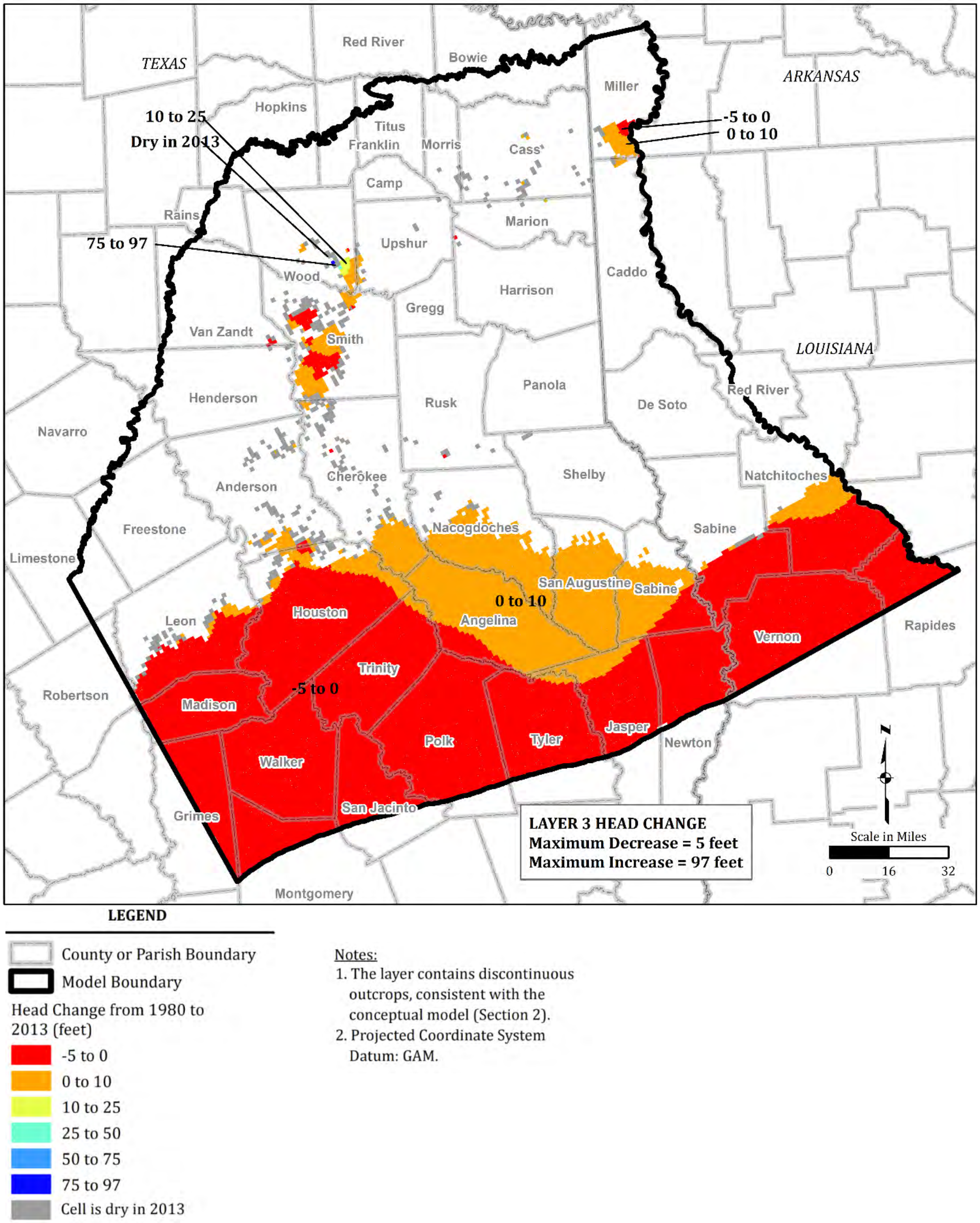


Appendix C Figure 3.2-30. Change in Water Level Elevations Between 1980 and 2013 in Quaternary Alluvium (Layer 1)



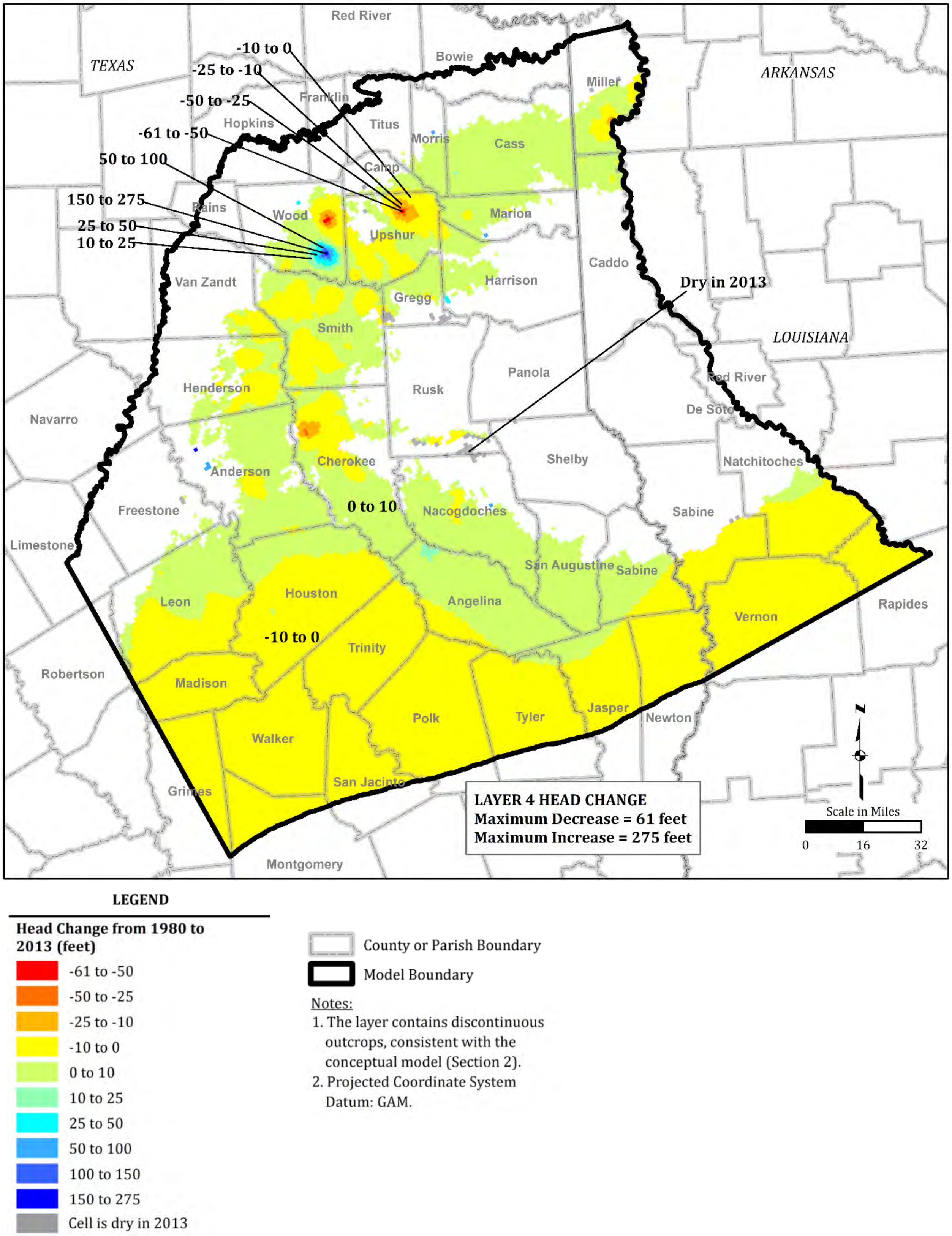
Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-31. Change in Water Level Elevations Between 1980 and 2013 in Sparta Aquifer (Layer 2)

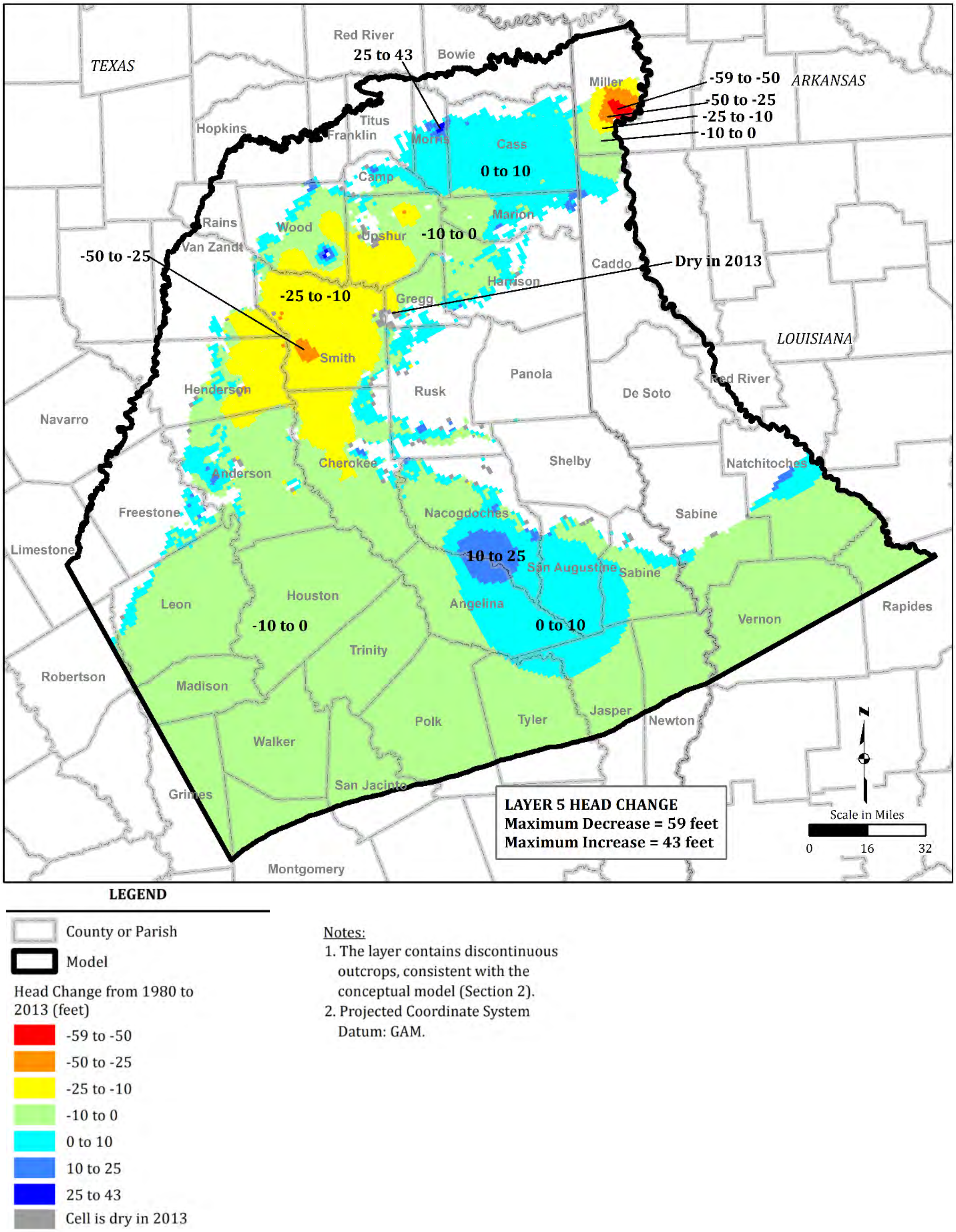


Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-32. Change in Water Level Elevations Between 1980 and 2013 in Weches Formation (Layer 3)

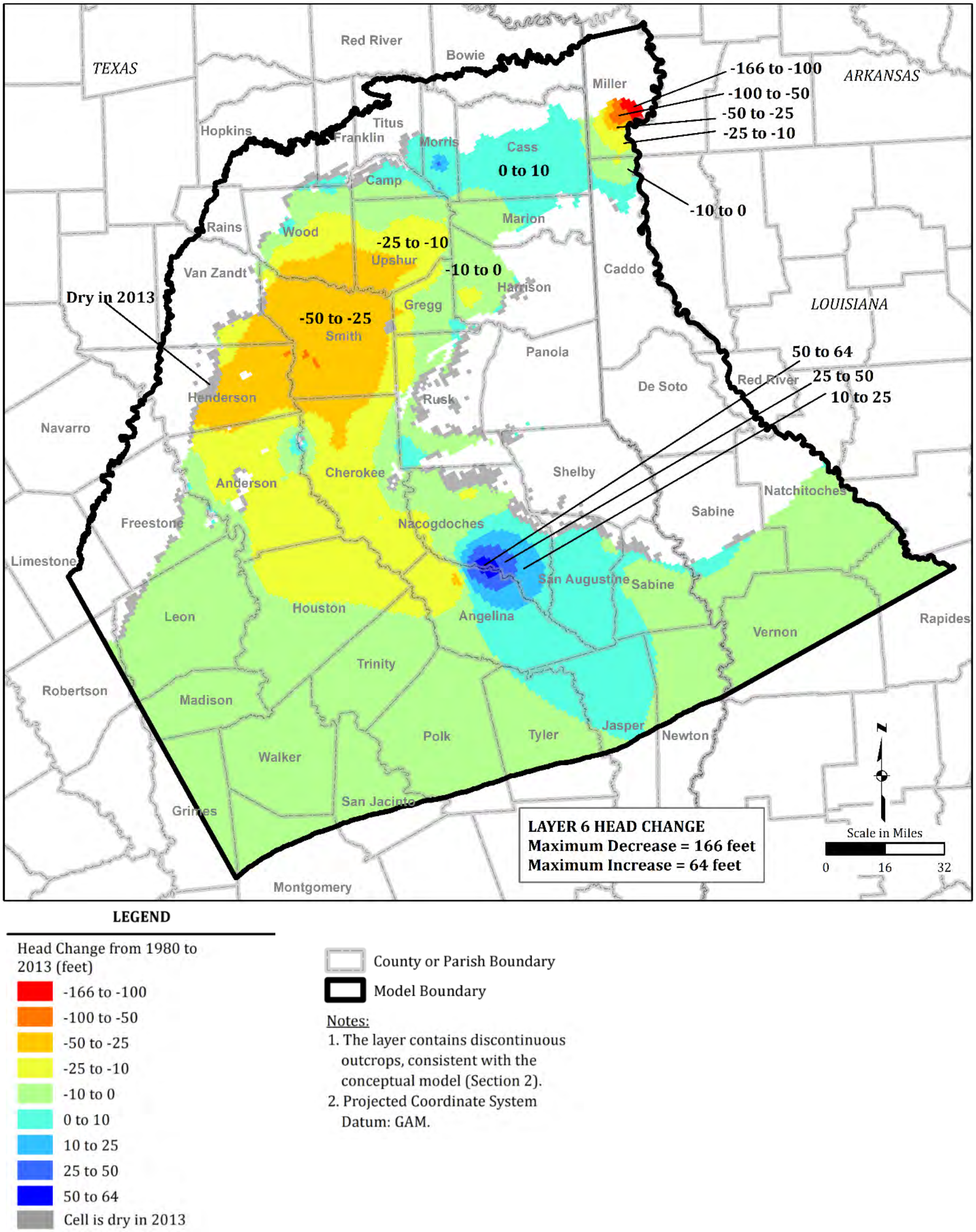


Appendix C Figure 3.2-33. Change in Water Level Elevations Between 1980 and 2013 in Queen City Aquifer (Layer 4)

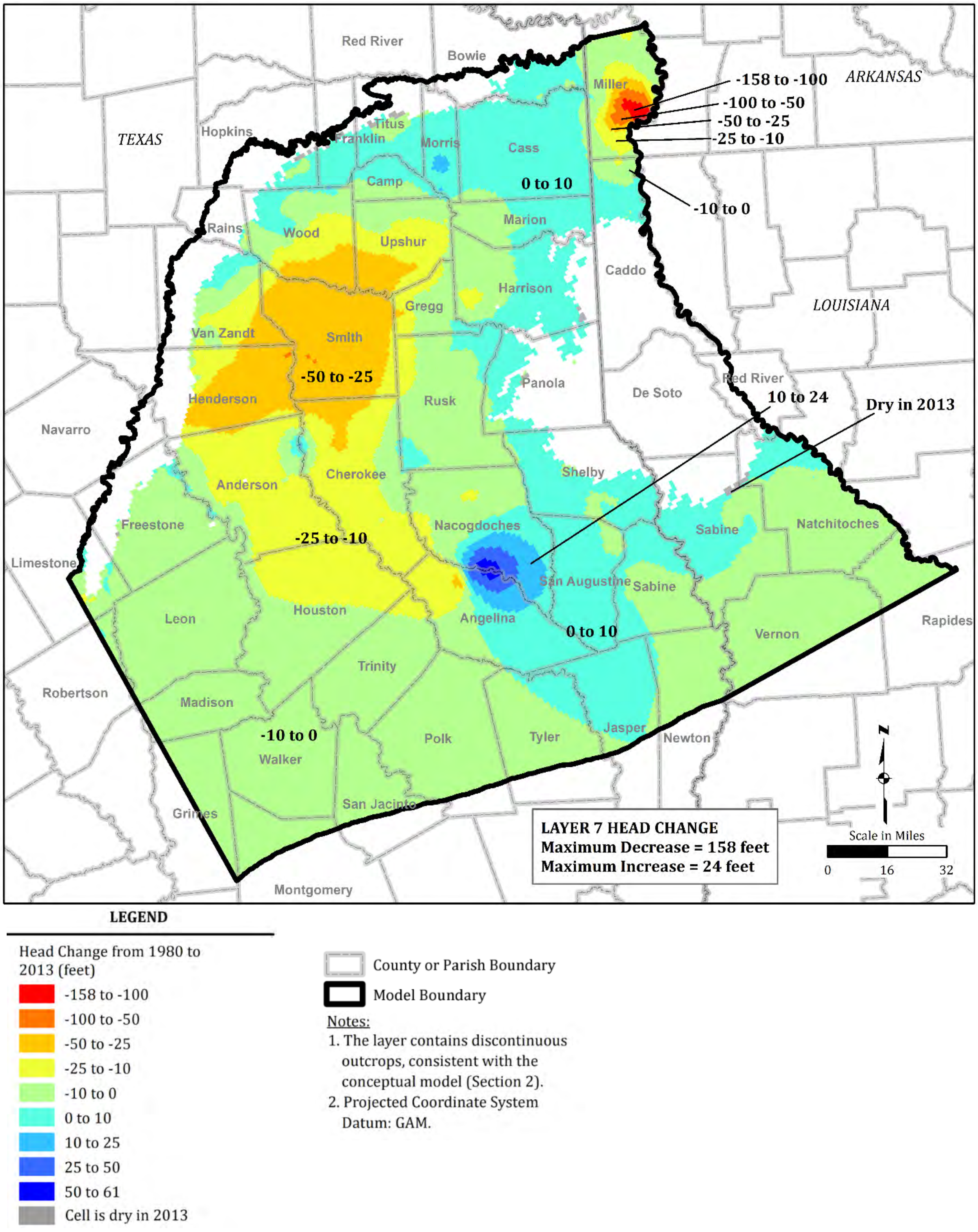


Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

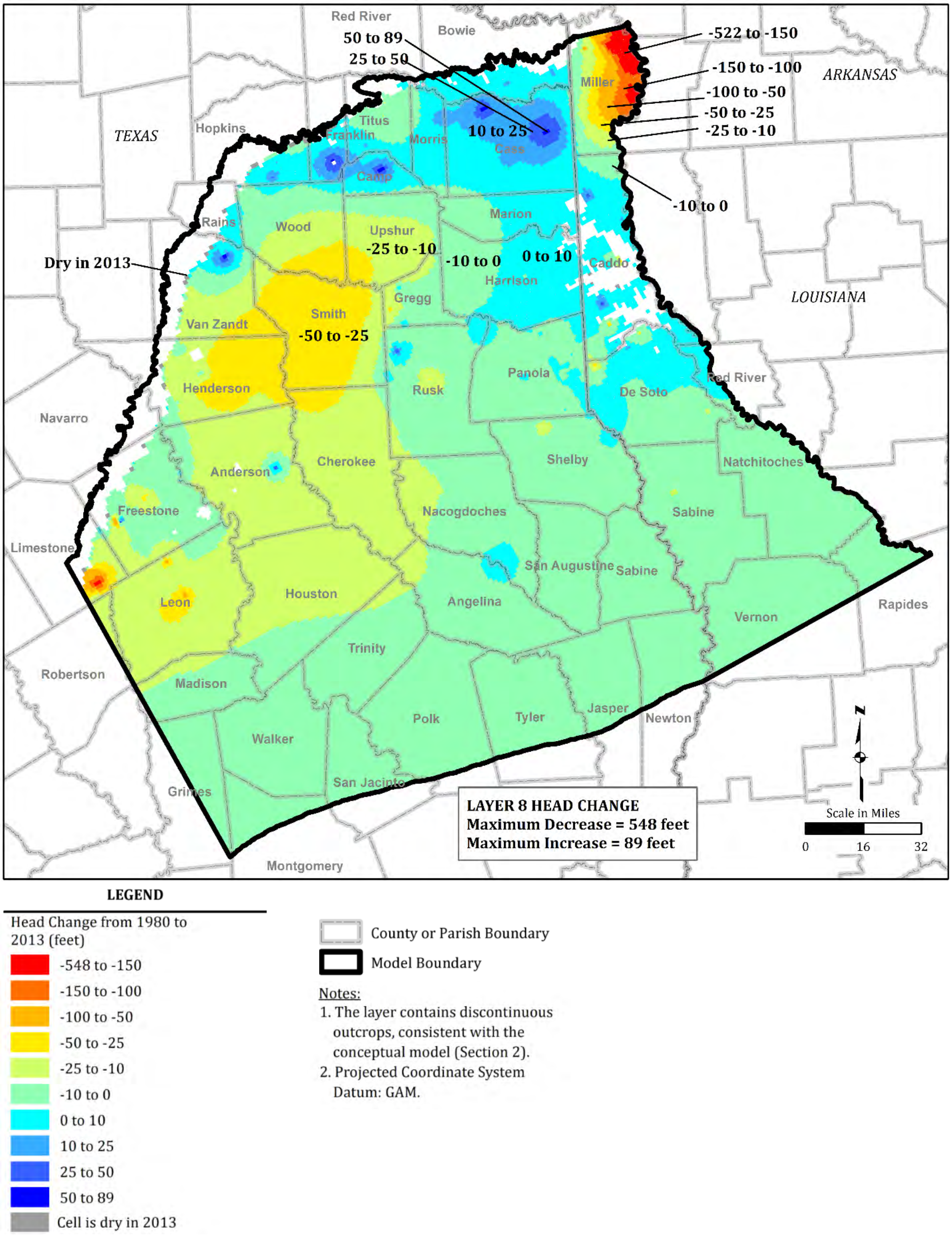
Appendix C Figure 3.2-34. Change in Water Level Elevations Between 1980 and 2013 in Reklaw Formation (Layer 5)



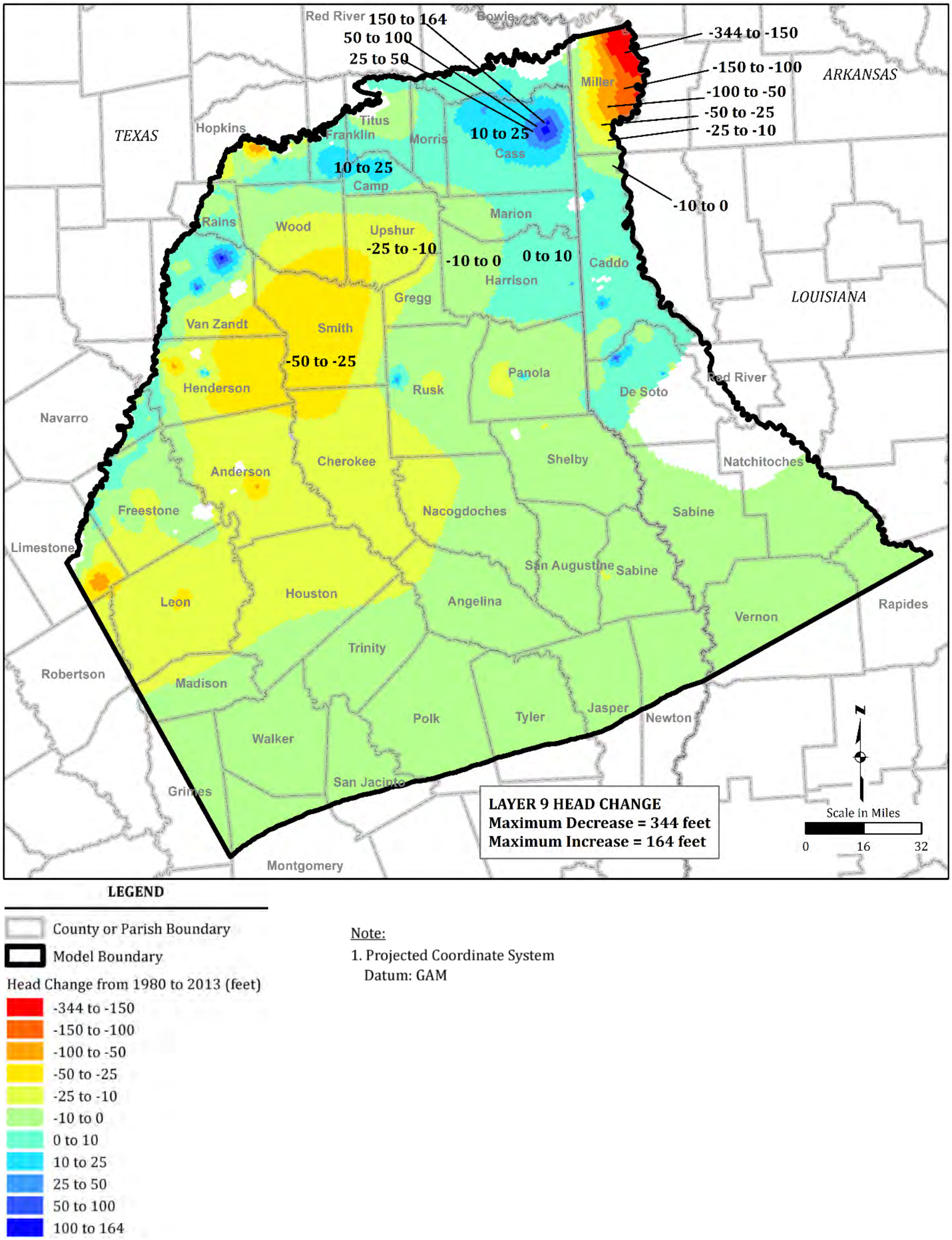
Appendix C Figure 3.2-35. Change in Water Level Elevations Between 1980 and 2013 in Carrizo Aquifer (Layer 6)



Appendix C Figure 3.2-36. Change in Water Level Elevations Between 1980 and 2013 in Upper Wilcox (Layer 7)



Appendix C Figure 3.2-37. Change in Water Level Elevations Between 1980 and 2013 in Middle Wilcox (Layer 8)



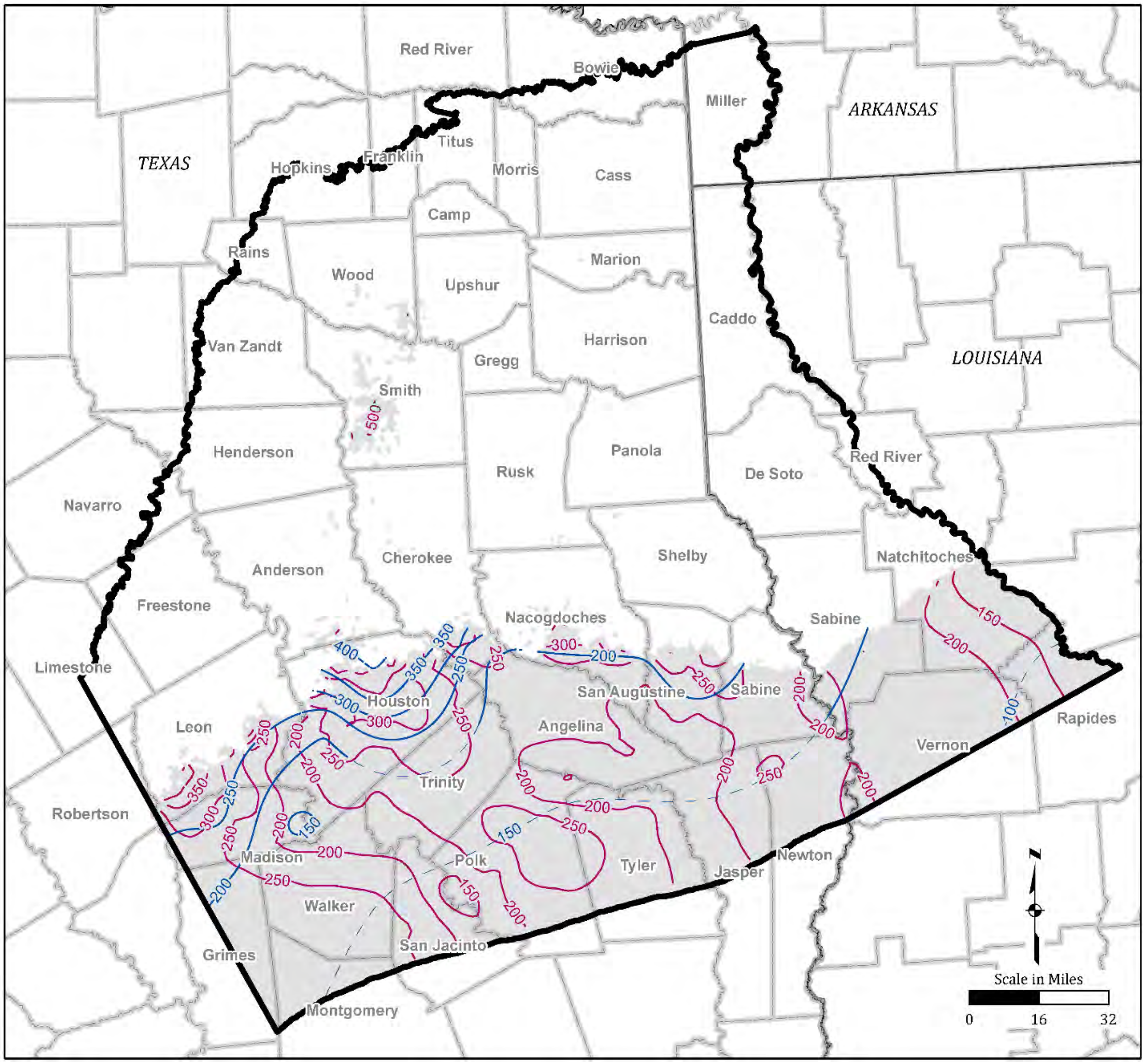
Appendix C Figure 3.2-38. Change in Water Level Elevations Between 1980 and 2013 in Lower Wilcox (Layer 9)

Another significant change in water level elevations occurs in Arkansas, in Miller County, located in the northernmost corner of the model. In this area, groundwater levels decrease which are greater with depth, up to 500 feet of decrease in the Middle Wilcox (model layer 8), as shown on Appendix C Figure 3.2-37. The remainder of the model domain shows relatively stable water levels from 1980 to 2013. There is a general area of groundwater increase between 1980 and 2013 centered about Nacogdoches and Angelina counties within the Reklaw Formation, Corrizo Aquifer, and Upper Wilcox (model layers 5, 6, and 7), as shown on Appendix C Figures 3.2-34 through 3.2-36, with largest rebound of over 60 feet in the Carrizo Aquifer (model layer 6).

Appendix C Figures 3.2-39 through 3.2-44 compare simulated groundwater level elevation contours from the end of the model simulation period, 2013, to the Conceptual Model groundwater level elevation contours using 2015 data presented in the Conceptual Model Report (Montgomery and Associates, 2020). The Conceptual Model Report used observed data to interpolate the 2015 groundwater level elevation surface, referred to the 2015 observed groundwater level elevations. Comparisons are provided for the Sparta Aquifer, Queen City Aquifer, Carrizo Aquifer, and Wilcox Aquifer (model layers 2, 4, 6, 7, 8, and 9). Even though comparisons are made between 2013 modeled conditions and 2015 observed conditions there is minimal change in average water level conditions between the two years.

The Sparta Aquifer (model layer 2) conceptual contours are uncertain over much of the layer, as indicated on Appendix C Figure 3.2-39 using dashed lines. Generally, 2013 simulated groundwater level elevations are consistent with the elevations of the observed 2015 water level surface with similar gradients pointed in the southward direction. The Queen City Aquifer (model layer 4) 2013 simulated and 2015 observed groundwater contours are similar, and both show southward flow, as shown on Appendix C Figure 3.2-40. The 2015 observed pumping centers near Wood and Cherokee counties are not clearly present in the 2013 simulated contours; however, the two-year time difference between the observed and simulated contours may account for some of these differences. The Carrizo Aquifer and Upper Wilcox (model layers 6 and 7) observed and simulated contours match more closely in terms and both show pumping centers in Nacogdoches and Smith counties with elevations of similar values, showing flow to the south, as shown on Appendix C Figures 3.2-41 and 3.2-42.

The Middle and Lower Wilcox (model layers 8 and 9) 2015 observed contours are uncertain in the south portion of the model, as shown on Appendix C Figures 3.2-43 and 3.2-44. In the Middle Wilcox (model layer 8), the 2013 simulated contours show similar features as the 2015 observed contours, including an elevation trough in the southern portion of the model, pumping in Smith County, and areas of groundwater mounding in Rusk and Harrison counties, shown on Appendix C Figure 3.2-43, though a cone of depression indicated by data in Cass County was not simulated. The Lower Wilcox (model layer 9) 2013 simulated contours show details such as areas of pumping and areas of groundwater mounding not captured in the 2015 observed contours; however, most of the 2015 contours are uncertain in the Lower Wilcox within the model domain, as shown on Appendix C Figure 3.2-44.

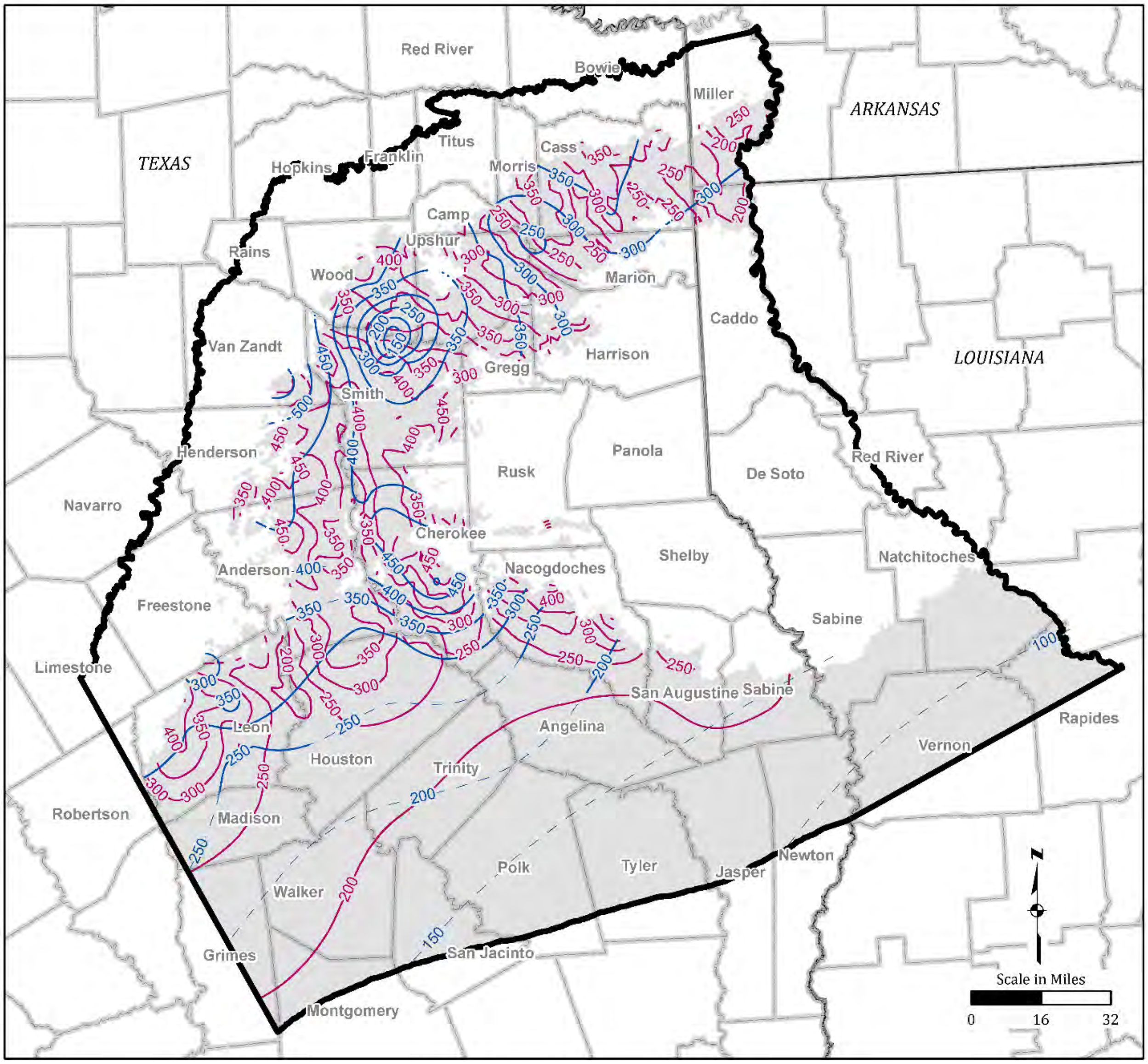


LEGEND

- Observed Groundwater Level Elevation Contour for 2015 (Dashed where uncertain)
- Modeled Groundwater Level Elevation Contour for 2013
- Layer Extent
- County or Parish Boundary
- Model Boundary

Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-39. Observed and Modeled Groundwater Level Elevation Contours for Sparta Aquifer (Layer 2)

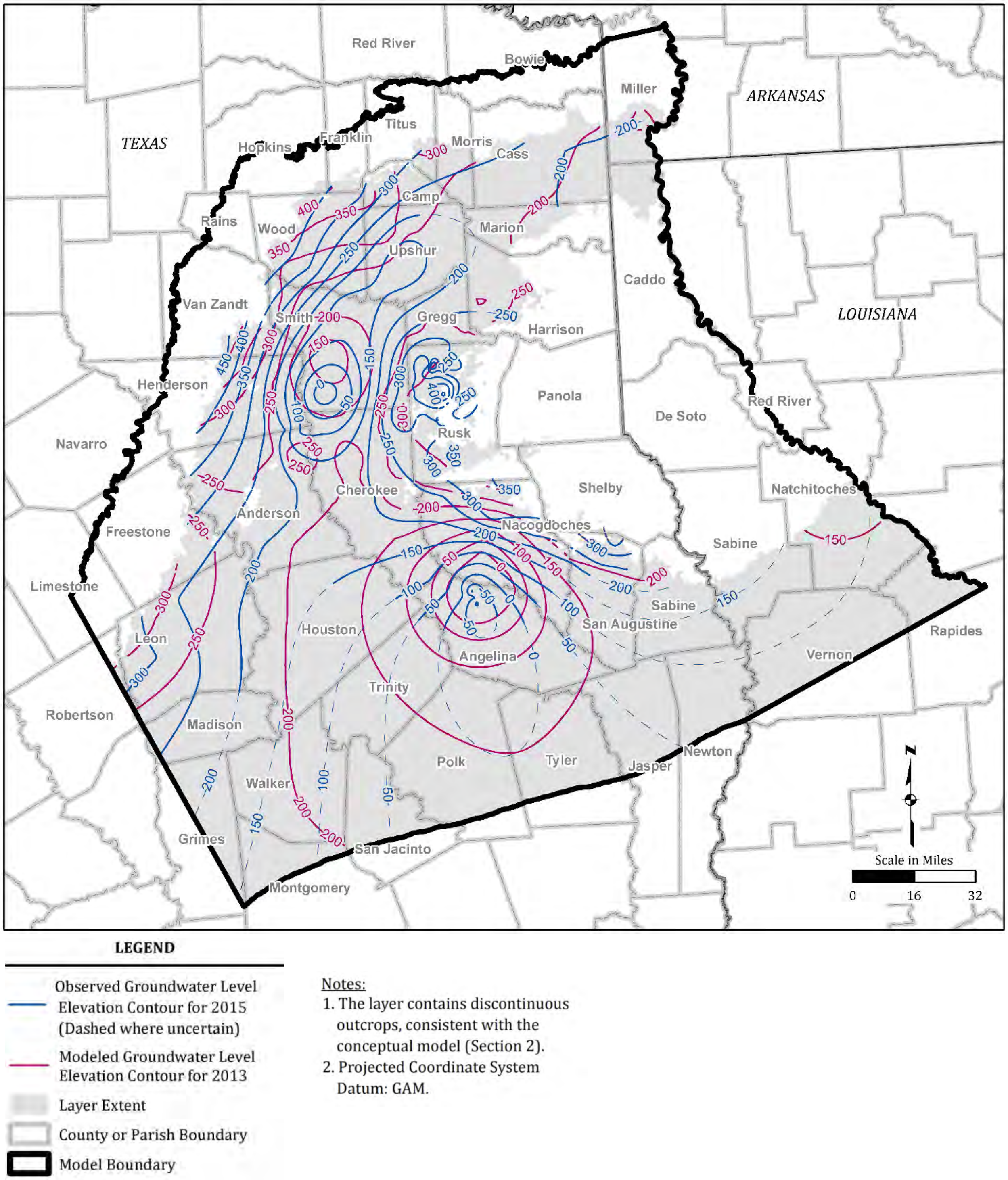


LEGEND

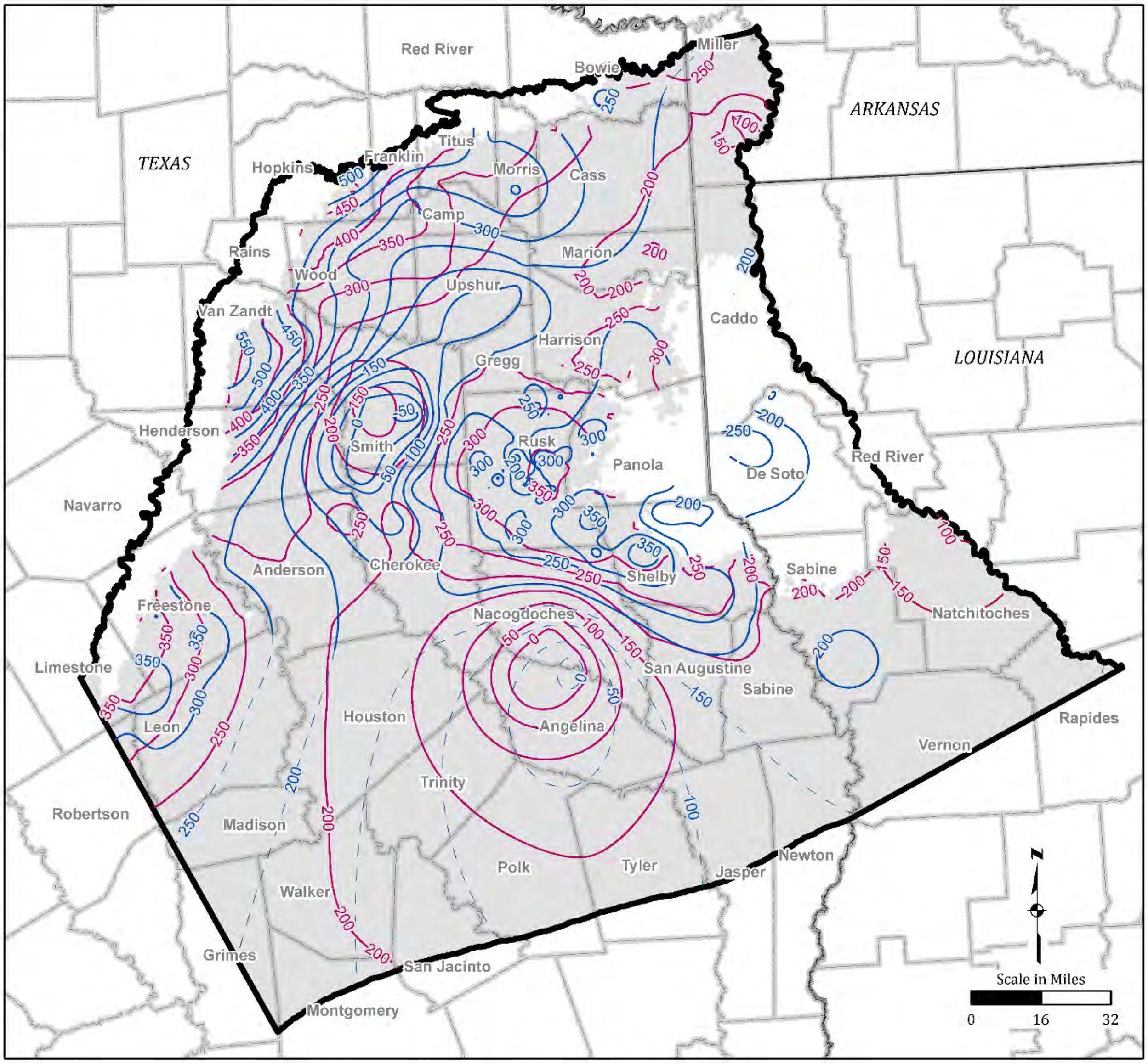
- Observed Groundwater Level Elevation Contour for 2015 (Dashed where uncertain)
- Modeled Groundwater Level Elevation Contour for 2013
- Layer Extent
- County or Parish Boundary
- Model Boundary

Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-40. Observed and Modeled Groundwater Level Elevation Contours for Queen City Aquifer (Layer 4)



Appendix C Figure 3.2-41. Observed and Modeled Groundwater Level Elevation Contours for Carrizo Aquifer (Layer 6)

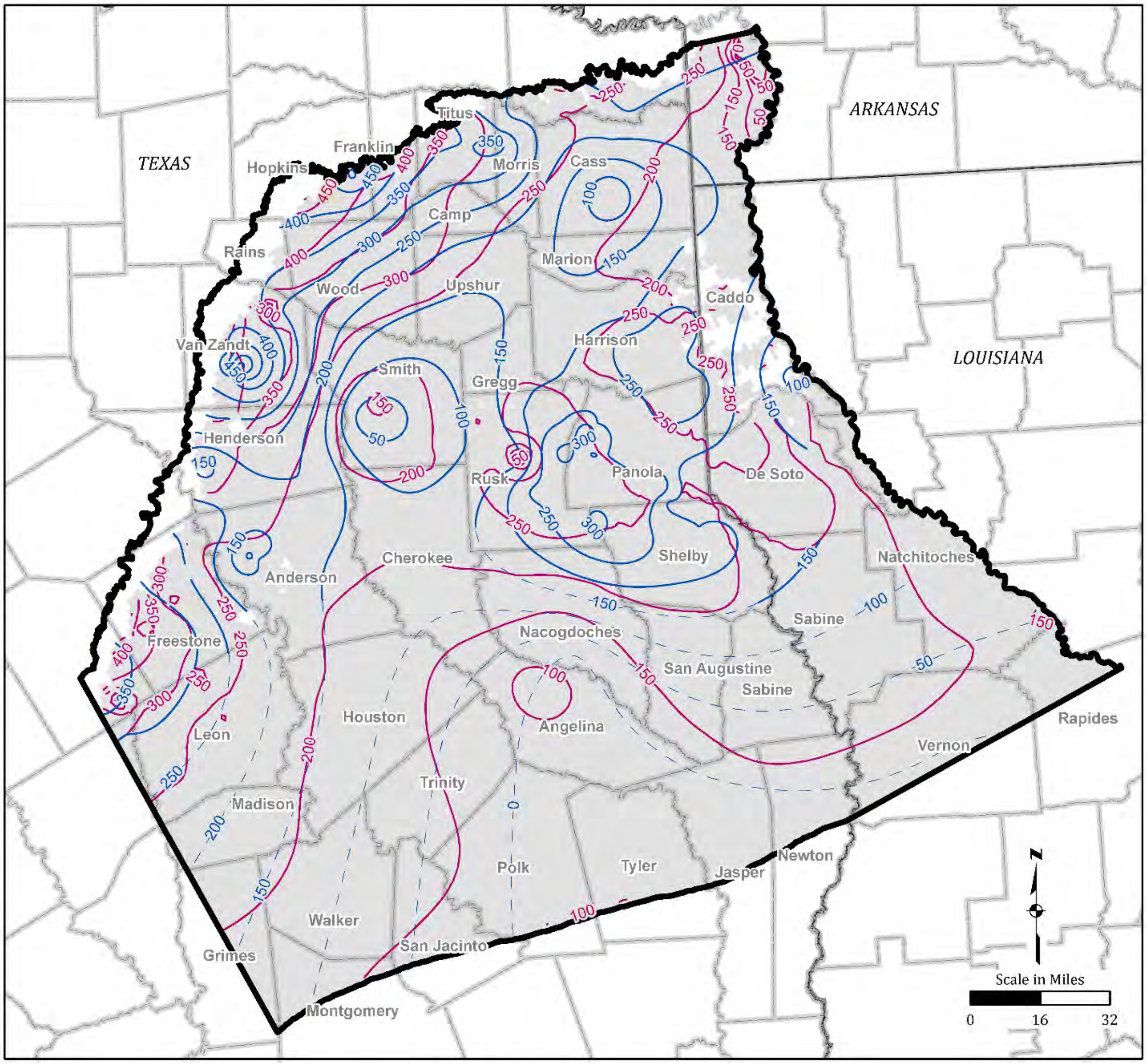


LEGEND

- Observed Groundwater Level Elevation Contour for 2015 (Dashed where uncertain)
- Modeled Groundwater Level Elevation Contour for 2013
- Layer Extent
- County or Parish Boundary
- Model Boundary

Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-42. Observed and Modeled Groundwater Level Elevation Contours for Upper Wilcox (Layer 7)

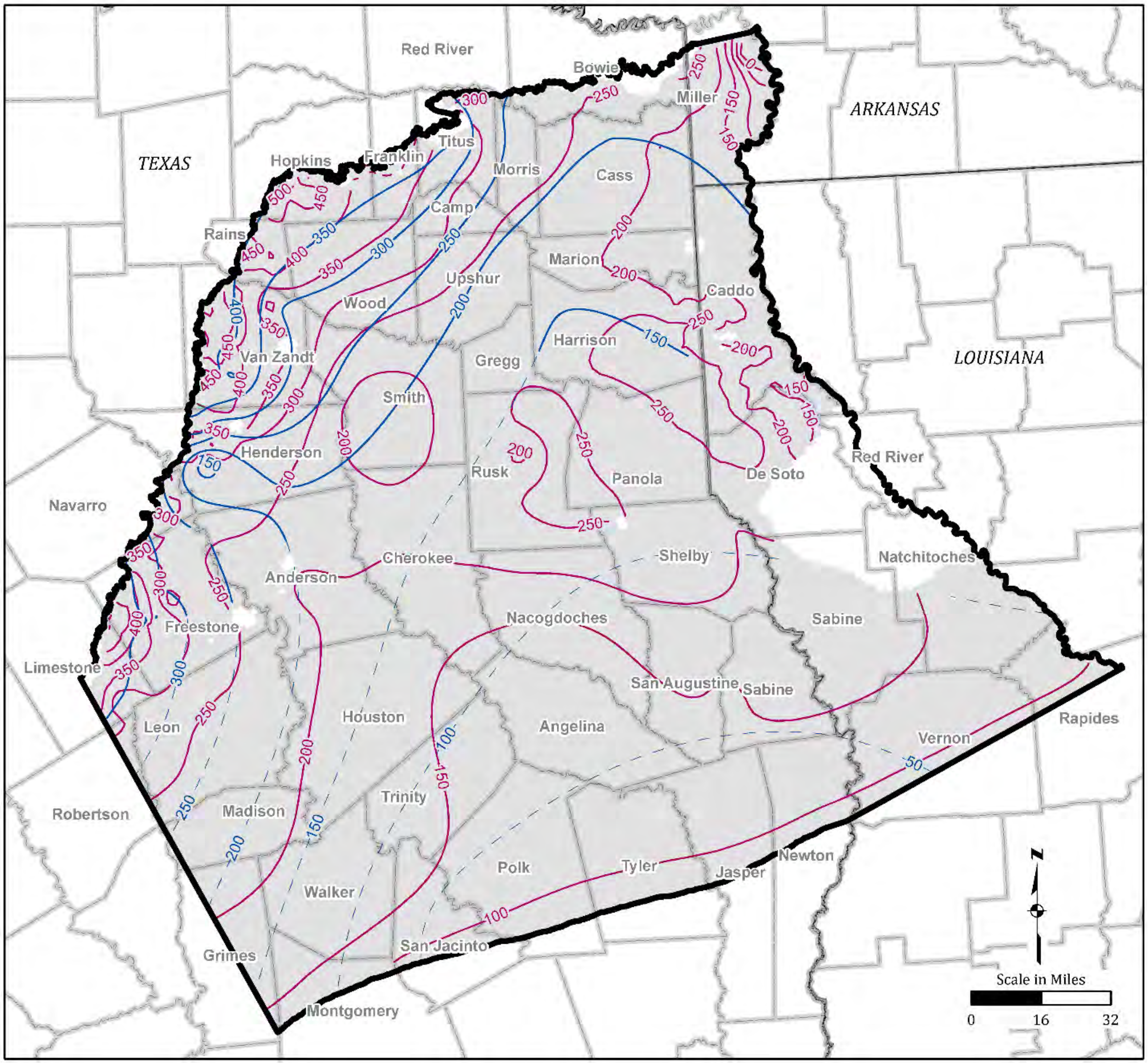


LEGEND

- Observed Groundwater Level Elevation Contour for 2015 (Dashed where uncertain)
- Modeled Groundwater Level Elevation Contour for 2013
- Layer Extent
- County or Parish Boundary
- Model Boundary

Notes:
1. The layer contains discontinuous outcrops, consistent with the conceptual model (Section 2).
2. Projected Coordinate System Datum: GAM.

Appendix C Figure 3.2-43. Observed and Modeled Groundwater Level Elevation Contours for Middle Wilcox (Layer 8)



LEGEND

Observed Groundwater Level Elevation Contour for 2015 (Dashed where uncertain)

Modeled Groundwater Level Elevation Contour for 2013

Layer Extent

County or Parish Boundary

Model Boundary

Note:

1. Projected Coordinate System Datum: GAM

Appendix C Figure 3.2-44. Observed and Modeled Groundwater Level Elevation Contours for Lower Wilcox (Layer 9)

3.3 Model Simulated Versus Measured Baseflow

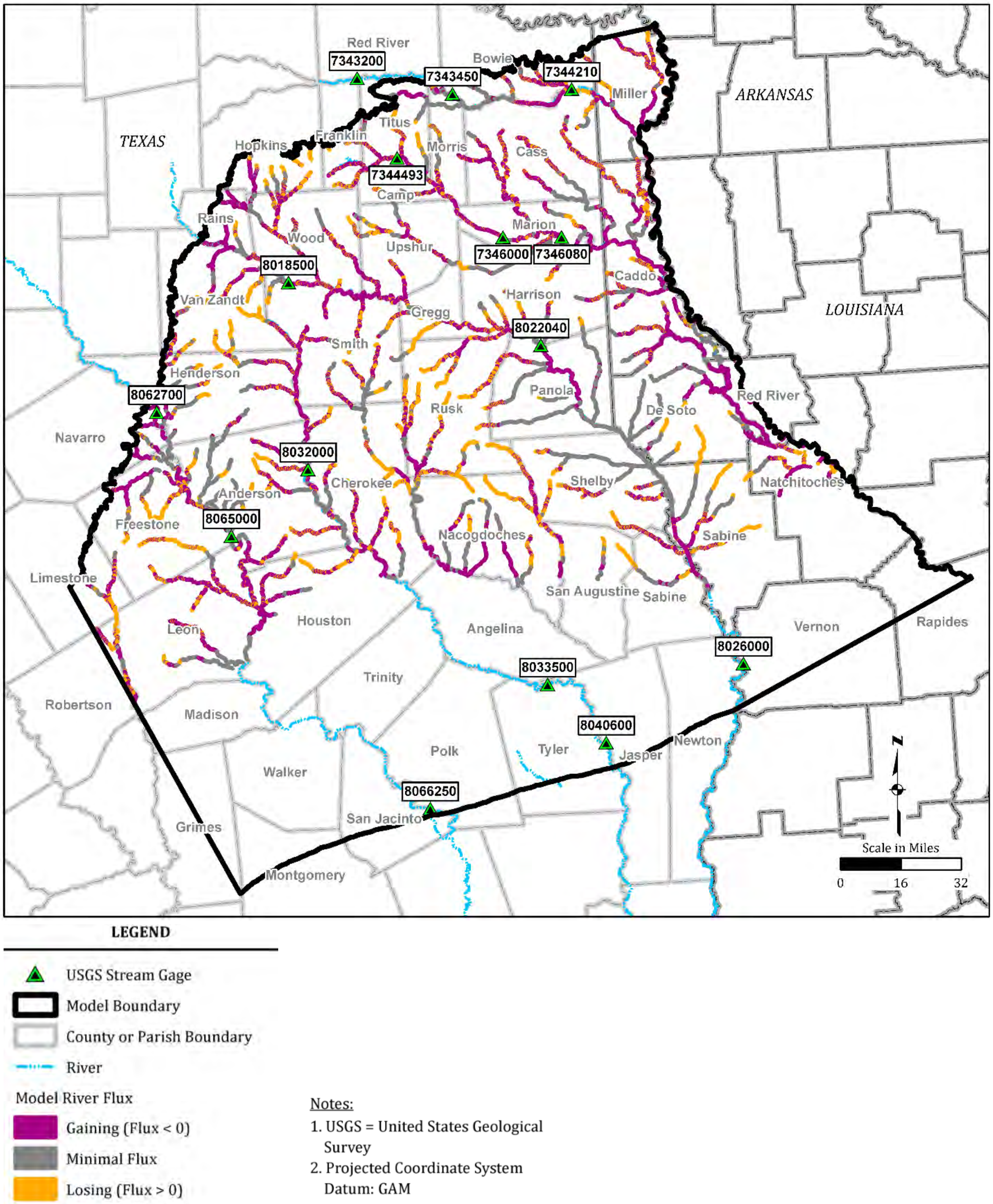
Surface-water to groundwater fluxes were used to constrain the model. The major rivers in the model domain were simulated with the RIV package as described in the Numerical Model Report Section 2.9. The Numerical Model Report Figures 2.9-1 through 2.9-5 show the annual flows at stream gages located on the major rivers in the model domain, which include the Trinity River, Neches River, Sabine River, Big Cypress Creek, and Sulphur River (Panday and others, 2020). The flow difference between stream gages was calculated at select river segments with unmanaged flows. A positive difference in flow signifies the river is gaining along the reach, and a negative difference in flow signifies the river is losing along the reach. The rivers simulated in the model are primarily gaining streams.

Measured stream gage data was used to evaluate simulated surface-water to groundwater fluxes. However, since the model does not simulate surface water flow, the flux between river and groundwater was evaluated qualitatively. Appendix C Figure 3.3-1 shows the simulated flux between the simulated rivers and the groundwater in the model domain. A negative flux value indicates a gaining reach and a positive flux value indicates a losing reach. Most of the reaches shown on Appendix C Figure 3.3-1 are gaining, which matches measured gage data, as shown in the Numerical Model Report Figures 2.9-1 through 2.9-5.

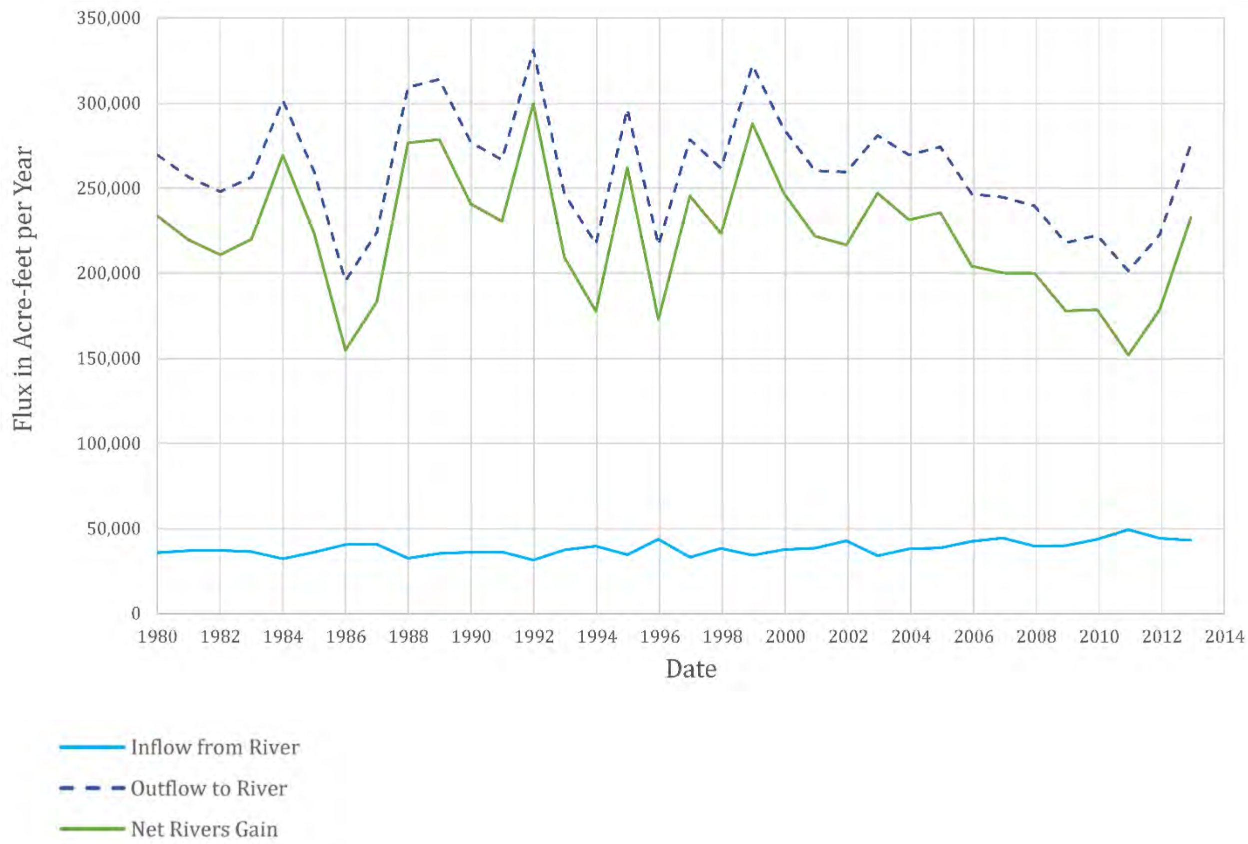
In addition, the simulated water budget for river inflow and outflow was evaluated. Appendix C Figure 3.3-2 shows the inflow from the river boundary condition, outflow to the river boundary condition, and net river gain. The inflow from the river boundary condition, which represents water flowing from the river boundary condition into groundwater, is flat during the simulation period, with an average of approximately 38,000 acre-feet per year (acre-feet/year). The outflow to the river boundary, which represents water flowing from groundwater into the river boundary condition, varies during the simulation period, with an average of approximately 260,000 acre-feet/year. The net flux from the groundwater to the river boundary condition average of approximately 222,000 acre-feet/year. Measured stream gage fluxes cannot be directly compared to simulated fluxes, as measured stream gage data is not measuring baseflow. However, the measured and simulated river flux both result in gaining stream conditions.

3.4 Model Simulated Water Budgets

The water budget for steady-state 1980 simulation is show in Appendix C Table 3.4-1. The largest inflow in the model domain (besides internal flow between layers) is recharge contribution in all layers and especially within the Quaternary Alluvium (model layer 1). Simulated rivers contribute a minor amount of inflow into the Quaternary Alluvium (model layer 1) as does the GHB into the Sparta Aquifer and Carrizo Aquifer (model layers 2 and 6). Within the 1980 simulation, the largest total outflows (besides internal layer outflows) are by evapotranspiration followed by outflow to the simulated rivers in the Quaternary Alluvium (model layer 1), and groundwater pumping. Although total extraction of groundwater is not the largest outflow for the steady-state 1980 simulation period, it is the largest outflow in the Carrizo Aquifer and Wilcox Aquifers (model layers 6, 7, 8, and 9).



Appendix C Figure 3.3-1. Simulated Groundwater Interaction Fluxes for 2013 Rivers



Appendix C Figure 3.3-2. Groundwater Budget for River Flux
1980 to 2013 Calibration Simulation

Appendix C Table 3.4-1. Draft Model Water Budget by Layer for the Steady-State 1980 Simulation

	Mass Balance Components	Layer 1 Flow (Quaternary Alluvium)	Layer 2 Flow (Sparta Aquifer)	Layer 3 Flow (Weches Formation)	Layer 4 Flow (Queen City Aquifer)	Layer 5 Flow (Reklaw Formation)	Layer 6 Flow (Carrizo Aquifer)	Layer 7 Flow (Upper Wilcox)	Layer 8 Flow (Middle Wilcox)	Layer 9 Flow (Lower Wilcox)	Total Model Component Flows
		(acre-feet per year)									
Inflows	Storage	--	--	--	--	--	--	--	--	--	--
	Layer Top	--	69.2	15,958.1	200,017.9	17,937.0	54,104.2	217,042.2	30,121.9	28,289.1	--
	Layer Bottom	431,635.6	1,311.6	755.7	2,332.6	352.9	53,390.6	8,104.0	3,095.9	0.0	--
	Well	--	--	--	--	--	--	--	--	--	--
	GHB	--	32,915.9	--	--	--	10,151.5	--	--	--	43,067.4
	River	34,079.5	--	--	--	--	--	--	--	--	34,079.5
	Recharge	337,212.0	42,892.9	13,945.0	94,048.0	29,915.8	21,247.2	61,181.7	32,082.6	7,148.2	639,673.2
	Evapotranspiration	--	--	--	--	--	--	--	--	--	--
	Total Inflows	802,927.1	77,189.5	30,658.8	296,398.5	48,205.6	138,893.5	286,327.9	65,300.4	35,437.2	716,820.1
Outflows	Storage	--	--	--	--	--	--	--	--	--	--
	Layer Top	--	3,324.8	3,114.5	224,856.7	855.5	12,369.8	218,170.6	14,254.7	24,032.4	--
	Layer Bottom	362,486.4	16,878.2	24,947.9	23,050.9	29,285.3	70,394.5	25,835.9	10,660.8	0.0	--
	Well	--	3,879.6	--	9,343.3	--	55,588.4	33,029.0	24,984.2	7,984.9	134,809.4
	GHB	--	32,137.1	--	995.6	--	1,136.0	835.6	142.7	366.8	35,613.7
	River	269,305.3	--	--	--	--	--	--	--	--	269,305.3
	Recharge	--	--	--	--	--	--	--	--	--	--
	Evapotranspiration	171,309.9	20,902.2	2,658.8	37,633.4	17,674.5	108.2	8,493.3	15,258.0	3,053.5	277,091.7
	Total Outflows	803,101.6	77,121.9	30,721.1	295,879.9	47,815.3	139,596.9	286,364.2	65,300.4	35,437.6	716,820.2
Net Flows	In-Out	-174.5	67.6	-62.4	518.6	390.2	-703.4	-36.3	0.0	-0.4	0.0
	Percent Discrepancy	-0.02%	0.09%	-0.20%	0.18%	0.81%	-0.51%	-0.01%	0.00%	0.00%	0.00%

Notes:

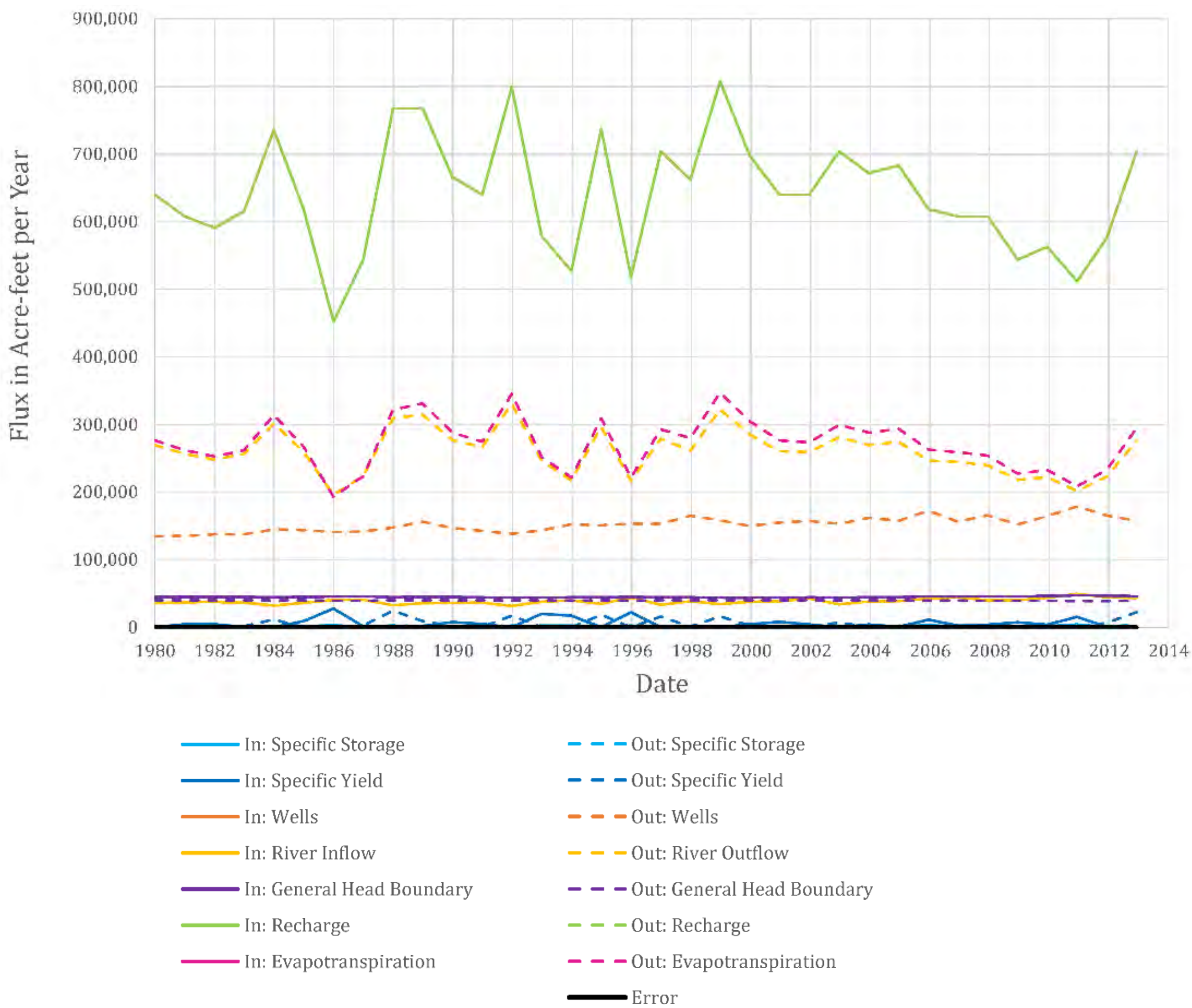
1. Mass balances per layer were obtained from Groundwater Vistas. Mass balance errors match those in the MODFLOW lst file though there are averaging differences for river and storage terms.
2. Pumping was not simulated in model layers 1, 3, and 5 (Quaternary Alluvium, Weches Formation, and Reklaw Formation).

The water budget for the transient simulation from 1980 through 2013 is shown in Appendix C Figure 3.4-1 and summarized in Appendix C Table 3.4-2. The largest model inflows and outflows are similar to those in the steady-state 1980 simulation. Inflows and outflows are dominated by recharge for inflow and rivers and evapotranspiration for outflow. Within individual layers, outflow was dominated by groundwater extraction in the Carrizo Aquifer and Wilcox Aquifers (model layers 6, 7, 8, and 9). Storage provided a negligible amount of inflow and outflow across the model.

Appendix C Figure 3.4-1 shows how the water budget fluctuates during the simulation period. Recharge (inflow) is the largest component in the model water budget and showed the greatest changes year to year. Recharge over time did not display a noticeable trend from 1980 to 2013 although recent drought conditions were reflected as an extended period of decreasing flux (2004 to 2012). River and evapotranspiration (outflows) showed some variability with time. Drought conditions were also reflected in the river and evapotranspiration water budget components with declining flows between 2004 and 2012. Groundwater extraction did not vary significantly year to year but showed an increasing trend from 1980 to 2013. Other inflow and outflow components were generally consistent across the model time interval and generally smaller in magnitude.

4.0 Summary and Conclusions

The final and draft model calibration statistics, water level measurements, and water budgets were similar, with the only notable difference in model calibration being improvement in Layer 4 (Queen City Aquifer) in the final model calibration statistics due to reassignment of eight target wells to alternate hydrostratigraphic units. Since there were no significant changes in calibration results from the draft to the final model, the sensitivity analyses and predictive sensitivities conducted using the draft model were considered valid for the final model.



Appendix C Figure 3.4-1. Water Budget for the 1980 to 2013 Calibration Simulation

Appendix C Table 3.4-2. Draft Model Water Budget by Layer at the End of the Transient 1980 to 2013 Simulation

	Mass Balance Components	Layer 1 Flow (Quaternary Alluvium)	Layer 2 Flow (Sparta Aquifer)	Layer 3 Flow (Weches Formation)	Layer 4 Flow (Queen City Aquifer)	Layer 5 Flow (Reklaw Formation)	Layer 6 Flow (Carrizo Aquifer)	Layer 7 Flow (Upper Wilcox)	Layer 8 Flow (Middle Wilcox)	Layer 9 Flow (Lower Wilcox)	Total Model Flows
		(acre-feet per year)									
Inflows	Storage	4.06E-07	13.1	--	--	4.06	--	--	0.01	38.59	55.76
	Layer Top	--	67.5	16,521.9	208,597.3	20,578.7	61,781.0	232,708.6	40,696.1	31,447.30	--
	Layer Bottom	427,745.4	1,233.9	772.9	1,592.4	421.5	60,990.2	7,467.7	3,695.2	--	--
	Well	--	--	--	--	--	--	--	--	--	--
	GHB	--	33,096.9	--	0.76	--	12,734.7	--	--	--	45,832.35
	River	41,449.3	--	--	--	--	--	--	--	--	41,449.33
	Recharge	370,360.7	47,174.0	15,325.0	104,018.6	32,822.9	23,458.2	67,624.0	35,163.1	7,873.55	703,820.03
	Evapotranspiration	--	--	--	--	--	--	--	--	--	--
	Total Inflows	839,555.4	81,585.4	32,619.8	314,209.1	53,827.1	158,964.1	307,800.2	79,554.4	39,359.44	791,157.47
Outflows	Storage	1,145.6	827.8	734.0	5,036.7	826.7	3,980.9	8,020.2	4,118.7	1,198.8	25,889.3
	Layer Top	--	3,374.7	3,026.4	230,556.1	845.8	10,513.0	217,051.8	13,223.1	25,328.2	--
	Layer Bottom	383,983.7	17,536.3	26,158.8	26,923.1	32,492.5	76,547.2	35,944.9	12,812.5	--	--
	Well	--	3,952.8	--	9,096.3	--	68,456.4	36,173.7	32,174.0	7,433.2	157,286.5
	GHB	--	31,891.0	--	1,414.3	--	150.6	1,263.0	2,253.2	2,294.6	39,266.6
	River	274,243.2	--	--	--	--	--	--	--	--	274,243.2
	Recharge	--	--	--	--	--	--	--	--	--	--
	Evapotranspiration	180,358.5	23,923.5	2,772.0	40,610.9	19,279.2	68.0	9,381.3	14,972.9	3,105.4	294,471.8
	Total Outflows	839,731.0	81,506.2	32,691.2	313,637.5	53,444.2	159,716.0	307,834.9	79,554.4	39,360.2	791,157.5
Net Flows	In-Out	-175.7	79.1	-71.4	571.6	382.9	-751.9	-34.7	0.0	-0.8	0.0
	Percent Discrepancy	-0.02%	0.10%	-0.22%	0.18%	0.71%	-0.47%	-0.01%	0.00%	0.00%	0.00%

Notes:
1. Mass balances per layer were obtained from Groundwater Vistas. Mass balance errors match those in the MODFLOW lst file though there are averaging differences for river and storage terms.
2. Mass balance rates shown are for the end of the transient simulation at stress period 34, time step 5 (end of 2013).
3. Pumping was not simulated in model layers 1, 3, and 5 (Quaternary Alluvium, Weches Formation, and Reklaw Formation).

5.0 References

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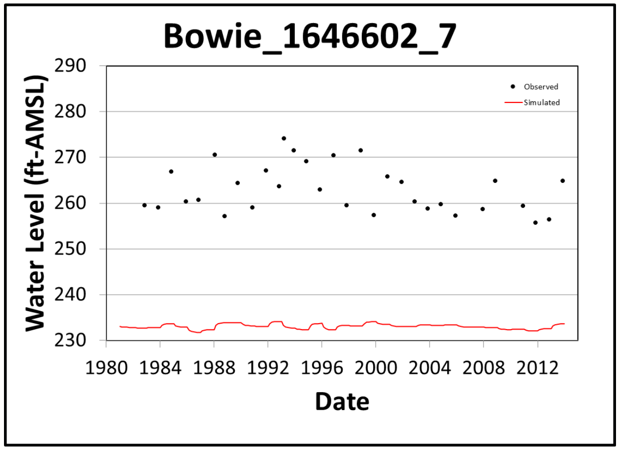
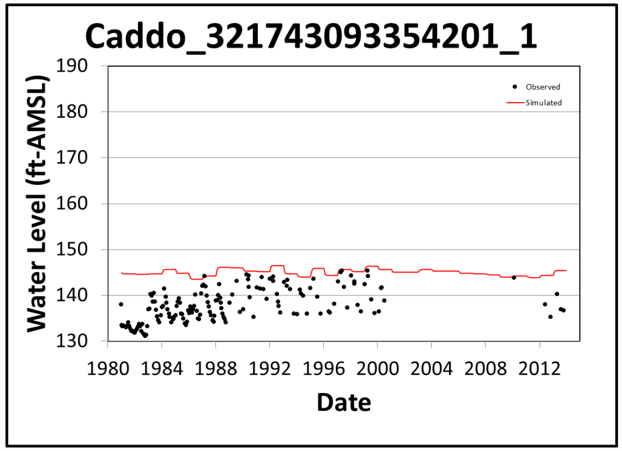
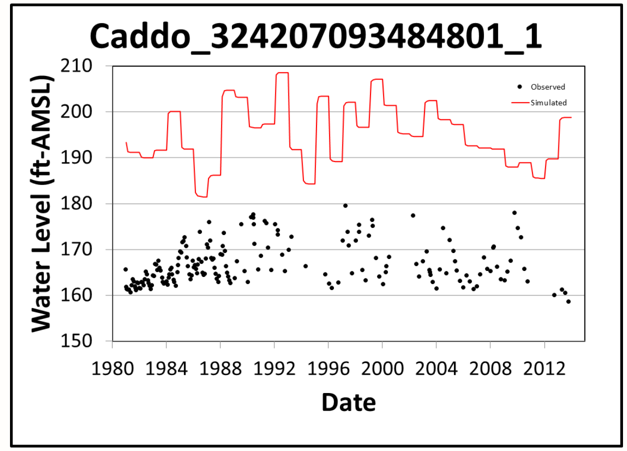
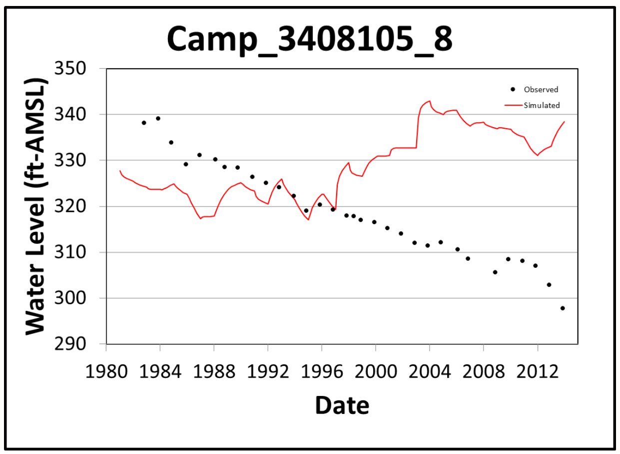
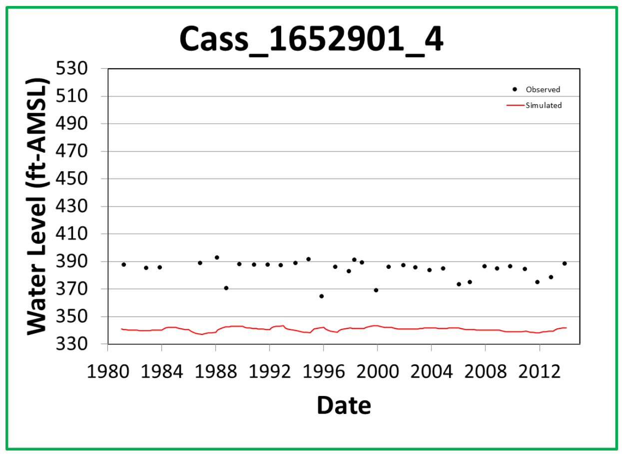
APPENDICES

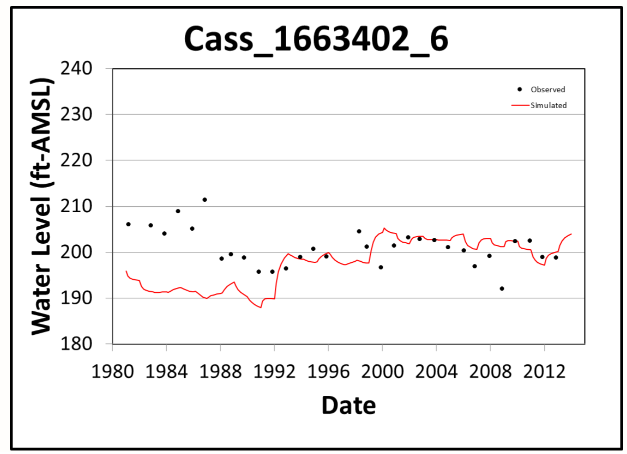












Notes:
1. Select wells represent model targets with a dataset that is unweighted (data weights = 1).
2. Chart name: county name, well name, model layer; ft-AMSL = feet above mean sea level
3. Chart outline color Y-axis: yellow = 400 feet; green = 200 feet; black = 60 feet.

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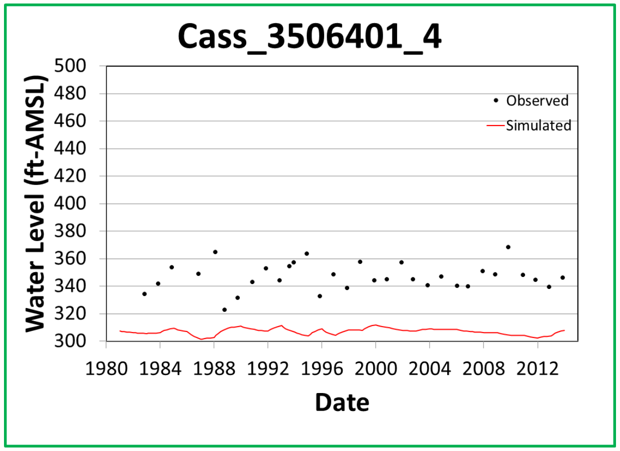
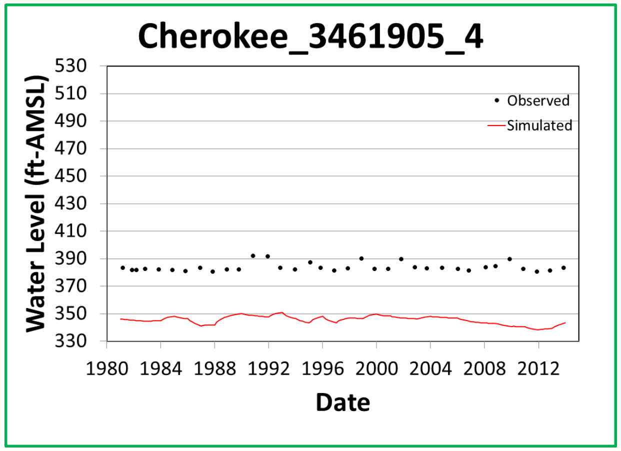
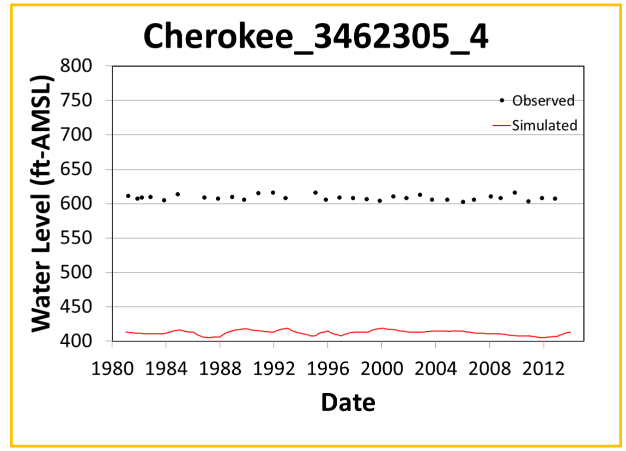
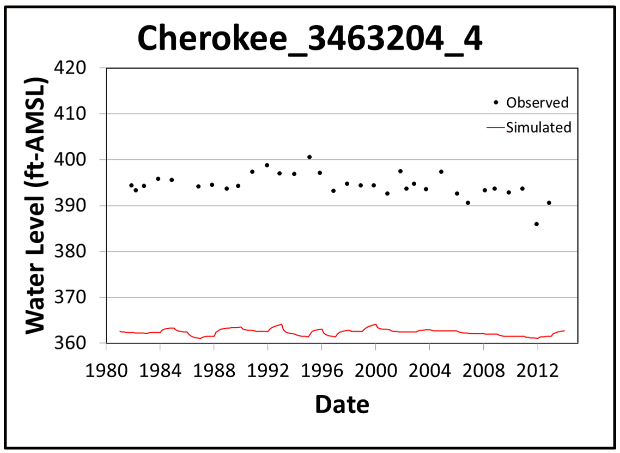
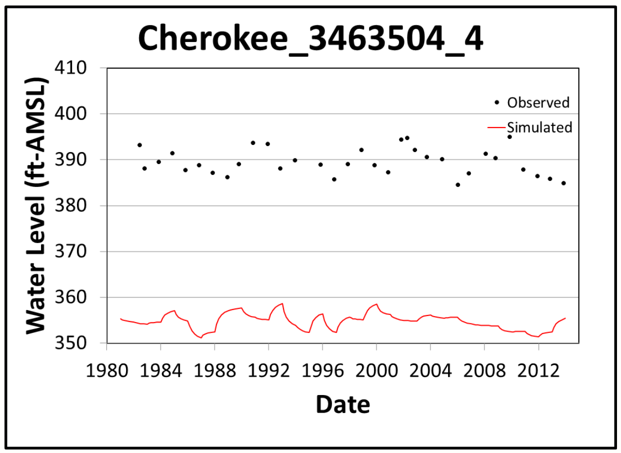
Appendix A – Hydrographs for Select Target Wells

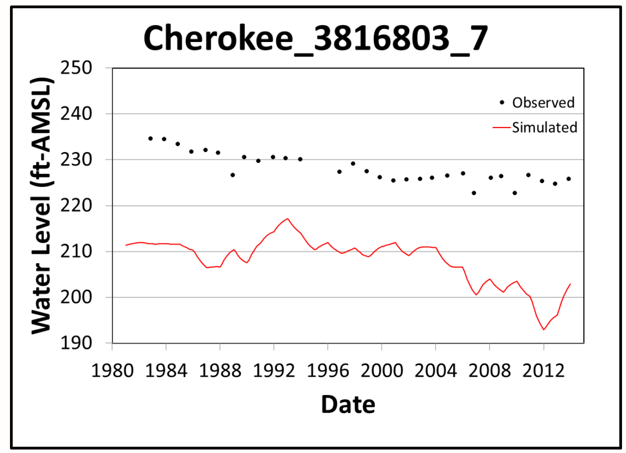












Notes:
1. Select wells represent model targets with a dataset that is unweighted (data weights = 1).
2. Chart name: county name, well name, model layer; ft-AMSL = feet above mean sea level.
3. Chart outline color Y-axis: yellow = 400 feet; green = 200 feet; black = 60 feet.

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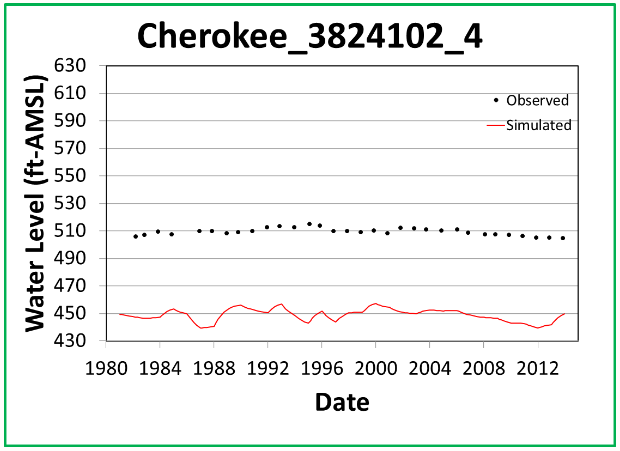
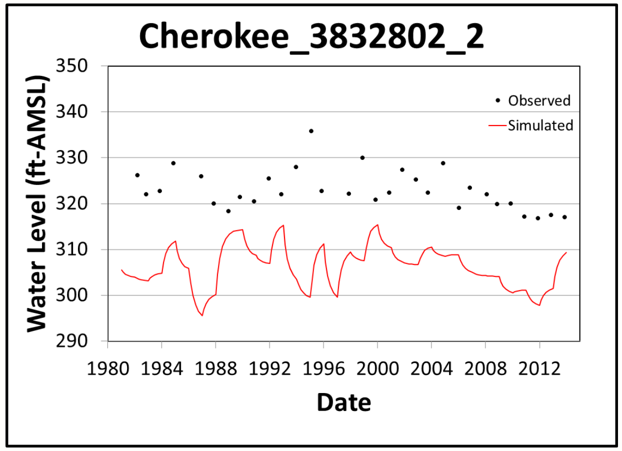
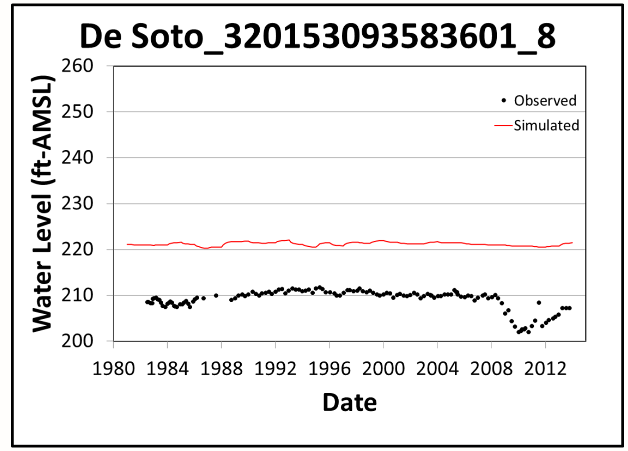
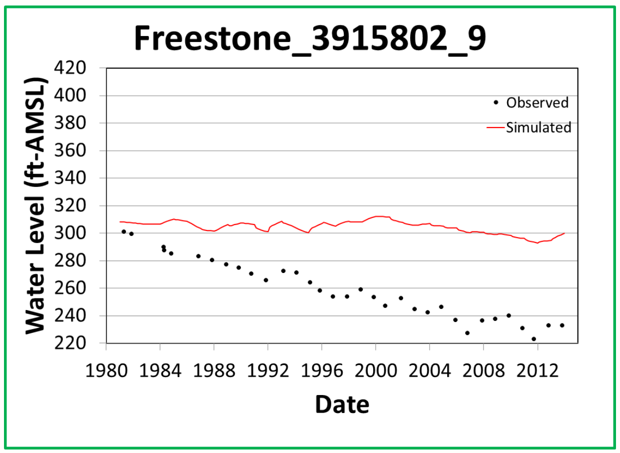
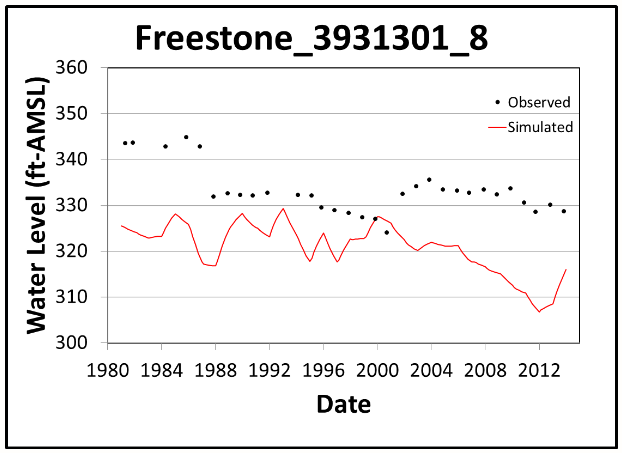
Appendix A – Hydrographs for Select Target Wells

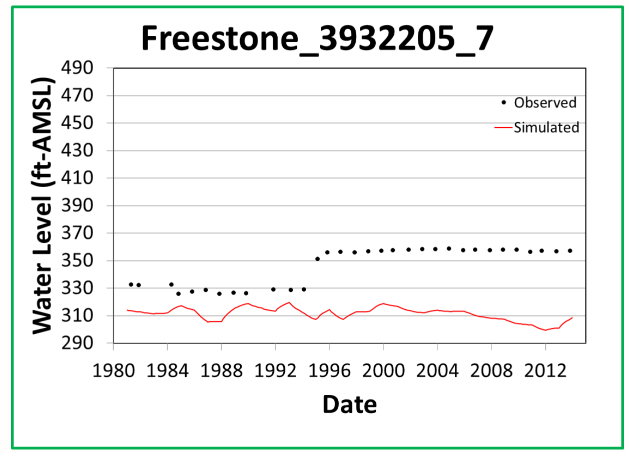












Notes:
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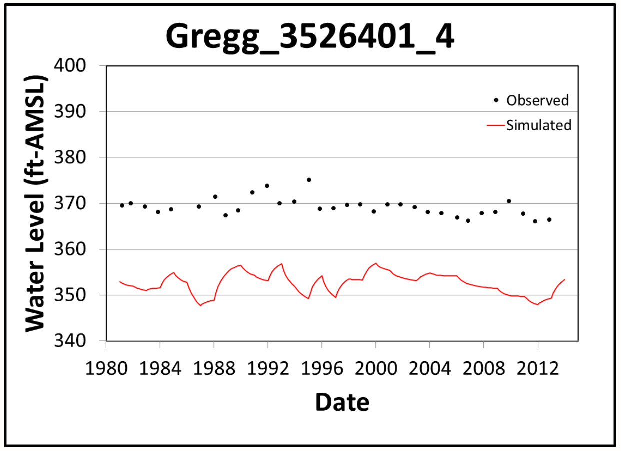
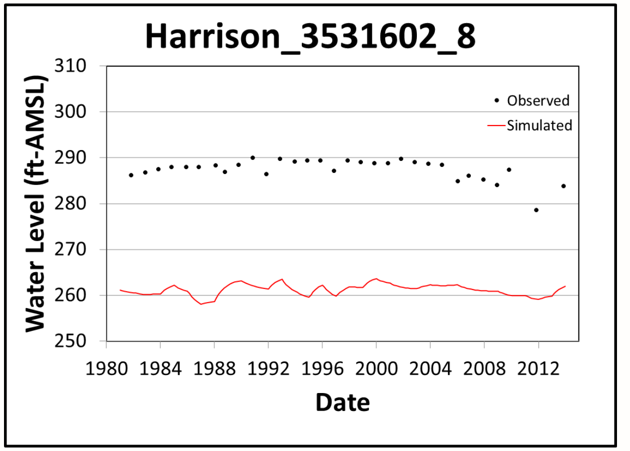
2. Chart name: county name, well name, model layer; ft-AMSL = feet above mean sea level.
3. Chart outline color Y-axis: yellow = 400 feet; green = 200 feet; black = 60 feet.

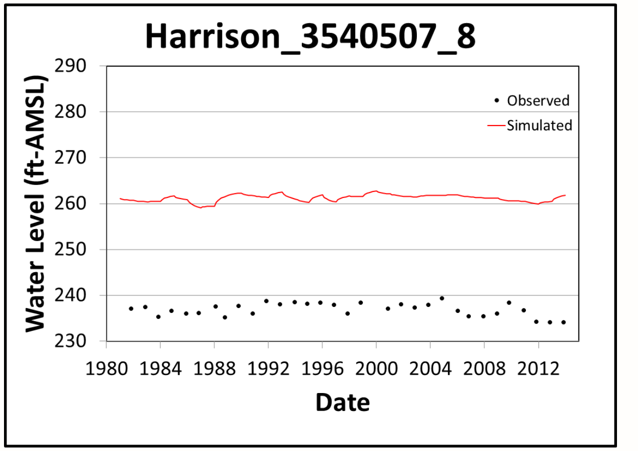
GSI ENVIRONMENTAL

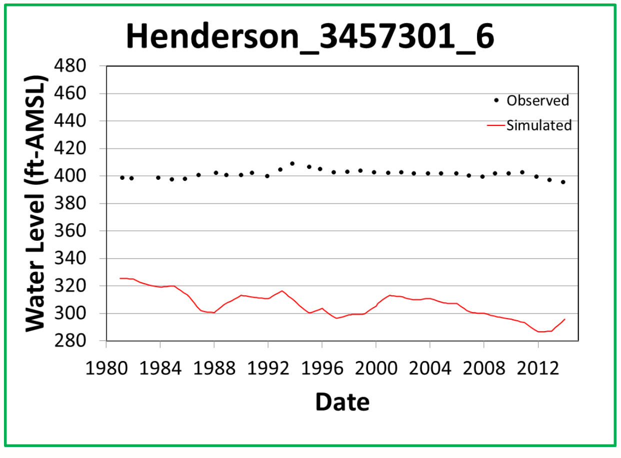
GSI Job No. 4529	Drawn By: HMH
Issued: 2020/07/09	Chk'd By:
Revised:	Aprv'd By:
Scale:	

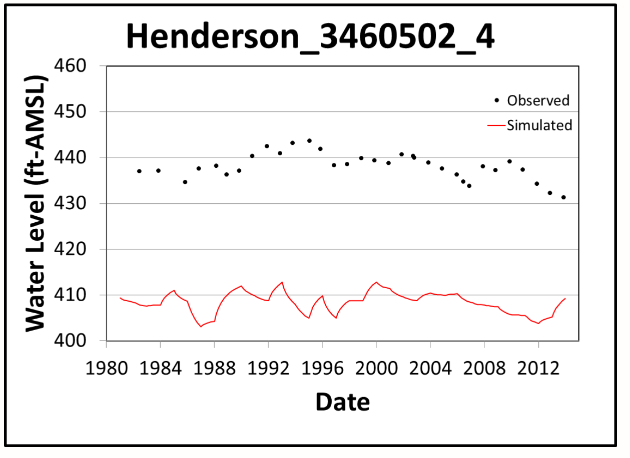
Appendix A – Hydrographs for Select Target Wells

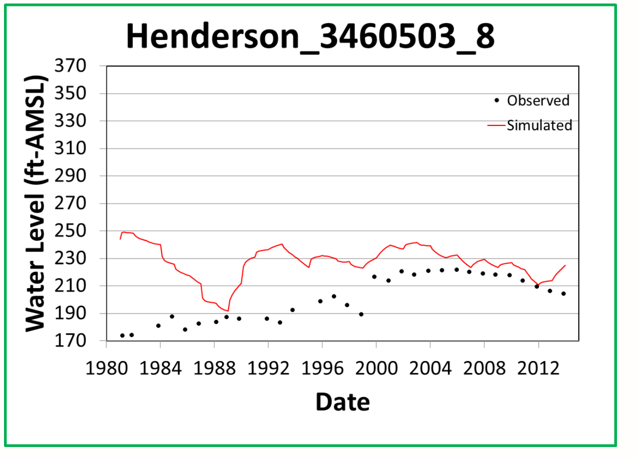












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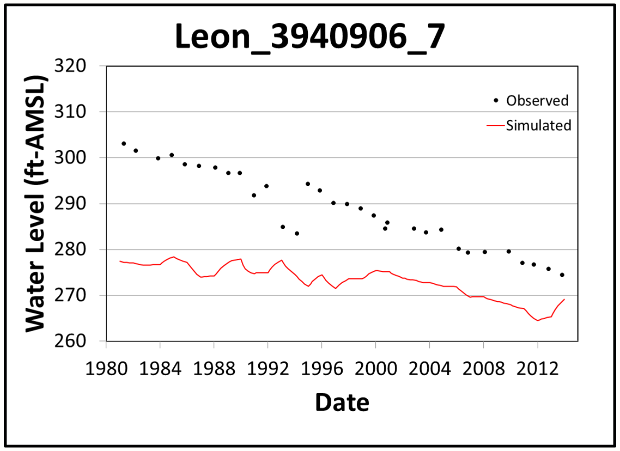
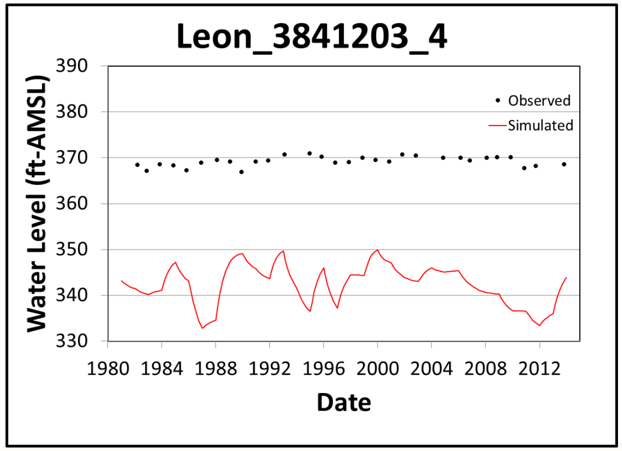
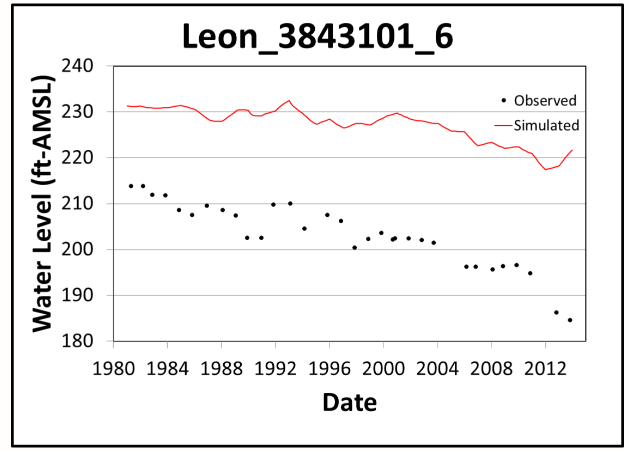
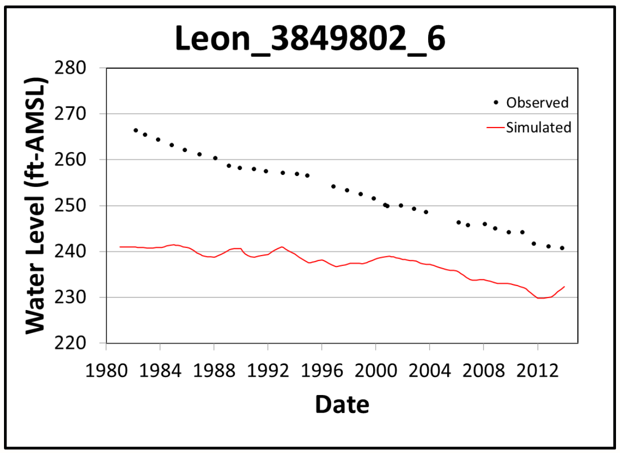
Issued:	2020/07/09	Chk'd By:	
Revised:		Aprv'd By:	
Scale:			

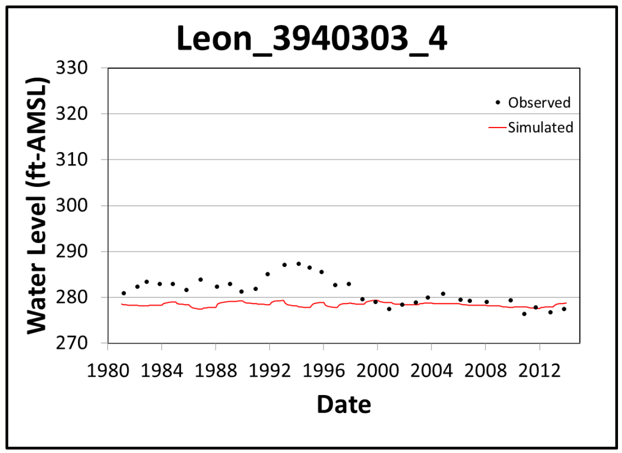
Appendix A – Hydrographs for Select Target Wells

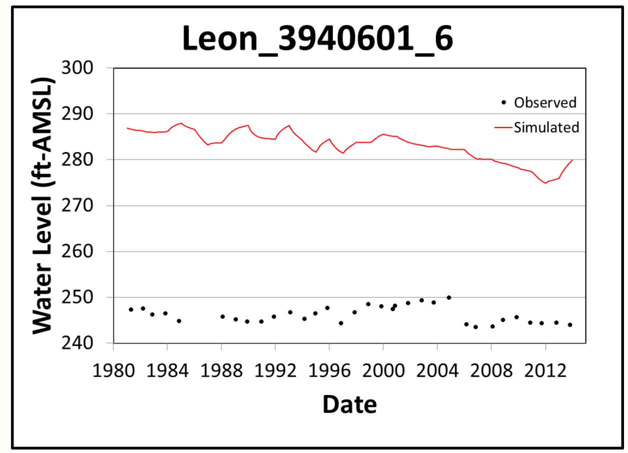












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Revised:	Aprv'd By:
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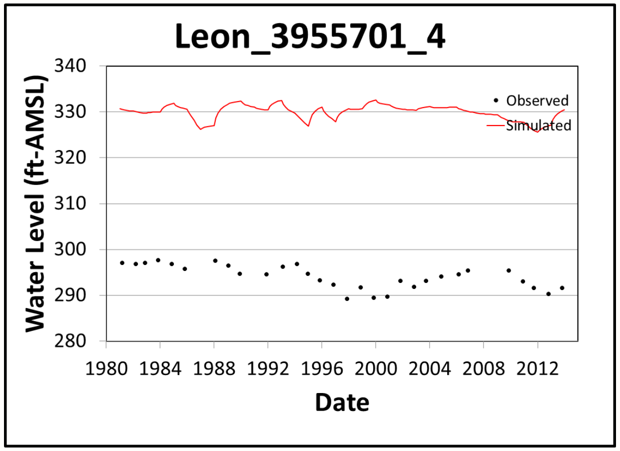
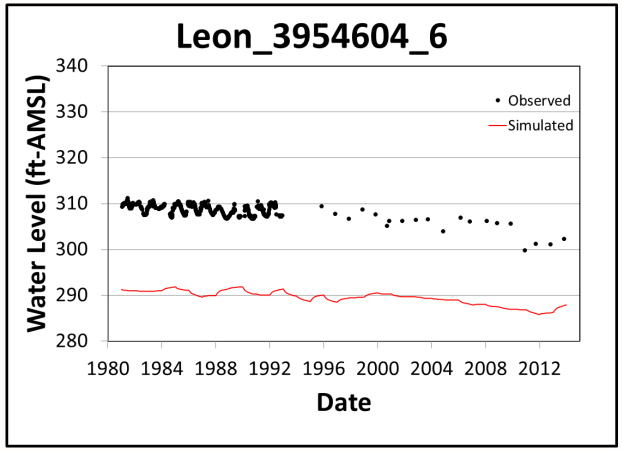
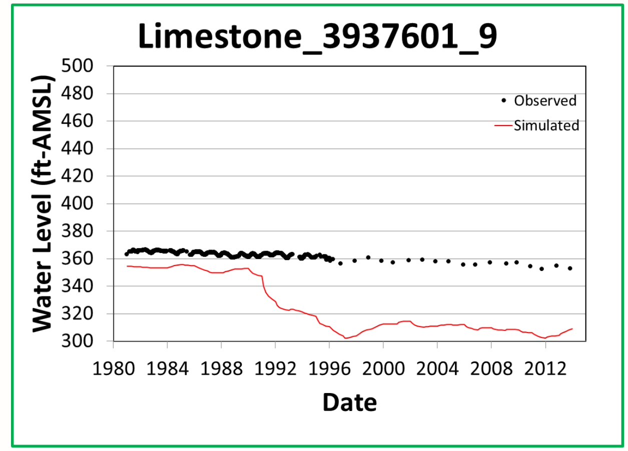
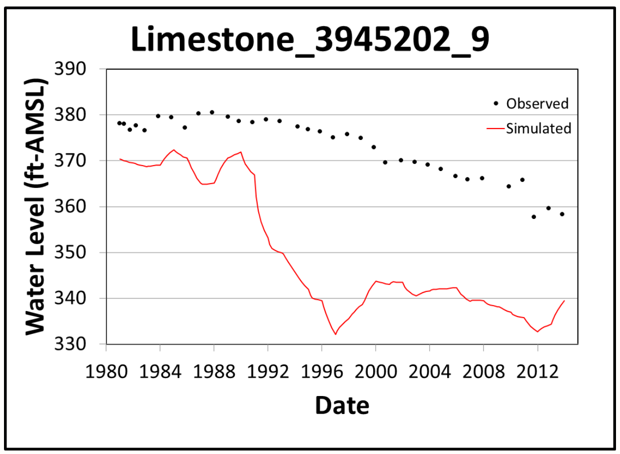
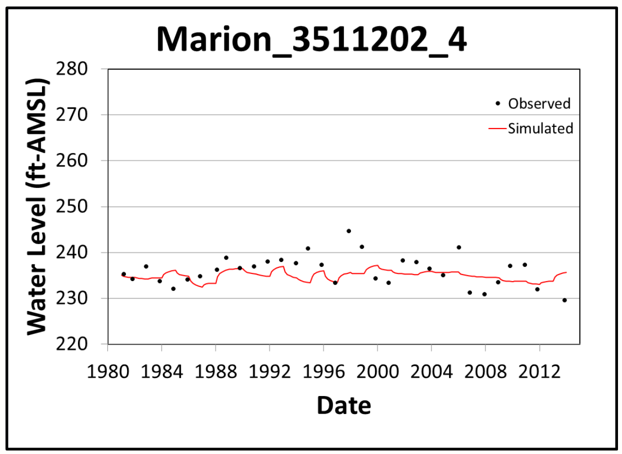
Appendix A – Hydrographs for Select Target Wells

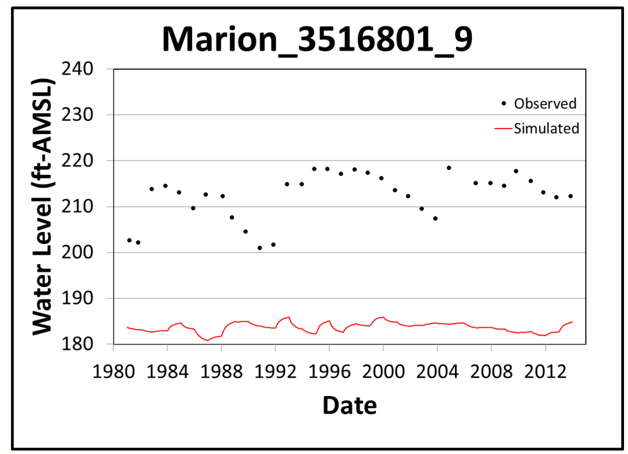












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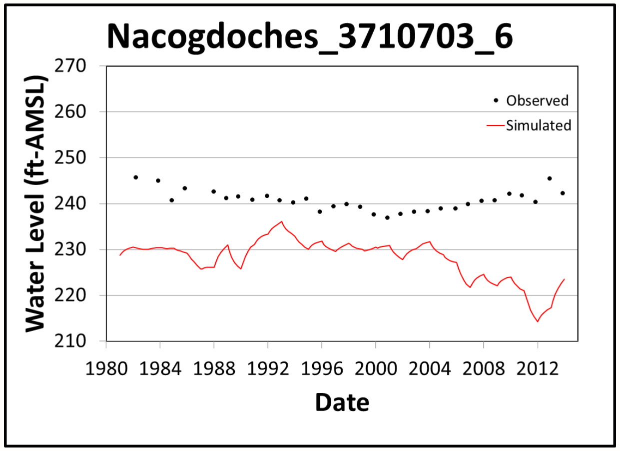
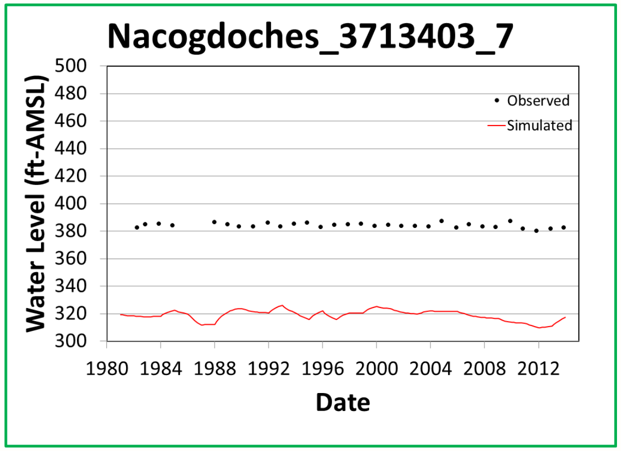
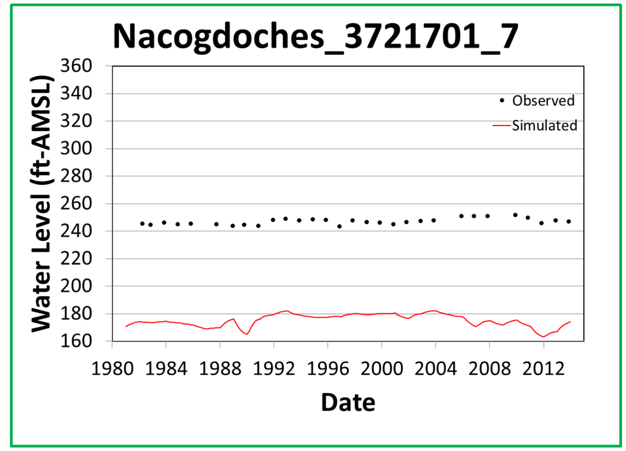
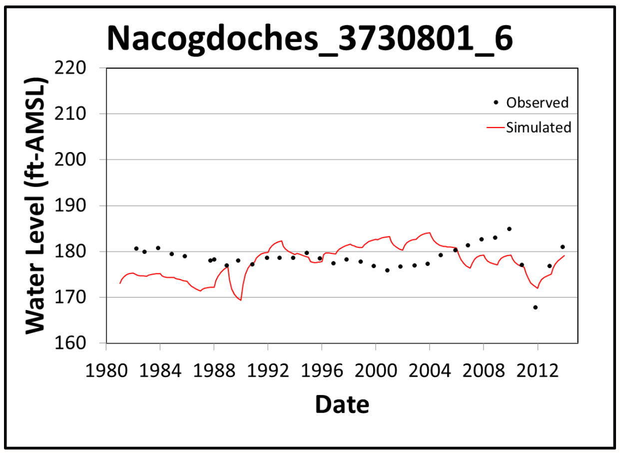
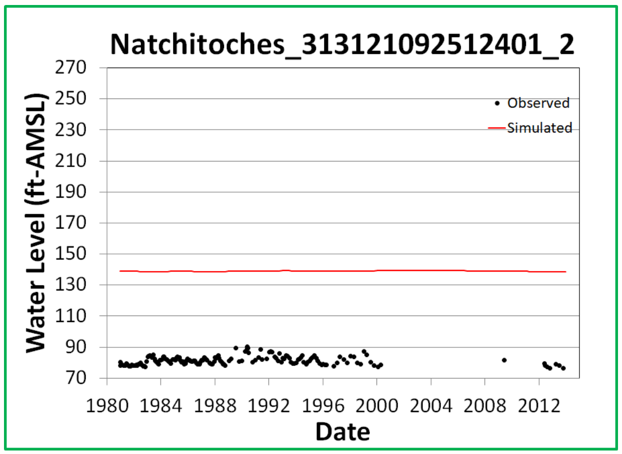
Appendix A – Hydrographs for Select Target Wells

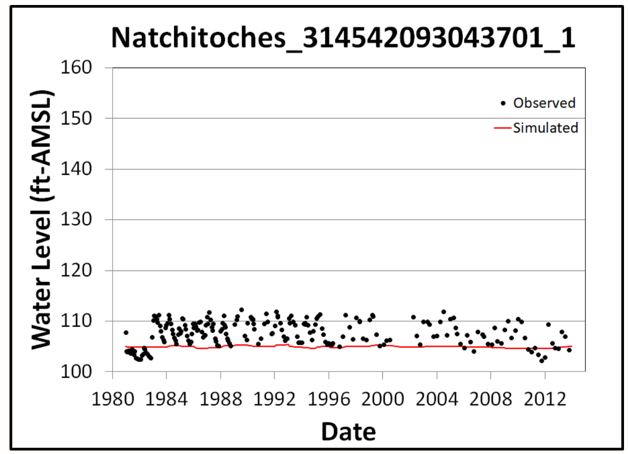












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Issued:	2020/07/09	Chk'd By:	
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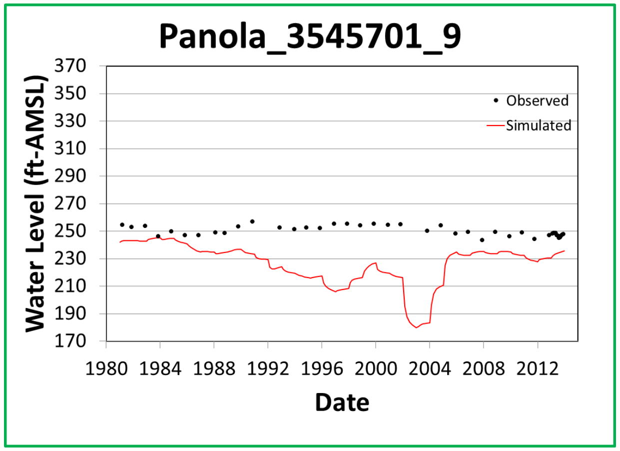
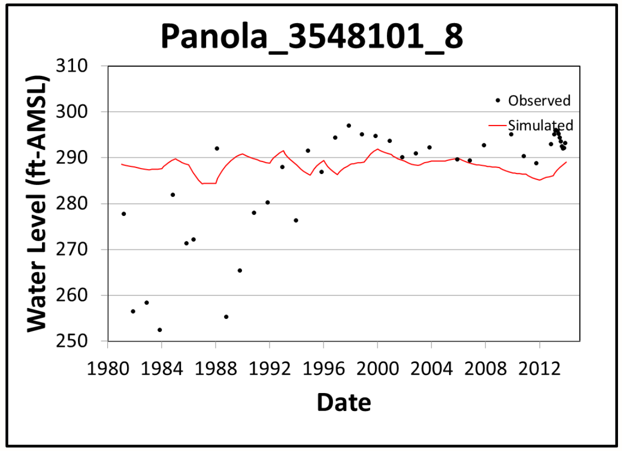
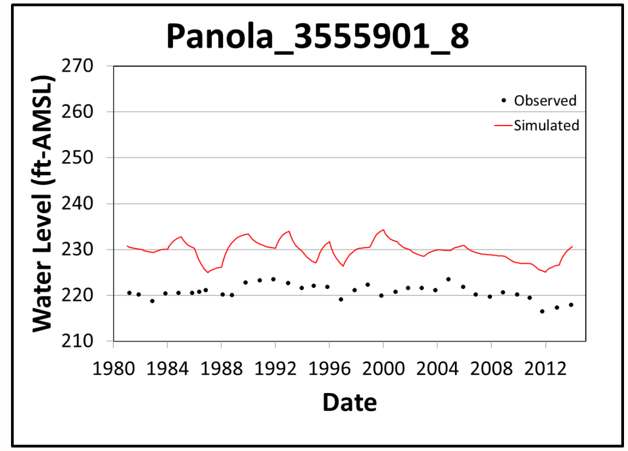
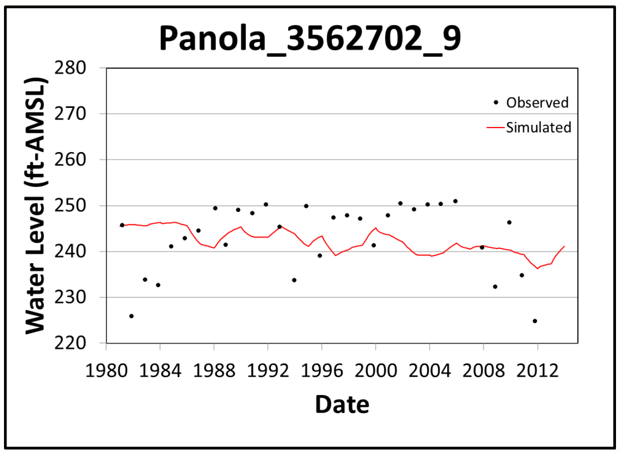
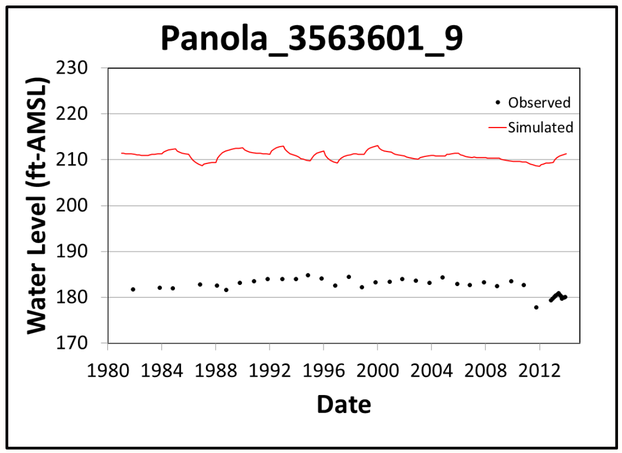
Appendix A – Hydrographs for Select Target Wells

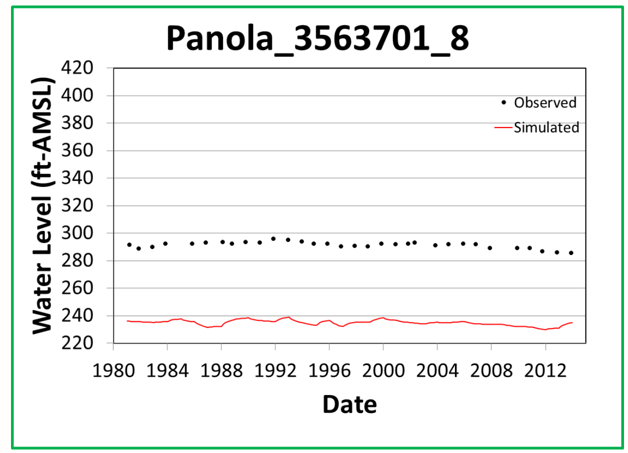












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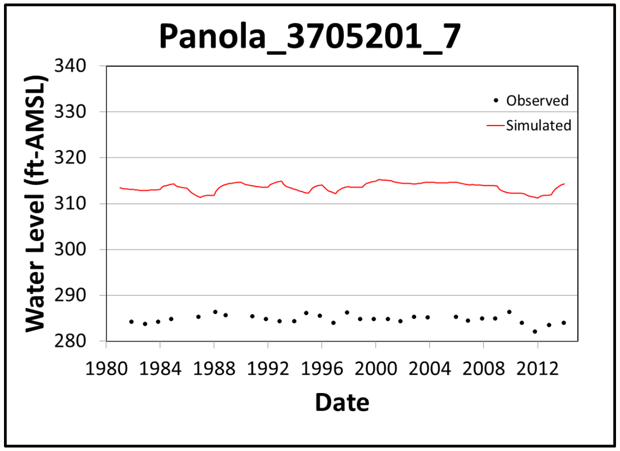
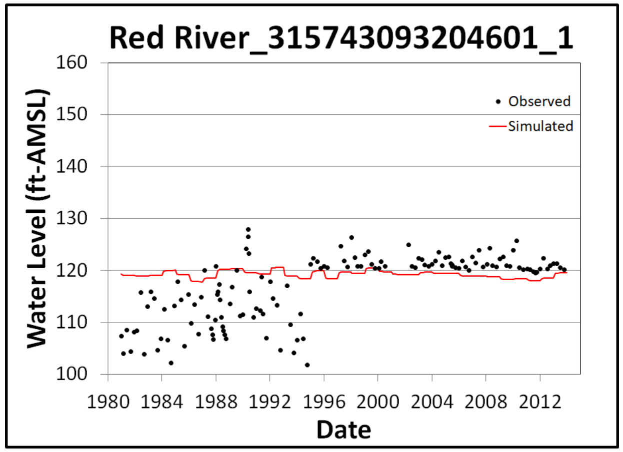
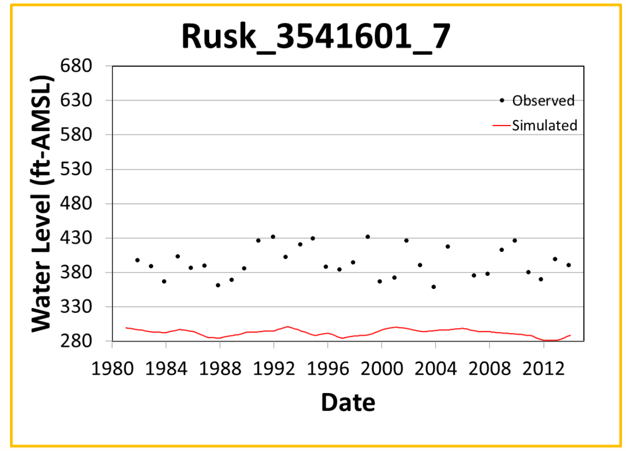
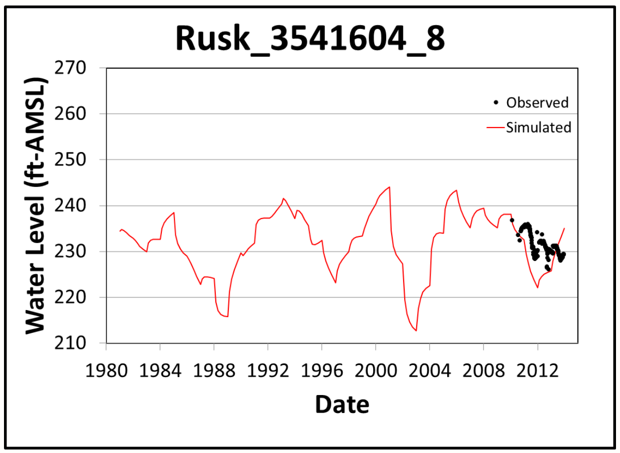
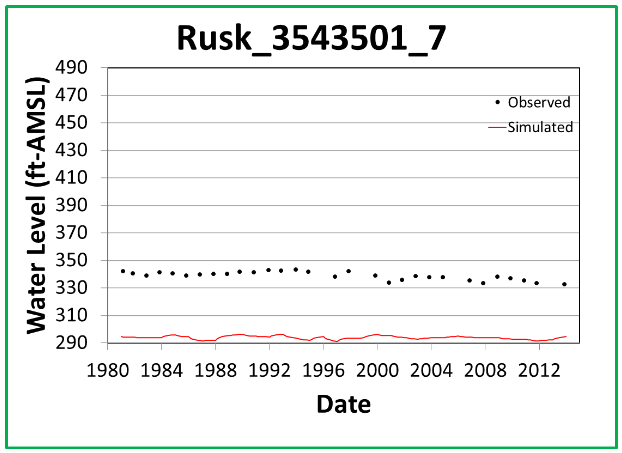
Appendix A – Hydrographs for Select Target Wells

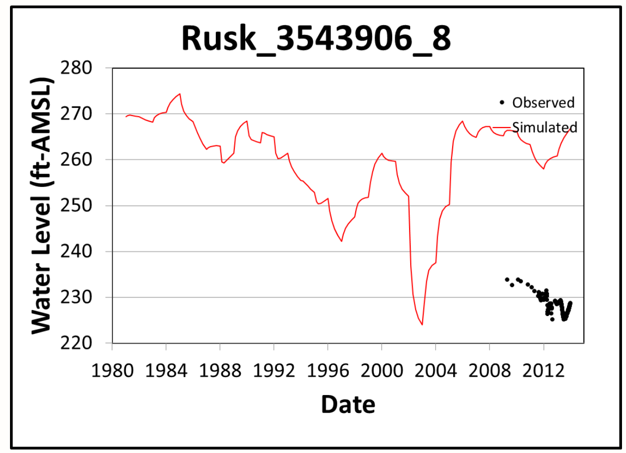












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GSI ENVIRONMENTAL

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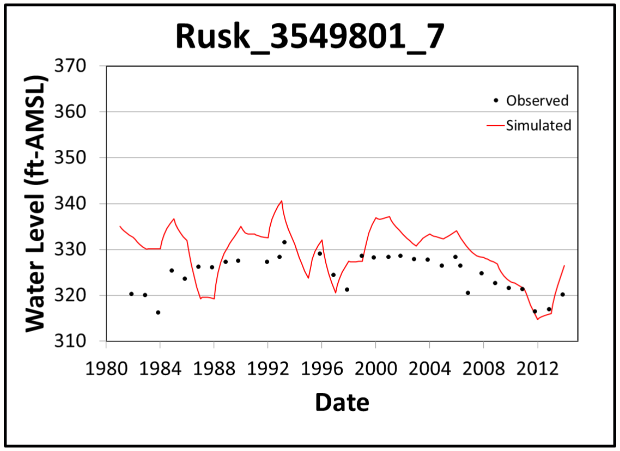
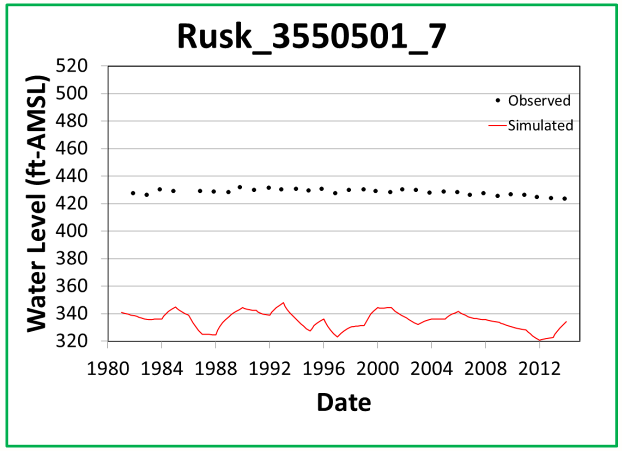
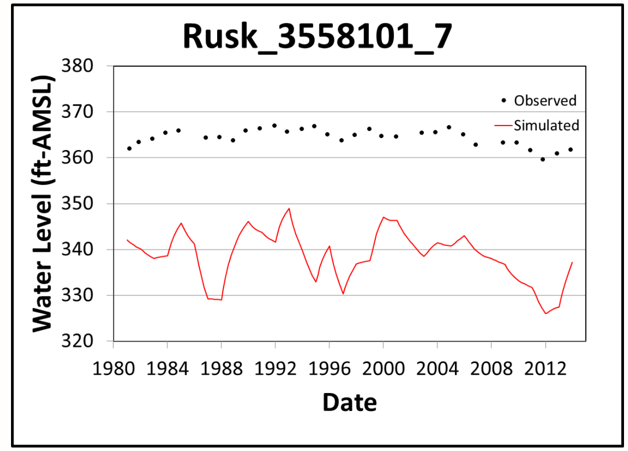
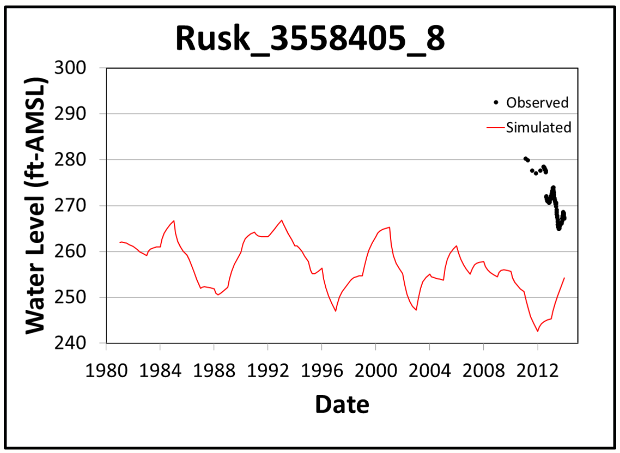
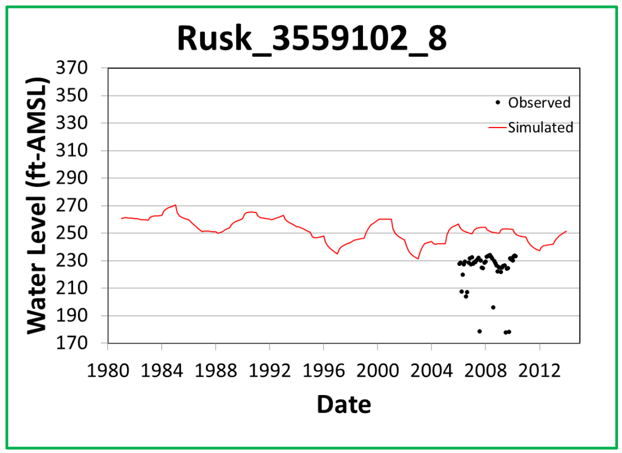
Appendix A – Hydrographs for Select Target Wells

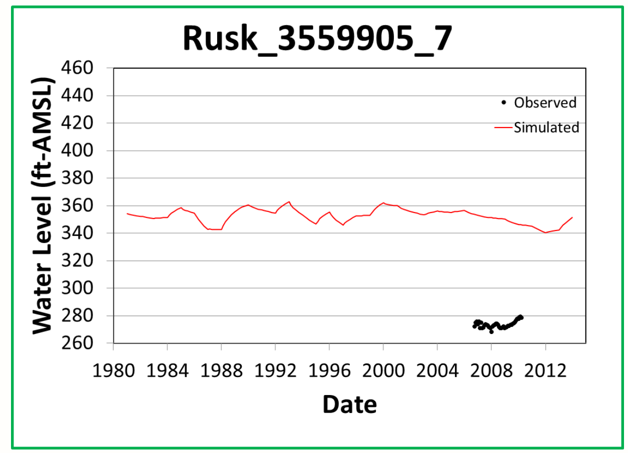












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GSI ENVIRONMENTAL

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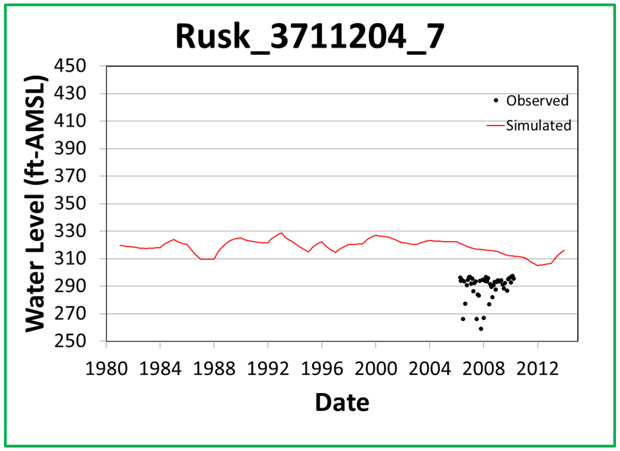
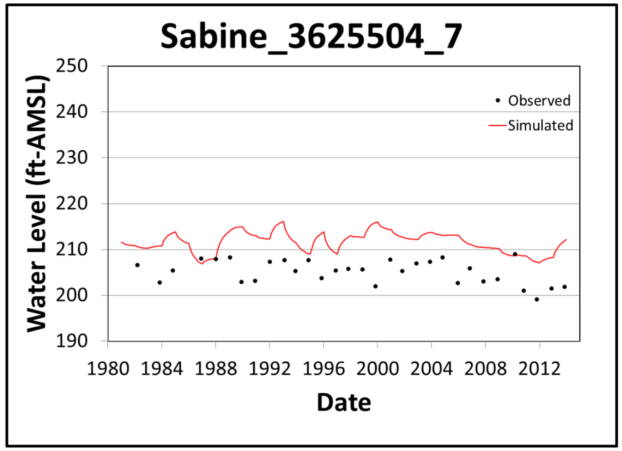
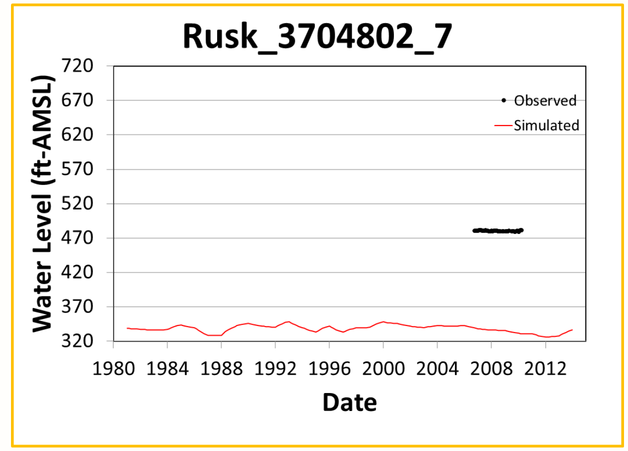
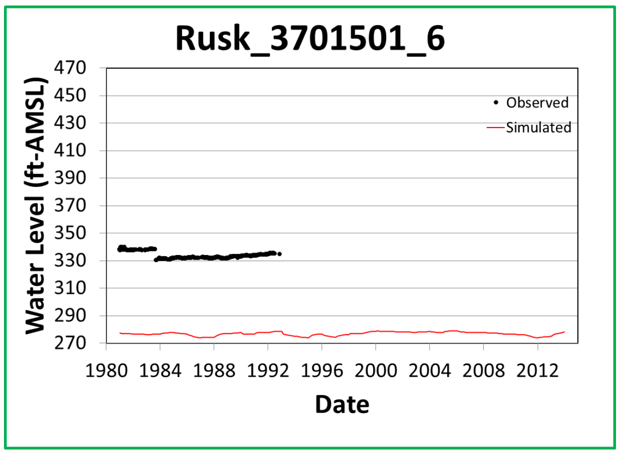
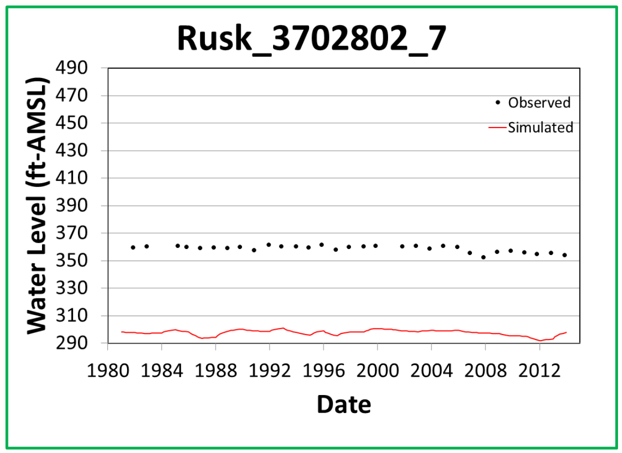
Issued: 2020/07/09	Chk'd By:	
Revised:	Aprv'd By:	
Scale:		

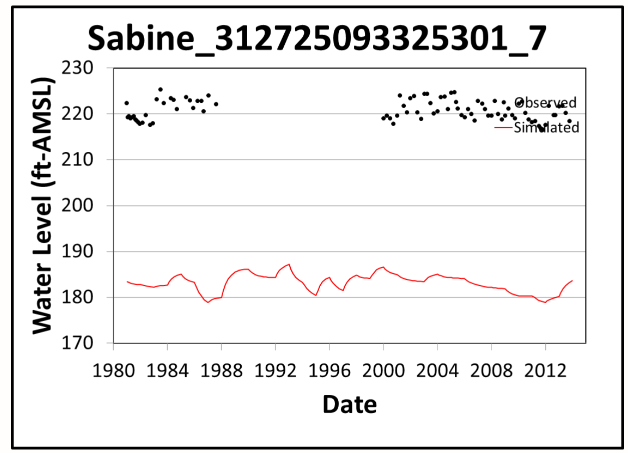












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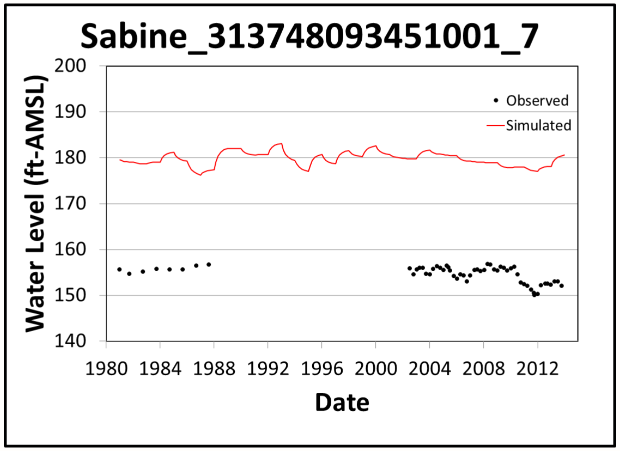
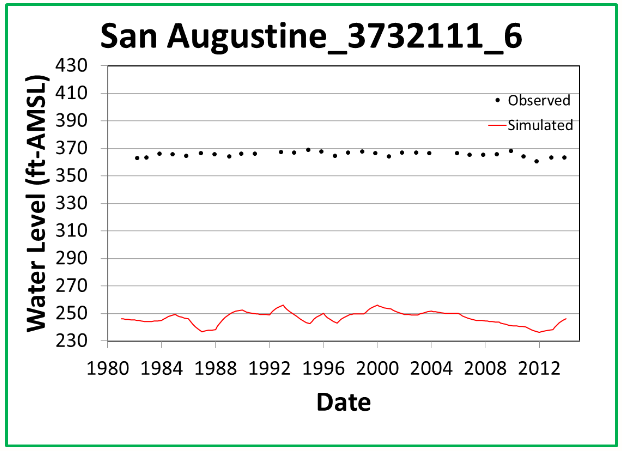
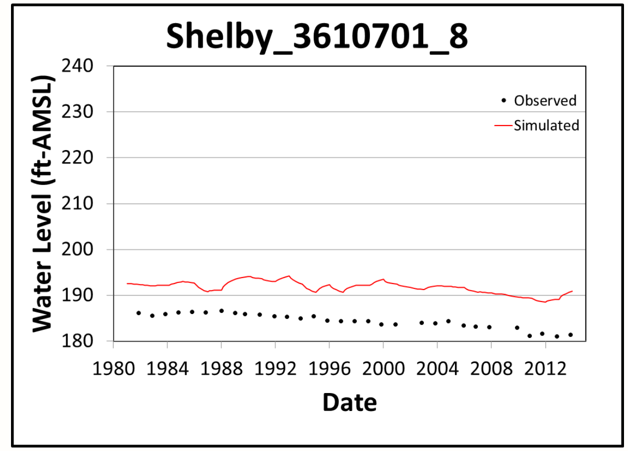
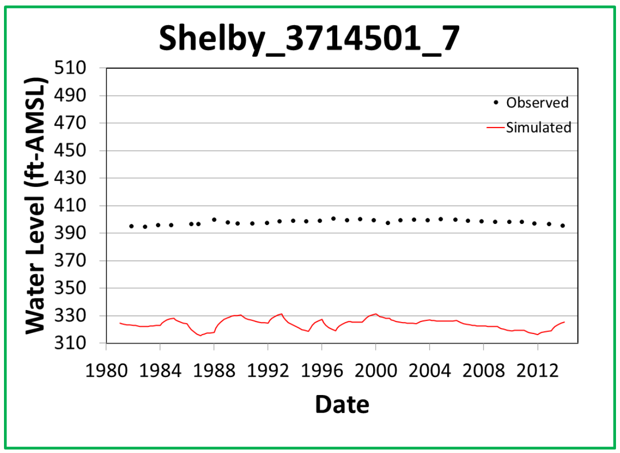
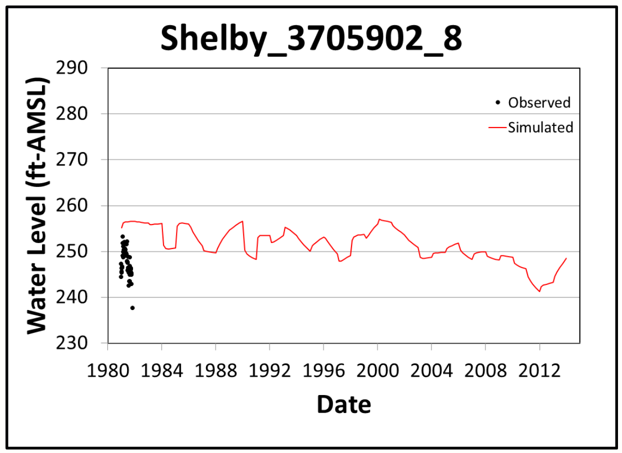
Appendix A – Hydrographs for Select Target Wells

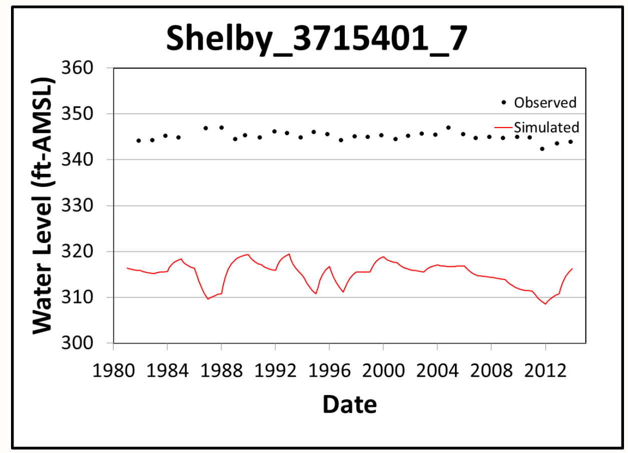












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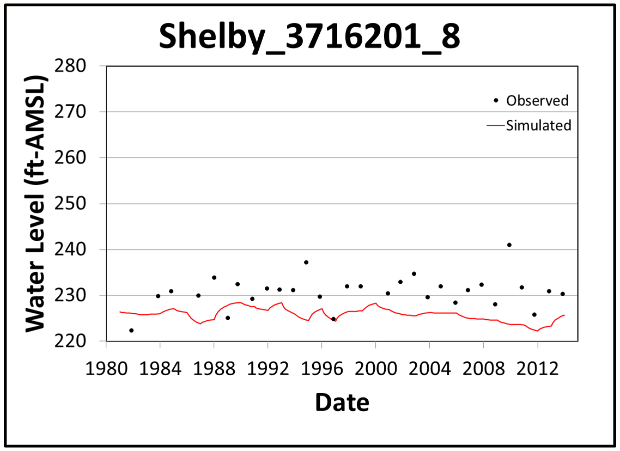

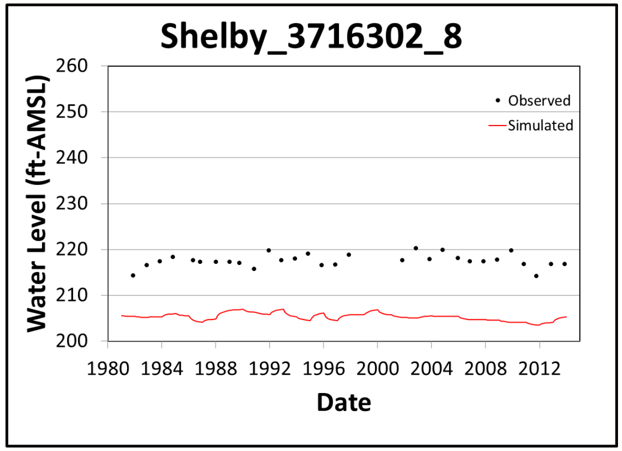

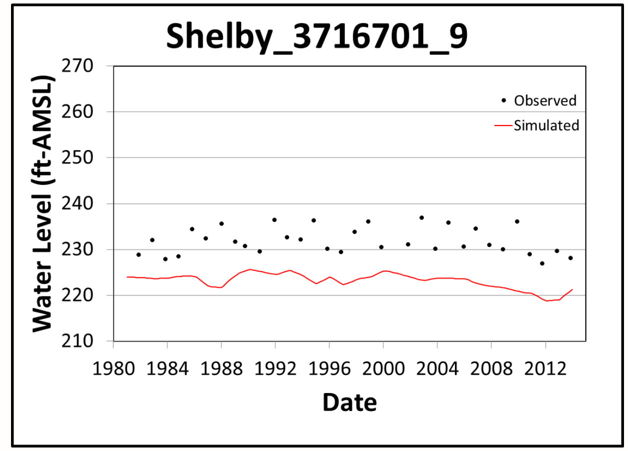

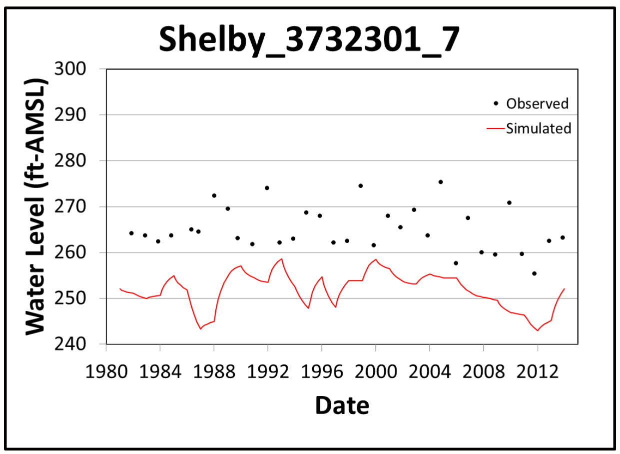

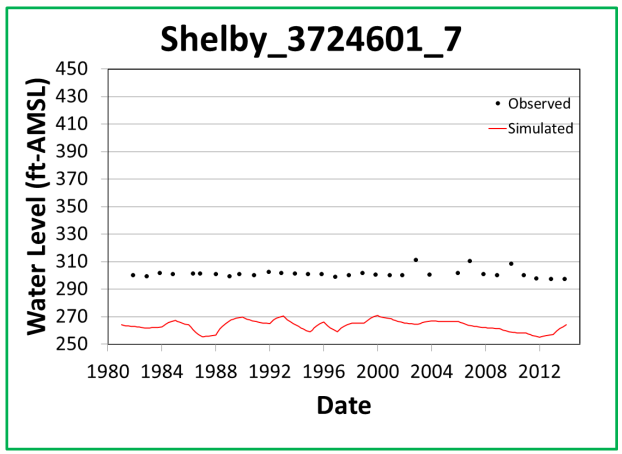

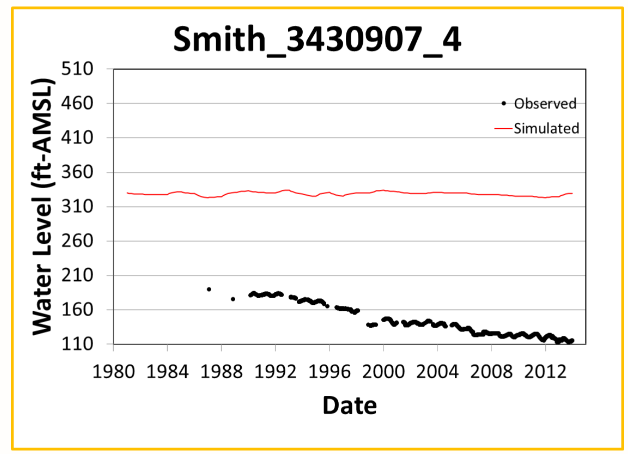

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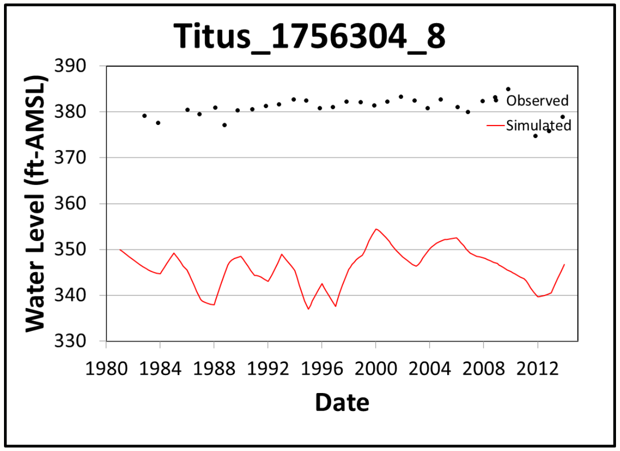
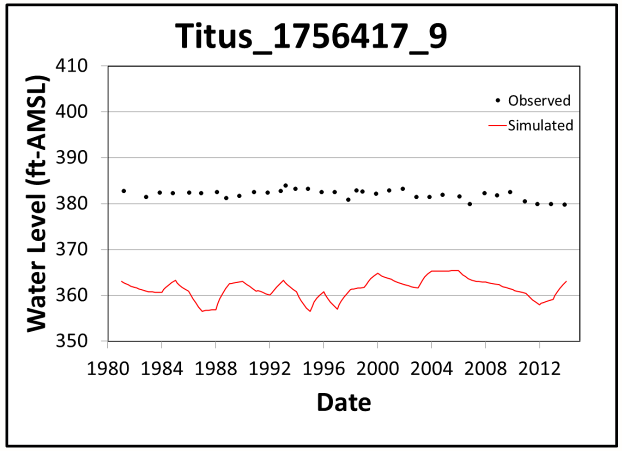
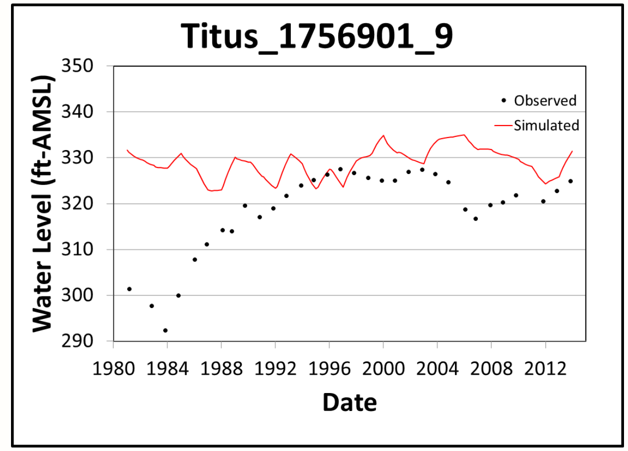
GSI ENVIRONMENTAL

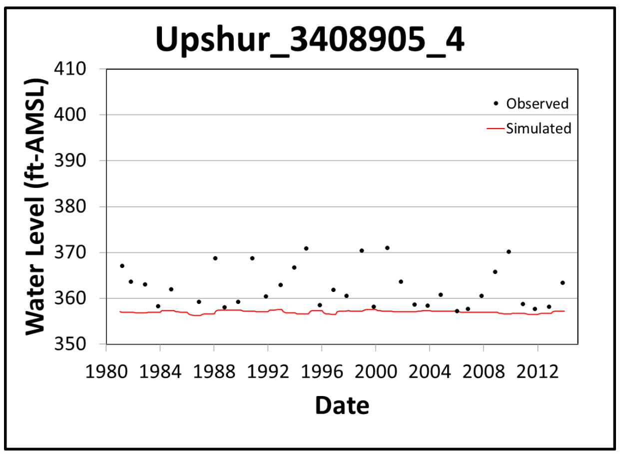
GSI Job No.	4529	Drawn By:	HMH
Issued:	2020/07/09	Chk'd By:	
Revised:		Aprv'd By:	
Scale:			

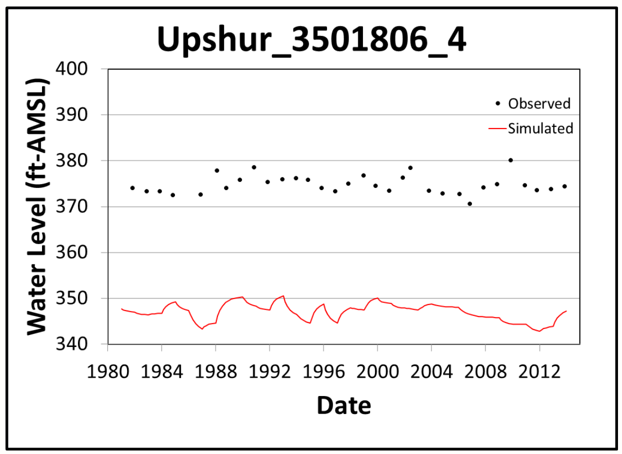
Appendix A – Hydrographs for Select Target Wells

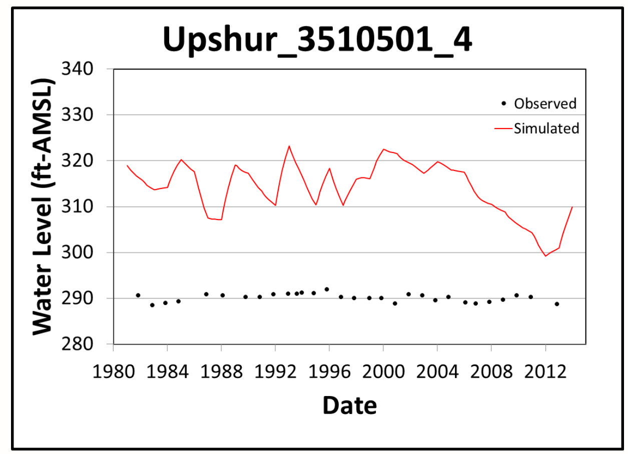












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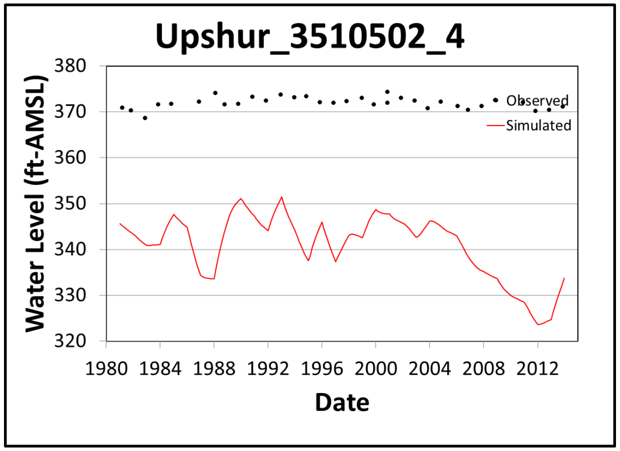
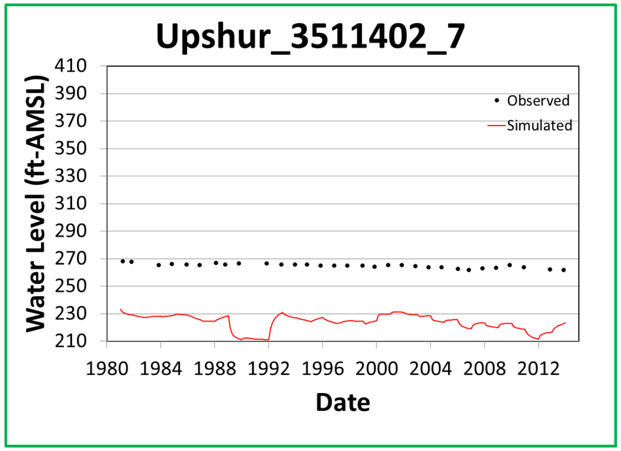
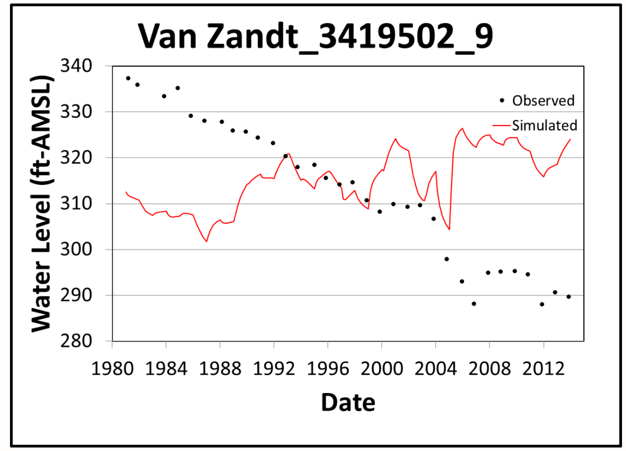
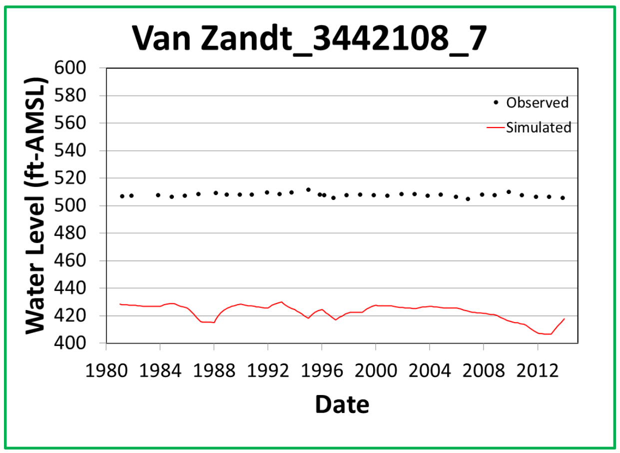
Scale:	

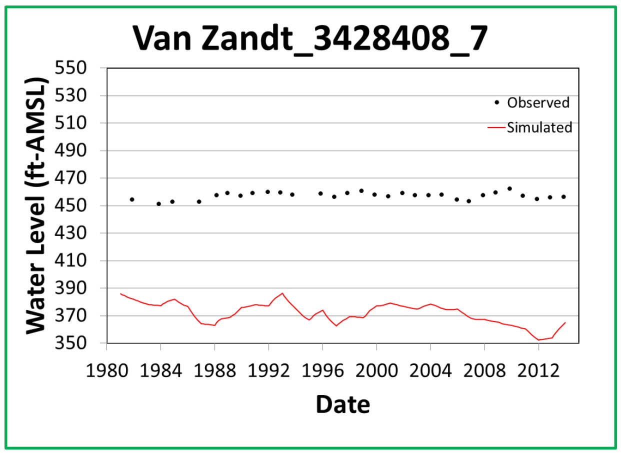
Appendix A – Hydrographs for Select Target Wells

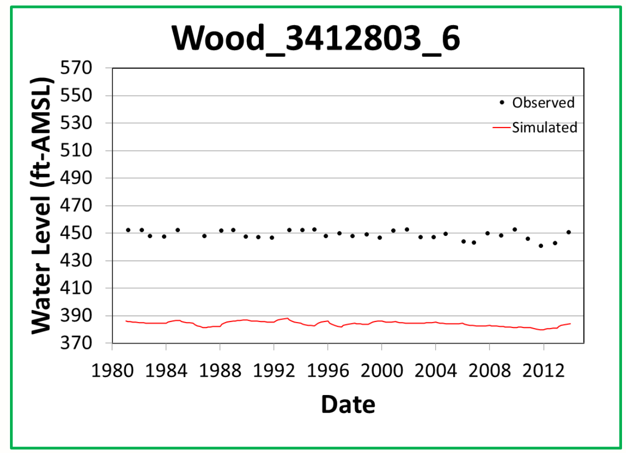












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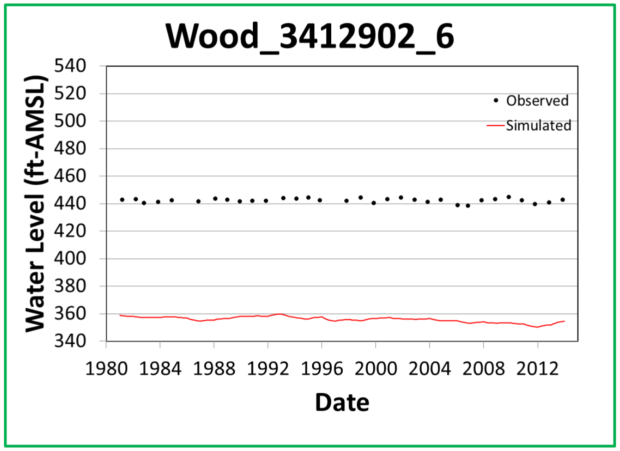
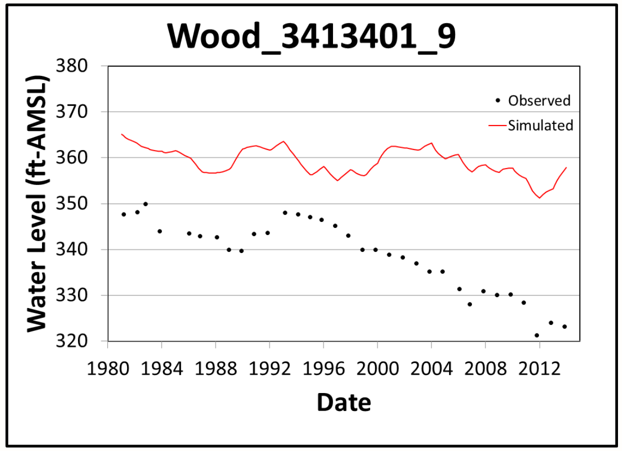
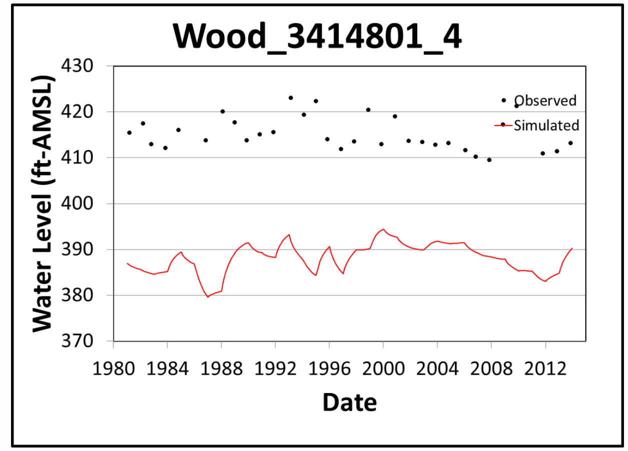
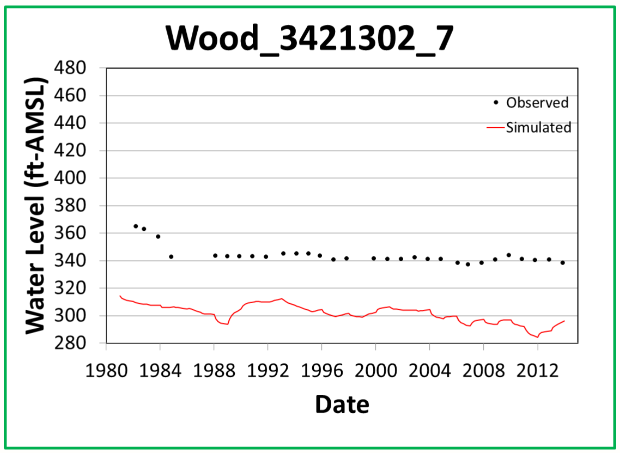
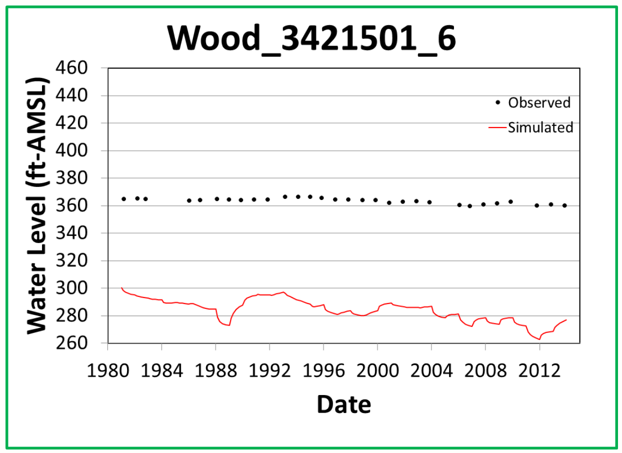
Appendix A – Hydrographs for Select Target Wells











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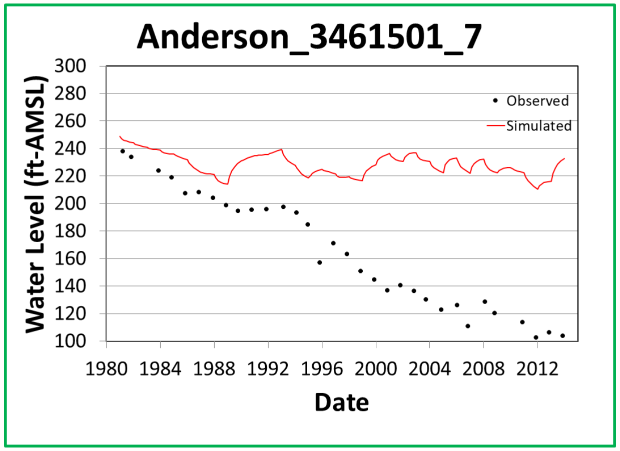
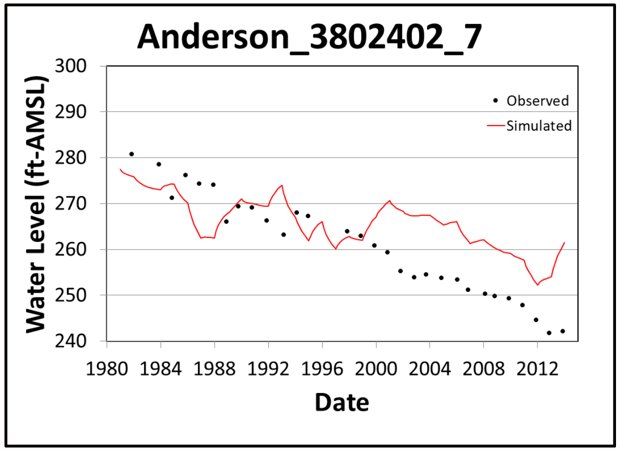
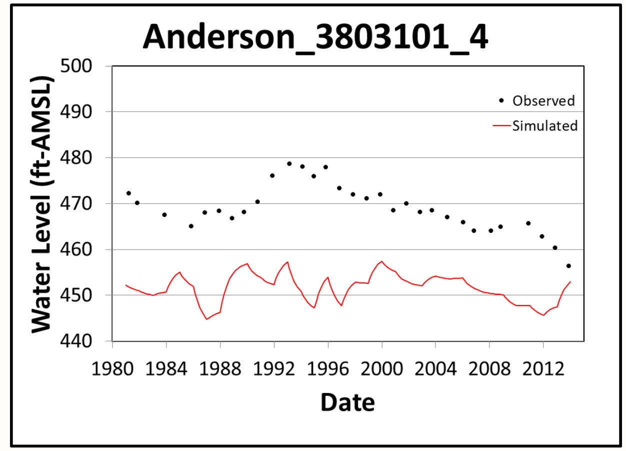
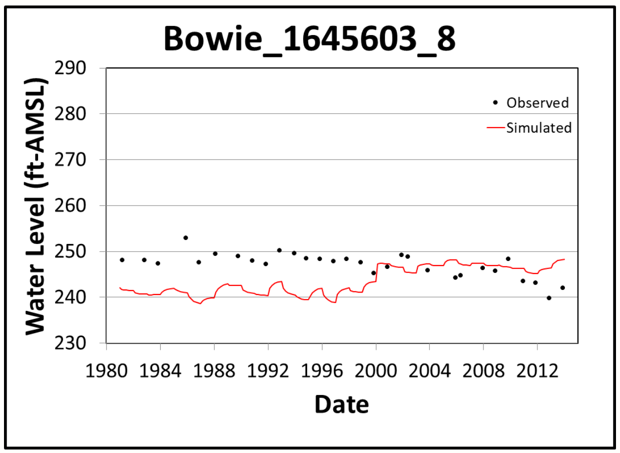
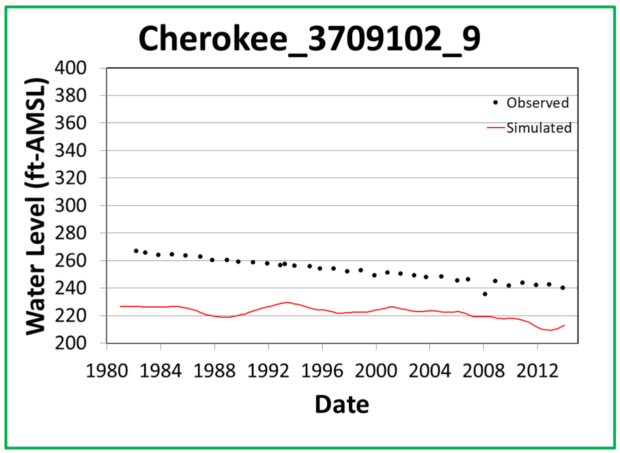
Appendix A – Hydrographs for Select Target Wells

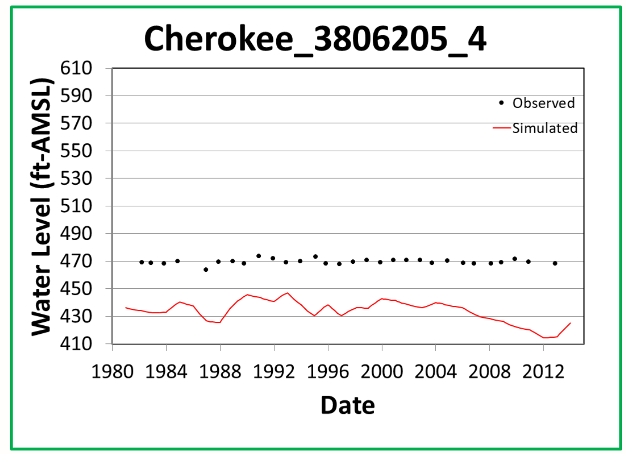












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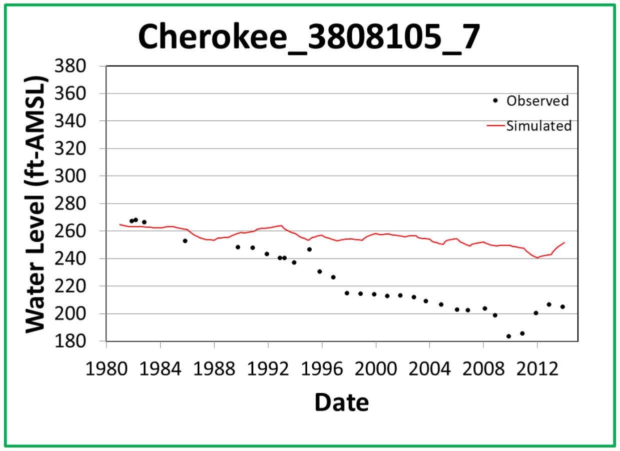
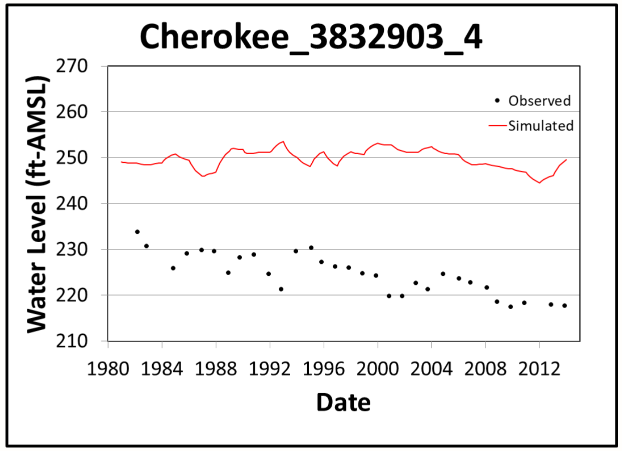
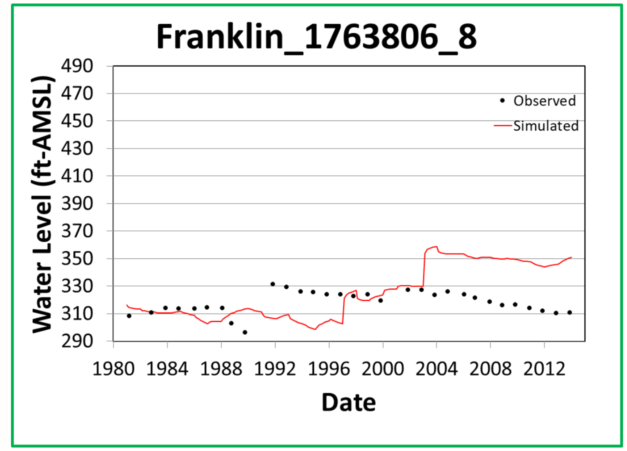
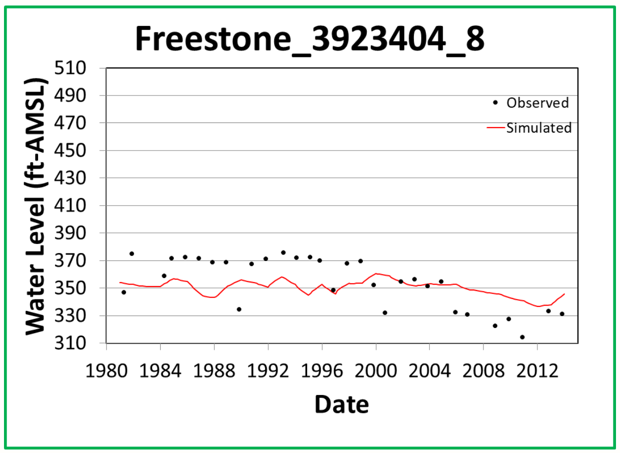
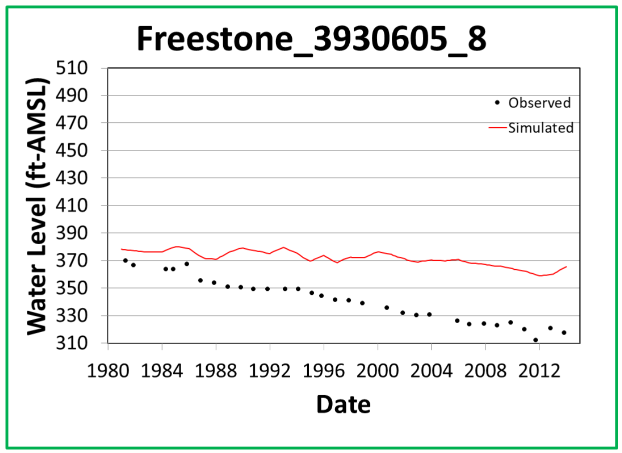
Appendix A – Hydrographs for Select Target Wells

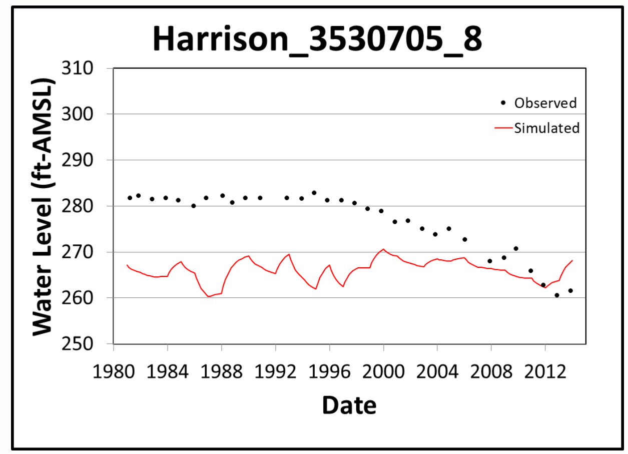












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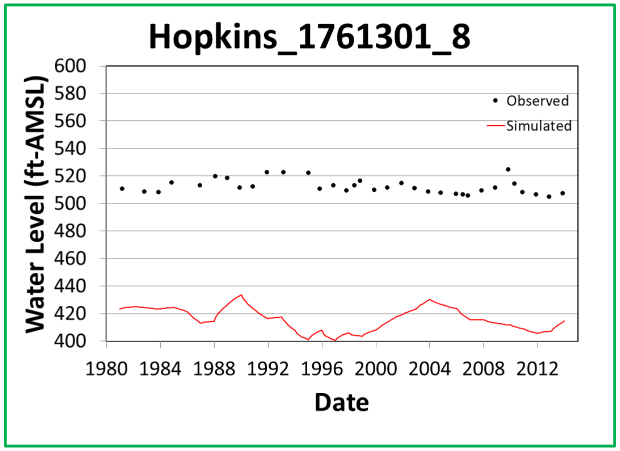
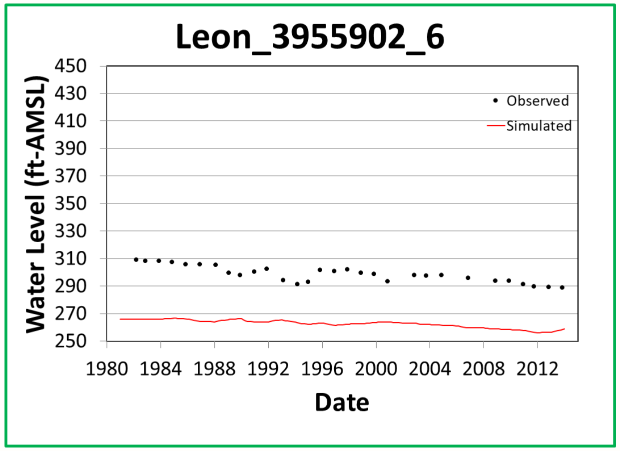
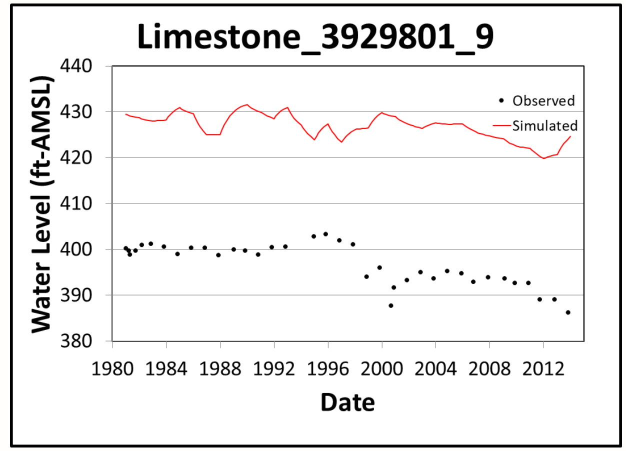
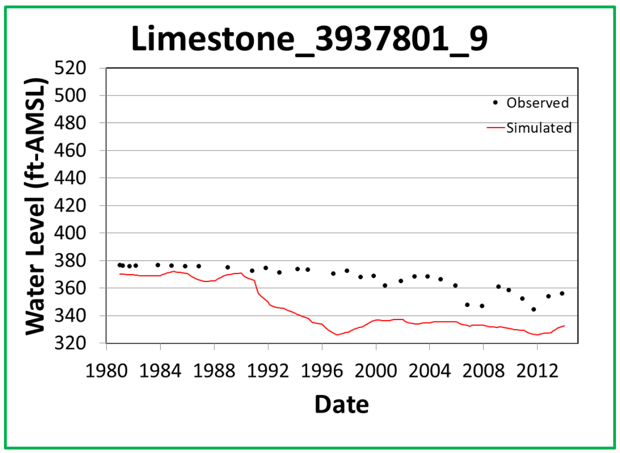
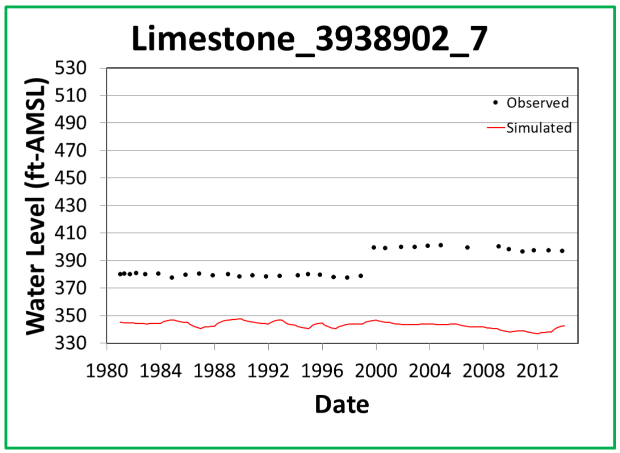
Appendix A – Hydrographs for Select Target Wells

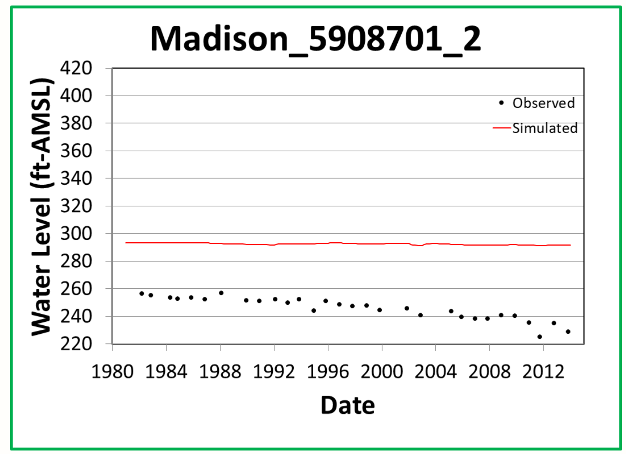












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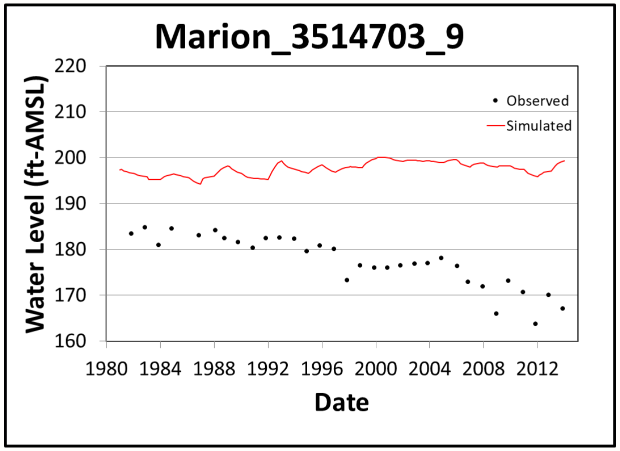
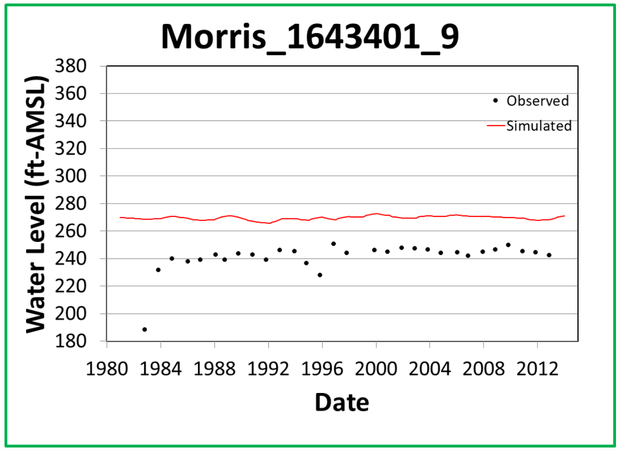
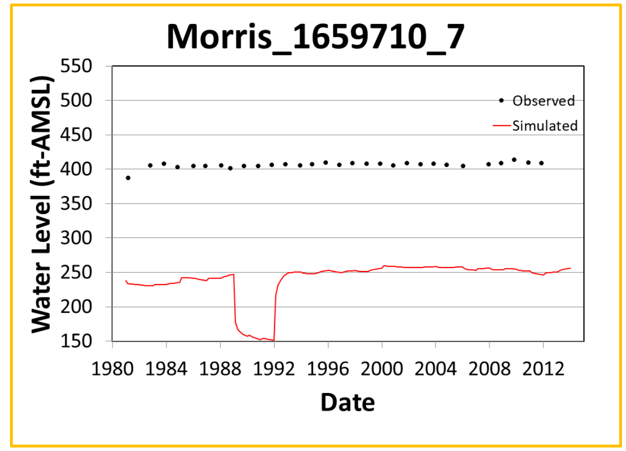
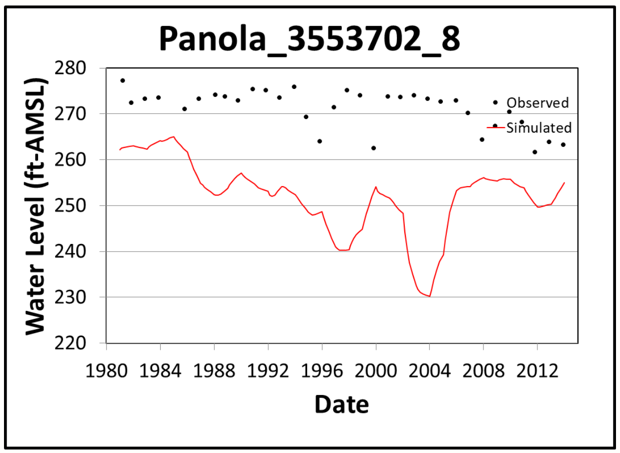
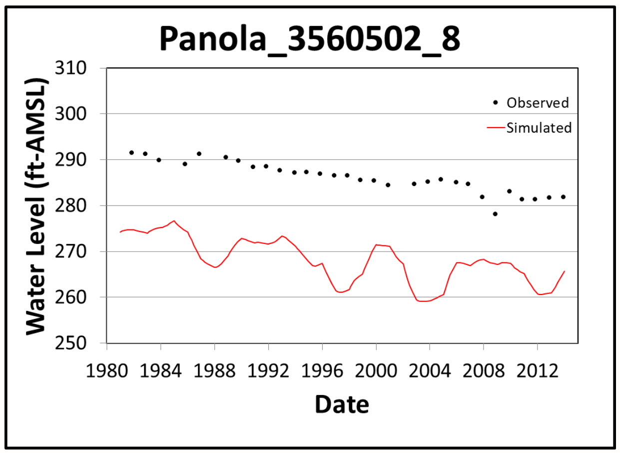
Appendix A – Hydrographs for Select Target Wells

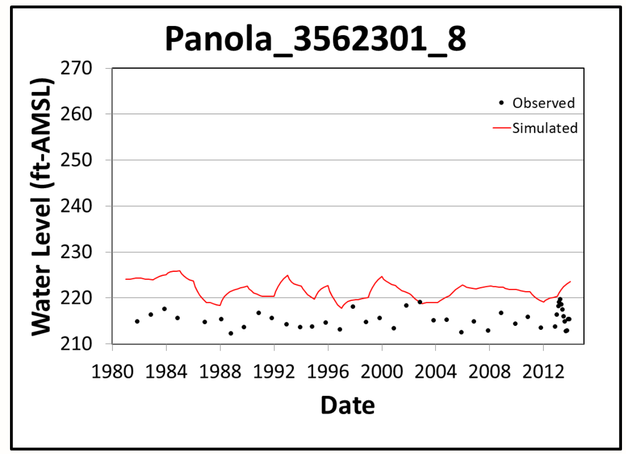












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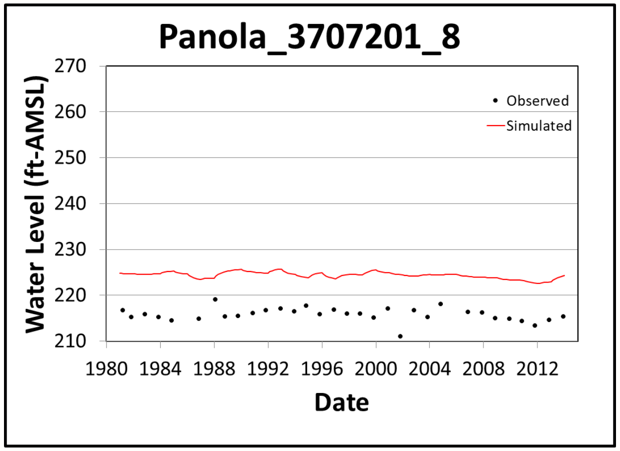
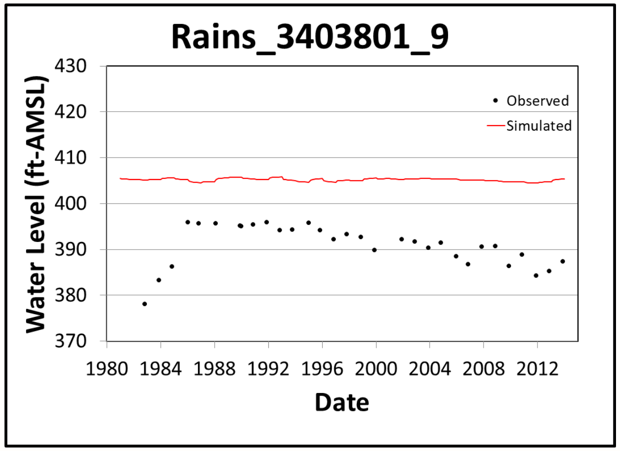
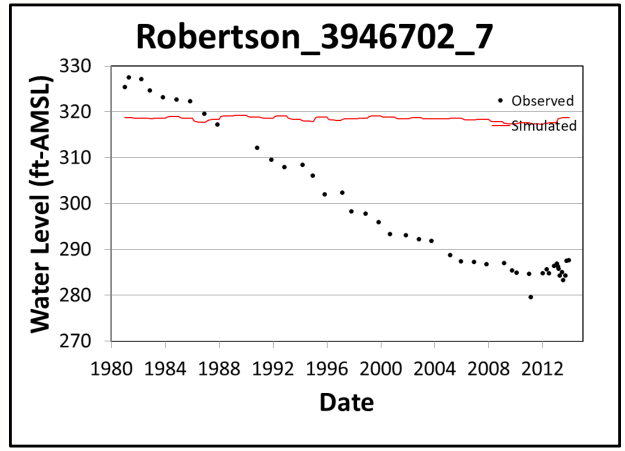
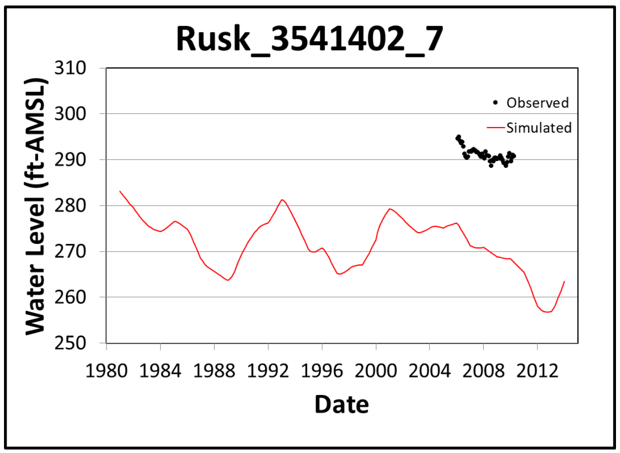
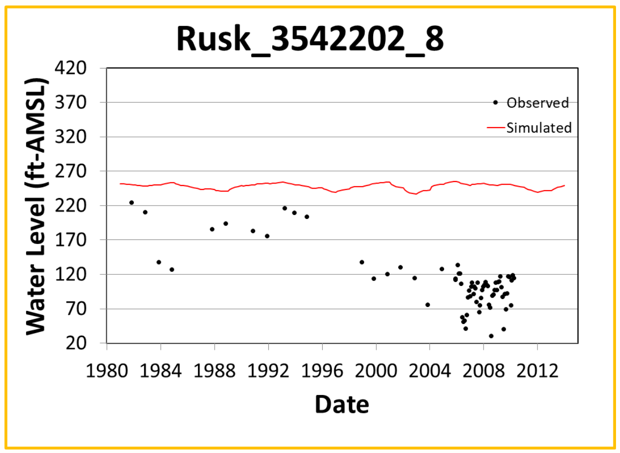
Appendix A – Hydrographs for Select Target Wells

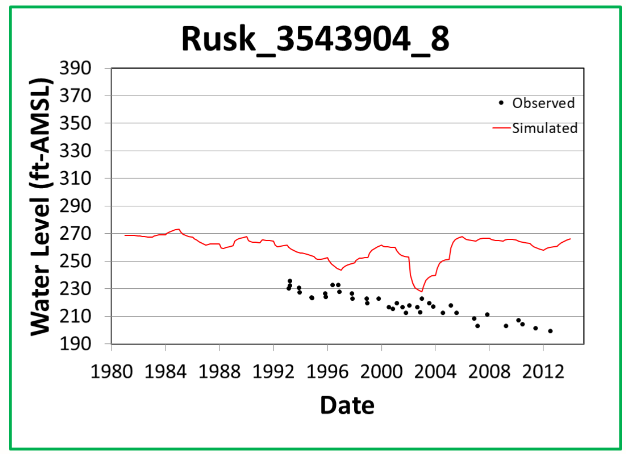












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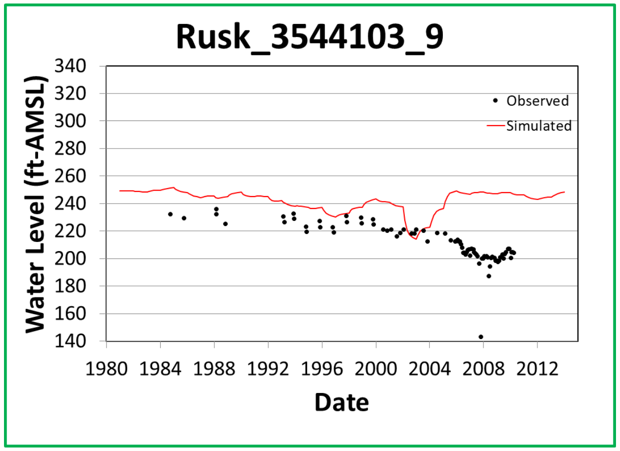

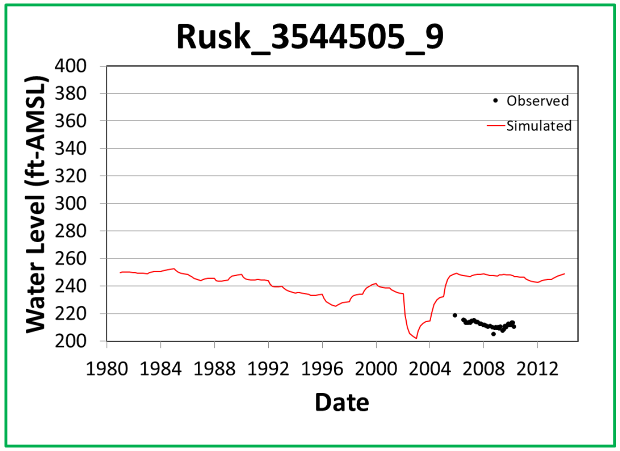

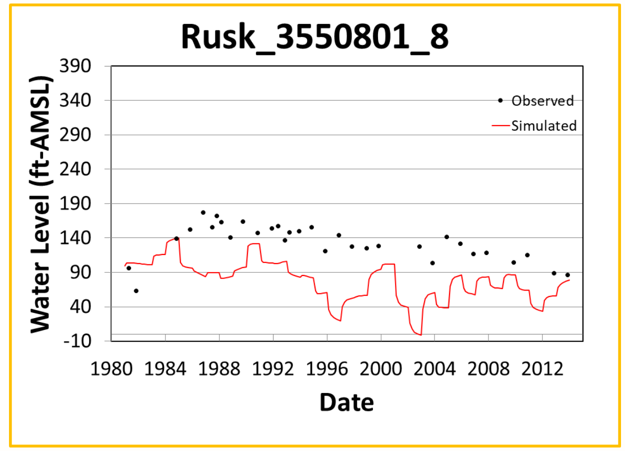

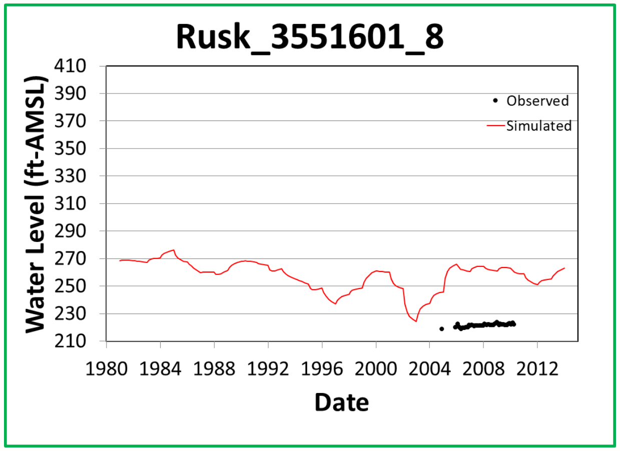

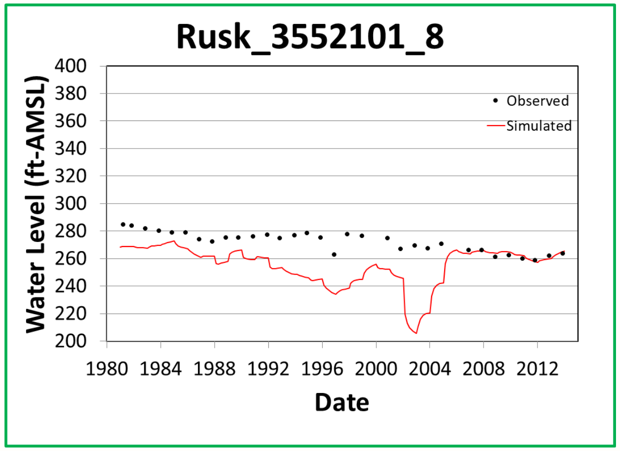

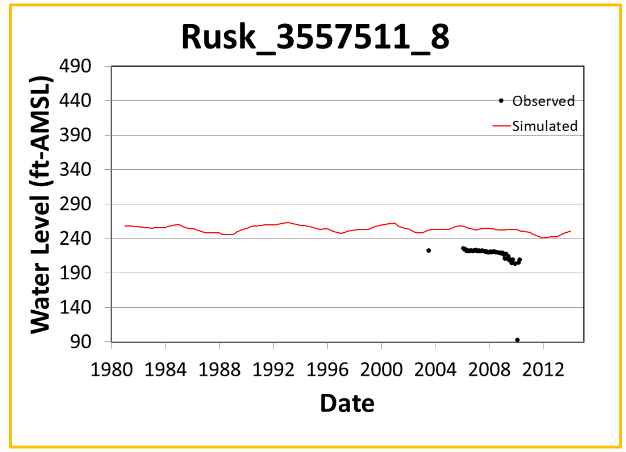

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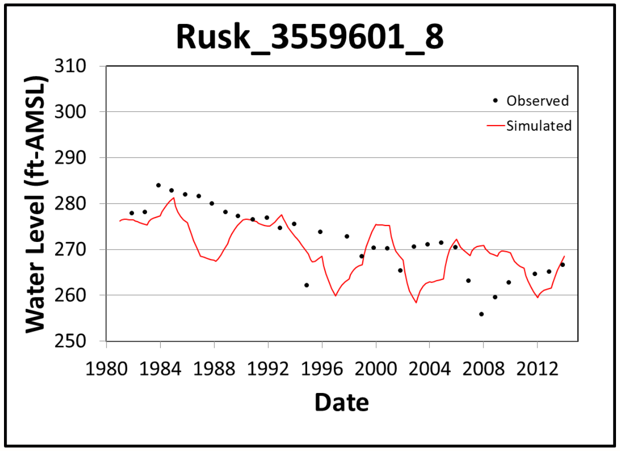

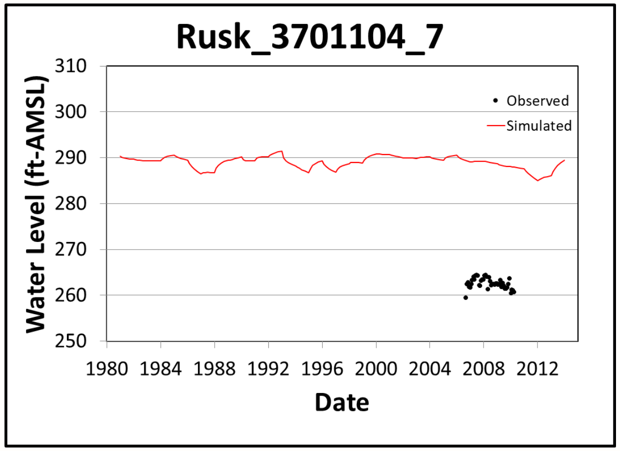

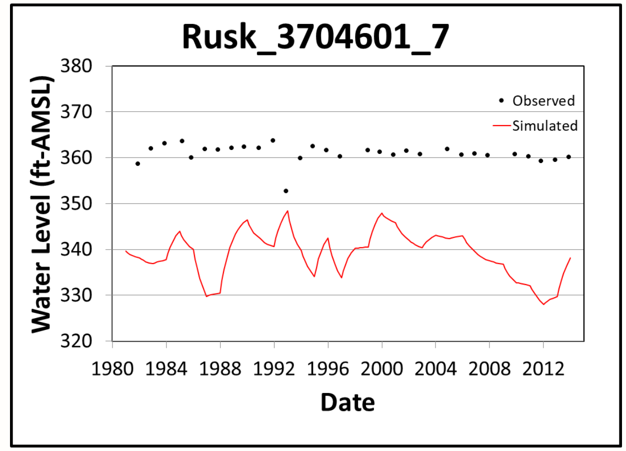

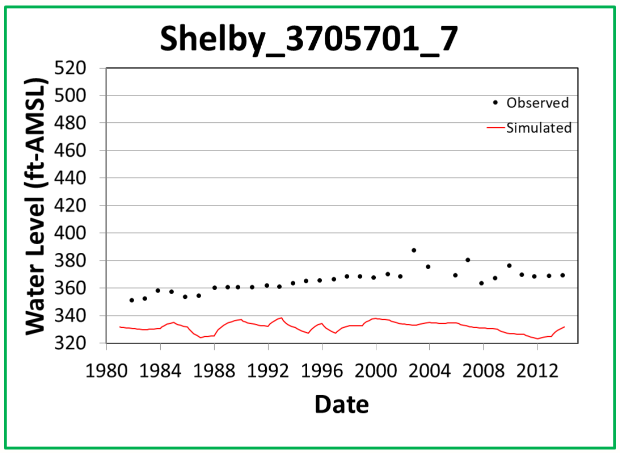

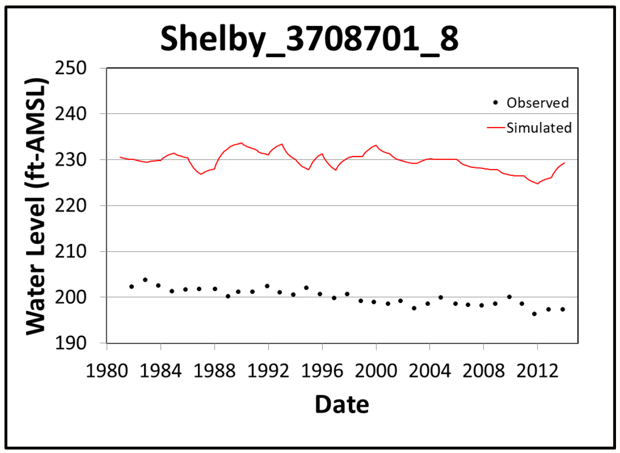

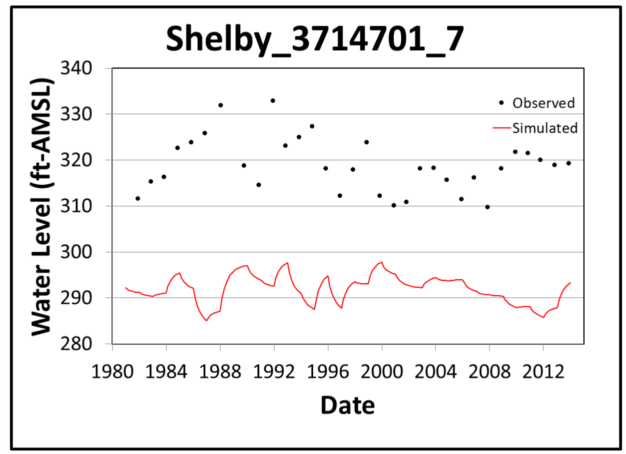

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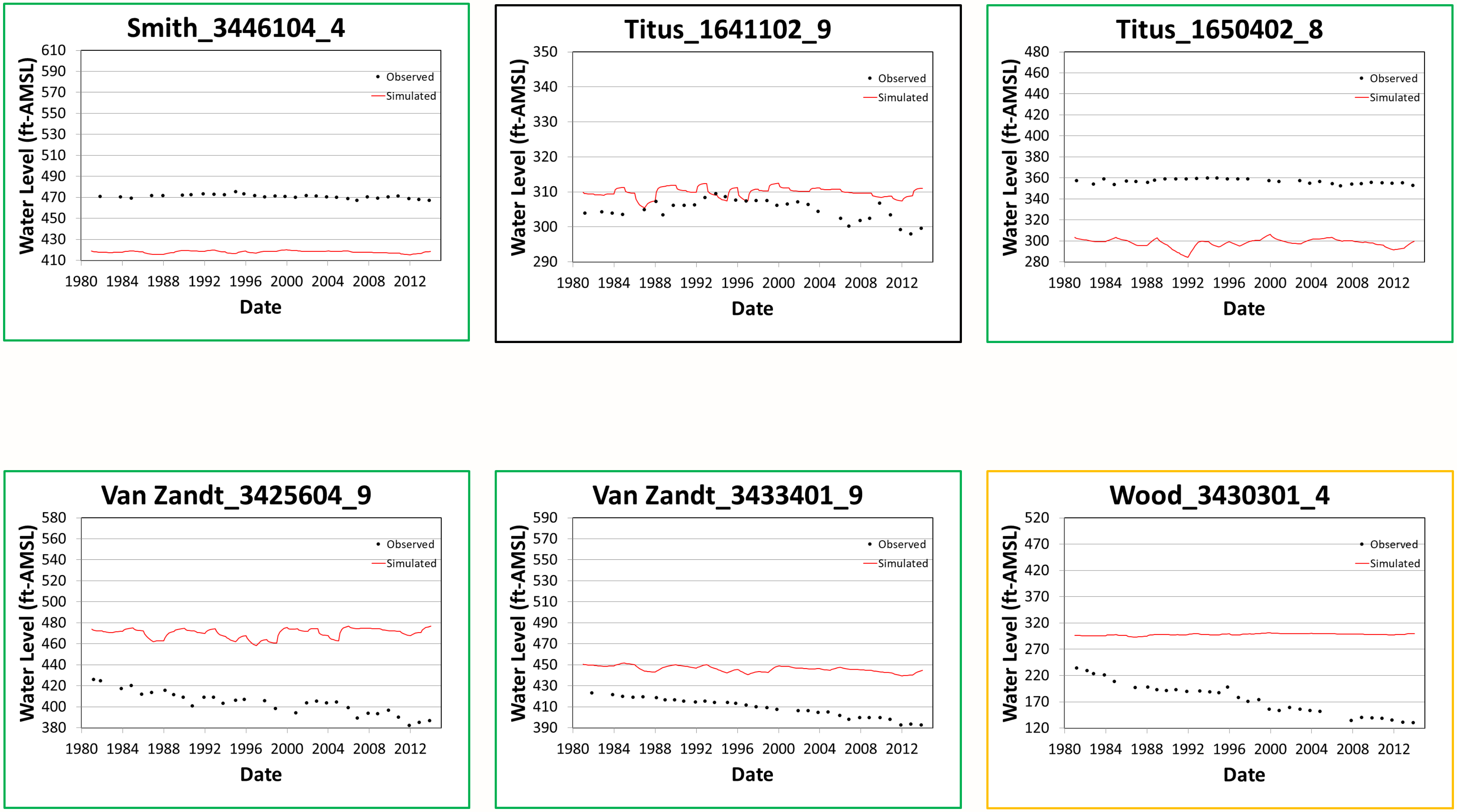
Scale:	

Appendix A – Hydrographs for Select Target Wells



Notes:

1. Select wells present model targets with a dataset of 30 or more measurements and weights.
2. Chart name: county name, well name, model layer; ft-AMSL = feet above mean sea level.
3. Chart outline color Y-axis: yellow = 400 feet; green = 200 feet; black = 60 feet.

GSI ENVIRONMENTAL

GSI Job No. 4529	Drawn By: HMH
Issued: 2020/10/19	Chk'd By:
Revised:	Aprv'd By:
Scale:	

Appendix A – Hydrographs for Select Target Wells

Technical Memorandum 1

Pumping Sensitivity

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November 21, 2020

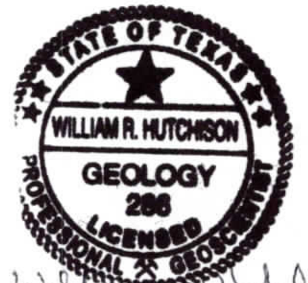
Technical Memorandum 1

Professional Engineer and Professional Geoscientist Seals

This report was prepared by William R. Hutchison, Ph.D., P.E., P.G., who is licensed in the State of Texas as follows:

- Professional Engineer (Geological and Civil) No. 96287
- Engineering Firm Registration No. 14526
- Professional Geoscientist (Geology) No. 286

William R Hutchison
11/21/2020



William R Hutchison
11/21/2020

Table of Contents

List of Figures

List of Tables

Appendix

A – Comparison of Maximum Drawdown Difference – Pumping Sensitivity (one graph per model layer, each graph shows 27 counties)

Associated Files

***PumpScenHydrographs.pdf* (213 hydrographs of average drawdown for each county-model layer unit)**

1.0 Executive Summary

Four simulations were run with the updated Groundwater Availability Model to understand the sensitivity of average drawdown due to variation in pumping on a county-model layer basis. For each scenario, pumping was assumed to be constant during the entire predictive period (2014 to 2080). Recharge was assumed equal to steady state conditions (stress period 1 of the calibrated model) and did not vary during the simulation. Other time dependent boundary conditions (general head boundaries, evapotranspiration, and parameters for surface water-groundwater interaction) were also assumed constant and equal to steady state conditions (stress period 1 of the calibrated model).

Results were processed and graphically summarized in 213 hydrographs of average drawdown for each county-model layer unit (saved as a pdf file), and summarized in nine bar graphs that compare the maximum drawdown range during the calibration period and the predictive period for each model layer. Each bar graph shows all 27 counties of Groundwater Management Area 11 that are covered by the Groundwater Availability Model domain.

This analysis demonstrated that the limitations of the previous Groundwater Availability Model related to rising groundwater elevations during the predictive period have been addressed and eliminated. All graphs show an initial response to the change in pumping followed by a period where equilibrium is reached. Achieving an equilibrium condition is present in all 213 hydrographs developed and demonstrates the suitability of the model for the joint planning process.

2.0 Background

The desired future conditions for Groundwater Management Area 11 that were adopted on January 11, 2017 were documented in the Desired Future Condition Explanatory Report (Hutchison, 2017a). As noted in the Explanatory Report, the desired future conditions were based on Groundwater Availability Model (GAM) Scenario 4 as documented in Hutchison (2017b). The selection of Scenario 4 as the basis for the desired future condition was made by the groundwater conservation districts in Groundwater Management Area 11 after the review of the results of seven simulations using the Groundwater Availability Model (Hutchison, 2017c).

In developing the initial seven simulations, a base pumping amount for each county-aquifer unit was developed. This base pumping amount was based on future pumping based on regional water plan data and the proposed Forestar project. The analysis in Hutchison (2017c) included three simulations that sequentially increased the pumping above the base amount and three simulations that sequentially decreased the pumping below the base amount to develop a practical analysis of the sensitivity of drawdown to various pumping amounts.

One of the uses of the updated Groundwater Availability Model documented in the main report will be to support the Joint Planning Process that leads to the adoption of desired future conditions by the groundwater conservation districts in Groundwater Management Area 11 and the calculation of the modeled available groundwater by TWDB. As part of the work associated with developing the updated Groundwater Availability Model, three technical memoranda appear in the Appendix of the report:

- Technical Memorandum 1: Pumping Sensitivity
- Technical Memorandum 2: Recharge Sensitivity
- Technical Memorandum 3: Calculation of Drawdown from Existing Modeled Available Groundwater Using Updated Groundwater Availability Model

This technical memorandum compares the average drawdown in each county-model layer unit under alternative assumptions of a base pumping amount. Specifically, the model calibration period is 1980 to 2013. Four alternative base pumping for the period 2014 to 2080 (the simulation period that will be used in simulations to support the joint planning process) were simulated: 2010, 2011, 2012, and 2013.

3.0 Parameters and Assumptions

The updated Groundwater Availability Model was calibrated with data from 1980 to 2013. Pumping by layer is graphically summarized in Figure 1. Please note that pumping in Layer 6 (Carrizo Aquifer) generally increases through the calibration period. Pumping in Layers 7 and 8 (Upper Wilcox and Middle Wilcox, respectively), while lower than the pumping in Layer 6 also increases during the calibration period. Pumping in the other layers is generally low and generally constant during the calibration period.

Figure 2 is a graphical summary of pumping by layer, but only for the years 2010 to 2013 (i.e. the last four years of the calibration period).

Pumping during the final year of the calibration period (2013) in Layers 6, 7, and 8 decreases from the 2012 pumping in each layer. If 2013 is used as the base pumping period and held constant for the entire simulation for predictive simulations through 2080, it is likely that groundwater elevations will initially increase since 2013 pumping is less than immediately previous years. Conversely, if 2011 is used as the base pumping period and held constant for the entire simulation for predictive simulations through 2080, it is likely that groundwater elevations will initially decline since 2011 pumping is more than immediately previous years.

Four simulations were run to evaluate the impact of different base pumping (i.e. constant pumping) on drawdown in each county-layer unit. The model files used for this practical sensitivity analysis are described below.

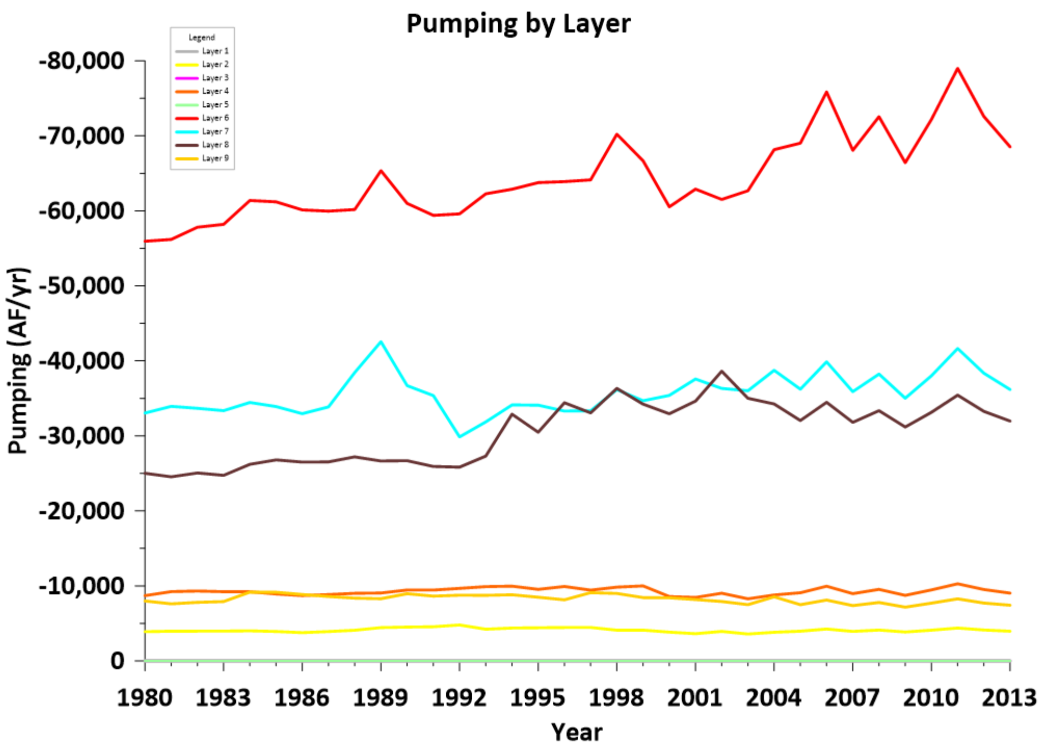


Figure 1. Layer Pumping from Calibrated Model (1980 to 2013)

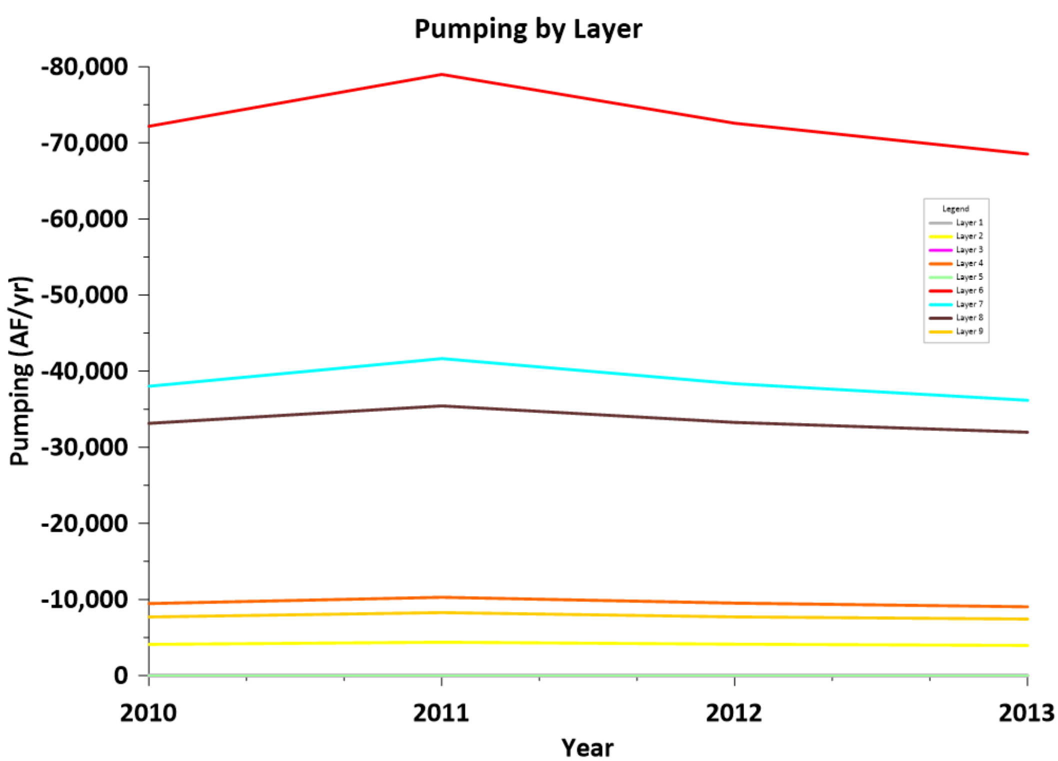


Figure 2. Layer Pumping from Calibrated Model (2010 to 2013)

3.1 Files Unchanged from Calibrated Model

Files that contain model input parameters related to the model grid and aquifer parameters were the same as the files used in the calibrated model as shown in Table 1.

Table 1. Predictive Model Files Unchanged from Calibrated Model

File Name	File Date	Description
findd.dis	4/10/2020	Spatial Discretization
findd.ims	4/10/2020	Solver Parameters
finddd.npf	4/10/2020	Node Property Flow
tr58_g.kx	4/10/2020	Horizontal Hydraulic conductivity
tr58_g.kz	4/10/2020	Vertical Hydraulic Conductivity
tr58_g.ss	4/10/2020	Specific Storage
tr58_g.sy	4/10/2020	Specific Yield

3.2 Time Discretization and Storage

The predictive simulation was run for the period 2014 to 2080, a total of 67 annual stress periods. The calibrated model included a steady-state stress period at the beginning of the simulation. Thus, the TDIS file was modified to reflect 67 annual stress periods and named *finddd.tdis*. The specification of steady state or transient stress period in MODFLOW 6 is contained in the STO file. This file was updated and named *finddd.sto.*

3.3 Groundwater Pumping (WEL Package)

This set of predictive simulations included evaluating the effect of alternative base pumping amounts from 2014 to 2080. The FORTRAN program *makebasepump.exe* was written to develop four model input files of pumping. The program reads the calibrated model file *tr58_g.wel*, which contains cell-by-cell pumping amounts from 1980 to 2013. The program then writes four files as follows:

- *pump2010.wel* specifies 2010 pumping for 2014 to 2080
- *pump2011.wel* specifies 2011 pumping for 2014 to 2080
- *pump2012.wel* specifies 2012 pumping for 2014 to 2080
- *pump2013.wel* specifies 2013 pumping for 2014 to 2080

3.4 Evapotranspiration (EVT Package)

The FORTRAN program *makeevt.exe* was written to develop a model input file for evapotranspiration. Inspection of the calibrated model input file for evapotranspiration (*tr58_g.evt*) shows that the same evapotranspiration parameters were used for each stress period of the calibration period (1980 to 2013). The program simply extracts the first stress period of the calibration period and writes it to a new file named *finddd.evt*.

3.5 General Head Boundaries (GHB Package)

The FORTRAN program *makeghb.exe* was written to develop a model input file for the general head boundaries, which were implemented to simulate the effects of overlying formations that are not formally part of the model domain.

Inspection of the calibrated model input file for general head boundaries (*tr58_g.ghb*) shows that the same general head boundary parameters were used for each stress period of the calibration period (1980 to 2013). The program simply extracts the first stress period of the calibration period and writes it to a new file named *finddd.ghb*.

3.6 Recharge (RCH Package)

The recharge input file *tr58_g.rch* contains the cell-by-cell recharge amounts for each stress period of the calibrated model (1980 to 2013). Recharge was implemented by defining a steady-state recharge (applied to stress period 1) and applying a stress period-specific factor to increase or decrease the recharge for each stress period. The first stress period of recharge was extracted from the calibrated model input file using a FORTRAN program named *makerch.exe*. The output file saved as *finddd.rch.*

3.7 River (RIV Package)

The calibrated model simulated surface water-groundwater interactions with the River (RIV) package specified in the file *tr58_g.rch*. Inspection of the input file yielded the conclusion that RIV head values changed slightly for each stress period. River conductance and bottom elevations remained the same in all stress periods.

The FORTRAN program *makeriv.exe* was written to extract the first stress period of RIV parameters for the predictive simulations and hold them constant for all stress periods. The output file from this program is *finddd.riv.*

3.8 Other Input Files

Other files that were developed for these predictive simulations are summarized in Table 2.

Table 2. Other Input Files Summary

File Name	Description	Modification
finddd.ic6	Starting Heads	Specified 2013 heads as starting heads
mfsim.nam	Global Simulation Name File	Updated tdis and ims file names
pumpXXXX.nam	Scenario Name File	Updated scenario file names (XXXX refers to specific scenario)
pumpXXXX.oc6	Output Control	Updated scenario-specific output files and adjusted number of stress periods (XXXX refers to specific scenario)

4.0 Methods and Results

4.1 Model Scenarios

Four scenarios were completed to evaluate the changes in average drawdown in each county-model layer unit due to different levels of constant pumping. Assumed pumping were based on applying 2010, 2011, 2012, and 2013 pumping from 2014 to 2080. The results were summarized for county-model layer units in Groundwater Management Area 11.

4.2 Post-Processing of MODFLOW 6 Results

A FORTRAN program named *getdd.exe* was written to extract groundwater elevation data from the model output files. The program was modified for each scenario to reflect different input and output file names unique to the scenario.

The program reads a list of county names and codes (*countynamelist.dat*) and a grid file of cell number, layer, and county code (*celllayercountyns.csv*). The program counts the number of cells in each county-model layer unit and reports the results in a file named *cellcount.dat.* The 27 counties within Groundwater Management Area 11 and the number of cells in each layer of those counties is presented in Table 3. Based on Table 3, there are 213 county-model layer units with at least one active model cell.

The program then reads the binary output files from the calibrated model (*tr58g.hds*) and the specific scenario of the predictive simulation (*pumpXXXX.hds*). The program then calculates the drawdown for each cell with a starting date of 2013 (the last year of the calibrated model). Drawdowns for each county-model layer unit are then summed, and the average drawdown for each county-model layer unit is calculated as the summed drawdown for that unit divided by the number of cells in that unit.

The program then reads a list of file names for each county-model layer unit for the 27 counties in Groundwater Management Area 11 and writes annual drawdowns for each layer to the county-based output files for the scenario.

4.3 Results

There is a total of 27 output files for each scenario (one for each county). Within each county file, there are average drawdown results for each model layer for each year of the simulation. Where there is no active cells, the drawdown is listed as -9999.00 to designate that there are no active cells. Also included are the county number (1 to 27), the county number of the entire list of counties in the model, the county code from the grid file, and the county name.

The 213 individual hydrographs that plot all scenarios for a county-model layer unit were saved in a pdf file (*PumpSensHydrographsDD.pdf*). The hydrographs are printed one to a page for easy viewing with a pdf reader. An example is shown in Figure 3.

Table 3. Cell Counts for Each County-Model Layer Unit

County	Number of Model Cells in Each County-Model Layer Unit									Number of Active Layers
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	
Anderson	19,582	106	359	3,276	3,455	1,932	1,639	1,203	1,087	9
Angelina	552	3,828	1,312	865	865	865	865	865	865	9
Bowie	6,382	0	0	0	0	0	1,312	1,034	522	4
Camp	2,674	0	0	392	371	387	451	233	201	7
Cass	12,311	5	61	3,249	1,843	716	1,524	1,221	988	9
Cherokee	14,757	603	676	3,030	2,404	1,885	1,414	1,096	1,059	9
Franklin	2,136	0	0	0	3	177	607	320	170	6
Gregg	4,065	0	0	414	557	928	465	290	274	7
Harrison	10,279	0	2	413	995	621	2,226	1,845	1,311	8
Henderson	11,104	0	9	1,445	1,072	701	1,071	1,471	1,540	8
Hopkins	4,213	0	0	0	1	23	500	634	839	6
Houston	7,210	5,267	2,187	2,455	1,424	1,238	1,237	1,237	1,237	9
Marion	7,315	1	5	899	1,017	336	1,214	694	545	9
Morris	3,694	0	6	484	509	169	344	636	317	8
Nacogdoches	13,147	1,630	1,706	1,456	1,595	1,390	1,787	1,094	983	9
Panola	12,656	0	0	0	1	4	996	3,921	1,269	6
Rains	3,109	0	0	0	0	0	56	246	864	4
Rusk	13,447	7	14	191	760	1,842	3,677	1,311	943	9
Sabine	3,513	2,242	795	398	566	566	1,121	658	577	9
SanAugustine	2,534	1,511	770	385	611	792	836	623	594	9
Shelby	10,606	8	3	1	2	42	2,558	2,546	1,037	9
Smith	12,534	331	837	3,653	2,053	1,234	1,107	964	947	9
Titus	6,547	0	0	32	221	245	1,096	876	559	7
Trinity	0	4,124	1,225	713	713	713	713	713	713	8
Upshur	6,347	20	49	1,905	1,142	928	636	595	595	9
VanZandt	9,253	0	7	268	293	384	1,940	1,013	1,723	8
Wood	9,934	77	215	1,681	1,070	839	1,516	1,046	740	9

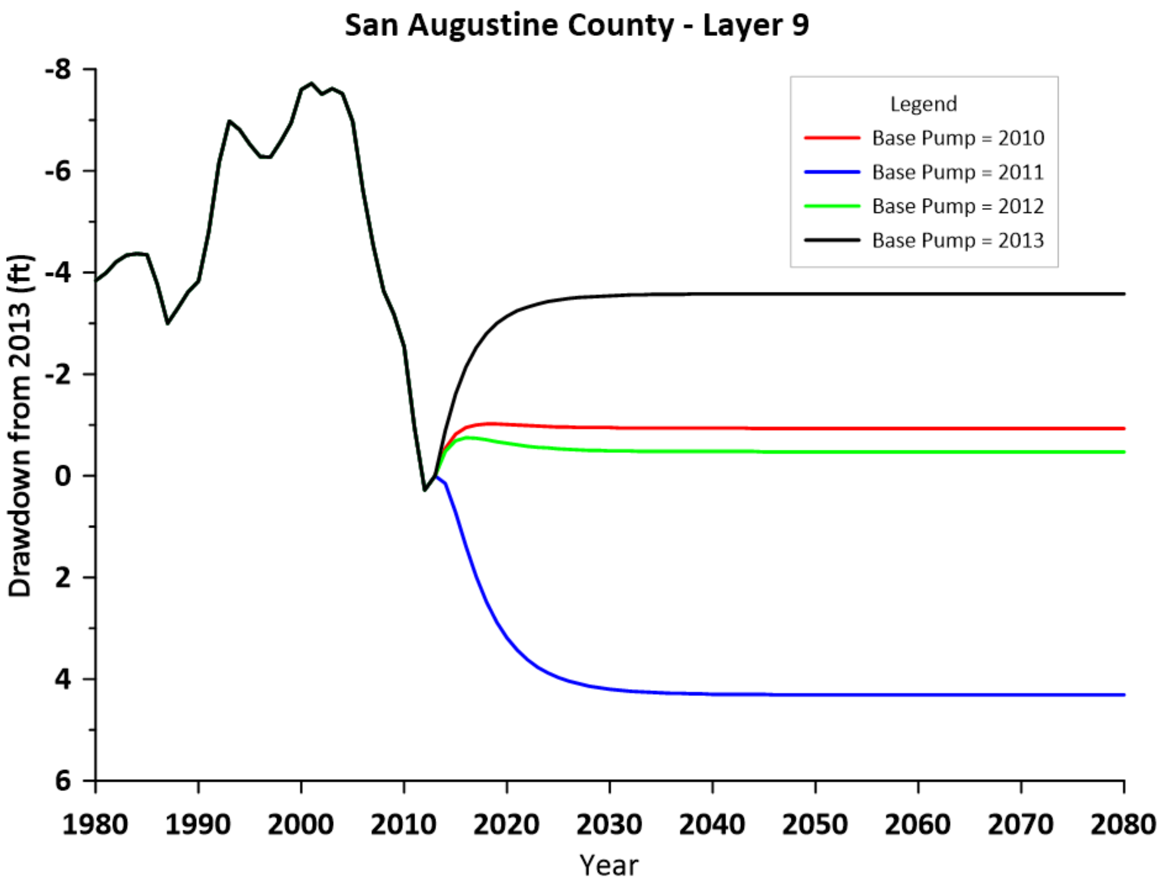


Figure 3. Average Drawdown in San Augustine County - Layer 9

From 1980 to 2013 (the calibration period) average drawdown from 2013 ranges from -7.62 ft in 2003 to 0.28 ft in 2012, a range of about 8 feet. From 2014 to 2080, the range in drawdown is defined by the difference of the 2013 simulation (black line) and the 2011 simulation (the blue line), also a difference of about 8 feet. Thus, the selection of the base pumping year will influence the simulated drawdown. If 2013 is chosen as the base year, the simulation results show an average recovery in groundwater elevation and, thus, a negative drawdown of about 4 feet. If 2011 is chosen as the base year, the simulation shows a decline in groundwater elevation, and, thus, a drawdown of about 4 feet.

Please note that the primary interpretation in Figure 3 is that there is an initial response to the change in pumping starting in 2014 (either a recovery or a decline, depending on the base pumping), and an equilibrium condition is achieved after a few years. Achieving an equilibrium condition is present in all 213 hydrographs developed, and demonstrates the suitability of the model for the joint planning process.

The example in Figure 3 can also be compared to a similar plot from Hutchison (2017b) reproduced below as Figure 4.

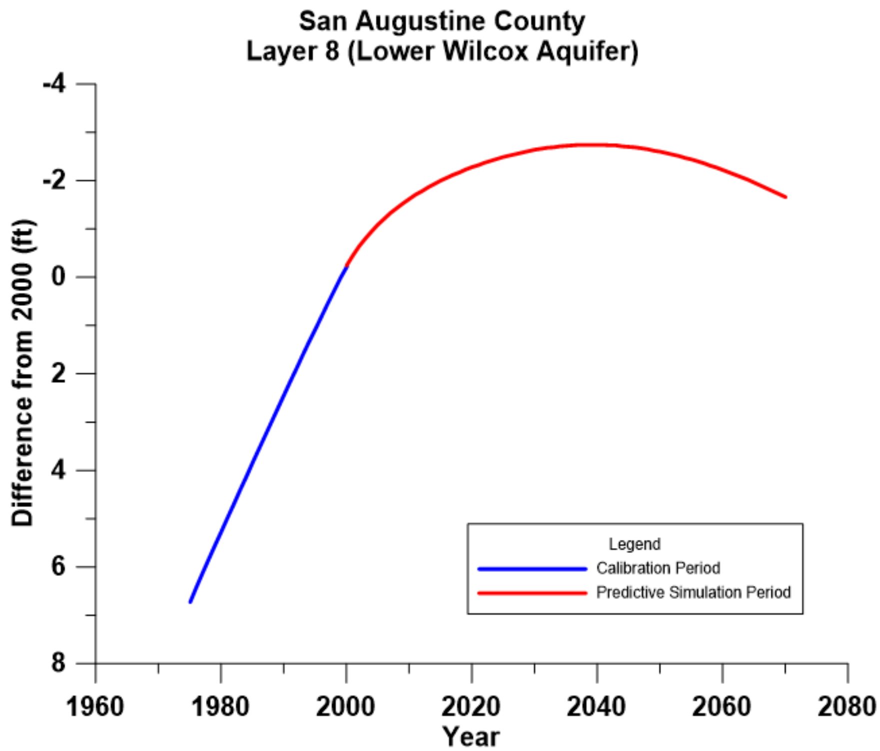


Figure 4. Average Drawdown from Previous Groundwater Availability Model - San Augustine County, Layer 8

Please note that in the previous Groundwater Availability Model, Layer 8 represented the Lower Wilcox Aquifer. This new Groundwater Availability Model has an extra layer to simulate alluvial formations in the areas of streams and rivers, so Layer 9 now represents the Lower Wilcox Aquifer.

As discussed in Hutchison (2017b), during the calibration period, average groundwater levels rose about 7 feet from 1975 to 1999. This suggests that the model is simulating actual conditions well. The model conditions that caused the rise from 1975 to 1999 continue to affect the change in average groundwater levels after 2000 (the simulation period). The rise continues until about 2030, and the model predicts a drop in average groundwater level after this peak. However, the decline from 2030 to 2070 leaves the average groundwater level higher than the average level in 2000 (the start of the simulation period). This was an example of a model limitation that had to considered when using the results of the old model in considering desired future conditions. Based on the hydrograph in Figure 3 and an inspection of all the hydrographs in Appendix A, this limitation has been eliminated in this updated Groundwater Availability Model.

Summary graphs that compare the range in calibration period drawdown and the range in the predictive period drawdown for all scenarios are presented in Appendix A. Each graph plots the range in drawdowns for each county for a specific layer. These plots, and companion plots in Technical Memorandum 2 are useful in interpreting simulation results for the joint planning process.

5.0 Limitations

The objective of these simulations was to provide a practical basis for selecting a base pumping year for simulations focused on joint planning. As a result, there are some limitations to the results given the regional nature of the objective:

- The scenarios considered only increases and decreases in overall pumping to assess general sensitivity of pumping on average drawdown. For this analysis, there were no attempts to understand sensitivity on a finer scale (i.e. varying pumping on an individual county-model layer unit).
- The scenarios did not attempt to distinguish the relative effect of "local" pumping (pumping within the county-model layer unit) versus neighboring pumping in adjacent county-model layer units.
- The results provide some insight on pumping sensitivity but are coupled with a companion analysis of sensitivity to recharge in Technical Memorandum 2.

6.0 References

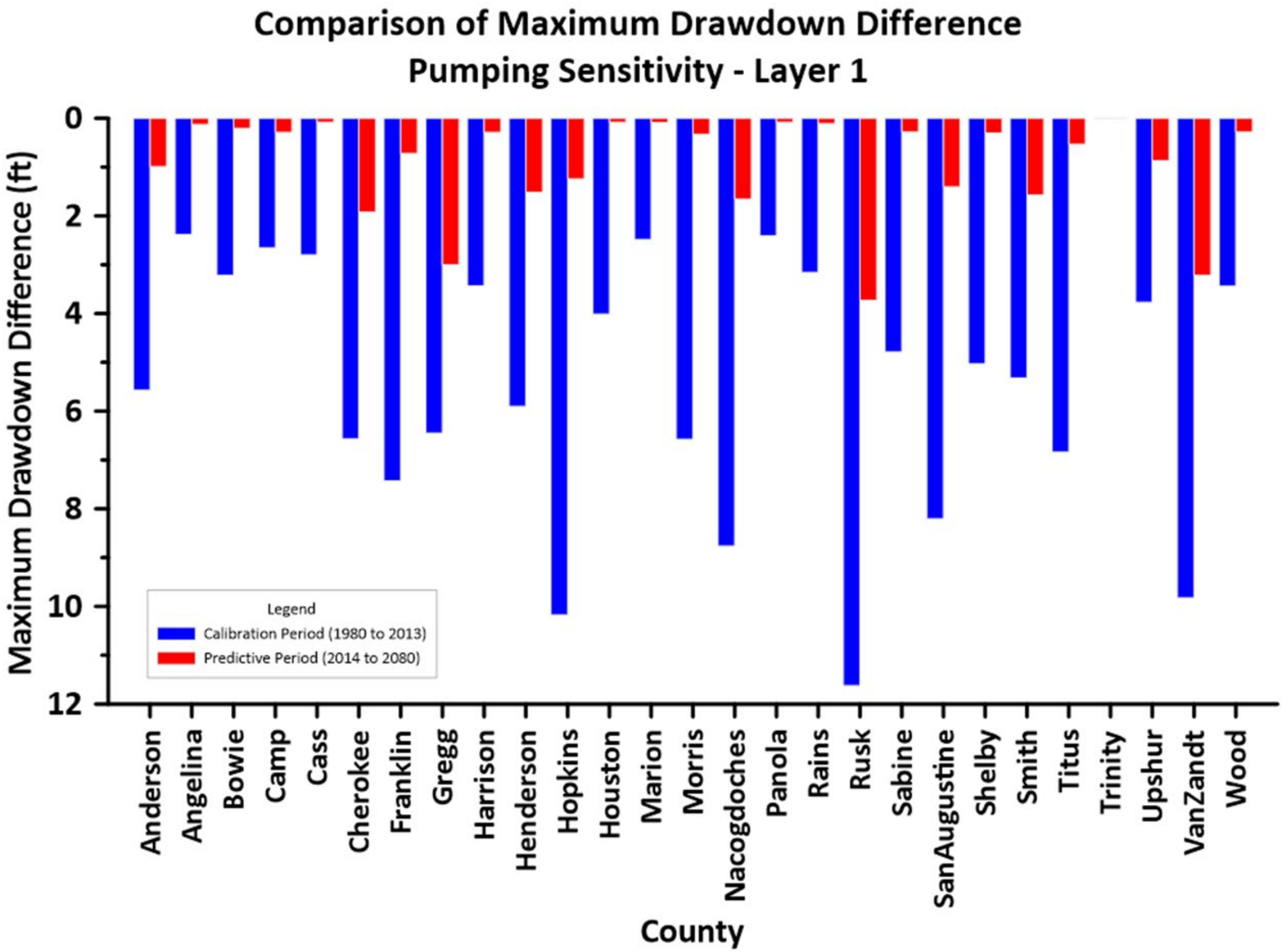
Hutchison, W.R., 2017a. Desired Future Condition Explanatory Report: Carrizo-Wilcox/Queen City/Sparta Aquifers for Groundwater Management Area 11. Report submitted to Texas Water Development Board, January 24, 2017, 445p.

Hutchison, W.R., 2017b. Use of Predictive Simulation Results from Scenario 4 in Desired Future Conditions for Sparta, Queen City, and Carrizo-Wilcox Aquifer. GMA 11 Technical Memorandum 16-02. Report submitted to Groundwater Management Area 11. January 24, 2017, 15p.

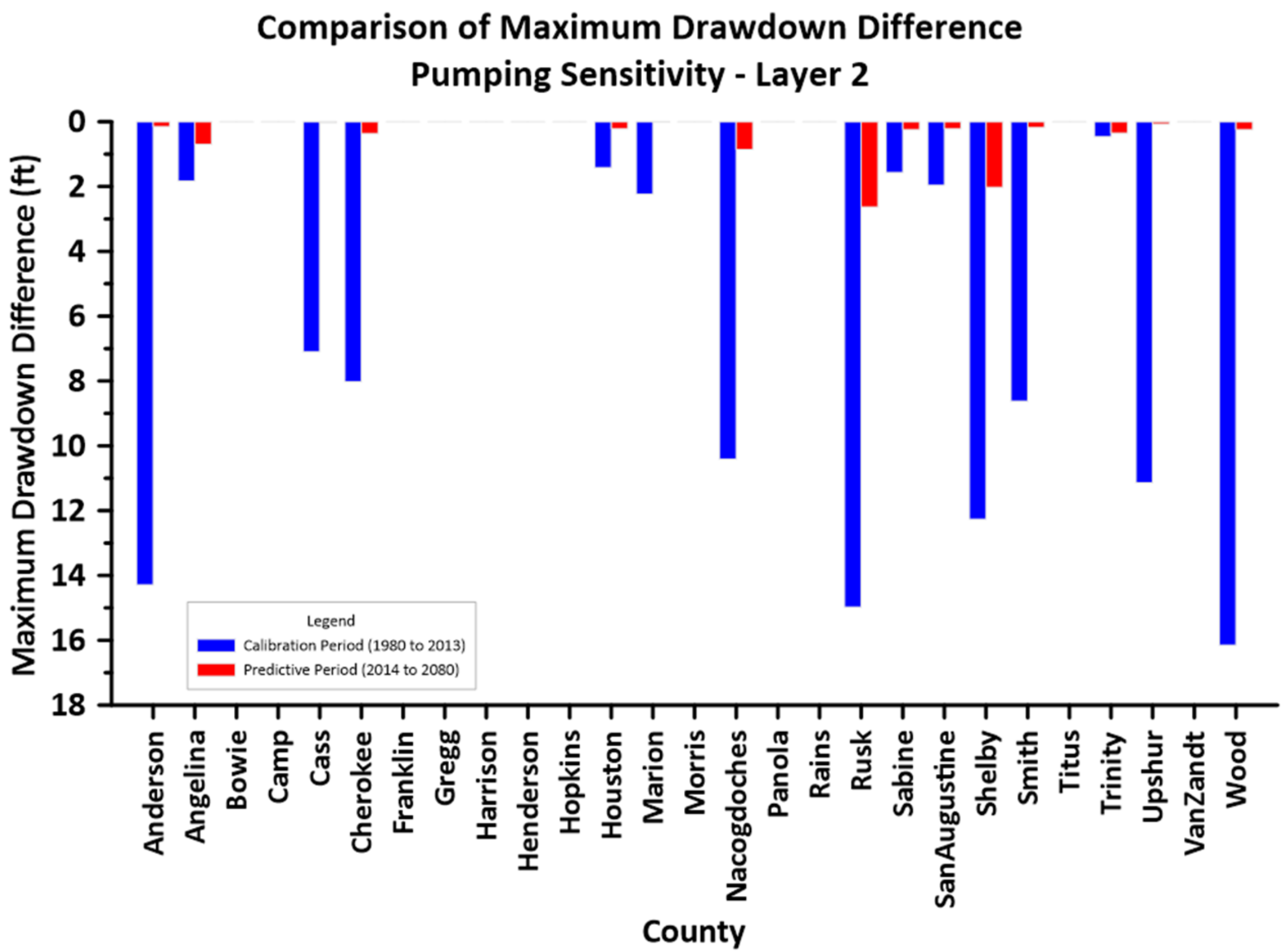
Hutchison, W.R., 2017c. Initial GAM Simulations for Sparta, Queen City and Carrizo-Wilcox Aquifers. GMA 11 Technical Memorandum 15-01. Report submitted to Groundwater Management Area 11. January 21, 2017, 109p.

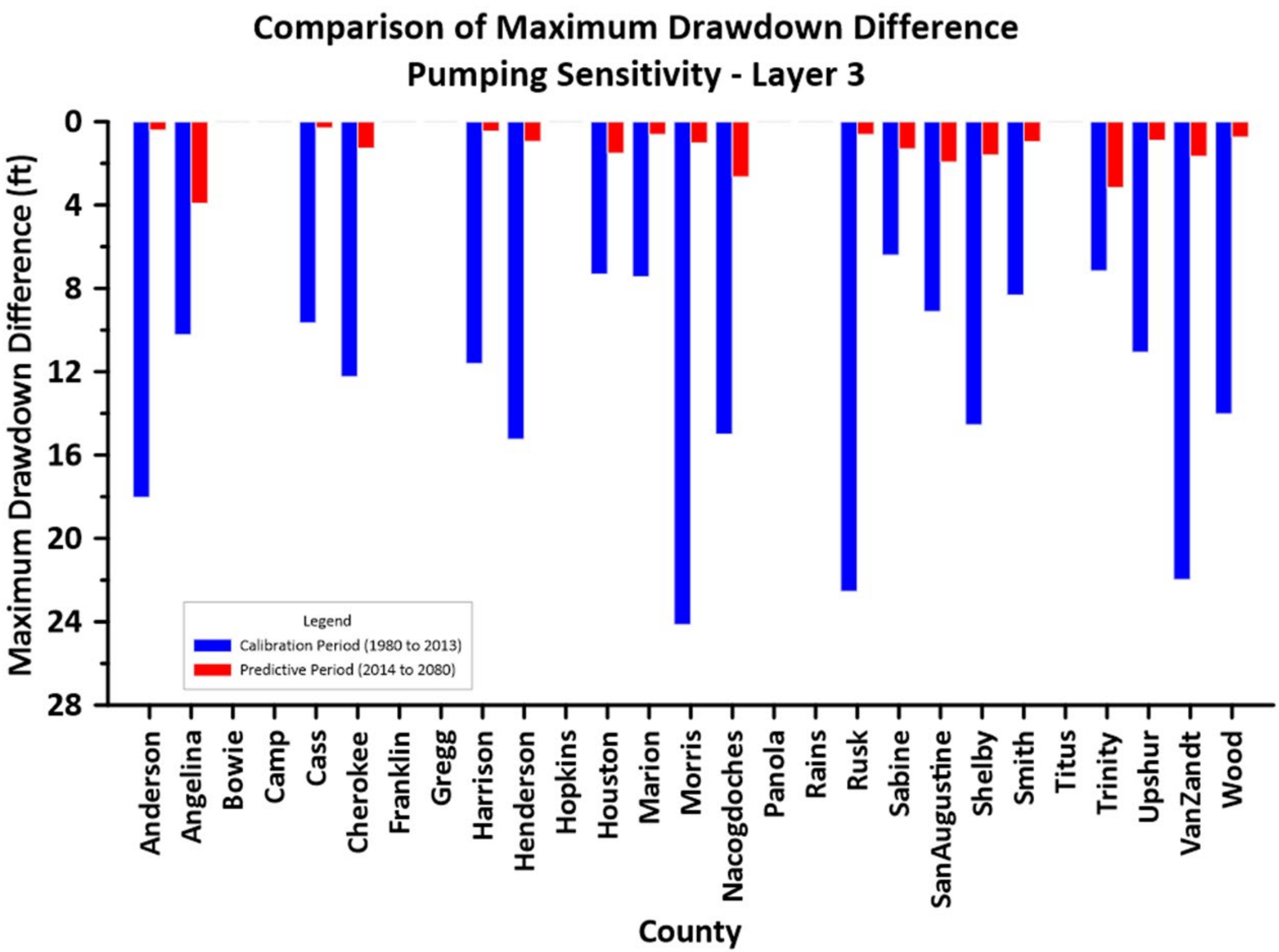
Appendix A

Comparison of Maximum Drawdown Difference – Pumping Sensitivity (one graph per model layer, each graph shows 27 counties)

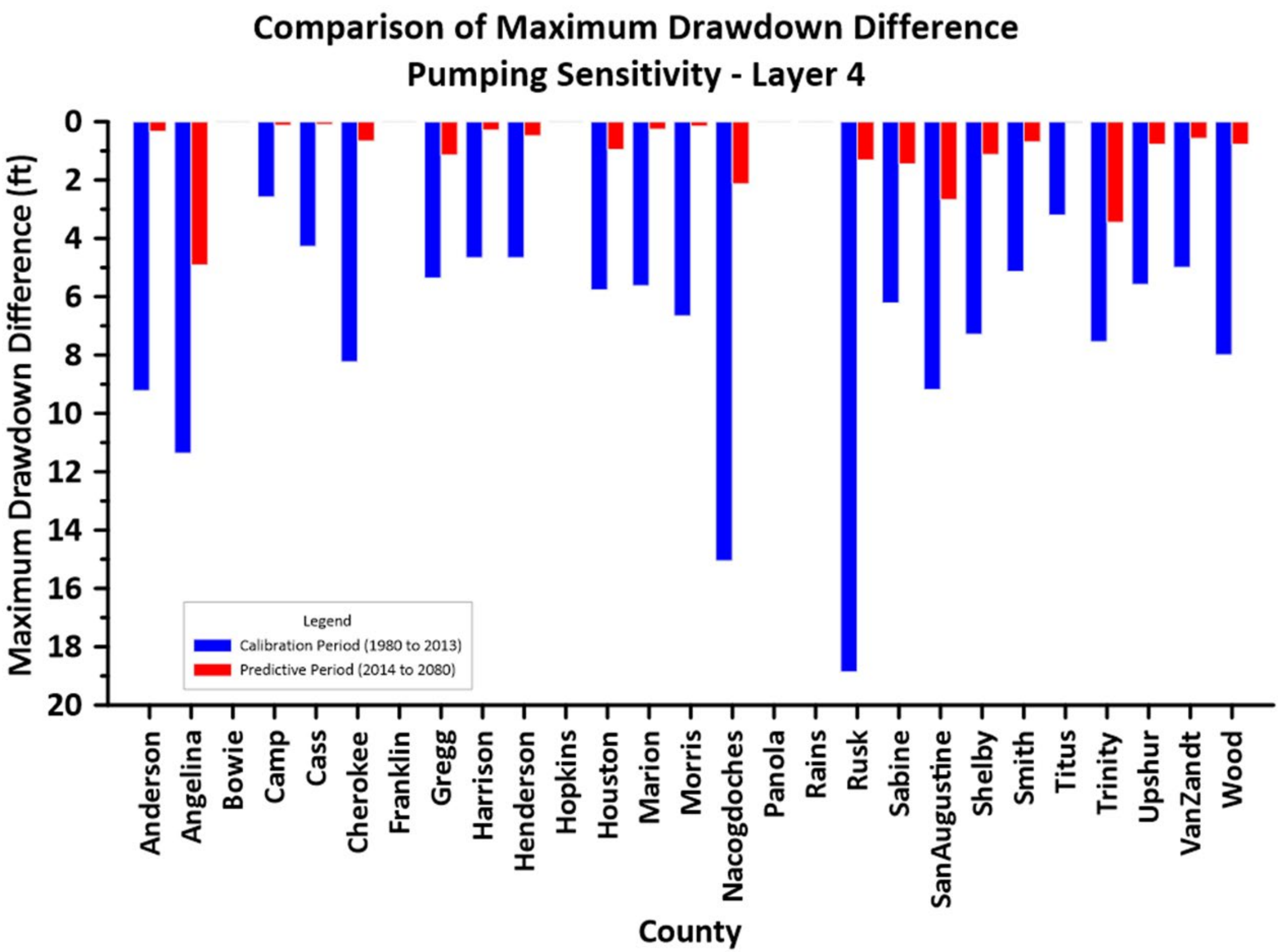


Comparison of Maximum Drawdown Difference
Pumping Sensitivity - Layer 1
Maximum Drawdown Difference (ft)
0
2
4
6
8
10
12
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County

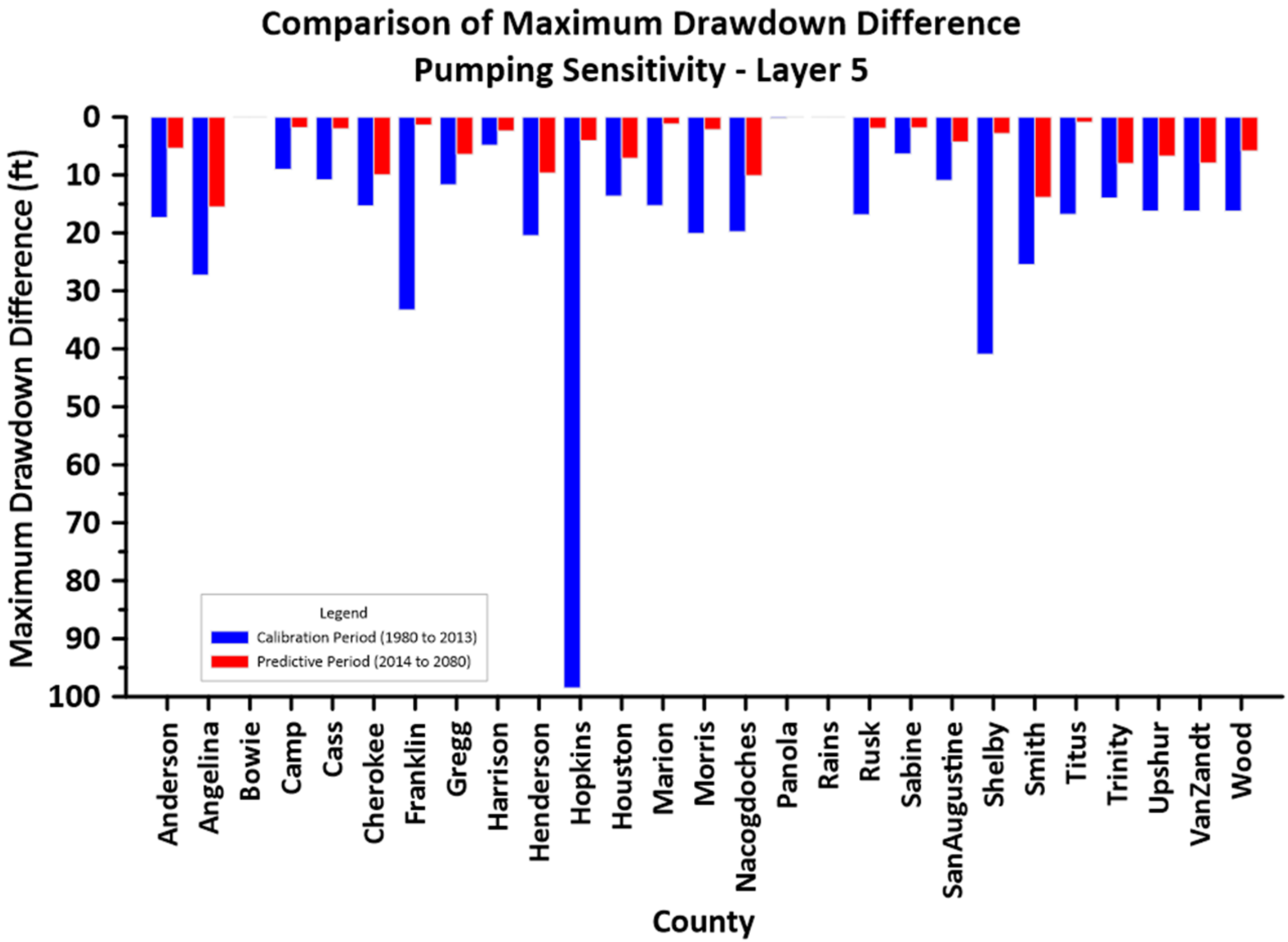

Comparison of Maximum Drawdown Difference
Pumping Sensitivity - Layer 2
Maximum Drawdown Difference (ft)
0
2
4
6
8
10
12
14
16
18
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County

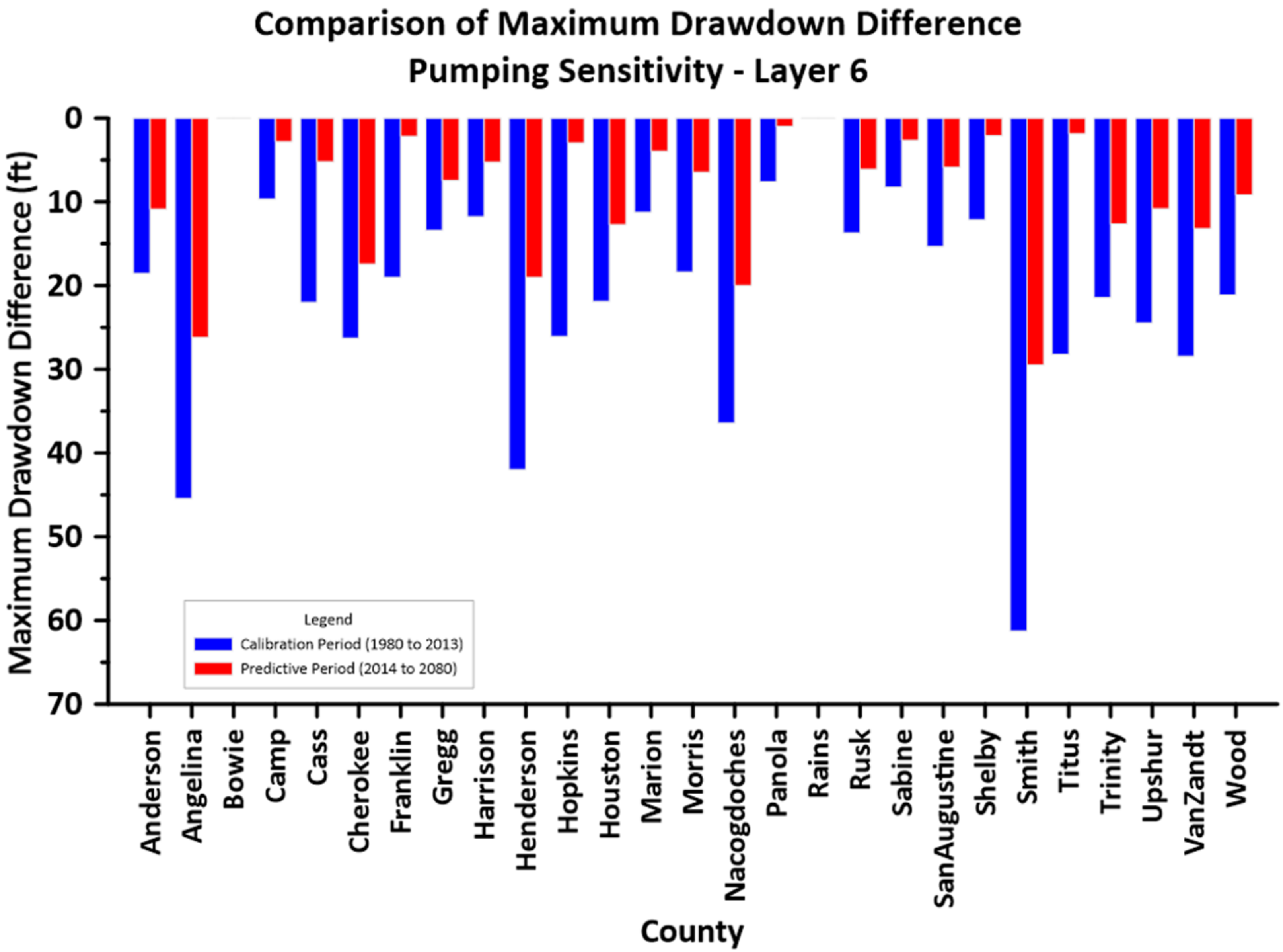


Comparison of Maximum Drawdown Difference
Pumping Sensitivity - Layer 3
Maximum Drawdown Difference (ft)
0
4
8
12
16
20
24
28
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County



Comparison of Maximum Drawdown Difference
Pumping Sensitivity - Layer 4
Maximum Drawdown Difference (ft)
0
2
4
6
8
10
12
14
16
18
20
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County


Comparison of Maximum Drawdown Difference
Pumping Sensitivity - Layer 5
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
70
80
90
100
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County


Comparison of Maximum Drawdown Difference
Pumping Sensitivity - Layer 6
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
70
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
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Shelby
Smith
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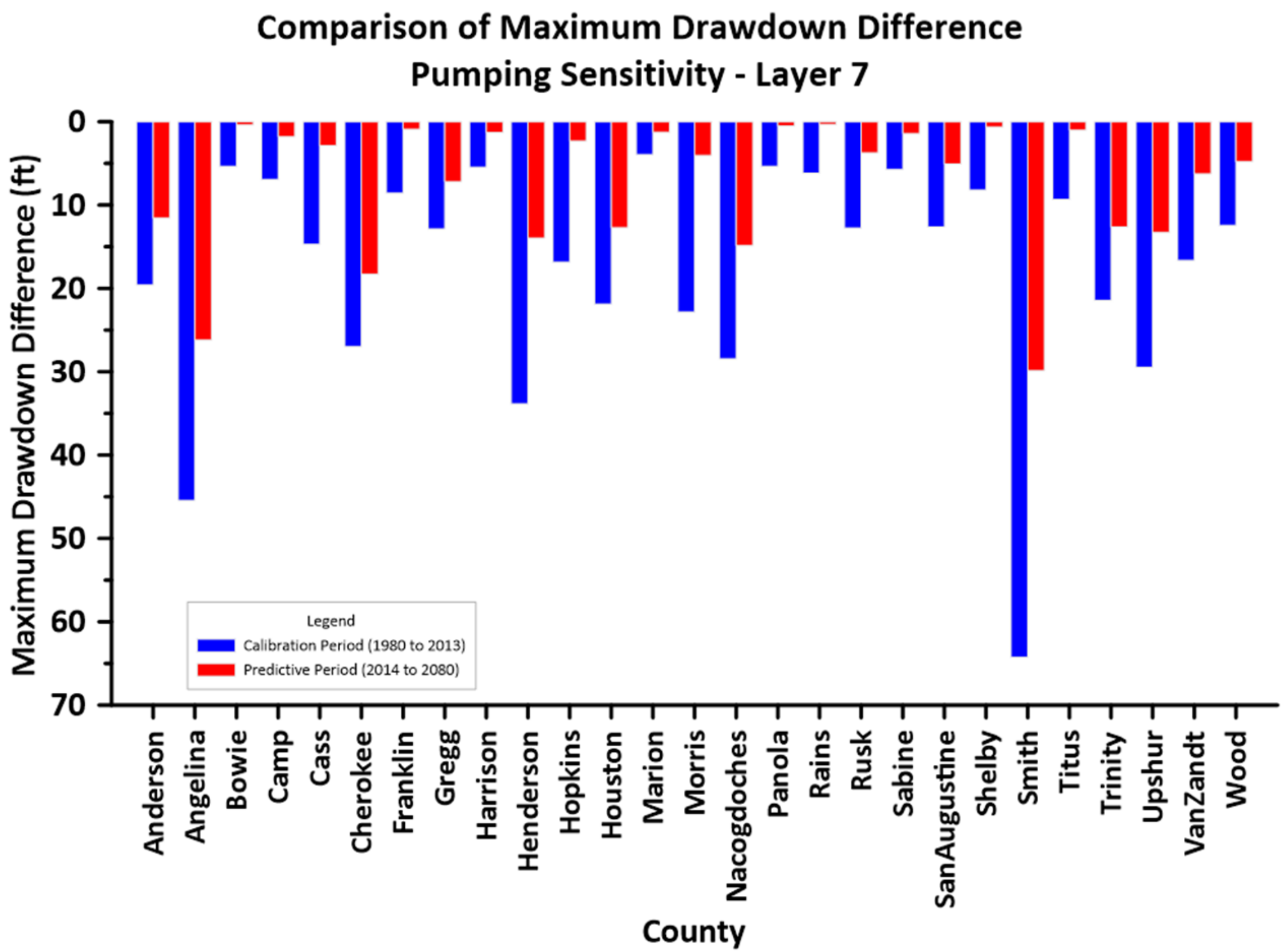
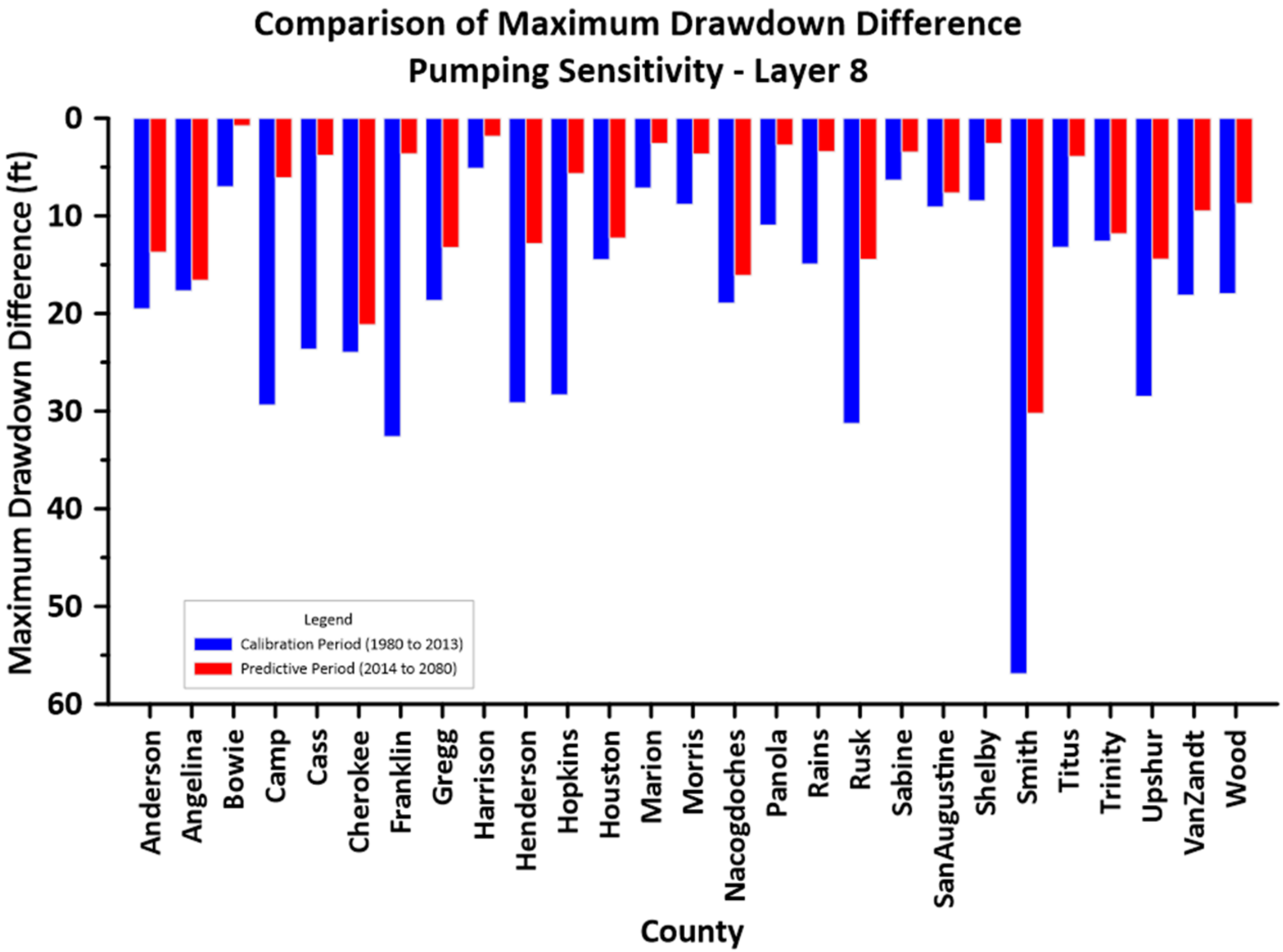
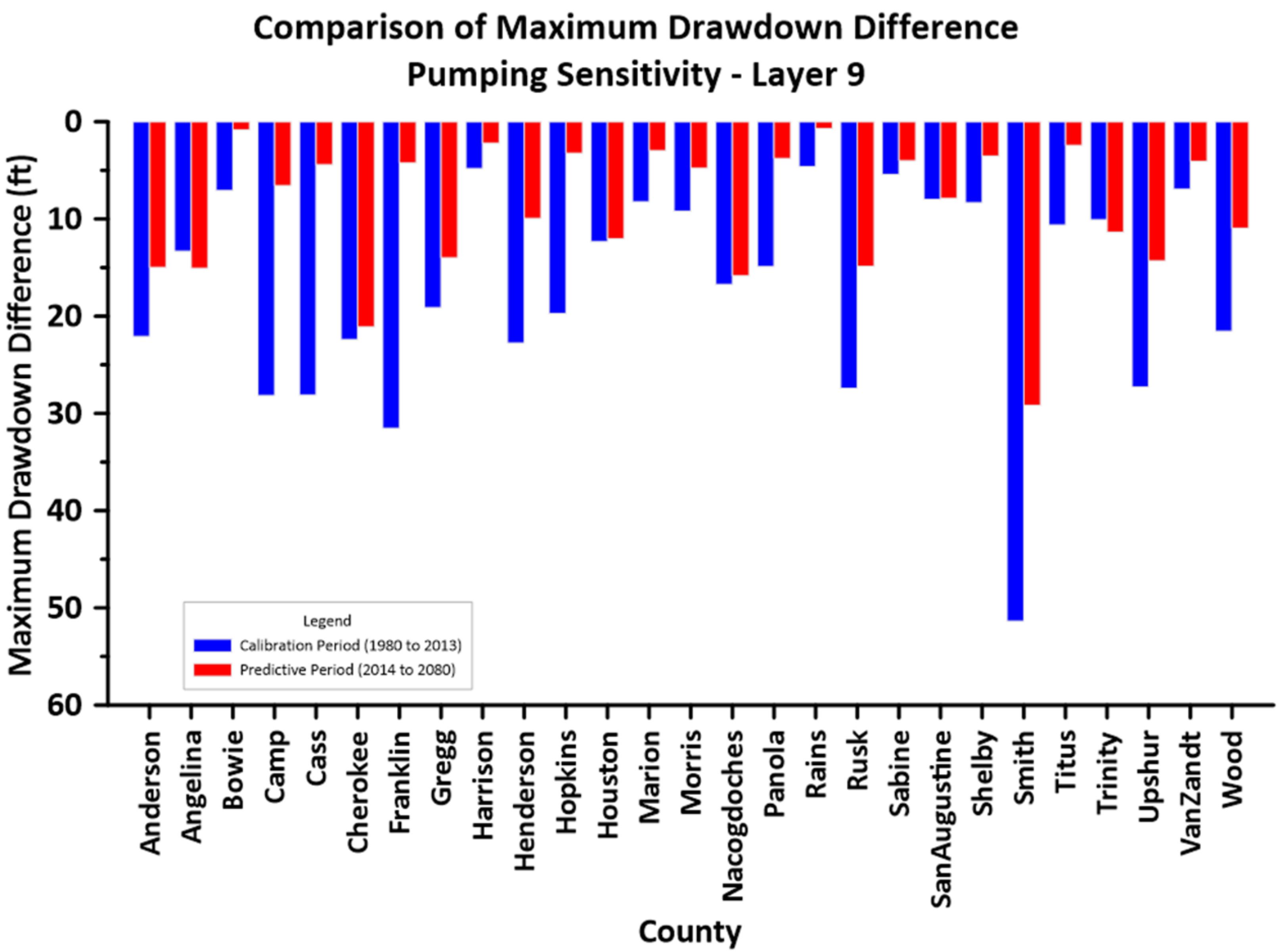
Trinity
Upshur
VanZandt
Wood
County



Comparison of Maximum Drawdown Difference
Pumping Sensitivity - Layer 7
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
70
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County


Comparison of Maximum Drawdown Difference
Pumping Sensitivity - Layer 8
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County


Comparison of Maximum Drawdown Difference
Pumping Sensitivity - Layer 9
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
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Titus
Trinity
Upshur
VanZandt
Wood
County

Technical Memorandum 2

Recharge Sensitivity

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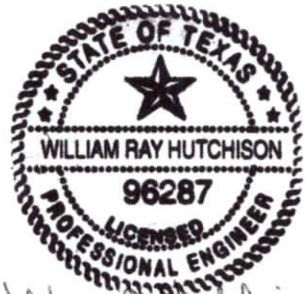
November 21, 2020

Technical Memorandum 2

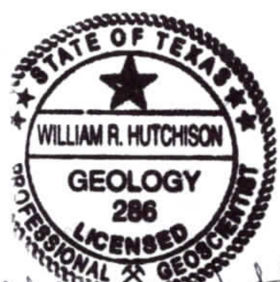
Professional Engineer and Professional Geoscientist Seals

This report was prepared by William R. Hutchison, Ph.D., P.E., P.G., who is licensed in the State of Texas as follows:

- Professional Engineer (Geological and Civil) No. 96287
- Engineering Firm Registration No. 14526
- Professional Geoscientist (Geology) No. 286



William R Hutchison
11/21/2020



William R Hutchison
11/21/2020

Table of Contents

List of Figures

List of Tables

Appendices

A – Comparison of Maximum Drawdown Difference – Recharge Sensitivity (one graph per model layer, each graph shows 27 counties)
B – Comparison of Predictive Period Average Drawdown – Recharge and Pumping Sensitivity (one graph per model layer, each graph shows 28 counties)

Associated Files

RechScenHydrographs.pdf **(213 hydrographs of average drawdown for each county-model layer unit)**

1.0 Executive Summary

Five simulations were run with the updated Groundwater Availability Model to understand the sensitivity of average drawdown due to variation in recharge on a county-model layer basis. Recharge was assumed to be constant during the entire predictive period (2014 to 2080). Pumping was assumed equal to the pumping simulated in 2011 in the calibrated model and did not vary during the simulation. Other time dependent boundary conditions (general head boundaries, evapotranspiration, and parameters for surface water-groundwater interaction) were assumed constant and equal to steady state conditions (stress period 1 of the calibrated model).

Results were processed and graphically summarized in 213 hydrographs of average drawdown for each county-model layer unit (saved as a pdf file), and summarized in nine bar graphs that compare the maximum drawdown range during the calibration period and the predictive period for each model layer. Each bar graph shows all 27 counties of Groundwater Management Area 11 that are covered by the Groundwater Availability Model domain.

This analysis demonstrated that the limitations of the previous Groundwater Availability Model related to rising groundwater elevations during the predictive period have been addressed and eliminated. All graphs show an initial response to the change in pumping followed by a period where equilibrium is reached. Achieving an equilibrium condition is present in all 213 hydrographs developed and demonstrates the suitability of the model for the joint planning process.

2.0 Background

The desired future conditions for Groundwater Management Area 11 that were adopted on January 11, 2017 were documented in the Desired Future Condition Explanatory Report (Hutchison, 2017a). As noted in the Explanatory Report, the desired future conditions were based on Groundwater Availability Model (GAM) Scenario 4 as documented in Hutchison (2017b). The selection of Scenario 4 as the basis for the desired future condition was made by the groundwater conservation districts in Groundwater Management Area 11 after the review of the results of seven simulations using the Groundwater Availability Model (Hutchison, 2017c).

In developing the initial seven simulations, a base pumping amount for each county-aquifer unit was developed. This base pumping amount was based on future pumping based on regional water plan data and the proposed Forestar project. The analysis in Hutchison (2017c) included three simulations that sequentially increased the pumping above the base amount and three simulations that sequentially decreased the pumping below the base amount to develop a practical analysis of the sensitivity of drawdown to various pumping amounts.

One of the uses of the updated Groundwater Availability Model documented in the main report will be to support the Joint Planning Process that leads to the adoption of desired future conditions by the groundwater conservation districts in Groundwater Management Area 11 and the calculation of the modeled available groundwater by TWDB. As part of the work associated with developing the updated Groundwater Availability Model, three technical memoranda appear in the Appendix of the report:

- Technical Memorandum 1: Pumping Sensitivity
- Technical Memorandum 2: Recharge Sensitivity
- Technical Memorandum 3: Calculation of Drawdown from Existing Modeled Available Groundwater Using Updated Groundwater Availability Model

This technical memorandum compares the average drawdown in each county-model layer unit under alternative assumptions of recharge. Specifically, the model calibration period is 1980 to 2013, which includes variation of recharge by applying a multiplication factor to the steady state recharge in stress period 1. Five alternative recharge files for the period 2014 to 2080 (the simulation period that will be used in simulations to support the joint planning process) were developed:

- 80 percent of steady state recharge
- 90 percent of steady state recharge
- 100 percent of steady state recharge
- 110 percent of steady state recharge
- 120 percent of steady state recharge

3.0 Parameters and Assumptions

The updated Groundwater Availability Model was calibrated with data from 1980 to 2013. Figure 1 shows the recharge factor that was applied to each stress period of the calibrated model. Please note that the values generally range from slightly over 1.2 to slightly less than 0.8. In order to cover a reasonable range for the sensitivity analysis, five scenarios were developed ranging from a factor of 0.8 (80 percent of steady state recharge) to a factor of 1.20 (120 percent of steady state recharge).

3.1 Files Unchanged from Calibrated Model

Files that contain model input parameters related to the model grid and aquifer parameters were the same as the files used in the calibrated model as shown in Table 1.

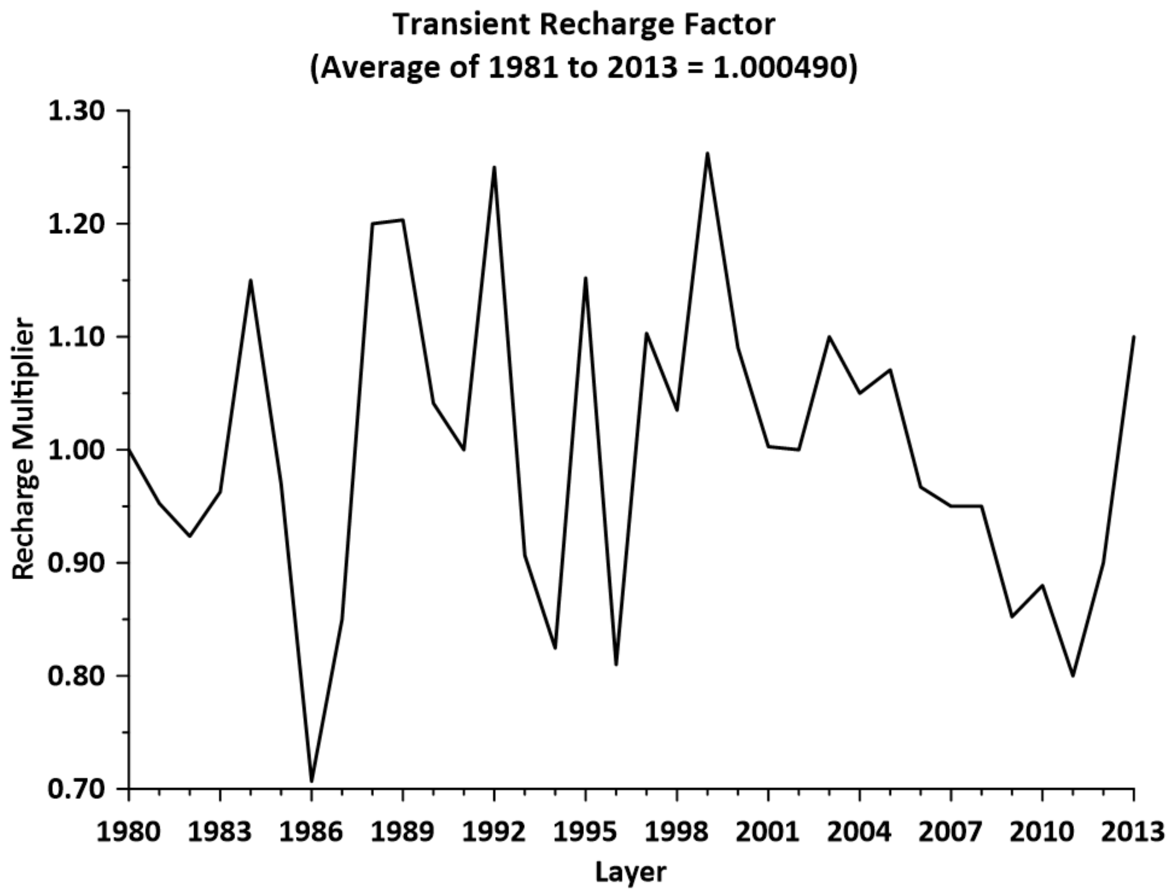


Figure 1. Recharge Factors for Each Stress Period of Calibrated Model

Table 1. Predictive Model Files Unchanged from Calibrated Model

File Name	File Date	Description
findd.dis	4/10/2020	Spatial Discretization
findd.ims	4/10/2020	Solver Parameters
finddd.npf	4/10/2020	Node Property Flow
tr58_g.kx	4/10/2020	Horizontal Hydraulic conductivity
tr58_g.kz	4/10/2020	Vertical Hydraulic Conductivity
tr58_g.ss	4/10/2020	Specific Storage
tr58_g.sy	4/10/2020	Specific Yield

3.2 Time Discretization and Storage

The predictive simulation was run for the period 2014 to 2080, a total of 67 annual stress periods. The calibrated model included a steady-state stress period at the beginning of the simulation. Thus, the TDIS file was modified to reflect 67 annual stress periods and named *finddd.tdis*. The specification of steady state or transient stress period in MODFLOW 6 is contained in the STO file. This file was updated and named *finddd.sto.*

3.3 Groundwater Pumping (WEL Package)

After evaluating the results of the companion pumping sensitivity documented in Technical Memorandum 1, the base pumping selected for the recharge sensitivity analysis was 2011. This year was selected since it was the highest pumping in the last four years, and generally resulted in declining groundwater elevations during the predictive period with steady state recharge.

The FORTRAN program *makebasepump.exe* was written to develop four model input files of pumping used in the pumping sensitivity analysis. The program reads the calibrated model file *tr58_g.wel*, which contains cell-by-cell pumping amounts from 1980 to 2013. The program then writes four files as follows:

- *pump2010.wel* specifies 2010 pumping for 2014 to 2080
- *pump2011.wel* specifies 2011 pumping for 2014 to 2080
- *pump2012.wel* specifies 2012 pumping for 2014 to 2080
- *pump2013.wel* specifies 2013 pumping for 2014 to 2080

The file *pump2011.wel* was used for the recharge sensitivity analysis.

3.4 Evapotranspiration (EVT Package)

The FORTRAN program *makeevt.exe* was written to develop a model input file for evapotranspiration. Inspection of the calibrated model input file for evapotranspiration (*tr58_g.evt*) shows that the same evapotranspiration parameters were used for each stress period of the calibration period (1980 to 2013). The program simply extracts the first stress period of the calibration period and writes it to a new file named *finddd.evt*.

3.5 General Head Boundaries (GHB Package)

The FORTRAN program *makeghb.exe* was written to develop a model input file for the general head boundaries, which were implemented to simulate the effects of overlying formations that are not formally part of the model domain.

Inspection of the calibrated model input file for general head boundaries (*tr58_g.ghb*) shows that the same general head boundary parameters were used for each stress period of the calibration period (1980 to 2013). The program simply extracts the first stress period of the calibration period and writes it to a new file named *finddd.ghb*.

3.6 Recharge (RCH Package)

The recharge input file *tr58_g.rch* contains the cell-by-cell recharge amounts for each stress period of the calibrated model (1980 to 2013). The FORTRAN program *makepredrch.exe* was written to develop four additional recharge input files (for 80 percent, 90 percent, 110 percent, and 120 percent of steady state recharge).

The program reads the steady state recharge file used in the pumping sensitivity analysis (renamed *basess.rch* for this program). Factors are applied to each cell-by-cell recharge value in the base file and written to the four new files. Please note that the factor is applied, and the cell value is written if the value is greater than zero. Inspection of the calibrated model recharge input file yields the conclusion that several cells have a zero recharge. Thus, the resulting files for this sensitivity analysis are slightly smaller than the base file.

The four files written by the program are:

- *rech080.rch* (for 80 percent of steady state recharge scenario)
- *rech090.rch* (for 90 percent of steady state recharge scenario)
- *rech110.rch* (for 110 percent of steady state recharge scenario)
- *rech120.rch* (for 120 percent of steady state recharge scenario)

3.7 River (RIV Package)

The calibrated model simulated surface water-groundwater interactions with the River (RIV) package specified in the file *tr58_g.rch*. Inspection of the input file yielded the conclusion that RIV head values changed slightly for each stress period. River conductance and bottom elevations remained the same in all stress periods.

The FORTRAN program *makeriv.exe* was written to extract the first stress period of RIV parameters for the predictive simulations and hold them constant for all stress periods. The output file from this program is *finddd.riv.*

3.8 Other Input Files

Other files that were developed for these predictive simulations are summarized in Table 2.

Table 2. Other Input Files Summary

File Name	Description	Modification
finddd.ic6	Starting Heads	Specified 2013 heads as starting heads
mfsim.nam	Global Simulation Name File	Udated tdis and ims file names
rechXXX.nam	Scenario Name File	Updated scenario file names (XXX refers to specific scenario)
rechXXX.oc6	Output Control	Updated scenario-specific output files and adjusted number of stress periods (XXX refers to specific scenario)

4.0 Methods and Results

4.1 Model Scenarios

Five scenarios were completed to evaluate the changes in average drawdown in each county-model layer unit due to different levels of constant recharge. Assumed recharge values were based on applying alternative multiplication factors of recharge based on the range in the calibrated model. The results were summarized for county-model layer units in Groundwater Management Area 11.

4.2 Post-Processing of MODFLOW 6 Results

A FORTRAN program named *getdd.exe* was written to extract groundwater elevation data from the model output files. The program was modified for each scenario to reflect different input and output file names unique to the scenario.

The program reads a list of county names and codes (*countynamelist.dat*) and a grid file of cell number, layer, and county code (*celllayercountyns.csv*). The program counts the number of cells in each county-model layer unit and reports the results in a file named *cellcount.dat.* The 27 counties within Groundwater Management Area 11 and the number of cells in each layer of those counties is presented in Table 3. Based on Table 3, there are 213 county-model layer units with at least one active model cell.

The program then reads the binary output files from the calibrated model (*tr58g.hds*) and the specific scenario of the predictive simulation (rech*XXX.hds*). The program then calculates the drawdown for each cell with a starting date of 2013 (the last year of the calibrated model). Drawdowns for each county-model layer unit are then summed, and the average drawdown for each county-model layer unit is calculated as the summed drawdown for that unit divided by the number of cells in that unit.

The program then reads a list of file names for each county-model layer unit for the 27 counties in Groundwater Management Area 11 and writes annual drawdowns for each layer to the county-based output files for the scenario.

4.3 Results

There is a total of 27 output files for each scenario (one for each county). Within each county file, there are average drawdown results for each model layer for each year of the simulation. Where there is no active cells, the drawdown is listed as -9999.00 to designate that there are no active cells. Also included are the county number (1 to 27), the county number of the entire list of counties in the model, the county code from the grid file, and the county name.

The 213 individual hydrographs that plot all scenarios for a county-model layer unit were saved in a pdf file (*RechSensHydrographsDD.pdf*). The hydrographs are printed one to a page for easy viewing with a pdf reader. An example is shown in Figure 3.

Table 3. Cell Counts for Each County-Model Layer Unit

County	Number of Model Cells in Each County-Model Layer Unit									Number of Active Layers
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	
Anderson	19,582	106	359	3,276	3,455	1,932	1,639	1,203	1,087	9
Angelina	552	3,828	1,312	865	865	865	865	865	865	9
Bowie	6,382	0	0	0	0	0	1,312	1,034	522	4
Camp	2,674	0	0	392	371	387	451	233	201	7
Cass	12,311	5	61	3,249	1,843	716	1,524	1,221	988	9
Cherokee	14,757	603	676	3,030	2,404	1,885	1,414	1,096	1,059	9
Franklin	2,136	0	0	0	3	177	607	320	170	6
Gregg	4,065	0	0	414	557	928	465	290	274	7
Harrison	10,279	0	2	413	995	621	2,226	1,845	1,311	8
Henderson	11,104	0	9	1,445	1,072	701	1,071	1,471	1,540	8
Hopkins	4,213	0	0	0	1	23	500	634	839	6
Houston	7,210	5,267	2,187	2,455	1,424	1,238	1,237	1,237	1,237	9
Marion	7,315	1	5	899	1,017	336	1,214	694	545	9
Morris	3,694	0	6	484	509	169	344	636	317	8
Nacogdoches	13,147	1,630	1,706	1,456	1,595	1,390	1,787	1,094	983	9
Panola	12,656	0	0	0	1	4	996	3,921	1,269	6
Rains	3,109	0	0	0	0	0	56	246	864	4
Rusk	13,447	7	14	191	760	1,842	3,677	1,311	943	9
Sabine	3,513	2,242	795	398	566	566	1,121	658	577	9
SanAugustine	2,534	1,511	770	385	611	792	836	623	594	9
Shelby	10,606	8	3	1	2	42	2,558	2,546	1,037	9
Smith	12,534	331	837	3,653	2,053	1,234	1,107	964	947	9
Titus	6,547	0	0	32	221	245	1,096	876	559	7
Trinity	0	4,124	1,225	713	713	713	713	713	713	8
Upshur	6,347	20	49	1,905	1,142	928	636	595	595	9
VanZandt	9,253	0	7	268	293	384	1,940	1,013	1,723	8
Wood	9,934	77	215	1,681	1,070	839	1,516	1,046	740	9

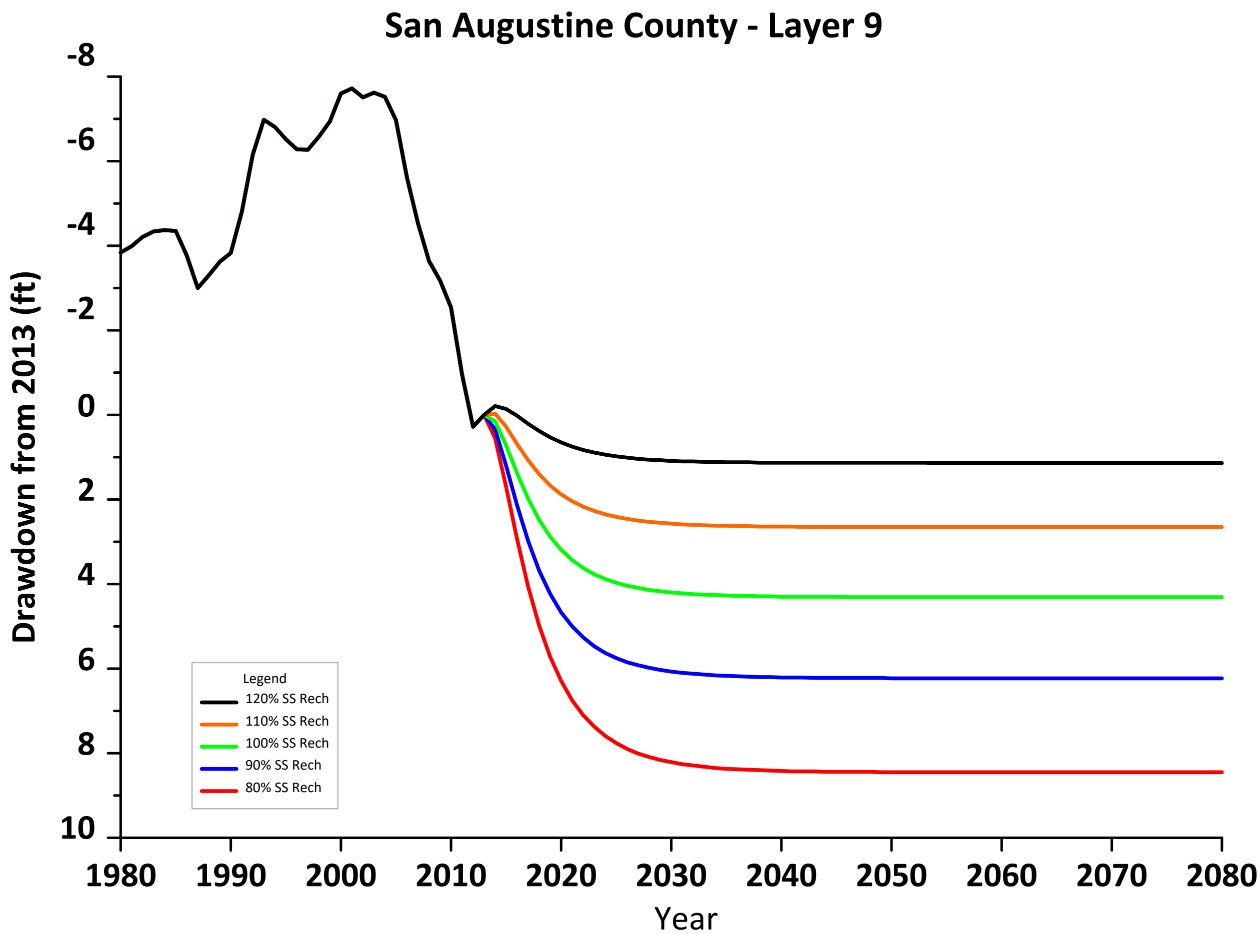


Figure 2. Average Drawdown in San Augustine County - Layer 9

From 1980 to 2013 (the calibration period) average drawdown from 2013 ranges from -7.62 ft in 2003 to 0.28 ft in 2012, a range of about 8 feet. From 2014 to 2080, the range in drawdown is defined by the difference of the 120 percent of steady state recharge (black line) and the 80 percent of steady state recharge (the red line), also a difference of about 8 feet. Thus, the selection of the recharge will influence the simulated drawdown.

Please note that the primary interpretation in Figure 3 is that there is an initial response to the change in recharge starting in 2014, and an equilibrium condition is achieved after a few years. Achieving an equilibrium condition is present in all 213 hydrographs developed and demonstrates the suitability of the model for the joint planning process.

The example in Figure 3 can also be compared to a similar plot from Hutchison (2017b) reproduced below as Figure 4.

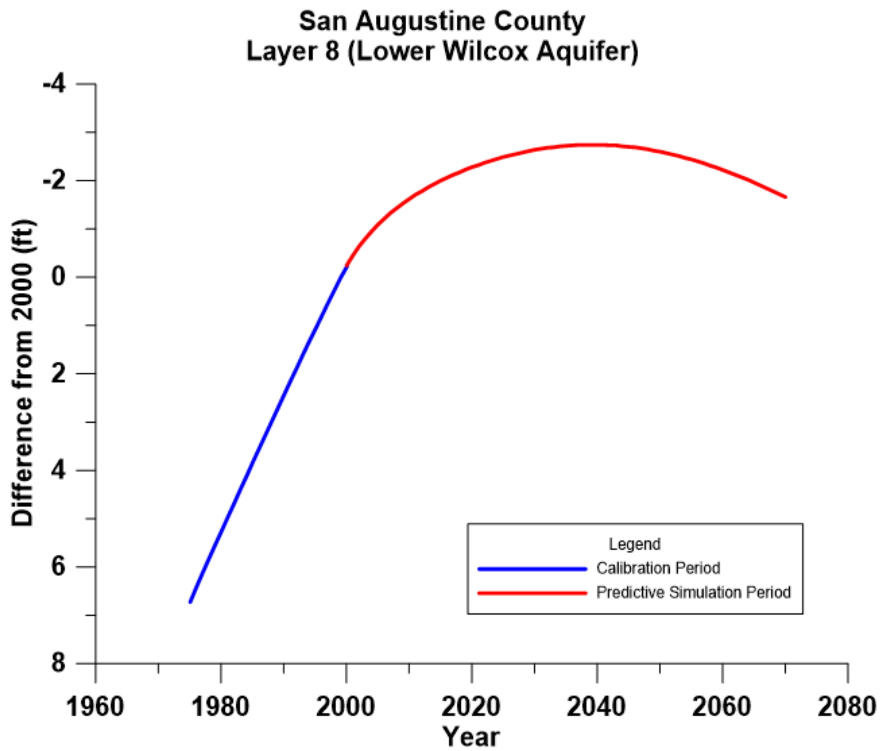


Figure 3. Average Drawdown from Previous Groundwater Availability Model - San Augustine County, Layer 8

Please note that in the previous Groundwater Availability Model, Layer 8 represented the Lower Wilcox Aquifer. This new Groundwater Availability Model has an extra layer to simulate alluvial formations in the areas of streams and rivers, so Layer 9 now represents the Lower Wilcox Aquifer.

As discussed in Hutchison (2017b), during the calibration period, average groundwater levels rose about 7 feet from 1975 to 1999. This suggests that the model is simulating actual conditions well. The model conditions that caused the rise from 1975 to 1999 continue to affect the change in average groundwater levels after 2000 (the simulation period). The rise continues until about 2030, and the model predicts a drop in average groundwater level after this peak. However, the decline from 2030 to 2070 leaves the average groundwater level higher than the average level in 2000 (the start of the simulation period). This was an example of a model limitation that had to considered when using the results of the old model in considering desired future conditions. Based on the hydrograph in Figure 3 and an inspection of all the hydrographs in Appendix A, this limitation has been eliminated in this updated Groundwater Availability Model.

Summary graphs that compare the range in calibration period drawdown and the range in the predictive period drawdown for all scenarios are presented in Appendix A. Each graph plots the range in drawdowns for each county for a specific layer. These plots, and companion plots in Technical Memorandum 1 are useful in interpreting simulation results for the joint planning process. The results in Appendix A were extracted from the individual drawdown files using a FORTRAN program named *sumrechsens.exe*. Please note that in Morris County, the drawdowns in 1989, 1990, and 1991 appeared to be outliers, possibly due to unusually high pumping. These years were discarded when calculating the maximum range of drawdown in Morris County during the calibration period.

A final comparison of the relative sensitivity of pumping and recharge during the predictive period is made with summary graphs in Appendix B, which includes nine plots that compare the predictive range of drawdown under the pumping scenarios documented in Technical Memorandum 1 and the predictive range of drawdowns under the recharge scenarios documented in this Technical Memorandum. Please note that the shallower formations show more sensitivity to recharge than pumping, and the deeper layers show much higher sensitivity to pumping. Although specific conclusions are county dependent, these results will be useful during the joint planning process. It is also consistent with the historic pumping in the area, which has been historically higher in the deeper formations (i.e. Carrizo-Wilcox) as compared with the Sparta and Queen City.

5.0 Limitations

The objective of these simulations was to provide a practical basis for selecting a base recharge amount for simulations focused on joint planning. As a result, there are some limitations to the results given the regional nature of the objective:

- The scenarios considered only increases and decreases in overall recharge pumping to assess general sensitivity of recharge on average drawdown. For this analysis, there were no attempts to vary the recharge year to year, which would occur (i.e. simulate wet periods and dry periods).
- The results provide some insight on recharge sensitivity but are coupled with a companion analysis of sensitivity to pumping contained in Technical Memorandum 2 and the graphs in Appendix B.

6.0 References

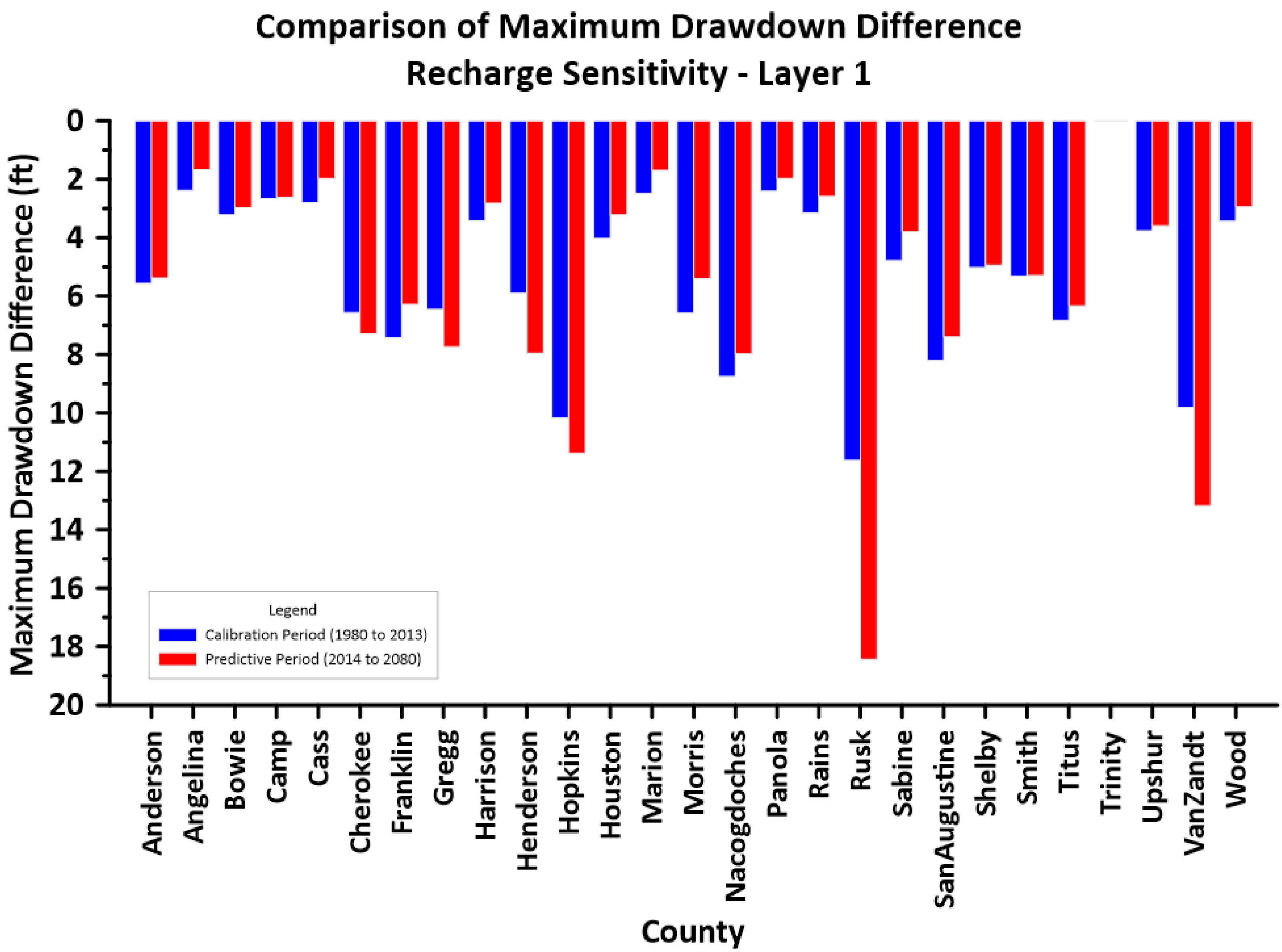
Hutchison, W.R., 2017a. Desired Future Condition Explanatory Report: Carrizo-Wilcox/Queen City/Sparta Aquifers for Groundwater Management Area 11. Report submitted to Texas Water Development Board, January 24, 2017, 445p.

Hutchison, W.R., 2017b. Use of Predictive Simulation Results from Scenario 4 in Desired Future Conditions for Sparta, Queen City, and Carrizo-Wilcox Aquifer. GMA 11 Technical Memorandum 16-02. Report submitted to Groundwater Management Area 11. January 24, 2017, 15p.

Hutchison, W.R., 2017c. Initial GAM Simulations for Sparta, Queen City and Carrizo-Wilcox Aquifers. GMA 11 Technical Memorandum 15-01. Report submitted to Groundwater Management Area 11. January 21, 2017, 109p.

Appendix A

Comparison of Maximum Drawdown Difference – Recharge Sensitivity (one graph per model layer, each graph shows 27 counties)


Comparison of Maximum Drawdown Difference
Recharge Sensitivity - Layer 1
Maximum Drawdown Difference (ft)
0
2
4
6
8
10
12
14
16
18
20
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
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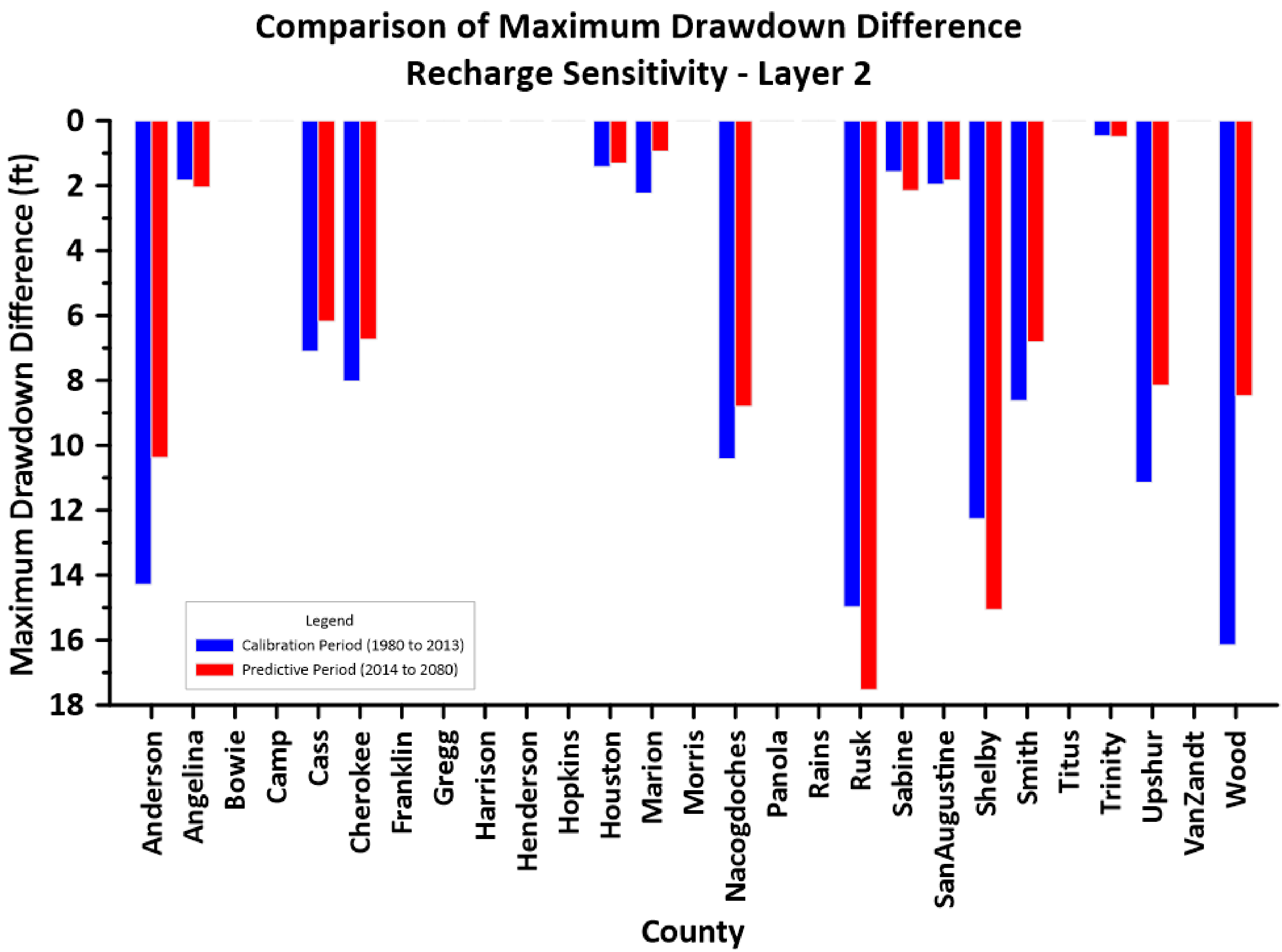
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County



Comparison of Maximum Drawdown Difference
Recharge Sensitivity - Layer 2
Maximum Drawdown Difference (ft)
0
2
4
6
8
10
12
14
16
18
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
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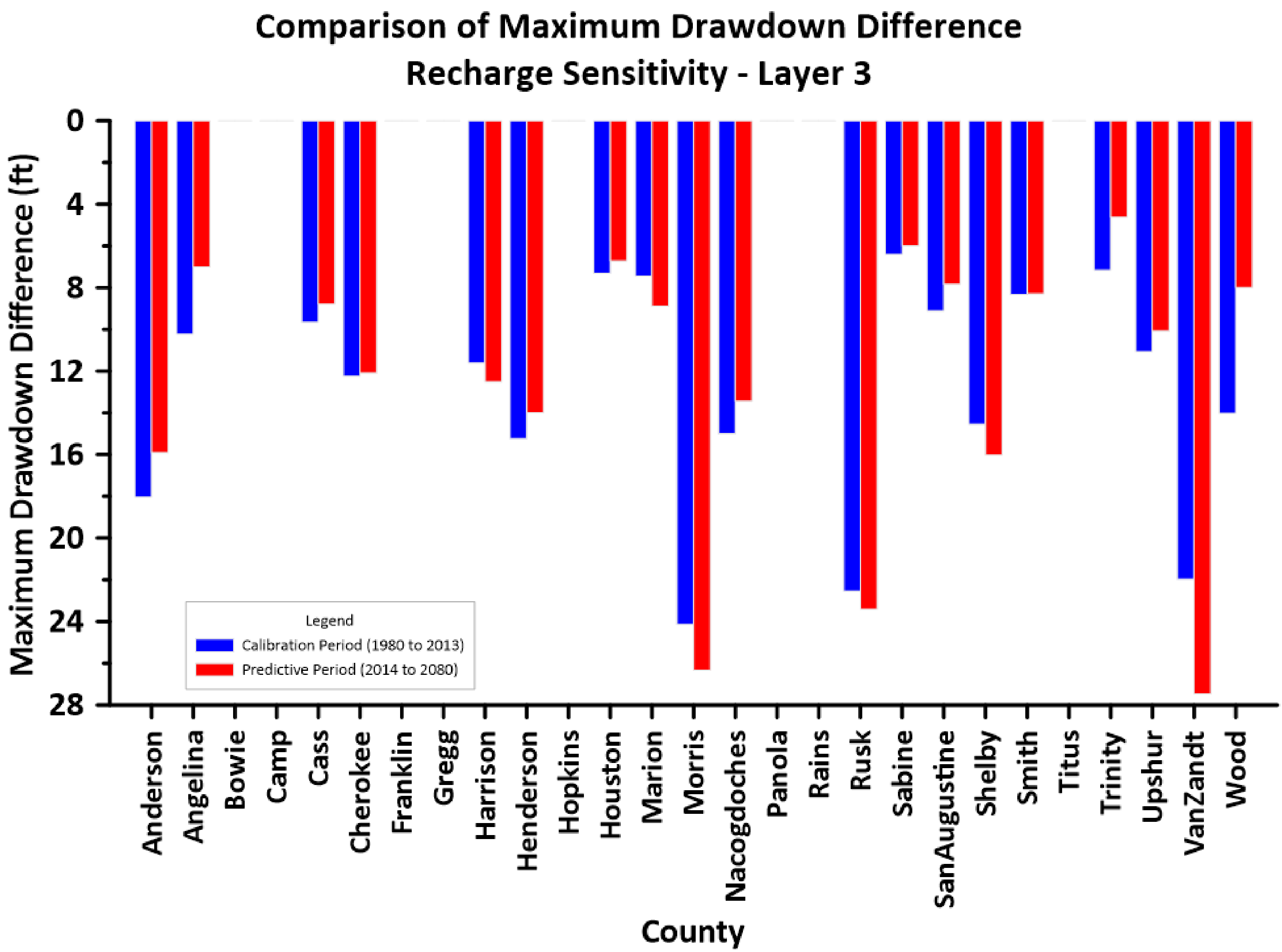
Wood
County


Comparison of Maximum Drawdown Difference
Recharge Sensitivity - Layer 3
Maximum Drawdown Difference (ft)
0
4
8
12
16
20
24
28
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
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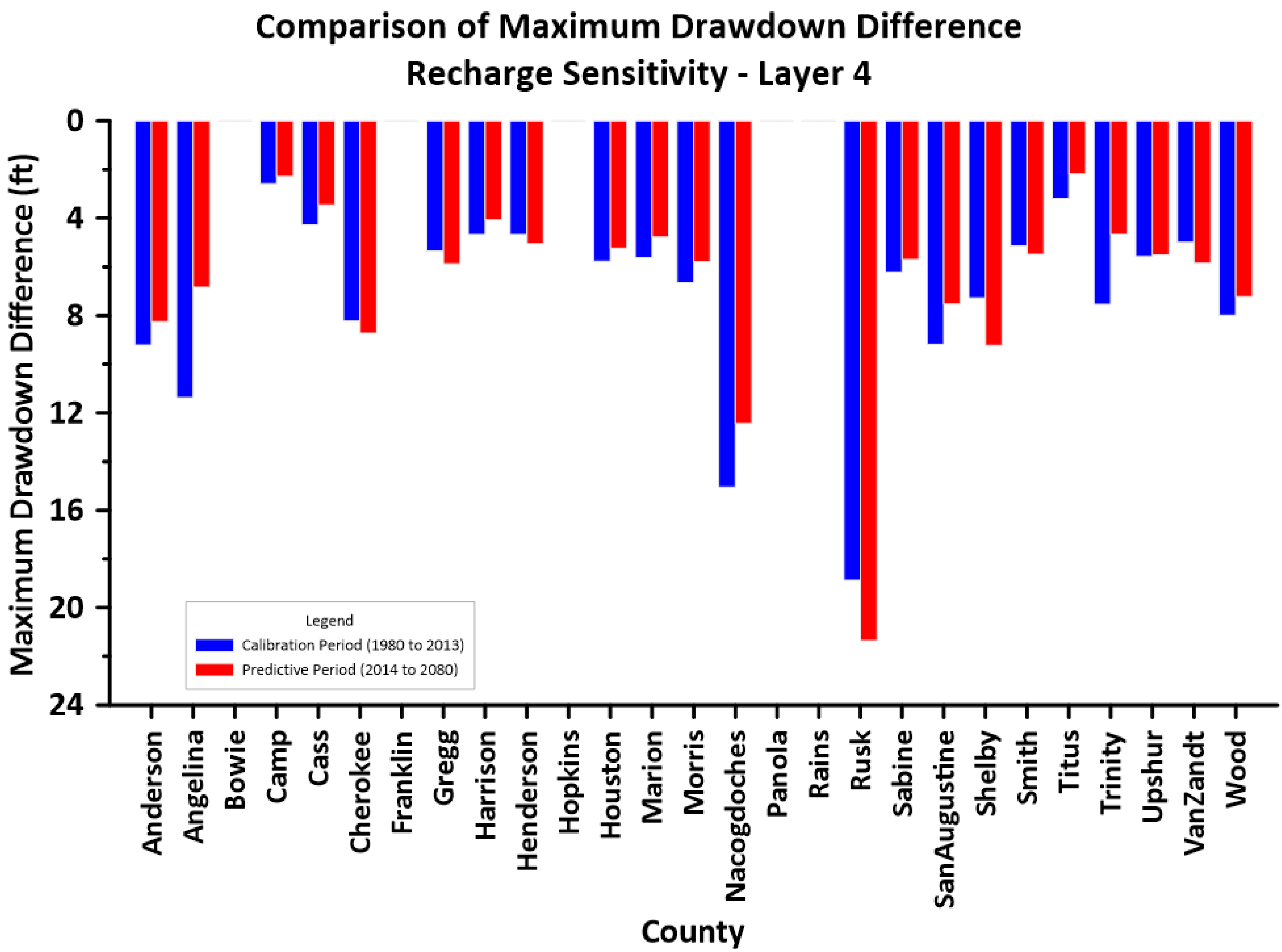

Comparison of Maximum Drawdown Difference
Recharge Sensitivity - Layer 4
Maximum Drawdown Difference (ft)
0
4
8
12
16
20
24
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
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Morris
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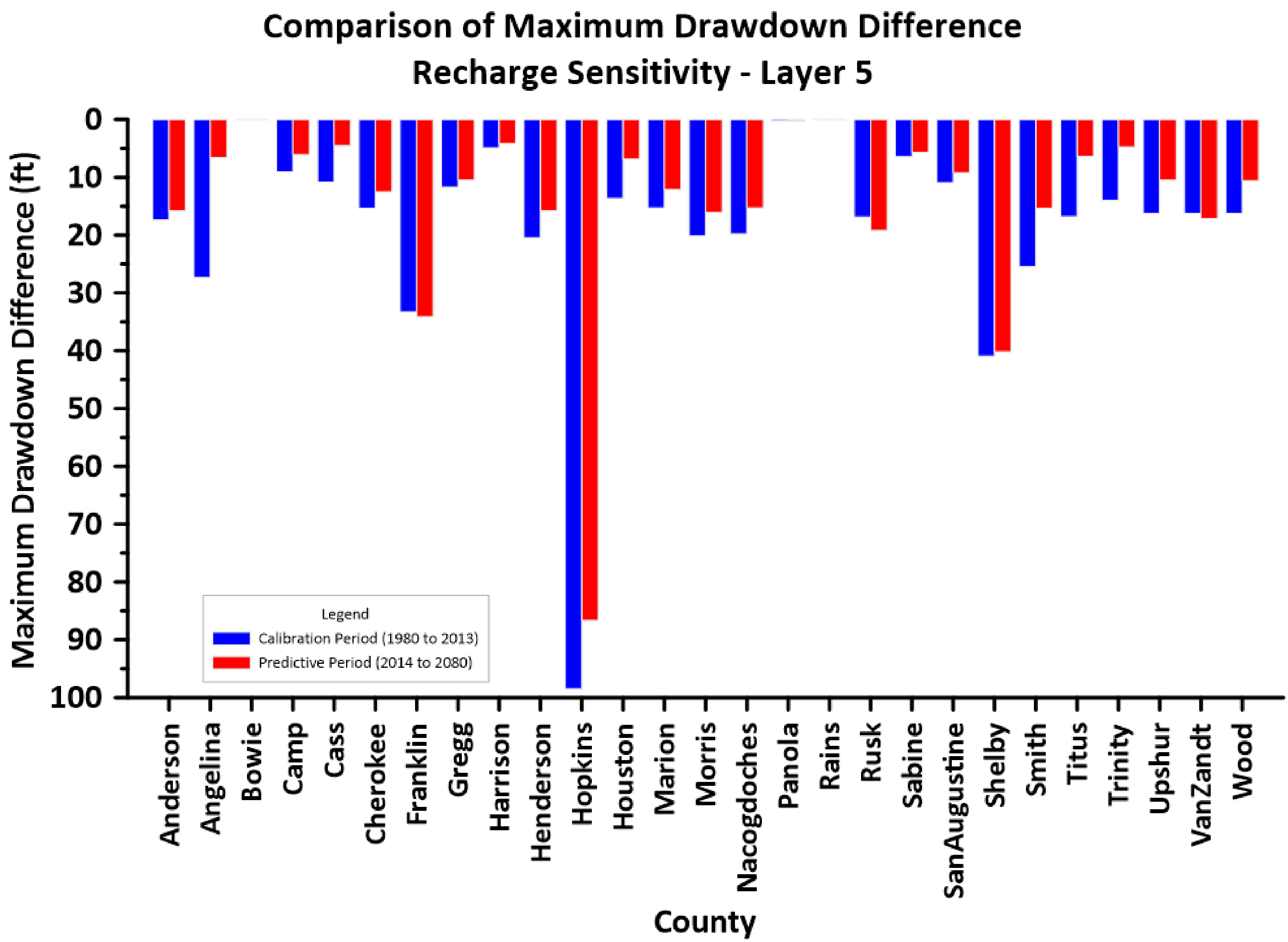

Comparison of Maximum Drawdown Difference
Recharge Sensitivity - Layer 5
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
70
80
90
100
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
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Cass
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Franklin
Gregg
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Henderson
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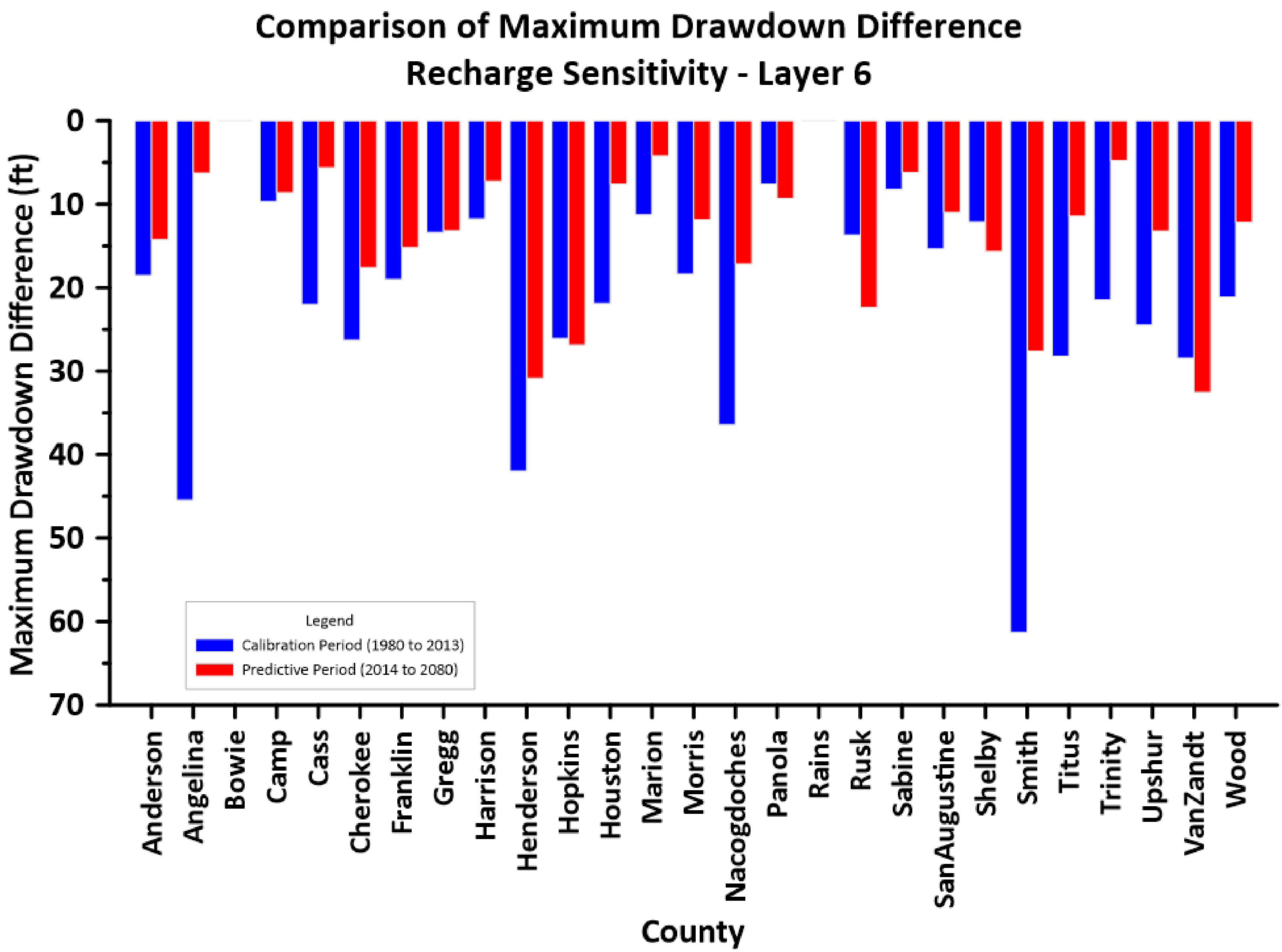

Comparison of Maximum Drawdown Difference
Recharge Sensitivity - Layer 6
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
70
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
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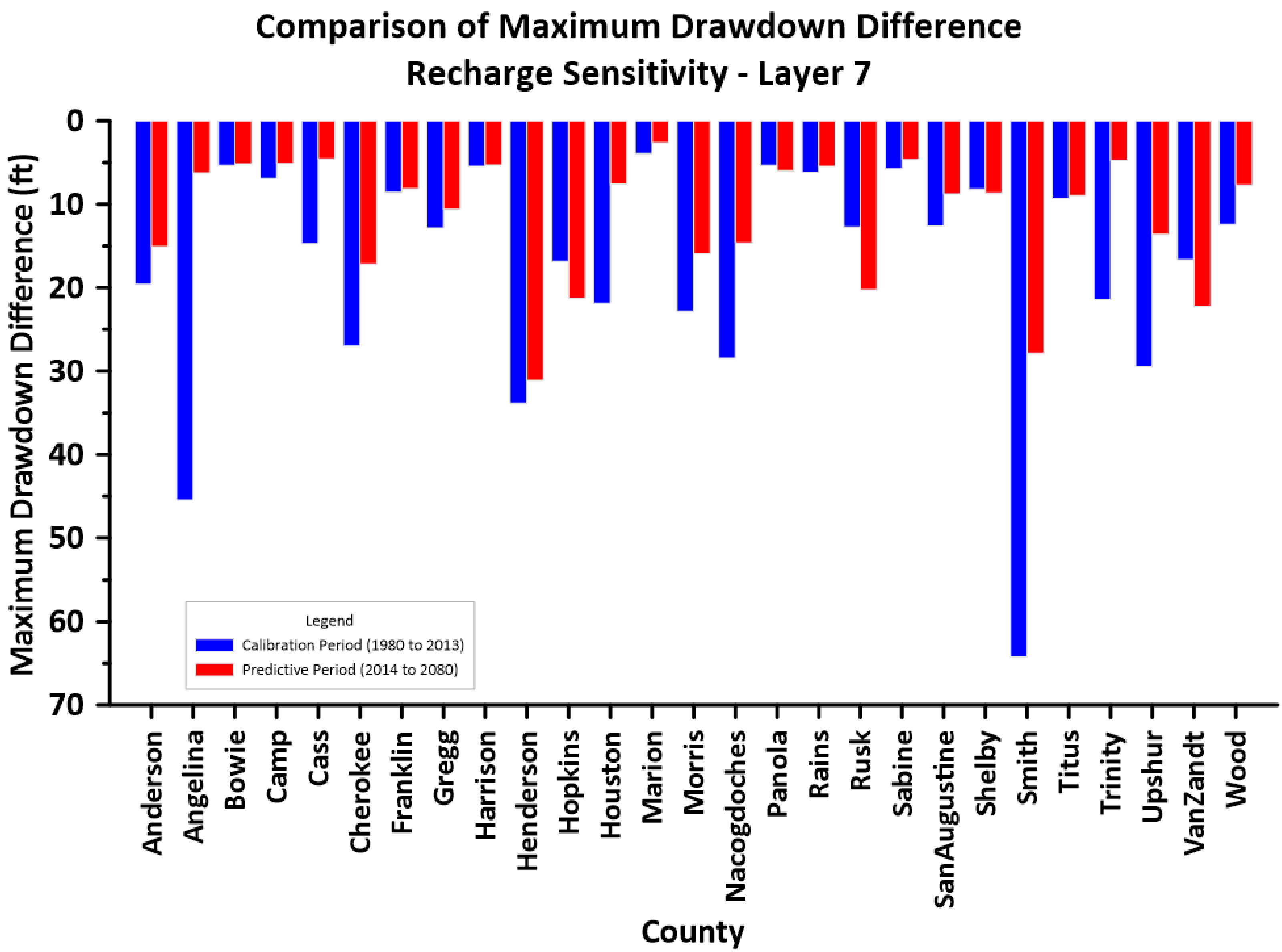
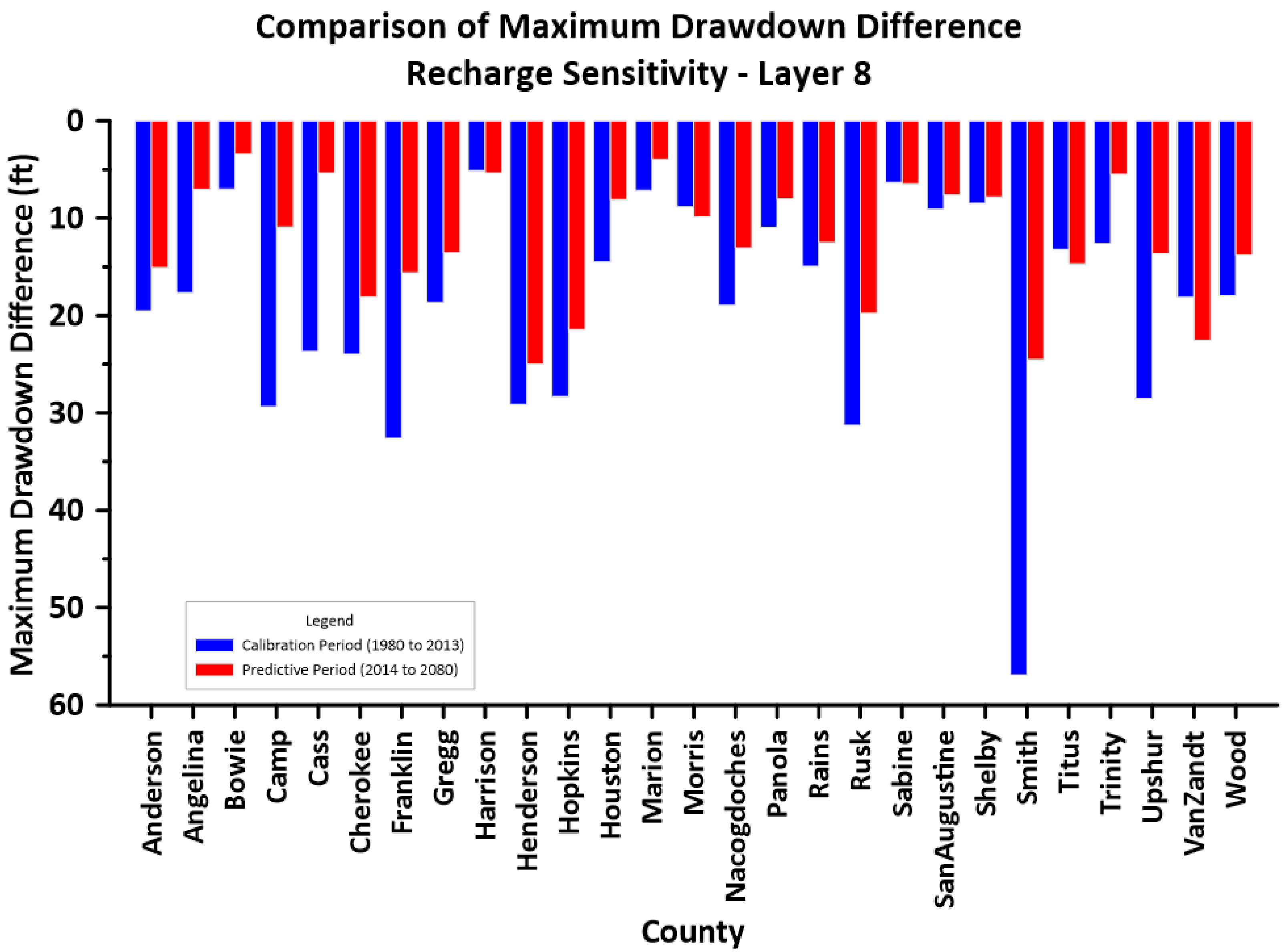
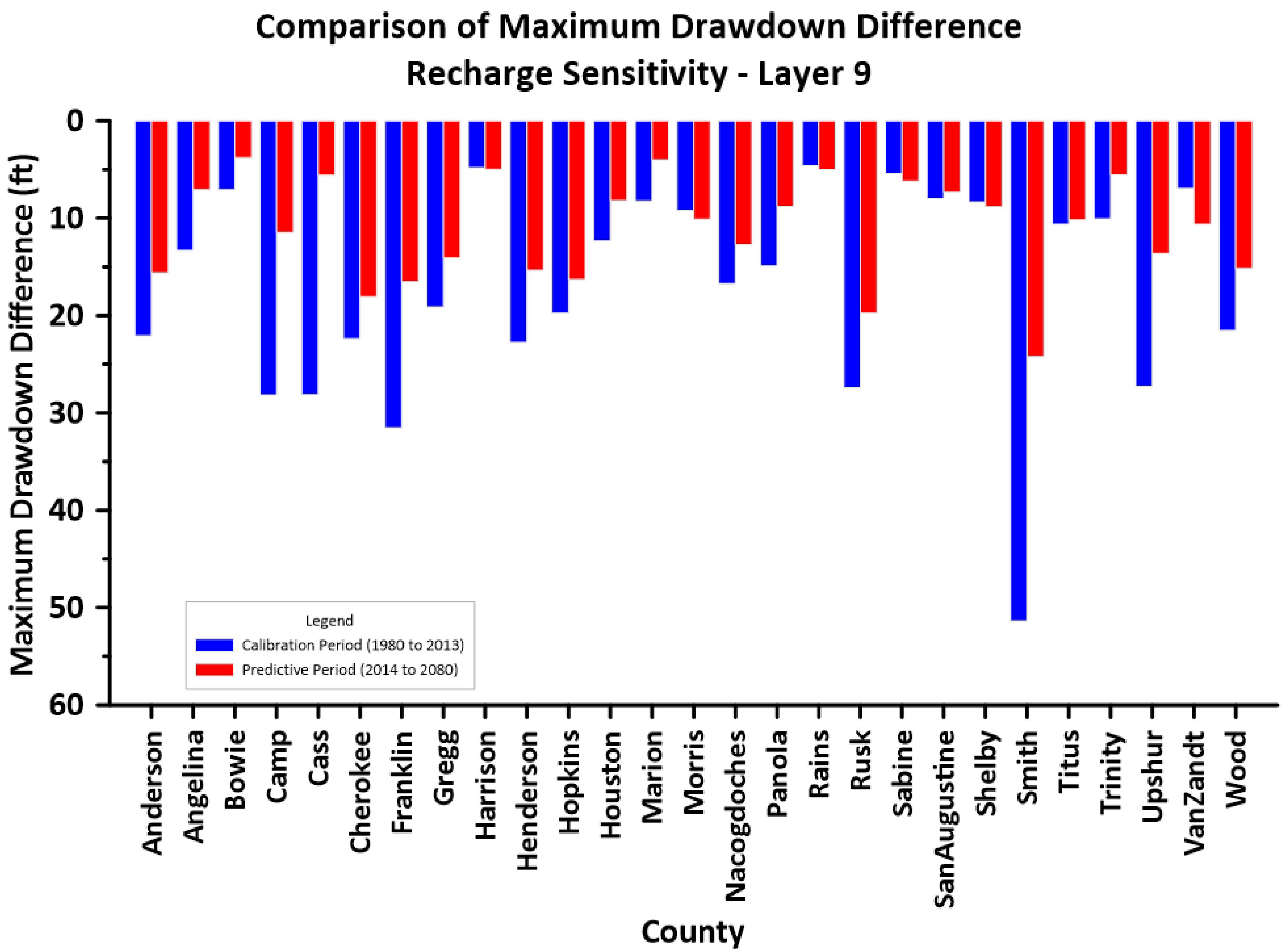
County

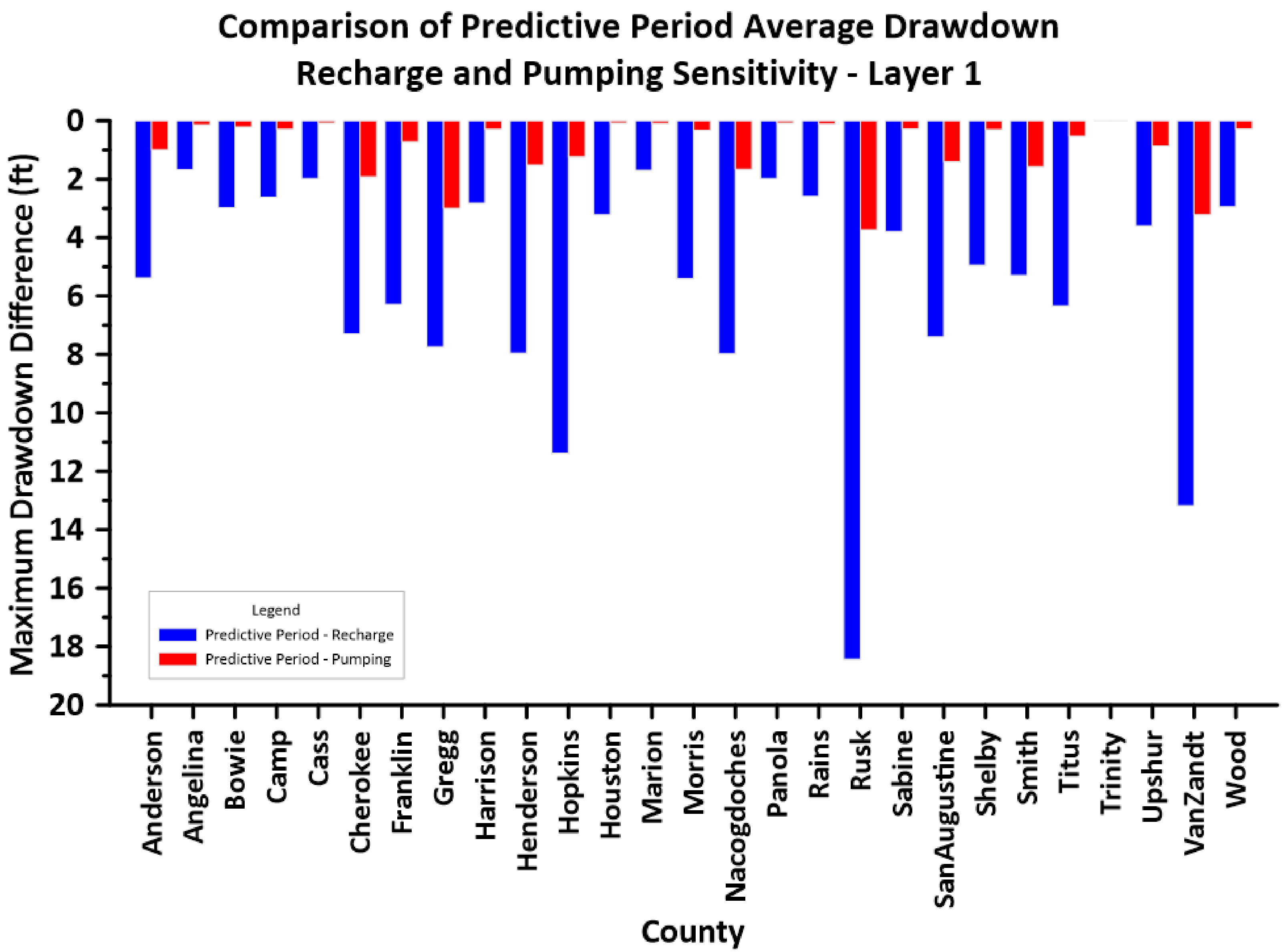

Comparison of Maximum Drawdown Difference
Recharge Sensitivity - Layer 7
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
70
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County

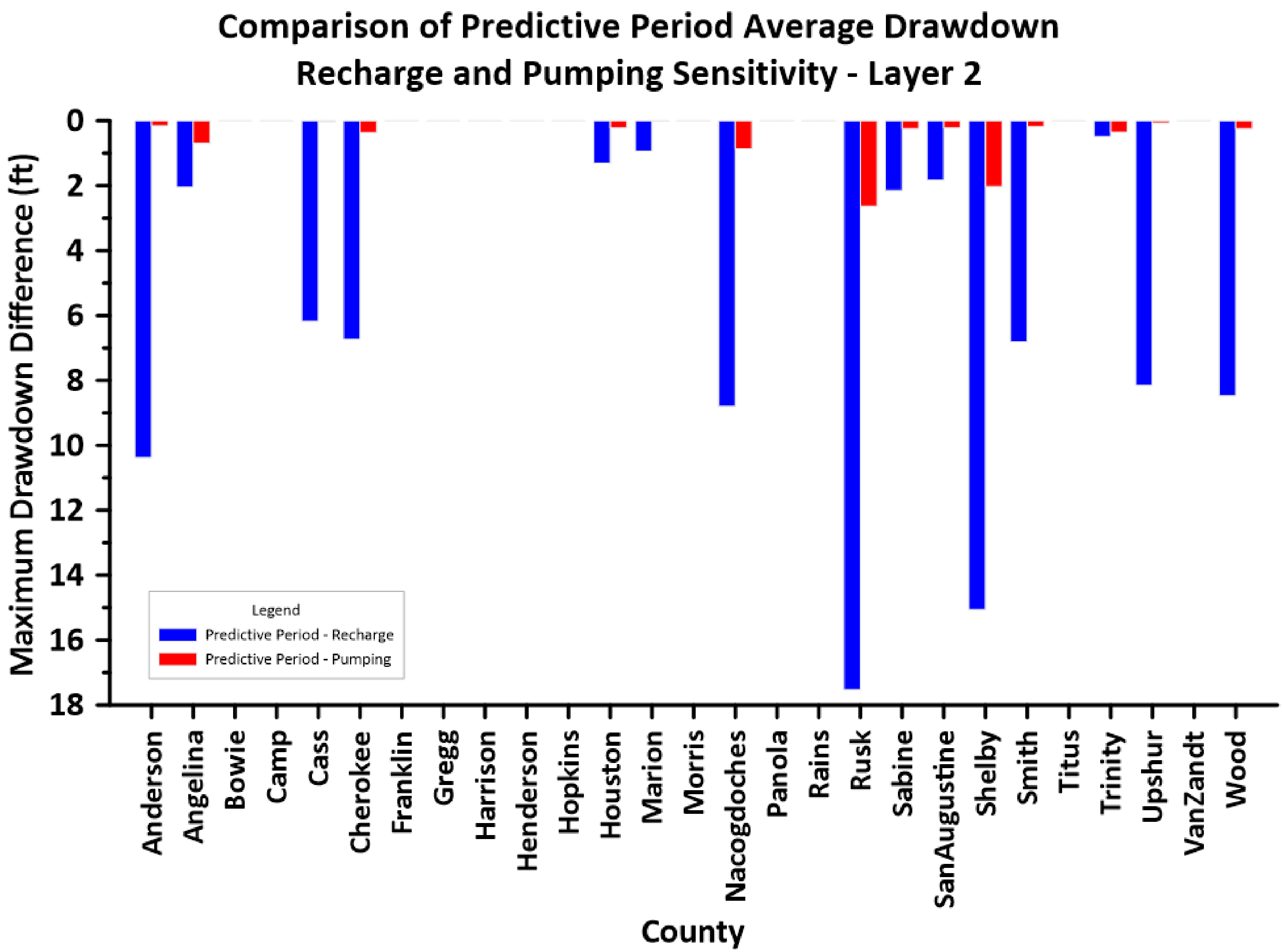

Comparison of Maximum Drawdown Difference
Recharge Sensitivity - Layer 8
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County


Comparison of Maximum Drawdown Difference
Recharge Sensitivity - Layer 9
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
Legend
Calibration Period (1980 to 2013)
Predictive Period (2014 to 2080)
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County

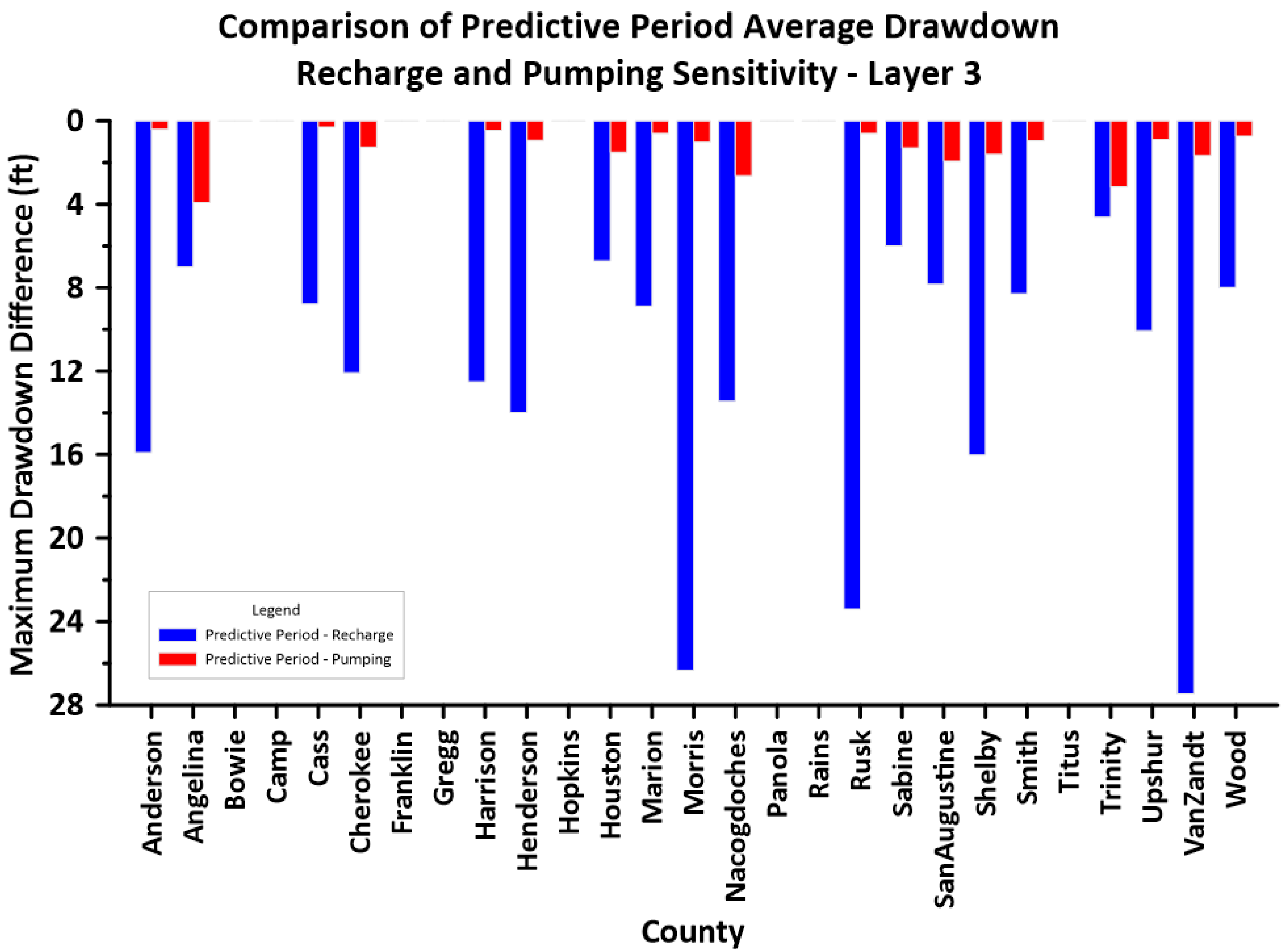
Appendix B

Comparison of Predictive Period Average Drawdown - Recharge and Pumping Sensitivity (one graph per model layer, each graph shows 27 counties)

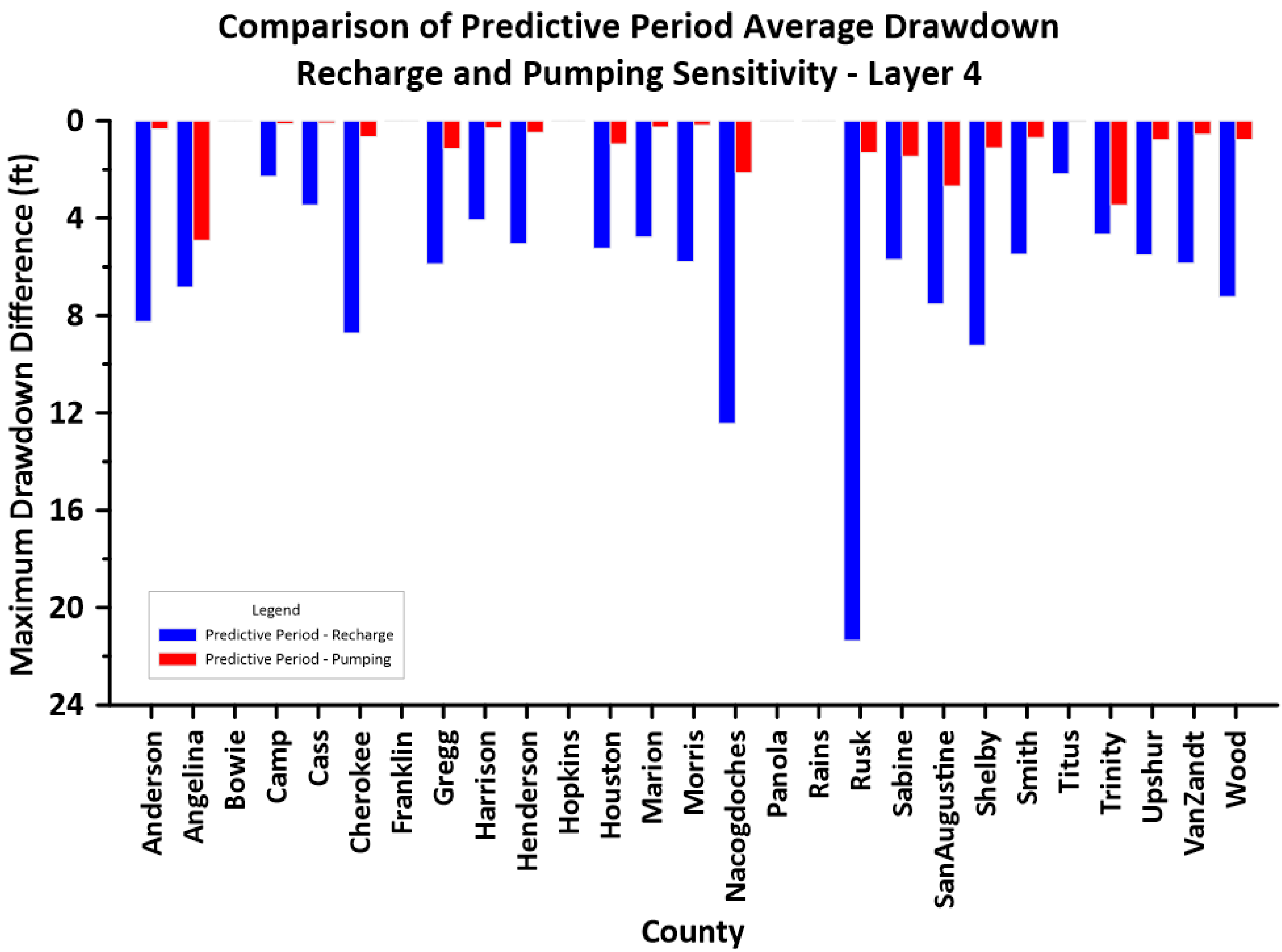

Comparison of Predictive Period Average Drawdown
Recharge and Pumping Sensitivity - Layer 1
Maximum Drawdown Difference (ft)
0
2
4
6
8
10
12
14
16
18
20
Legend
Predictive Period - Recharge
Predictive Period - Pumping
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County

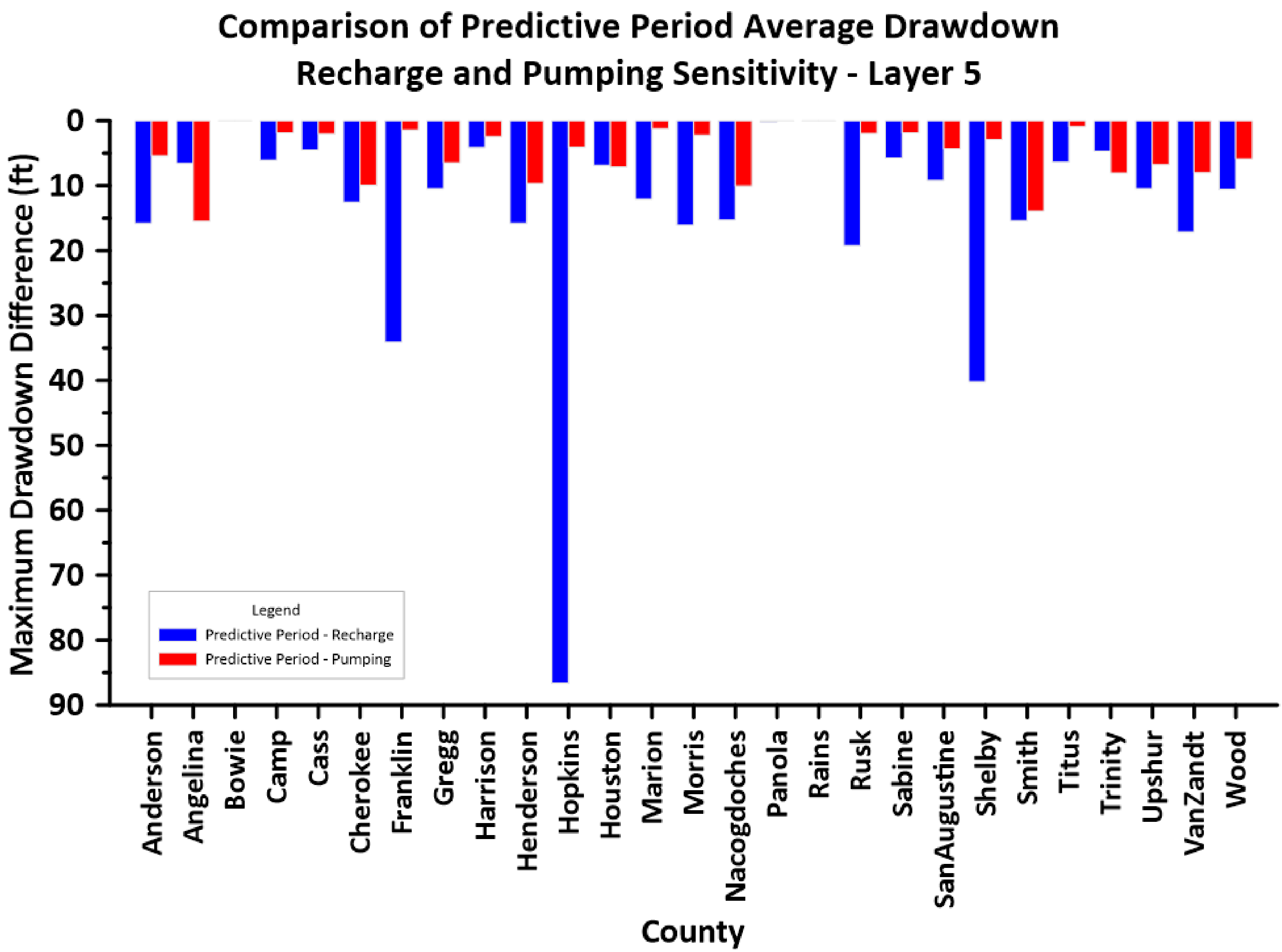


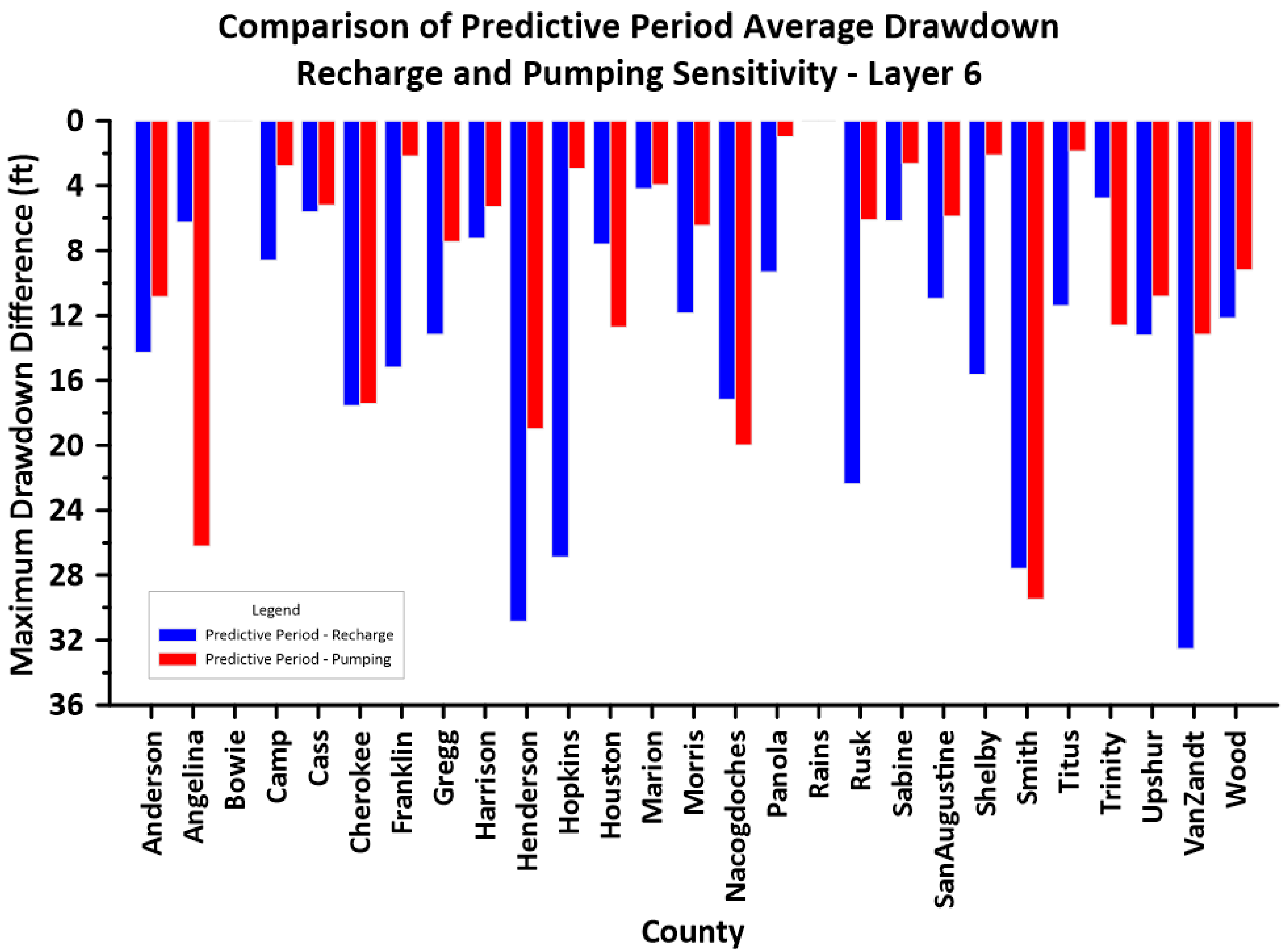
Comparison of Predictive Period Average Drawdown
Recharge and Pumping Sensitivity - Layer 2
Maximum Drawdown Difference (ft)
0
2
4
6
8
10
12
14
16
18
Legend
Predictive Period - Recharge
Predictive Period - Pumping
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County

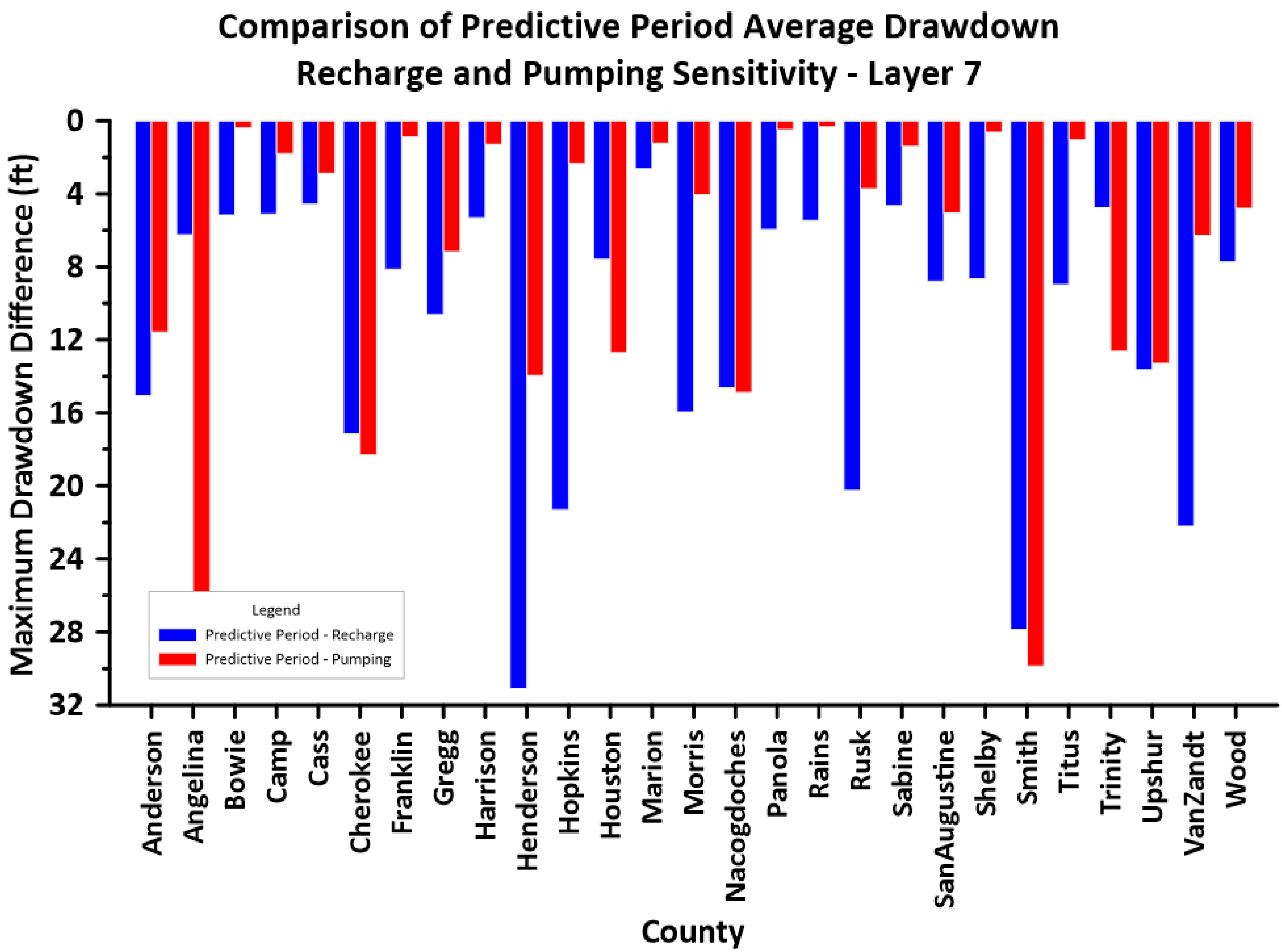


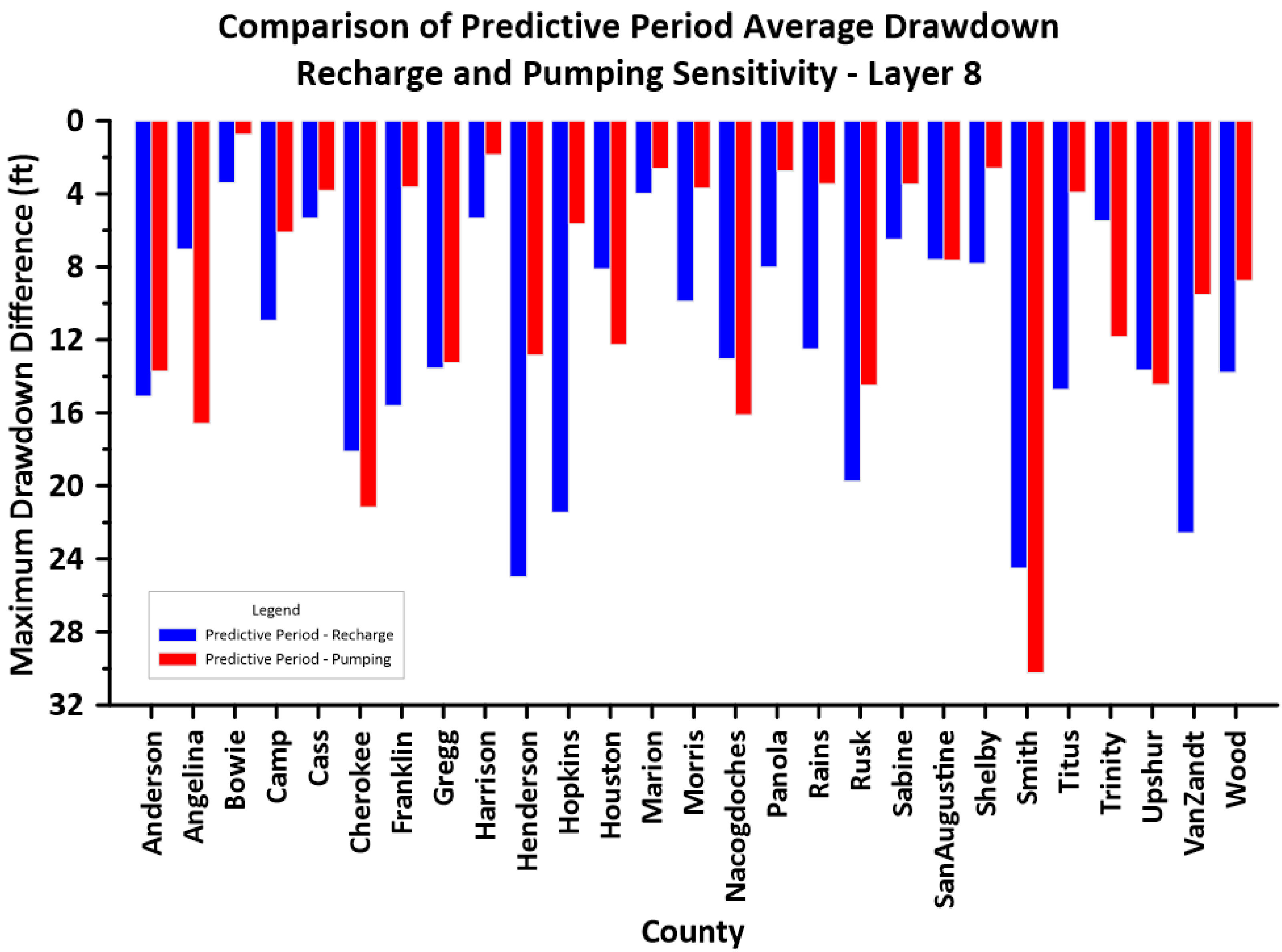
Comparison of Predictive Period Average Drawdown
Recharge and Pumping Sensitivity - Layer 3
Maximum Drawdown Difference (ft)
0
4
8
12
16
20
24
28
Legend
Predictive Period - Recharge
Predictive Period - Pumping
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County


Comparison of Predictive Period Average Drawdown
Recharge and Pumping Sensitivity - Layer 4
Maximum Drawdown Difference (ft)
0
4
8
12
16
20
24
Legend
Predictive Period - Recharge
Predictive Period - Pumping
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County

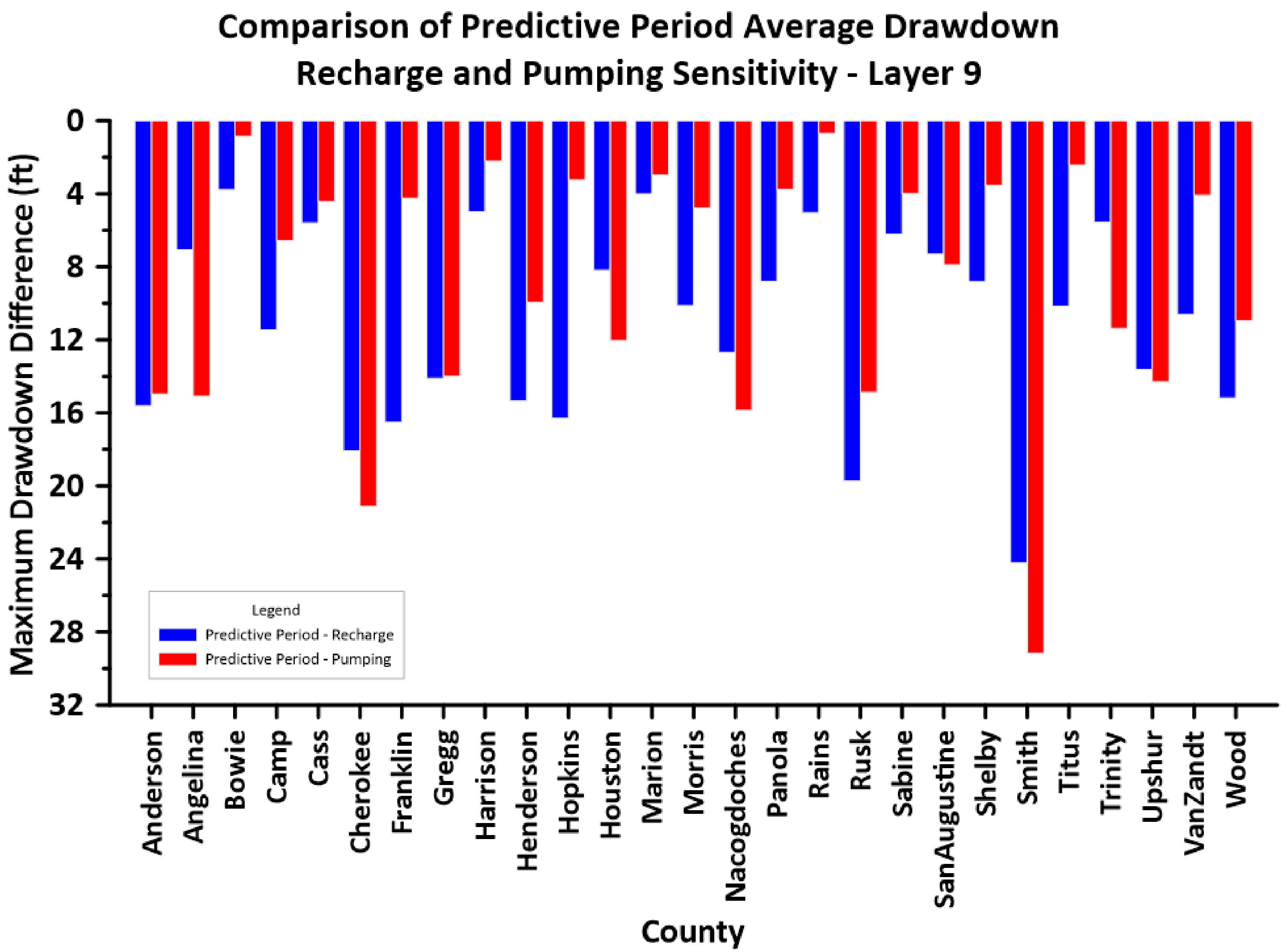

Comparison of Predictive Period Average Drawdown
Recharge and Pumping Sensitivity - Layer 5
Maximum Drawdown Difference (ft)
0
10
20
30
40
50
60
70
80
90
Legend
Predictive Period - Recharge
Predictive Period - Pumping
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County


Comparison of Predictive Period Average Drawdown
Recharge and Pumping Sensitivity - Layer 6
Maximum Drawdown Difference (ft)
0
4
8
12
16
20
24
28
32
36
Legend
Predictive Period - Recharge
Predictive Period - Pumping
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County


Comparison of Predictive Period Average Drawdown
Recharge and Pumping Sensitivity - Layer 7
Maximum Drawdown Difference (ft)
0
4
8
12
16
20
24
28
32
Legend
Predictive Period - Recharge
Predictive Period - Pumping
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County



Comparison of Predictive Period Average Drawdown
Recharge and Pumping Sensitivity - Layer 8
Maximum Drawdown Difference (ft)
0
4
8
12
16
20
24
28
32
Legend
Predictive Period - Recharge
Predictive Period - Pumping
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County


Comparison of Predictive Period Average Drawdown
Recharge and Pumping Sensitivity - Layer 9
Maximum Drawdown Difference (ft)
0
4
8
12
16
20
24
28
32
Legend
Predictive Period - Recharge
Predictive Period - Pumping
Anderson
Angelina
Bowie
Camp
Cass
Cherokee
Franklin
Gregg
Harrison
Henderson
Hopkins
Houston
Marion
Morris
Nacogdoches
Panola
Rains
Rusk
Sabine
SanAugustine
Shelby
Smith
Titus
Trinity
Upshur
VanZandt
Wood
County

Technical Memorandum 3

Calculation of Drawdown from Existing Modeled Available Groundwater Using Updated Groundwater Availability Model

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November 21, 2020

Professional Engineer and Professional Geoscientist Seals

This report was prepared by William R. Hutchison, Ph.D., P.E., P.G., who is licensed in the State of Texas as follows:

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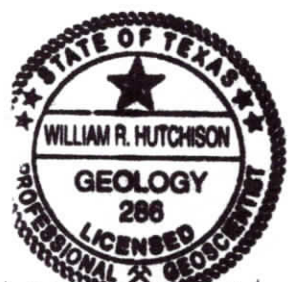
- Professional Geoscientist (Geology) No. 286

William R Hutchison
11/21/2020



William R Hutchison
11/21/2020

Table of Contents

List of Figures

List of Tables

1.0 Executive Summary

A simulation was completed that calculates the drawdown based on the existing modeled available groundwater using the updated Groundwater Availability Model. The results are summarized in an accompanying Excel spreadsheet (*ddcompare.xlsx*).

The results show that the new GAM predicts greater drawdown using the same pumping as the old GAM, but that a near-equilibrium condition develops after a few to several years of pumping. The old GAM had numerous instances of negative drawdowns (i.e. groundwater elevation recovery) that appear to have been limitations with the old GAM. These limitations include the role of recharge in the changes in outcrop groundwater elevations and the ability of the old GAM to move water effectively from the outcrop area to the downdip area. These limitations have been corrected in the new GAM. However, the results of the simulation suggest that close attention must be given to the aquifer capabilities and the simulated impacts of future pumping.

2.0 Background

The desired future conditions for Groundwater Management Area 11 that were adopted on January 11, 2017 were documented in the Desired Future Condition Explanatory Report (Hutchison, 2017a). As noted in the Explanatory Report, the desired future conditions were based on Groundwater Availability Model (GAM) Scenario 4 as documented in Hutchison (2017b). The selection of Scenario 4 as the basis for the desired future condition was made by the groundwater conservation districts in Groundwater Management Area 11 after the review of the results of seven simulations using the Groundwater Availability Model (Hutchison, 2017c).

In developing the initial seven simulations, a base pumping amount for each county-aquifer unit was developed. This base pumping amount was based on future pumping based on regional water plan data and the proposed Forestar project. The analysis in Hutchison (2017c) included three simulations that sequentially increased the pumping above the base amount and three simulations that sequentially decreased the pumping below the base amount to develop a practical analysis of the sensitivity of drawdown to various pumping amounts.

One of the uses of the updated Groundwater Availability Model documented in the main report will be to support the Joint Planning Process that leads to the adoption of desired future conditions by the groundwater conservation districts in Groundwater Management Area 11 and the calculation of the modeled available groundwater by TWDB. As part of the work associated with developing the updated Groundwater Availability Model, three technical memoranda appear in the Appendix of the report:

- Technical Memorandum 1: Pumping Sensitivity
- Technical Memorandum 2: Recharge Sensitivity
- Technical Memorandum 3: Calculation of Drawdown from Existing Modeled Available Groundwater Using Updated Groundwater Availability Model

This technical memorandum presents the results of a simulation that calculates the drawdown based on the existing modeled available groundwater using the updated Groundwater Availability Model.

3.0 Basis for Pumping Estimates

The simulation to calculate average drawdown for each county-model layer unit in the 27 counties of GMA 11 requires the development of a pumping input file that considers the existing modeled available groundwater, the input pumping from the calibrated model, and the output pumping from the calibrated model.

3.1 Existing Modeled Available Groundwater

The modeled available groundwater values for GMA 11 are documented in Wade (2017). The underlying input and output files for Scenario 4 are documented in Hutchison (2017b). Hutchison (2107b) documented output pumping in a file named *pumpout2070s4.dat* and is shown in Table 1.

Table 1. Summary of Pumping for Scenario 4 (AF/yr)

County	Layer 1 (Sparta)	Layer 2 (Weches confining Unit)	Layer 3 (Queen City)	Layer 4 (Reclaw confining Unit)	Layer 5 (Carrizo)	Layer 6 (Upper Wilcox)	Layer 7 (Middle Wilcox)	Layer 8 (Lower Wilcox)	Overall
Anderson	616	0	20,853	0	9,893	9,748	9,147	281	50,538
Angelina	687	0	1,102	0	28,764	3,486	0	0	34,039
Bowie	0	0	0	0	0	1,468	7,167	358	8,993
Camp	0	0	4,202	0	1,965	1,111	969	2	8,249
Cass	0	0	39,114	0	9,162	4,285	3,350	856	56,767
Cherokee	358	0	23,058	0	6,512	9,683	4,262	0	43,873
Franklin	0	0	0	0	1,894	1,256	6,328	301	9,779
Gregg	0	0	7,568	0	4,363	2,501	1,171	0	15,603
Harrison	0	0	10,323	0	6,378	2,163	2,011	268	21,143
Henderson	0	0	15,838	0	6,303	2,774	2,053	2,444	29,412
Hopkins	0	0	0	0	478	232	3,194	2,484	6,388
Houston	1,492	0	2,321	0	9,142	8,274	9,006	0	30,235
Marion	0	0	15,456	0	1,861	556	303	4	18,180
Morris	0	0	9,355	0	1,188	403	971	5	11,922
Nacogdoches	407	0	4,994	0	12,314	11,094	771	1	29,581
Panola	0	0	0	0	660	770	5,763	869	8,062
Rains	0	0	0	0	0	449	1,000	295	1,744
Rusk	0	0	60	0	6,923	5,153	8,727	0	20,863
Sabine	295	0	0	0	4,212	1,691	469	469	7,136
SanAugustine	204	0	8	0	1,129	651	9	0	2,001
Shelby	0	0	0	0	828	3,314	4,853	104	9,099
Smith	0	0	58,866	0	16,157	14,775	4,933	0	94,731
Titus	0	0	183	0	1,591	1,904	5,938	33	9,649
Trinity	613	0	0	0	2,216	0	0	0	2,829
Upshur	0	0	27,127	0	4,189	2,324	614	0	34,254
VanZandt	0	0	4,877	0	2,203	1,549	4,128	2,084	14,841
Wood	0	0	10,105	0	13,036	5,904	2,279	3	31,327
GMA 11	**4,672**	**0**	**255,410**	**0**	**153,361**	**97,518**	**89,416**	**10,861**	**611,238**

3.2 Updated Model Pumping (Input)

Based on the results of the pumping sensitivity documented in Technical Memorandum 1, the base pumping year is 2011 for the predictive simulations. The input pumping for 2011 organized by county-model layer unites was extracted from the calibrated model input file (*tr58_g.wel*) using the FORTRAN program *welin.exe*.

The program reads the grid file (*celllayercountyns.csv*) and a list of county names, county codes, and output file names. This file also contains a code to identify whether a county is in GMA 11 or not. The input file is read, pumping values are converted to AF/yr, and summed for each year in the county-model layer unit.

The output from the program consists of a summary file for 2011 pumping by county-model layer unit for all counties (*2011wellinAll.dat*) and for the 27 counties in GMA 11 (*2011welinGMA11.dat*). Individual files for each county are also written.

A summary of input pumping for the GMA 11 counties for 2011 is presented in Table 2.

Table 2. Summary of 2011 Input Pumping for GMA 11 Counties (AF/yr)

County	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
Anderson	0	55	0	733	0	3,811	1,315	233	183
Angelina	0	340	0	97	0	23,221	1,997	0	0
Bowie	0	0	0	0	0	0	2,370	650	142
Camp	0	0	0	178	0	758	386	273	2
Cass	0	0	0	587	0	1,496	807	228	157
Cherokee	0	223	0	1,101	0	4,614	4,979	14	0
Franklin	0	0	0	0	0	155	196	210	150
Gregg	0	0	0	262	0	1,770	1,062	436	0
Harrison	0	0	0	399	0	2,499	841	493	184
Henderson	0	0	0	762	0	4,492	1,813	1,313	1,419
Hopkins	0	0	0	0	0	7	241	905	2,075
Houston	0	799	0	219	0	962	6	0	0
Marion	0	0	0	172	0	918	260	140	3
Morris	0	0	0	142	0	536	213	535	4
Nacogdoches	0	266	0	330	0	11,213	4,766	326	1
Panola	0	0	0	0	0	431	298	2,058	727
Rains	0	0	0	0	0	0	365	159	331
Rusk	0	0	0	26	0	2,199	1,939	3,618	0
Sabine	0	55	0	0	0	522	217	61	61
SanAugustine	0	23	0	0	0	466	387	3	3
Shelby	0	0	0	0	0	711	946	1,847	33
Smith	0	0	0	1,226	0	7,366	6,686	2,163	0
Titus	0	0	0	0	0	533	417	1,226	13
Trinity	0	19	0	1	0	34	0	0	0
Upshur	0	0	0	1,448	0	3,337	1,906	452	0
VanZandt	0	0	0	265	0	1,257	1,027	2,327	972
Wood	0	0	0	1,792	0	3,707	1,649	611	4

3.3 Updated Model Pumping (Output)

During execution of the model, pumping in a cell is reduced if the pumping results in the head of the cell dropping below the bottom of the cell. The output of the model includes a cell-by-cell pumping amount that, therefore, may be different than the input value. The FORTRAN program *welout.exe* was written to extract the cell-by-cell values of pumping from the output file.

The program reads the grid file (*celllayercountyns.csv*) and a list of county names, county codes, and output file names. This file also contains a code to identify whether a county is in GMA 11 or not. The model output file is read, pumping values are converted to AF/yr, and summed for each year in the county-model layer unit.

The output from the program consists of a summary file for 2011 pumping by county-model layer unit for all counties (*2011welloutAll.dat*) and for the 27 counties in GMA 11 (*2011weloutGMA11.dat*). Individual files for each county are also written.

A summary of output pumping for the GMA 11 counties for 2011 is presented in Table 3.

Table 3. Summary of 2011 Output Pumping for GMA 11 Counties (AF/yr)

County	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
Anderson	0	45	0	733	0	3,733	1,315	233	183
Angelina	0	340	0	97	0	23,221	1,997	0	0
Bowie	0	0	0	0	0	0	2,370	649	142
Camp	0	0	0	53	0	671	386	273	2
Cass	0	0	0	554	0	1,496	807	228	157
Cherokee	0	223	0	1,056	0	4,596	4,979	14	0
Franklin	0	0	0	0	0	102	196	188	147
Gregg	0	0	0	232	0	1,700	1,062	436	0
Harrison	0	0	0	392	0	2,434	841	493	184
Henderson	0	0	0	762	0	2,991	1,794	1,304	1,419
Hopkins	0	0	0	0	0	3	241	828	1,699
Houston	0	795	0	219	0	962	6	0	0
Marion	0	0	0	172	0	918	260	140	3
Morris	0	0	0	119	0	536	213	535	4
Nacogdoches	0	266	0	330	0	10,655	4,766	326	1
Panola	0	0	0	0	0	0	298	2,058	727
Rains	0	0	0	0	0	0	216	154	331
Rusk	0	0	0	23	0	1,791	1,939	3,618	0
Sabine	0	55	0	0	0	498	217	61	61
SanAugustine	0	23	0	0	0	422	387	3	3
Shelby	0	0	0	0	0	147	926	1,847	33
Smith	0	0	0	1,225	0	7,314	6,686	2,163	0
Titus	0	0	0	0	0	313	417	1,199	13
Trinity	0	19	0	1	0	34	0	0	0
Upshur	0	0	0	1,448	0	3,337	1,906	452	0
VanZandt	0	0	0	265	0	872	1,027	2,018	972
Wood	0	0	0	1,643	0	3,644	1,649	611	4

3.4 Comparison of Input and Output Pumping

The difference in input and output pumping (calculated as input minus output) for the 27 GMA 11 counties is presented in Table 3. Table 4 presents the difference calculated as the difference divided by the input pumping times 100 to express the difference as a percentage.

Table 4. Difference Between Input and Output Pumping (AF/yr)

County	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
Anderson	0	10	0	0	0	78	0	0	0
Angelina	0	0	0	0	0	0	0	0	0
Bowie	0	0	0	0	0	0	0	1	0
Camp	0	0	0	125	0	87	0	0	0
Cass	0	0	0	33	0	0	0	0	0
Cherokee	0	0	0	45	0	18	0	0	0
Franklin	0	0	0	0	0	53	0	22	3
Gregg	0	0	0	30	0	70	0	0	0
Harrison	0	0	0	7	0	65	0	0	0
Henderson	0	0	0	0	0	1501	19	9	0
Hopkins	0	0	0	0	0	4	0	77	376
Houston	0	4	0	0	0	0	0	0	0
Marion	0	0	0	0	0	0	0	0	0
Morris	0	0	0	23	0	0	0	0	0
Nacogdoches	0	0	0	0	0	558	0	0	0
Panola	0	0	0	0	0	431	0	0	0
Rains	0	0	0	0	0	0	149	5	0
Rusk	0	0	0	3	0	408	0	0	0
Sabine	0	0	0	0	0	24	0	0	0
SanAugustine	0	0	0	0	0	44	0	0	0
Shelby	0	0	0	0	0	564	20	0	0
Smith	0	0	0	1	0	52	0	0	0
Titus	0	0	0	0	0	220	0	27	0
Trinity	0	0	0	0	0	0	0	0	0
Upshur	0	0	0	0	0	0	0	0	0
VanZandt	0	0	0	0	0	385	0	309	0
Wood	0	0	0	149	0	63	0	0	0

Please note that this comparison in this table identifies a potential limitation of the model relative to joint planning. Some of the pumping amounts in specific wells were reduced due to limited saturated thickness. If predictive simulations specify pumping amounts above those in the calibrated model, the reduction in pumping will persist. This limitation can be effectively addressed if the specific locations where reductions take place are distinguished from well locations where pumping is not reduced. This should be the practice in any simulations for joint planning.

Table 5. Difference Between Input and Output Pumping (Percent of Input)

County	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
Anderson	0.00	18.18	0.00	0.00	0.00	2.05	0.00	0.00	0.00
Angelina	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bowie	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.00
Camp	0.00	0.00	0.00	70.22	0.00	11.48	0.00	0.00	0.00
Cass	0.00	0.00	0.00	5.62	0.00	0.00	0.00	0.00	0.00
Cherokee	0.00	0.00	0.00	4.09	0.00	0.39	0.00	0.00	0.00
Franklin	0.00	0.00	0.00	0.00	0.00	34.19	0.00	10.48	2.00
Gregg	0.00	0.00	0.00	11.45	0.00	3.95	0.00	0.00	0.00
Harrison	0.00	0.00	0.00	1.75	0.00	2.60	0.00	0.00	0.00
Henderson	0.00	0.00	0.00	0.00	0.00	33.41	1.05	0.69	0.00
Hopkins	0.00	0.00	0.00	0.00	0.00	57.14	0.00	8.51	18.12
Houston	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Morris	0.00	0.00	0.00	16.20	0.00	0.00	0.00	0.00	0.00
Nacogdoches	0.00	0.00	0.00	0.00	0.00	4.98	0.00	0.00	0.00
Panola	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00
Rains	0.00	0.00	0.00	0.00	0.00	0.00	40.82	3.14	0.00
Rusk	0.00	0.00	0.00	11.54	0.00	18.55	0.00	0.00	0.00
Sabine	0.00	0.00	0.00	0.00	0.00	4.60	0.00	0.00	0.00
SanAugustine	0.00	0.00	0.00	0.00	0.00	9.44	0.00	0.00	0.00
Shelby	0.00	0.00	0.00	0.00	0.00	79.32	2.11	0.00	0.00
Smith	0.00	0.00	0.00	0.08	0.00	0.71	0.00	0.00	0.00
Titus	0.00	0.00	0.00	0.00	0.00	41.28	0.00	2.20	0.00
Trinity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Upshur	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
VanZandt	0.00	0.00	0.00	0.00	0.00	30.63	0.00	13.28	0.00
Wood	0.00	0.00	0.00	8.31	0.00	1.70	0.00	0.00	0.00

3.5 Factors Applied to 2011 Pumping to Achieve Existing MAG Pumping

The base pumping file for the predictive simulation is based multiplication factors applied to the 2011 pumping from the calibrated model. The MAG pumping (previously presented in Table 1) divided by the output 2011 pumping from the calibrated model (previously presented in Table 3) yields these factors. The Excel spreadsheet *SumPumpFac.xlsx* has five sheets:

- MAG – modeled available groundwater values from Table 1
- ngWelin - 2011 input pumping from the calibrated model from Table 2
- ngWelout – 2011 output pumping from the calibrated model from Table 3
- PredFac(in) – MAG pumping divided by 2011 input pumping
- PredFac(out) – MAG pumping divided by 2011 output pumping

The factors calculated from the input pumping (PredFac(in)) are presented in Table 6.

Table 6. Pumping Adjustment Factors

County	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
Anderson	1.00	11.20	1.00	28.45	1.00	2.60	7.41	39.26	1.54
Angelina	1.00	2.02	1.00	11.36	1.00	1.24	1.75	1.00	1.00
Bowie	1.00	1.00	1.00	1.00	1.00	1.00	0.62	11.03	2.52
Camp	1.00	1.00	1.00	23.61	1.00	2.59	2.88	3.55	1.00
Cass	1.00	1.00	1.00	66.63	1.00	6.12	5.31	14.69	5.45
Cherokee	1.00	1.61	1.00	20.94	1.00	1.41	1.94	304.43	1.00
Franklin	1.00	1.00	1.00	1.00	1.00	12.22	6.41	30.13	2.01
Gregg	1.00	1.00	1.00	28.89	1.00	2.46	2.35	2.69	1.00
Harrison	1.00	1.00	1.00	25.87	1.00	2.55	2.57	4.08	1.46
Henderson	1.00	1.00	1.00	20.78	1.00	1.40	1.53	1.56	1.72
Hopkins	1.00	1.00	1.00	1.00	1.00	68.29	0.96	3.53	1.20
Houston	1.00	1.87	1.00	10.60	1.00	9.50	1379.00	1.00	1.00
Marion	1.00	1.00	1.00	89.86	1.00	2.03	2.14	2.16	1.33
Morris	1.00	1.00	1.00	65.88	1.00	2.22	1.89	1.81	1.25
Nacogdoches	1.00	1.53	1.00	15.13	1.00	1.10	2.33	2.37	1.00
Panola	1.00	1.00	1.00	1.00	1.00	1.53	2.58	2.80	1.20
Rains	1.00	1.00	1.00	1.00	1.00	1.00	1.23	6.29	0.89
Rusk	1.00	1.00	1.00	2.31	1.00	3.15	2.66	2.41	1.00
Sabine	1.00	5.36	1.00	1.00	1.00	8.07	7.79	7.69	7.69
SanAugustine	1.00	8.87	1.00	1.00	1.00	2.42	1.68	3.00	0.00
Shelby	1.00	1.00	1.00	1.00	1.00	1.16	3.50	2.63	3.15
Smith	1.00	1.00	1.00	48.01	1.00	2.19	2.21	2.28	1.00
Titus	1.00	1.00	1.00	1.00	1.00	2.98	4.57	4.84	2.54
Trinity	1.00	32.26	1.00	0.00	1.00	65.18	1.00	1.00	1.00
Upshur	1.00	1.00	1.00	18.73	1.00	1.26	1.22	1.36	1.00
VanZandt	1.00	1.00	1.00	18.40	1.00	1.75	1.51	1.77	2.14
Wood	1.00	1.00	1.00	5.64	1.00	3.52	3.58	3.73	0.75

4.0 Parameters and Assumptions

4.1 Files Unchanged from Calibrated Model

Files that contain model input parameters related to the model grid and aquifer parameters were the same as the files used in the calibrated model as shown in Table 7.

Table 7. Predictive Model Files Unchanged from Calibrated Model

File Name	File Date	Description
findd.dis	4/10/2020	Spatial Discretization
findd.ims	4/10/2020	Solver Parameters
finddd.npf	4/10/2020	Node Property Flow
tr58_g.kx	4/10/2020	Horizontal Hydraulic conductivity
tr58_g.kz	4/10/2020	Vertical Hydraulic Conductivity
tr58_g.ss	4/10/2020	Specific Storage
tr58_g.sy	4/10/2020	Specific Yield

4.2 Time Discretization and Storage

The predictive simulation was run for the period 2014 to 2080, a total of 67 annual stress periods. The calibrated model included a steady-state stress period at the beginning of the simulation. Thus, the TDIS file was modified to reflect 67 annual stress periods and named *finddd.tdis*. The specification of steady state or transient stress period in MODFLOW 6 is contained in the STO file. This file was updated and named *finddd.sto.*

4.3 Groundwater Pumping (WEL Package)

The WEL package for this simulation was developed by the FORTRAN program *makescenwel.exe.* The program reads the grid file (*celllayercountyns.csv*) and the pumping factors previously presented in Table 6 (*ScenPumpFac.csv*). The 2011 pumping file used for the pumping sensitivity analysis documented in Technical Memorandum 1 is opened (*pump2011.wel*). The simulation WEL file is opened (*finddd.wel*). The 2011 file is read line by line, appropriate factors are applied to the pumping amount based on the county-model layer unit, and the results are written to the simulation WEL file.

As a quality control check, the FORTRAN program *welincheck.*exe reads the resulting simulation WEL file (*finddd.wel*) and calculates the total pumping for each county-model layer unit. Results are written in two files, one for all counties (*2011welinAll.dat*) and one for the 27 GMA 11 counties (*2011welinGMA11.dat*). Results were saved to an Excel file (*CrossCheck.xlsx*) and a summary comparison with the existing modeled available groundwater is presented in Figure 1.

Please note that the comparison yields the conclusions that all simulation input values are within rounding error of the existing modeled available groundwater values with two notable exceptions. Titus County (Layer 4) and Houston County (Layer 8) have a modeled available groundwater value greater than zero, but the calibrated model has no wells in these county-model layer units.

The modeled available groundwater value in the Queen City Aquifer in Titus County is small (183 AF/yr), and a well can be added during the joint planning process to accommodate this pumping, if requested.

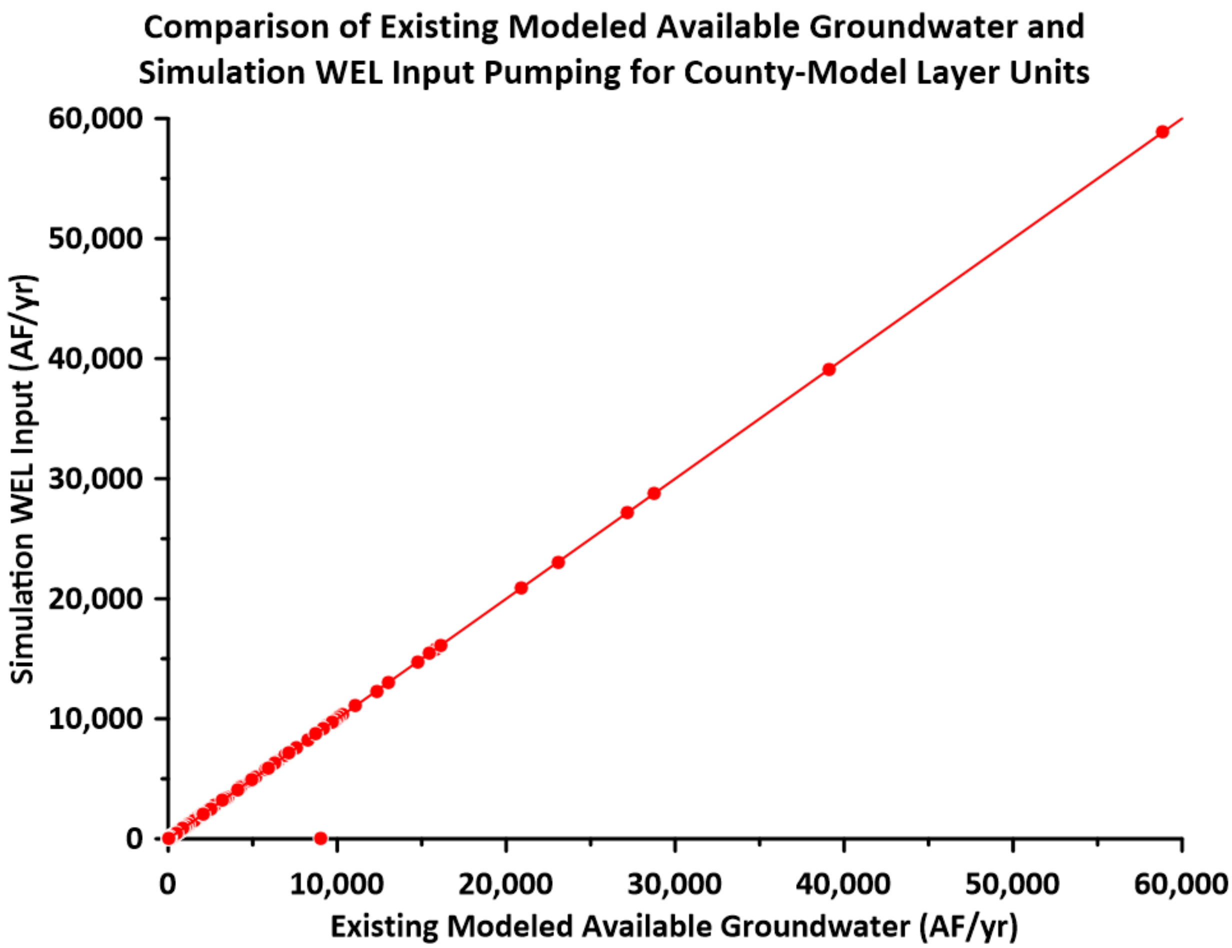


Figure 1. Comparison of MAG and Simulation WEL Input

The modeled available groundwater for the Middle Wilcox Aquifer in Houston County is 9,006 AF/yr and is associated with the proposed Forestar project. This pumping was specifically added in the last round of joint planning. Because these wells do not currently exist, they are not included in the updated calibrated model. During joint planning, the wells associated with the Forestar project will be added and included.

4.4 Evapotranspiration (EVT Package)

The FORTRAN program *makeevt.exe* was written to develop a model input file for evapotranspiration. Inspection of the calibrated model input file for evapotranspiration (*tr58_g.evt*) shows that the same evapotranspiration parameters were used for each stress period of the calibration period (1980 to 2013). The program simply extracts the first stress period of the calibration period and writes it to a new file named *finddd.evt*.

4.5 General Head Boundaries (GHB Package)

The FORTRAN program *makeghb.exe* was written to develop a model input file for the general head boundaries, which were implemented to simulate the effects of overlying formations that are not formally part of the model domain.

Inspection of the calibrated model input file for general head boundaries (*tr58_g.ghb*) shows that the same general head boundary parameters were used for each stress period of the calibration period (1980 to 2013). The program simply extracts the first stress period of the calibration period and writes it to a new file named *finddd.ghb*.

4.6 Recharge (RCH Package)

The recharge input file *tr58_g.rch* contains the cell-by-cell recharge amounts for each stress period of the calibrated model (1980 to 2013). Recharge was implemented by defining a steady-state recharge (applied to stress period 1) and applying a stress period-specific factor to increase or decrease the recharge for each stress period. The first stress period of recharge was extracted from the calibrated model input file using a FORTRAN program named *makerch.exe*. The output file saved as *finddd.rch.*

4.7 River (RIV Package)

The calibrated model simulated surface water-groundwater interactions with the River (RIV) package specified in the file *tr58_g.rch*. Inspection of the input file yielded the conclusion that RIV head values changed slightly for each stress period. River conductance and bottom elevations remained the same in all stress periods.

The FORTRAN program *makeriv.exe* was written to extract the first stress period of RIV parameters for the predictive simulations and hold them constant for all stress periods. The output file from this program is *finddd.riv.*

4.8 Other Input Files

Other files that were developed for these predictive simulations are summarized in Table 8.

Table 8. Other Input Files Summary

File Name	Description	Modification
finddd.ic6	Starting Heads	Specified 2013 heads as starting heads
mfsim.nam	Global Simulation Name File	Udated tdis and ims file names
finddd.nam	Scenario Name File	Updated scenario file names
finddd.oc6	Output Control	Updated scenario-specific output files and adjusted number of stress periods

5.0 Methods and Results

5.1 Post-Processing of MODFLOW 6 Results

A FORTRAN program named *getdd.exe* was written to extract groundwater elevation data from the model output files assuming a base year for the drawdown calculation as 2013 (the last year of the calibrated model). For comparative purposes, the program was modified (*getdd2000.exe)* to extract results with a base year for the drawdown calculations as 2000 to facilitate comparison with the existing desired future conditions.

The program reads a list of county names and codes (*countynamelist.dat*) and a grid file of cell number, layer, and county code (*celllayercountyns.csv*). The program counts the number of cells in each county-model layer unit and reports the results in a file named *cellcount.dat.* The 27 counties within Groundwater Management Area 11 and the number of cells in each layer of those counties is presented in Table 9. Based on Table 9, there are 213 county-model layer units with at least one active model cell.

The program then reads the binary output files from the calibrated model (*tr58g.hds*) and the binary output file of the predictive simulation (*finddd.hds*). The program then calculates the drawdown for each cell with a starting date of 2013 (the last year of the calibrated model), or a starting date of 2000, depending on the version. Drawdowns for each county-model layer unit are then summed, and the average drawdown for each county-model layer unit is calculated as the summed drawdown for that unit divided by the number of cells in that unit.

The program then reads a list of file names for each county-model layer unit for the 27 counties in Groundwater Management Area 11 and writes annual drawdowns for each layer to the county-based output files for the scenario.

Summary results are written for both post-processors report include drawdown results for 2070 (*dd2070.dat*) and 2080 (*dd2080.dat*). The 2070 results are comparable to the last round of desired future conditions, the 2080 results are useful to understand the drawdowns that will be calculated for the next round of desired future conditions.

Table 9. Cell Counts for Each County-Model Layer Unit

County	Number of Model Cells in Each County-Model Layer Unit									Number of Active Layers
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	
Anderson	19,582	106	359	3,276	3,455	1,932	1,639	1,203	1,087	9
Angelina	552	3,828	1,312	865	865	865	865	865	865	9
Bowie	6,382	0	0	0	0	0	1,312	1,034	522	4
Camp	2,674	0	0	392	371	387	451	233	201	7
Cass	12,311	5	61	3,249	1,843	716	1,524	1,221	988	9
Cherokee	14,757	603	676	3,030	2,404	1,885	1,414	1,096	1,059	9
Franklin	2,136	0	0	0	3	177	607	320	170	6
Gregg	4,065	0	0	414	557	928	465	290	274	7
Harrison	10,279	0	2	413	995	621	2,226	1,845	1,311	8
Henderson	11,104	0	9	1,445	1,072	701	1,071	1,471	1,540	8
Hopkins	4,213	0	0	0	1	23	500	634	839	6
Houston	7,210	5,267	2,187	2,455	1,424	1,238	1,237	1,237	1,237	9
Marion	7,315	1	5	899	1,017	336	1,214	694	545	9
Morris	3,694	0	6	484	509	169	344	636	317	8
Nacogdoches	13,147	1,630	1,706	1,456	1,595	1,390	1,787	1,094	983	9
Panola	12,656	0	0	0	1	4	996	3,921	1,269	6
Rains	3,109	0	0	0	0	0	56	246	864	4
Rusk	13,447	7	14	191	760	1,842	3,677	1,311	943	9
Sabine	3,513	2,242	795	398	566	566	1,121	658	577	9
SanAugustine	2,534	1,511	770	385	611	792	836	623	594	9
Shelby	10,606	8	3	1	2	42	2,558	2,546	1,037	9
Smith	12,534	331	837	3,653	2,053	1,234	1,107	964	947	9
Titus	6,547	0	0	32	221	245	1,096	876	559	7
Trinity	0	4,124	1,225	713	713	713	713	713	713	8
Upshur	6,347	20	49	1,905	1,142	928	636	595	595	9
VanZandt	9,253	0	7	268	293	384	1,940	1,013	1,723	8
Wood	9,934	77	215	1,681	1,070	839	1,516	1,046	740	9

5.2 Results

The summary results from the post-processors were gathered into an Excel spreadsheet named *ddcompare.xlsx*. The first tab (Current DFC) is the drawdown that was the basis of the current desired future condition. The next three tabs represent the following:

- dd2070(2013) are the drawdowns for each county-model layer unit in 2070 with a base year of 2013
- dd2070(2000) are the drawdowns for each county-model layer unit in 2070 with a base year of 2000
- dd2080(2013) are the drawdowns for each county-model layer unit in 2080 with a base year of 2013

The last tab is named CrossCheck and includes the results from the previous four tabs in a format that facilitates plotting. Also, differences between results are included in columns G through K.

Figure 2 presents a comparison of drawdowns in 2070 using 2000 as a base year. The x-axis are the drawdowns associated with the current desired future condition (i.e. based on the old GAM) and the y-axis are the drawdowns calculated from the new GAM using the same modeled available groundwater values (i.e. the pumping from the last round of joint planning). As detailed above, some county-model layer units have slightly different pumping than the modeled available groundwater, but they are isolated cases and do not affect the main conclusions of the comparison

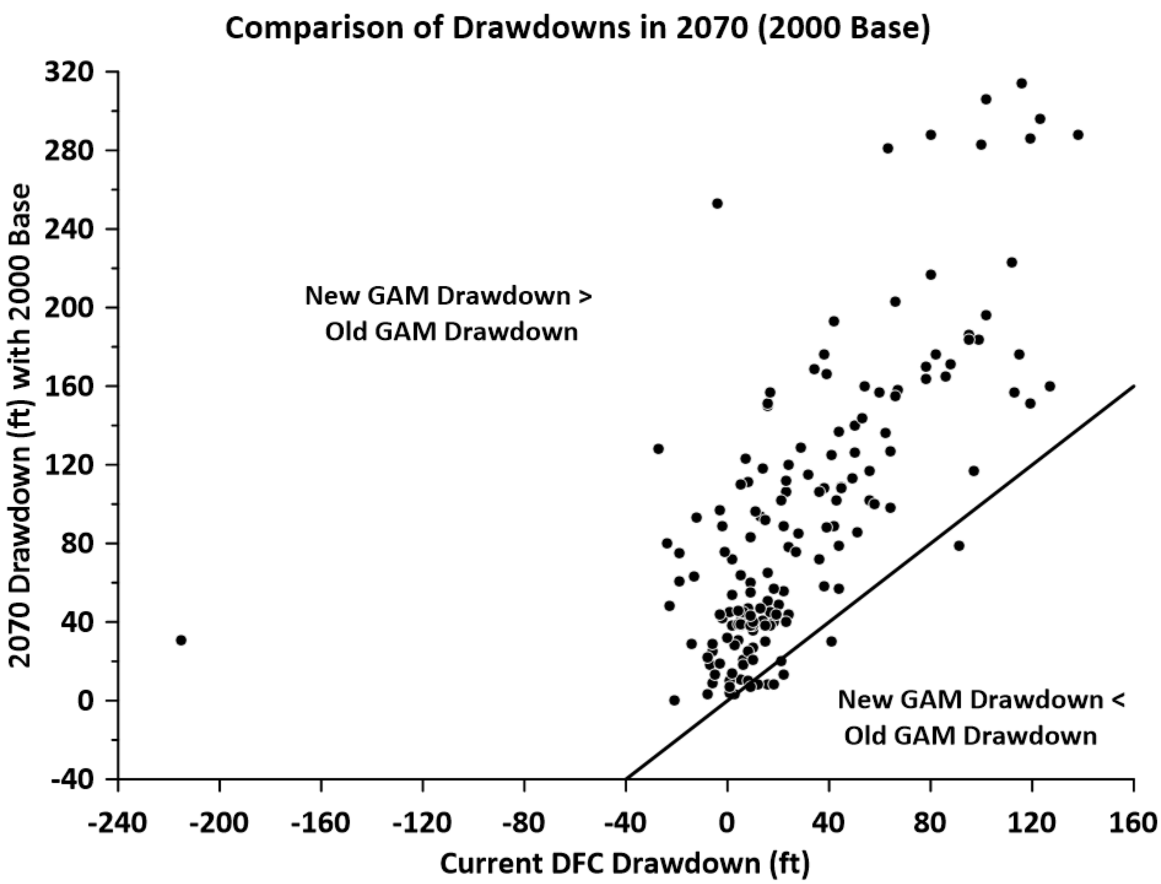


Figure 2. Comparison of Existing DFC Drawdown and Drawdowns from New GAM

Please note that on Figure 2, a one-to-one line of drawdowns is presented. Above and to the left of that line, the new GAM predicts greater drawdown than the old GAM. Below and to the right of that line, the new GAM predicts less drawdown than the old GAM. Based on these results, the new GAM will generally predict greater drawdown than the old GAM. In many cases, the difference is substantial. This will be an important topic of discussion for the groundwater conservation districts in Groundwater Management Area 11.

Please note that the current DFC drawdown includes several county-model layer units with negative drawdowns, or predicted groundwater elevation recoveries, from 2000 to 2070. An extreme example of this is the predicted recovery of 215 feet in Hopkins County in old GAM layer 8 (new GAM layer 9) as documented in Hutchison (2017b, page 5). The underlying issue of the negative drawdowns, as described in Hutchison (2017b), appears to be some combination of high recharge estimates in the old GAM and the inability of groundwater to move from the outcrop areas to the downdip areas. The new GAM effectively addresses those issues as documented in Technical Memoranda 1 and 2.

In the current round of joint planning, TWDB has requested that drawdowns be calculated through the year 2080 to facilitate the use of the modeled available groundwater results for the Regional Planning process. As described in Technical Memoranda 1 and 2, the new GAM results suggest a near-equilibrium state is reached with constant pumping and/or constant recharge. Figure 3 presents a comparison of drawdowns for each county-model layer unit in 2070 and 2080 when 2013 is used as a base year for the drawdown calculation. Based on these results, it appears that there is not significant drawdown from 2070 to 2080, which is the expected result after considering the findings of Technical Memoranda 1 and 2. This conclusion suggests that the new GAM simulates a system that will reach near-equilibrium conditions in a few to several years, even with relatively large increases in future pumping.

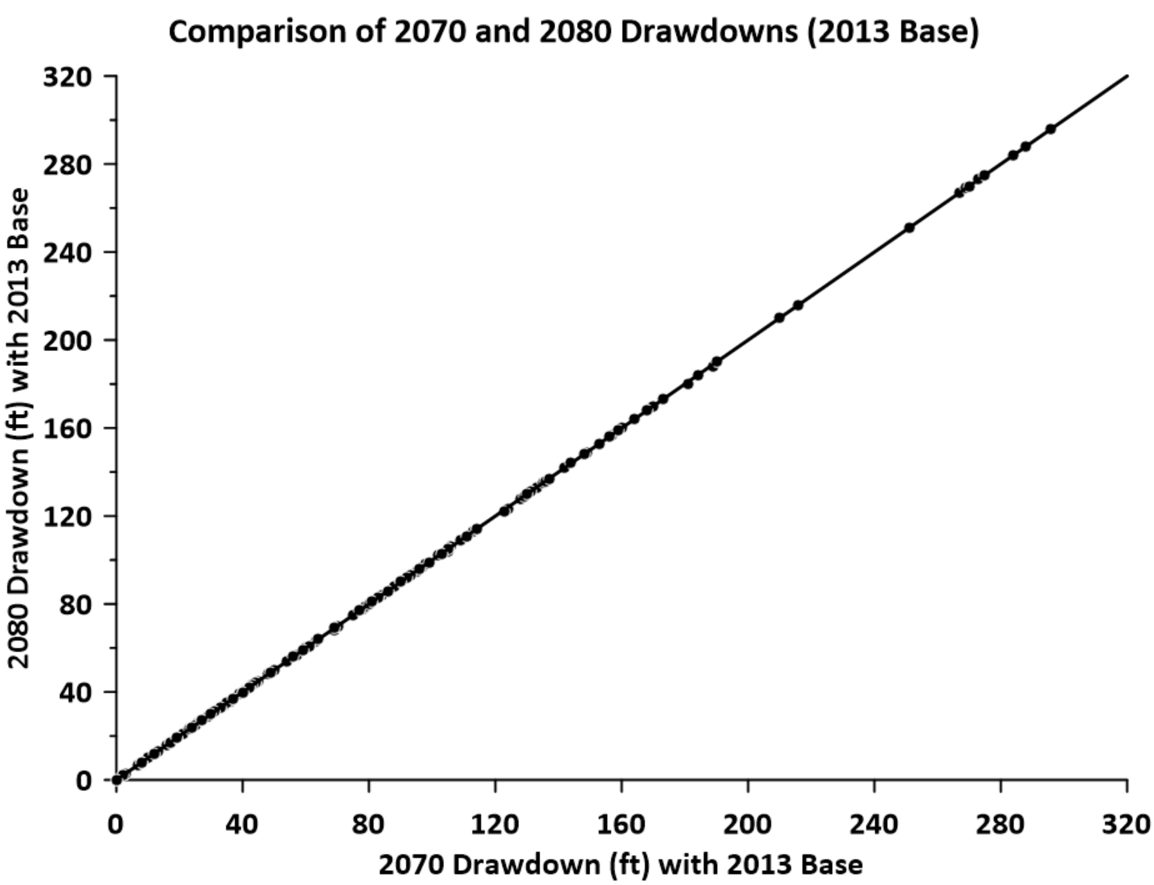


Figure 3. Comparison of 2070 and 2080 Drawdowns (2013 Base)

6.0 Limitations

The objective of these simulations was to provide a practical basis for selecting a base pumping year for simulations focused on joint planning. As a result, there are some limitations to the results given the regional nature of the objective:

- The scenarios considered only increases and decreases in overall pumping to assess general sensitivity of pumping on average drawdown. For this analysis, there were no attempts to understand sensitivity on a finer scale (i.e. varying pumping on an individual county-model layer unit).
- The scenarios did not attempt to distinguish the relative effect of "local" pumping (pumping within the county-model layer unit) versus neighboring pumping in adjacent county-model layer units.
- The simulation failed to converge in stress period 1. The standard output noted that a cell in Titus County in layer 8 consistently had a maximum head change greater than the user-specified tolerance. Convergence was achieved in all other stress periods. To avoid this from occurring in the future, the pumping could be increased over a period of years, or the number of time steps could be increased for the first stress period.
- The old GAM may have been the basis for some of the large pumping increases in the Sparta and Queen City aquifers associated with the first and second round of joint planning. The new GAM shows greater drawdowns than the old GAM. The capability of the Sparta and Queen City aquifers, as well as the various subdivisions of the Carrizo-Wilcox aquifer needs to be reviewed by the groundwater conservation districts of Groundwater Management Area 11. Specific issues related to the impact of recharge on changes in groundwater elevations, the ability of water to move from the outcrop areas to the downdip areas, and the impact of larger drawdowns have always been issues of interest that have been influenced by the limitations of the old GAM. These results from the new GAM may provide additional insight and provide for improved planning and management of the groundwater in the area.

7.0 References

Hutchison, W.R., 2017a. Desired Future Condition Explanatory Report: Carrizo-Wilcox/Queen City/Sparta Aquifers for Groundwater Management Area 11. Report submitted to Texas Water Development Board, January 24, 2017, 445p.

Hutchison, W.R., 2017b. Use of Predictive Simulation Results from Scenario 4 in Desired Future Conditions for Sparta, Queen City, and Carrizo-Wilcox Aquifer. GMA 11 Technical Memorandum 16-02. Report submitted to Groundwater Management Area 11. January 24, 2017, 15p.

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Wade, S.C., 2017. GAM Run 17-024 MAG: Modeled Available Groundwater for the Carrizo-Wilcox, Queen City, and Sparta Aquifers in Groundwater Management Area 11. Texas Water Development Board, Groundwater Division, Groundwater Availability Modeling Department, June 19, 2017, 24p.

Technical Memorandum 4

Comparison of Input and Output Pumping: Previous Groundwater Availability Model and Updated Groundwater Availability Model

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November 25, 2020

Technical Memorandum 4

Professional Engineer and Professional Geoscientist Seals

This report was prepared by William R. Hutchison, Ph.D., P.E., P.G., who is licensed in the State of Texas as follows:

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- Engineering Firm Registration No. 14526
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Table of Contents

Appendices

1.0 Background

Comment 19 from the Texas Water Development Board was:

> ***Page 10, Section 2.7 WEL Package, first full paragraph, sentence 3****: The text states 'the previous model data represents pumping from 1980 through 2005.' However, the previous GAM represents pumping from 1980 through 1999 in stress periods 6 through 25. Stress periods 1 through 5 represent a transient adjustment period to go from predevelopment to 1980 and were not calibration stress periods (Section 6.2.3 Model Simulation Periods in previous GAM Report). Please clarify this discrepancy in the report.*

This technical memorandum documents a comparison of the input and output pumping from the existing Groundwater Availability Model and the input and output pumping from the updated Groundwater Availability Model that is the subject of the comment on the draft report.

As described in Section 2.7 of the main report, initial attempts to calibrate the model using pumping estimates from TWDB were unsuccessful. Data from the previous Groundwater Availability Model were used. Section 2.7 of the main report provides an overview of how previous Groundwater Availability Model estimates were used and extended to the later years of the calibration period. This Technical Memorandum provides more detail on a comparison of the pumping estimates used in the previous Groundwater Availability Model and the pumping estimates used in this updated Groundwater Availability Model

2.0 Previous Groundwater Availability Model

Hutchison (2017) extracted input and output pumping from the previous Groundwater Availability Model as part of the joint planning process for Groundwater Management Area 11. Input and output pumping were extracted and reported because in the previous GAM, some model cells went dry during the simulation period (1975 to 1999). This causes all pumping in that cell to be reset to zero. Thus, in some counties, the input pumping is higher than the output pumping. The output pumping is the basis for TDWB to set the Modeled Available Groundwater.

The files are organized and named based on whether they contain input or output pumping ("pumpin" or "pumpout") and include the name of the county. A total of 54 files are included with file dates of 8/5/2015. The files are zipped into a single file named oldGAMinout.zip.

For each file, the first column is the year, the next 8 columns represent the pumping from the model layer, and the final column is the total of all the individual layer pumping (i.e. total county pumping).

3.0 Updated Groundwater Availability Model

The input and output pumping from the updated GAM were extracted from model files provided by GSI-Environmental. The updated GAM uses MODFLOW 6 and the upstream weighting option, in some cases, the input pumping is reduced in order to avoid dry cells. This can result in output pumping that is less than the input pumping.

3.1 Input Pumping

The input pumping was extracted with the FORTAN code *welinfinalnew.exe* that was written for this project. Source code for the code is provided in Appendix A of this Technical Memorandum.

The code:

1. Declares arrays in lines 10 to 13
2. Initializes the array with county and layer pumping for each year in lines 17 to 23
3. Reads the model grid file (celllayercountns.csv) in lines 25 to 29
4. Reads a list of output file names (countynamelist.dat) in lines 31 to 34
5. Reads the pumping input file (tr58_g_final_model_gwv.wel) in lines 36 to 56
6. Fills the pumping array (indexed by layer, county, and stress period) in lines 58 to 69
7. Writes a 2013 summary file (2013pumping.dat) in lines 71 to 75
8. Writes the input pumping to the 56 individual county files in lines 77 to 84. These files contain pumping from each individual model layer.
9. Writes a summary file (newinppumpsum.dat) for all years and all counties (one column per county) in lines 86 to 91.

All files associated with the input pumping of the updated GAM (source code, executable, input files and output files) are zipped in a file named *NewGAMPumpIn.zip* and included with this Technical Memorandum.

3.2 Output Pumping

The output pumping was extracted with the FORTAN code *getpumpout.exe* that was written for this project. Source code is provided in Appendix B of this Technical Memorandum.

The code:

1. Declares arrays in lines 8 to 14
2. Opens the cell-by-cell output file (tr58_g_final_model_gwv.cbb) in line 15
3. Opens a header file (header.dat) that is an output file for quality control purposes in line 16
4. Opens a file (pumpout.dat) where all pumping is output for quality control purposes in line 17
5. Reads the model grid file (celllayercountyns.csv) in lines 19 to 23
6. Reads a list of output file names (countynamelist.dat) in lines 25 to 28

7. Reads a file (tsnum.dat) that lists the number of time steps in each stress period in lines 30 to 33
8. Reads the cell-by-cell file in lines and fills the county-based pumping array each stress period 35 to 78
10. Writes the output pumping to the 56 individual county files in lines 80 to 88. These files contain pumping from each individual model layer.
9. Writes a summary file (countysum.dat) for all years and all counties (one column per county) in lines 90 to 94

All files associated with the output pumping of the updated GAM (source code, executable, input files and output files) are zipped in a file named. The cell-by-cell file is not included in the zip file but is included in the directory.

4.0 Pumping Comparisons

Total pumping for each county were combined into a single file with a tab for the county pumping (*oldGAMnewGAMinoutpump.xlsx*) with a tab for each set of results:

- New-in has total input county pumping for the updated GAM
- New-out has the total output county pumping for the updated GAM
- Old-in has the total input county pumping for the existing GAM
- Old-out has the total output county pumping for the existing GAM

These results were then plotted on comparison hydrographs and are presented in Appendix C.

As shown in the hydrographs, there are several instances where the input pumping of the existing GAM is higher than the output pumping in the existing GAM. This occurs because of dry cells that cause the model to shut off pumping. There are also instances where the input pumping of the updated GAM is higher than the output pumping in the updated GAM. This occurs when the upstream weighting calculations in the model cause pumping reductions to avoid dry cells.

It is evident from the hydrographs, however, that the comparison between the output pumping of the existing GAM and the updated GAM are consistent.

5.0 References

Hutchison, W.R., 2017. Initial Simulations for Sparta, Queen City, and Carrizo-Wilcox Aquifers. GMA 11 Technical Memorandum 15-01, January 21, 2017, 109p.

Appendix A

Source Code for *welinfinalnew.exe*

```
! welinfinalnew.exe
!
! reads grid file
! reads county list file
! reads wel input file
! calculates county-layer pumping totals

! declare arrays

dimension icounty(637536),ilay(637536)
dimension ilcounty(56)
dimension pumpin(34,637536),copump(10,56,34)
character*40 text,countyname(56),txt1,txt2,fnam(56)

! initialize arrays

do 10 k1=1,10
do 11 k2=1,56
do 12 k3=1,34
copump(k1,k2,k3)=0
12 continue
11 continue
10 continue

open (1,file='celllayercountyns.csv')
read (1,*) text
do 100 k=1,637536
read (1,*) kk,ilay(k),icounty(k)
100 continue

open (2,file='countynsamelist.dat')
do 200 k=1,56
read (2,*) ilcounty(k),countyname(k),fnam(k)
200 continue

open (3,file='tr58_g_final_model_gwv.wel')
open (4,file='weltxt.dat')
do 300 k=1,8
read (3,410) text
write (4,410) text
410 format (a40)
300 continue

isp=1
301 read (3,*,err=398,end=399) txt1,txt2
if (txt1.eq.'END') isp=isp+1
```

```
if (txt1.ne.'BEGIN'.and.txt1.ne.'END') then
read (txt1,*) nn
read (txt2,*) tpump
pumpin(isp,nn)=pumpin(isp,nn)+tpump
write (4,411) isp,nn,pumpin(isp,nn)
end if
398 continue
411 format (2i10,f15.6)
goto 301
399 continue

do 500 isp=1,34
do 501 nn=1,637536
pumpaf=-pumpin(isp,nn)*365/43560
do 502 ic=1,56
if (ilcounty(ic).eq.icounty(nn)) then
copump(ilay(nn),ic,isp)=copump(ilay(nn),ic,isp)+pumpaf
copump(10,ic,isp)=copump(10,ic,isp)+pumpaf
end if
502 continue

501 continue
500 continue

open (6,file='2013pumping.dat')
do 600 ico=1,56
write (6,610) ico,ilcounty(ico),countyname(ico),(copump(il,ico,34),il=1,9)
610 format (2i10,1x,a15,1x,9f10.0)
600 continue

do 700 ico=1,56
open (7,file=fnam(ico))
do 701 isp=1,34
iyr=isp+1979
write (7,710) iyr,(copump(il,ico,isp),il=1,9)
710 format (i10,9f10.0)
701 continue
700 continue

open (8,file='newinpumpsum.dat')
do 800 isp=1,34
iyr=isp+1979
write (8,810) iyr,(copump(10,ico,isp),ico=1,56)
810 format (i10,56f10.0)
800 continue
```

```
stop
end
```

Appendix B

Source Code for *weloutfinalnew.exe*

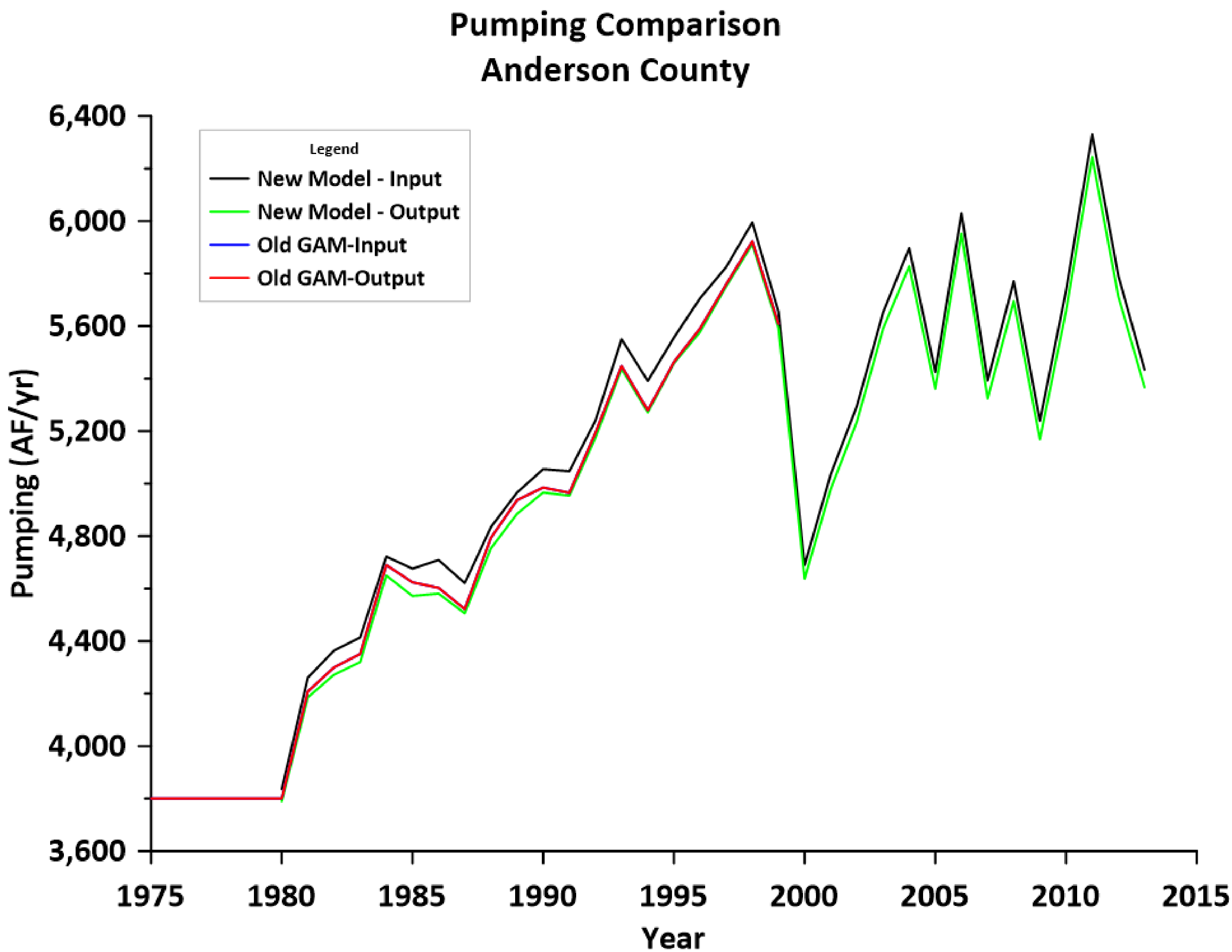
```
! getpumpout.exe

! reads cbb file (MODFLOW 6)
! writes pumping summary

! declare arrays

dimension id1(637536),id2(637536)
character*16 text,txt1id1,txt2id1,txt1id2,txt2id2,auxtxt(400)
double precision delt,pertim,totim
double precision data(4338894),data2d(4,4338894)
dimension icounty(637536),ilay(637536),copump(10,56,34)
dimension ilcounty(56),itsnum(34)
character*40 countyname(56),fnam(56)
open (1,file='tr58_g_final_model_gwv.cbb',form='binary')
open (2,file='header.dat')
open (3,file='pumpout.dat')

open (11,file='celllayercountyns.csv')
read (11,*) text
do 1100 k=1,637536
read (11,*) kk,ilay(k),icounty(k)
1100 continue

open (12,file='countynsamelist.dat')
do 1200 k=1,56
read (12,*) ilcounty(k),countyname(k),fnam(k)
1200 continue

open (13,file='tsnum.dat')
do 1300 isp=1,34
read (13,*) itsnum(isp)
1300 continue

kk=0
100 read (1,end=199) kstp,kper,text,ndim1,ndim2,nd3
kk=kk+1
ndim3=-nd3
read (1) imeth,delt,pertim,totim
write (2,210) kstp,kper,text,ndim1,ndim2,ndim3,imeth,delt,pertim,totim
210 format (2i10,1x,a16,1x,4i10,3f15.4)

if (imeth.eq.1) read (1) (data(j),j=1,ndim1)

if (imeth.eq.6) then
read (1) txt1id1
```

```
read (1) txt2id1
read (1) txt1id2
read (1) txt2id2
read (1) ndat
read (1) (auxtxt(n),n=1,ndat-1)
read (1) nlist
if (ndat.eq.1) write (2,211) txt1id1,txt2id1,txt1id1,txt2id2,ndat,nlist
if (ndat.eq.2) write (2,212) txt1id1,txt2id1,txt1id1,txt2id2,ndat,nlist,auxtxt(1)
211 format (4a16,i10,i10)
212 format (4a16,i10,i10,a16)
read (1) ((id1(n),id2(n),(data2d(i,n),i=1,ndat)),n=1,nlist)
if (kk.eq.4) then
do 120 n=1,nlist
if (data2d(1,n).ne.0.and.kstp.eq.itsnum(kper)) then
write (3,310) kper,text,id1(n),data2d(1,n)
pumpaf=-data2d(1,n)*365/43560
do 121 ic=1,56
if (ilcounty(ic).eq.icounty(id1(n))) then
copump(ilay(id1(n)),ic,kper)=copump(ilay(id1(n)),ic,kper)+pumpaf
copump(10,ic,kper)=copump(10,ic,kper)+pumpaf
end if
121 continue
end if
310 format (i10,1x,a16,i10,f15.4)
120 continue
end if
end if
if (kk.eq.8) kk=0
goto 100
199 continue
do 700 ico=1,56
open (7,file=fnam(ico))
do 701 isp=1,34
iyr=isp+1979
write (7,710) iyr,(copump(il,ico,isp),il=1,10)
710 format (i10,10f10.0)
701 continue
close (7)
700 continue
open (8,file='countysum.dat')
do 800 isp=1,34
write (8,810) isp+1979,(copump(10,ico,isp),ico=1,56)
```

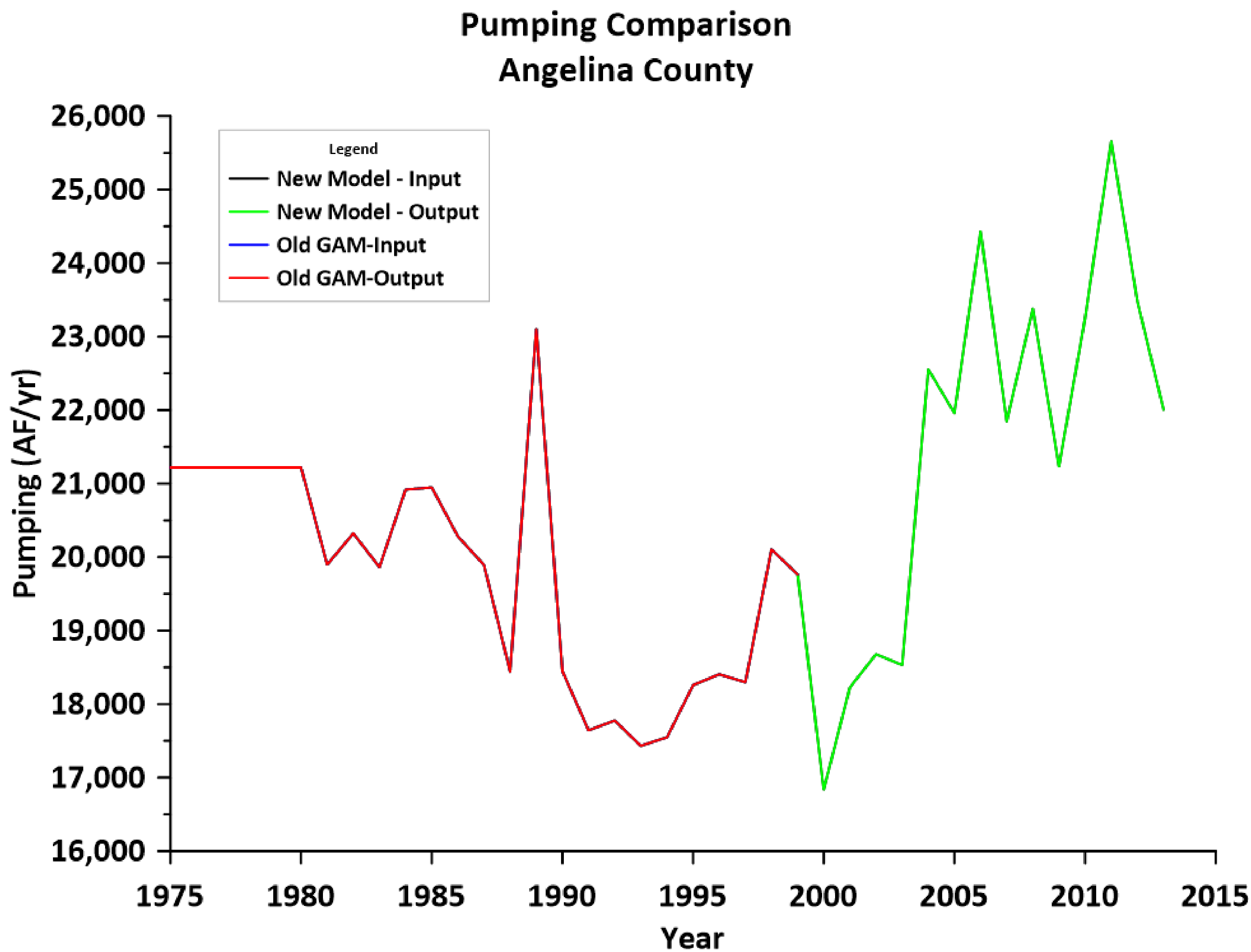
```
810 format (i10,56f10.0)
800 continue


stop
end
```

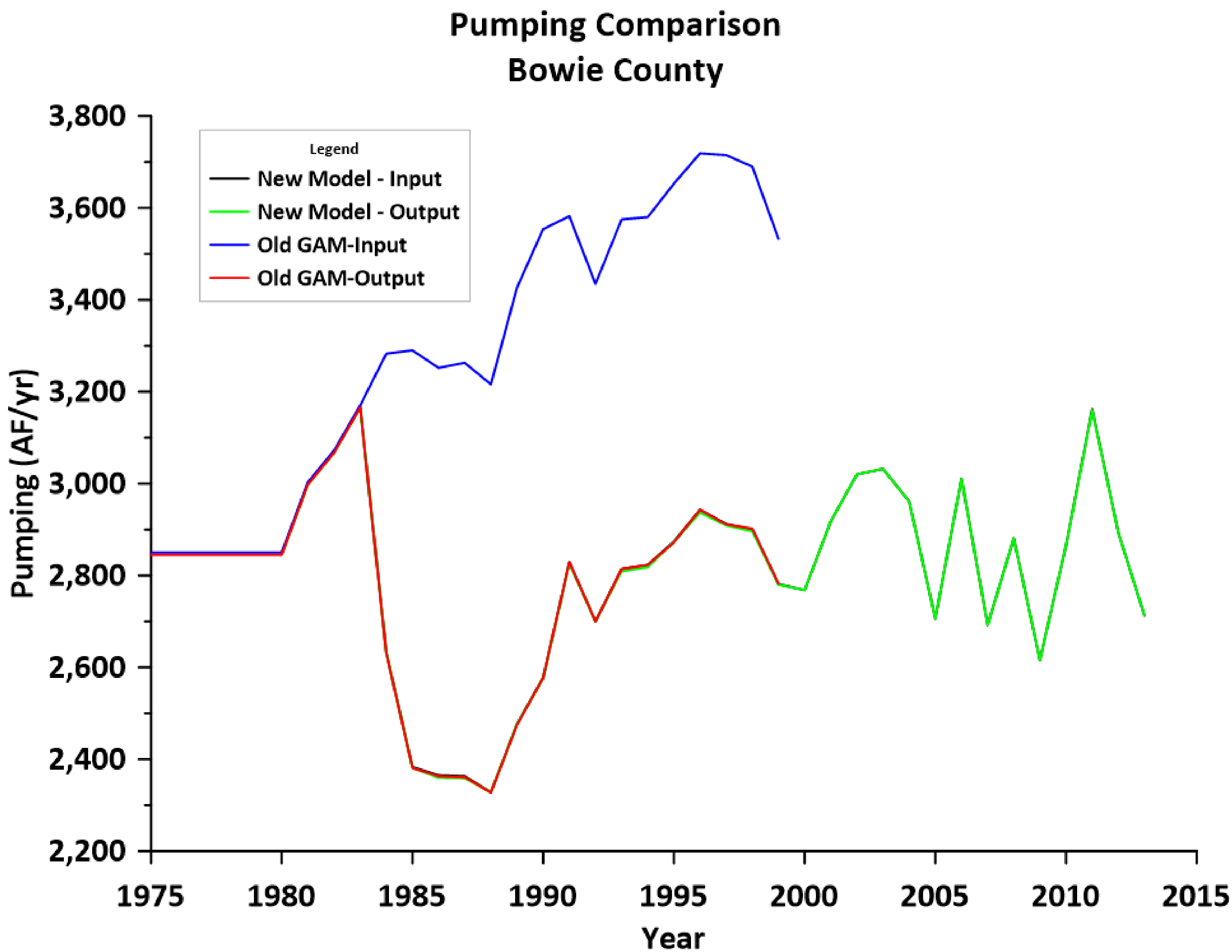
Appendix C

Hydrographs Comparing Input and Output Pumping for Existing GAM and Updated GAM

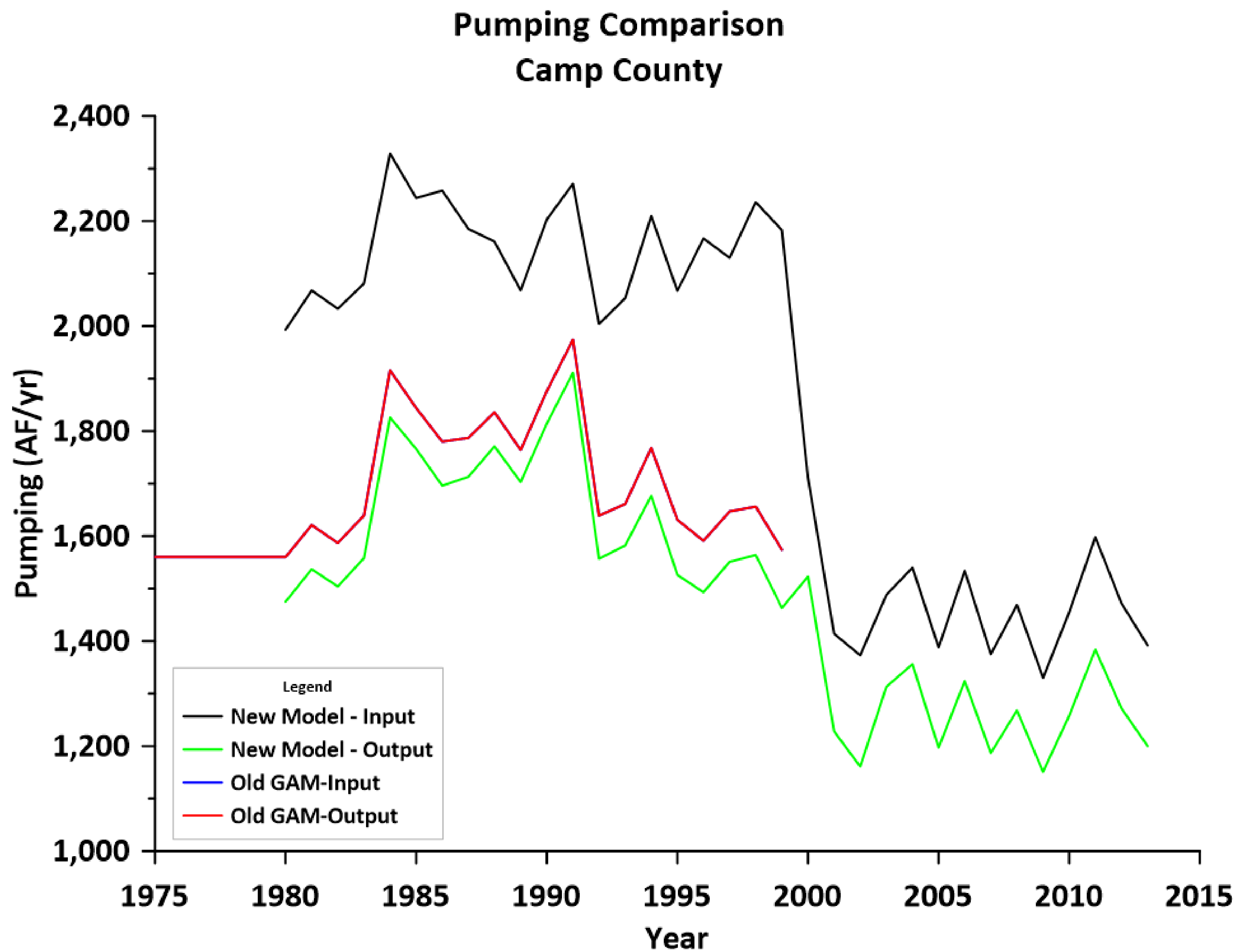


Pumping Comparison
Anderson County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
6,400
6,000
5,600
5,200
4,800
4,400
4,000
3,600
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

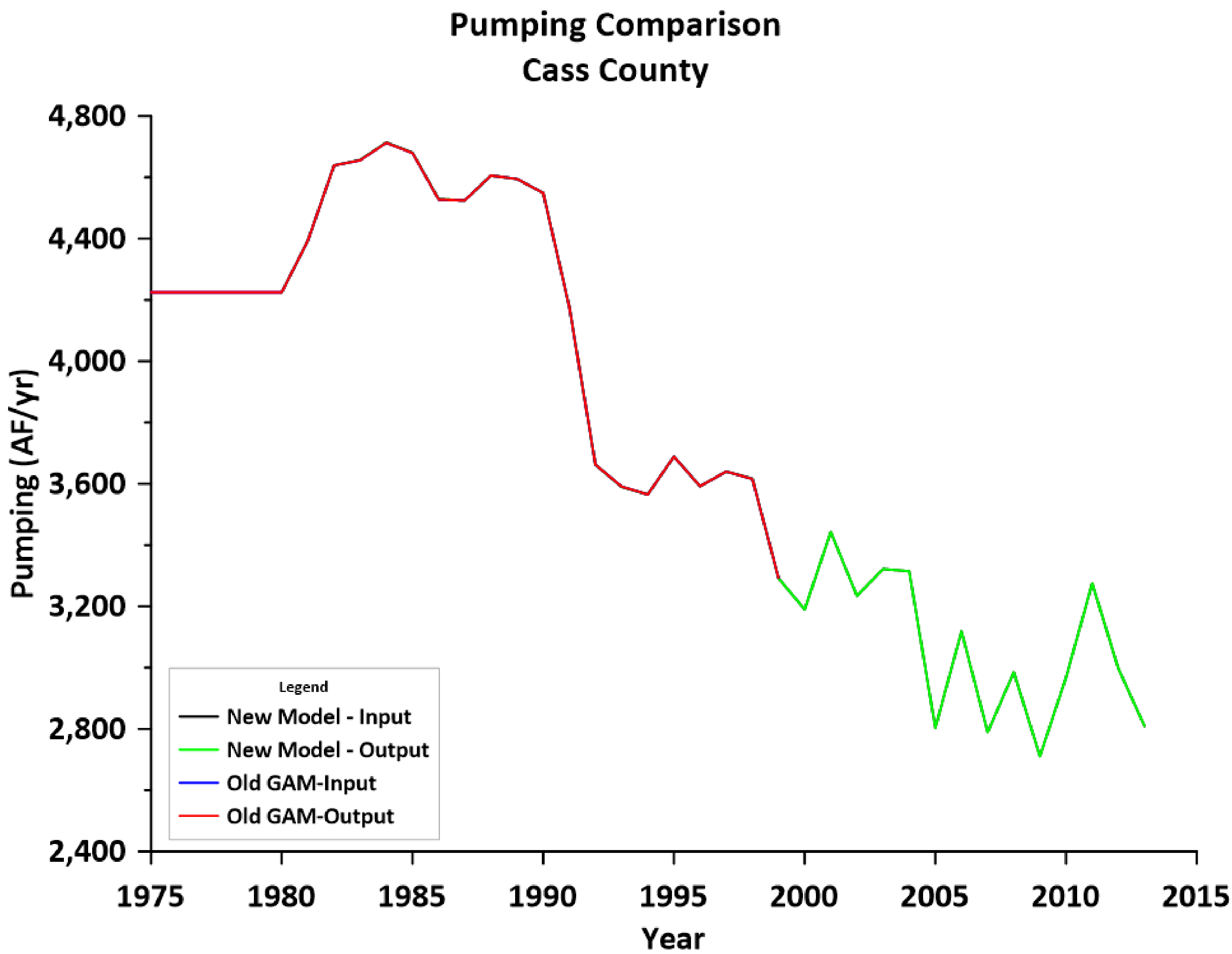

Pumping Comparison
Angelina County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
26,000
25,000
24,000
23,000
22,000
21,000
20,000
19,000
18,000
17,000
16,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

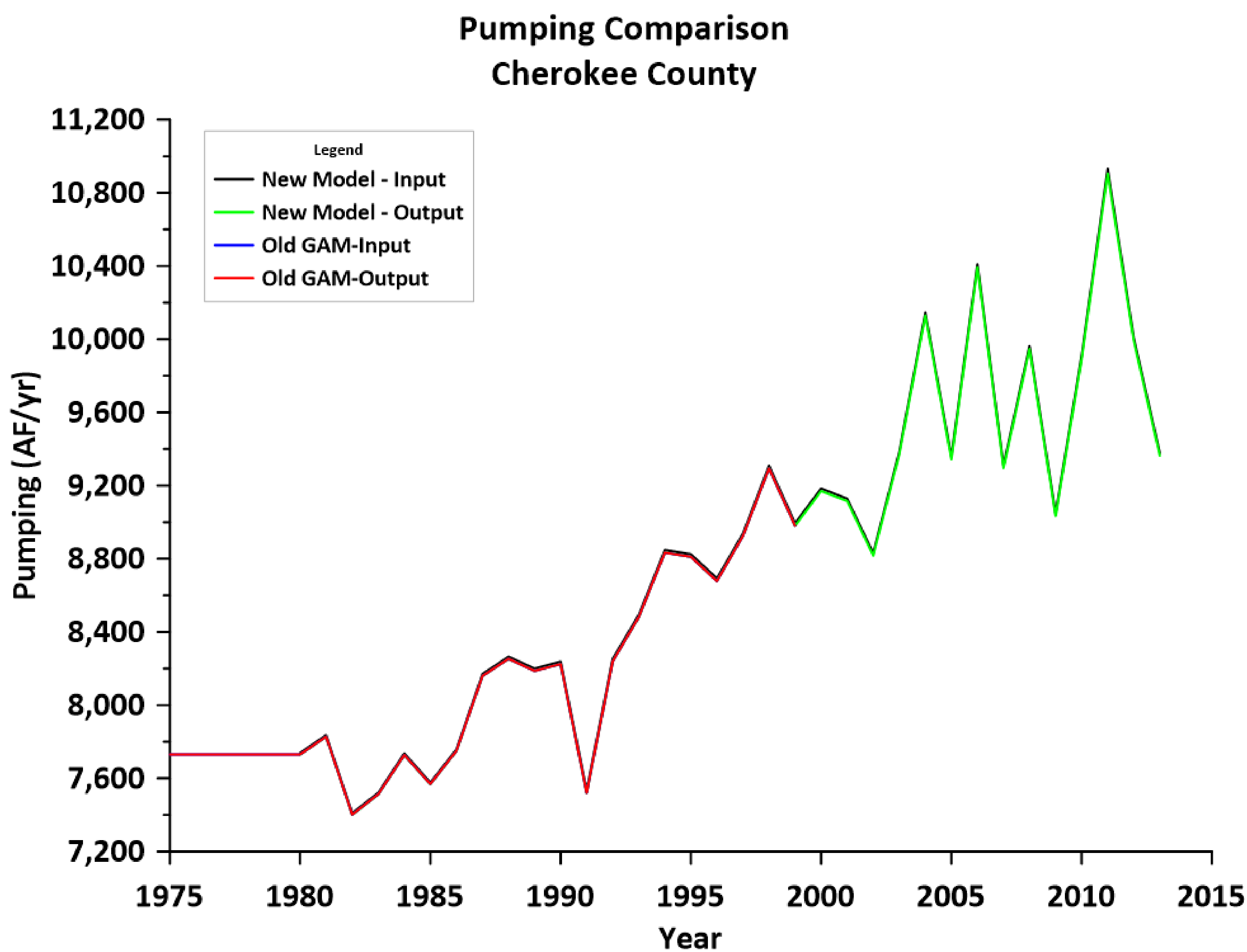


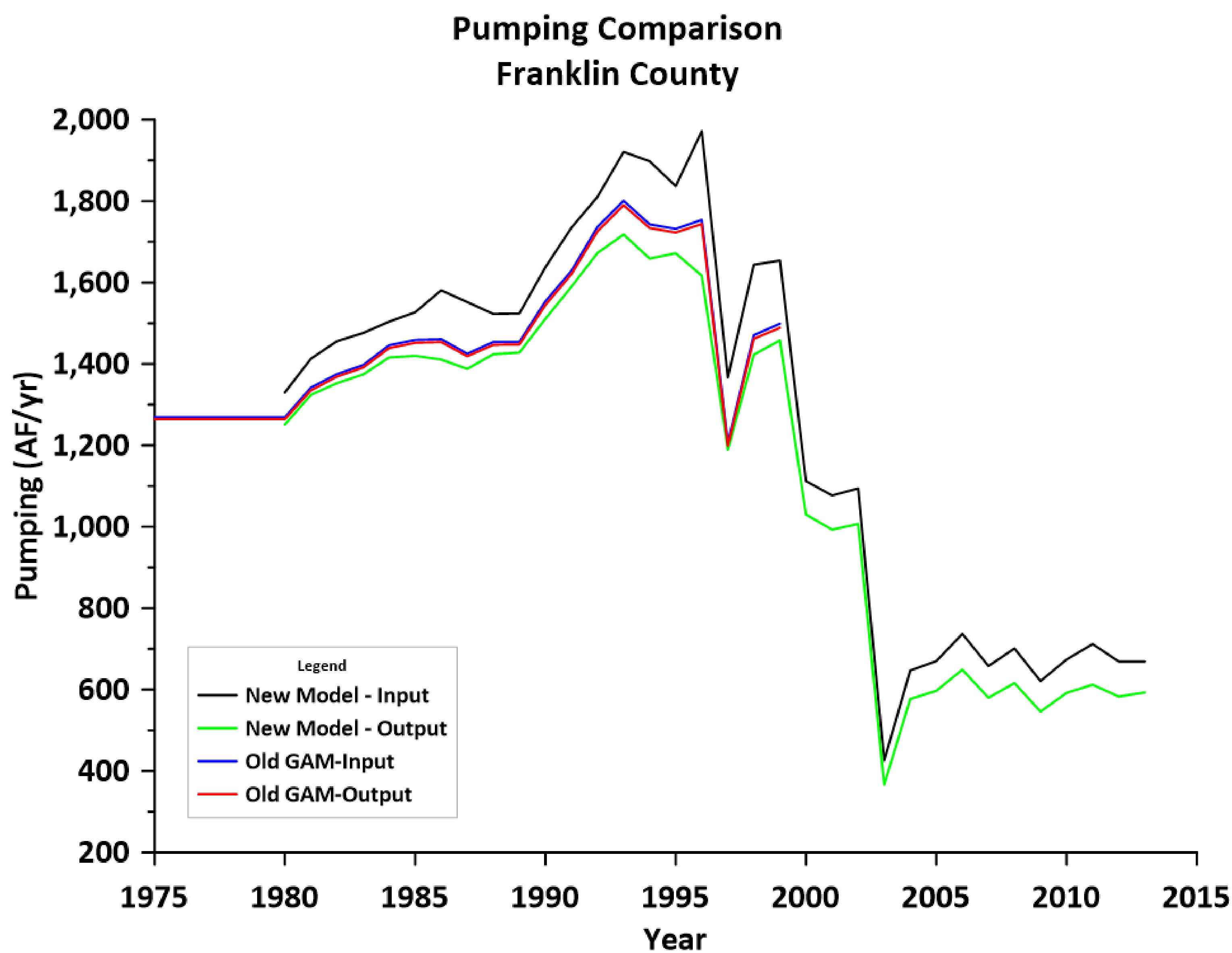
Pumping Comparison
Bowie County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
3,800
3,600
3,400
3,200
3,000
2,800
2,600
2,400
2,200
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

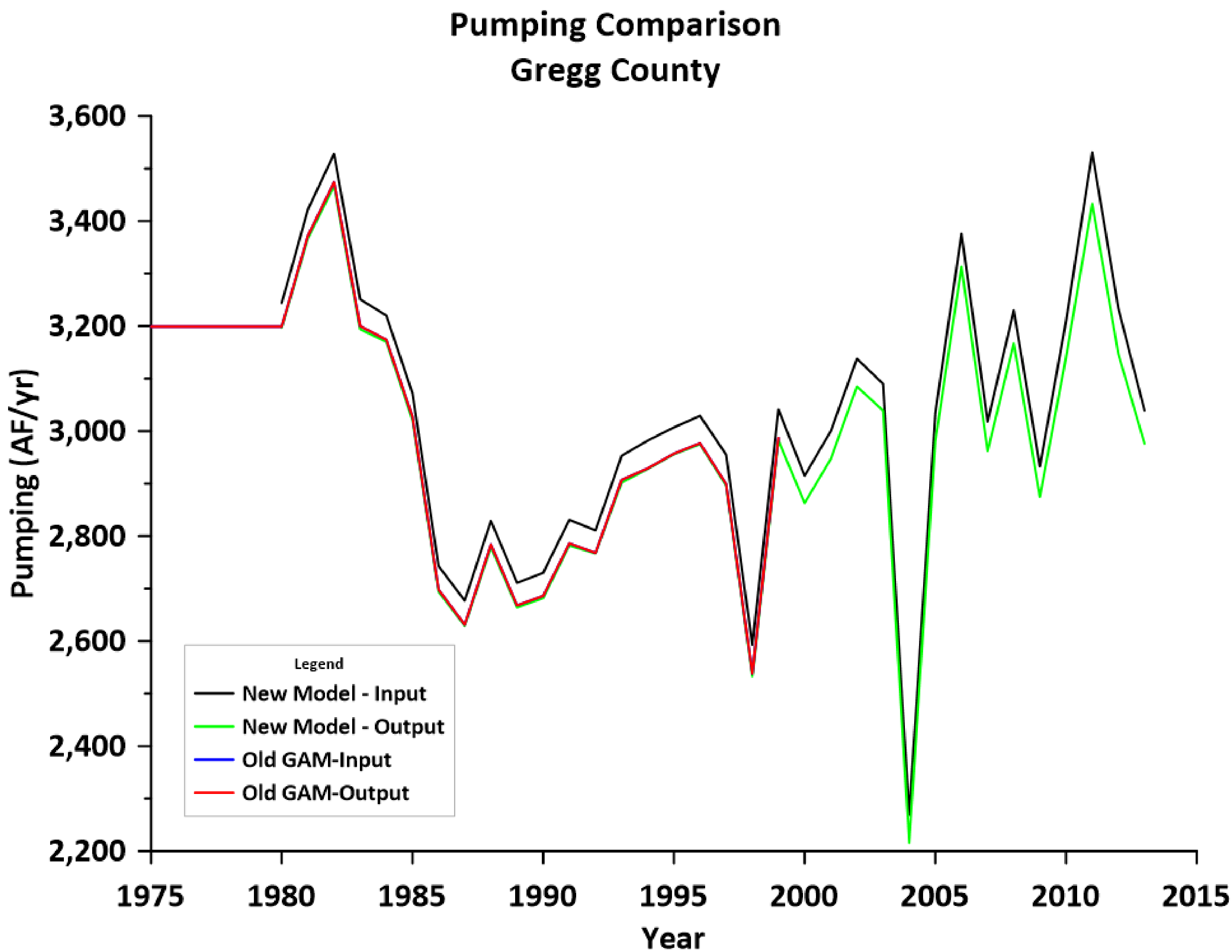


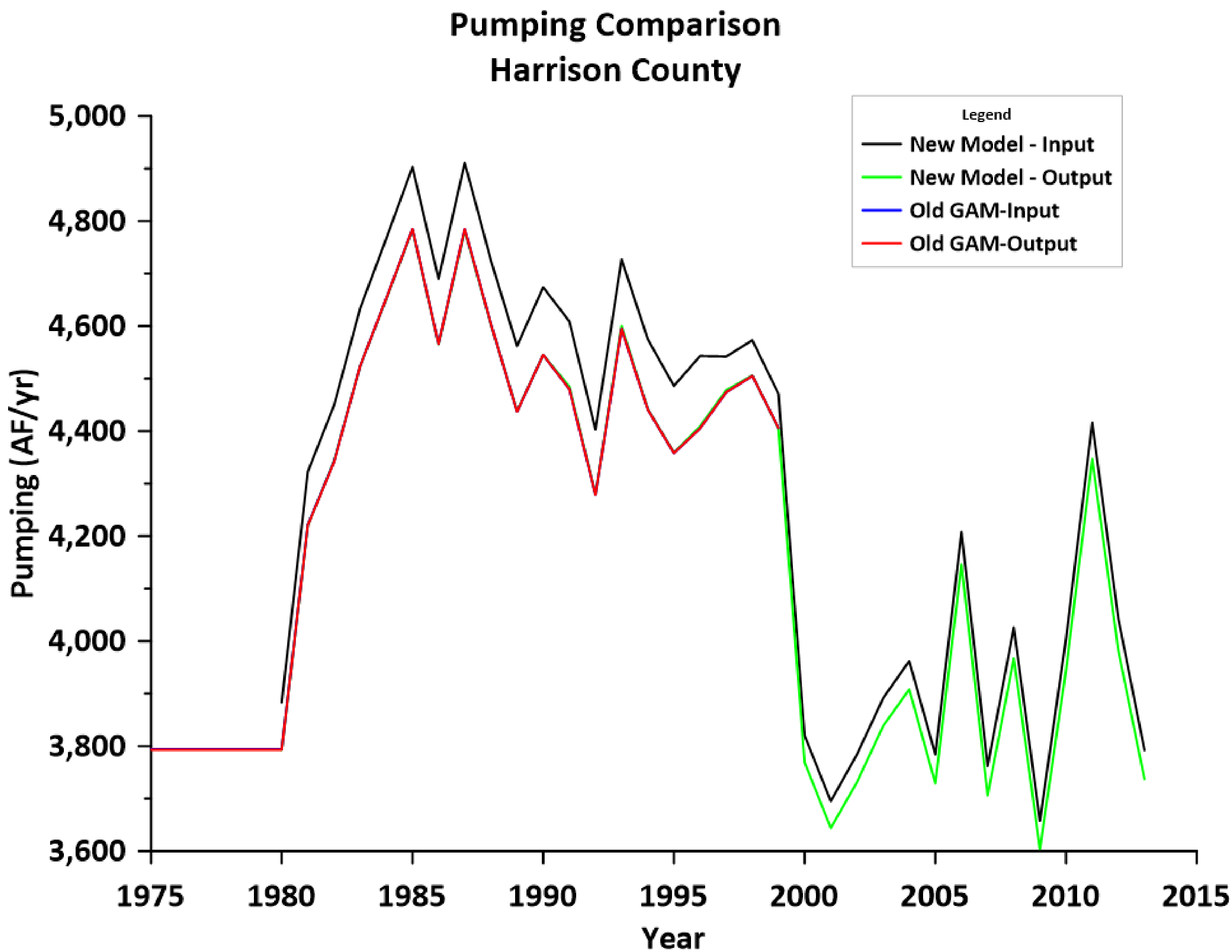
Pumping Comparison
Camp County
2,400
2,200
2,000
1,800
1,600
1,400
1,200
1,000
Pumping (AF/yr)
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output


Pumping Comparison
Cass County
Pumping (AF/yr)
4,800
4,400
4,000
3,600
3,200
2,800
2,400
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output

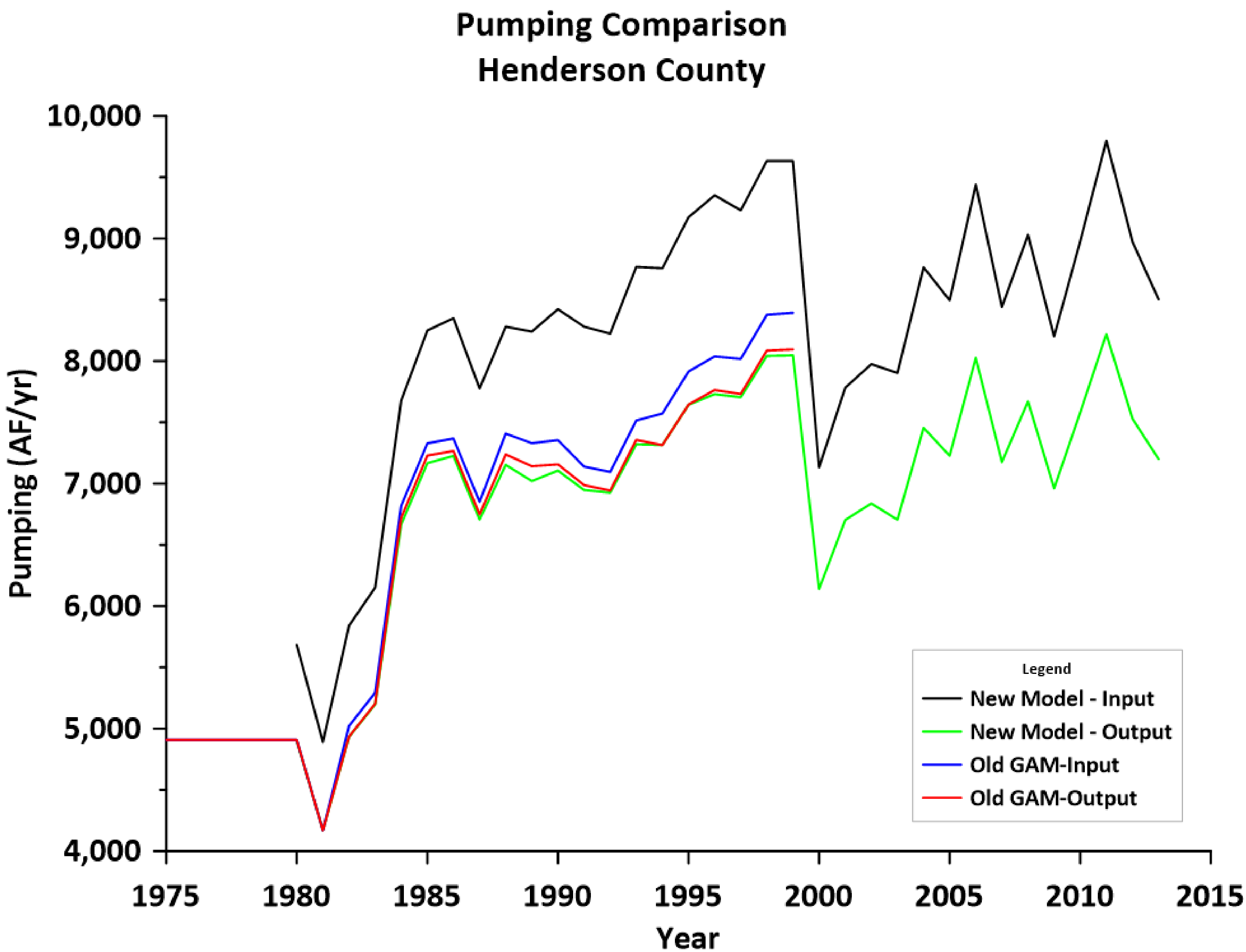

Pumping Comparison
Cherokee County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
Year
11,200
10,800
10,400
10,000
9,600
9,200
8,800
8,400
8,000
7,600
7,200
1975
1980
1985
1990
1995
2000
2005
2010
2015

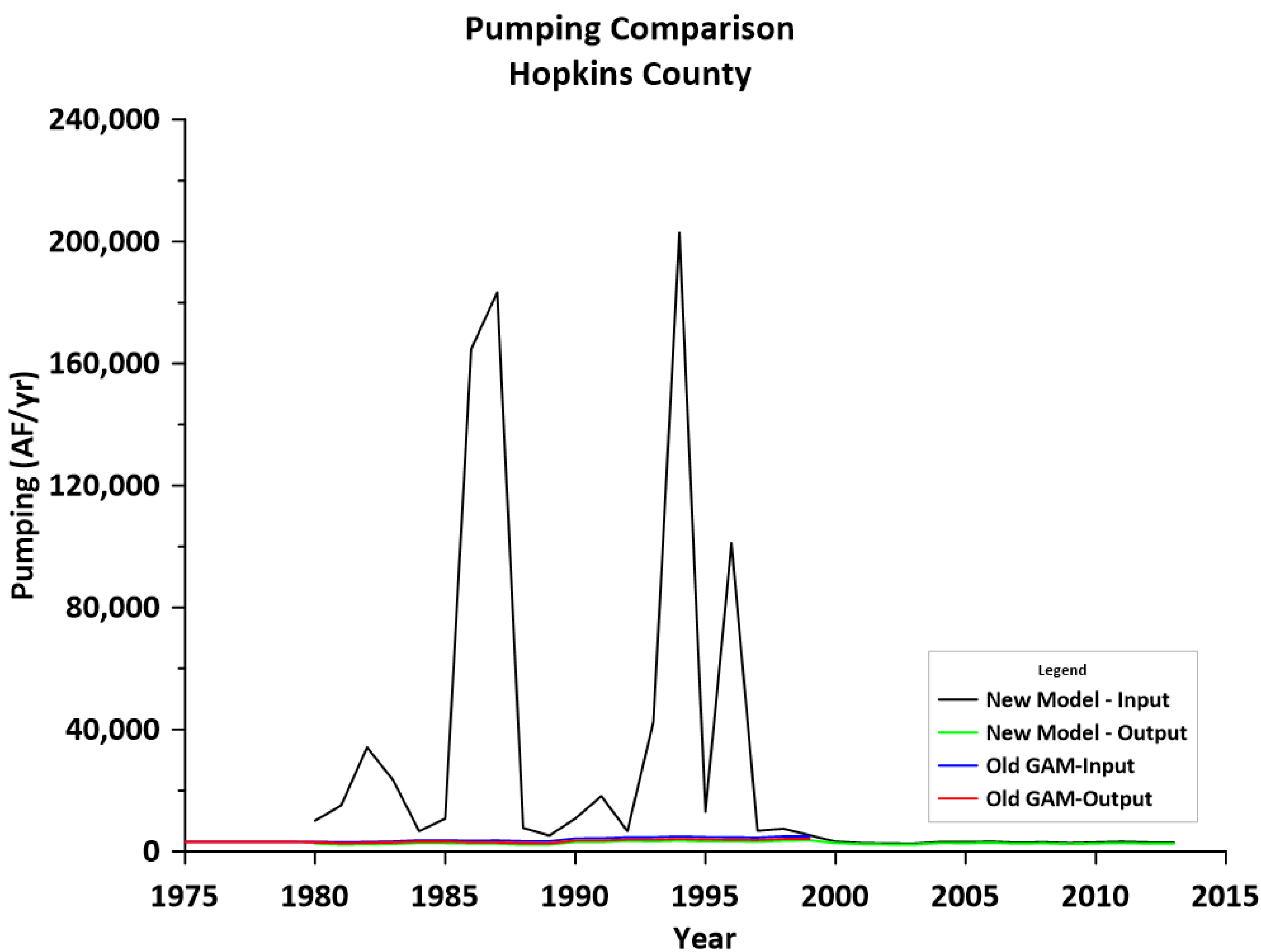

Pumping Comparison
Franklin County
Pumping (AF/yr)
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output


Pumping Comparison
Gregg County
3,600
3,400
3,200
3,000
2,800
2,600
2,400
2,200
Pumping (AF/yr)
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output

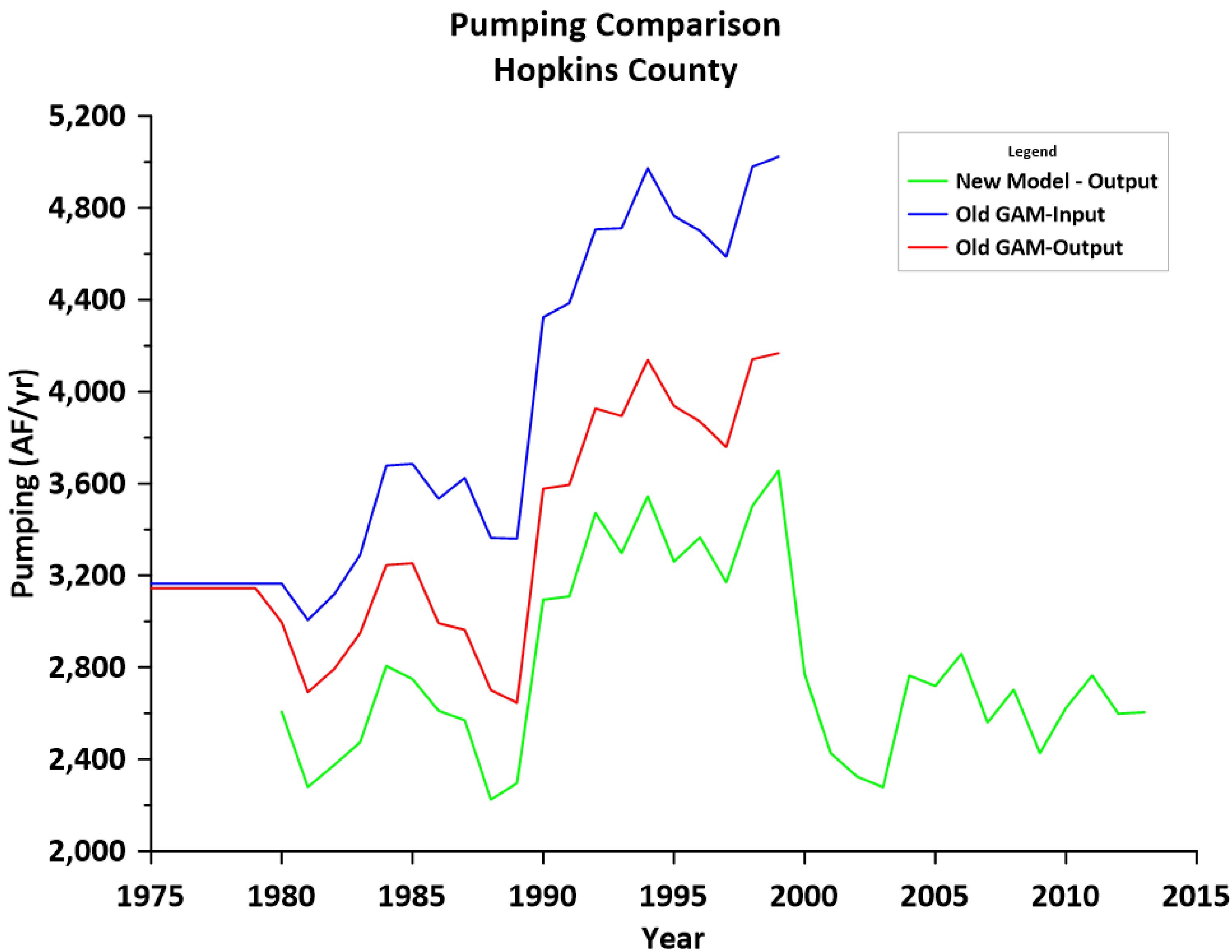


Pumping Comparison
Harrison County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
5,000
4,800
4,600
4,400
4,200
4,000
3,800
3,600
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

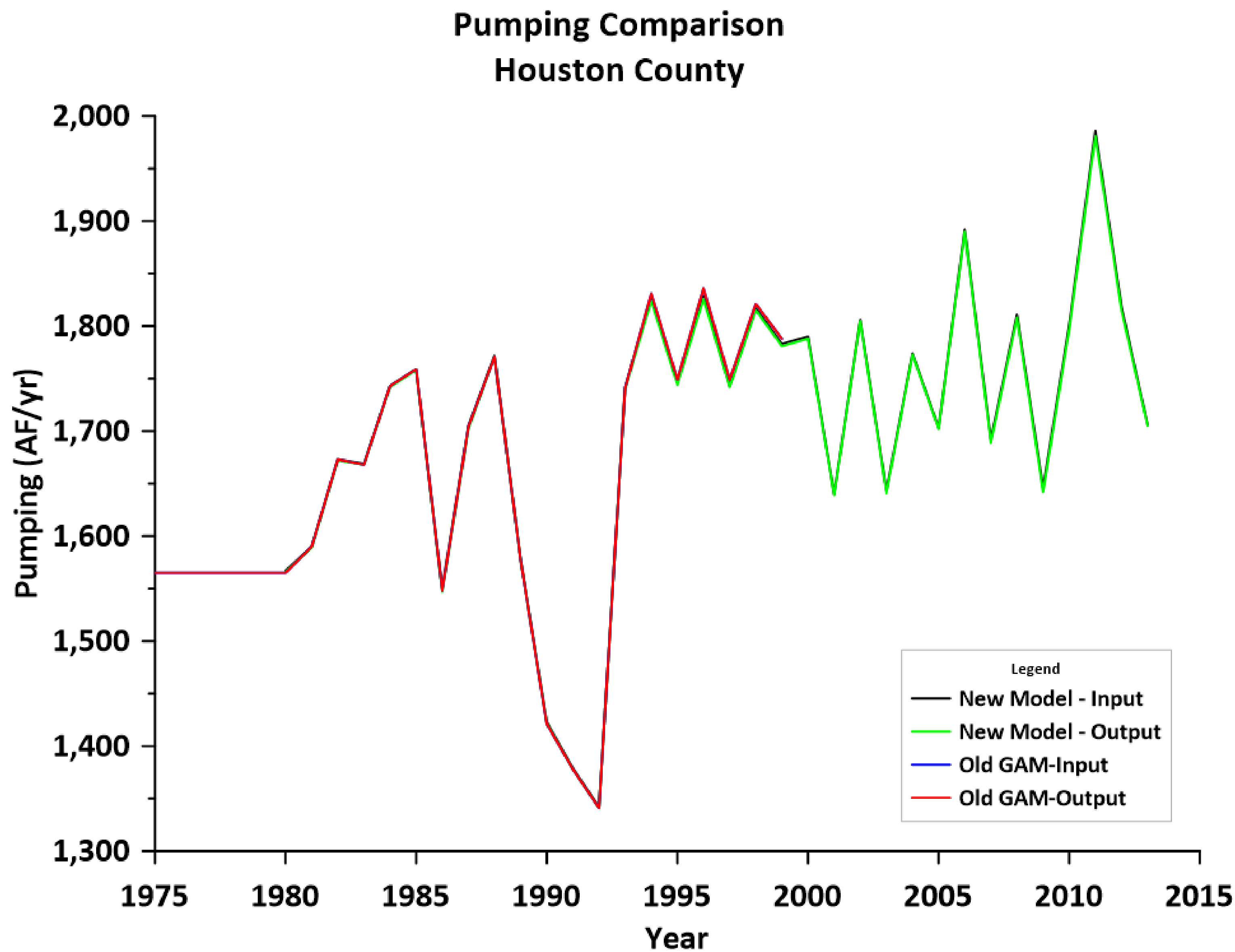

Pumping Comparison
Henderson County
10,000
9,000
8,000
7,000
6,000
5,000
4,000
Pumping (AF/yr)
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output

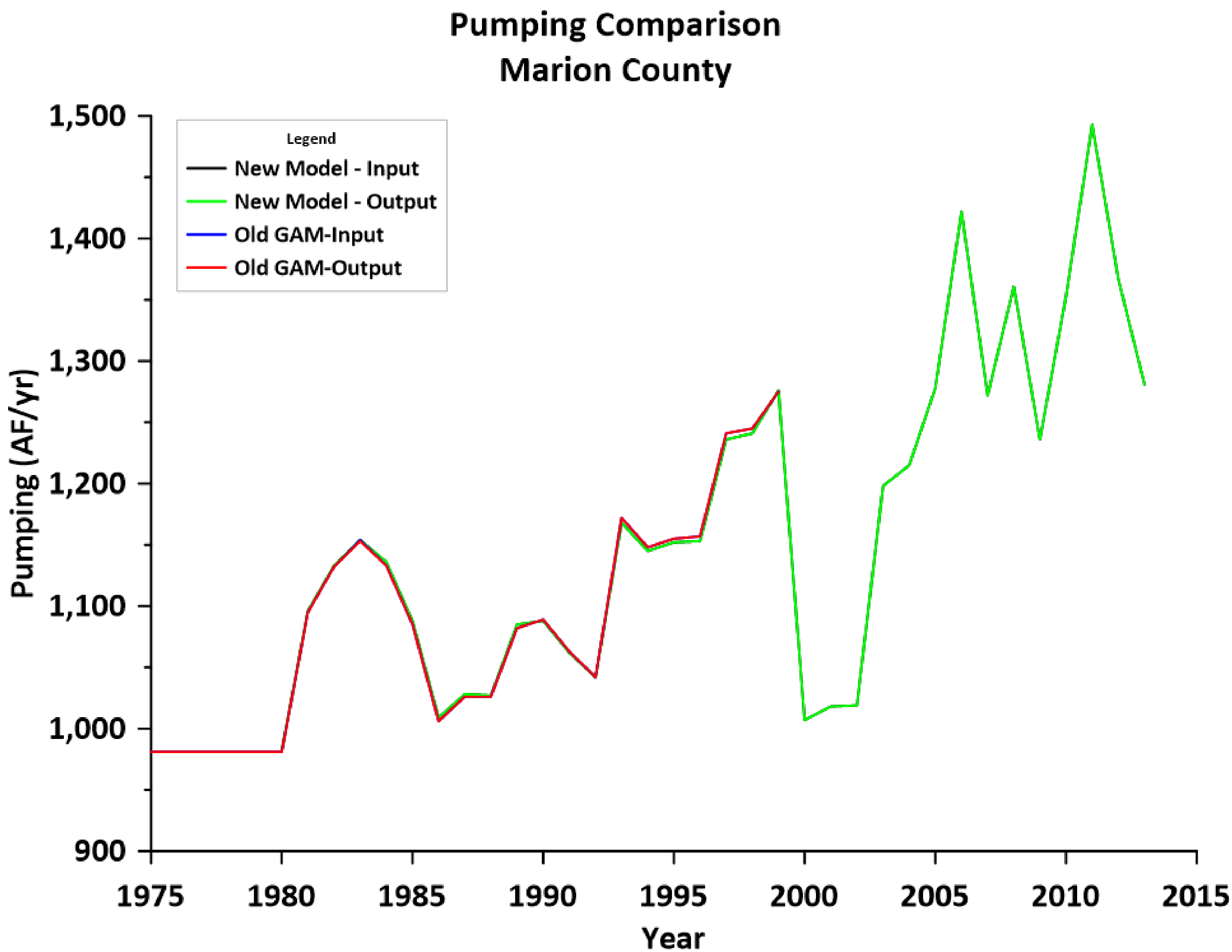


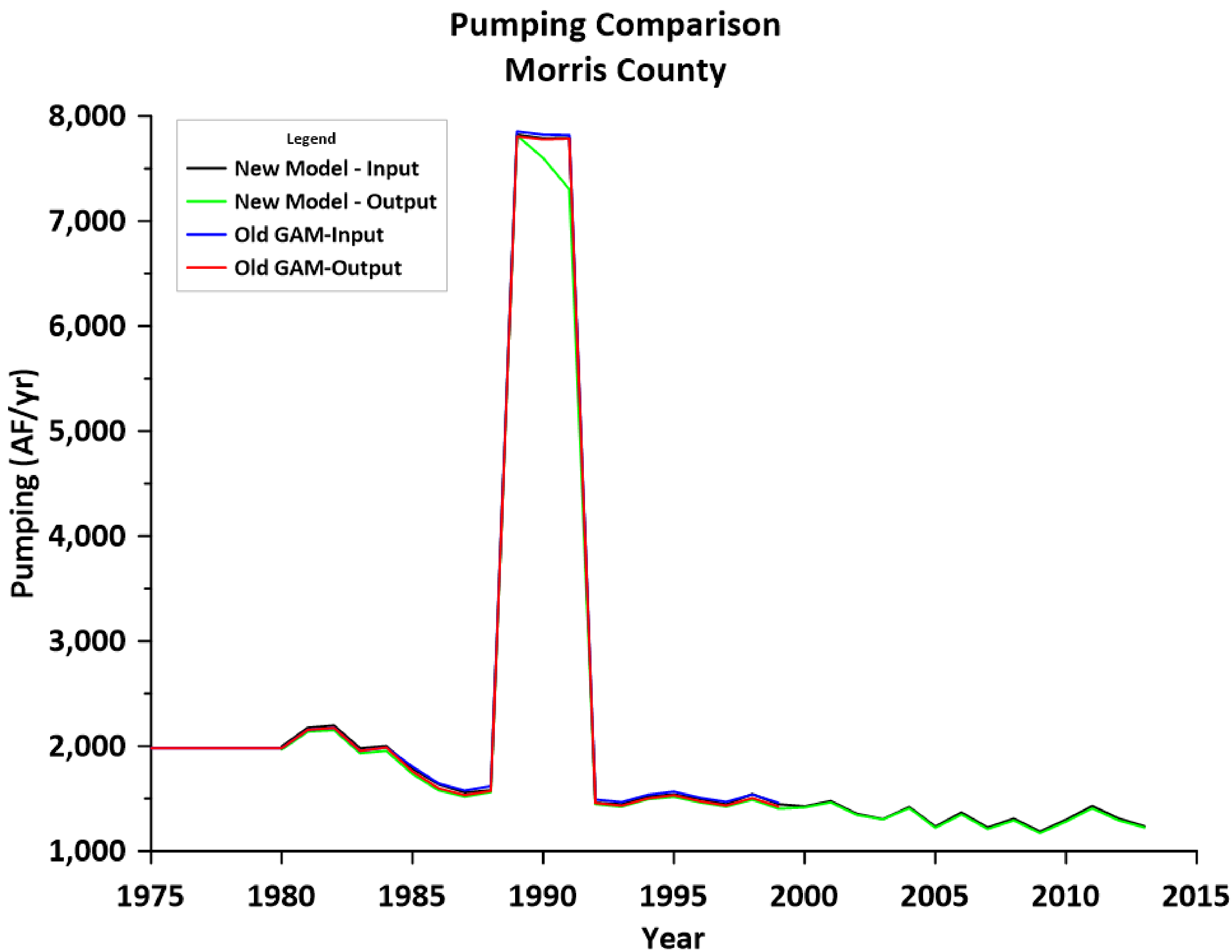
Pumping Comparison
Hopkins County
Pumping (AF/yr)
240,000
200,000
160,000
120,000
80,000
40,000
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output

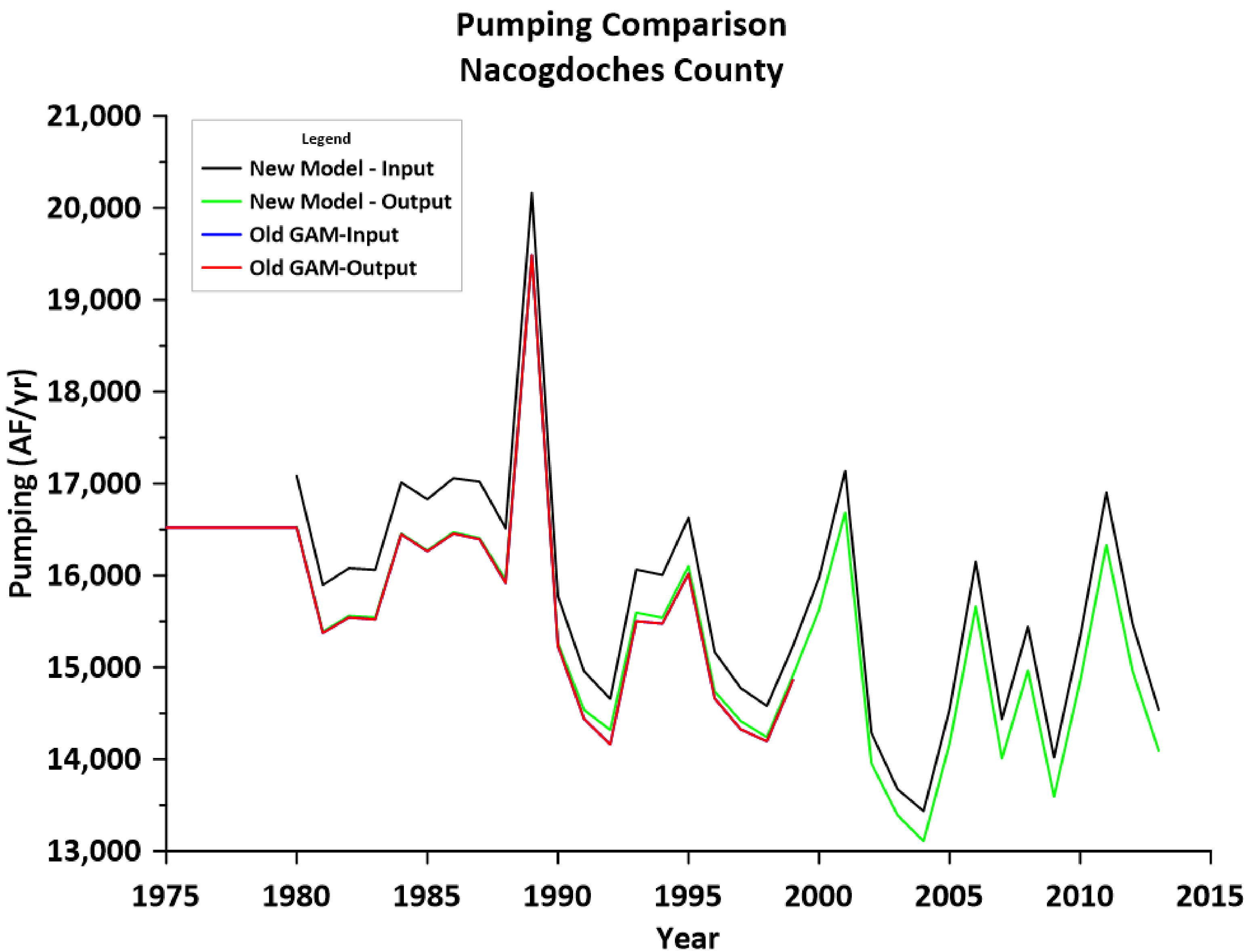


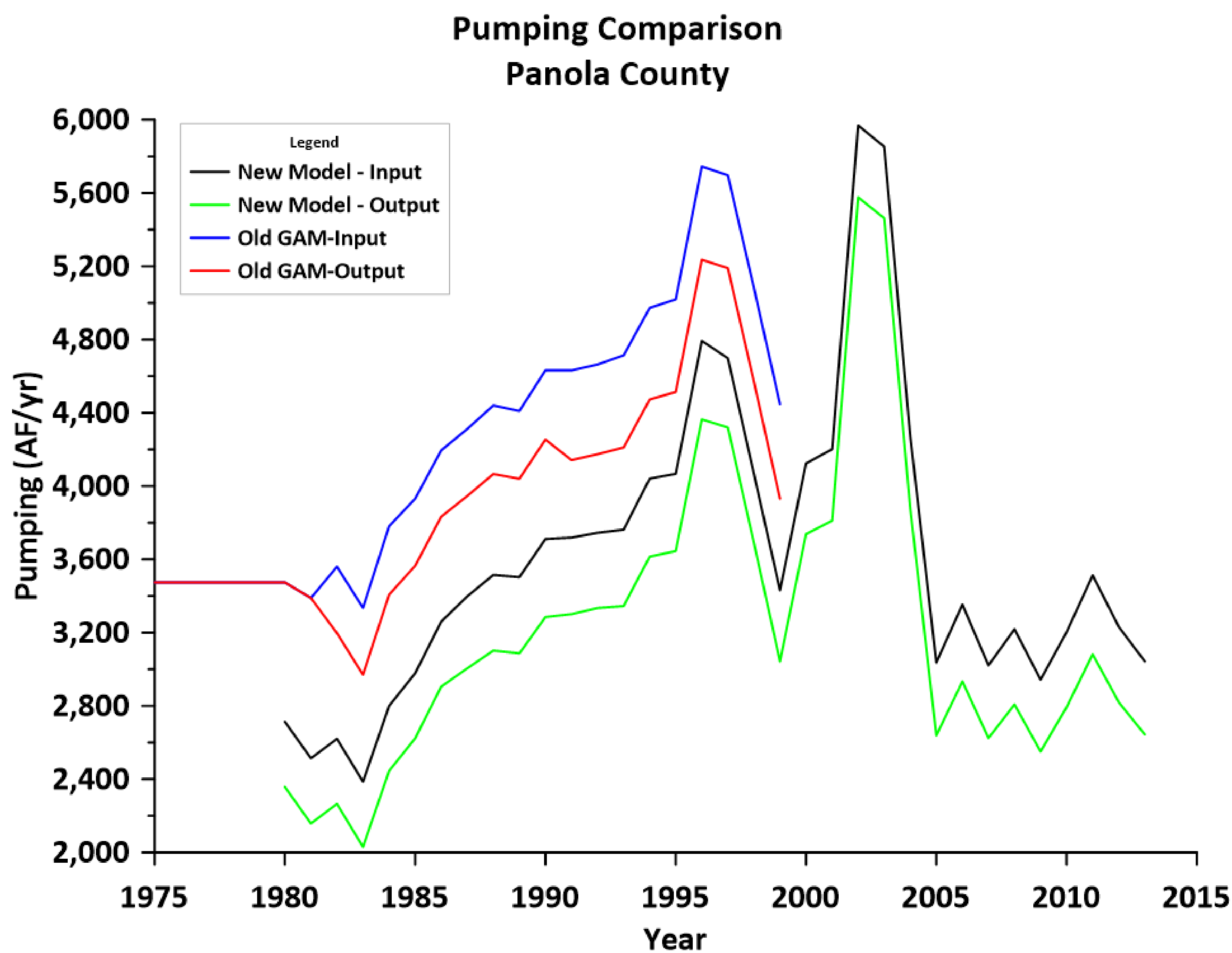
Pumping Comparison
Hopkins County
Legend
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
5,200
4,800
4,400
4,000
3,600
3,200
2,800
2,400
2,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

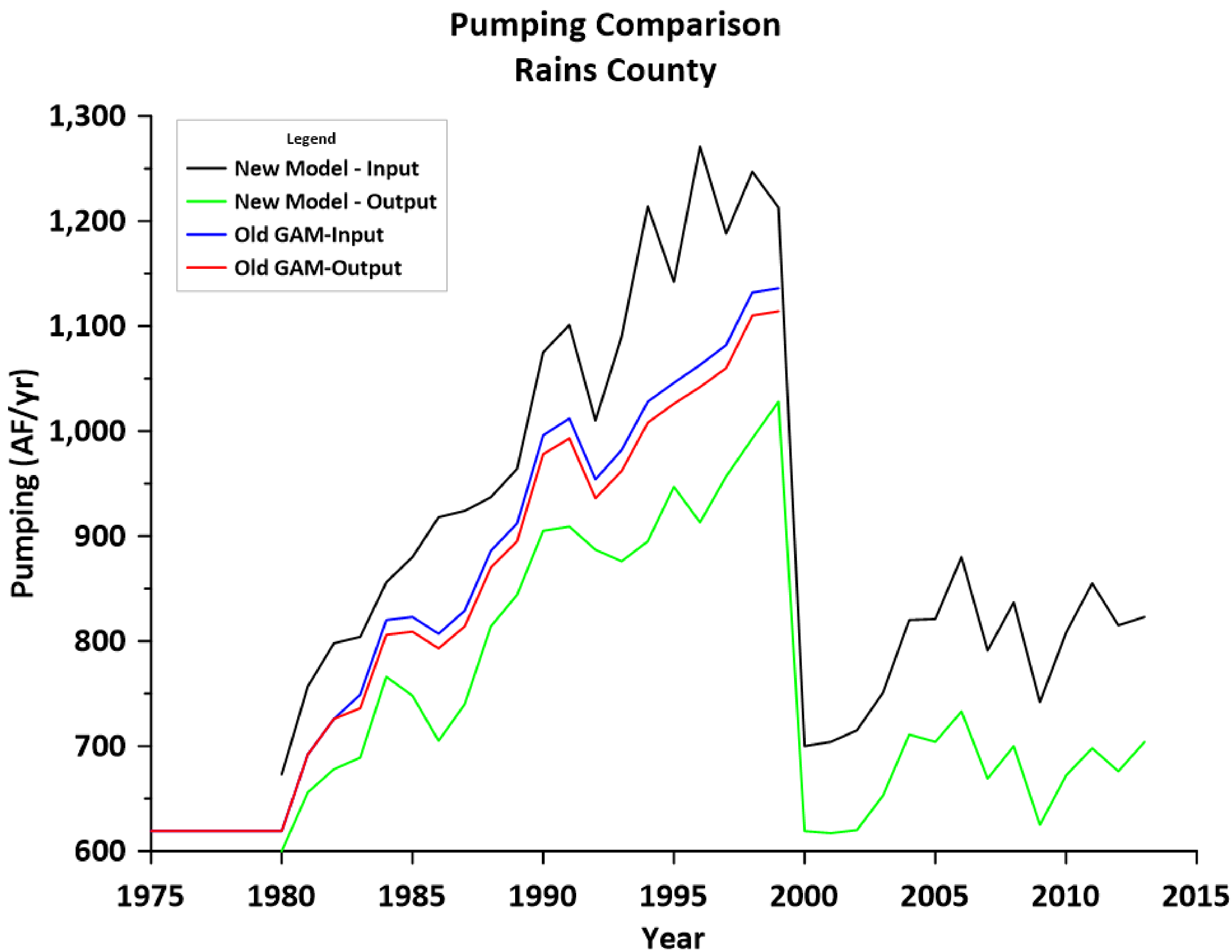

Pumping Comparison
Houston County
Pumping (AF/yr)
2,000
1,900
1,800
1,700
1,600
1,500
1,400
1,300
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output


Pumping Comparison
Marion County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
1,500
1,400
1,300
1,200
1,100
1,000
900
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

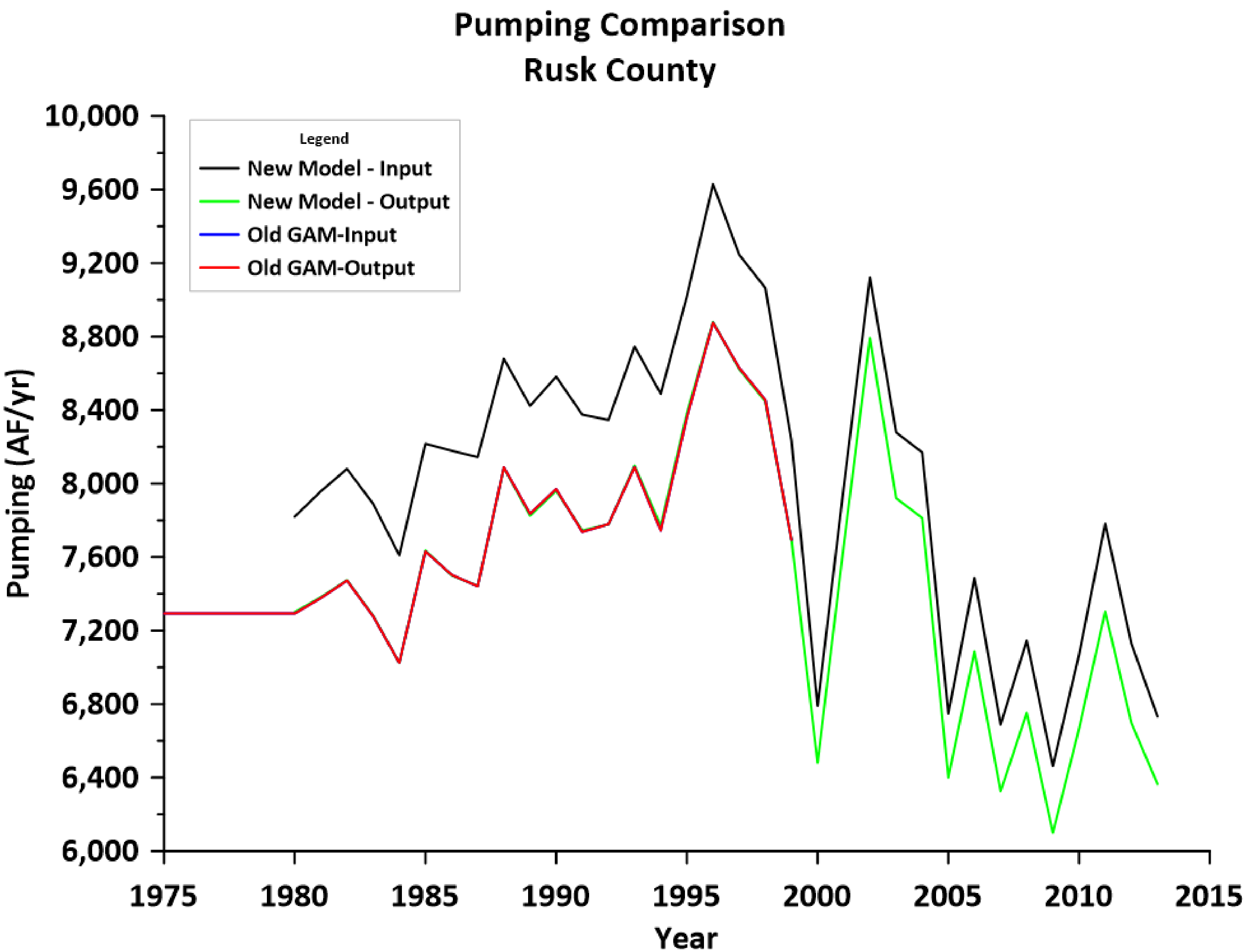

Pumping Comparison
Morris County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year


Pumping Comparison
Nacogdoches County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
21,000
20,000
19,000
18,000
17,000
16,000
15,000
14,000
13,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

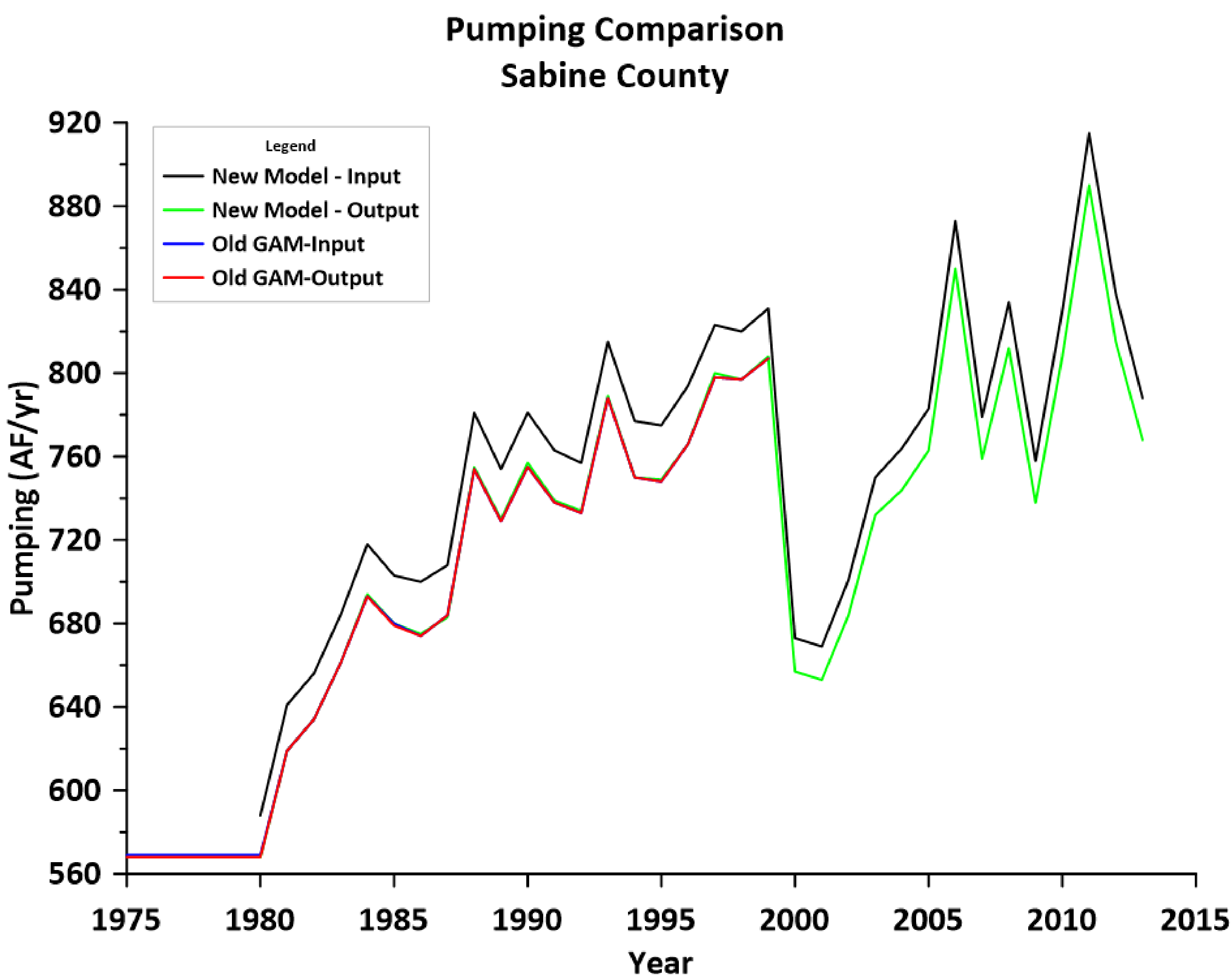

Pumping Comparison
Panola County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
6,000
5,600
5,200
4,800
4,400
4,000
3,600
3,200
2,800
2,400
2,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

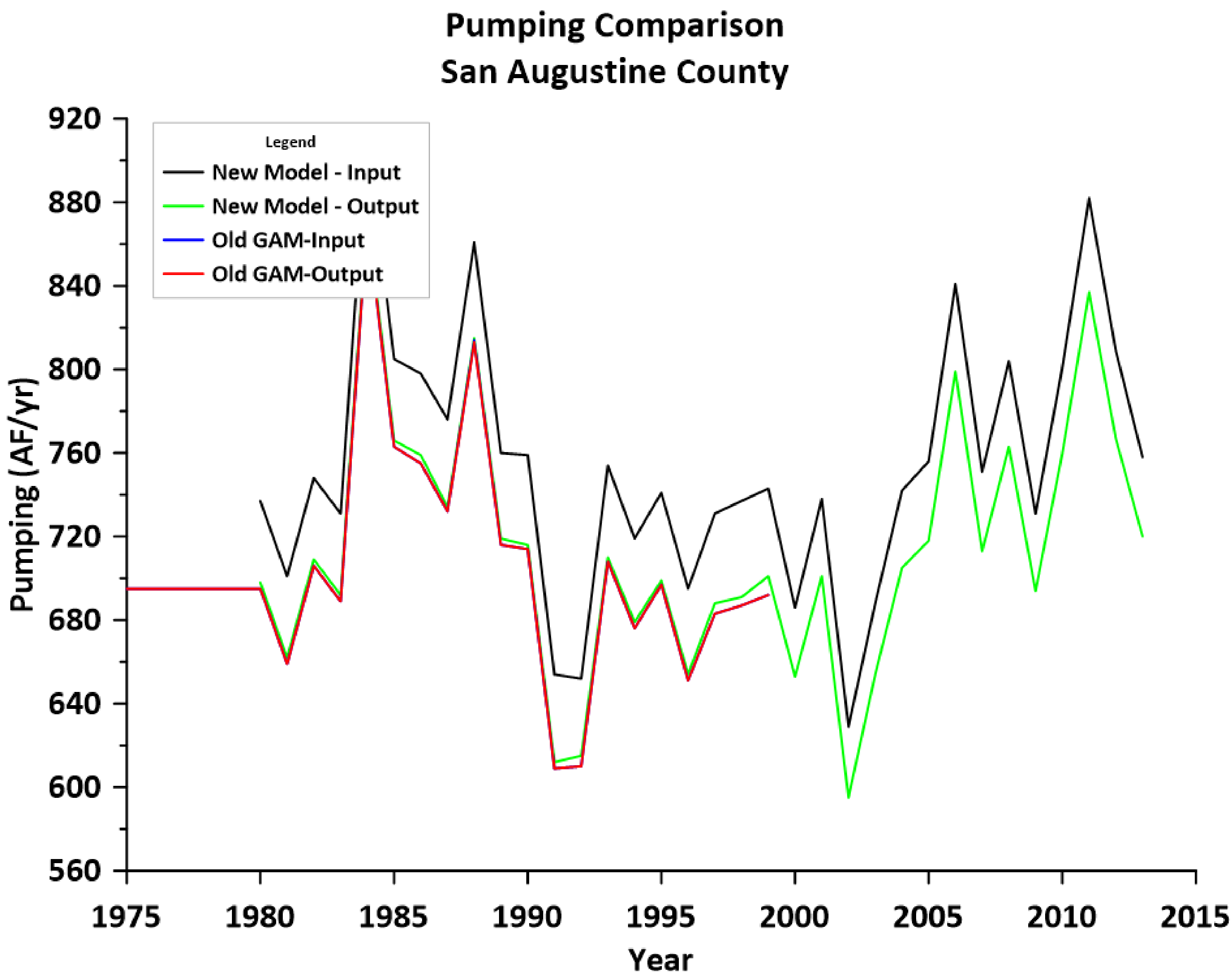


Pumping Comparison
Rains County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
1,300
1,200
1,100
1,000
900
800
700
600
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

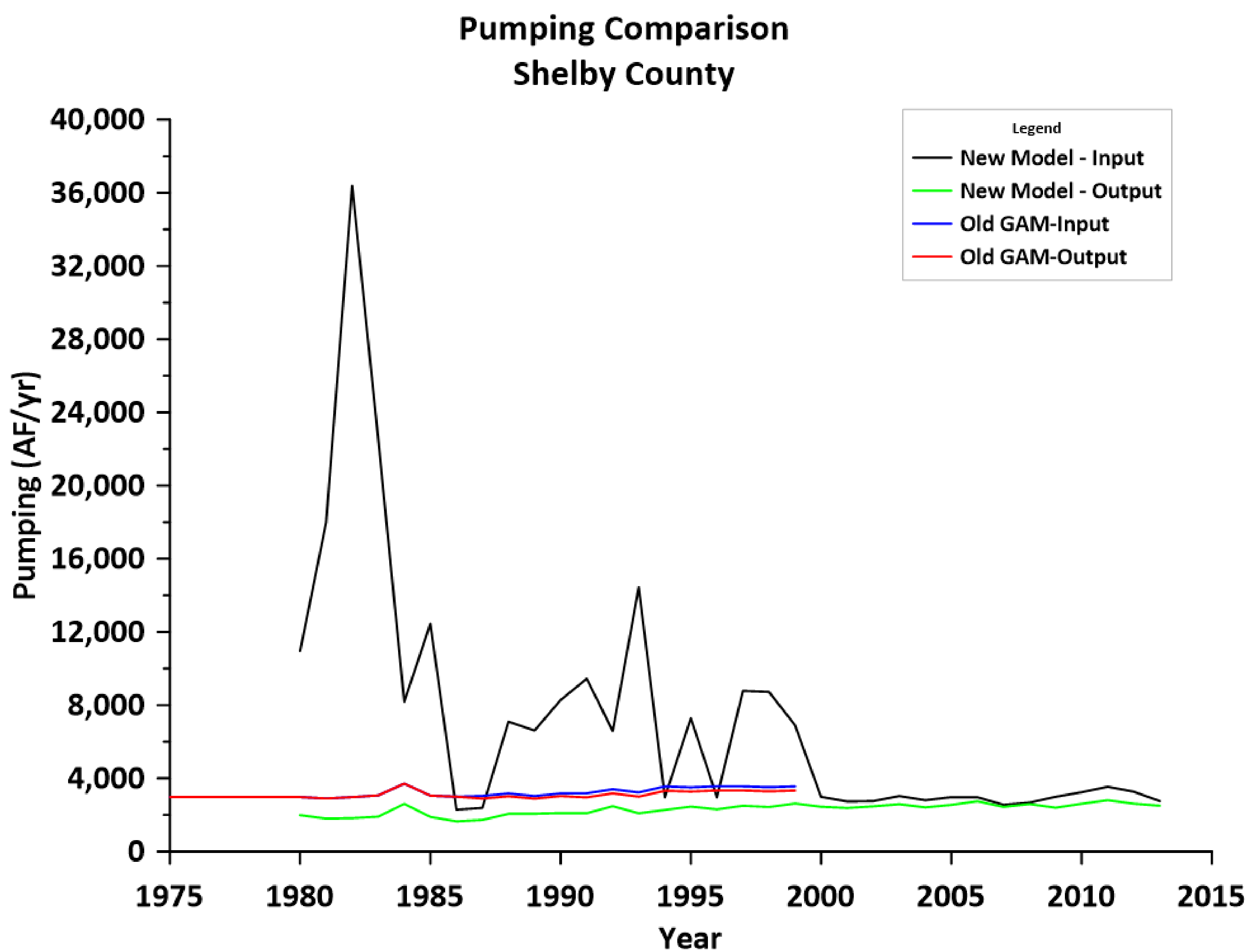


Pumping Comparison
Rusk County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
10,000
9,600
9,200
8,800
8,400
8,000
7,600
7,200
6,800
6,400
6,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

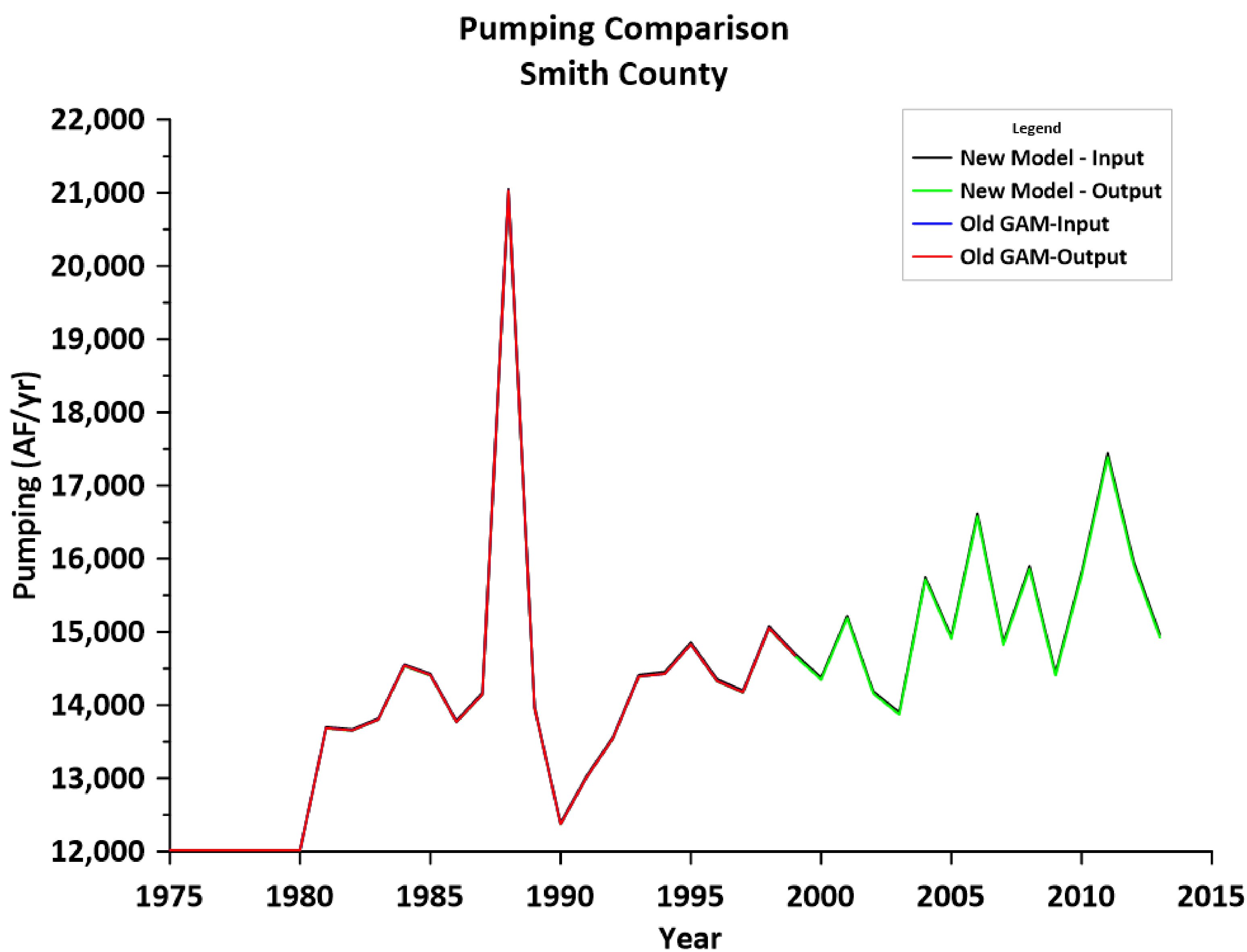

Pumping Comparison
Sabine County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
Year
920
880
840
800
760
720
680
640
600
560
1975
1980
1985
1990
1995
2000
2005
2010
2015

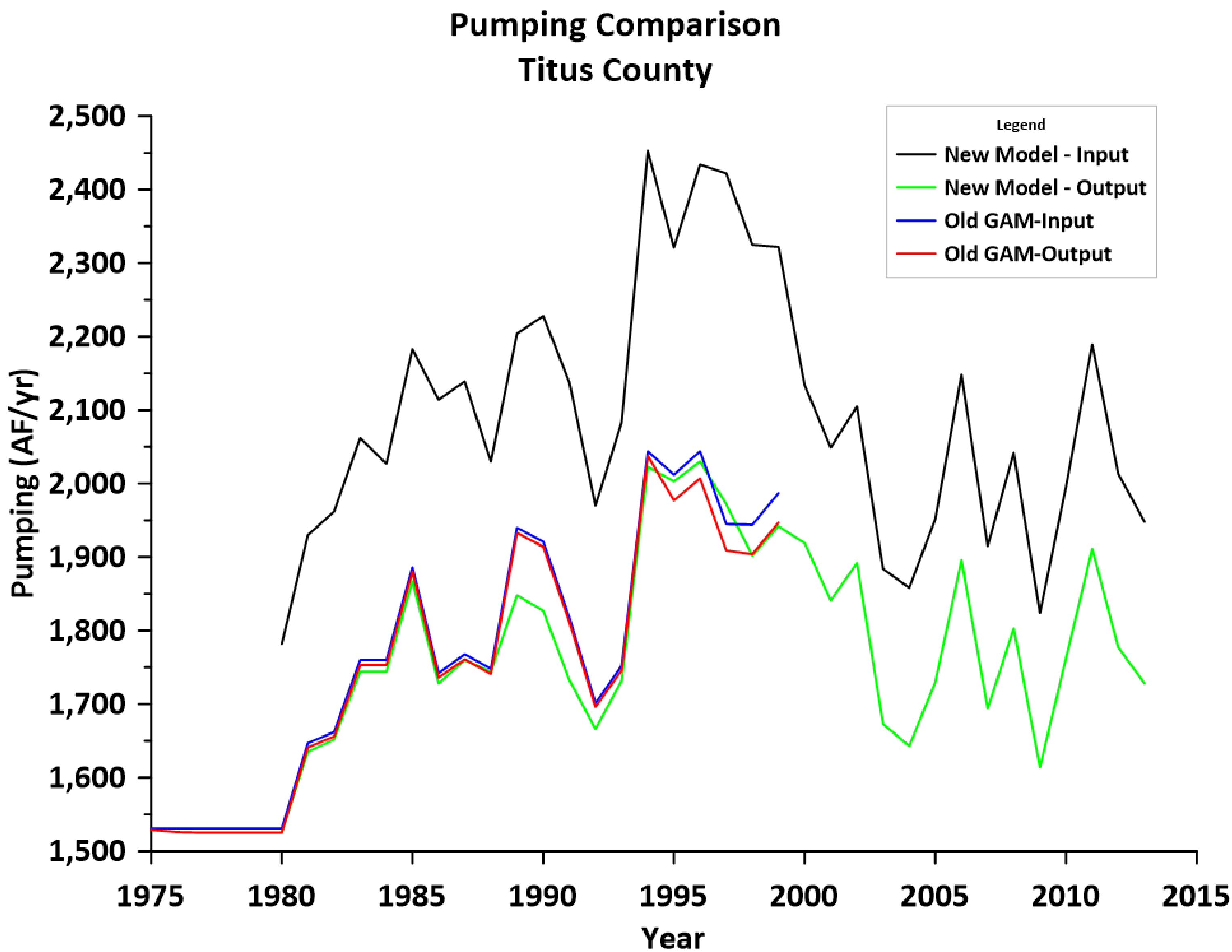


Pumping Comparison
San Augustine County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
Year
920
880
840
800
760
720
680
640
600
560
1975
1980
1985
1990
1995
2000
2005
2010
2015

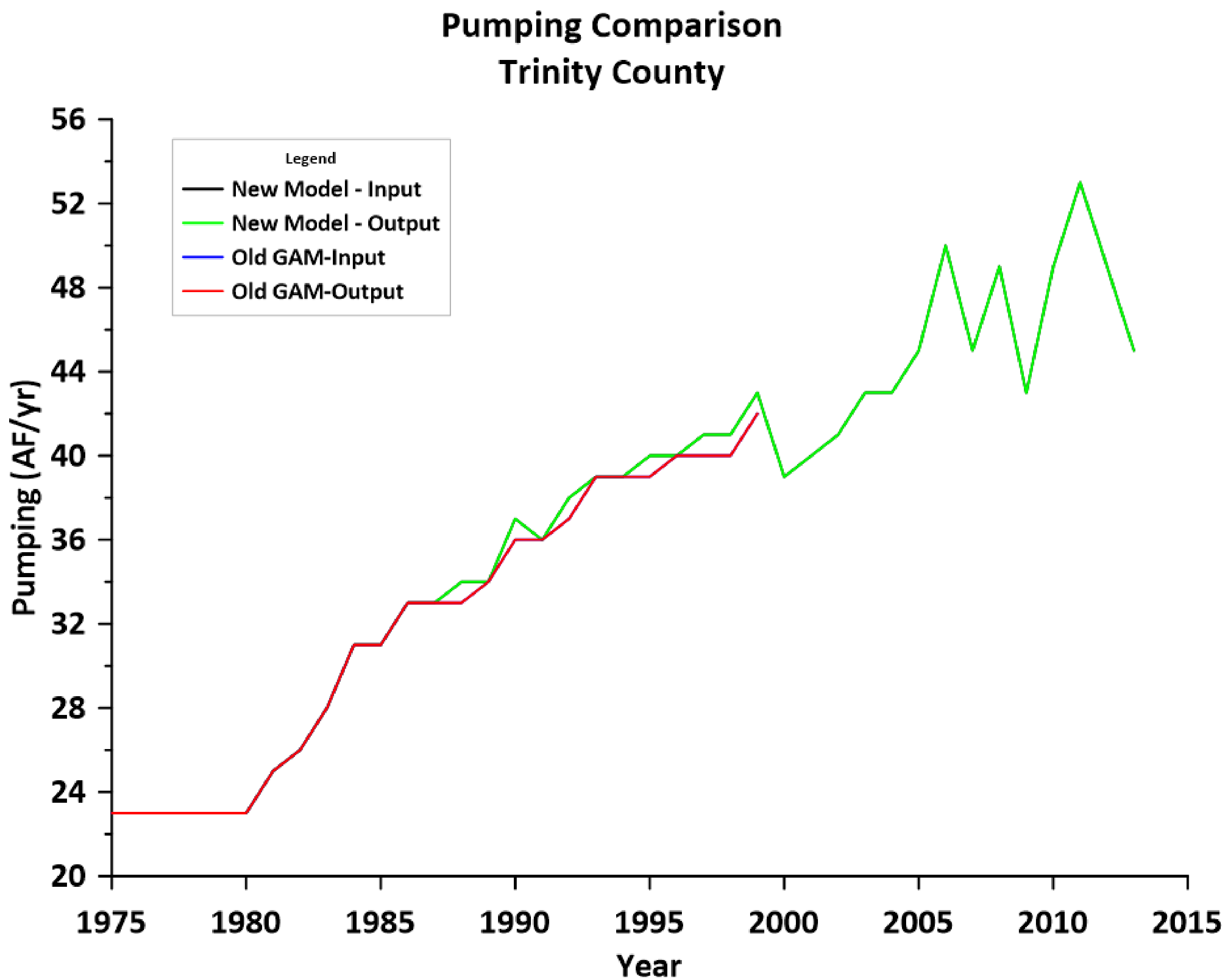


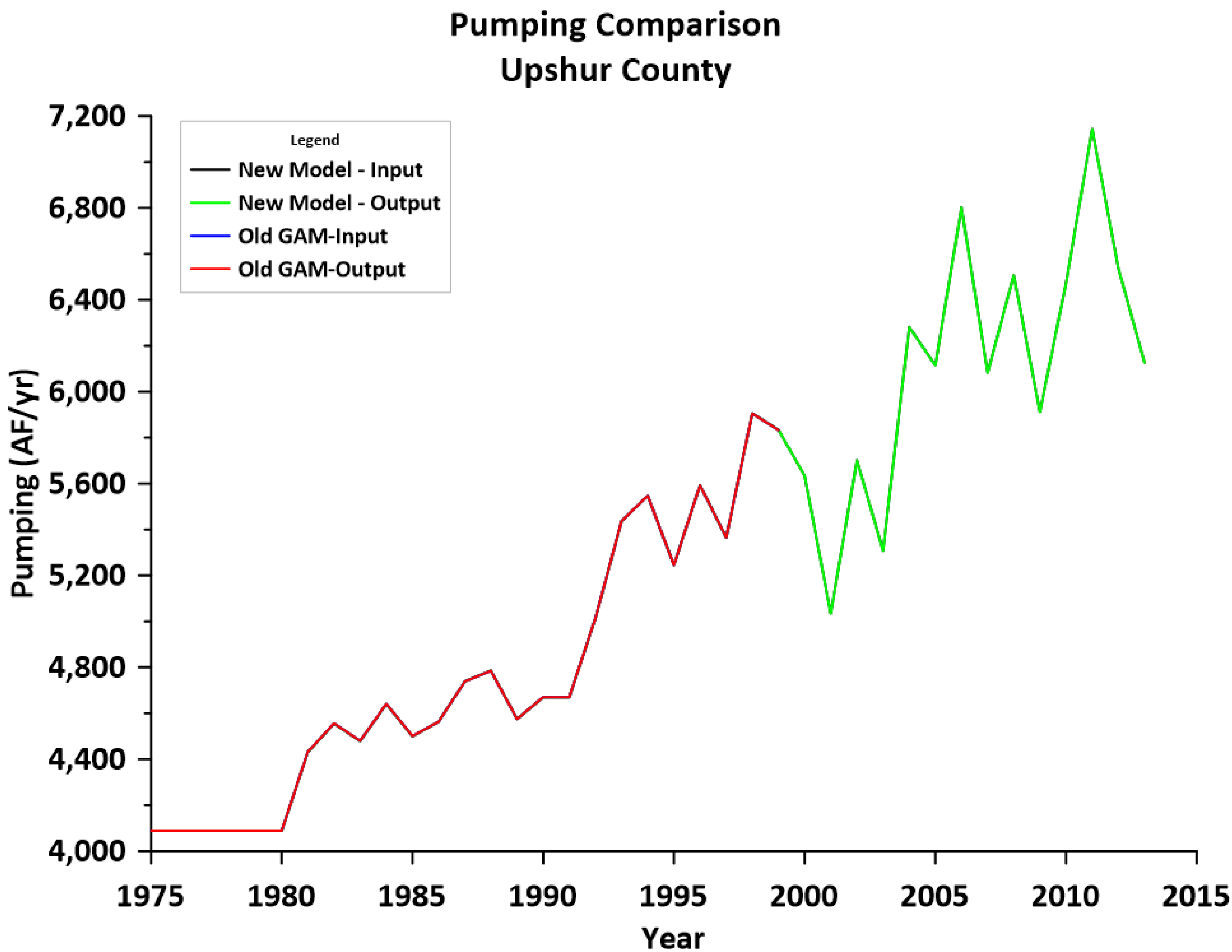
Pumping Comparison
Shelby County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
40,000
36,000
32,000
28,000
24,000
20,000
16,000
12,000
8,000
4,000
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

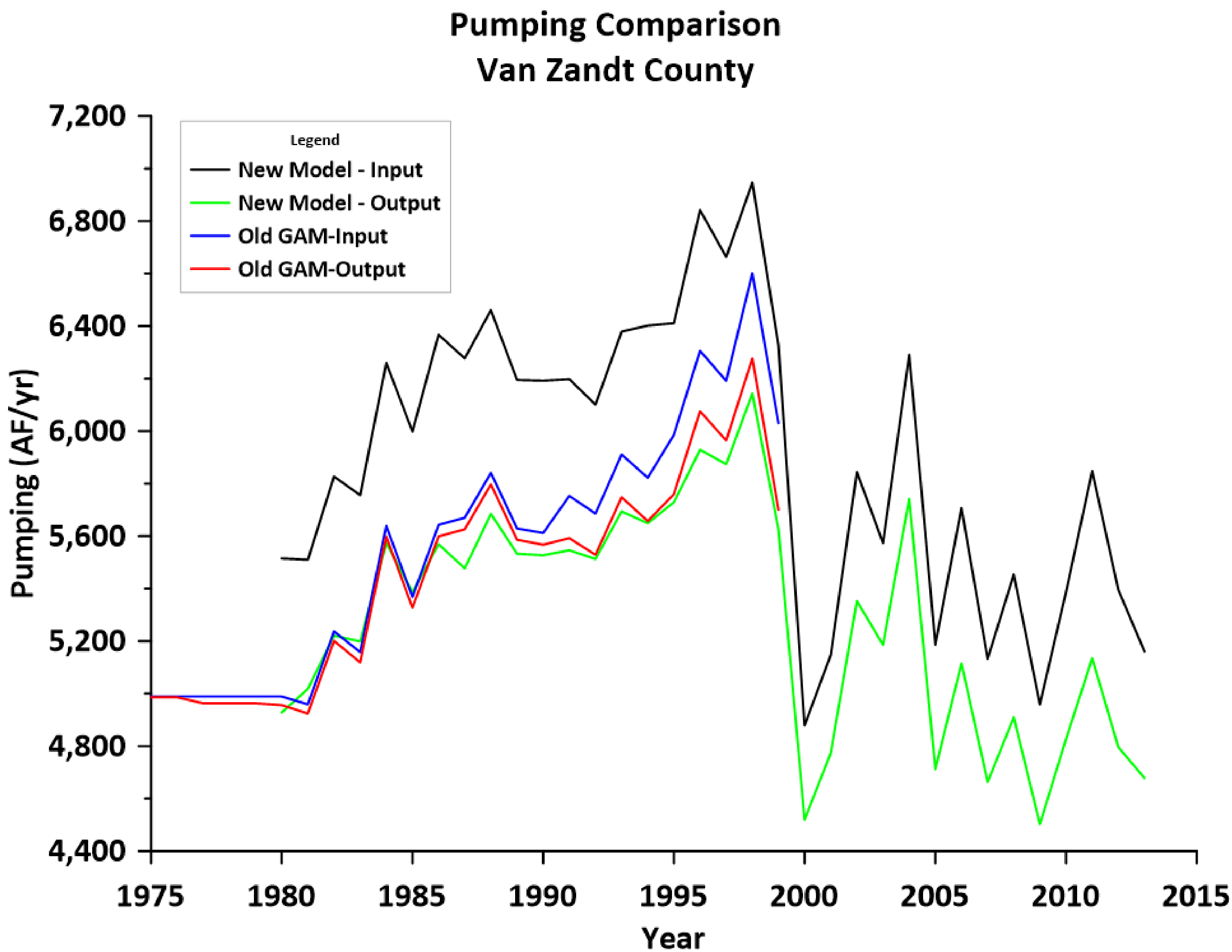

Pumping Comparison
Smith County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
22,000
21,000
20,000
19,000
18,000
17,000
16,000
15,000
14,000
13,000
12,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

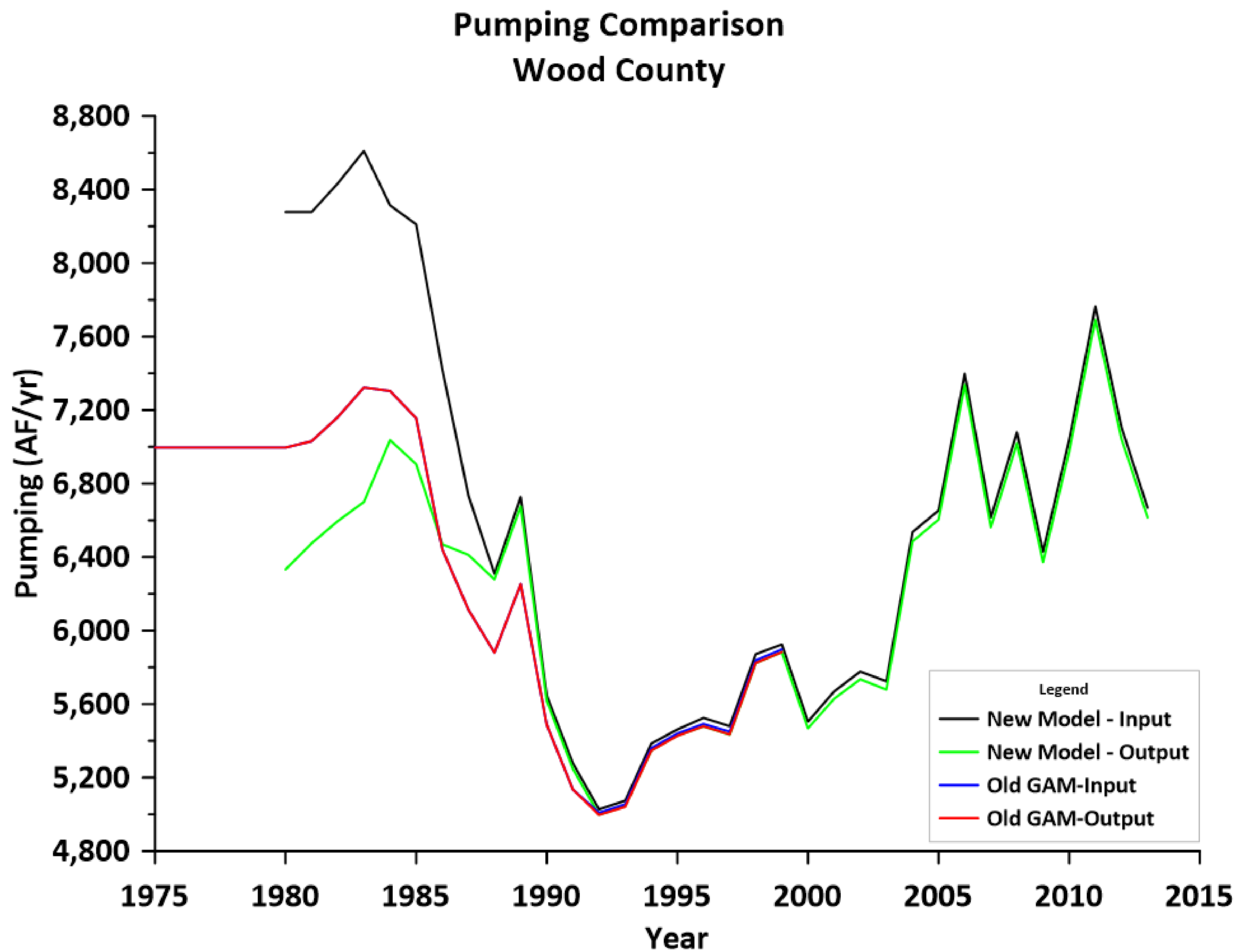


Pumping Comparison
Titus County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
2,500
2,400
2,300
2,200
2,100
2,000
1,900
1,800
1,700
1,600
1,500
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year


Pumping Comparison
Trinity County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
Year
56
52
48
44
40
36
32
28
24
20
1975
1980
1985
1990
1995
2000
2005
2010
2015


Pumping Comparison
Upshur County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
7,200
6,800
6,400
6,000
5,600
5,200
4,800
4,400
4,000
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year


Pumping Comparison
Van Zandt County
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output
Pumping (AF/yr)
7,200
6,800
6,400
6,000
5,600
5,200
4,800
4,400
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year



Pumping Comparison
Wood County
8,800
8,400
8,000
7,600
7,200
6,800
6,400
6,000
5,600
5,200
4,800
Pumping (AF/yr)
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
Legend
New Model - Input
New Model - Output
Old GAM-Input
Old GAM-Output

Appendix H – Responses to Comments

Comments provided by TWDB are dated November 4, 2020. Comments are shown in italics font. Responses to comments are shown in regular font.

<u>Draft Numerical Model Report comments (# 1 to 80)</u>

General comments to be addressed:

1. Per Contract Section II, Article III, number 5, please ensure that the final report complies with Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites).

Response: The final digital report will be formatted with accessibility features to comply with Texas Administrative Code Chapters 206 and 213.

2. Per Contract Exhibit B, Attachment 1, pages 29-30, please clearly identify each appendix required and any additional appendices in the final report

Response: Additional appendices were identified and have been added to the report. Final appendices consist of:

Appendix A: Table showing pumping totals per county by layer; tables showing model water balances for Conservation District or Texas counties within the model domain.

Appendix B: Table listing all targets for the numerical model; target text file listing all model observed and simulated pairs water level elevations, along with well information; and, hydrographs for select target wells.

Appendix C: Draft numerical model technical report.

Appendices D, E, and F: predictive simulation technical memos.

Appendix G: Response to comments.

3. Per Contract Exhibit B, Attachment 3, Guidelines for Authors Submitting Contract Reports, please use the Cambria font for all text and tables in the report. Some tables and the numbers for some sections, page numbers, and the headers are in Times New Roman.

Response: Cambria font has been used for all text and tables.

4. Per Contract Exhibit B, Attachment 3, Guidelines for Authors Submitting Contract Reports: Please follow the report format specifications in the author guidelines. For example, graphics should be within 1-inch margins and figures should be embedded within the text after being called out in the report. The figure caption should be part of the Word document and should not be part of the figure image.

Response: Figures and tables have been embedded in the report document. Figures are also provided as stand-alone files.

5. Per Contract Exhibit B, Attachment 3, Guidelines for Authors Submitting Contract Reports, please proofread the report before the final submittal. This report would benefit from a detailed *review for correct grammar, complete sentences, and clarity, particularly Section 3. Some items that need to be corrected are listed in the suggestions below, but additional review is recommended.*

Response: Editing of the report for clarity and grammar will be conducted prior to submittal of the final report.

6. References to figures in the conceptual model report do not match actual figure numbers in the conceptual model report. For example, on page 6 of the numerical model report (last paragraph, sentence 1), '…are shown on Figure 2.4-21 (Figure 2.2.2 of the Conceptual Model Report)', but there is no Figure 2.2.2 in the conceptual model report. In all instances where figures are compared to figures of the conceptual model report, please update the figure numbers to correctly reference to the conceptual model report.

Response: References to the Conceptual Model Report (Montgomery and Associates, 2020) are updated.

Specific comments to be addressed:

7. Section 2.0 Model Overview and Packages: Per Contract Exhibit B, Attachment 1, Section 3.2.4 Recharge and Surface Water, please discuss the reasoning for not using the drain package for springs in the numerical model report text. The conceptual model report Figure 5.0.1 (block diagram) lists springs and also includes discussion and data for springs in the study area.

Response: Section 2.9 of the report is edited for a discussion of springs in the model domain. Springs are not simulated in the model. Springs that contribute directly to river flows are indirectly simulated while springs that are isolated are not simulated but have negligible contributions to the system.

8. Section 2.0 Model Overview and Packages: Per Contract Exhibit B, Attachment 1, page 24, please include a final block diagram showing the hydrogeologic units and summarizing the flows within the model and how the conceptual model was translated into the computer model, updated with any changes from the conceptual model report, if necessary.

Response: Figure 2.0-2, Conceptual Block Diagram, has been added. This figure is based on the Conceptual Model Report figure by Montgomery and Associates (2020).

9. Page 6, Section 2.4.1 Stress Period Setup: Please explain why the model only extends to 2013 when the conceptual model report presents pumping information to 2015 and water level data even later. If the model had extended to 2015, then it would be more appropriate to compare the water level contours for 2015 from the conceptual model report to the water level contours at the end of the transient calibration.

Response: The model extends to 2013 in accordance with the technical approach laid out in the contract. This choice was also supported by the available pumping and water level elevation data for the model domain. Simulating the model to 2013 is discussed in Section 2.4.1.

10. Section 2.4.2 Model Domain Discretization (DIS), Figures 2.4-2 through 2.4-20: Many of these figures show isolated cells. Please confirm if these isolated cells were used or, as suggested later in the report, as possibly representing salt domes. If they were later discarded, please update these figures and other figures in the report to reflect what was in the final model.

Response: The report text in Section 2.4.2 was edited to state that discontinuous sections of geologic units are simulated in the model but the cells are not isolated, rather they are connected to other model cells vertically above or below.

11. Section 2.4.2 Model Domain Discretization (DIS), Figures 2.4-2 through 2.4-20: There is not a figure for the top elevation of the Sparta (model layer 2). Please include a figure of the top elevation of layer 2.

Response: A figure was added to show the top elevation of model layer 2, Figure 2.4-5.

12. Section 2.4.2 Model Domain Discretization (DIS), Figures 2.4-15 through 2.4-20: The layer extents in the bottom elevation figures do not match the layer extent in the thickness figures. Please update the thickness figures to accurately represent layer extents for layers 7, 8, and 9 or provide an explanation in the text for the discrepancy between the extent (footprint) of the layer bottom elevation and the layer thicknesses for layers 7, 8, and 9.

Response: The layer shapefiles were switched. Figures have been corrected.

13. Section 2.4.2 Model Domain Discretization (DIS), Figure 2.4-31: There are several grid cells that appear to be floating above the aquifer. Please clarify if these were later removed or what was missing below these grids as they do not appear to represent faults or salt domes. If they were removed, please update the figure with what was modeled.

Response: The report text in Section 2.4.2 was edited to state that discontinuous sections of geologic units are simulated in the model but the cells are not isolated, rather they are connected to other model cells vertically above or below.

14. Section 2.5 Node Property Flow (NPF) Package: The MODFLOW 6/Groundwater Vistas file set includes a file with the extension '.sand'. Please clarify if this file was used for the calculation of the hydraulic conductivity values and if the file used by Groundwater Vistas or MODFLOW 6. Please discuss the sand (.sand) file included with the MODFLOW 6 input files and please discuss how it is used in the text of the report.

Response: The report text of Section 2.5 was edited to explain that '.sand' files are generated by Groundwater Vistas when the leakance property is used to store sand fraction values. Groundwater Vistas uses the file to calculate the effective model hydraulic conductivity of each layer.

15. Section 2.5 Node Property Flow (NPF) Package: The MODFLOW 6/Groundwater Vistas file set includes files with the extensions '._kz' and '._kx'. Please clarify if these files are used by Groundwater Vistas or MODFLOW 6 and please discuss in the report text how the files are used.

Response: The report text of Section 2.5 was edited to explain that horizontal and vertical hydraulic conductivity values calculated by Groundwater Vistas are saved in the text files with the extensions 'kx' and 'kz', respectively.

16. Section 2.6 Storage (STO) Package: The MODFLOW 6/Groundwater Vistas file set includes files with the extensions '._ss' and '._sy'. Please clarify if these files are used by Groundwater Vistas or MODFLOW 6 and please discuss in the report text how the files are used.

Response: The report text of Section 2.6 was edited to explain that these files are created by Groundwater Vistas and called by the MODFLOW 6 Storage package.

17. Section 2.7 WEL Package: Per Contract, Exhibit B, Attachment 1, Section 2.4, Well (WEL) Package, please include a table of total pumping per county per stress period for each layer.

Response: A table has been created showing pumping by county per stress period and per layer. Due to the large size of the table, it is being provided as part of Appendix A rather than imbedded in the report document.

18. Page 9, Section 2.7 WEL Package, second to last sentence: Please revise this sentence to read something along the lines of 'The water level datasets were considered to be more reliable because they are directly measured values; whereas the water use estimates in the TWDB database include values which are, in some cases, estimated from indirect methods.'

Response: This sentence has been added to the Section 2.7.

19. Page 10, Section 2.7 WEL Package, first full paragraph, sentence 3: The text states 'the previous model data represents pumping from 1980 through 2005.'However, the previous GAM represents pumping from 1980 through 1999 in stress periods 6 through 25. Stress periods 1 through 5 represent a transient adjustment period to go from predevelopment to 1980 and were not calibration stress periods (Section 6.2.3 Model Simulation Periods in previous GAM Report). Please clarify this discrepancy in the report.

Response: The draft report incorrectly stated that the previous model extended through 2005. Section 2.7 has been edited to state that the previous model ended in 1999.

20. Section 2.7 WEL Package, Figures 2.7-2 to 2.7-7: Please update the figure legends to include the years used to calculate the total pumping.

Response: The figure legends have been updated to say "1980 to 2013 total pumping".

21. Section 2.7 WEL Package, Figure 2.7-8b: Please clarify the pumping in Morris County is not an outlier and if applicable, please adjust figure and model accordingly. In addition, please confirm the high and abrupt pumping in the Carrizo Sand in Hopkins County is realistic.

Response: The text in Section 2.7 has been edited to discuss uncertainty in the pumping data for Morris and Hopkins counties.

22. Section 2.8 General Head Boundary (GHB) Package, Table 2.8-1, Layer 2 Hydraulic Feature: Table 2.8-1 lists the GHB feature in layer 2 as a lateral boundary; however, the discussion in the text describes it as interaction with younger units. Please review and investigate if this should be described as something other than a lateral boundary in Table 2.8-1. Please verify the table and update if necessary

Response: Table 2.8-1 has been updated to show that the GHB feature in model layer 2 represents interaction with the Younger Units.

23. Page 11, Section 2.9 RIV Package: Please discuss in the text of the report how reservoirs and lakes were modeled. If they are part of the RIV package, please discuss the advantages and disadvantages of using this package instead of the LAK package.

Response: Section 2.9 has been edited to state that lakes and reservoirs are not simulated in the model although reservoirs along rivers are indirectly simulated.

24. Section 2.10 RCH Package: Per Contract Exhibit B, Attachment 1, page 6, Section 3.1.6 Recharge, please discuss how 'rejected recharge' was modeled in the numerical model report text. The conceptual model report includes a discussion of rejected recharge, but the numerical model report does not clarify that rejected recharge was addressed in the model.

Response: Section 2.9 was edited to discuss rejected recharge as a flow component not directly simulated in the model.

25. Page 15, Section 3.1.2 Calibration of Aquifer Parameters, paragraph 1: The manual adjustments to the storage coefficient (3.898x 10-8) and specific yield (0.0007) seem extremely low. According to Freeze and Cherry (1979), in confined aquifers, storage coefficients range in value from 0.005 to 0.00005. Please verify if the storage parameter reported is actually the specific storage and not the storage coefficient. If not the specific storage, please justify and provide references for the storage coefficient having values three orders of magnitude lower than the lowest end of the published range. Even if this storage parameter is specific storage, it appears to be on the very low end of the range. Please discuss reasoning and justification for this value.

Response: The values referenced above are for specific storage and not the storage coefficient. The value reflects compressibility of water but not the matrix and therefore represents a low end of values. Section 3.1.2 was edited to make clear this more clear. Also, it is noted to not be a sensitive parameter.

26. Page 15, Section 3.1.2 Calibration of Aquifer Parameters, paragraphs 2 and 4 and Table 3.1-2: The calibrated value of horizontal hydraulic conductivity for the Carrizo (0.12 feet per day) is less than the lower end of the observed range (0.3 to 198 feet per day), much less than the horizontal hydraulic conductivity of the Weches Formation, and almost equal to the horizontal hydraulic conductivity of the Reklaw Formation. The Reklaw and the Weches are confining units and the Carrizo Sand is a productive aquifer. In the model of the central portion of the Queen City, Sparta, and Carrizo aquifers, the mean value of hydraulic conductivity for the Carrizo Aquifer is 8.6 feet per day with a range of 2.01 to 23.9 feet per day. In the predictive model run for this project, the Carrizo Aquifer has significantly more pumping that the other aquifers except the Queen City Aquifer (see Table 1 of the Predictive Model report for this project); therefore, it is important for this layer to have realistic properties. Please discuss whether the very low value of hydraulic conductivity for the Carrizo Aquifer (0.12 feet per day) in this model is reasonable.

Response: The calibrated horizontal hydraulic conductivity for the Carrizo Aquifer was increased to 7.04 feet per day in the Final Calibrated model as discussed in Section 3.1.

27. Section 3.2.2 Simulated Versus Observed Heads: Per Contract Exhibit B, Attachment 1, page 27, Section 3.2 Model Simulated Versus Measured Heads, please provide a histogram of the frequency of residuals in each model layer.

Response: Histogram figures have been created and are discussed in Section 3.2.3.

28. Page 18, Section 3.2.2 Simulated Versus Observed Heads, paragraph 1 and Table 3.2-4: Per contract Exhibit B, Attachment 1, page 11, Section 3.3 Model Calibration, 'the mean absolute error or root mean squared error shall be less than 10 percent of the measured hydraulic-head drop across the *model area for each model layer, and better if possible.' Calibration statistics for the Queen City Aquifer layer are about 20 percent of the range in heads. In the predictive model run for this project, the Queen City Aquifer has significantly more pumping that the other aquifers (see Table 1 of the Predictive Model report for this project); therefore, it is important for this layer to be well calibrated. Please consider improving the calibration of the Queen City Aquifer or justify why it is not possible to get a better calibration fit for the Queen City Aquifer layer. If the calibration cannot be improved, this should be included in the Modeling Limitations and Future Improvement sections of the report.*

Response: The calibration statistics were improved for the Queen City Aquifer (model layer 4) by examining the target wells within the layer and moving 8 target wells to the aquifers above and below. Updated calibration statistics are shown in Table 3.2-4. Target layer assignments are shown in the Appendix B Table 1, Model Targets and Weights for 1980 to 2013 Simulation. Section 3.2 discusses these changes further.

29. Section 3.2.2 Simulated Versus Observed Heads: Per Contract Exhibit A, page 37, item F, you proposed to test MODFLOW-2005, MODFLOW-NWT, and MODFLOW-USG to select the best alternative to suit the modeling effort. MODFLOW 6 was released after your response to the request for qualifications. Based on conversations during update meetings between the contract team and the TWDB, MODFLOW 6 was an acceptable substitution for MODFLOW-USG, however, we discussed that testing was still needed for MODFLOW-2005 and MODFLOW-NWT to ensure MODFLOW 6 is the best alternative. Please include a more detailed discussion of the code selection process, tests with other versions of MODFLOW, and discuss further why MODFLOW 6 was chosen.

Response: We have tested MODFLOW-NWT and the test is presented in the report. Statistics are similar to the MODFLOW 6 simulation. A MODFLOW 2005 test simulation is also discussed in the model report. The test run could not converge. MODFLOW-2005 is an outdated scheme that has issues with drying and rewetting of cells which is then overcome using heuristic methods, if at all. That makes the solution unreliable, if it does converge.

30. Section 3.2.5 Simulated Water Levels, Figure 3.2-39: There appears to be a missing hole of data in Angelina and Nacogdoches counties or the color ramp range does not include the data within that hole where drawdown exceeds 24 feet. Please verify and extend the color ramp to the full range if necessary.

Response: The figure is corrected. The figure number has been updated to 3.2-40.

31. Section 3.2.5 Simulated Water Levels, Figures 3.2-46 and 3.2-47: These figures appear to have the modeled water levels results for the Middle Wilcox (Layer 8) and Lower Wilcox (Layer 9) extents switched. Please verify and update as necessary. Also, please verify that they are shown with the correct contour estimates from the conceptual model.

Response: These figures have been corrected; figure numbers have been updated to Figures 3.2-47 and 3.2-48.

32. Section 3.3 Model Simulated Versus Measured Baseflow, Figure 3.3-2: The water budget periods appear to be shifted one year to the right. The last model stress period represents 2013, but this chart show values plotted in 2014. Please clarify and/or update this chart.

Response: Figure 3.3-2 has been corrected.

33. Section 3.4 Model Simulated Water Budgets, Table 3.4-2: Comparing the budget terms in the table for recharge and evapotranspiration to the MODFLOW 6 listing file and Figure 3.4-1, Table 3.4-2 shows much lower recharge and evapotranspiration. This could be from the mass balance error shown in Table 3.4-2 (6.75 percent—one percent or less is expected). For example, the MODFLOW listing file shows a recharge value of 703,820 acre-feet per year. The river package terms in Table 3.4-2 appear rather high as well. Please re-evaluate the budget presented in Table 3.4-2 and verify that it is consistent with the MODFLOW 6 listing file. The mass balance error in the MODFLOW 6 listing file is zero percent.

Response: A bug in Groundwater Vistas resulted in the graphic user interface providing different mass balance values than the MODFLOW output. The bug has been corrected and mass balance matches MODFLOW. There remains a minor difference reflecting net values for model nodes with multiple river cells and for net storage from cells. However, the IN minus OUT term (the net flux to/from the river boundary) is preserved. Mass balance tables for the final and draft models have been updated.

34. Section 3.4 Model Simulated Water Budgets, Table 3.4-2: Please indicate whether the budget summary table is an average for all stress periods or whether it is the budget at the end of the simulation. If it is an average, please include the years averaged in the caption or legend and please also include a budget table for stress period 34, time step 5 (end of the simulation).

Response: The table title has been updated to say "Water Budget by Layer at End of Transient 1980 to 2013 Simulation".

35. Section 3.4 Model Simulated Water Budgets, Figure 3.4-1: The water budget periods appear to be shifted one year to the right. The last model stress period represents 2013, but this chart show values plotted in 2014. Please clarify and/or update this chart.

Response: Figure 3.4-1 has been updated.

36. Page 24, Section 4.1 Procedure of Sensitivity Analysis, paragraph 1: Previous paragraphs in this section state that parameters with significant changes to model predictions changes, but insignificant changes to model calibration residuals, would be Type IV. This paragraph says that parameters with small prediction changes will be classified as Type IV and parameters with large prediction changes will be classified as Type I. Please review the last paragraph of this section and clarify as appropriate.

Response: The classification descriptions were incorrect in the draft report. The text has been edited.

37. Page 24, Section 4.2.1 Sensitivity to Aquifer Hydraulic Conductivity Parameters, paragraph 3: This paragraph states that the Middle and Lower Wilcox and Queen City layers showed hydraulic conductivity sensitivity and that 'the remaining layers show little to no sensitivity to increases or decreases in the sand hydraulic conductivity.' Considering that insensitivity, the hydraulic conductivity of the Carrizo Aquifer could be increased to a value more reflective of the data range without affecting the model calibration. See comment 25 above.

Response: The calibrated horizontal hydraulic conductivity for the Carrizo Aquifer was increased to 7.04 feet per day for the Final Calibrated model as discussed in Section 3.1.

38. Section 7.0 Future Improvements: Thank you for including the comment on sand fractions and hydraulic conductivity in the future improvement section. While sand fractions are less reliable than pump test data to estimate hydraulic properties (transmissivity and storage coefficients), better options are available. In the conceptual model report, there were about 3,000 hydraulic conductivity values available from specific capacity tests and pumping tests in the study area. Please include a point in this section discussing that pump test data supplemented with sand fraction data would improve calibration.

Response: This item has been added as a recommendation in Section 7.0.

39. Appendix A: Per Contract Exhibit B, Attachment 1, page 29, Appendix A of the report should contain water budgets for the model by county, groundwater conservation district, and layer. Please provide water budgets by county, groundwater conservation district, and layer in Appendix A.

Response: Tables showing water budgets per conservation district or county have been created and are included in Appendix A.

40. Appendix D, Draft Technical Memorandum 3, Table 1: The total pumping amounts for the Queen City and Carrizo aquifers in the file developed for joint planning in the last cycle (Scenario 4) for the Queen City and Carrizo aquifers are significantly greater than the other model aquifer layers. However, the calibration statistics for the Queen City Aquifer in the draft model are about 20 percent, and the calibrated hydraulic conductivity for the Carrizo Aquifer layer is 0.12 feet per day, which is below the lower end of the observed hydraulic conductivity range for the Carrizo Aquifer in the study area. Please discuss the impact that the uncertainty in properties for these two layers might have on the model-calculated drawdown given that they account for most of the predictive pumping in the model.

Response: The final model has updated hydraulic conductivity in the Carrizo Aquifer and improved calibration statistics for the Queen City Aquifer. However, these are still the highest pumping layers in the predictive simulations. Although the calibration is improved, it follows that, given the high pumping, the uncertainty would manifest more in these layers than in the others. However, the primary objective of the predictive simulations was to compare variations in pumping and variations in recharge. Thus, the analyses were more comparative which are less likely to be affected by uncertainty. Most importantly, the predictive simulations demonstrated that equilibrium conditions are observed within 10 to 20 years with constant pumping and/or constant recharge, which was not observed with the old GAM and a major limitation in using the old GAM for joint planning.

Suggestions for the Numerical Model Report:

41. Please remove the TWDB logo from the cover of the report.

Response: The logo has been removed.

42. Please use the Oxford comma consistently throughout the report.

Response: The text has been proofread and the Oxford comma used.

43. Please spell out 'percent' instead of using '%'.

Response: '%' has been replaced by 'percent'.

44. Please consistently use either ‘MODFLOW6’ or ‘MODFLOW 6’.

Response: The final report uses ‘MODFLOW 6’.

45. Please avoid all acronyms except TWDB with the words spelled out. Some exceptions include MODFLOW package names, other MODFLOW terminology, and ASTM after they have been described. Also, please refer to the model as the ‘groundwater availability model for the northern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers’ rather than the ‘northern QCSCW’ throughout the report.

Response: Acronyms have been minimized in the report. The model name has been updated.

46. When referring to the Sparta Aquifer or Queen City Aquifer in an official aquifer context, please do not use ‘sand’.

Response: ‘Sand’ has been replaced by ‘aquifer’ in the report text, tables, and figures.

47. When referring to multiple counties in a list, please do not capitalize ‘counties’. For example, ‘Rusk County’ versus ‘Rusk and Panola counties’.

Response: Text has been edited.

48. Please consider using ‘to’ to show a range of years or values throughout the text and in all the figures instead of a dash. For example, ‘1983 to 2013’ or ‘-31 to -25’.

Response: Text has been edited in the report, tables, and figures.

49. For tables that span across multiple pages, please add ‘continued’ starting on the second page to the captions to indicate there is more to the table. For example, ‘Table 3.2-1 (continued) Model Targets and Weights…’.

Response: Since the table showing 1,797 targets was moved to Appendix B, there are no tables within the report text that are more than 1 page. However, the usage of “continued” is used for appendix tables.

50. Please update all figures that have labels for Arkansas and Louisiana to include a label for Texas. In addition, please add state labels to all related figures, including, but not limited to, figures 3.1-2, 3.1-3, 3.1-4. 3.1-5, 3.1-7, 3.1-8, and 3.1-10.

Response: Figures showing the three states have been updated for a Texas label.

51. Page 1, Executive Summary, paragraph 1, sentence 1: please change ‘Groundwater Availability Model (GAM) program’ to ‘Groundwater Availability Modeling program’.

Response: The text has been updated.

52. Page 1, Executive Summary, paragraph 1, sentence 2: Please change ‘norther’ to ‘northern’.

Response: The text has been updated.

53. Page 3, Section 1.0 Introduction and Purpose of the Model, paragraph 1, sentence 2: Please change ‘norther’ to ‘northern’.

Response: The text has been updated.

54. Page 3, Section 1.0 Introduction and Purpose of the Model, paragraph 1, last sentence: Please make this incomplete sentence complete.

Response: The text has been updated.

55. Page 3, Section 1.0 Introduction and Purpose of the Model, paragraph 2, last sentence: Please change 'groundwater Management Area' to 'Groundwater Management Area'.

Response: The text has been updated.

56. Section 2.0 Model Overview and Packages: Throughout this section, please spell out the MODFLOW package names in the section headings and spell out the first instances of the abbreviations in the body text for each section discussing the packages, as is done for some of the package sections.

Response: Headers have been updated and the package names spelled out in the first instance.

57. Page 4, Section 2.1 MODFLOW6 Overview and Packages, second paragraph, first sentence: Please correct the Mehl and Hill reference year to match what is listed in Section 9, References.

Response: The text has been updated.

58. Section 2.1 MODFLOW6 Overview and Packages, Figure 2.1-1: The county/parish boundary does not add useful information to the map and items in the study area. Please consider moving that layer on top of the model layer.

Response: The figure has been updated and county labels added.

59. Section 2.4 Discretization (DIS) Package: Table 2.4-2 does not appear to be cited anywhere in the text. Please mention Table 2.4-2 in the text at least once.

Response: The text has been updated.

60. Page 6, Section 2.4.2 Model Domain Discretization (DIS), paragraph 1, sentence 4: Please do not capitalize 'major and minor aquifers'.

Response: The text has been updated.

61. Page 6, Section 2.4.2 Model Domain Discretization (DIS), paragraph 1: Please review this paragraph for consistent use of past tense.

Response: The text has been updated.

62. Page 7, Section 2.5 Node Property Flow (NPF) Package, paragraph 1, sentence 1: Please spell out the first instances of 'NPF' and 'STO'.

Response: The text has been updated.

63. Page 7, Section 2.5 Node Property Flow (NPF) Package, paragraph 3, sentence 1: Please correct the spelling of the Weches Formation.

Response: The text has been updated.

64. Page 8, Section 2.5 Node Property Flow (NPF) Package, equations: Please consider replacing the two equations with higher resolution images to better read the subscripts.

Response: The equations are now typed in instead of being graphics.

65. Section 2.5 Node Property Flow (NPF) Package, Figure 2.5-4: Please revise the legend to match the other sand fraction figures.

Response: The figure legend has been corrected.

66. Section 2.7 WEL Package, Figures 2.7-2 through 2.7-7: Please consider making the points displayed on the map slightly transparent.

Response: The figure has been updated with transparent dots.

67. Section 2.7 WEL Package, Figures 2.7-8a through 2.7-8e, pumping by county figures: Please consider making the outlines for the charts match the symbology in the legend. The dotted line for a 5,000 acre-feet per year axis range does not read like a dotted line border on the charts.

Response: The symbology has been updated to better match the chart outlines.

68. Section 3.1.1 Calibration of Recharge: The calibrated groundwater recharge for the years 1981 to 2013 was based on 1980 and was adjusted using factors. It would be helpful to the readers if a comparison between the simulated recharge and precipitation is presented for those years.

Response: A new figure has been created which shows the initial and calibrated recharge factors for the model, Figure 2.10-2.

69. Page 17, Section 3.2.2 Simulated Versus Observed Heads: Please spell out the first instance of 'RMS'.

Response: The text has been updated.

70. Page 18, Section 3.2.2 Simulated Versus Observed Heads, paragraph 3, sentence 2: Please remove the extra 's' after 'Figure 3.2-9'.

Response: The text has been updated.

71. Page 19, Section 3.2.4 Water Level Hydrographs, sentence 3 and Figure 3.2-17: Please change the sentence to '…except for the well in Caddo County where simulated water levels are higher than observed'.

Response: The text has been updated.

72. Page 20, Section 3.2.5 Simulated Water Levels, paragraph 2: Please review this paragraph for clarity, spelling, and grammar.

Response: The text has been reviewed and updated.

73. Page 20, Section 3.2.5 Simulated Water Levels, paragraph 3, sentence 3: Please edit this sentence for clarity.

Response: The text has been updated.

74. Page 22, Section 3.3 Model Simulated Versus Measured Baseflow, paragraph 2, second to last sentence: Please use 'baseflow' rather than 'base flow'.

Response: The text has been updated.

75. Section 3.3 Model Simulated Versus Measured Baseflow Figure 3.3-1: Please consider adding labeled counties to this figure.

Response: The figure has been updated for county labels.

76. Section 4.1 Procedure of Sensitivity Analysis: Please consider organizing the four sensitivity types listed after the third paragraph in a bulleted list.

Response: The text has been updated.

77. Page 29, Section 7.0 Future Improvements, bulleted list: Please be consistent in using either a semi-colon or period for each item.

Response: The text has been updated.

78. Section 9.0, References: Please correct the formatting of the Panday reference to match the other references.

Response: The text has been updated.

79. Section 9.0 References: Please remove the reference for Intera, 2004. This is the same reference as Kelley and others, 2004.

Response: The text has been updated.

80. Appendix B, Draft Technical Memorandum 1, Section 2.0 Background, paragraph 2, last sentence: There appears to be missing text between 'amount' and 'develop'. Please review this sentence and update as necessary.

Response: The technical memo has been updated.

Draft Final Conceptual Model Report comments (# 81 to 99)

These comments and responses are provided in the Conceptual Model Report (Montgomery and Associates, 2020).

Draft Model File Deliverables comments (#100 to 101)

100. The Groundwater Vistas file included with the draft deliverables crashes when attempting to producing a mass balance hydrograph. Please provide suggestions about how to use Groundwater Vistas to post-process the water budget.

Response: Groundwater Vistas bug has been fixed to resolve this issue.

Suggestions for Draft Model File Deliverables:

101. The discretization file for the calibrated model written by Groundwater Vistas has an extension name of '.dis'; the discretization file included with the predictive model has an extension of '.disu'. These files are identical. However, when Groundwater Vistas loads the MODFLOW 6 output files for post-processing, it is looking for a binary grid file with the extension '.dis.grb' not '.disu.grb'. Therefore, for output files of these predictive runs to be compatible with the calibrated model Groundwater Vistas file it is better if the extension for the discretization file be renamed ".dis".

Response: The '.disu' files were converted to '.dis' files and the technical memos were updated.

Draft Geodatabase and Data Deliverables comments (# 102 to 114)

These comments and responses are provided in the Conceptual Model Report (Montgomery and Associates, 2020).

Draft Leapfrog Deliverables Comments (#115 to 117)

These comments and responses are provided in the Conceptual Model Report (Montgomery and Associates, 2020).

Draft BRACS Database and Data Deliverables comments (# 118)

This comment and response are provided in the Conceptual Model Report (Montgomery and Associates, 2020).

Addendum

The TWDB received final deliverables for this contract on December 11, 2020. Further clarification was required during review of the final deliverables. TWDB comments and contractor responses are summarized below:

Note: Contractor responses to comments are shown below in italic font.

1. The final conceptual model and numerical model reports do not pass accessibility checks in Adobe Acrobat (see comments #1 and #82). Please fix any alternative text issues and other accessibility issues that are indicated in accessibility reports within Adobe Acrobat.

   A revised accessible document was provided on February 2, 2021 to TWDB. Additional accessibility issues were addressed during February 2021, with submittal of a final document on February 8, 2021.

2. Table 3.4-2 in the numerical model report appears to have been corrected as requested in comment #33, but the value in the Total Inflows row for Layer 1 is equal to the Total Model Flows value. Please check the table and update as necessary.

   A revised table 3.4-2 with corrected mass balance values for layer 1 was submitted to TWDB on January 26, 2021. A revised table 3.4-2 text file was also submitted to replace the data table in the geodatabase.

3. Groundwater Vistas (version 7.24 Build 266; downloaded 12/16/2020) still crashes when attempting to generate a mass balance hydrograph (comment #100 in Appendix H of Numerical Model Report). Will this be fixed in Groundwater Vistas 8?

   Yes, this has been fixed in Version 8 of Groundwater Vistas.

4. The model will not run with the latest version of MODFLOW 6 on the U.S. Geological Survey website (version 6.2.0) dated 10/22/2020. It runs with the version of MODFLOW 6 (mf6.exe) provided with the predictive model files and provided with the Groundwater Vistas 7 software folder (version 6.0.5) dated 4/20/2019. MODFLOW 6 version 6.1.1 (6/11/2020) results in the same errors.

   The later version of MODFLOW 6 (version 6.1.1) does additional checking of "gaps" between formations and, if found, stops the run rather than posting a warning. In constructing the model, any unit that had a thickness of 5 feet or less was built as a pinch-out. The resulting construction with pinch-out "gaps" should not impact results except that it creates issues with running the model with version 6.1.1. We will request USGS to post this issue as warnings instead of stopping execution in later releases of the code.