Final: Application of Geostatistical Techniques to Quantify Changes in Water Levels

Prepared for:

Calhoun County Groundwater Conservation District
Refugio Groundwater Conservation District
Texana Groundwater Conservation District
Victoria County Groundwater Conservation District

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EXECUTIVE SUMMARY

The study accomplished the following tasks for Calhoun County Groundwater Conservation District (GCD), Refugio GCD, Texana GCD, and Victoria County GCD:

1. Assembled measured groundwater elevations from GCD and Texas Water Development Board (TWDB) databases over the interval from 2000 to 2020 and integrated them into a single data set;
2. Employed geostatistical methods for interpolating annual groundwater for the Chicot and Evangeline aquifers from 2000 to 2020;
3. Evaluated the annual changes in the measured groundwater elevations across the four counties and in selected wells;
4. Provided recommendations for future work.

Dataset of Measured Water Levels

Water level data were assembled from 658 wells from the TWDB groundwater database for Calhoun, Jackson, Refugio, and Victoria counties and for nine surrounding counties. Groundwater data were also assembled from 258 wells from the four GCDs that manage groundwater in Calhoun, Jackson, Refugio, and Victoria counties. The integration of the two data sets included identifying wells that were shared in both data sets but were assigned different names. One hundred twenty-seven wells were matched between the two data sets based on well depths, well location, and measured water levels. Annual water levels were determined for each year using measured water levels over a 6-month period. A total of 6,081 annual water levels were created from 2000 through 2020 at 801 wells for the 13 counties. Out of the 801 wells, 253 of the wells were located in Calhoun, Jackson, Refugio, and Victoria counties.

Spatial Interpolation of Measured Groundwater Elevations

Ordinary Kriging was used to interpolate the annual water levels. Kriging is a geostatistical interpolation technique that considers both the distance and the degree of variation between known data points when estimating values in unknown areas. Ordinary Kriging provides the best linear unbiased prediction at unsampled locations and reproduces the measured values at all sampled locations exactly. To meet underlying assumptions to apply Kriging, the measured water levels were detrended prior to the application of Kriging using water levels simulated by the central Gulf Coast Groundwater Availability Model (GAM). Ordinary Kriging was implemented using a six-step process described below:

Step #1 - Assemble and inspect the data for evidence of a trend.

Step #2 – Develop a trend surface based on a smoothing the water levels simulated by the GAM.

Step #3 – Calculate the residual at each well location -- a residual is the difference between the measured value and value produced by the trend. Check whether the set of calculated residuals are normally distributed. If the residuals do not resemble a normal distribution, then repeat Step #2.

Step #4 – Construct an experimental and a theoretical semivariogram for the set of residuals for the Chicot Aquifer and for the Evangeline Aquifer.

Step #5 – Krige the residuals to produce a continuous surface across the area of interest.

Step #6 – Combine the trend surface and the Kriged surface to generate the final surface.

The residuals calculated in Step #3 were shown to approximate a normal distribution based on visual comparisons of the theoretical and actual distribution function and by statistical comparison using Liffiefors test for normality based on the Kolmogorov-Smirnov test. All of the experimental semivariograms generated from the analysis were fitted to spherical theoretical variogram models.

Ordinary Kriging was used to interpolate the water level residuals for the years 2000 through 2020 for both the Chicot Aquifer, the Evangeline Aquifer, and the Chicot and Evangeline Aquifer, which is created by combing the Chicot and Evangeline aquifers into single aquifer. The interpolation generated interpolated surfaces with a resolution of 1,000 feet (ft) for each year from 2000 to 2020. Using these surfaces, the average water levels were calculated by county and by year. The tabulation below shows results for the results at five-year intervals.

County	Aquifer	Water Level Metric	2000	2005	2010	2015	2020
Calhoun County	Chicot	avg. WL (ft, msl)	-7.0	1.9	-2.6	-7.7	-2.6
		WL change (ft)*	0.0	8.9	4.4	-0.6	4.5
	Evangeline	avg. WL (ft, msl)	17.7	13.3	18.1	3.6	16.4
		WL change (ft)*	0.0	-4.4	0.4	-14.2	-1.3
	Chicot & Evangeline	avg. WL (ft, msl)	-3.2	3.3	0.4	-6.1	0.5
		WL change (ft)*	0.0	6.6	3.6	-2.8	3.7
Jackson County	Chicot	avg. WL (ft, msl)	21.3	29.3	27.1	22.1	28.0
		WL change (ft)*	0.0	8.0	5.8	0.8	6.7
	Evangeline	avg. WL (ft, msl)	17.0	22.0	17.1	12.0	15.9
		WL change (ft)*	0.0	5.1	0.1	-4.9	-1.0
	Chicot & Evangeline	avg. WL (ft, msl)	19.0	25.6	22.0	16.9	21.9
		WL change (ft)*	19.1	6.6	3.0	-2.1	2.9
Refugio County	Chicot	avg. WL (ft, msl)	24.8	28.3	22.7	14.5	18.4
		WL change (ft)*	0.0	3.5	-2.1	-10.3	-6.4
	Evangeline	avg. WL (ft, msl)	32.5	40.7	21.7	22.3	30.9
		WL change (ft)*	0.0	8.1	-10.8	-10.3	-1.7
	Chicot & Evangeline	avg. WL (ft, msl)	26.3	31.8	20.7	16.7	22.6
		WL change (ft)*	0.0	5.6	-5.5	-9.5	-3.7
Victoria County	Chicot	avg. WL (ft, msl)	49.8	52.6	52.8	48.2	47.9
		WL change (ft)*	0.0	2.8	3.0	-1.6	-1.9
	Evangeline	avg. WL (ft, msl)	29.8	48.9	44.8	41.4	39.1
		WL change (ft)*	0.0	19.1	15.0	11.5	9.3
	Chicot & Evangeline	avg. WL (ft, msl)	41.3	52.2	50.2	46.3	45.1
		WL change (ft)*	0.0	10.9	8.9	5.0	3.8

Note: WL=water level elevation, change is measured relative to 2000; ft = feet; msl = mean sea level
negative numbers indicate a decline in groundwater elevation over time

Alternative Water Level Maps

Because the method used to detrend and Krige the measured water levels has not been used in Texas prior to this study, the method was compared to several alternative methods for constructing water level maps to investigate the sensitivity of the results to changes in the method's implementation and to compare the results produced by alternative methods. Among some of the notable observations are:

- The Kriged values results are not very sensitive to the amount the GAM-simulated water levels are smoothed to generate the trend surface used for detrending.
- The Kriged results can be very sensitive if the trend surface is updated to account for annual differences in the GAM simulations that account for different pumping rates.
- The Kriging of water levels without detrending can produce significantly different results than Kriging with detrending.
- The results for the Evangeline Aquifer are more sensitive to changes in how Kriging is performed than results for the Chicot Aquifer.

Spatial and Temporal Changes in Water Levels

The surfaces generated by Kriging the measured water levels were used to generate maps showing the spatial distribution of water level change across Calhoun, Jackson, Refugio, and Victoria counties. The maps were generated for the Chicot Aquifer and the Evangeline Aquifer for 20-, 10-, and 5-year intervals. Notable changes from 2000 to 2020 are:

Calhoun County

- Chicot Aquifer: Water levels rose across about 80% of the county. The largest increase of about 20 ft occurred in northeast. Areas of decrease occurred in northwest and north regions.
- Evangeline Aquifer: Water levels dropped across about 70% of the county. The largest decrease of about 7 ft occurred in the northeast.

Jackson County

- Chicot Aquifer: Water levels rose across about 90% of the county. Increases of about 25 ft occurred in northeast and of about 20 ft occurred in south. In the remaining areas, water levels dropped less than 5 ft.
- Evangeline Aquifer: Water levels increased across about 50% of the county with the largest increase of about 12 ft occurring in the northern region. Water levels dropped across the remaining county with the greatest decline of 10 ft occurring in the southern region.

Refugio County

- Chicot Aquifer: Water levels dropped across about 70% of the county and in the northwest region where the largest decrease of about 27 ft occurred near the Goliad county line. An increase of less than 5 ft occurred across most of the southeastern portion of the county.
- Evangeline Aquifer: Water levels decreased across about 75% of the county with the largest decline of 15 ft in the north-central region of the county.

Victoria County

- Chicot Aquifer: Water levels increased across about 50% of the county and primarily in the northeast region. The largest increase of about 25 ft occurred at the center of the county. Water levels dropped in the southwest region where the largest decrease was about 15 ft.

- Evangeline Aquifer: Water levels rose across about 60% of the county and primarily in the northwest portion of the county. The largest increase of about 70 ft occurred at the center of the county. In southwest region of the county, changes in the groundwater levels ranged from about a 10 ft increase to a 20 ft decrease.

Hydrographs were generated for wells with annual water levels that are located in Calhoun, Jackson, Refugio, and Victoria counties. Hydrographs with more than four measured water level are presented and discussed in Section 6. In about half of the wells, the changes in the measured water levels over time are relatively flat (stable) over time. At about 60% of these wells, the GAM simulated water levels also were characterized as being relatively flat over time. For the wells, where there was a recognizable increase or decrease in the measured water levels over time, only about 30% of GAM -simulated water levels matched the temporal trend associated with measured water levels.

Recommendations for Future Work

Recommendations for future work were grouped into three general categories: (1) coordinating with the TWDB to integrate the GCD well information into the TWDB groundwater database; (2) expanding the monitoring well network and monitoring programs; and (3) expanding and improving on the geostatistical analysis provided in this study.

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ACROYNMS AND ABBREVIATIONS

CDF cumulative density function

DFC desired future condition
DEM digital elevation model

ft feet

GAM groundwater availability model
GCD groundwater conservation district
GMA groundwater management area

TWC Texas Water Code
TWDB Texas Water Development Board

1.0 INTRODUCTION

As stated in §36.1005 of the Texas Water Code (TWC), groundwater conservation districts (GCDs) are the state's preferred method of groundwater management. The responsibilities of GCDs include the monitoring and analysis of groundwater levels to assess the conditions of the groundwater resource. In recognizing the value of using best science available to develop and implement their rule-making, four GCDs in Groundwater Management Area (GMA) 15 funded this study to use geostatistical techniques to interpret measured water levels for the purpose of quantifying change across an aquifer and evaluating compliance with Desired Future Conditions (DFCs). The four GCDs are: Calhoun County GCD, Refugio GCD, Texana GCD, and Victoria County GCD.

1.1 Project Overview

The project overview provides a brief introduction to the study area and lists the project objectives.

1.1.1 Study Area

Figure 1-1 shows the location of Calhoun County GCD, Refugio GCD, Texana GCD, and Victoria County GCD. The four GCDs are part of GMA 15. Figure 1-1 shows the boundary for GMA 15, which includes all or parts of fourteen counties. GMAs were created by the Texas legislature "in order to provide for the conservation, preservation, protection, recharging, and prevention of waste of the groundwater, and of groundwater reservoirs or their subdivisions, and to control subsidence caused by withdrawal of water from those groundwater reservoirs or their subdivisions" (TWC §35.001).

The primary groundwater reservoir in GMA 15 is the Gulf Coast Aquifer System. GMA 15 is currently using the central Gulf Coast Groundwater Availability Model (GAM) (Chowdhury and others, 2004) for assessing impacts of pumping on groundwater levels in the Gulf Coast Aquifer System. The central Gulf Coast GAM represents the Gulf Coast Aquifer System as four major hydrogeologic units. These four units are, from youngest to oldest, the Chicot Aquifer, the Evangeline Aquifer, the Burkeville Confining Unit, and the Jasper Aquifer. As a general rule, the Burkeville Confining Unit is considered as a clay-rich unit with low potential for producing groundwater.

Figure 1-2 shows three vertical cross-sections through the GMA 15 GAM. The cross-sections show the upper and lower boundaries for the four units. As shown in Figure 1-2, all four units dip to the coast. Along the coastline, there are few water wells that penetrate below the lower portion of the Evangeline Aquifer because of relatively saline groundwater and because the depth is greater than 1000 feet (ft).

1.1.2 Study Objectives

This study has the three study objectives for Calhoun County GCD, Refugio GCD, Texana GCD, and Victoria County GCD:

- Employ appropriate geostatistical methods for interpolating water level conditions across the Chicot and Evangeline aquifers from each year from 2000 to 2020;

- Employ appropriate geostatistical methods for interpolating water level conditions over time for the Chicot and Evangeline aquifers;
- Develop technical reports documenting condition assessments and evaluations, data sources, methods, assumptions and rationale for selected methods and assumptions.

1.2 Report Outline

The report contains seven sections after this introduction (Section one). Section two describes the methods used to assemble the measured water levels for evaluating groundwater level conditions in the Chicot and Evangeline aquifers. Section three introduces geostatistical techniques, explains how geostatistical methods can be used to interpolate water levels, and discusses several potential benefits offered by geostatistics over conventional interpolation methods. Section four documents the application of detrending and ordinary Kriging to interpolate measured water levels and generate maps of contoured groundwater elevations for the Chicot and the Evangeline aquifers. Section five provides the change in annual average in water levels per county and measured water levels using well hydrographs. Section seven provides suggestions for future work. Section eight provides the references.

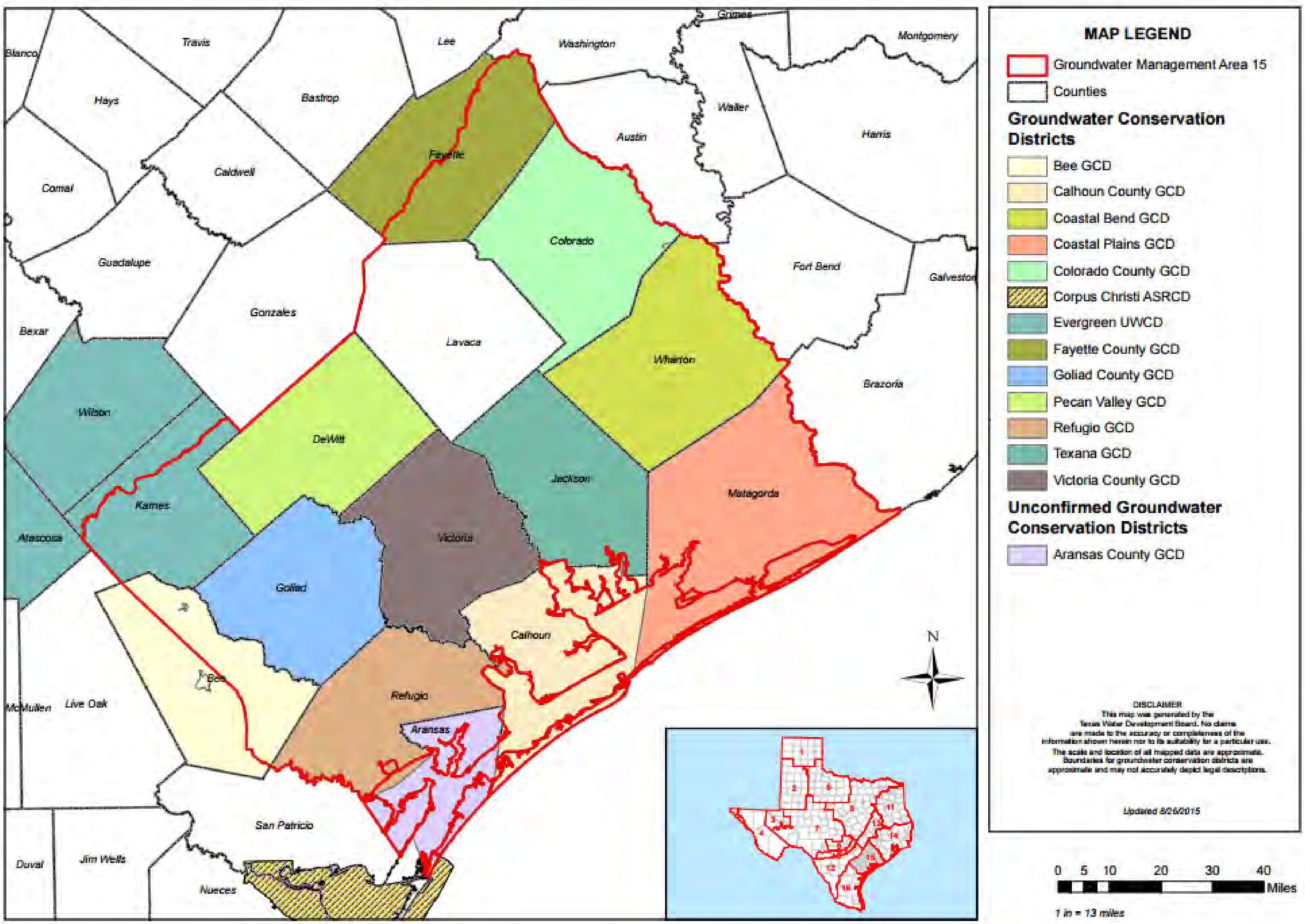


Figure 1-1 Delineation of GMA 15 showing locations of GCDs (obtained from http://www.twdb.texas.gov/groundwater/management_areas/gma15.asp)

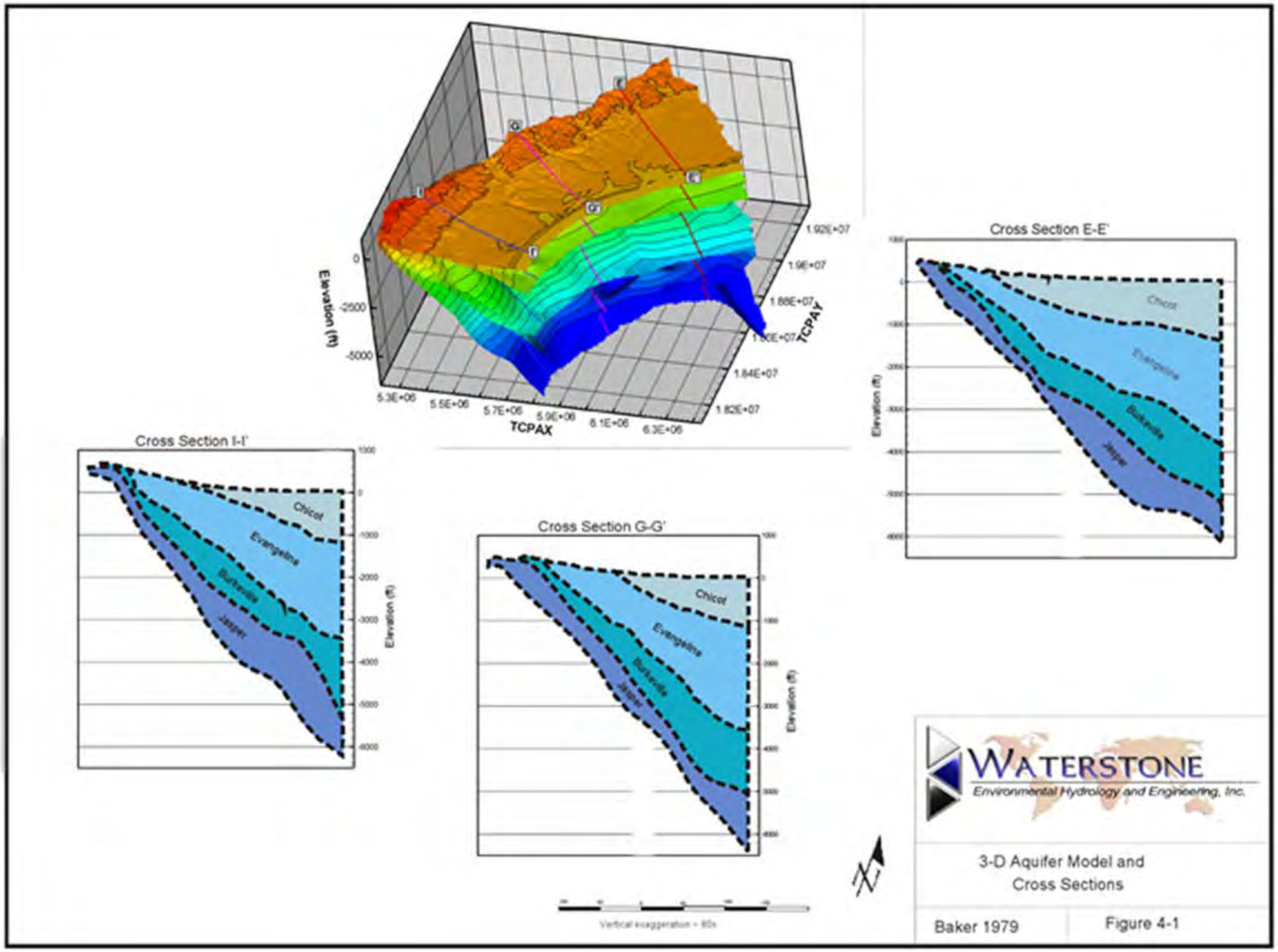


Figure 1-2 Vertical cross-sections through GMA 15 showing the four geological units that comprise the Gulf Coast Aquifer System: Chicot Aquifer, Evangeline Aquifer, Burkeville Unit, and the Jasper Aquifer (Waterstone and Parsons, 2003)

2.0 MEASURED WATER LEVELS

This section discusses the development of the measured water levels database used for the groundwater analysis.

2.1 Data Sources

Two sources of measured water levels were used for this study. Both data sets contained measured water levels for the period from 2000 to 2020. One data set was obtained from Calhoun County GCD, Refugio GCD, Texana GCD, and Victoria County GCD. The GCD data set consisted of 1,809 depth to water measurements at 256 wells for Calhoun, Jackson, Refugio, and Victoria counties. The second data set was the Texas Water Development Board (TWDB) groundwater data set. The TWDB data set consisted of 13,800 depth to water measurements at 658 wells. The TWDB data set was filtered to remove water levels that may have been affected by pumping by using appropriate flags in the TWDB data set. **Figure 2-1** shows the location of the wells associated with the GCD and TWDB data sets.

2.2 Merging of TWDB and GCD Datasets

As shown in Figure 2-1, the TWDB and GCD data sets include several of the same wells but with different names. INTERA's investigation method to verify 96 well pairs identified in the GCD data set was based on comparing well location, well depth, and water level data. Based on a comparison of these three attributes, INTERA identified 127 well pairs between the two data sets.

Appendix A lists the names and locations for the GCD and TWDB wells that are matched. Except for one well pair, the GCD and the TWDB data sets have different values for the location of the matched wells. Appendix A provides the distance calculated between the two well locations in the TWDB and the GCD data sets for each of the 127 well pairs. The locations of the matched wells in the GCD and TWDB are within 100 ft of each other for 105 of the 127 well pairs. For eight of the well pairs, the locations in the GCD and TWDB data sets are greater than 200 ft apart.

An important part of the process of identifying well pairs was the comparison of water levels in the GCD and the TWDB data sets. This comparison was performed visually using the type of plots shown in **Figure 2-2**. Figure 2-2 shows plots of water levels for four well pairs. Each plot shows measured water levels over time using the same datum. The TWDB water levels are shown using blue dots and the GCD water levels are shown using red dots that are slightly smaller than the blue dots. Potential well pairs were identified using information provided by the GCDs and a comparison of well locations and well depths in the two data sets. The final decision on whether two wells were determined to be a well pair was based on whether or not red dots plotted inside the blue dots for water levels measured on the same date. Merging of the two data water level data sets was achieved by augmenting the TWDB data set with any new data provided in the GCD data set.

The 127 well pairs include 88 of the 96 well pairs identified in the GCD database. **Table 2-1** shows the eight well pairs that were not confirmed based on the INTERA analysis. For four of the eight well pairs, INTERA did not have sufficient information to confirm or reject the GCD well pair because the matched wells did not have measured water levels for the same date. For the other four well pairs identified by the GCD, INTERA had matched the GCD well with different TWDB well than the well provided in the GCD data set.

Table 2-1 List of eight well pairs in the GCD data set that were not confirmed by INTERA

GCD Well ID	TWDB Well ID	
	Paired by INTERA	Paired in GCD Data Set
Refugio GCD - NW-00475	7946803	7946810
Victoria County GCD - GW-000950	8018601	8016601
Victoria County GCD - GW-000603	7916703	7916603
Refugio GCD - NW-00340	8033203	8033205
Texana GCD - GW-00284	NA	8011502
Victoria County GCD - GW-000310	NA	8018404
Texana GCD - GW-00385	NA	8012502
Victoria County GCD - GW-000189	NA	7915306

The data set generated by merging the GCD and the TWDB data used the GCD-provided location and well depth instead of the TWDB-provided information where possible. The data used for land surface elevations for each well were obtained from three sources. The order of priority used for selecting the land surface elevation were: the GCD data set (if available), the TWDB data set (if available), and then the 30-meter Digital Elevation Model (DEM) for the Texas Gulf Coast.

The merging of the GCD and the TWDB data sets generated 889 unique wells. Each of the 889 wells were assigned a unique INTERA ID. **Appendix B** lists the 889 wells in the numerical order of their INTERA ID. For each well, Appendix B lists the GCD name (if assigned), the TWDB State well number (if assigned), the land surface elevation, the well depth, and the assigned aquifer.

Each well was assigned to a geologic unit based on the elevation of the bottom of the well. The bottom elevation was determined by subtracting the well depth from the ground surface elevation. The aquifer assignment was determined by where the well's bottom elevation is located in the three-dimensional numerical grid of the central Gulf Coast GAM (Chowdhury and others 2004). Wells with no well depth information were not assigned to a geologic unit and were instead assigned the category of "Shallow". Conversely, wells whose bottom elevation plotted below the lowest layer in the GAM were also not assigned to a geologic unit and were instead assigned the category of "Deep".

2.3 Average annual water level

A single annual water level average was calculated each year using measurements that were made over a 6-month period that spanned from October through December of the year before and from January through March of the current year. A total of 6,081 average winter water level averages are available from 2000 through 2020 at 801 wells. **Appendix C** lists the number of water level measurements that are available for the 6-month period from the TWDB data set and the GCD data set for 127 well pairs.

For 80 of these well pairs, the addition of the GCD data set increased the number of annual water level measurements.

2.4 Average annual water level

Table 2-2 lists the number of wells in Calhoun, Jackson, Refugio, and Victoria counties that were used in the study. These wells were assigned to an aquifer and have at least one annual water level calculated from 2000 to 2020. The locations of these wells are shown in **Figures 2-3** through **2-6**.

Table 2-2 Number of wells with measured water levels in Calhoun, Jackson, Refugio, and Victoria counties that were used in the study

County	Number of Wells		
	Chicot	Evangeline	Total
Calhoun	19	0	19
Jackson	68	8	76
Refugio	26	9	35
Victoria	53	70	123
Total	166	87	253

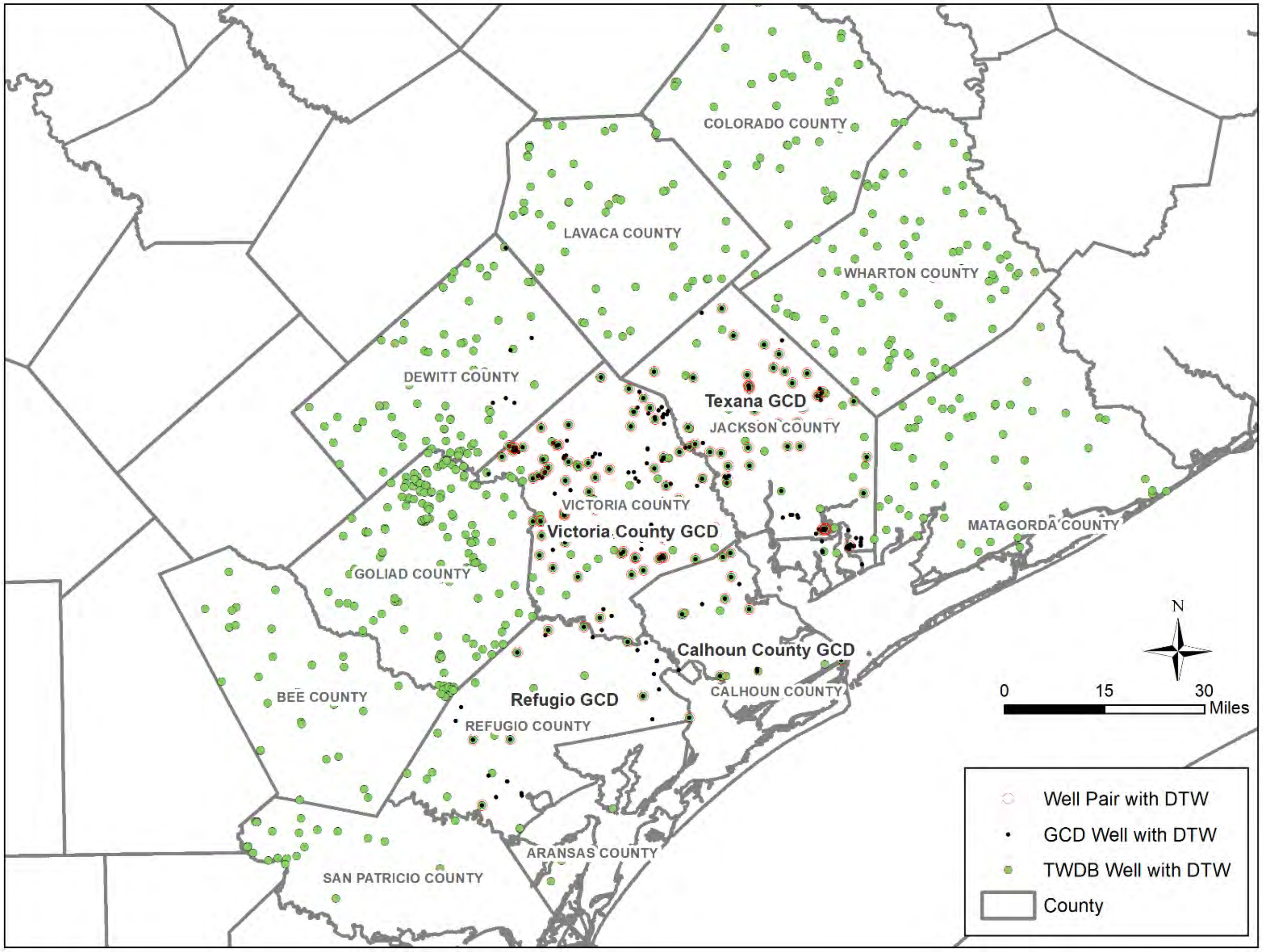


Figure 2-1 Location of the wells with measured depth to water (DTW) that were evaluated for this study

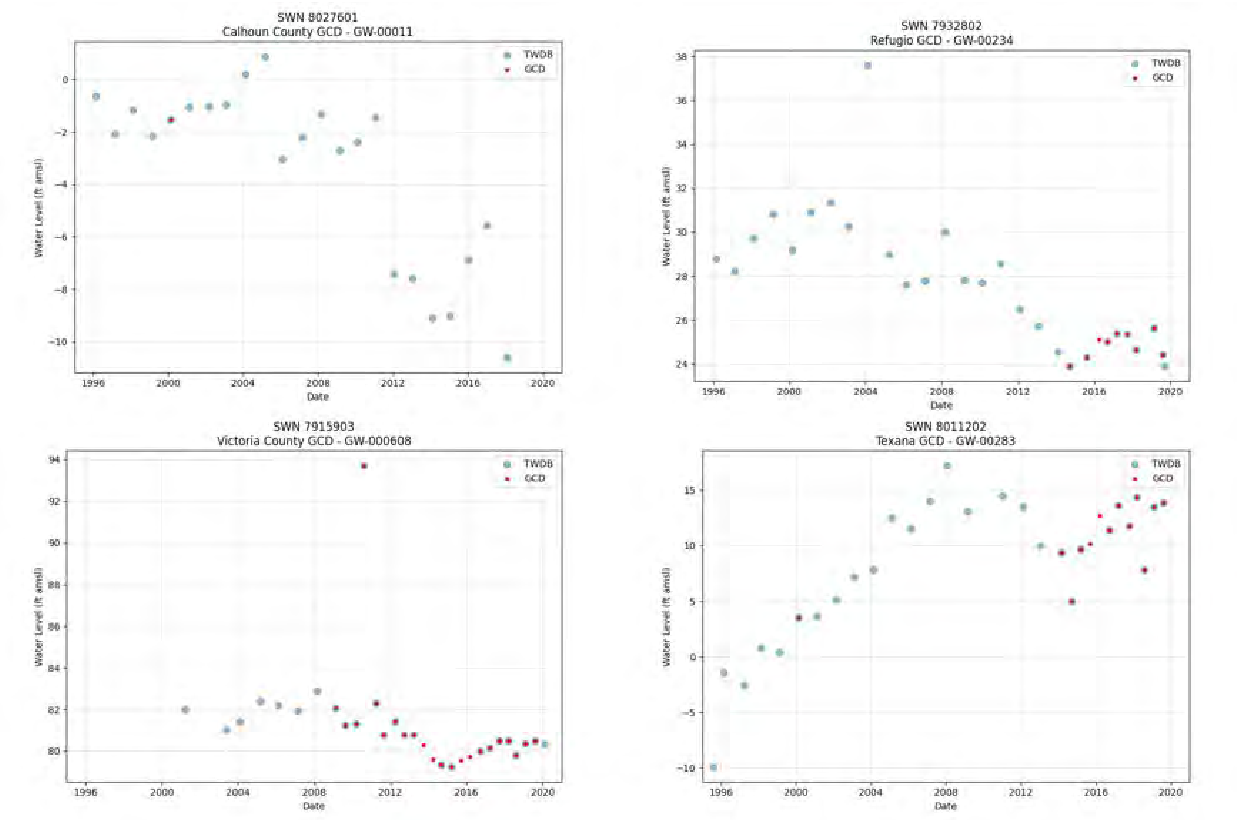


Figure 2-2 Comparison of measured water levels from the GCD and the TWDB data sets for four well pairs

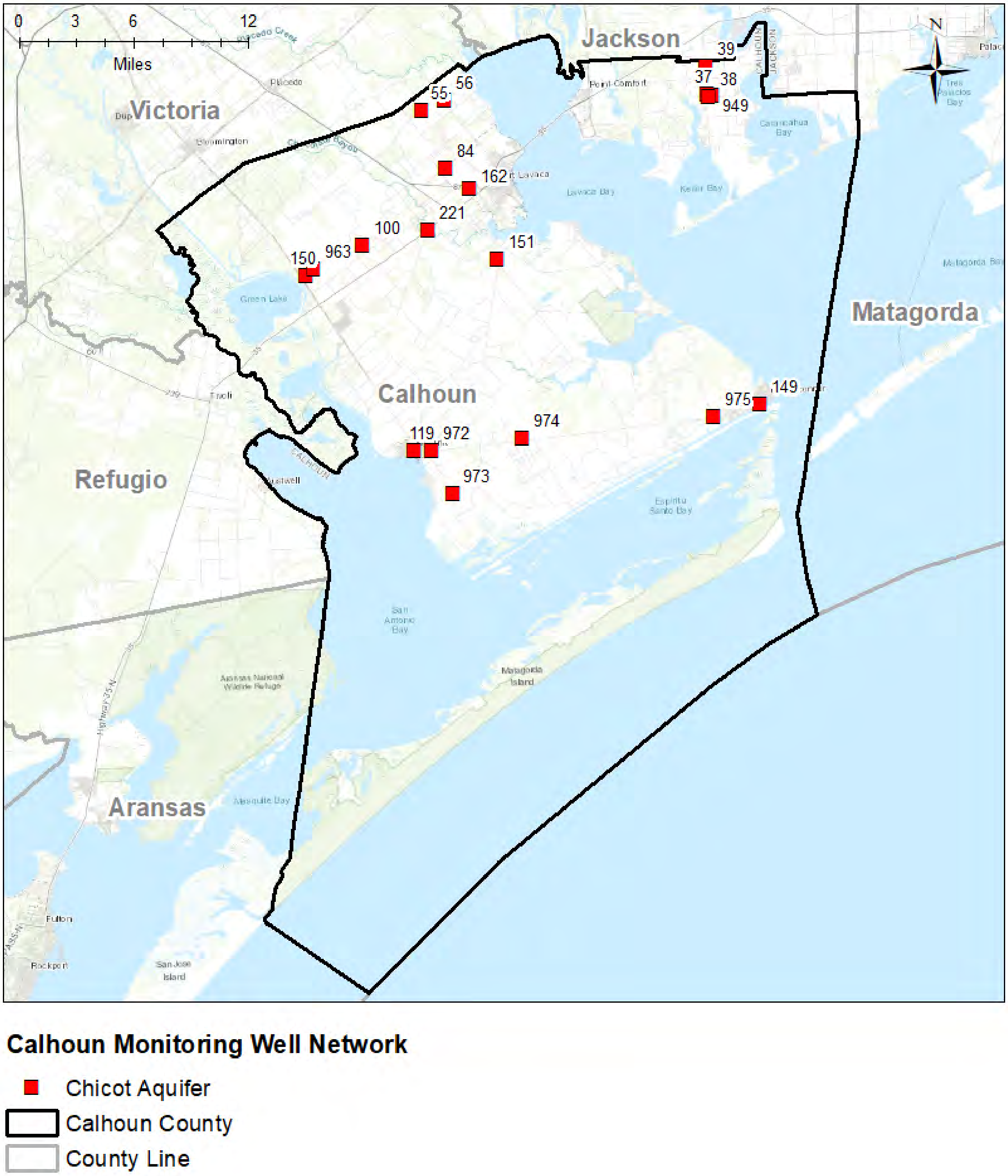


Figure 2-3 Location and INTERA IDs for water wells in Calhoun County used for this study

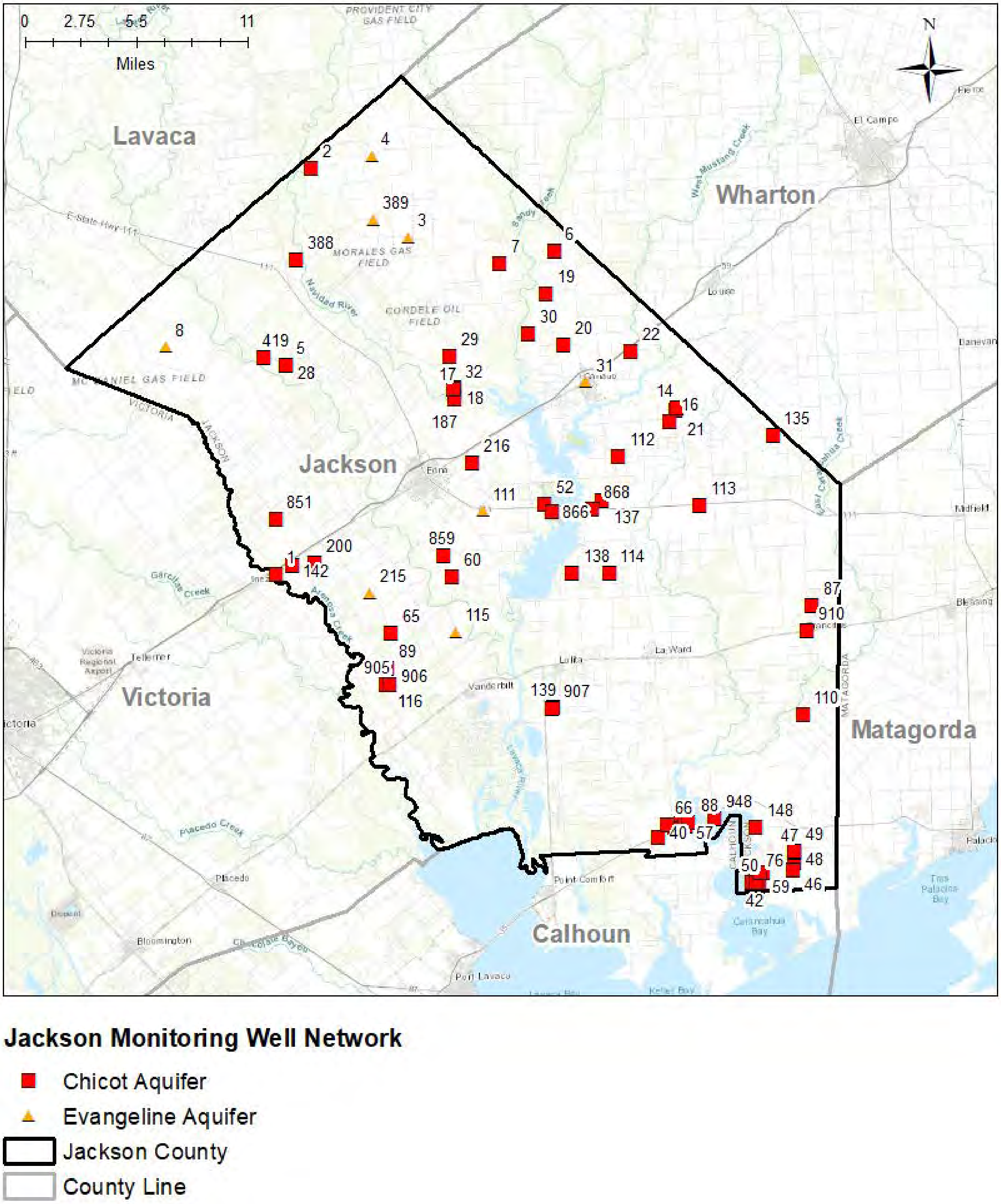


Figure 2-4 Location and INTERA IDs for water wells in Jackson County used for this study

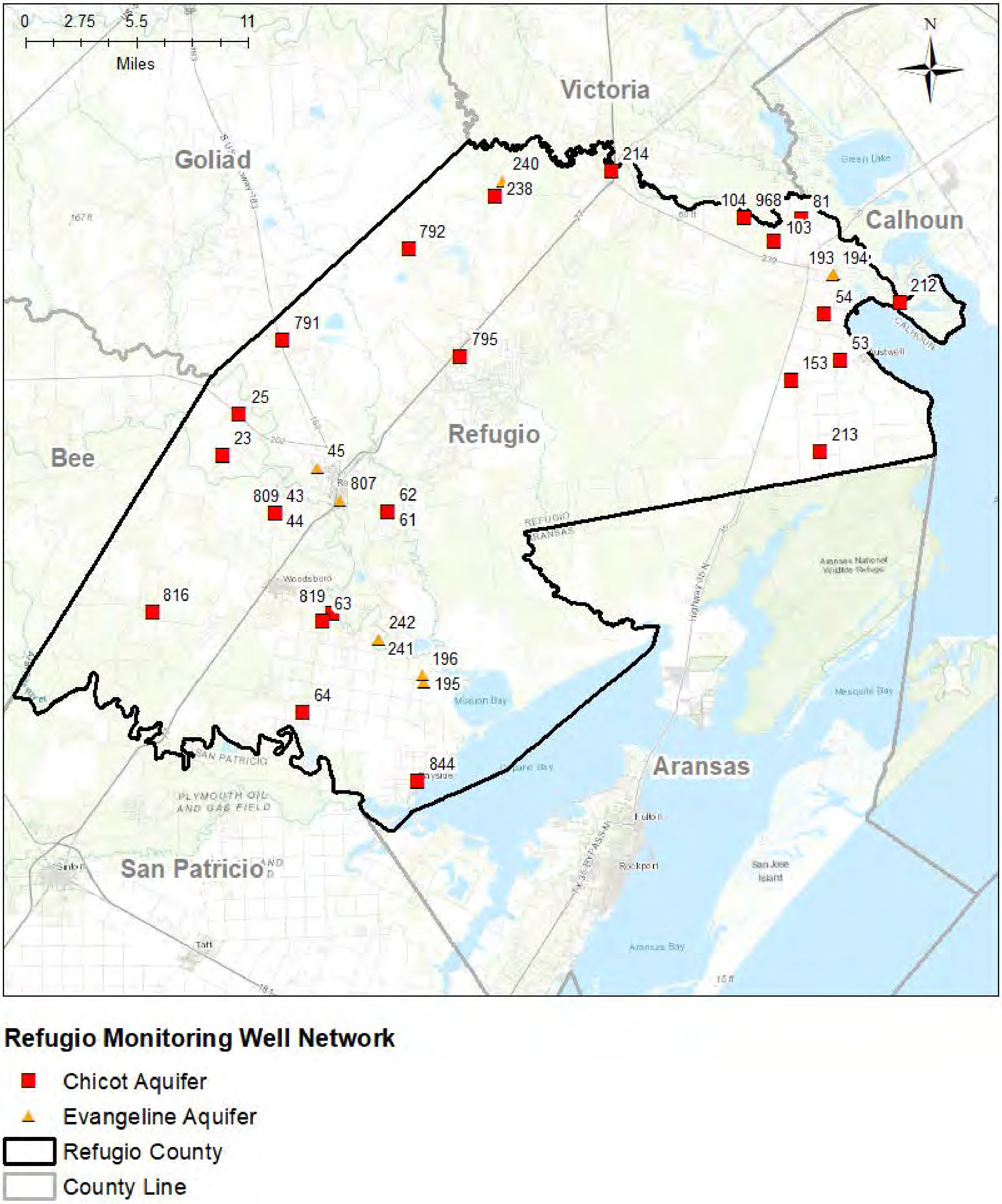


Figure 2-5 Location and INTERA IDs for water wells in Refugio County used for this study

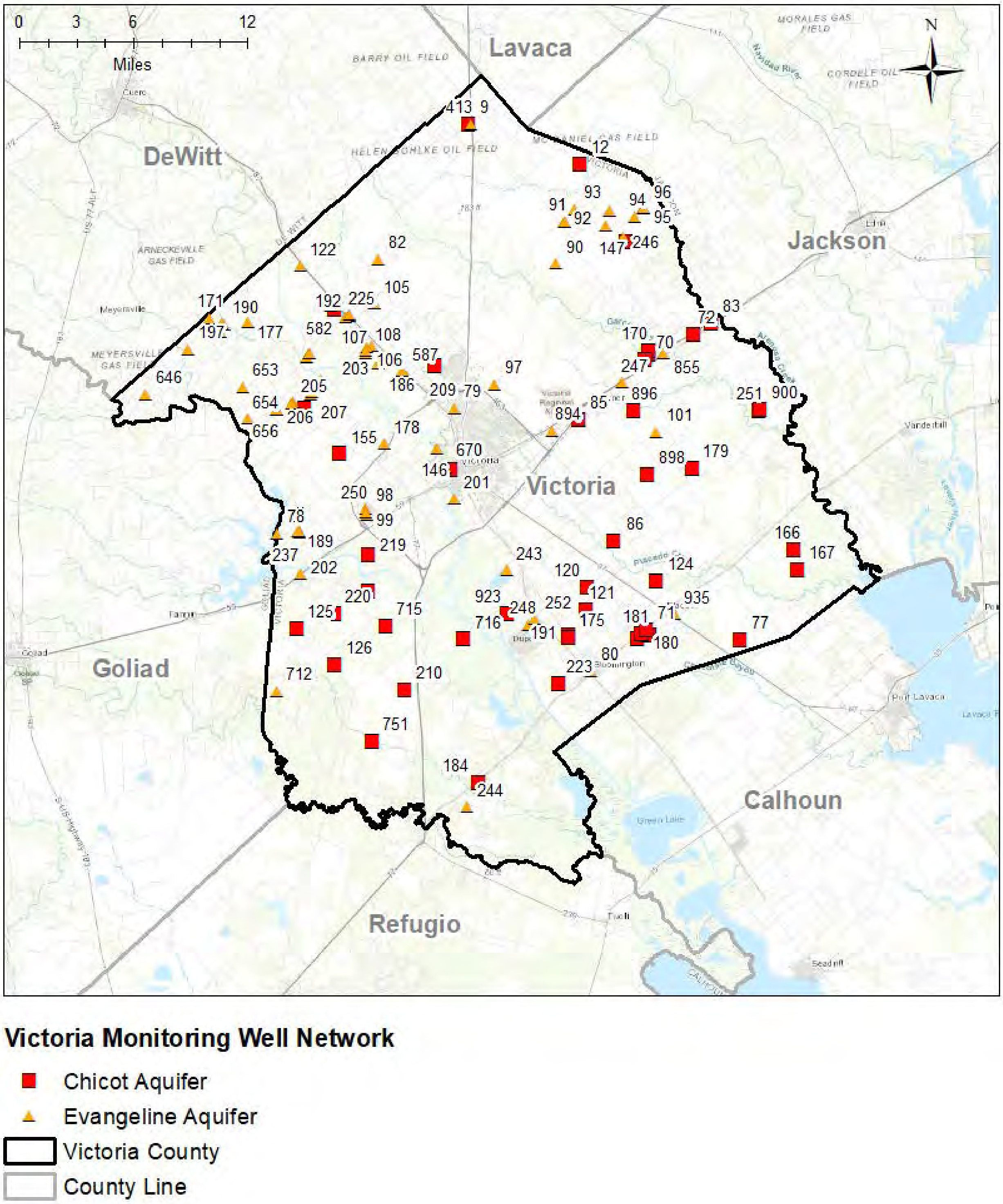


Figure 2-6 Location and INTERA IDs for water wells in Victoria County used for this study

3.0 GEOSTATISTICAL APPROACH FOR INTERPOLATION

3.1 Spatial Interpolation

When making decisions involving aquifer data across one or more counties, GCDs generally lack the resources to establish a robust monitoring network of adequate spatial and temporal resolution. As a result, there is a need for GCDs to find reliable and technically defensible approaches to interpolate water levels to answer questions associated with changes in aquifer conditions over time. Interpolation techniques can be classified as one of two types: deterministic or geostatistical. Deterministic methods rely on using mathematical equations with fitting parameters to generate values at unsampled locations. Examples of deterministic functions are spline interpolation routines, which apply smoothing and inverse distance routines based on the extent of data set similarity. Geostatistical methods rely on using both statistical correlations and mathematical methods to generate values an unsampled locations. The most common geostatistical interpolation method is Kriging. Kriging algorithms are rooted in the principles of spatial autocorrelation, which quantifies the correlation between variables relative to varying spatial extents (distance). As a general rule, if the variable of interest does exhibit spatial correlation, then application of geostatistical methods would provide a relatively robust and viable option for interpolation compared to deterministic methods.

3.2 Geostatistical Techniques

Statistics is the science of collecting, pooling, and making inferences from quantitative data. Geostatistics is the branch of science that focuses on geoscientific data. Geostatistics attempts to quantify the spatial relationship between data and the uncertainty in that relationship. The first notable papers on geostatistics were generated in the 1950s by Georges Matheron, who was working for the French Geological Survey on estimating ore resources.

3.2.1 Semivariogram

The semivariogram plays a central role in the analysis of geostatistical analysis and Kriging, which is the most common geostatistical interpolation method. The semi-variogram is a measure of the spatial continuity of the data and how quickly the data values change on the average. **Figure 3-1** provides a schematic of a semivariogram.

Conceptually, a semivariogram shows how the semivariance (i.e. half of the variance) of the data changes with an increase in the distance between the paired data values. In geostatistics, the distances between paired data at which the semivariance is calculated are called lags. For instance, if the lag is set at 100 ft, then the bins for which semivariances would be calculated at 100 ft, 200 ft, 300 ft, 400 ft, etc., Because points may not be spaced exactly at distances at intervals of 100 ft apart, the lag settings include a lag tolerance value that is typically set to half of the distance between lags. For the previous example, that would mean that the first lag of 100 ft would include all pairs of points that are between 50 and 150 ft from each other.

In general, two observations closer together are more similar than two observations further apart. The underlying reason for generating a semivariogram is to characterize the spatial correlation between data points. There are two types of semivariogram: experimental and theoretical. The experimental semivariogram is constructed based on the analysis of the field data, which is expressed by the dots in Figure 3-1. The theoretical semivariogram is generated by fitting a semivariogram model to the data, which is shown by the black line in Figure 3-1.

Introductions to semivariogram modeling and geostatistics are found in literature such as Isaaks and Srivastava (1989), American Society of Civil Engineers (1990), and Kitanidis (1997). The mathematical foundation and derivation of the semivariogram are beyond the scope of this report. The experimental variograms that will be calculated later in this report for water elevations is based on **Equation 3-1**.

$$\Upsilon(\boldsymbol{h}) = \frac{1}{2N(\boldsymbol{h})} \sum_{i=1}^{N(\boldsymbol{h})} [\boldsymbol{z}(\boldsymbol{u}_{\mathrm{i}}) - \boldsymbol{z}(\boldsymbol{u}_{\mathrm{i}} + \boldsymbol{h})]^2 \qquad \textit{Eq 3-1}$$

Where:

- $\Upsilon(\mathbf{h})$ = semivariance as a function of lag distance h, (ft^2)
- **h** = the lag spacing vector (ft)
- $\boldsymbol{z}(\boldsymbol{u}_{\mathrm{i}})$ = the elevation water level (ft) at spatial location $\boldsymbol{u}_{\mathrm{i}}$,
- $\boldsymbol{u}_{\mathrm{i}}$ = a vector of spatial coordinates (x,y) for the sample locations of each measured water level

The experimental variogram must be modeled for two reasons: (1) there is a need to interpolate the variogram function for h values where too few or no experimental data pairs are available, and (2) the variogram measure γ(h) must have the mathematical property of "positive definiteness" for the corresponding covariance model. The three most commonly used theoretical variogram models are Gaussian, exponential, and spherical. The theoretical variogram has three attributes that summarize important aspects of the spatial data. These three attributes are described in Figure 3-1 and below.

- **Range –** the maximum distance between points up to which there is information on the correlation/spatial relationship between two data points.
- **Sill –** the sample variance, which is a measure of the spread or variability in the data points that are not correlated.
- **Nugget Effect –** reflects measurement error and the discontinuity in the variogram at distances below the minimum lag distance

3.2.2 Kriging

Kriging is a geostatistical interpolation technique that considers both the distance and the degree of variation between known data points when estimating values in unknown areas. Kriging accounts for the degree of variation, or spatial correlation, among the data points through a semivariogram model. The basic idea of Kriging is to predict the value of a function at a given point by computing a weighted average of the known values of the function in the neighborhood of the point.

Kriging is named for Dr. Krige, who published an early (Krige, 1951) application of kriging to the estimation of the extent and volume of a mineral ore body. Kriging methods have been studied and applied extensively since 1970 and have been adapted, extended, and generalized. There are many forms of Kriging. The different forms of Kriging are detailed in Goovaerts (1997). The most commonly used forms of Kriging include: simple Kriging, ordinary Kriging, universal Kriging, cokriging, and Kriging with external drift. Ordinary Kriging is among the most commonly used types of Kriging and is the basis of geostatistics (Ryu and others, 2002). Ordinary Kriging gives the optimal prediction under the assumption of second-order stationary, a normal distribution for the modeled variable, and the absence of any trend in the data. By optimal prediction, what is meant is that Kriging provides the best linear unbiased prediction at unsampled locations and reproduces the measured values at all sampled locations exactly.

A concern with using ordinary Kriging to interpolate water level data is how best to account for the trends in the water level data. The existence of trends is evident in **Figure 3-2**, which shows contours of groundwater levels simulated by the GMA 15 GAM for the Chicot Aquifer. Among the causes for trends in the water level data is large regional effects associated with flow toward the ocean and moderate regional effects associated hydraulic impacts from rivers, lakes, and large well fields. The process to account for a trend in the data consists of six steps which are described below and are illustrated in **Figure 3-3**. The example application described in Figure 3-3 is for annual precipitation amounts measured across Texas (Gimond, 2021).

Step #1 - Assemble and inspect the data for evidence of a trend.

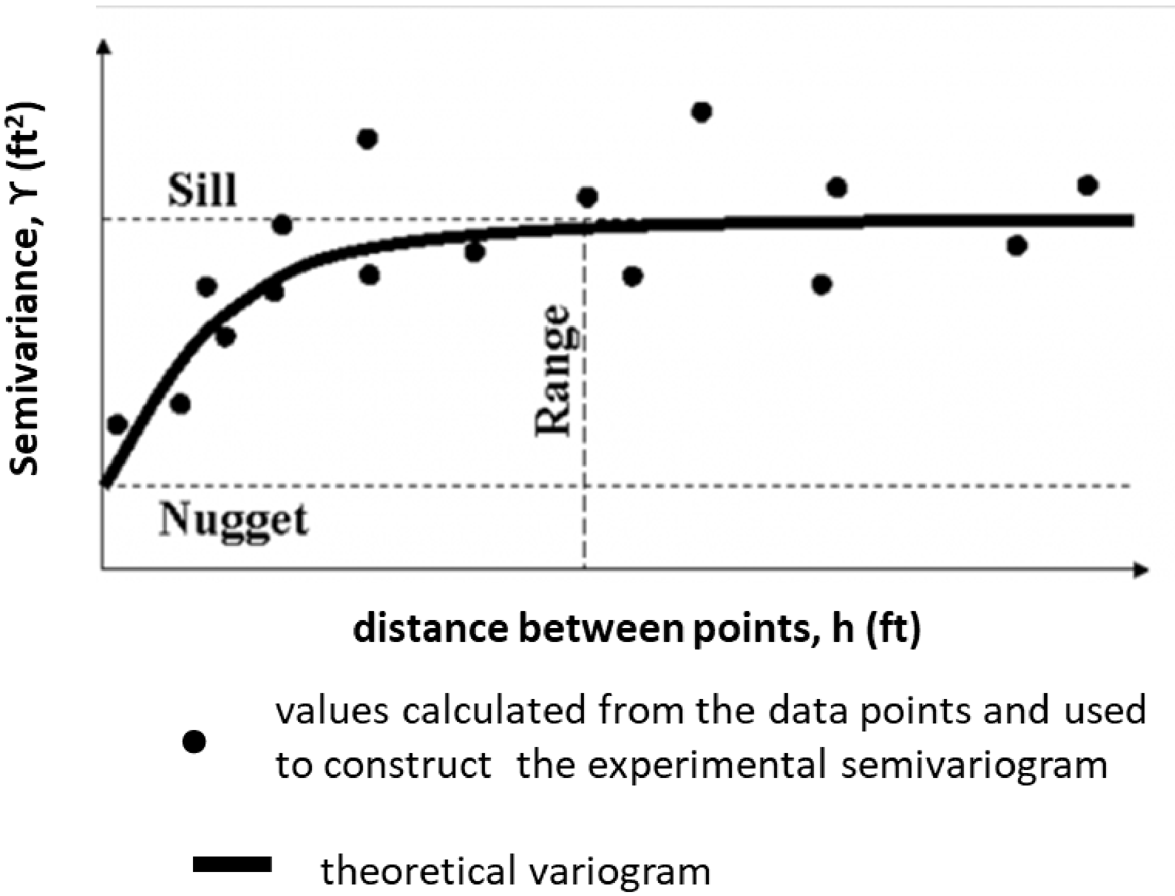
Step #2 – Develop a trend surface based on fitting the data and a conceptual understanding of the factors responsible for the trend.

Step #3 – Calculate the residual at each data location. A residual is the difference between the measured value and value produced by the trend at the location of the measured data. Check whether the set of calculated residuals are normally distributed. If the residuals do not resemble a normal distribution, then repeat Step #2.

Step #4 – Construct an experimental and a theoretical semivariogram for the set of residuals.

Step #5 – Krige the residuals to produce a continuous surface across the area of interest.

Step #6 – Combine the trend surface and the Kriged surface to generate the final surface.



Range – the maximum distance between points up to which there is information on the correlation/spatial relationship between two data points

Sill – the sample variance, which is a measure of the spread or variability in the data points that are not correlated

Nugget Effect – reflects measurement error and the discontinuity in the variogram at distances below the minimum lag distance

Figure 3-1 Schematic of a experimental and theoretical semivariogram

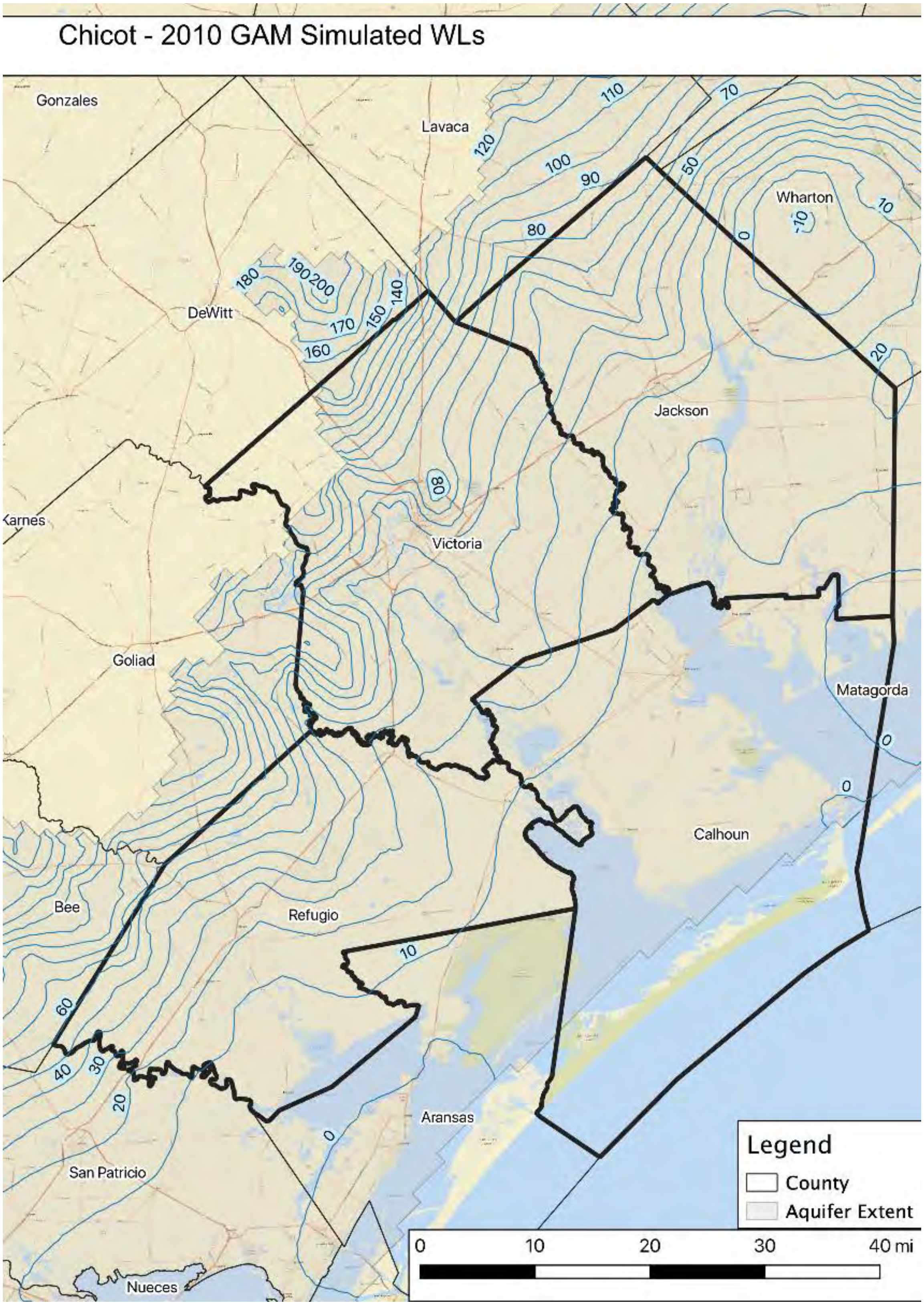


Figure 3-2 Contours of 2010 groundwater levels simulated by the GMA 15 GAM for the Chicot Aquifer

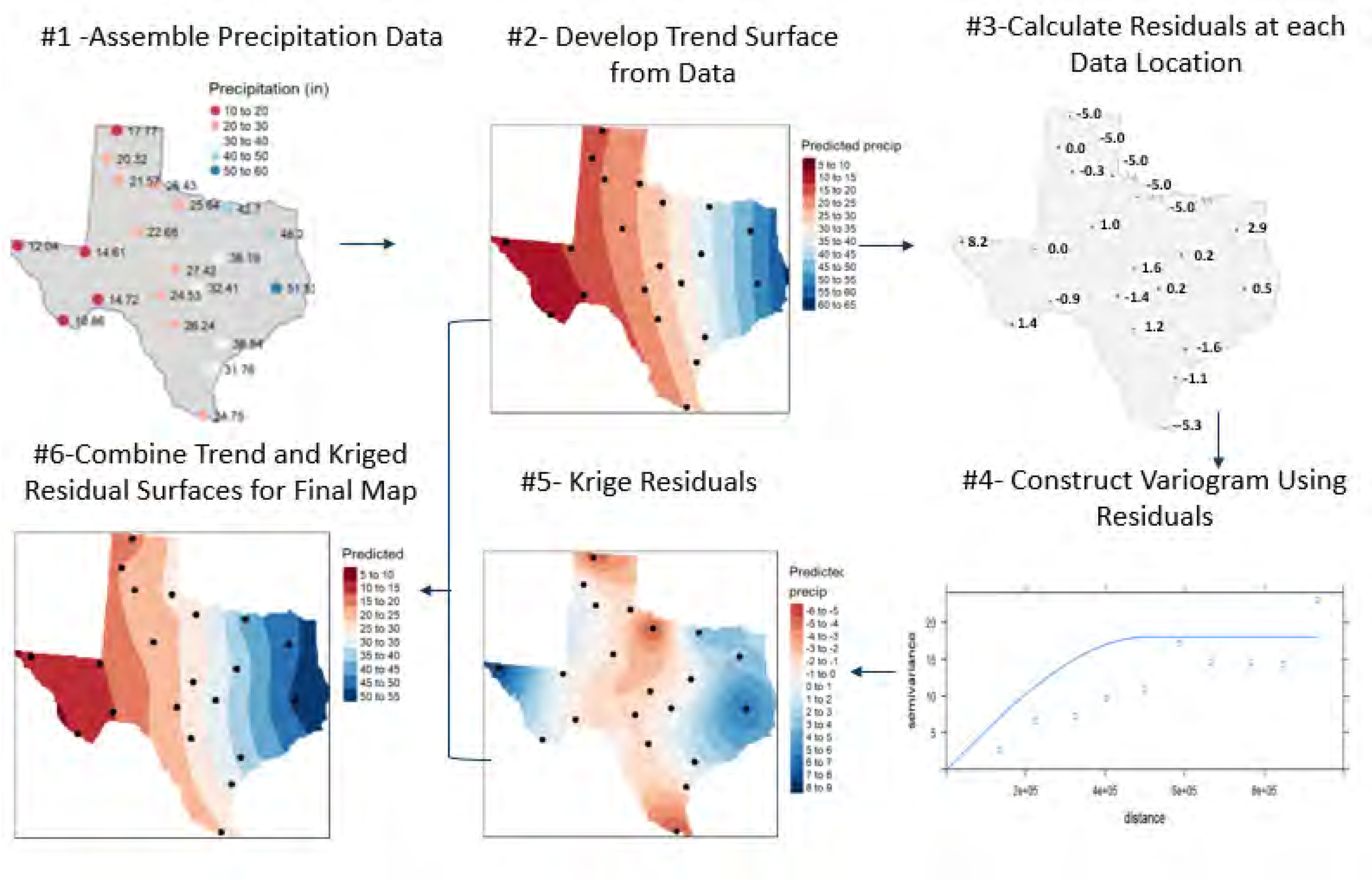


Figure 3-3 Workflow showing the a six-step process for using ordinary Kriging in develop a continuous surface for a data set that contains a trend

4.0 APPLICATION OF KRIGING WITH DETRENDING TO GENERATE WATER LEVEL MAPS

This section presents application of detrending and ordinary Kriging to interpolate measured water levels and to generate yearly water level maps for 2000 to 2020. The section documents the process of detrending the measured water levels, calculating the water level residuals, creating experimental variograms and fitting them to theoretical variogram models, Kriging the water level residuals, and constructing the final water level maps.

4.1 Detrending Approach

An inspection of Figure 3-2 shows evidence that the water levels simulated by the GAM contains trends at several different spatial scales. The trends are evident in the gradual decrease in elevation of the contours in the southeast direction toward the ocean, the distortion in water levels contours near large rivers such as the Guadalupe River in Victoria County and Lavaca River in Jackson County, and the cones of depression (i.e. circular contours) caused by pumping from large well fields near the City of Victoria and in southeast Wharton County.

Our review of the simulated waters for multiple years indicates that there are mathematical equations that can be used to detrend the data. Among the concerns associated with detrending the water levels using an inappropriate surface is that biases would be introduce into the residuals because the equations are not properly capturing the physics responsible for the underlying trends. Our assessment of the water level data found that the best tool for generating possible surfaces to detrend the measured water levels was the central Gulf Coast GAM (Chowdhury and others, 2004). The version of the GAM used for the study was obtained from Mr. Mike Keester from LRE Water, who is the consultant for GMA 15 that is developing GAM runs for the joint planning process. Because the GAM is known not to be the perfect predictor of the impacts of surface water features and pumping on water levels, there is a concern of introducing biases into the detrending process if the GAM-simulated water levels were used without some tempering to help to minimize bias into the water level residuals. Several options were investigated for spatially smoothing the simulated water levels.

The software selected for smoothing the GAM simulated water is part of SciPy (Virtanen and others, 2021). SciPy is a free and open-source Python library used for scientific computing and technical computing. The smoothing function is call “ndimage” and part of the class called “uniform_filter”. Ndimage is a type of moving average filter that smooths in two dimensions (northing and easting). After multiple iterations using Ndimage, a smoothing interval of 64,000 ft was selected. **Figures 4-1** and **4-2** shows the effect of this smoothing interval on the GAM simulated water levels for 2015 in the Chicot and Evangeline aquifers. The criteria used to select the interval of 64,000 ft include visual changes in the water level contours and a statistical evaluation of the residual for normality.

4.2 Water Level Residuals

Figures 4-3 and **4-4** illustrate the process of detrending the measured water levels to create the water level residuals. Figure 4-3a shows the location of the 2015 measured water levels superimposed onto the smoothed GAM simulated water levels for 2015. Figure 4-3b shows the calculated water level residuals at each of the well locations. Figure 4-4 shows the similar data sets for the smoothed GAM simulated water levels and measured water levels for the Evangeline Aquifer in 2015.

The method used to generate the water level residuals in **Figures 4-3** and **4-4** was used to calculate water level residuals for the years 2000 to 2020. Each set of annual water level residuals by aquifer was checked for normality using three criteria. One criterion was visual inspection of the histograms of water levels; residuals are compared to a normal distribution based on the mean and standard deviation of the water level residuals. The visual inspection was to assess whether or not the histogram mimics the shape and magnitude of the bell-shaped curve. **Figure 4-5** shows an example of this comparison using the 2015 water levels residuals. These figures provided useful information for identifying outliers that could impact a quantitative analysis of normality. Another criterion was visual inspection of the probability plots of the empirical cumulative density function (CDF) to the theoretical CDF for the water level residuals. The visual inspection was to assess whether or not the plotted points approximated a straight line, where the empirical and theoretical CDFs are equal. These figures provide useful information on whether there were any meaningful shifts in the distribution away from normality. **Figure 4-6** shows an example of this visual test for normality using the 2015 water levels residuals. The last criterion was to use the Liffiefors test (Liffiefors, 1967) for normality based on the Kolmogorov-Smirnov test.

The Liffiefors test provides a quantitative assessment of normality. The test evaluates the null hypothesis that data derive from a normally distributed population, when the null hypothesis does not specify the expected value and variance of the distribution. The Liffiefors test evaluated the likelihood that the data set was generated from a random distribution at the 95% confidence limit. The majority of both the Chicot and the Evangeline residual data sets passed the Liffiefors test for normality at the 95% confidence limit without any adjustments. All of the residual data sets passed the Liffiefors test at the 95% confidence limit after several of the largest residuals were removed. The average of one residual value needed to be removed per data set for all 42 data sets to pass the Liffiefors test for normality at the 95% confidence limit. The 42 data sets are comprised of 21 data sets for the Chicot Aquifer and 21 data sets for the Evangeline Aquifer. Based on results from both the visual inspections and from the Liffiefors tests, the water level residuals data sets were considered to approximate a normal distribution.

4.3 Semivariogram analysis

Semivariogram analyses were performed on all 42 water level residual data sets. The lag distance was set to 25,000 ft (4.7 miles) and the maximum distance was set to 450,000 ft (85.2 miles). The total number of bins was 18. All the experimental semivariograms were fitted to a spherical theoretical variogram. **Figures 4-7** and **4-8** show the experimental (points) and theoretical (lines) variograms water level residuals for the Chicot and Evangeline aquifers for six of the 21 annual data sets (e.g., 2000 through 2020). The median value for the range, which is the maximum distance at which the residuals are no longer spatially correlated, for the 21 variograms for the Chicot Aquifer is about 190,000 ft (36.0 miles). The media value for the range for the 21 variograms for the Evangeline Aquifer is about 430,000 ft (81.4 miles).

4.4 Final Map of the Water Levels

Ordinary Kriging was used to interpolate the water level residuals for the years 2000 through 2020 for both the Chicot and the Evangeline aquifers. The semivariograms developed in section 4.3 were used to determine the weight assigned to the sampled locations. The Kriging was implemented in **R**. **R** is a programming language and free software environment for statistical computing and graphics supported by the R Foundation for Statistical Computing. The interpolation generated a raster composed of pixels measuring 1,000 by 1,000 ft. **Figures 4-9** and **4-10** show examples of the Kriged surfaces. Figure 4-9 shows contours of the Kriged values and the location of the water level residuals at the sampled locations for the Chicot Aquifer in 2015. Figure 4-10 shows contours of the Kriged values and the location of the water level residuals at the sampled locations for the Evangeline Aquifer in 2015.

The final map of for the Kriged water levels were constructed by combining the surface of the Kriged residuals with the trend surface, which is the smoothed GAM simulated water levels. **Figure 4-11** shows the process of adding together the surfaces for the Kriged water levels and the trend surface to create the final map of the 2015 Chicot water levels. **Figure 4-12** shows the process of adding together the surfaces for the Kriged water levels and the trend surface to create the final map of the 2015 Evangeline water levels.

Figures 4-13 through **4-17** shows the final maps of the Kriged water levels for the years 2000, 2005, 2010, 2015, and 2020 for the Chicot and the Evangeline aquifers. Interpolated water levels are truncated at the boundaries of the aquifers defined in the GAM 15 GAM. The extent of the Chicot and the Evangeline aquifers are marked by shading the area corresponding to each aquifer. Although the interpolated water levels cover the 13 counties in Figure 2-1, the figures focused on an area containing Calhoun, Jackson, Refugio, and Victoria counties.

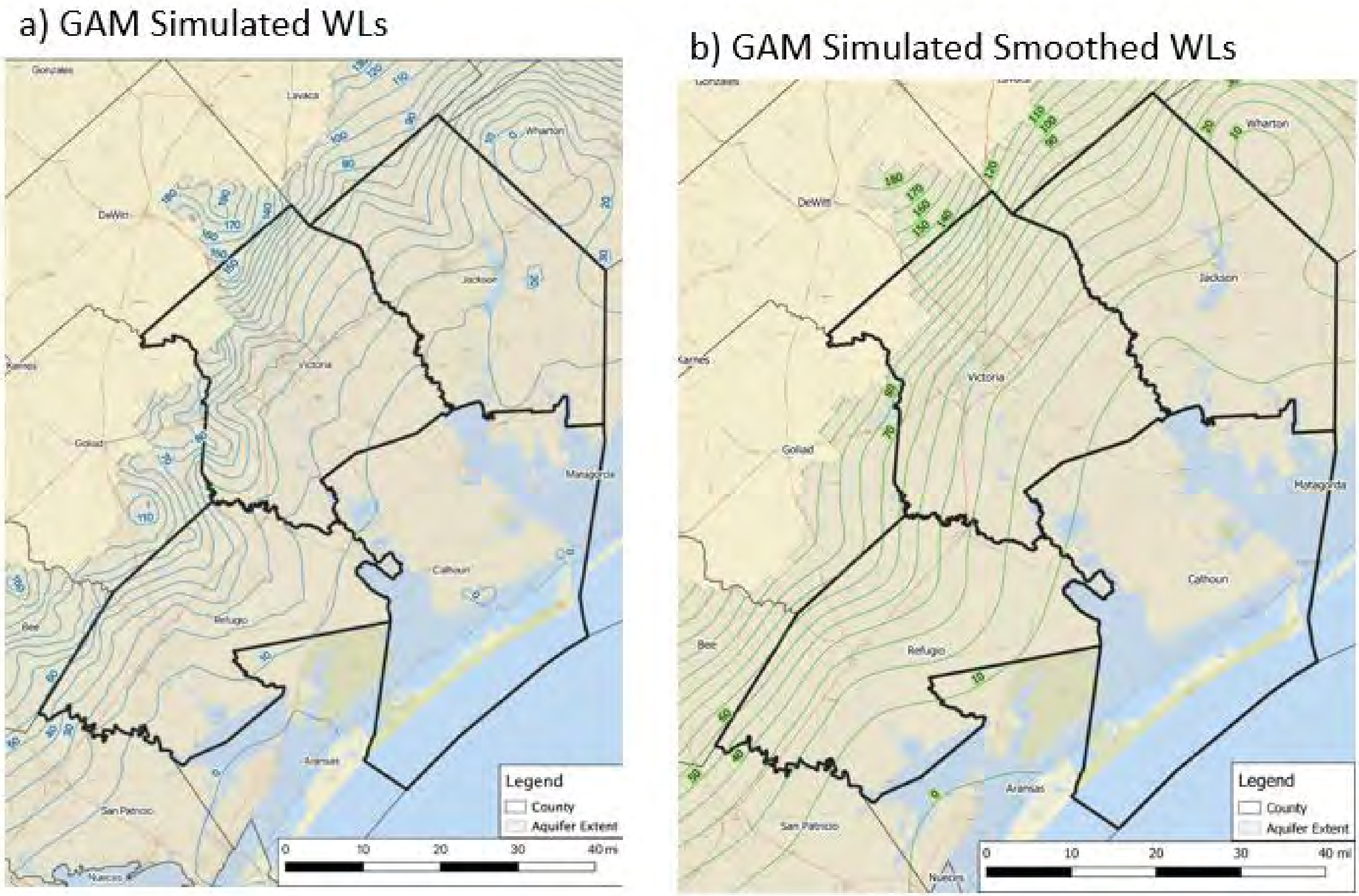


Figure 4-1 GMA simulated 2015 water levels for the Chicot Aquifer, a) actual values; b) smoothed using SciPy function ndimage with a distance of 64,000 feet

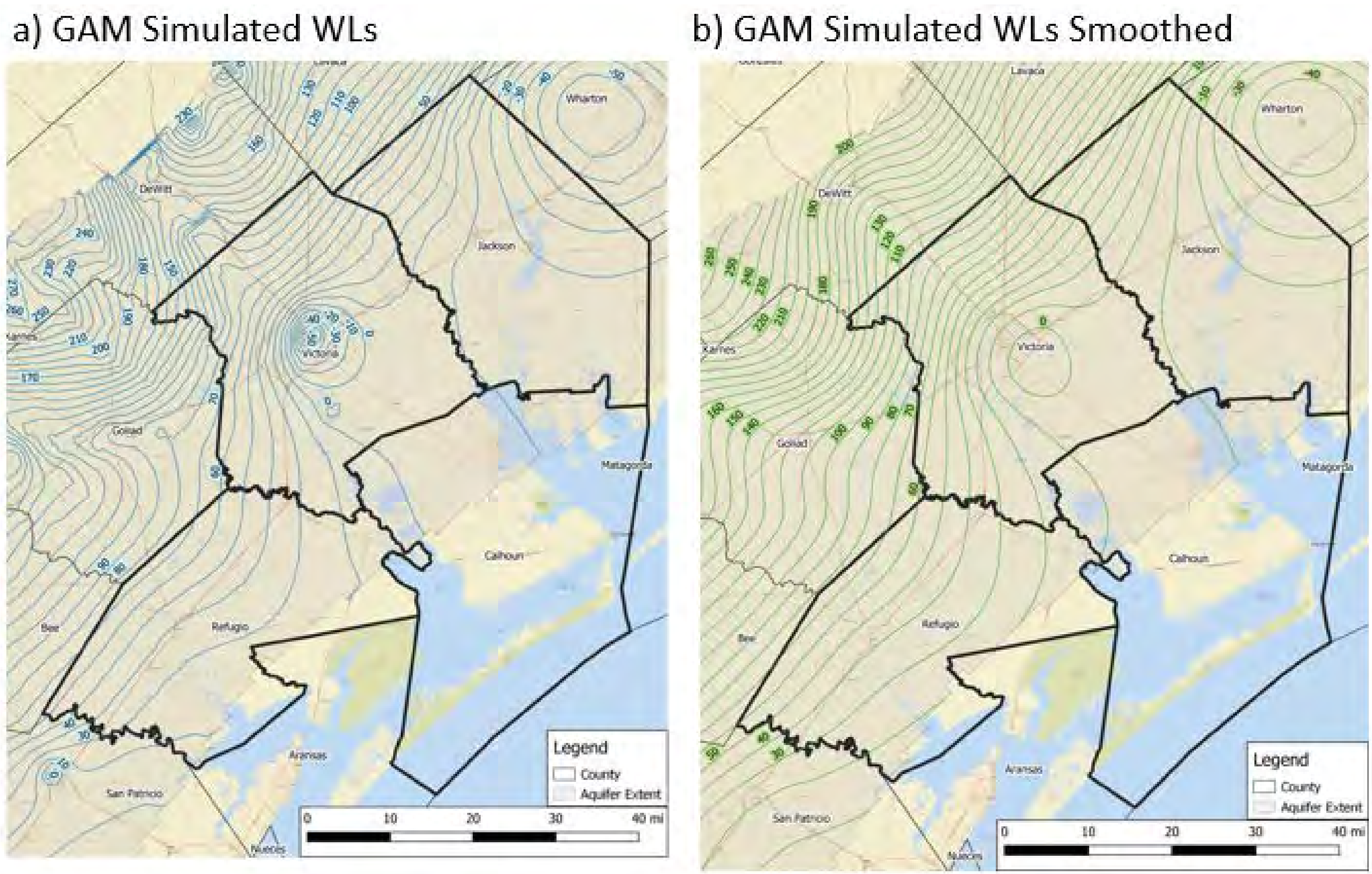


Figure 4-2 GMA simulated 2015 water levels for the Evangeline Aquifer, a) actual values; b) smoothed using SciPy function ndimage with a distance of 64,000 feet

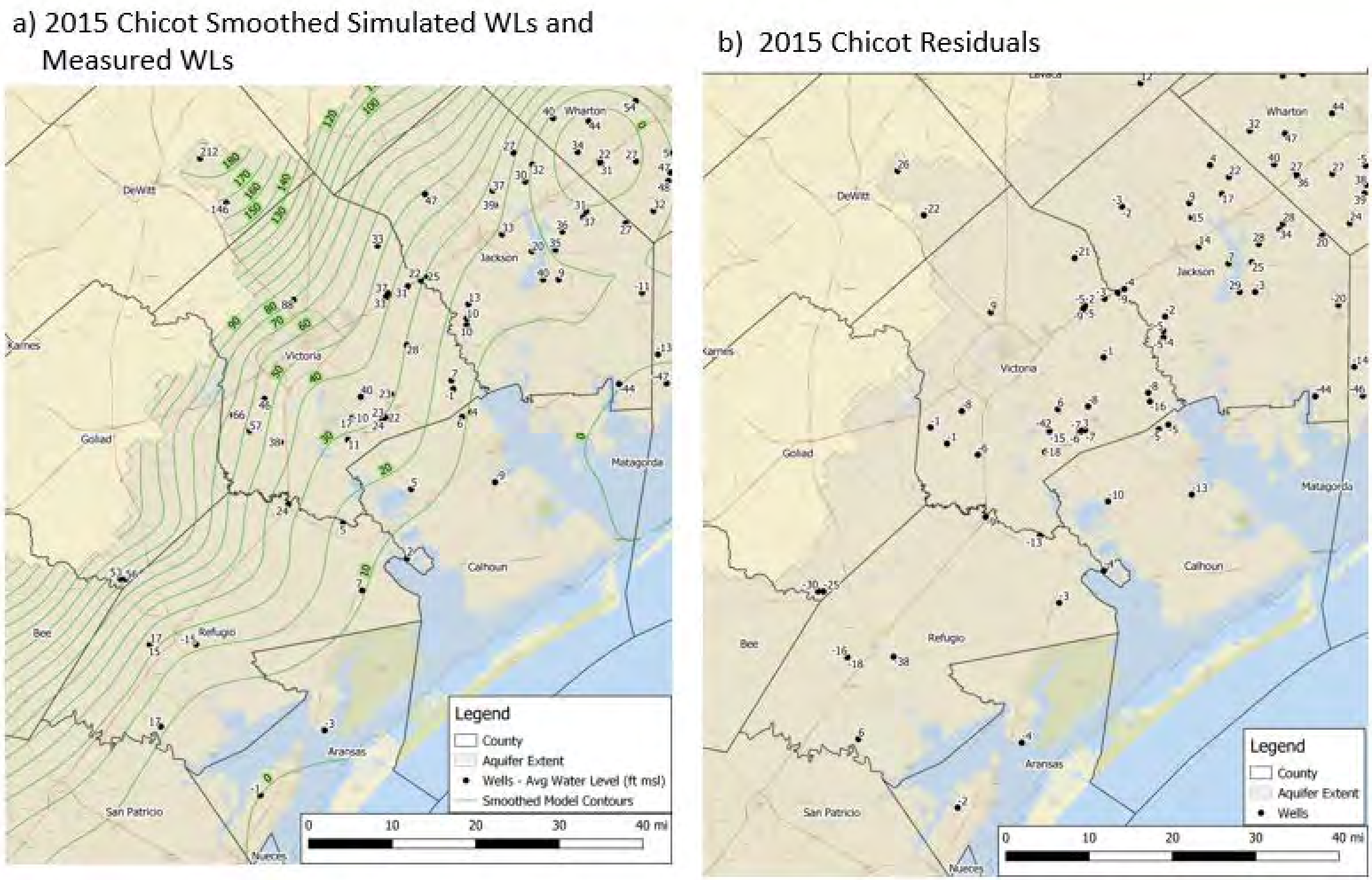


Figure 4-3 Example calculation of residuals Chicot Aquifer, a) 2015 smoothed simulated water levels and 2015 measured Chicot water levels; b) calculated 2015 Chicot residuals posted at well locations

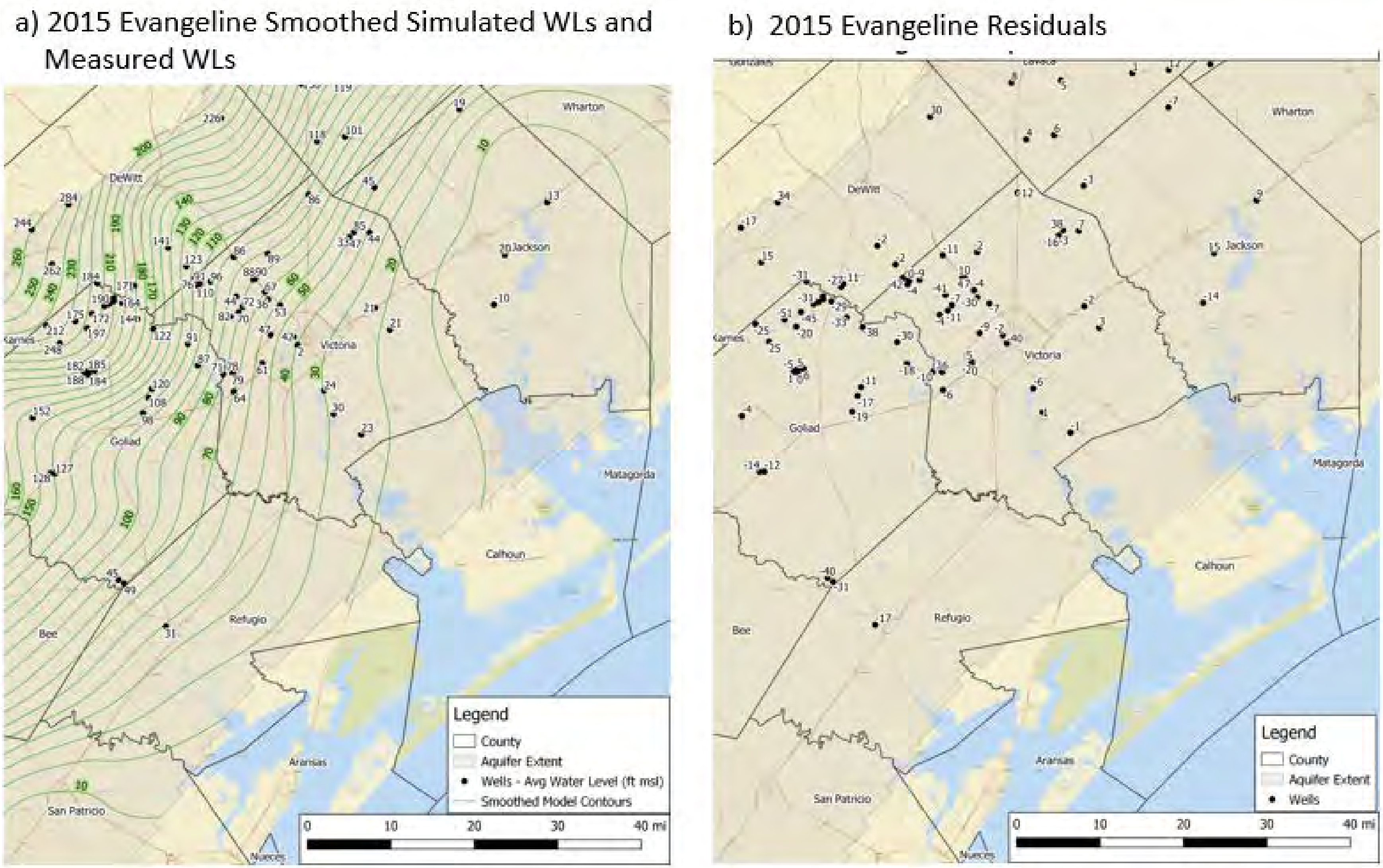


Figure 4-4 Example calculation of residuals Evangeline Aquifer, a) 2015 smoothed simulated water levels and 2015 measured Evangeline water levels; b) calculated 2015 Evangeline residuals posted at well locations

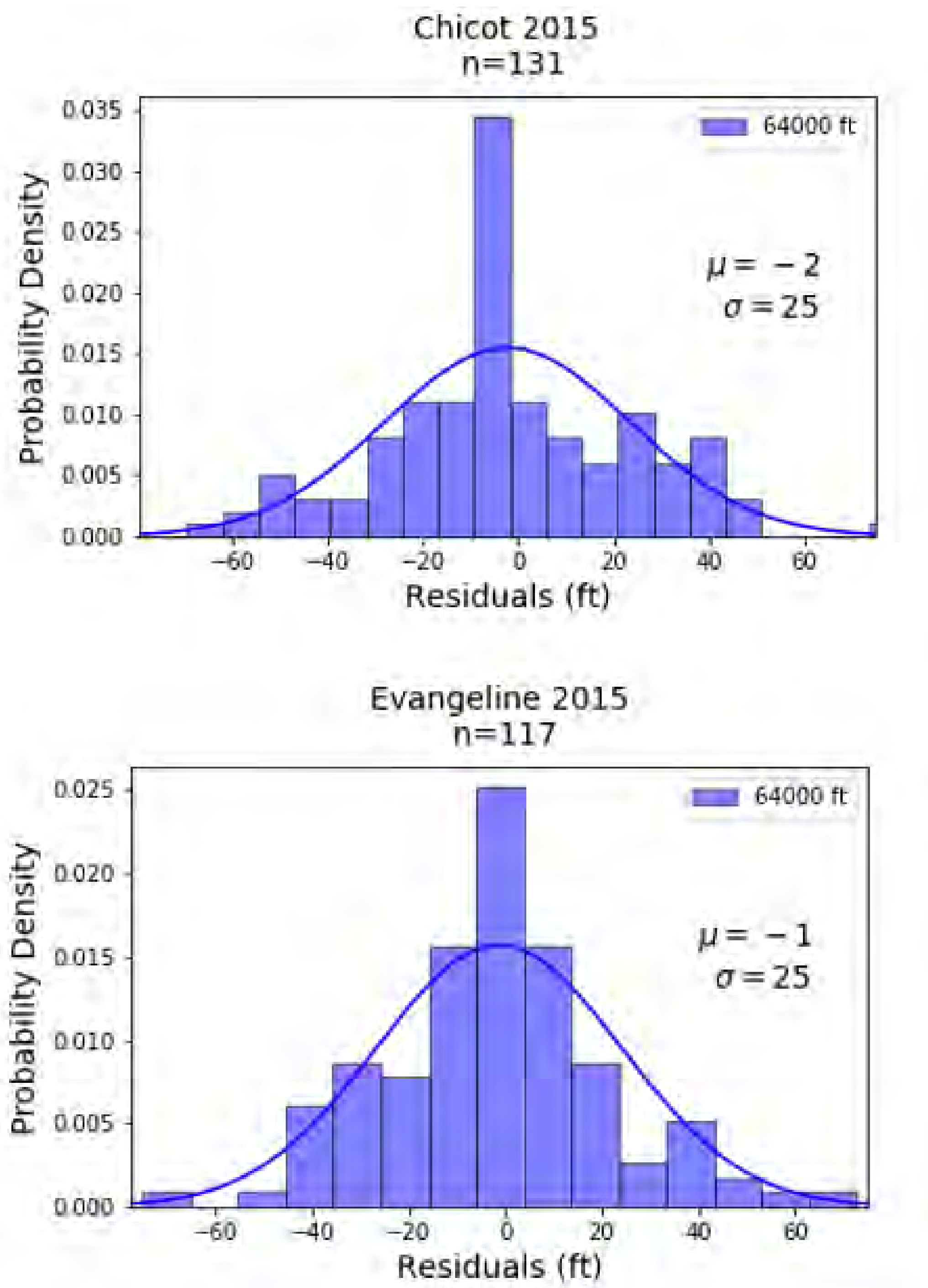
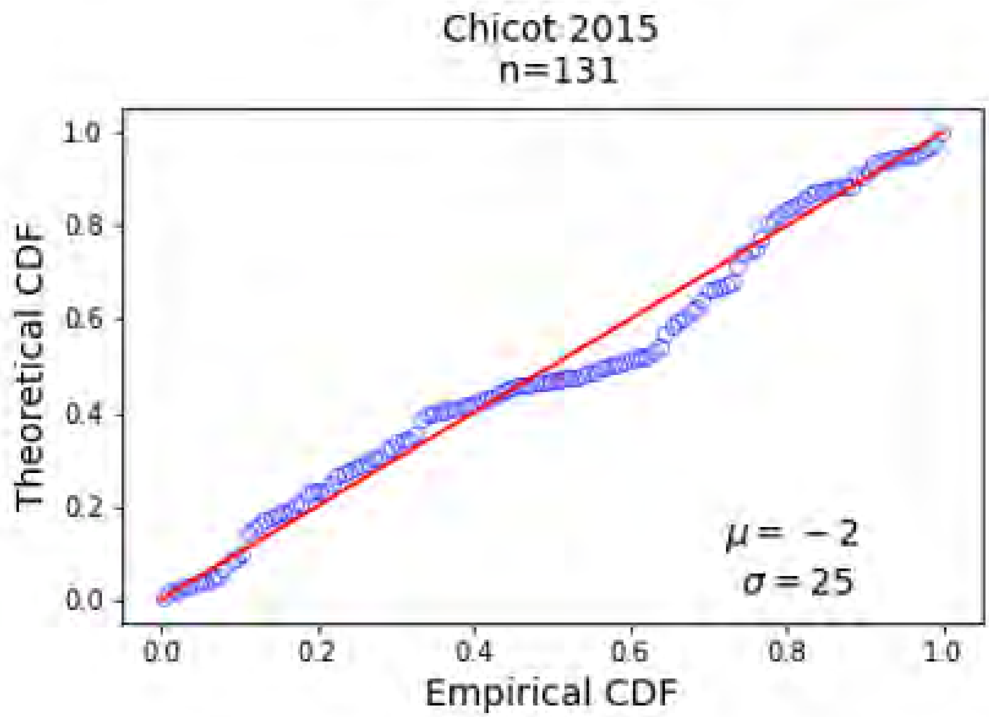


Figure 4-5 Histograms of 2015 water levels residuals for the Chicot and the Evangeline aquifers that are compared to a normal distribution based on the mean and standard deviation of the water level residuals



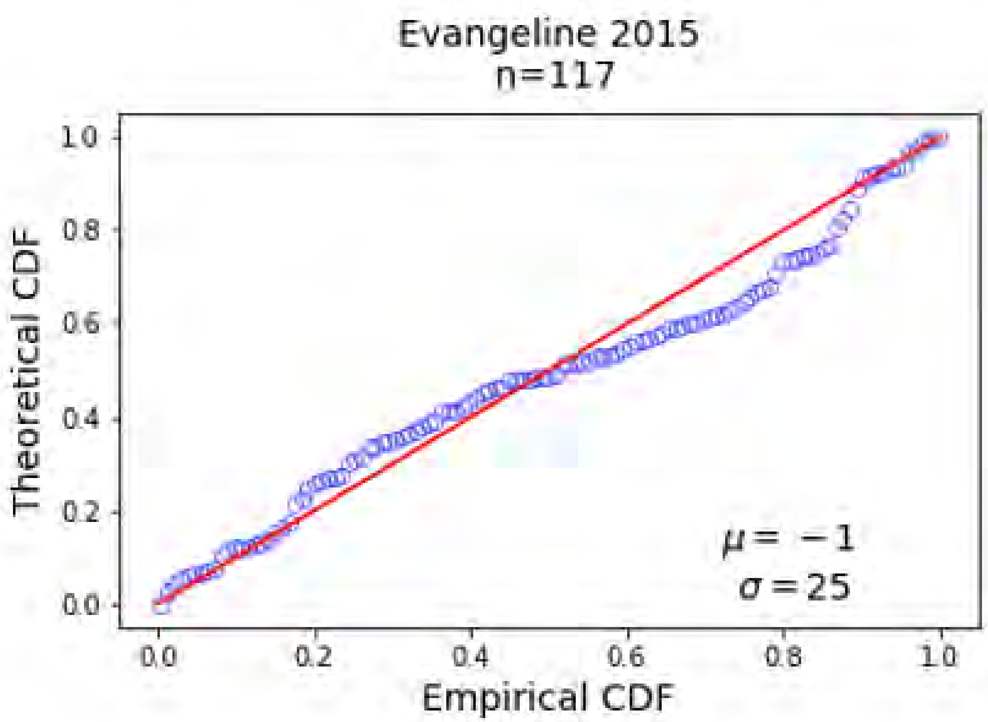


Figure 4-6 Probability plots of the 2015 water levels residuals for the Chicot and the Evangeline aquifers that compares the empirical cumulative density function (CDF) to the theoretical CDF

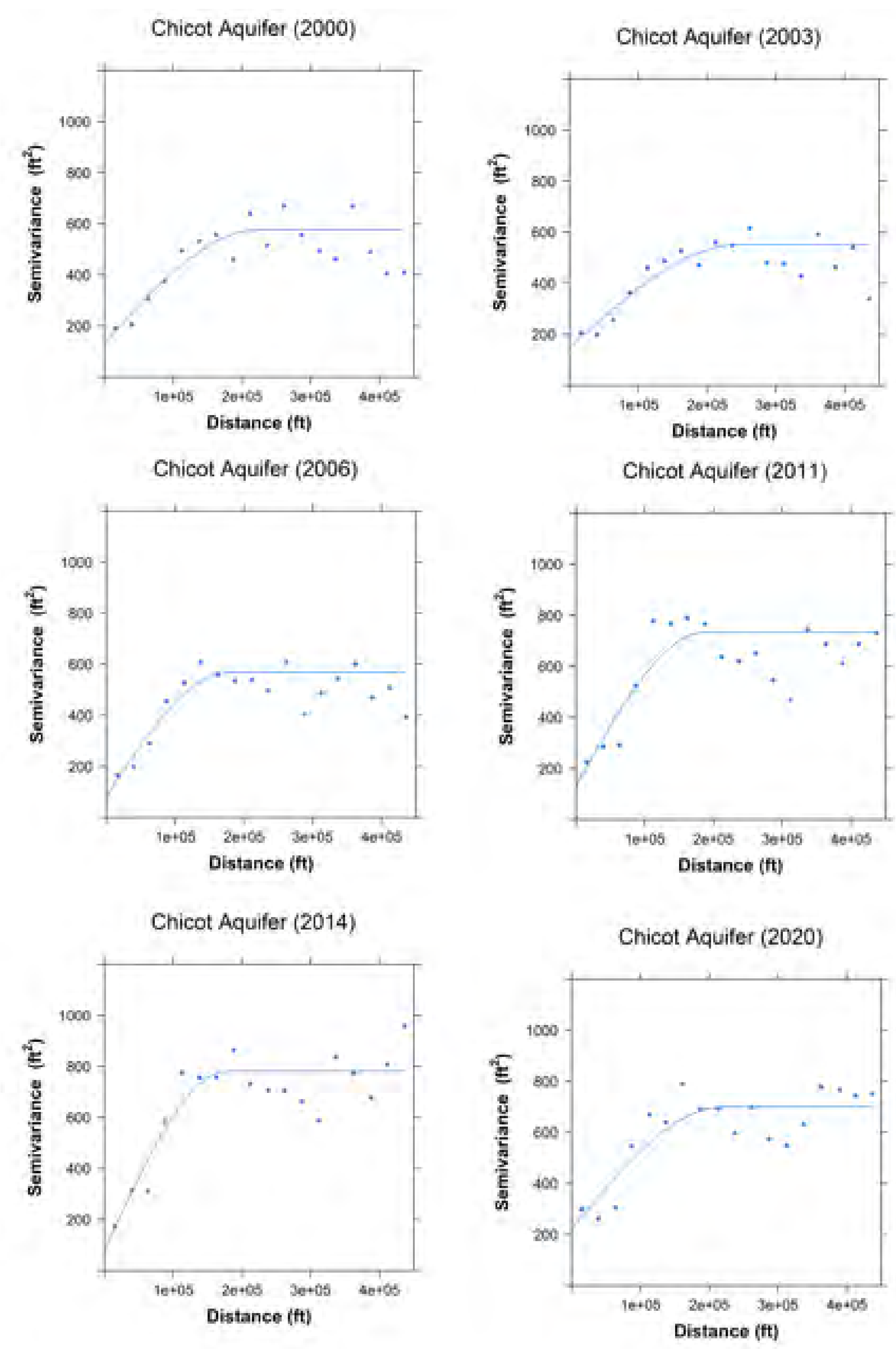


Figure 4-7 Experimental and theoretical spherical semivariogams for the residuals for 2000, 2003, 2006, 2011, 2014, and 2015 generated by detrending the measured groundwater levels in the Chicot Aquifer

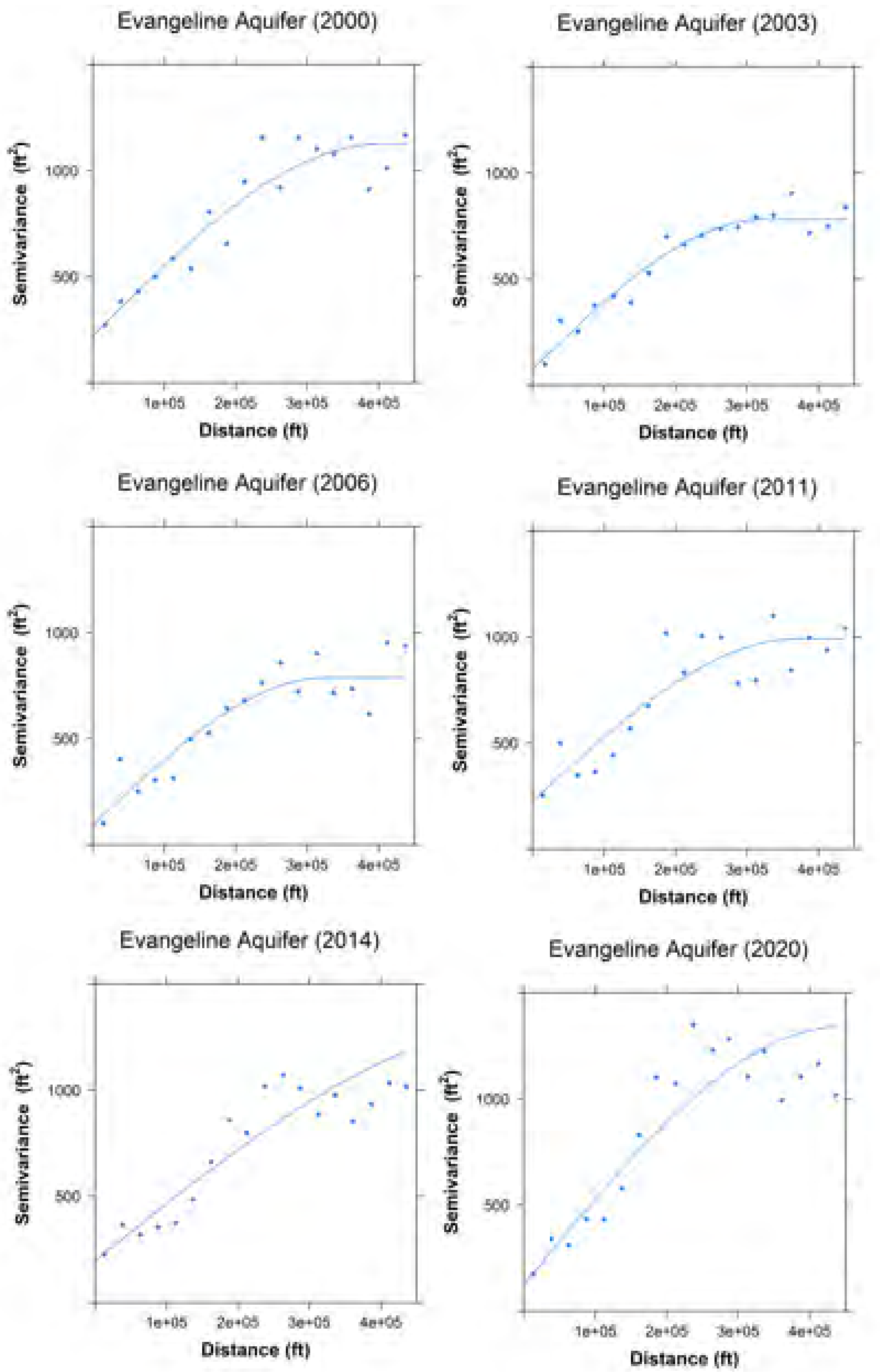


Figure 4-8 Experimental and theoretical spherical semivariogams for the residuals for 2000, 2003, 2006, 2011, 2014, and 2015 generated by detrending the measured groundwater levels in the Evangeline Aquifer

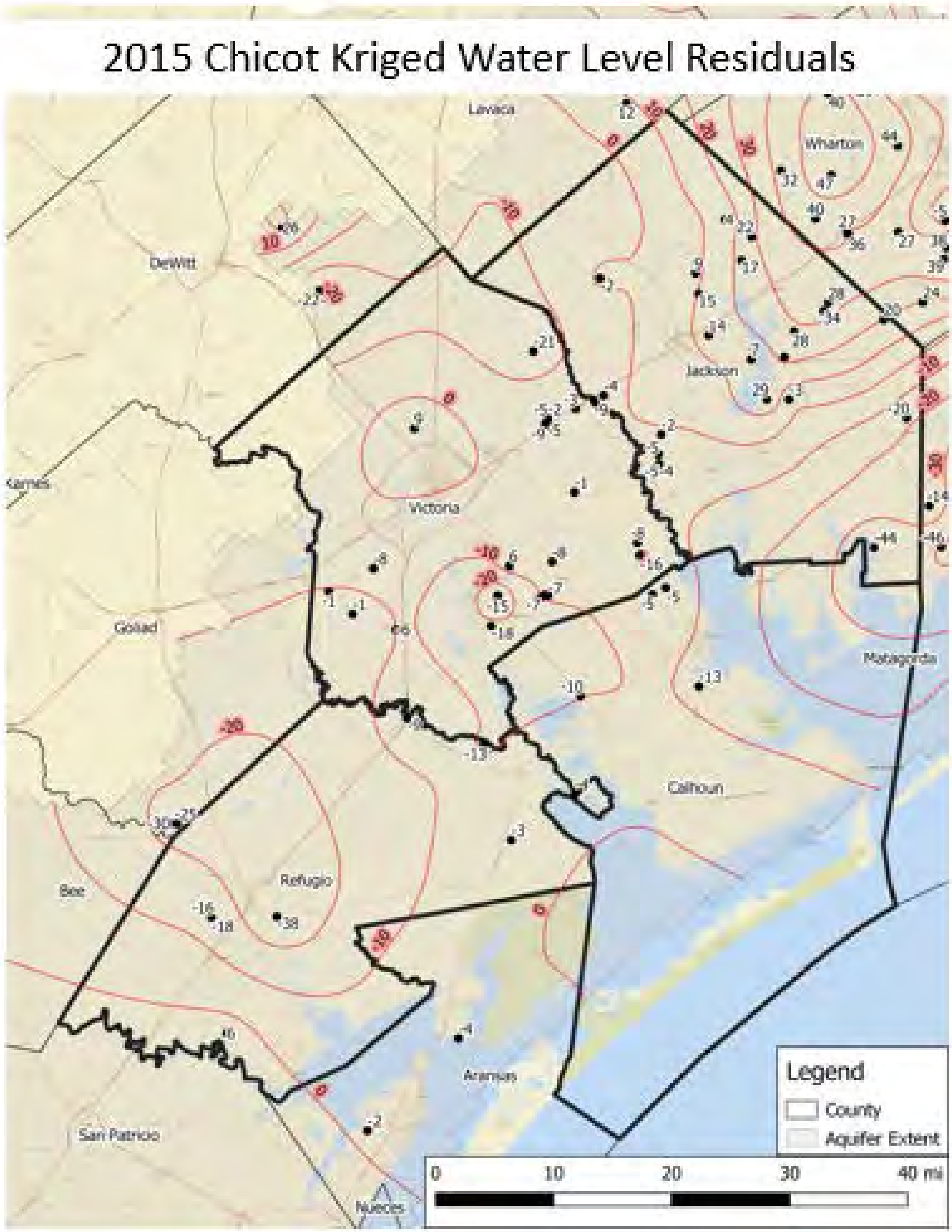


Figure 4-9 Contours for the Kriged 2015 water level residuals for the Chicot Aquifer

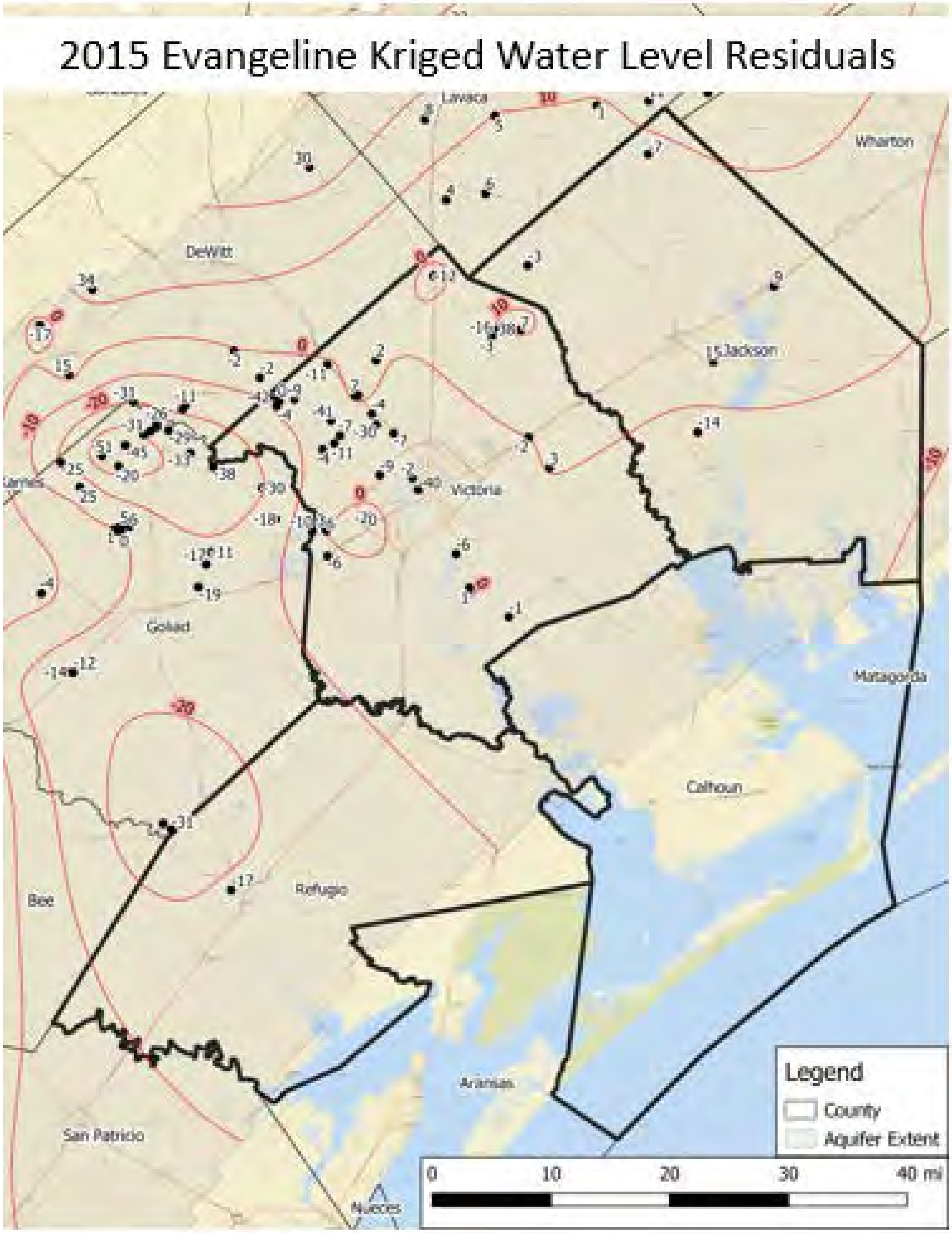


Figure 4-10 Contours for the Kriged 2015 water level residuals for the Evangeline Aquifer

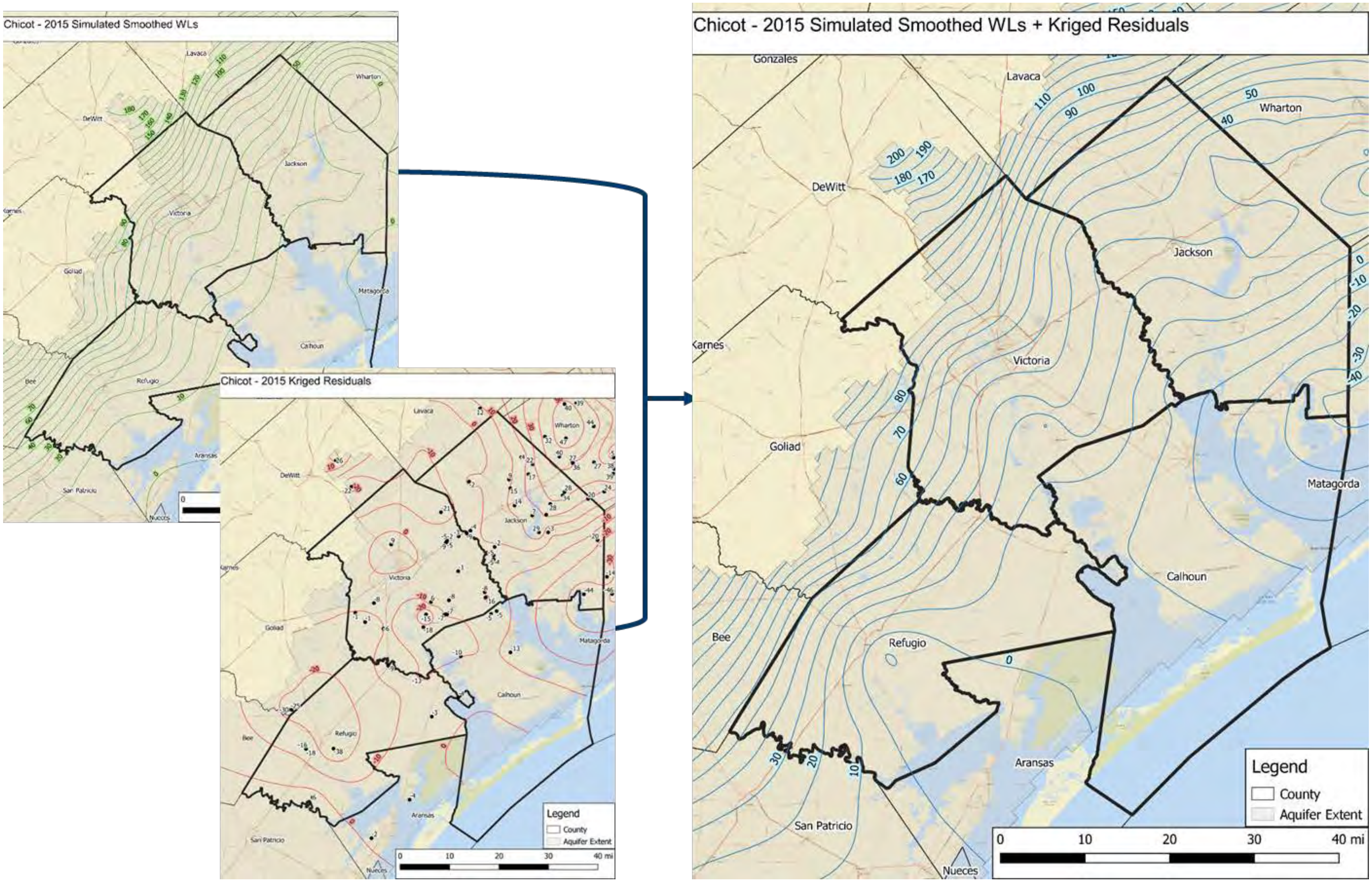


Figure 4-11 Combining the trend water level surface and the Kriged water level residual surface to produce the final surface for the 2015 Chicot water levels

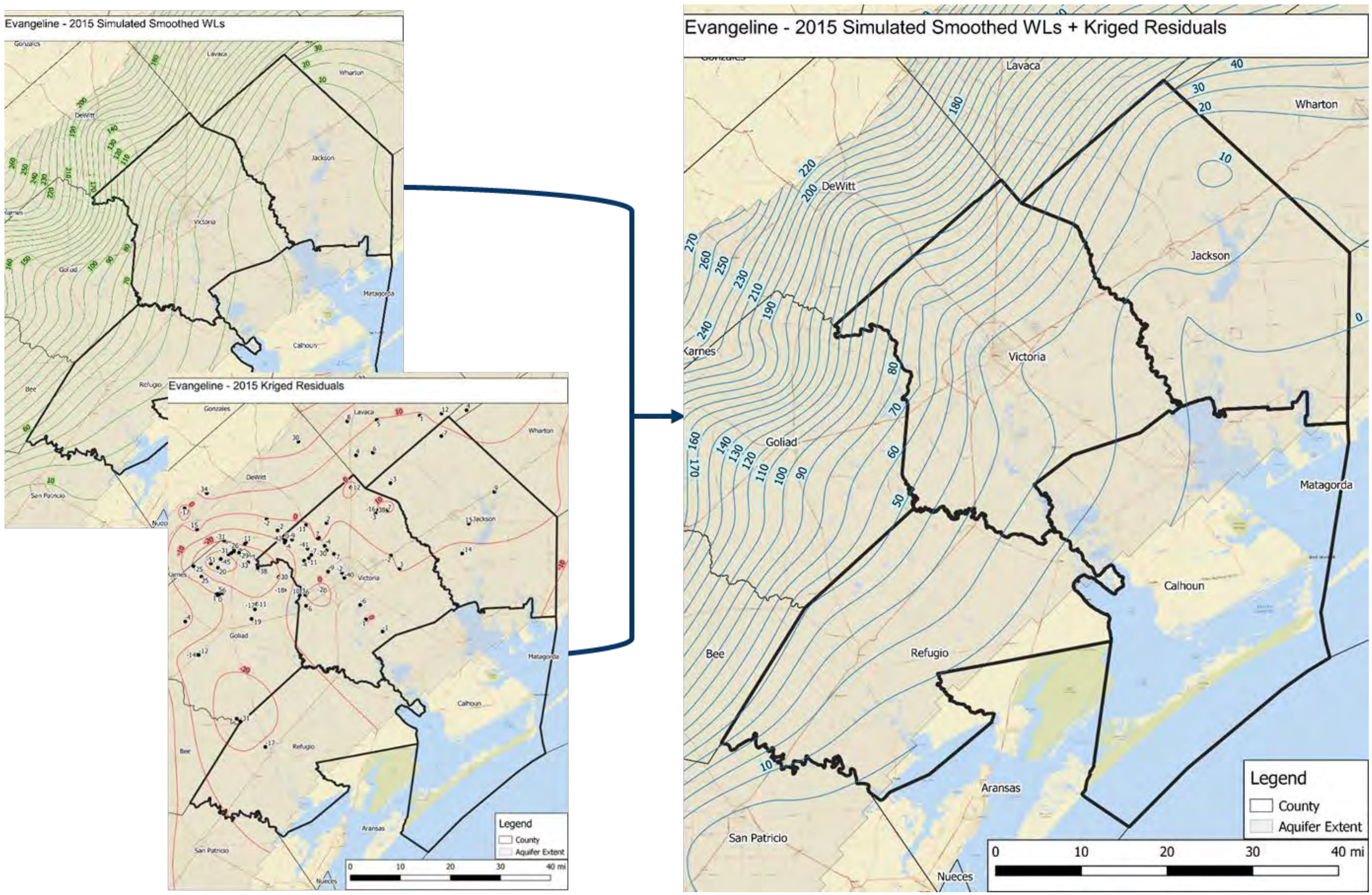


Figure 4-12 Combining the trend water level surface and the Kriged water level residual surface to produce the final surface for the 2015 Evangeline water levels

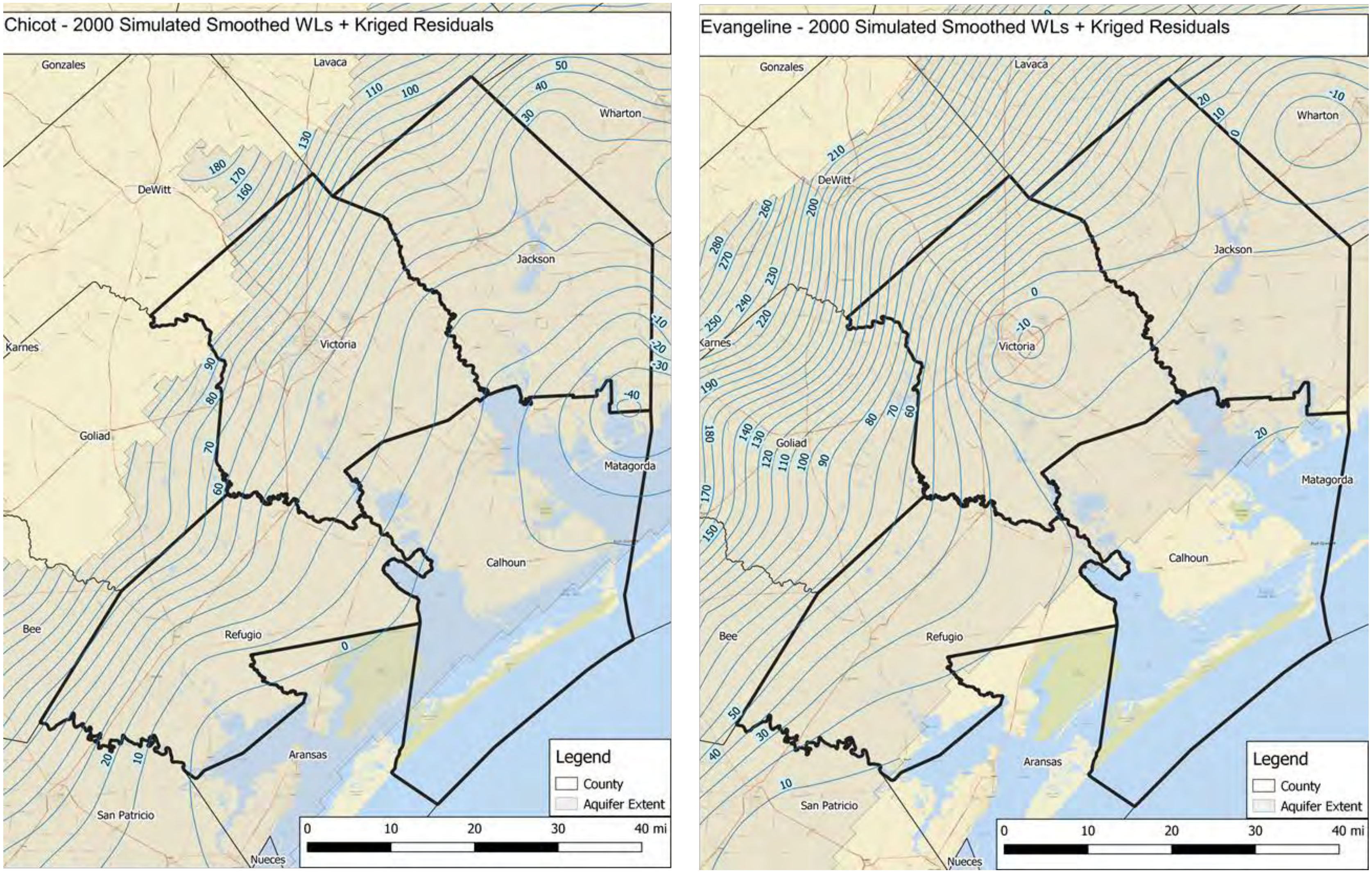


Figure 4-13 Contours of water levels for the Chicot and the Evangeline Aquifer in 2000 based on combining GAM simulated smoothed water levels and Kriged residual for the measured water levels.

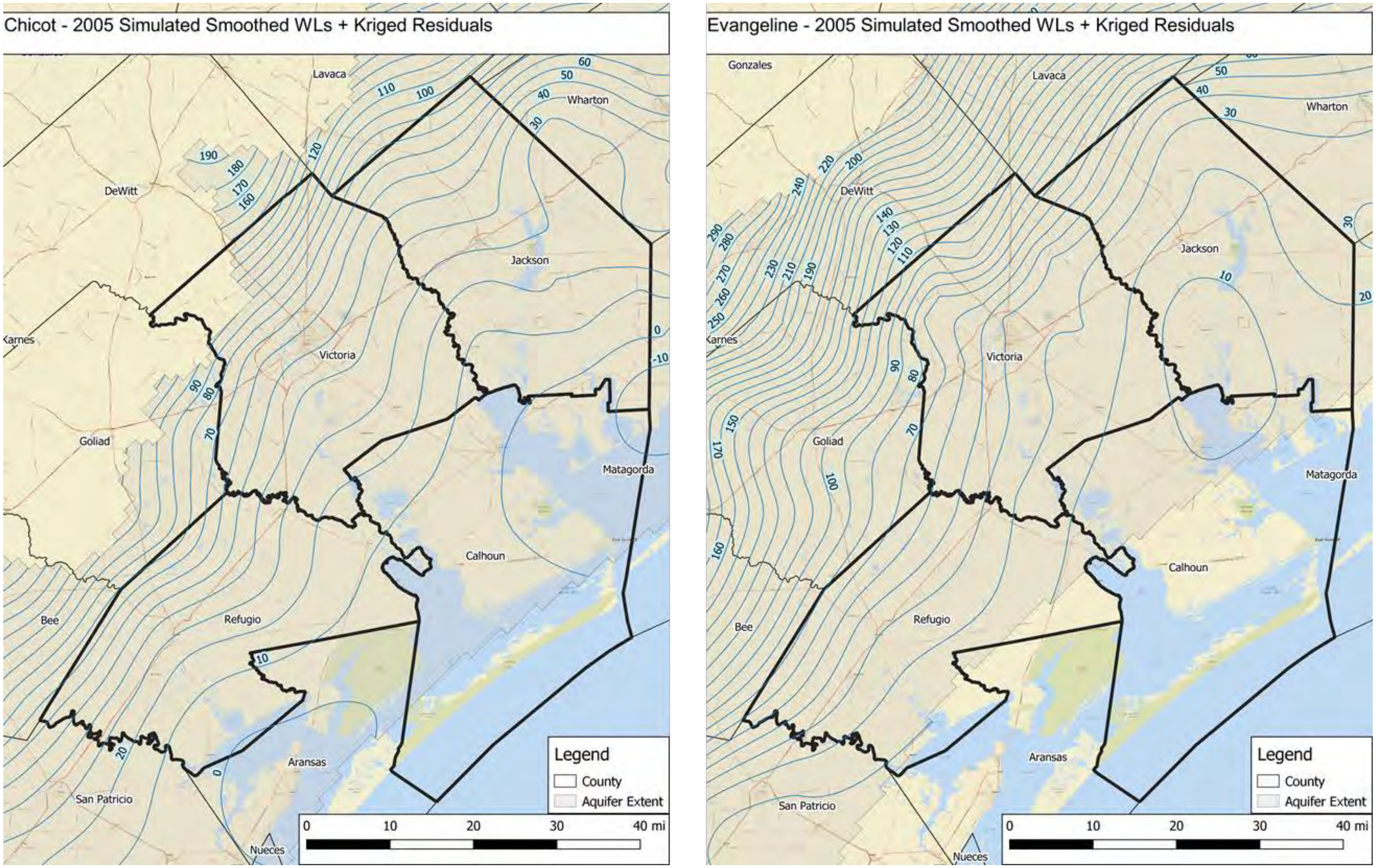


Figure 4-14 Contours of water levels for the Chicot and the Evangeline Aquifer in 2005 based on combining GAM simulated smoothed water levels and Kriged residual for the measured water levels.

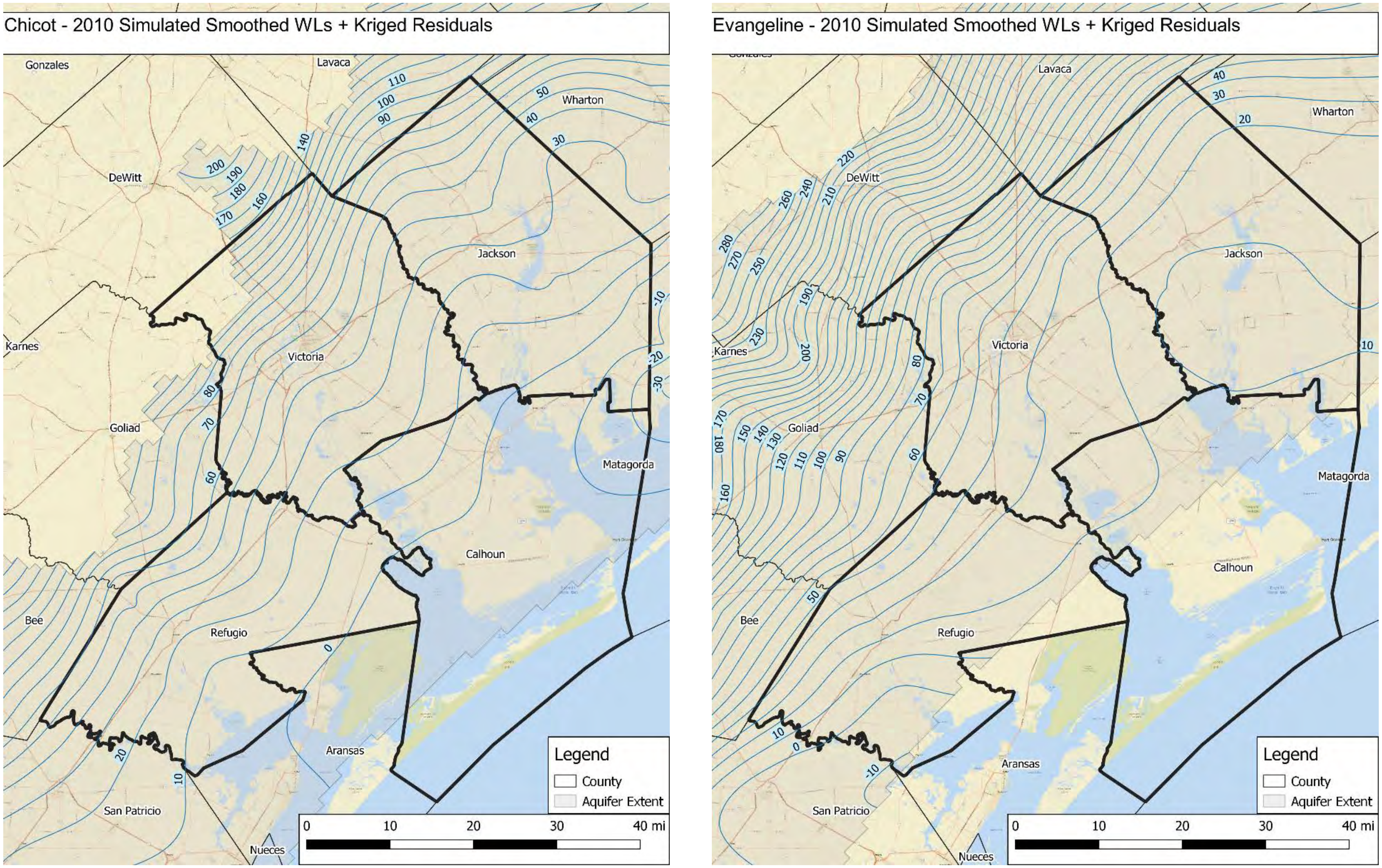


Figure 4-15 Contours of water levels for the Chicot and the Evangeline Aquifer in 2010 based on combining GAM simulated smoothed water levels and Kriged residual for the measured water levels.

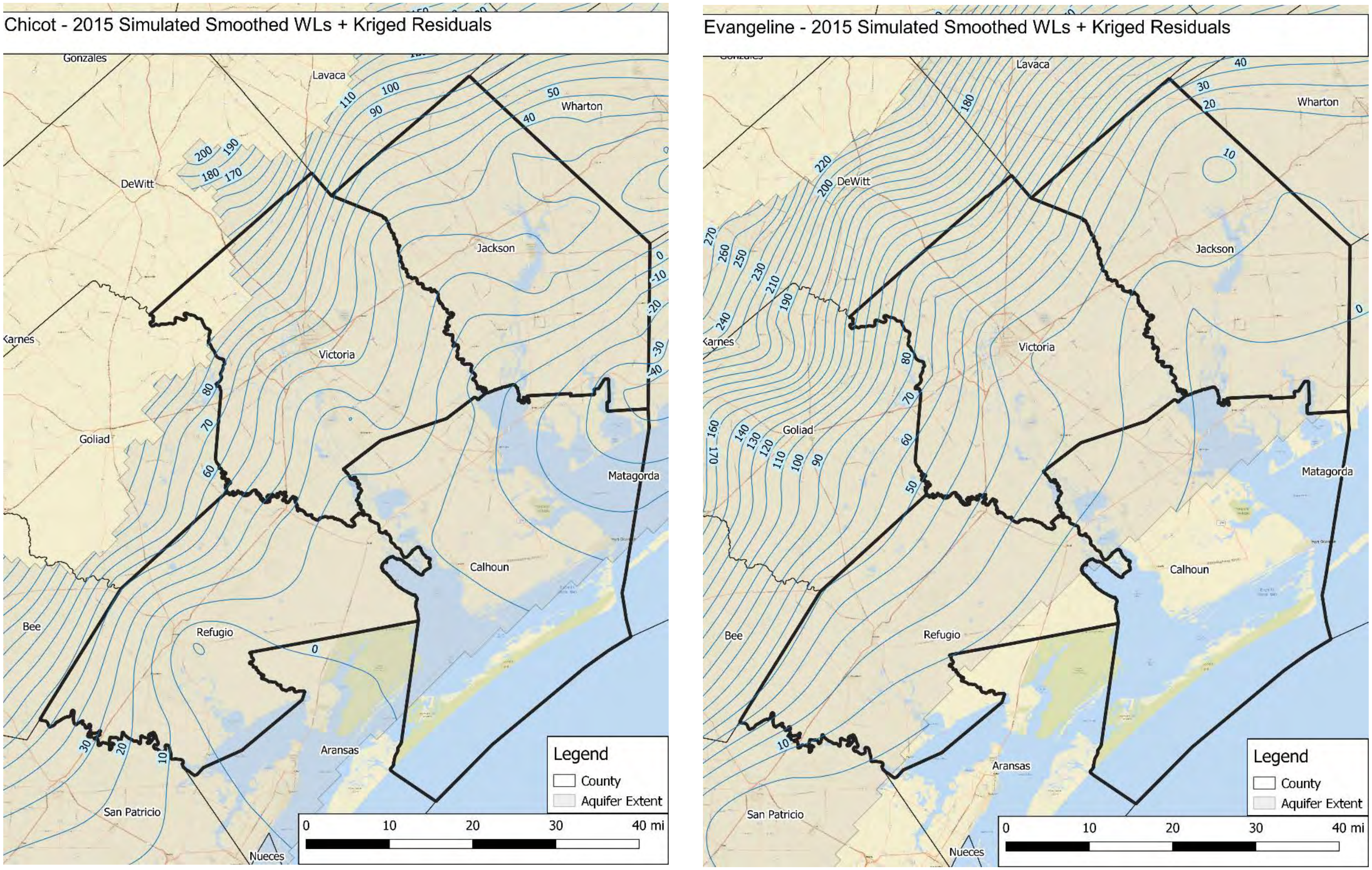


Figure 4-16 Contours of water levels for the Chicot and the Evangeline Aquifer in 2015 based on combining GAM simulated smoothed water levels and Kriged residual for the measured water levels.

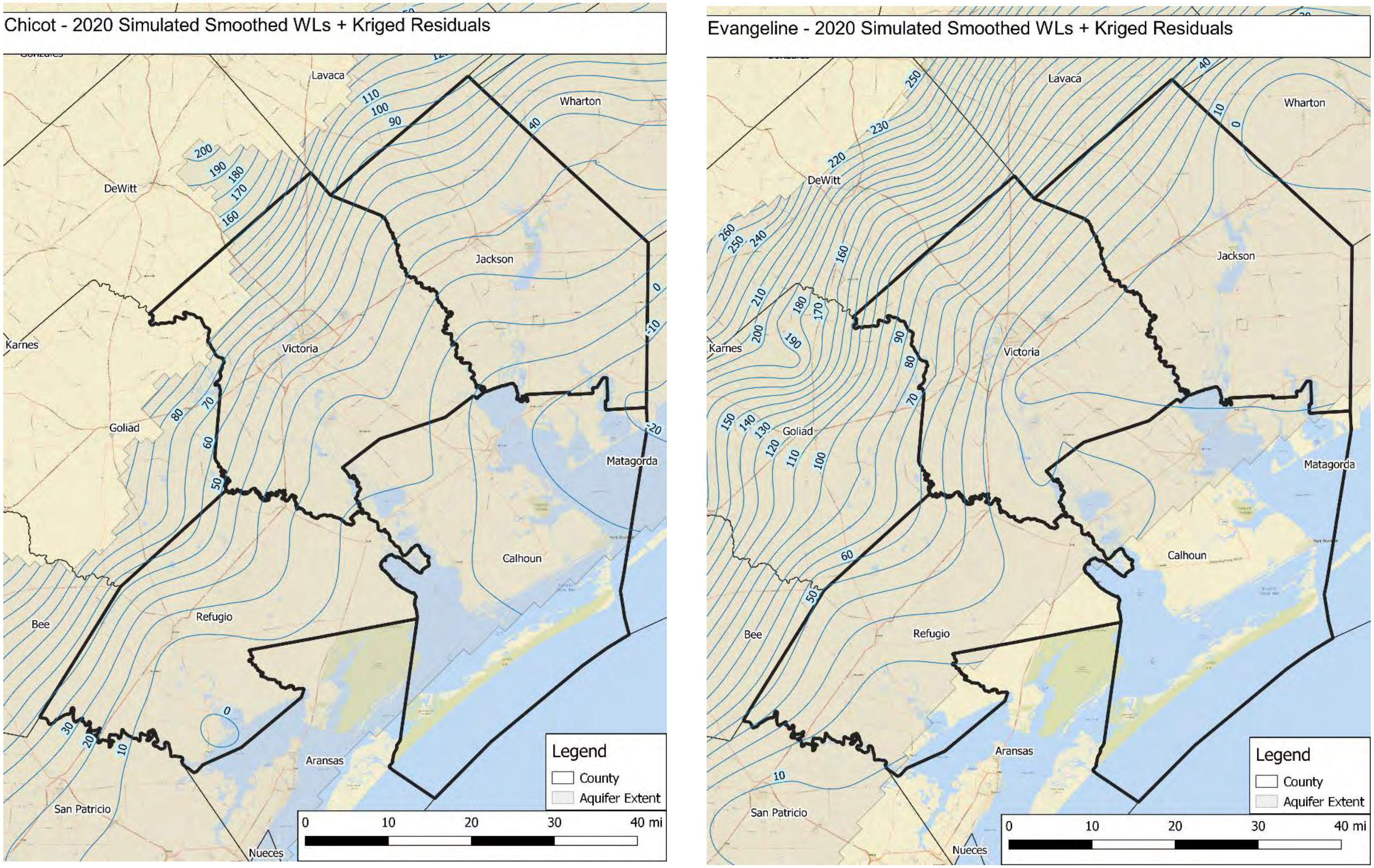


Figure 4-17 Contours of water levels for the Chicot and the Evangeline Aquifer in 2020 based on combining GAM simulated smoothed water levels and Kriged residual for the measured water levels.

5.0 CHANGE IN ANNUAL AVERAGE WATER LEVELS

This section presents provides graphs and tables that show how the average annual water level changes in Calhoun, Jackson, Refugio, and Victoria counties from 2000 to 2020. A useful metric for assessing changes in water levels across a county is a single number that represents the average water level elevation for the entire county. For this study, all water level maps are generated using grid cells that measure 1,000 by 1,000 ft. Therefore, each grid cell has an area of 1 million ft^2, which is the equivalent to about 23 acres or 0.36 $mile^2$. To determine the average water level for an area, one averages the water levels associated with the grid cells that comprise the area.

Tables 5-1 through **5-4** provide the average annual water levels calculated for the Chicot Aquifer, Evangeline Aquifer, and for a Chicot & Evangeline Aquifer from 2000 to 2020 for Calhoun, Jackson, Refugio, and Victoria counties using the SSWL+KR method. The average for the Chicot & Evangeline aquifers is calculated as if the Chicot and Evangeline aquifers were fused into a single aquifer. Tables 5-1 through 5-4 also provide the change in the average annual water levels relative to 2000. **Figures 5-1** through **5-4** plot the annual change in for the Chicot Aquifer, the Evangeline Aquifer, and the Chicot & Evangeline Aquifer. For all four counties, the Evangeline Aquifer has greater variability in the average water level change than does the Chicot Aquifer. From 2000 to 2020, the net changes in water level elevation that occurred in the Chicot Aquifer, the Evangeline Aquifer, and the Chicot & Evangeline Aquifer are:

- 4.5, -1.3, and 3.7 ft, respectively, for Calhoun County;
- 6.7, -1.0, and -2.9 ft, respectively, for Jackson County;
- -6.4, -1.7, and -3.7 ft, respectively, for Refugio County;
- -1.9, 9.3, and 3.8 ft, respectively, for Victoria County

Appendix D provides a sensitivity analysis of how changes in the method for constructing the water level maps impacts the amount of the average annual water levels. Among the notable observations from this sensitivity analysis are:

- The Kriged values results are not very sensitive to the amount the GAM simulated water level are smoothed to generate the trend surface used for detrending.
- The Kriged results can be very sensitive if the trend surface trend surface is updated to account for annual differences in the GAM simulations that account for different pumping rates.
- The Kriging of water levels without detrending can produce significantly different results than Kriging with detrending.
- The results for the Evangeline Aquifer are more sensitive to changes how Kriging is performed than results for the Chicot Aquifer.

Table 5-1 Average annual water level (ft, msl) and change in the average annual water level for Calhoun County for the Chicot Aquifer, the Evangeline Aquifer and the Chicot & Evangeline aquifers

Aquifer	Water Level/ Change	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Chicot	avg. WL (ft)	-7.0	-5.9	-4.9	-0.3	-1.8	1.9	-4.5	-1.0	0.8	-2.6	-2.6	-1.2	-7.6	-5.1	-6.8	-7.7	-7.8	-2.6	-4.2	-2.9	-2.6
	change (ft)*	0.0	1.1	2.1	6.7	5.2	8.9	2.5	6.1	7.8	4.4	4.4	5.8	-0.6	2.0	0.2	-0.6	-0.8	4.4	2.8	4.1	4.5
Evangeline	avg. WL (ft)	17.7	11.3	8.1	25.2	13.7	13.3	21.8	28.0	15.1	16.5	18.1	14.6	18.7	10.3	1.2	3.6	3.6	11.6	-8.0	15.2	16.4
	change (ft)*	0.0	-6.4	-9.6	7.5	-4.0	-4.4	4.1	10.3	-2.6	-1.2	0.4	-3.1	1.0	-7.4	-16.5	-14.2	-14.1	-6.1	-25.8	-2.5	-1.3
Chicot & Evangeline	avg. WL (ft)	-3.2	-3.7	-3.5	3.7	0.2	3.3	-0.2	3.7	3.1	0.2	0.4	1.0	-3.1	-2.8	-5.7	-6.1	-6.2	-0.4	-5.7	-0.1	0.5
	change (ft)*	0.0	-0.5	-0.3	7.0	3.4	6.6	3.1	6.9	6.3	3.4	3.6	4.2	0.1	0.4	-2.5	-2.8	-3.0	2.8	-2.5	3.1	3.7

* change is measured relative to the year 2000; avg WL is measured relative to mean sea level

Table 5-2 Average annual water level (ft, msl) and change in the average annual water level for Jackson County for the Chicot Aquifer, the Evangeline Aquifer and the Chicot & Evangeline aquifers

Aquifer	Water Level/ Change	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Chicot	avg. WL (ft)	21.3	19.3	23.4	26.5	26.5	29.3	23.0	29.9	30.7	26.4	27.1	28.1	20.2	23.6	20.3	22.1	20.6	25.9	25.7	26.2	28.0
	change (ft)*	0.0	-2.0	2.1	5.2	5.2	8.0	1.7	8.6	9.4	5.1	5.8	6.8	-1.1	2.2	-1.0	0.8	-0.7	4.6	4.4	4.9	6.7
Evangeline	avg. WL (ft)	17.0	19.2	21.8	21.0	22.0	22.0	21.5	32.6	27.5	20.9	17.1	19.6	6.2	20.4	1.7	12.0	21.0	17.4	-3.5	15.4	15.9
	change (ft)*	0.0	2.3	4.9	4.0	5.1	5.1	4.6	15.7	10.6	3.9	0.1	2.6	-10.7	3.4	-15.2	-4.9	4.1	0.4	-20.4	-1.5	-1.0
Chicot & Evangeline	avg. WL (ft)	19.0	19.1	22.5	23.6	24.2	25.6	22.2	31.2	29.0	23.5	22.0	23.8	13.1	21.9	11.0	16.9	20.7	21.5	11.0	20.8	21.9
	change (ft)*	19.1	0.1	3.5	4.6	5.2	6.6	3.1	12.2	10.0	4.5	3.0	4.8	-5.9	2.8	-8.1	-2.1	1.7	2.5	-8.0	1.7	2.9

* change is measured relative to the year 2000; avg WL is measured relative to mean sea level

Table 5-3 Average annual water level (ft, msl) and change in the average annual water level for Refugio County for the Chicot Aquifer, the Evangeline Aquifer and the Chicot & Evangeline aquifers

Aquifer	Water Level/ Change	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Chicot	avg. WL (ft)	24.8	23.6	28.3	27.2	24.5	28.3	24.6	27.4	29.0	24.3	22.7	23.5	23.0	19.4	4.5	14.5	19.6	19.2	19.0	20.0	18.4
	change (ft)*	0.0	-1.2	3.6	2.5	-0.2	3.5	-0.1	2.6	4.3	-0.5	-2.1	-1.2	-1.8	-5.4	-20.2	-10.3	-5.2	-5.6	-5.8	-4.8	-6.4
Evangeline	avg. WL (ft)	32.5	31.7	34.2	39.8	37.9	40.7	38.3	35.4	31.2	31.7	21.7	31.6	33.1	27.0	23.9	22.3	24.6	30.4	20.5	28.2	30.9
	change (ft)*	0.0	-0.8	1.6	7.2	5.3	8.1	5.8	2.8	-1.3	-0.9	-10.8	-1.0	0.5	-5.5	-8.6	-10.3	-7.9	-2.2	-12.0	-4.3	-1.7
Chicot & Evangeline	avg. WL (ft)	26.3	25.4	29.1	31.0	28.8	31.8	28.9	29.0	28.5	26.1	20.7	25.6	25.8	21.4	11.9	16.7	20.4	22.8	18.6	22.4	22.6
	change (ft)*	0.0	-0.9	2.8	4.7	2.5	5.6	2.6	2.7	2.2	-0.1	-5.5	-0.7	-0.5	-4.9	-14.4	-9.5	-5.8	-3.5	-7.7	-3.9	-3.7

* change is measured relative to the year 2000; avg WL is measured relative to mean sea level

Table 5-4 Average annual water level (ft, msl) and change in the average annual water level for Victoria County for the Chicot Aquifer, the Evangeline Aquifer and the Chicot & Evangeline aquifers

Aquifer	Water Level/ Change	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Chicot	avg. WL (ft)	49.8	49.2	47.8	48.8	49.6	52.6	51.8	52.0	52.4	50.9	52.8	48.0	43.5	50.1	45.5	48.2	49.9	51.4	52.0	49.9	47.9
	change (ft)*	0.0	-0.6	-2.0	-1.0	-0.2	2.8	2.0	2.2	2.6	1.1	3.0	-1.7	-6.3	0.3	-4.3	-1.6	0.1	1.6	2.2	0.1	-1.9
Evangeline	avg. WL (ft)	29.8	32.0	40.6	48.8	51.0	48.9	47.6	53.4	53.0	47.7	44.8	41.3	32.4	45.3	40.9	41.4	45.6	46.1	30.6	38.0	39.1
	change (ft)*	0.0	2.2	10.8	19.0	21.2	19.1	17.7	23.5	23.1	17.8	15.0	11.5	2.5	15.4	11.0	11.5	15.7	16.3	0.7	8.2	9.3
Chicot & Evangeline	avg. WL (ft)	41.3	42.4	46.0	50.6	51.9	52.2	51.2	54.2	54.2	50.7	50.2	46.2	39.3	49.3	44.8	46.3	49.3	50.4	42.7	45.6	45.1
	change (ft)*	0.0	1.0	4.6	9.2	10.5	10.9	9.9	12.9	12.9	9.4	8.9	4.9	-2.0	7.9	3.4	5.0	7.9	9.0	1.4	4.2	3.8

* change is measured relative to the year 2000; avg WL is measured relative to mean sea level

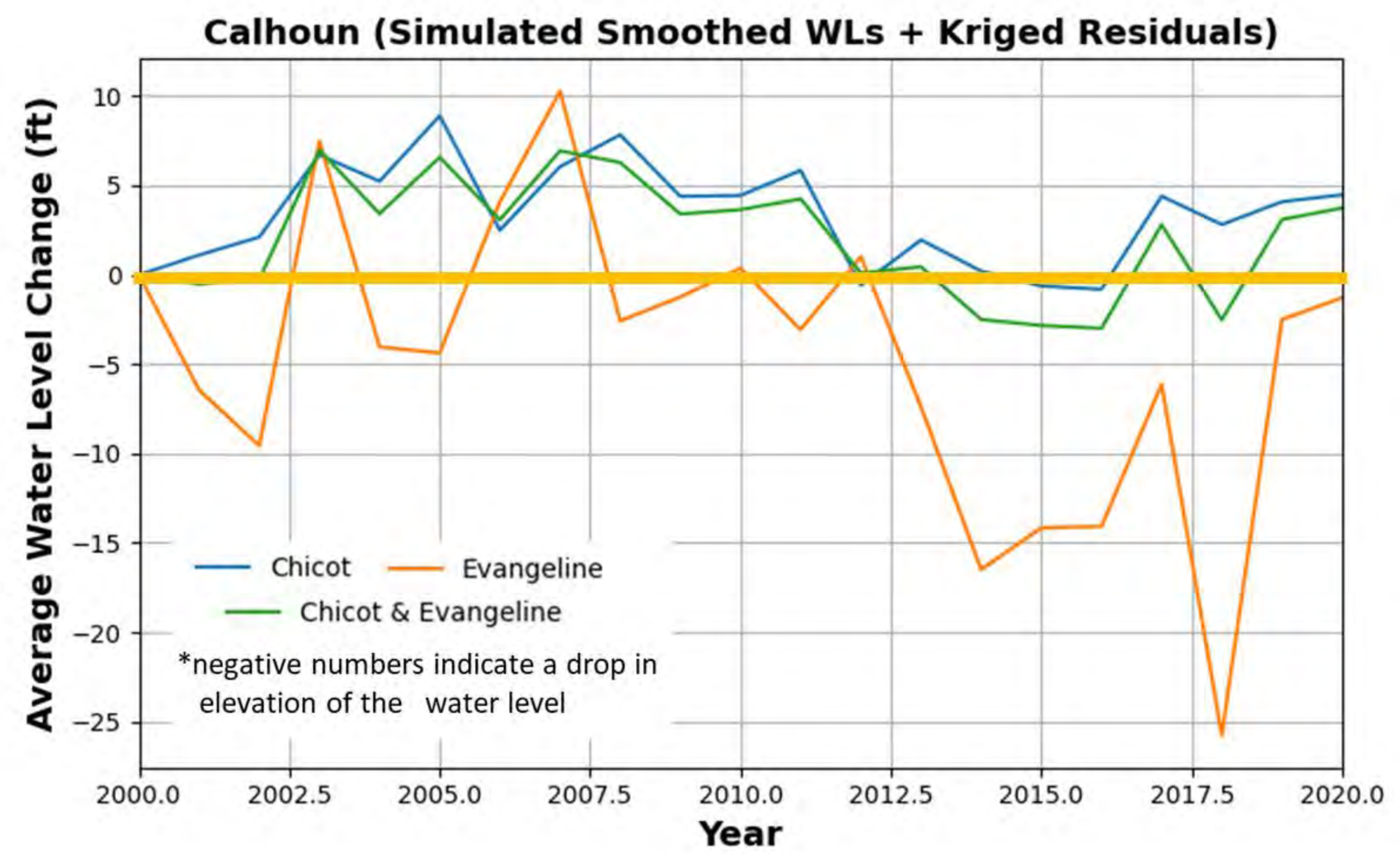


Figure 5-1 Change in the average annual water level calculated in Calhoun County for the Chicot Aquifer, the Evangeline Aquifer, and the combination of Chicot and Evangeline aquifers based on the analysis of aquifer levels determined using GAM simulated smoothed water levels and Kriged residual for the measured water levels.

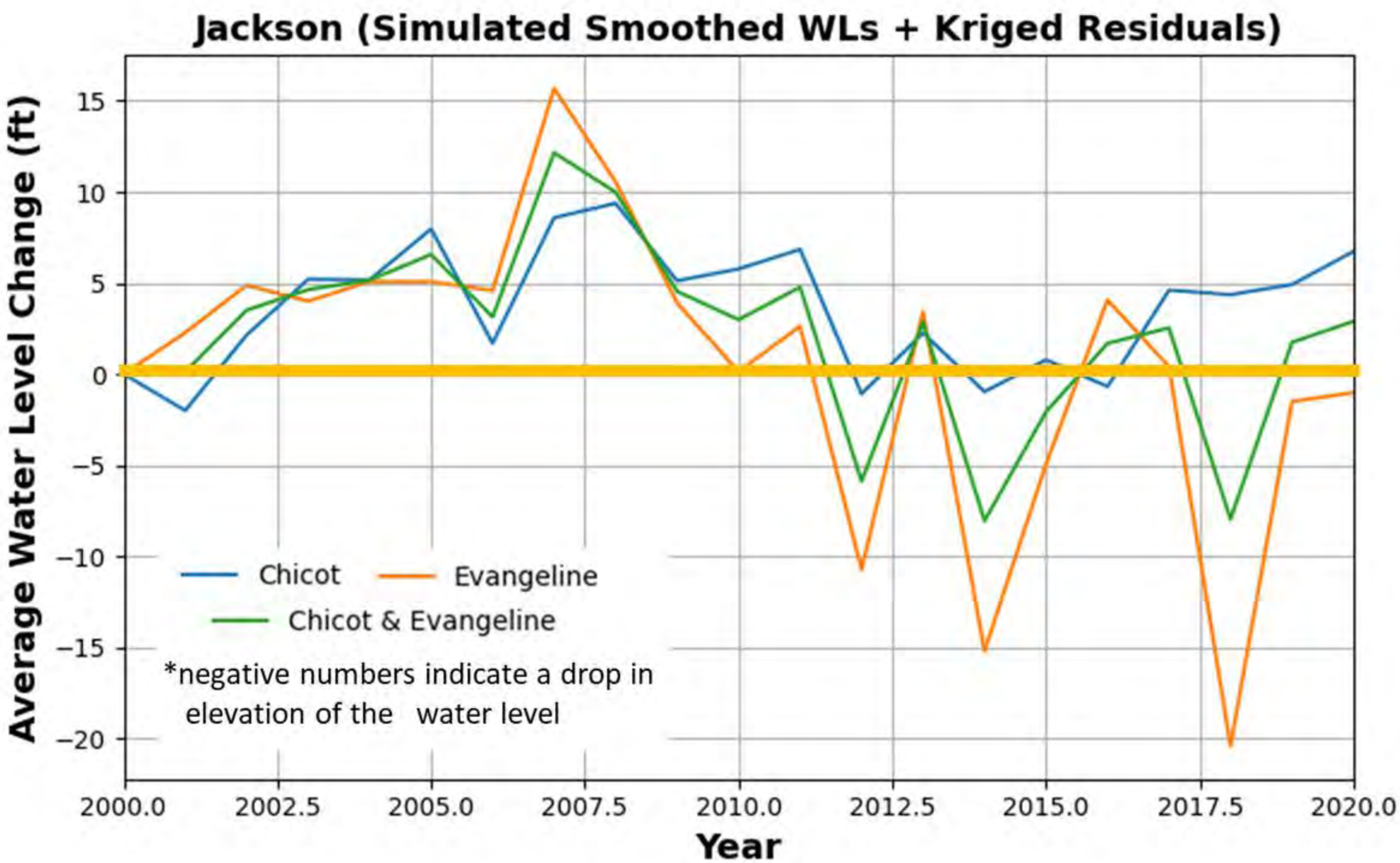


Figure 5-2 Change in the average annual water level calculated in Jackson County for the Chicot Aquifer, the Evangeline Aquifer, and the combination of Chicot and Evangeline aquifers based on the analysis of aquifer levels determined using GAM simulated smoothed water levels and Kriged residual for the measured water levels.

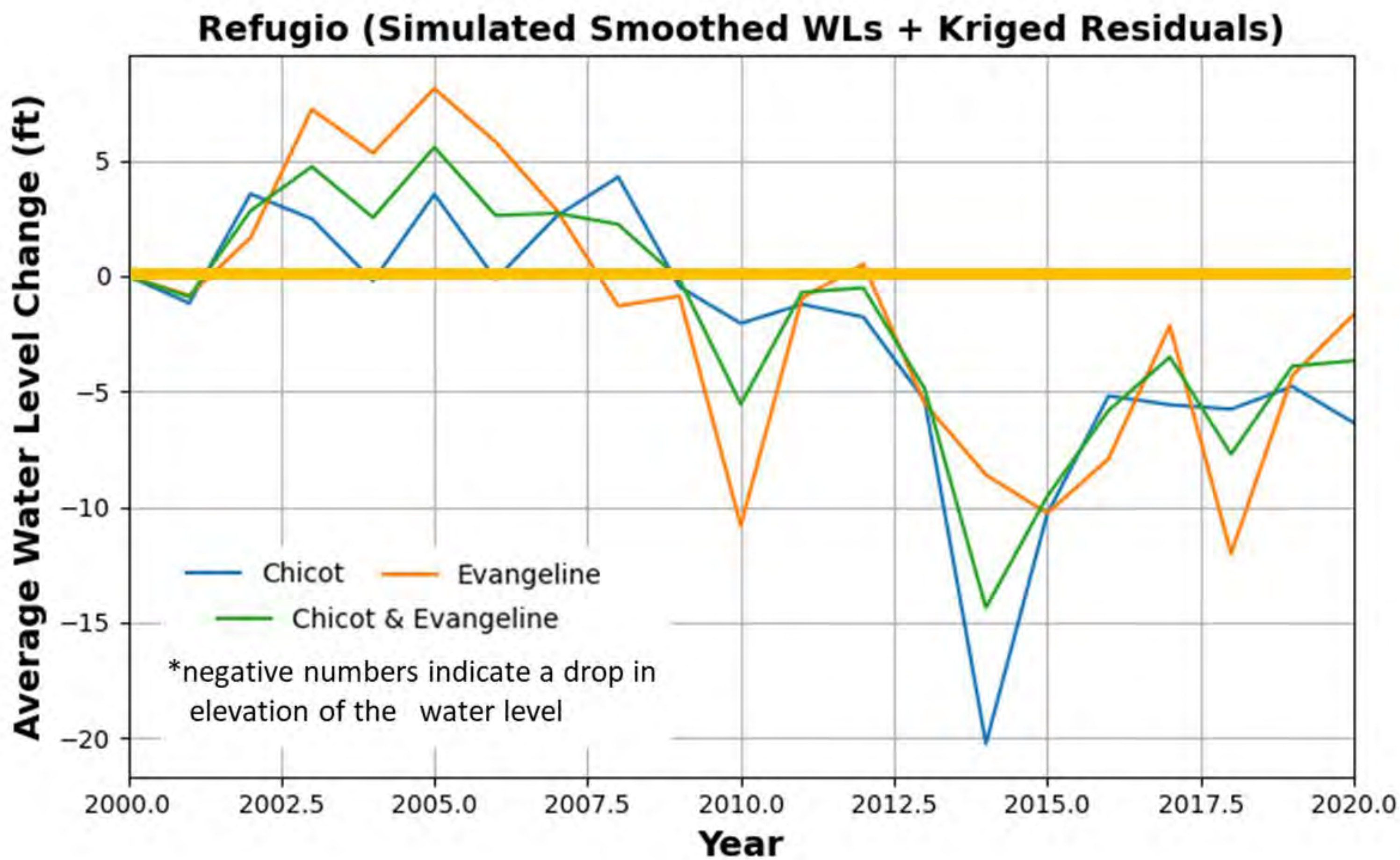


Figure 5-3 Change in the average annual water level calculated in Refugio County for the Chicot Aquifer, the Evangeline Aquifer, and the combination of Chicot and Evangeline aquifers based on the analysis of aquifer levels determined using GAM simulated smoothed water levels and Kriged residual for the measured water levels.

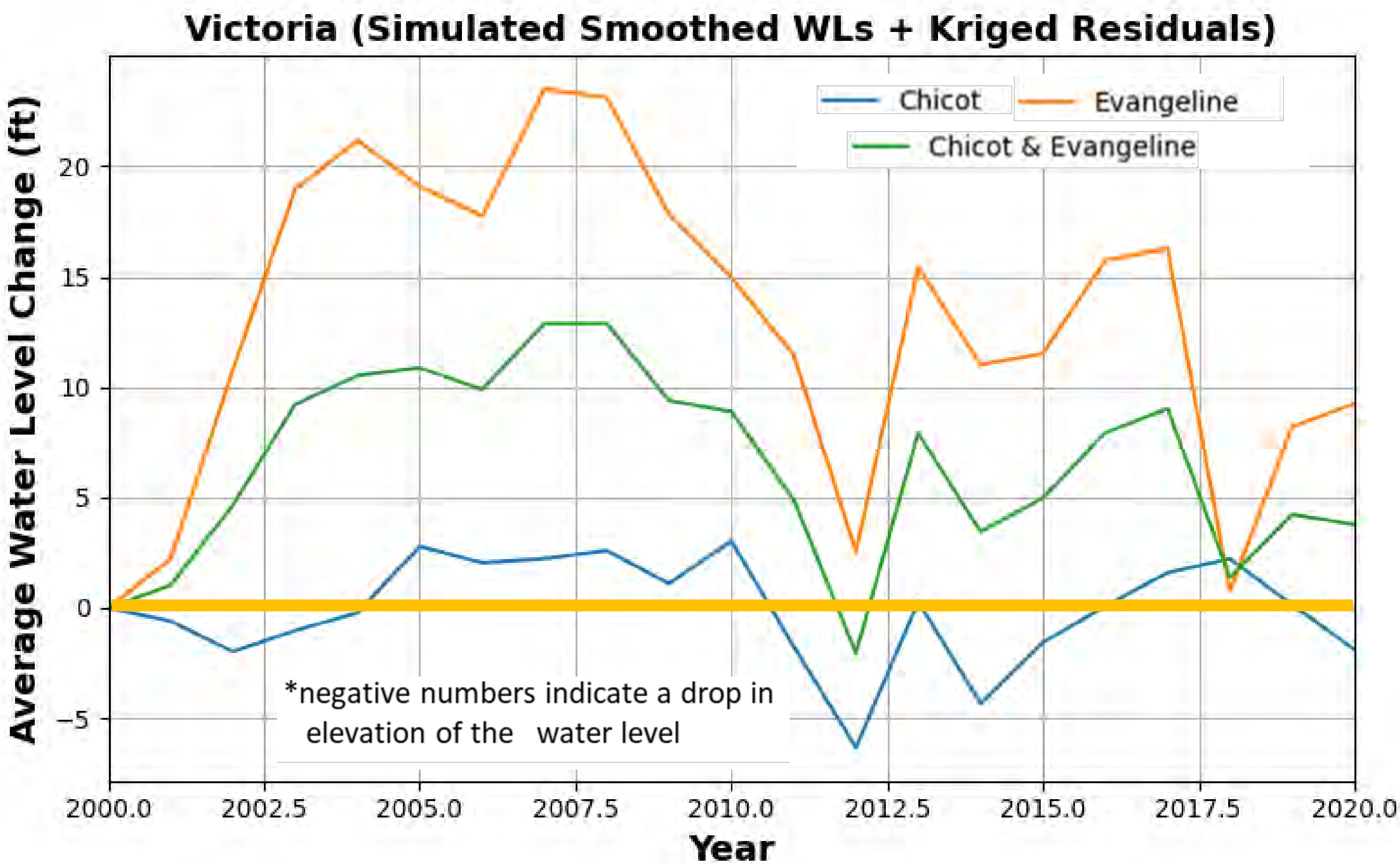


Figure 5-4 Change in the average annual water level calculated in Victoria County for the Chicot Aquifer, the Evangeline Aquifer, and the combination of Chicot and Evangeline aquifers based on the analysis of aquifer levels determined using GAM simulated smoothed water levels and Kriged residual for the measured water levels.

6.0 SPATIAL AND TEMPORAL CHANGES IN WATER LEVELS

This section presents tables and figures that illustrate changes in the water levels across the counties and at wells. The maps showing contours of water level change across counties are based on the differences in the mapped annual water levels determined for the Chicot Aquifer, Evangeline Aquifer, and the Chicot & Evangeline Aquifer in Section 5. The groundwater elevation changes at wells are based on hydrographs of the measured water levels.

6.1 Water Level Changes Across Counties

Figures 6-1 through **6-4** show the net change in water levels in from 2000 to 2020 in Calhoun, Jackson, Refugio, and Victoria counties. Maps are provided for both the Chicot and the Evangeline aquifers. The coverages for both aquifers are truncated to the aquifer boundaries delineated in the central Gulf Coast GAM (Chowdhury and others, 2004). The water level changes are delineated using contours and color floods. Positive numbers and blue and green colors show where water level elevations increased over time. Negative numbers and yellow and orange colors indicate where water level elevations have decreased over time. **Appendix E** provides figures that divides the twenty-year interval into 10-year and 5-year periods. Several notable observations made from Figures 6-1 through 6-4 and Appendix E are listed below.

<u>Calhoun County</u>

- Chicot Aquifer
  - 2000-2020: Water levels increased across about 80% of the county. The largest increase of about 20 ft occurred in northeast region. Areas of decrease occurred in northwest and north regions.
  - 2000-2010: Water levels increased across about 80% of the county. The largest increase was of 23 ft in water levels with greatest increase occurring in northeast. Areas of decreased water levels occurred in southwest with maximum declines of about 5 ft.
  - 2010-2020: Water levels decreased in about 60% of the county. The decreases occurred primarily in the northeast. The largest decrease of about 12 ft occurred in northeast. Areas of decreased water levels occurred in southwest with maximum declines of about 5 ft.
- Evangeline Aquifer
  - 2000-2020: Water levels decreased across about 70% of the county. The largest decrease of about 7 ft occurred in the northeast.
  - 2000-2010: Water levels decreased across the county except for about 10% of the county in the northwest corner of the county. Decreased water levels were generally less than 5 ft and the increased water levels were generally less than 2.5 ft.
  - 2010-2020: Water levels increased in about 90% of the county. The largest increase was about 5 ft. Water levels decreased along the Jackson county line. The largest decrease was 2.5 ft.

<u>Jackson County</u>

- Chicot Aquifer
  - 2000-2020: Water levels increased across about 90% of the county. Increases of about 25 ft occurred in the northeast and of about 20 ft occurred in south. In the remaining areas, water levels decreased less than 5 ft.
  - 2000-2010: Water levels increased across about 90% of county. Increased water levels of 20 ft occurred in the northeast and southwest corners of the county.
  - 2010-2020: Water levels across most of the county changed less than 5 ft. The largest increase in water levels of 10 ft occurred in southeast; the largest decrease in water levels of about 15 ft occurred in southwest.
- Evangeline Aquifer
  - 2000-2020: Water levels increased across about 50% of the county with the largest increase of about 12 ft occurring in the northern region. Water levels decreased across the remaining county with the greatest decline of 10 ft occurring in the southern region.
  - 2000-2010: Water levels increased 5 ft across most of the central and northern part of the county. In the southeast part of the county, the water levels decreased averaged about 5 ft also.
  - 2010-2020: Across about 90% of the county, the water levels changed less than 5 ft.

<u>Refugio County</u>

- Chicot Aquifer
  - 2000-2020: Water levels decreased across about 70% of the county and in the northwest region where the largest decrease of about 27 feet occurred near the Goliad county line. An increase of less than 5 ft occurred across most of the remaining southeastern portion of the county.
  - 2000-2010: Water levels in northeast that cover about 60% decreased. The largest groundwater elevation decrease of 17 ft occurred along the Goliad county line. Water levels increased between 0 to 10 ft in southwestern region of the county.
  - 2010-2020: Water levels decreased across about 80% of the county with greatest decrease of about 18 ft near center of the county. Water levels in the remaining portion of the county increased 2 to 7 ft.
- Evangeline Aquifer
  - 2000-2020: Water levels decreased across about 75% of the county with the largest decline of 15 ft in the north-central region of the county.
  - 2000-2010: Water levels decreased across the entire county. The declines ranged from about 5 ft in the northeast to about 25 ft in the southeast.
  - 2010-2020: Water levels increased across 95% of the county. Most of the increases were between 7 and 17 ft. The largest increase of about 22 ft occurred in the southwest corner of the county.

<u>Victoria County</u>

- Chicot Aquifer
  - 2000-2020: Water levels increased across about 50% of the county and primarily in the northeast region. The largest increase of about 25 ft occurred at the center of the county. Water levels decreased in the southwest region where the largest decrease was about 15 ft.

- 2000-2010: Water levels increased across about 65% of the county and primarily in the northeast and east regions. The largest increase in water levels of about 25 ft occurred at center of the county. In southwest portion of the county, the water levels decreased. The declines range between 5 and 10 ft.
- 2010-2020: Water levels decreased across about 60% of the county and primarily in the southeast portion of the county. The groundwater level declines were primary between 2 and 10 ft. In the northeast corner of the county, the groundwater levels increased about 5 to 10 ft.

- Evangeline Aquifer
  - 2000-2020: Water levels increased across about 60% of the county and primarily in the northwest portion of the county. The largest increase of about 70 ft occurred at the center of the county. In southwest region of the county, changes in the groundwater levels ranged from about a 10 ft increase to a 20 ft decrease.
  - 2000-2010: Water levels increased across about 85% of the county. The largest increase of about 80 ft occurred at the center of the county and lessen radially outward.
  - 2010-2020: Water levels decreased across about 80% of county. The largest declines of 20 to 25 ft occurred near the center and near the southwest corner of the county. Groundwater levels increased about 5 to 10 ft in northwest region of the county.

6.2 Water Level Changes at Wells

Appendices F and **G** provide hydrographs for wells located in Calhoun, Jackson, Refugio, and Victoria counties. Appendix F shows hydrographs for the Chicot Aquifer. Appendix G shows hydrographs for the Evangeline Aquifer. Each hydrograph shows the measured water level as blue dots and the corresponding water levels associated with the trend surface created using the smoothed GAM simulated water levels as red dots. The blue lines were constructed by performing a linear regression on the measured water levels. **Figures 6-5** through **6-11** show selected hydrographs by aquifer and by county. Only wells with at least four annual measurements were considered. Each hydrograph is assigned a color dot to indicate whether the water levels were increasing, relatively flat, or decreasing over time. Also, simulated water levels were rated from 1 to 10 based on their similarity to the measured water levels. A score of 10 indicates the simulated water level accurately reflects both the values and the temporal trend in the measured water levels. Notable observations are listed below by county.

<u>Calhoun County</u>

- Chicot Aquifer
  - Six hydrographs are provided. They are located in the half of the county closest to Victoria county. Four of the hydrographs show a relatively flat trend over time for the measured groundwater elevations.
  - The smoothed simulated water levels are within 10 ft of the measured water levels. However, for five out of the six wells, the simulated water levels exhibit increases of 5 to 10 ft from 2000 to 2020 whereas the measured groundwater levels indicate a change of less than a few feet. The GAM-simulated water levels are rated an 8 out of 10.

- Evangeline Aquifer
  - No hydrographs are available for review.

<u>Jackson County</u>

- Chicot Aquifer
  - Twelve hydrographs are provided. They are located across the county except for near the Calhoun County line. Eight of the hydrographs show a relatively flat trend over time for the measured water levels. The remaining four hydrographs show an increase in the measured water levels.
  - A comparison between simulated and measured water levels at the twelve well locations produced mixed results. For several wells, such as wells #907 and #5, the simulated elevations are within a few feet and have a similar temporal trend as the measured elevations but there are other wells such as wells #137 and #112 where, the simulated elevations are differed by as much as 40 ft and have a dissimilar temporal trend than do the measured elevations. The GAM-simulated water levels are rated a 4 out of 10.
- Evangeline Aquifer
  - Seven hydrographs are provided. They are located across the county. Three hydrographs indicate nearly flat temporal trends in the measured water levels, and three hydrographs indicate an increase in the measured water levels. The GAM-simulated water levels are rated a 5 out of 10.
  - A comparison between simulated and measured water levels at the twelve well locations produce mixed results. The comparisons are generally better for years closer to 2000 than for the years closer to 2020. For 2020, four of the wells have differences between 20 and 40 ft between the measured and simulated water levels. The GAM-simulated water levels are rated a 6 out of 10.

<u>Refugio County</u>

- Chicot Aquifer
  - Eight hydrographs are provided. They are located across the county. Four of the hydrographs show a relatively flat temporal trend in the measured water levels and three hydrographs show a decreasing trend in the measured elevations. Wells # 44 and #61 may have unrepresentative measured water levels. The shift of about 20 ft in 2014 at Well #44 may have occurred because of a change in the datum used in the field.
  - A comparison between simulated and measured water levels at the twelve well locations produce mixed results. The GAM-simulated water levels are rated a 5 out of 10.
- Evangeline Aquifer
  - Two hydrographs are provided. One shows a relatively flat trend in the measured water levels and the other shows a decreasing trend in the measured water levels.
  - The simulated and measured water levels are similar for the one well but are notably different for the other well. The GAM simulated water levels are rated a 6 out of 10.

<u>Victoria County</u>

- Chicot Aquifer
  - Twelve hydrographs are provided. They are located across the county except in the center of the county. Seven of the hydrographs show a relatively flat temporal trend in the measured water levels. Three hydrographs show an increasing trend in the measured water levels.
  - The measured and simulated water levels compare favorably at four wells. At five other wells, the simulated and measured water levels have similar trends but the data sets are

offset by 10 to 30 ft. At three wells, notable trends of increasing water levels with the measured data are not provided in the simulated values. The GAM-simulated water levels are rated a 5 out of 10.

- Evangeline Aquifer
  - Twelve hydrographs are provided. They are located across the county. Seven of the hydrographs show a relatively flat temporal trend in the measured water levels. Three hydrographs show an increasing trend in the measured water levels.
  - The measured and simulated water levels compare favorably at five wells. At four other wells, the simulated and measured water levels have similar trends but the data sets are offset by 10 to 30 ft. At two wells, notable trends in the measured water levels are not reproduced in the simulated values. The GAM-simulated water levels are rated a 6 out of 10.

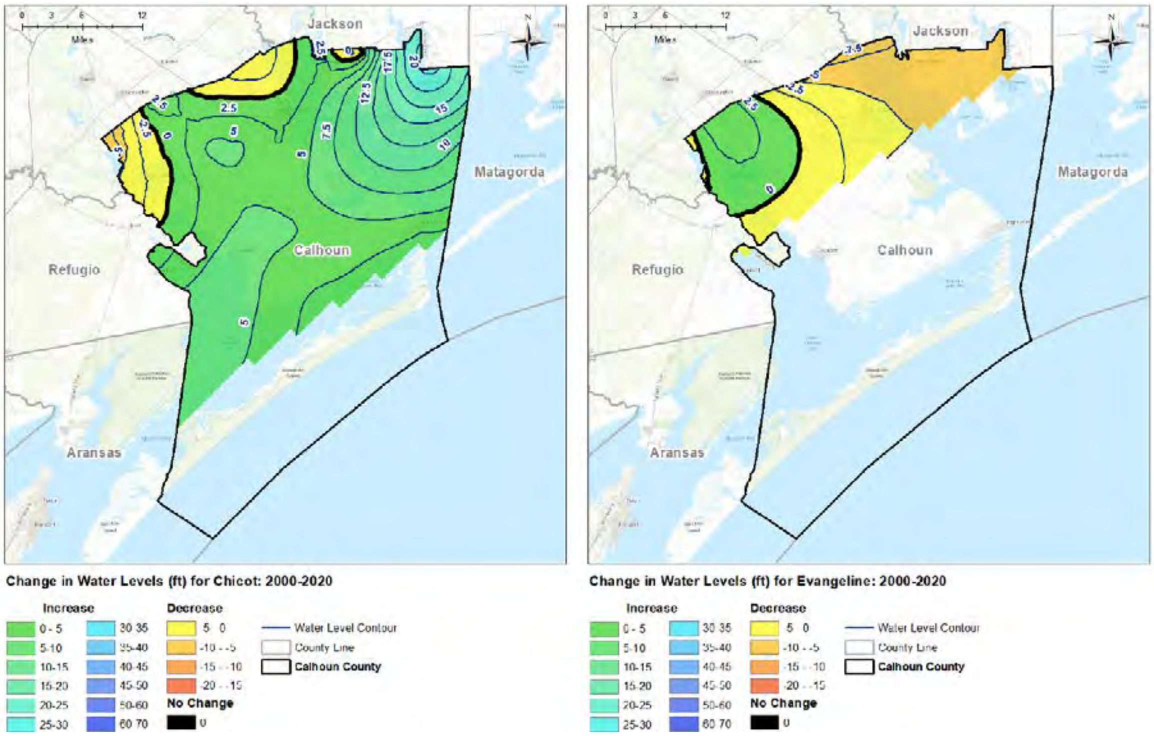


Figure 6-1 Water level elevation change in Chicot and Evangeline Aquifers across Calhoun County for 2000 - 2020

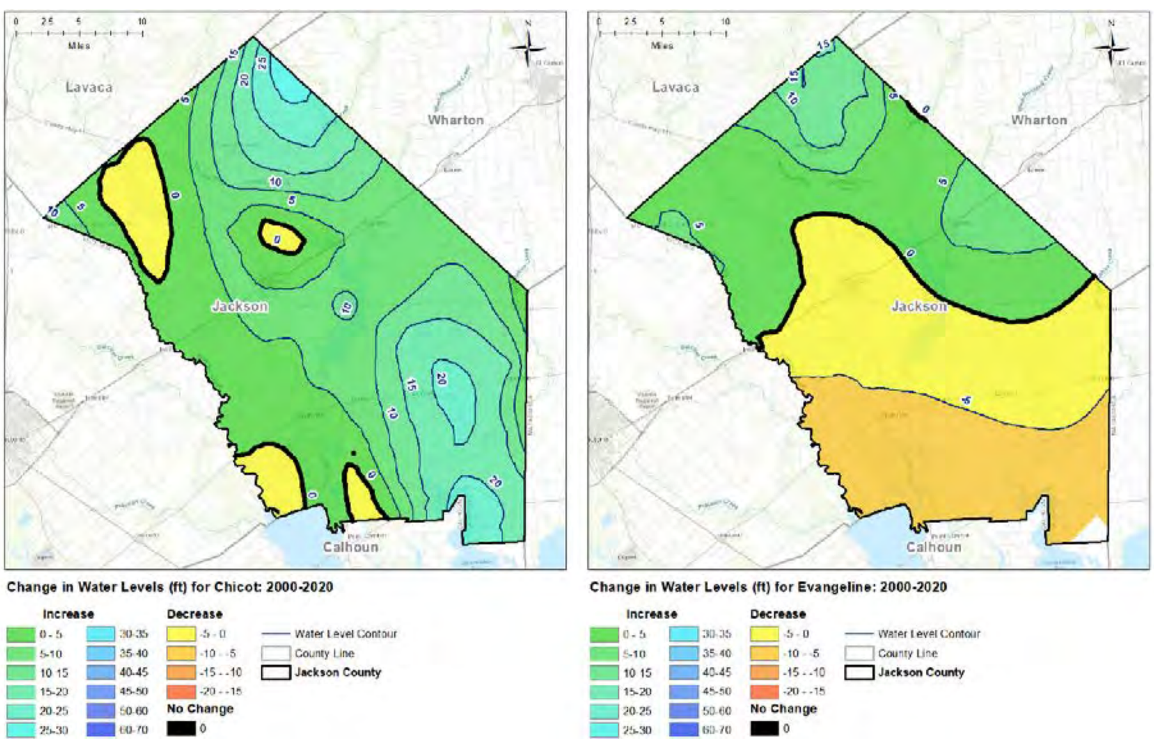


Figure 6-2 Water level elevation change in Chicot and Evangeline Aquifers across Jackson County for 2000 - 2020

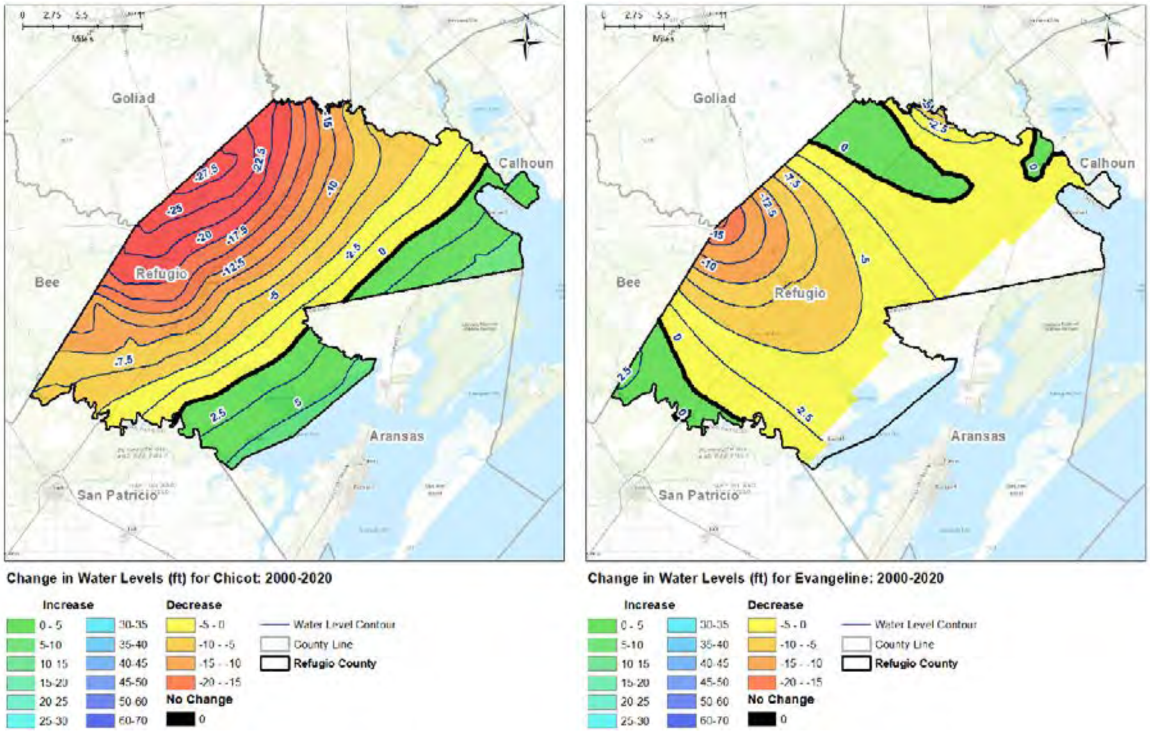


Figure 6-3 Water level elevation change in Chicot and Evangeline Aquifers across Refugio County for 2000 - 2020

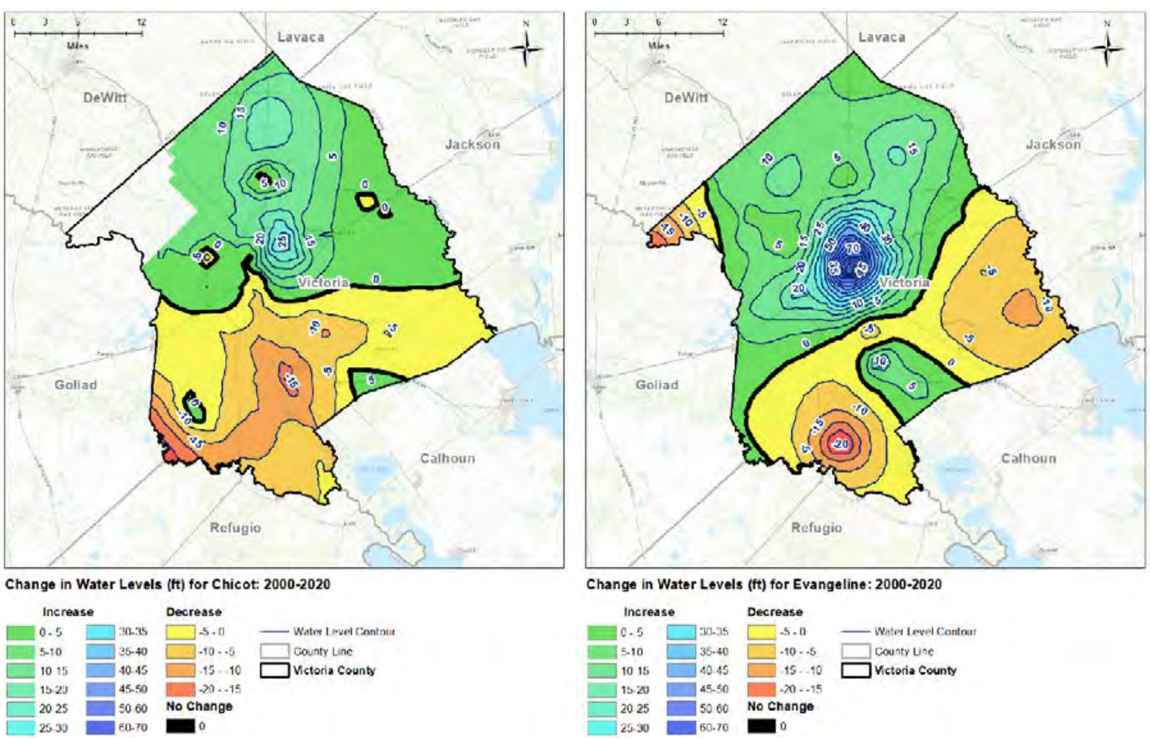


Figure 6-4 Water level elevation change in Chicot and Evangeline Aquifers across Victoria County for 2000 - 2020

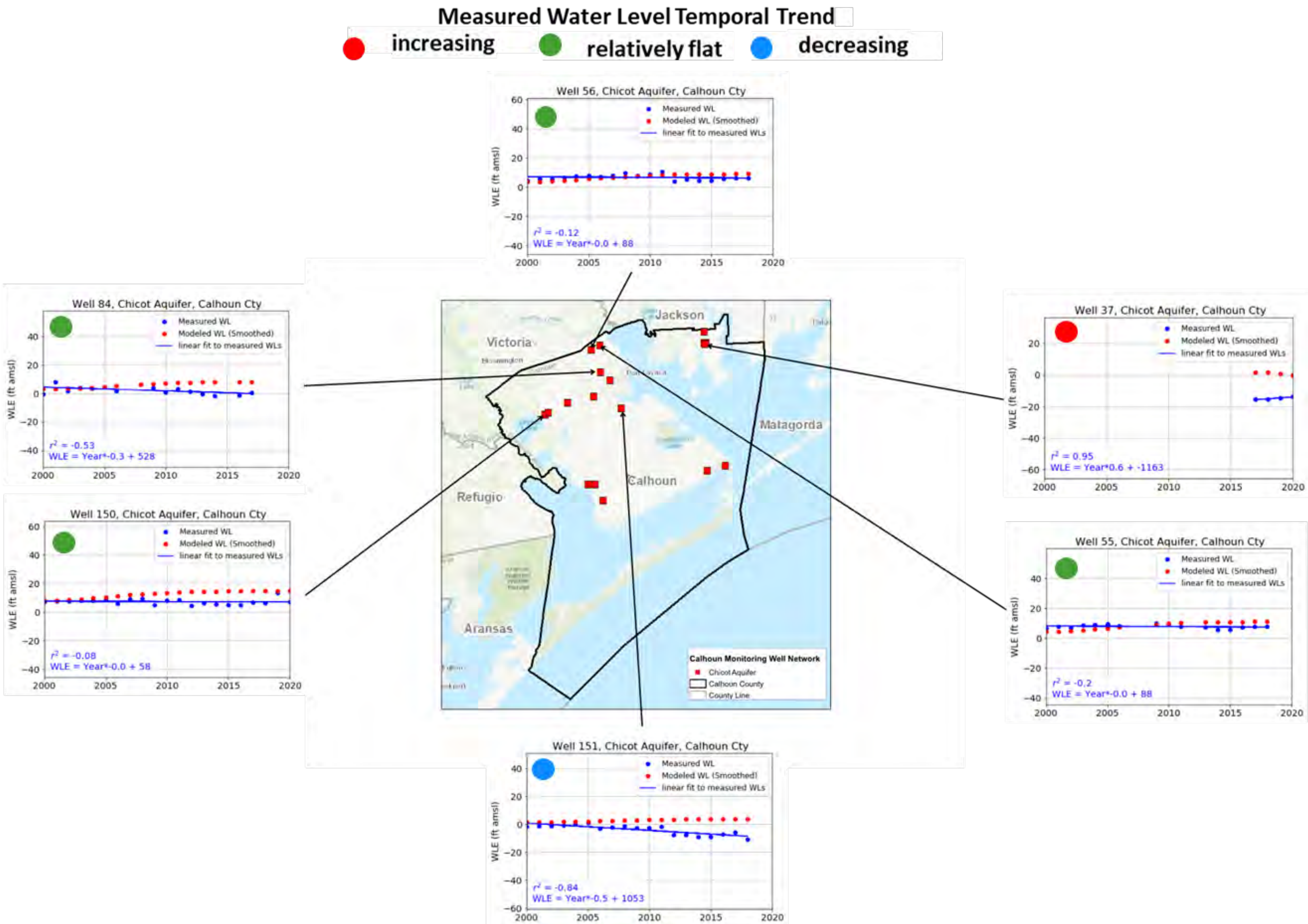


Figure 6-5 Hydrographs for Chicot wells with four or more measured water levels in Calhoun County

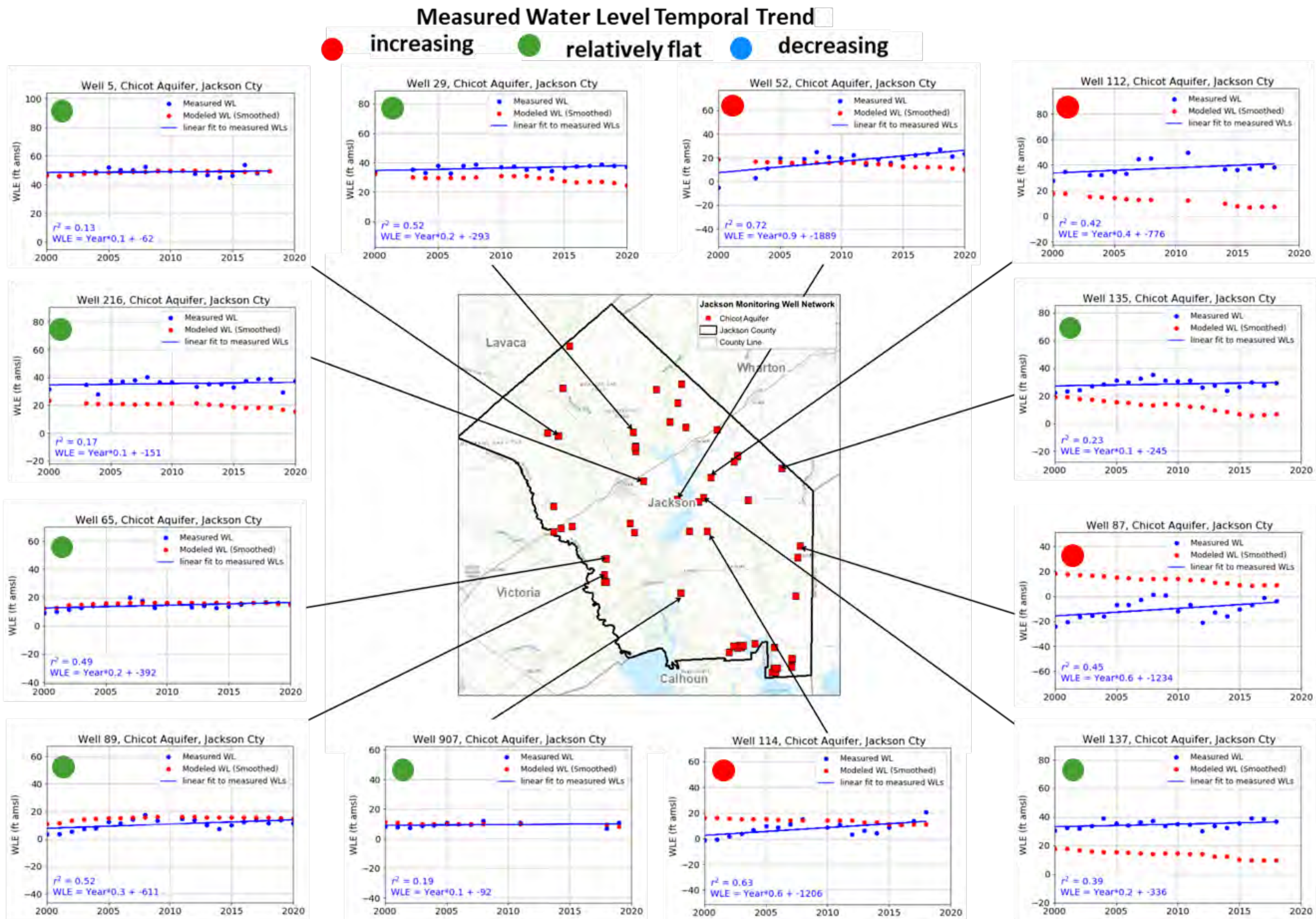


Figure 6-6 Hydrographs for Chicot wells with four or more measured water levels in Jackson County

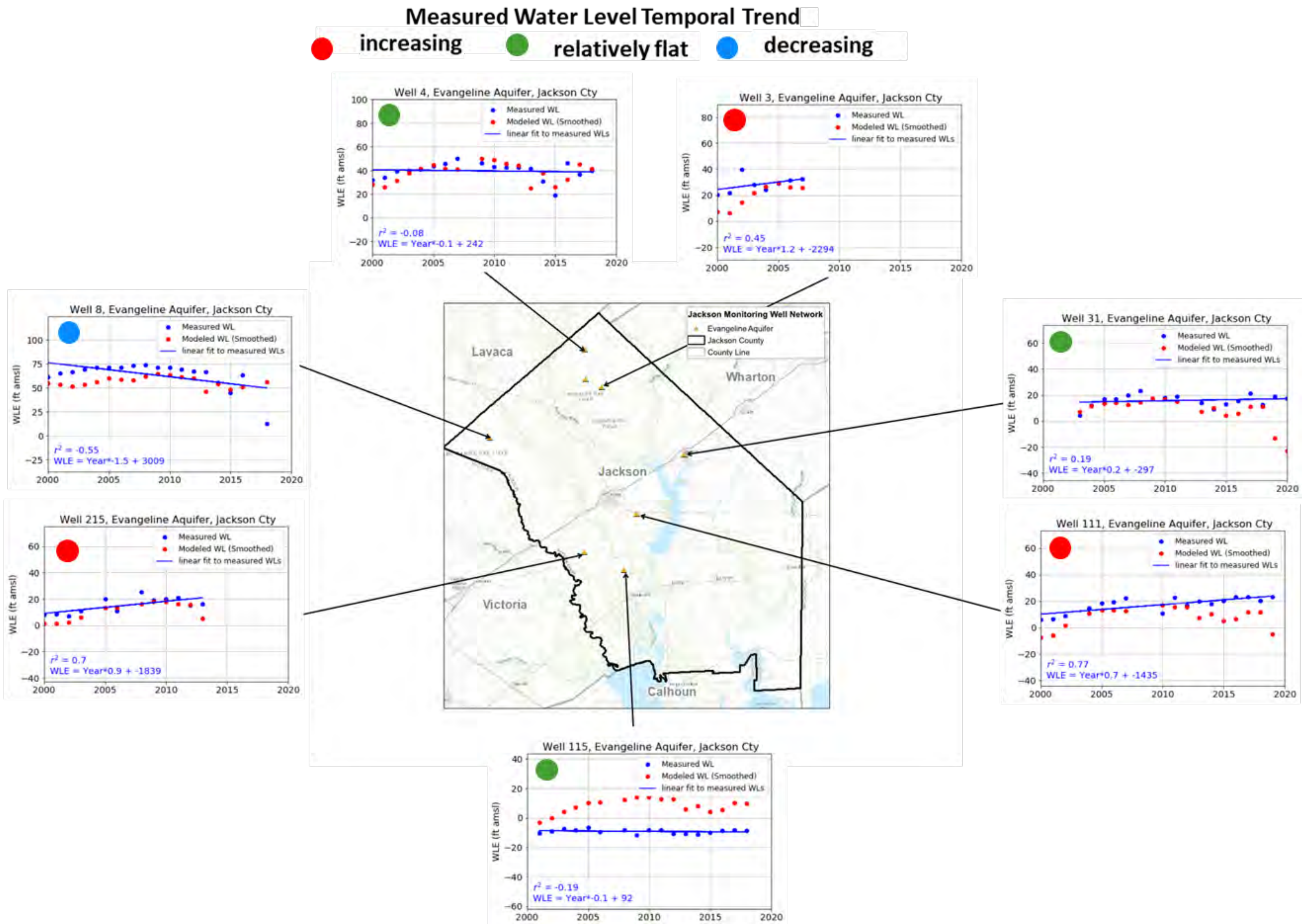


Figure 6-7 Hydrographs for Evangeline wells with four or more measured water levels in Jackson County

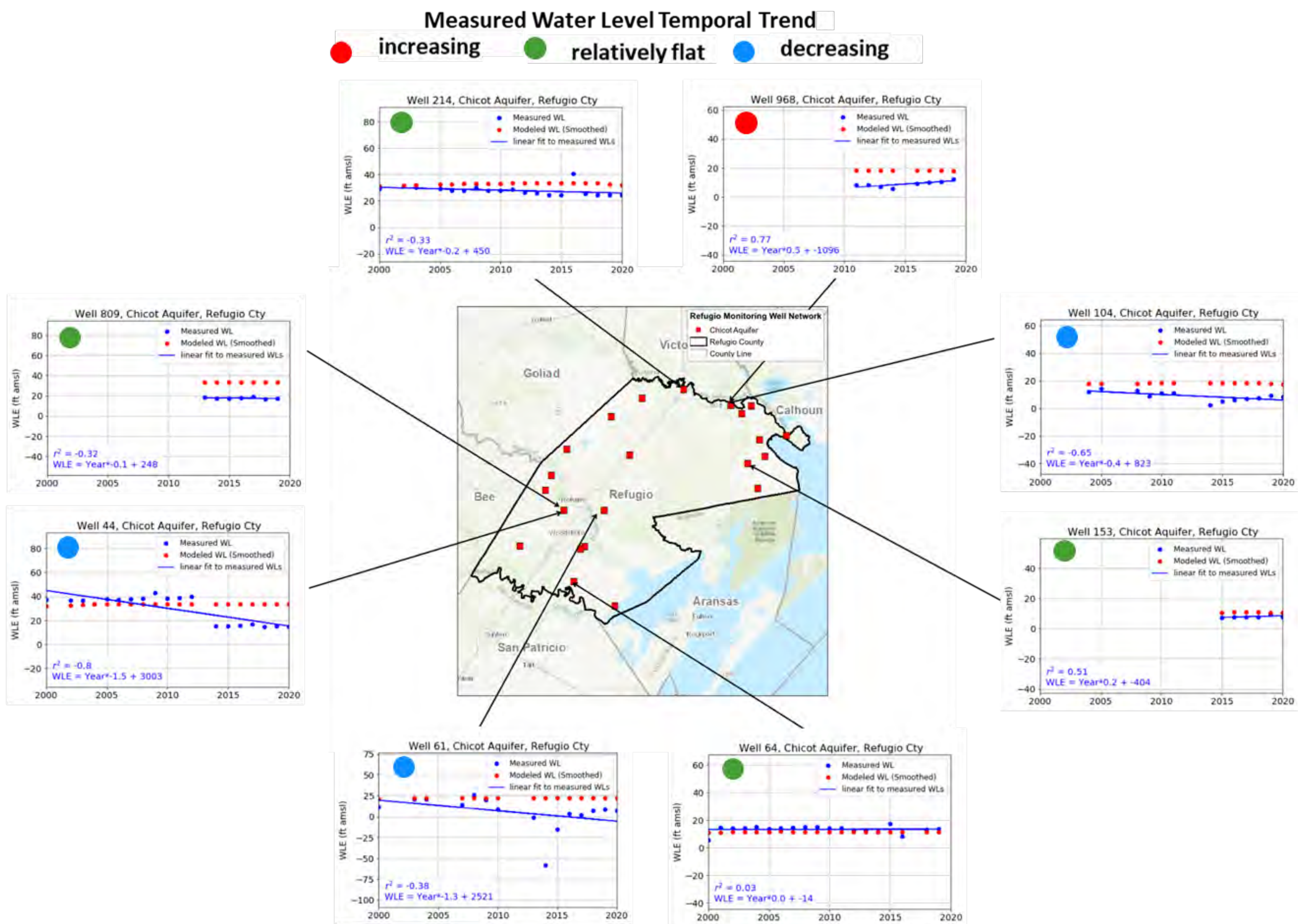


Figure 6-8 Hydrographs for Chicot wells with four or more measured water levels in Refugio County

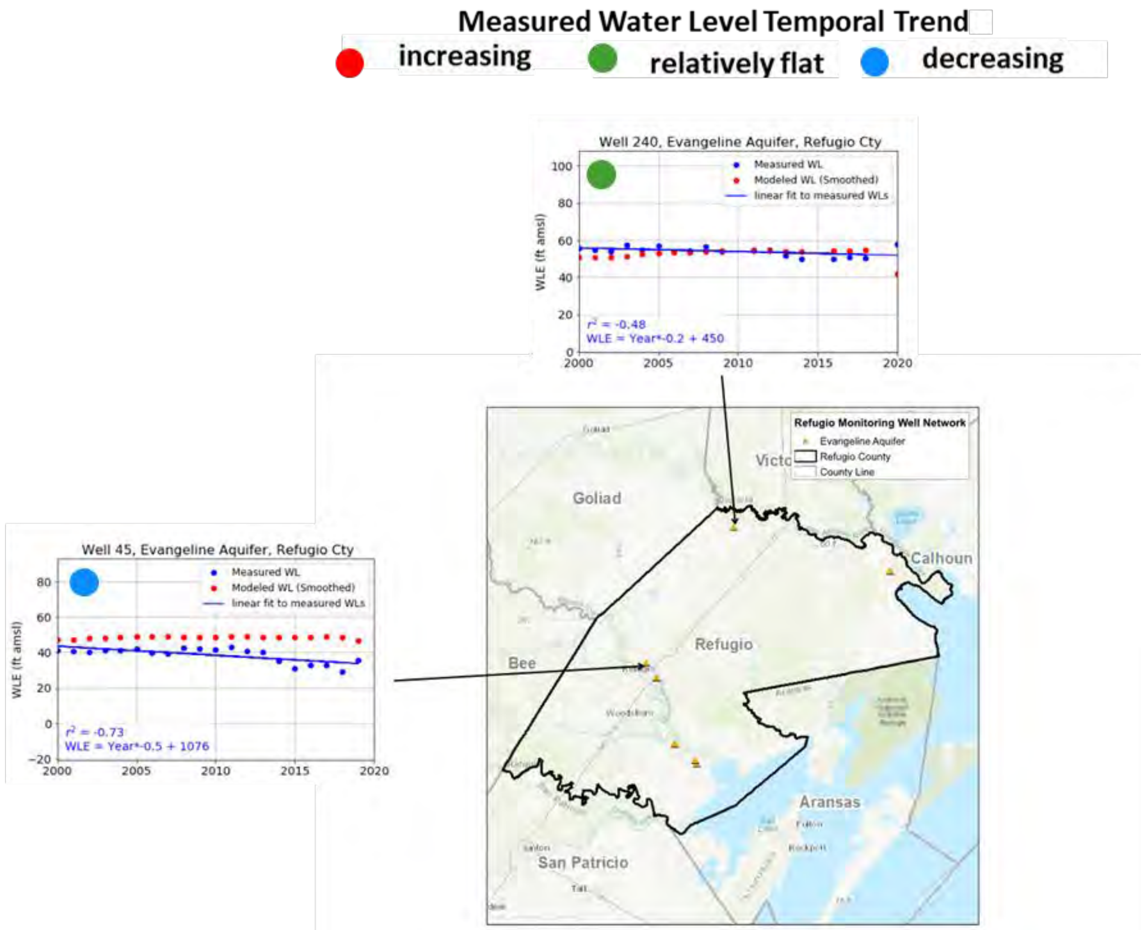


Figure 6-9 Hydrographs for Evangeline wells with four or more measured water levels in Refugio County

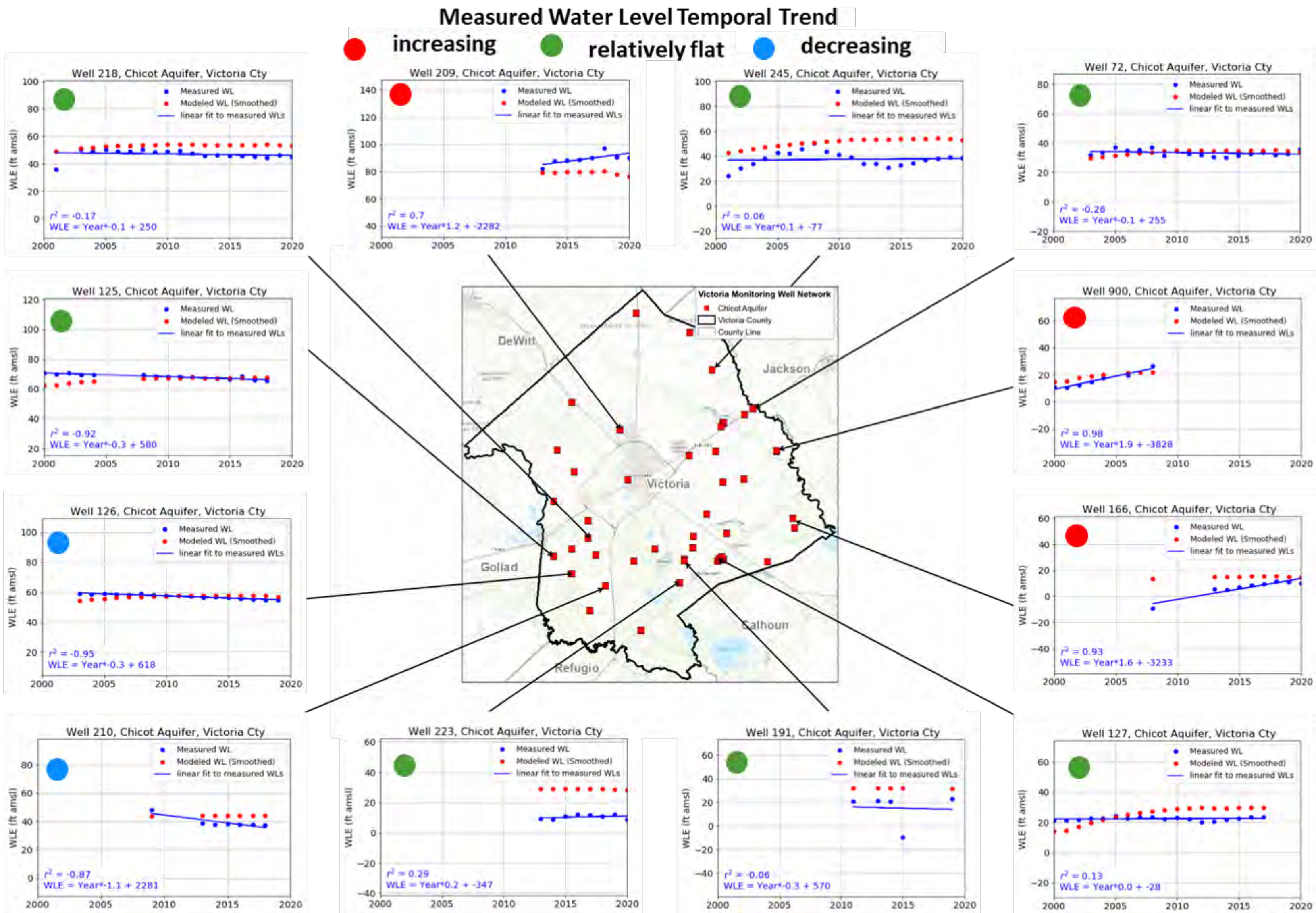


Figure 6-10 Hydrographs for Chicot wells with four or more measured water levels in Victoria County

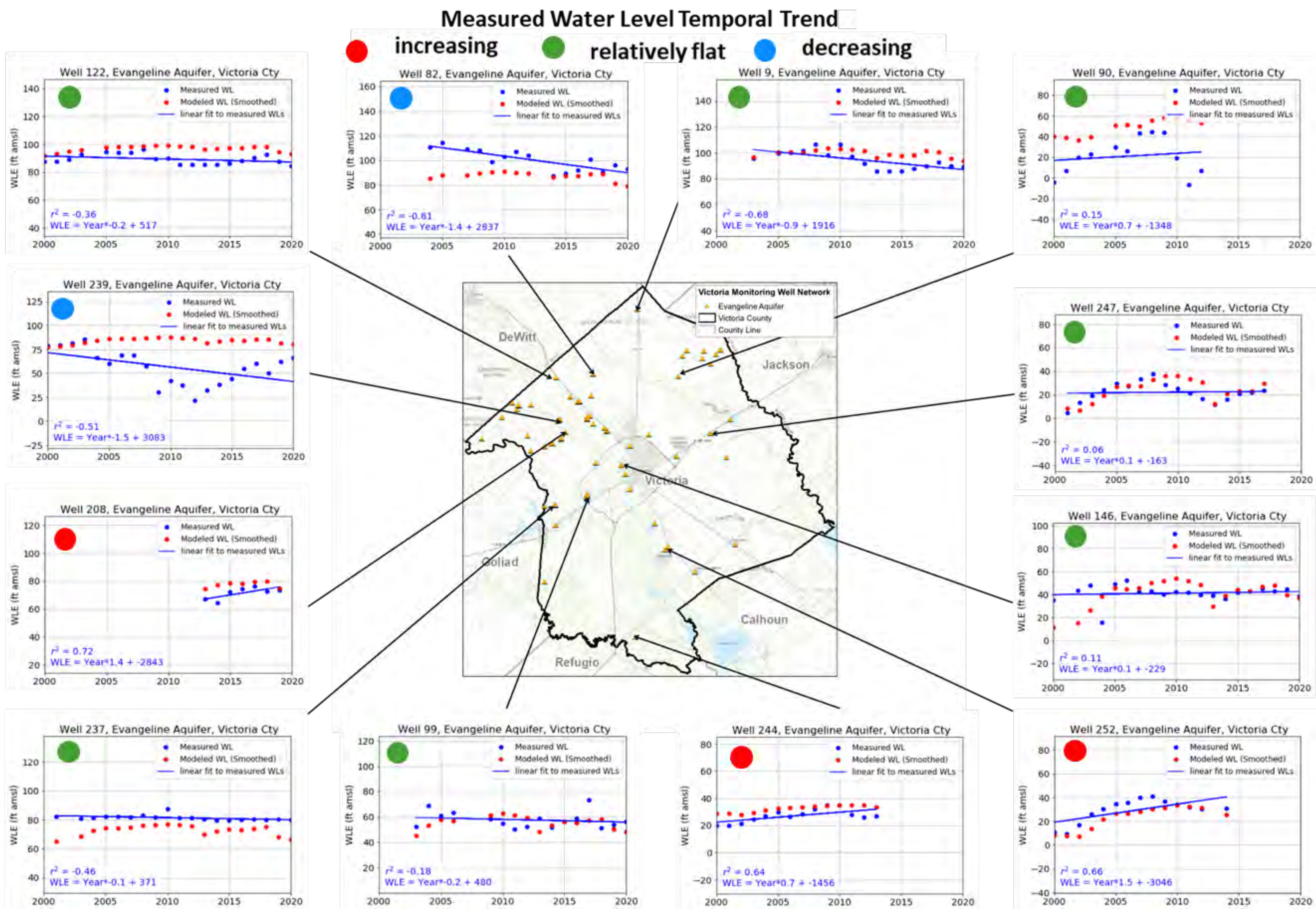


Figure 6-11 Hydrographs for Evangeline wells with four or more measured water levels in Victoria County

7.0 RECOMMENDATIONS FOR FUTURE WORK

This section presents recommendations for future work that includes coordinating with the TWDB to integrate the GCD well information into the TWDB groundwater database, expanding and improving the monitoring well network and monitoring programs, and performing additional geostatistical analysis.

7.1 Incorporation of GCD well information into the TWDB Groundwater Database

The data mining and analysis performed in Section 2 documents two points. One point is that there is a considerable amount of water level data in the GCD data sets that is not included in the TWDB groundwater database. The second point is that, for most of the 127 wells identified in both the GCD and the TWDB data sets, the two data sets have different locations. Recommendations for future work with coordinating with the TWDB on the well information include:

- Select a common set of latitude and longitude for the 127 wells that shared between the GCD data set and the TWDB groundwater database.
- Survey the location of wells whose locations are in question after a review of the existing data
- Compare well depth and screen information between the GCD data set and the TWDB groundwater database for the purpose of making the two sets of values consistent
- Agree on a methodology with the TWDB for assigning an aquifer to a well and implement it for all wells located in Calhoun, Jackson, Refugio, and Victoria counties.

7.2 Expand the Monitoring Well Network and Monitoring Program

There are not studies that have evaluated whether the GCD monitoring well programs are measuring sufficient water level data to provide the resolution and accuracy that the GCDs need to adequately determine average water level conditions and how these water levels change over time. However, it is evident from Figures 2-3 to 2-6 there are areas where the monitoring well density appears sparse and likely too few wells to provide a clear picture of how pumping is affecting water levels over time. Recommendations for future work with expanding and improving the GCD monitoring well network include:

- Establish criteria for assessing the adequacy of well coverage in the Chicot and Evangeline aquifers to address the needs of the GCDs. Possible criteria include well density, spatial distribution of historical and future pumping, and reducing the uncertainty with the interpolated water levels.
- Priority-rank the existing wells for as candidate to augment the existing well network.
- Develop a program of expanding the monitoring network over time.
- Develop protocols for measuring water levels and for establishing criteria for develop protocols for flagging measured water levels that appear to be unrepresentative of actual aquifer conditions.

7.3 Expand and Build on the Geostatistical Analysis

Geostatistical techniques include a robust set of algorithms that extend beyond the interpolation of water levels using Kriging. A primary benefit of geostatistical techniques is that they can provide quantification of uncertainty. As illustrated in **Figure 7-1**, the quantification of uncertainty supports two types of analyses that are important to groundwater monitoring. One analysis is estimating the uncertainty associated with the Kriged values calculated for unsampled location. Knowledge of the predictive uncertainty provides useful information regarding: (1) the potential benefits of gathering additional monitoring data, and (2) the likelihood that the interpolated water level at a location (or many locations) exceeds a specified value. The other analysis that geostatistics can provide is determining the best location for a future monitoring well for reducing the predictive uncertainty associated with the interpolation. Knowledge of the optimum monitoring locations to reduce predictive uncertainty is useful information regarding: (1) deciding on the where to add new locations to the monitoring well network, and (2) determining how to expand the monitoring well network to achieve a specific level of confidence associated with the predicted water levels. Recommendations for future work coordinating with the TWDB on the well information include:

- Identify and evaluate potential benefits to groundwater monitoring of quantifying the predictive uncertainty with the Kriged interpolation values in Section 4 and the average annual water levels provided in Section 5.
    - Pending results from the previous task, quantify the predictive uncertainty of the Kriged interpolation values in Section 4 and the average annual water levels provided in Section 5 to best achieve the GCD monitoring goals.
- Develop an approach for determining the best locations for adding new wells to the groundwater monitoring networks and determine there are potential benefits for incorporating geostatistics into the decision-making process.
    - Pending results from the previous task, use geostatistics to help determine the future monitoring well locations that provide the most cost-effective approach for achieve the GCD goals for the monitoring well network.

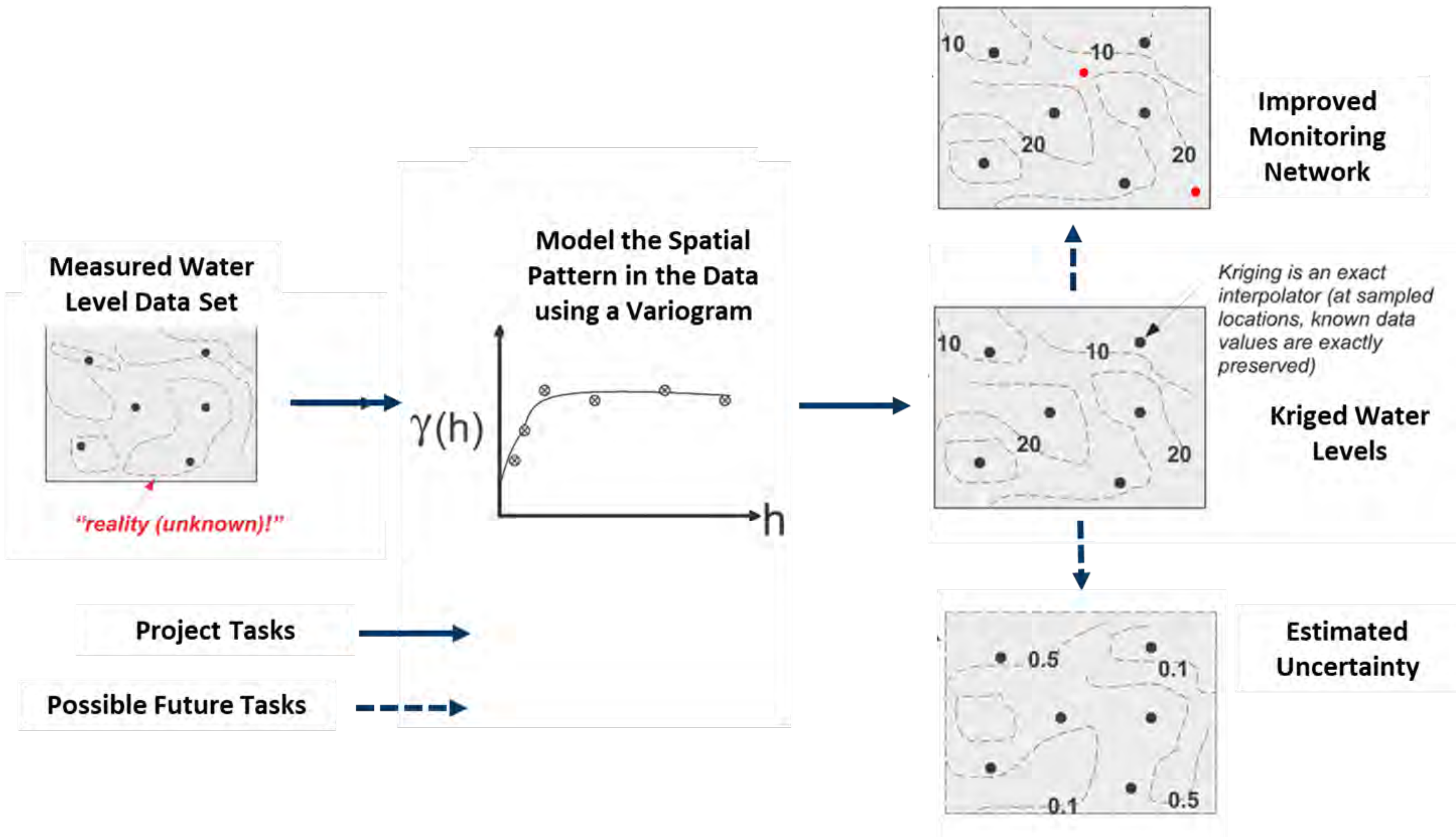


Figure 7-1 Schematic showing the application of geostatistical technial to interpolate water levels, to estimated uncertianity associated with the interpolated water levels, and to improve the design of monitoring well networks

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