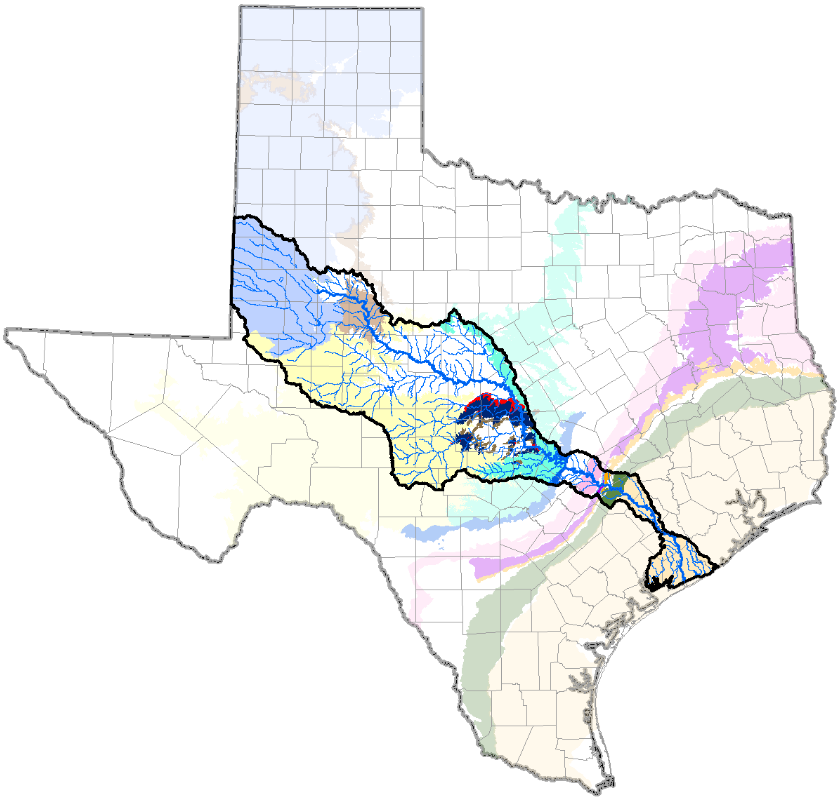
Final Report: Field Studies and Updates to the Central Carrizo-Wilcox, Queen City, and Sparta GAM to Improve the Quantification of Surface Water-Groundwater Interaction in the Colorado River Basin



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Texas Water
Development Board

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PURSUANT OT HOUSE BILL 1 AS APPROVED BY THE 84TH TEXAS LEGISLATURE, THIS STUDY REPORT WAS FUNDED FOR THE PURPOSE OF STUDYING ENVIRONMENTAL FLOW NEEDS FOR TEXAS RIVERS AND ESTUARISE AS PART OF THE ADAPTIVE MANAGEMENT PHASE OF THE SENATE BILL 3 PROCESS FOR ENVIRONMENTAL FLOWS ESTABLISHED BY THE 80TH TEXAS LEGISLATURE. THE VIEWS AND CONCLUSIONS EXPRESSED HEREIN ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF THE TEXAS WATER DEVELOPMENT BOARD.

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Executive Summary

In 2015, the Colorado-Lavaca Basin and Bay Area Stakeholder Committee created a subcommittee to identify and prioritize a list of projects from their work plan to be recommended for funding. The subcommittee's recommendations included a request that the Texas Water Development Board fund a project to help improve the capability to simulate surface water-groundwater interaction with the groundwater availability model currently under development for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. The work presented here is part of Texas Water Development Board efforts to improve its understanding and management of environmental flows for the Colorado and Lavaca river basins, and to improve its capability to properly characterize and model surface water-groundwater interaction using the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. Primary objectives of the work include providing a framework for understanding field studies and computer models related to surface water-groundwater interaction; describing the characteristics of the Colorado River and Colorado River Basin; reviewing previous surface water-groundwater studies for the Colorado River; mapping the Colorado River alluvium in Groundwater Management Area 12; revising the model discretization in the vicinity of the Colorado River and its major tributaries in the update of the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers currently underway; and developing a work plan for field studies designed to quantify surface water-groundwater interaction at specific locations in the Colorado River Basin for use in guiding modeling of groundwater base-flow contribution to streams.

The Colorado River Basin in Texas extends from the Texas-New Mexico border to the Gulf of Mexico, draining an area of approximately 40,000 square miles. The Colorado River originates south of Lubbock near the base of the Llano Escarpment and flows to the east through several physiographic regions toward the Gulf of Mexico and empties into Matagorda Bay. The river is characterized by intermittent flow in its upper reaches and acquires a base-flow component when it reaches the Llano Uplift region. Springs provide a reliable source of base flow to the river in its central portion. Below the Highland Lakes, the river is highly regulated to provide water and hydroelectricity and provide flood control. Numerous stream gages operated by the United States Geological Survey and cooperatively by the Survey and the Lower Colorado River Authority are located along the river. Evaluation of gage data show an increase in streamflow and stream height with increasing distance down the river.

Numerous studies related to surface water-groundwater interaction have been conducted for the Colorado River, including general studies, gain/loss studies, and hydrograph-separation studies. Gain/loss studies conducted on the same reach of river at different times can show both gaining and losing conditions, indicating that flow between the river and alluvium varies temporally. Several hydrograph-separation studies conducted using data from gages located below the Highland Lakes did not account for regulation of the river and off-stream diversions. Therefore, the resultant base flow estimates overpredict groundwater discharge to the river. A gain/loss study conducted from Coke to Matagorda counties in 1918 provides a good overview of where the river is naturally gaining and losing. In general, the studies indicate little to no base flow component of river flow in the upper reaches, that springs provide substantial water to the river in the middle reaches, and that base flow from groundwater discharge is most significant for the lower reaches below the Highland Lakes.

The Colorado River alluvium was characterized through review of the literature, information reported on drillers logs, and data available in Texas Water Development Board databases. A study in the lower Colorado River Basin that constructed contour maps of water elevation based on stream height and water levels in wells indicates that groundwater in the aquifers flows toward the river and its major tributaries, except in a localized area in the Gulf Coast Aquifer where groundwater has been impacted by pumping and does not flow to the river. Estimates of the hydraulic conductivity for the alluvium were obtained from the literature for locations in Travis and Bastrop counties and were calculated using well yield and drawdown data from productivity tests reported on drillers logs for the portion located in Groundwater Management Area 12. These estimates suggest that, typically, the hydraulic conductivity of the alluvium ranges from about 60 to 130 feet per day. The areal extent of the Colorado River alluvium for implementation in the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers was developed based on surface geology mapping and locations of wells with alluvium as determined through review of lithology logs from drillers reports. Review of the lithology logs also provided data on the depth to the base of the alluvium. These data, along with control points at the location of the Colorado River and its major tributaries, enabled construction of a bottom elevation and thickness for the alluvium. Bottom elevations are lowest along the Colorado River and generally increase toward the alluvium boundary. The thickness of the alluvium is typically 25 to 50 feet, but locations with thicknesses up to 95 feet were identified in northern Bastrop County.

Water chemistry for the Colorado River and groundwater indicate similar ranges in specific conductance and nitrate. Runoff after storm events dilutes salts in the river, which results in a reduction in the specific conductance. The magnitude of the observed reduction increases with distance from reservoirs as the impact of releases from the reservoirs decreases. A corresponding reduction does not occur in the groundwater, providing an opportunity to evaluate interaction between the surface water and groundwater after storm events. Daily and seasonal fluctuations in groundwater temperature are relatively small compared to those in surface water. Studies have shown that the movement of water between streams and aquifers can be successfully assessed using temperature. Specific conductance data indicate that the river is a very dynamic system affected by reservoir operations, climatic conditions, natural processes, and anthropogenic activities.

The update of the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers will include modifications to the grid cell sizes and model layers to better represent the Colorado River and its tributaries and the areal and vertical extent of the Colorado River alluvium. Advantages of using a refined grid are improved location for the river, its tributaries, and adjacent wells; a reduction in the footprint of the river and tributaries, and improved resolution of tributary connectivity, especially in areas where more than one tributary connects with a larger river segment. Using Quadtree mesh refinement in MODFLOW-USG, the grid cells containing the river and tributaries were reduced from the 1-mile by 1-mile grids in the existing groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers to 0.25-mile by 0.25-mile grid cells in the updated model. To directly incorporate the Colorado River alluvium in the updated model, an additional model layer was constructed to represent the alluvium. This approach was possible because MODFLOW-USG allows a model layer to be present over only a portion of the model domain.

To improve the quantification of surface water-groundwater interaction between the Colorado River and groundwater in the alluvium, a work plan was developed for conducting field studies at a site in Bastrop County and a second site in either Wharton or Matagorda counties. Six possible sites were identified in Bastrop, Fayette, Colorado, Wharton, and Matagorda counties. These sites are locations where the alluvium overlies the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson and Gulf Coast aquifers, respectively. Important questions that cannot be answered by traditional gain/loss and hydrograph-separation studies could be answered with the proposed field studies. Specifically, (1) what is the direction and magnitude of water exchange between the alluvium and stream under stable low-flow conditions, (2) what is the origin of water gained by the stream during low-flow conditions (the alluvium or from bank storage), and (3) how might pumping affect stream gains or losses over time? To help identify the origin of the water in the alluvium, the study recommends installing wells under the alluvium to evaluate the groundwater flux between the underlying geologic units and the alluvium.

The field data collected from the studies would be analyzed using both numerical modeling and traditional methods. Semi-automated calibration of a numerical flow model to water-level data uploaded from the field sites would provide the direction and magnitude of flow between the alluvium and river. Solute and temperature modeling would enable identification of the source of water gained by the stream to determine whether the water originated from the stream and flowed into the alluvium (bank storage) or originated from the aquifer as base flow. Solute and transport modeling provide the means for understanding bank storage and determining how much of the water gained by a stream is original stream water sourced from bank storage or is actually groundwater from the alluvium. Traditional analyses of the data would also be conducted as a check of the numerical predictions and to evaluate the impact of bank storage on traditional hydrograph-separation methods.

Site selection for the field studies was based on the extent and permeability of the alluvium adjacent to the river, the observed reduction in the surface water specific conductance in response to runoff after rainfall events, the observed range in daily and seasonal surface water temperature, and the locations of existing stream gages, existing nearby wells, and groundwater conservation districts. The work plan is divided into two phases, with Phase I designed to analyze data gaps and Phase II designed for implementation of the work plan. Each phase is divided into major tasks and associated costs.

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1 Introduction

Senate Bill 3 of the 80th Texas Legislature in 2007 created a stakeholder-driven process for identifying and quantifying flows needed to maintain sound rivers and estuaries in Texas. The process led to the adoption of flow standards between 2011 and 2014 by the Texas Commission on Environmental Quality for seven major basins and bay areas in Texas. The Senate Bill 3 process contained an adaptive management component that called for continued studies to validate and refine the environmental flow analyses, recommendations, and standards, and to identify strategies to achieve those standards.

In 2013, the 83rd Texas Legislature appropriated funds to the Texas Water Development Board (TWDB) for the continued study of environmental flows. In 2014, the TWDB approved the use of this funding to implement 15 priority work plan studies in five basin and bay areas. In 2015, the 84th Texas Legislature appropriated funds to the TWDB in its baseline budget for the 2016-2017 biennium in support of Strategy A.1.1, Environmental Impact Information for the collection and analysis of environmental flow information to support a sound ecological environment in the State's streams, rivers, bays, and estuaries. To support this strategy, TWDB staff sought input from Senate Bill 3 stakeholder committees by requesting that they submit for consideration a prioritized list of studies from work plans developed for their basins.

In 2015, the Colorado-Lavaca Basin and Bay Area Stakeholder Committee created a subcommittee to identify and prioritize a list of projects from their work plan to be recommended for funding. The full stakeholder committee approved the subcommittee's recommendations on October 27, 2015, and requested that the TWDB fund a project to help improve the capability to simulate surface water-groundwater interaction with the groundwater availability model currently under development for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers.

The work associated with this report is part of TWDB efforts to improve its understanding and management of environmental flows for the Colorado and Lavaca river basins, and to improve its capability to properly characterize and model surface water-groundwater interaction using the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. Among the primary objectives of this report are documentation of work associated with the following tasks:

- Introduce terms and concepts that are useful for understanding field studies and computer models related to the interaction between surface water and groundwater.
- Provide a general description of the Colorado River Basin and Colorado River, including flow data from the river, the location of river gages, the aquifer outcrops intercepted by the Colorado River, the areal extent of the Colorado River alluvium, and the location of wells near the river.
- Review the findings from previous studies conducted to evaluate surface water-groundwater interaction and/or estimate base flow or gain/loss for the Colorado River.
- Assemble data from previous studies of the Colorado River alluvium and from drillers logs in Travis, Bastrop, and Fayette counties to map the Colorado River alluvium and terrace deposits in Groundwater Management Area 12.

- Document that the update of the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers includes 0.25-mile-sized grid cells in the vicinity of the Colorado River alluvium and its major tributaries and the addition of a model layer to represent the Colorado River alluvium.
- Document completed and on-going work associated with model updates related to faults, aquifer hydraulic properties, recharge, water levels, historical pumping, conversion of the model from MODFLOW-96 to MODFLOW-USG, and model calibration.
- Develop a work plan for measuring surface water-groundwater interactions at specific locations in the Colorado River Basin in order to provide guidance for use in modeling the groundwater base-flow contribution to streamflows.

2 Overview of Surface Water-Groundwater Interaction

This section provides general information regarding the interaction between groundwater and streams. The information is intended to familiarize readers with terms and concepts central to understanding previous field studies along the Colorado River (Section 4) and the proposed field studies (Section 7).

2.1 Gaining and Losing Streams

The water table which exists in a shallow aquifer is the upper zone of saturation, where the pores of the aquifer are filled with water and where the hydraulic head pressure is equal to atmospheric pressure. In most situations, the elevation of the water table can be equated with the elevation of the water level in a shallow well. A key metric that controls the exchange of water between an aquifer and a stream is the difference in elevation between the water table in the aquifer and the water level in the stream. Based on these measured water elevations, streams can be classified as either "gaining" or "losing".

A gaining stream is one in which the elevation of the stream water level is lower than the level of the surrounding water table in the aquifer. Under these conditions, the groundwater system discharges water to the stream, increasing flow in the stream. Figure 2-1a illustrates groundwater flow toward a stream in vertical cross-section perpendicular to the stream. The flow system is in equilibrium where recharge to the aquifer equals discharge to the stream. The water table slopes toward the stream and is at the same elevation as the stream surface where the aquifer and stream meet. Figure 2-1b shows an aerial view of water table contours in the vicinity of a gaining stream. Near the stream, the water table contours bend and point in the upstream direction.

A losing stream is one in which the elevation of the stream water level is higher than the level of the surrounding water table in the aquifer. Under these conditions, the river recharges water to the aquifer, increasing groundwater flow. Figure 2-2a illustrates groundwater flow away from a stream in vertical cross-section perpendicular to the stream. The water table slopes away from the stream and is at the same elevation as the stream surface where the aquifer and stream meet. In Figure 2-2a, the aquifer beneath the river bed is saturated. For some losing streams, the stream may be disconnected from the saturated aquifer by an unsaturated zone. Figure 2-2b shows an aerial view of water table contours in the vicinity of a losing stream. Near the stream, the water contours bend and point in the downstream direction.

A stream might always lose water to an aquifer or always gain water from an aquifer. Perennial streams are generally gaining streams, while intermittent and ephemeral streams are often losing streams. Along many streams, the flow conditions can vary over time and across space such that it is characterized as both losing and gaining. The conditions that cause changes can be either natural, such as flood events, or anthropogenic, such as pumping. During flood events, stream levels can temporarily rise above groundwater levels, causing streams to recharge the groundwater system adjacent to the stream. However, when water levels in the stream return to normal, this water will drain back into the stream.

The rate at which water flows between a stream and adjoining aquifer depends on the hydraulic gradient between the two water bodies as well as on the hydraulic conductivity of the geologic material located at the surface water-groundwater interface. A thick, silty streambed, for example, will tend to reduce the rate of flow between a stream and an aquifer compared to a thin, sandy or gravelly streambed.

The equation describing flow between the aquifer and the stream in MODFLOW can be written as (Prudic and others, 2004):

$$Q_L = \frac{KwL}{m}(h_s - h_a) \qquad \text{Equation 2-1}$$

where:

Q_L = volumetric flow between a section of stream and aquifer (units of volume per time)
K = hydraulic conductivity of streambed sediments (units of length per time)
w = representative width of stream (units of length)
L = length of stream corresponding to a volume of aquifer (units of length)
m = thickness of streambed deposits (units of length)
h_s = water-level elevation in stream (units of length)
h_a = water table elevation in aquifer beneath the streambed (units of length)

2.2 Bank Storage

Streams and groundwater interact in distinctly different ways during flood events than during base-flow periods. The rise of floodwater not only maintains losing segments of a river but also can make gaining sections become losing sections, inducing flow from the river into the aquifer resulting in groundwater recharge.

Figure 2-3 shows three conditions in a stream. Figure 2-3a shows a gaining stream during average flow conditions, when the water table slopes toward the stream. Figure 2-3b shows the same stream after a sudden rise in the surface water elevation following an intense precipitation event. After the rise in the elevation of the stream level, the stream becomes losing and water flows from the stream into the aquifer and, thereby, causing a reversal in the hydraulic gradient in the aquifer near the stream relative to that during average conditions. Figure 2-3c shows a situation where the flooding event is sufficient to overtop the stream banks and flood large areas of the river alluvium where recharge into the alluvium deposits occurs by infiltration.

The stream water that enters into and is stored in the aquifer during a flood event is called bank storage. Bank storage provides partial relief to elevated stream stages during storm events and, in combination with groundwater recharge, may sustain base flow during prolonged inter-storm periods and supplies moisture for aquatic organisms and riparian vegetation. The amount of water that can be stored as bank storage depends on the water table in the aquifer, the stage of the stream reach, the hydraulic conductivity of the stream bank materials, and sufficient volumes of permeable bank material (Rassam and Werner, 2008). Depending on the frequency, magnitude, and intensity of storms and on the related magnitude of increases in stream stage, some streams and adjacent shallow aquifers may be in a continuous readjustment from interactions related to bank storage and overbank flooding (Winter and others, 1998).

2.3 Effects of Groundwater Pumping

Withdrawing water from a shallow aquifer near a stream can diminish the available surface water supply by capturing some of the groundwater flow that otherwise would have discharged to the stream or by inducing flow from the stream into the surrounding aquifer system. Figure 2-4 illustrates how a well can affect groundwater flow in the vicinity of a stream.

Figure 2-4a shows a gaining stream under predevelopment conditions, where the recharge into the aquifer equals the groundwater discharge to the stream. For convenience, groundwater flow is only towards the stream. Figure 2-4b modifies the predevelopment condition in Figure 2-4a by adding a well that captures most, but not all, of the groundwater flow that had entered the stream under predevelopment. In Figure 2-4b, recharge into the aquifer is greater than the pumping rate, and a groundwater divide exists between the well and the stream. The groundwater divide represents a line that marks changes in the groundwater flow direction. On the left side of the divide, groundwater flows toward the well. On the right side of the divide, groundwater flows toward the stream. In Figure 2-4b, the stream is still a gaining stream, but it is receiving less groundwater flow than it did under predevelopment conditions. In Figure 2-4c, the pumping rate in the well is greater than the aquifer recharge rate, so the well captures all of the recharge and some of the streamflow. The pumping rate in Figure 2-4c is high enough to lower the water table at the aquifer-stream interface to below the stream level and cause the gaining stream to become a losing stream in the vicinity of the well.

The process whereby pumping captures flow from a stream is referred to as induced infiltration of streamflow. Streamflow depletion is a term used to represent the amount of flow that a well captures from induced infiltration of streamflow and reduction of groundwater flow to a stream. The factors that control the timing and magnitude of a streamflow depletion response to pumping are the structure, dimensions, and hydraulic properties of the aquifer; the locations and hydrologic conditions along the boundaries of the groundwater system, including the streams; and the horizontal and vertical distances of wells from the stream.

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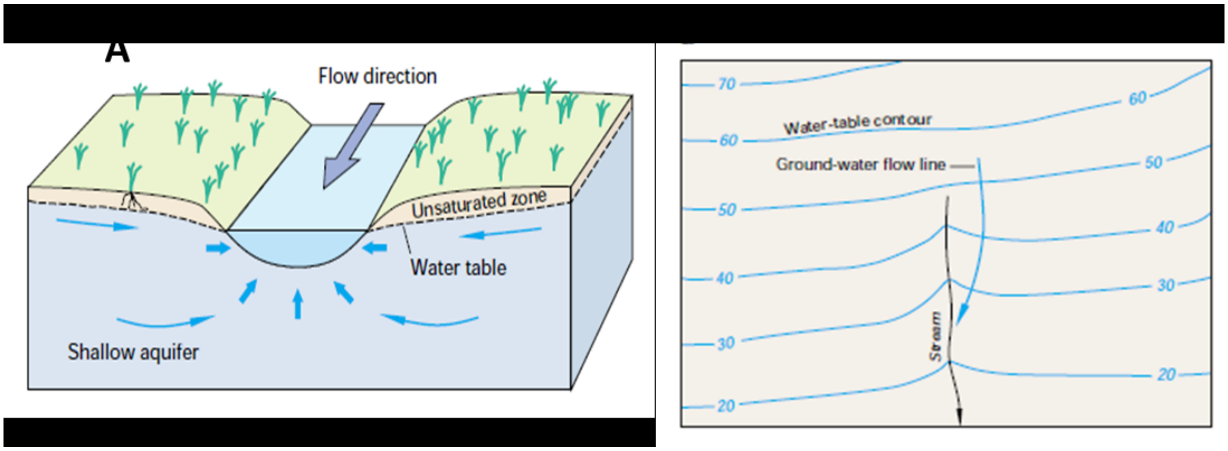


Figure 2-1. **Schematic showing groundwater flow toward a gaining stream (A). Contour map of a water table near a gaining stream that shows contours pointing in the upstream direction near the stream and groundwater flow paths pointing toward the stream (B) (from Winter and others, 1998).**

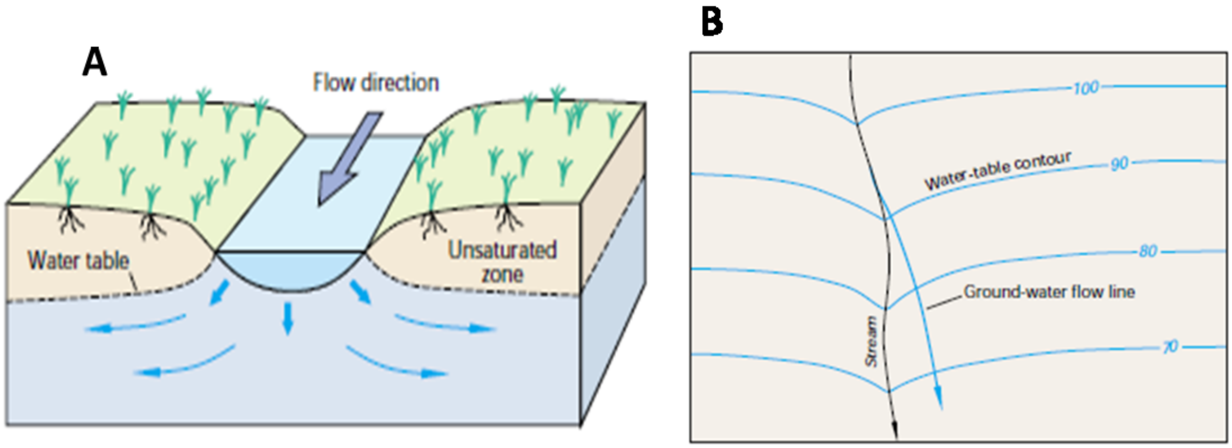


Figure 2-2. **Schematic showing groundwater flow away from a losing stream (A). Contour map of a water table near a losing stream that shows contours pointing in the downstream direction near the stream and groundwater flow paths pointing away from the stream (B) (from Winter and others, 1998).**

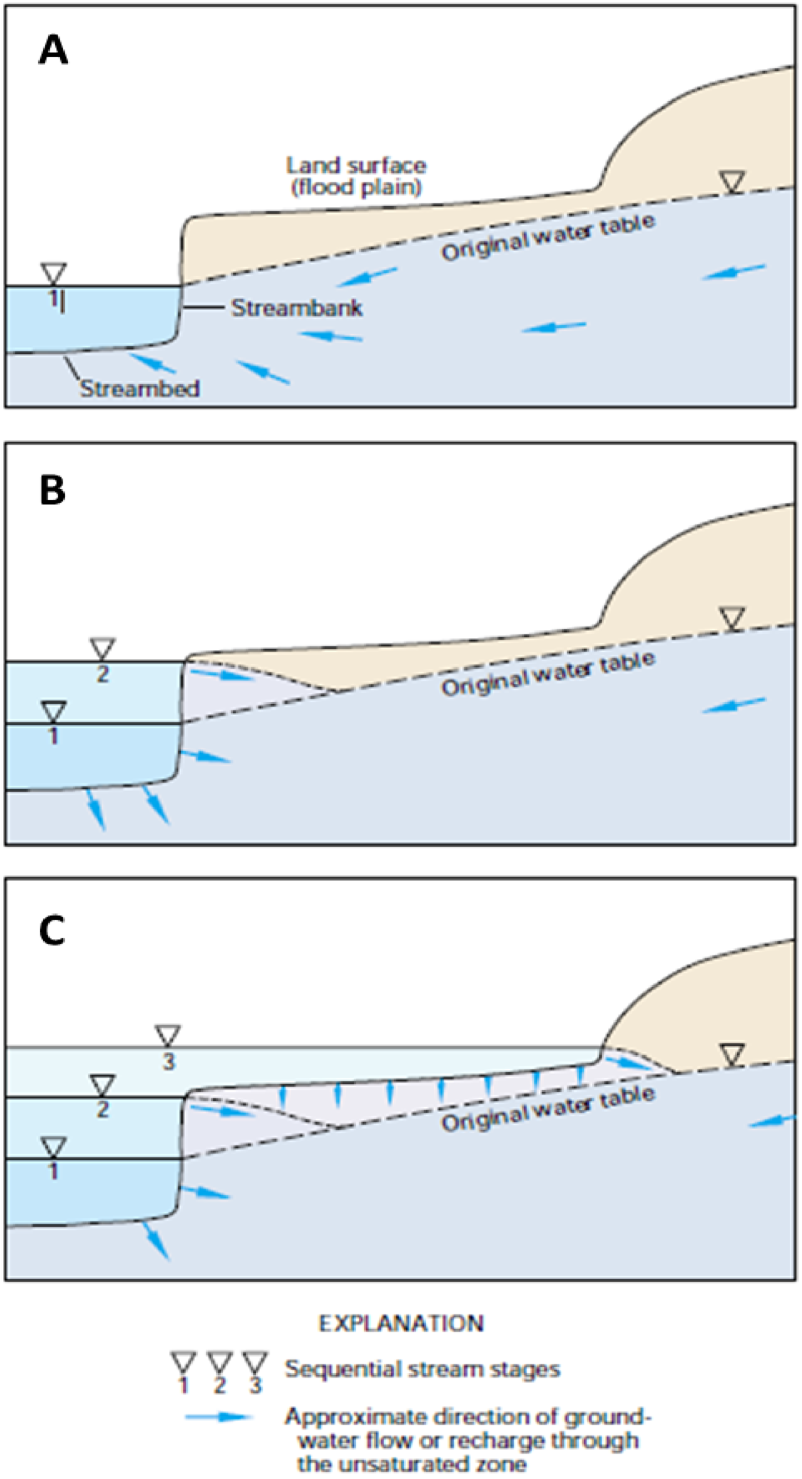


Figure 2-3. **Schematic showing groundwater flow toward a gaining stream during average flow conditions (A). Increase in stream elevation caused by flooding event causes hydraulic gradient reversal at stream-aquifer interface and streamflow enters and becomes storage in the stream bank (B). Stream elevation rising above the stream bank during a flooding event and floodwaters recharging the stream bank and flooded area from above (C) (from Winter and others, 1998).**

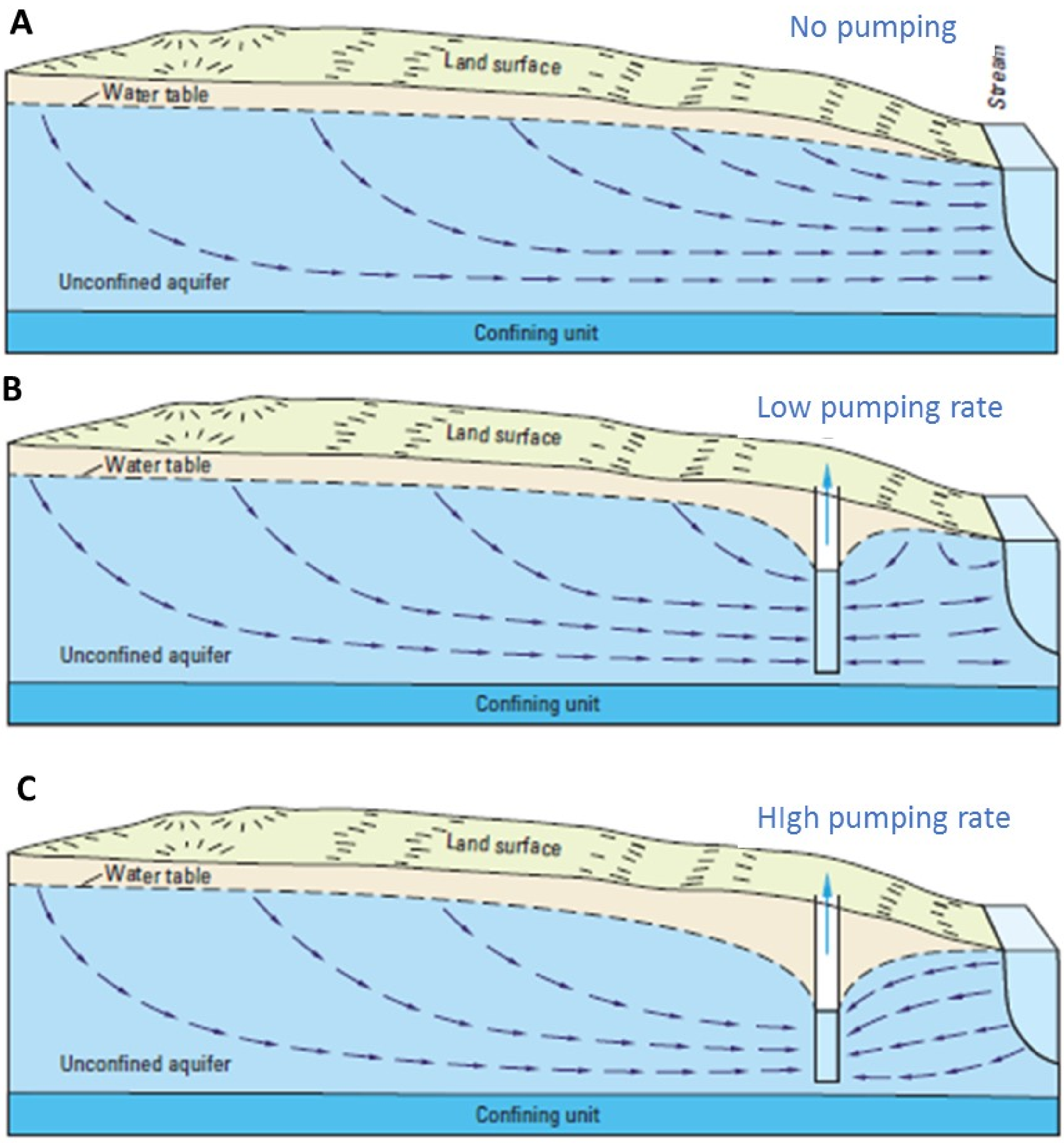


Figure 2-4. **Schematic showing groundwater flow toward a gaining stream with no groundwater pumping (predevelopment conditions) (A). Groundwater pumping in a well near a stream that captures some of the groundwater flow that would have entered the gaining stream under predevelopment conditions (B). Groundwater pumping that prevents groundwater flow from reaching the stream and causes the gaining stream to become a losing stream in the vicinity of the well (C) (from Barlow and Leake, 2012).**

3 Colorado River

This section provides a general description the Colorado River Basin and Colorado River. The description includes flow data from the river, the location of river gages, the aquifer outcrops intercepted by the Colorado River, the areal extent of Colorado River alluvium, and the location of wells near the river.

3.1 Colorado River Basin

Figure 3-1 shows the Colorado River Basin and Colorado River. The basin has a total drainage area of approximately 40,000 square miles and comprises all or part of 64 counties (J.R. Brandes Company, 2001). The Colorado River originates south of Lubbock near the base of the Llano Escarpment and flows to the east through several physiographic regions toward the Gulf of Mexico and empties into Matagorda Bay. Although it is impounded at several points in the North Central Plains, the Colorado River is not a perennial stream until it reaches the Llano Uplift region, where the river establishes a component of base flow. Springs in San Saba, Llano, and Burnet counties serve as reliable sources for base flow. Major manmade reservoirs on the river include Lake Buchanan, Inks Lake, Lake Lyndon B. Johnson, Lake Marble Falls, Lake Travis, Lake Austin, and Lady Bird Lake. Collectively, these lakes are known as the Highland Lakes. The Lower Colorado River Authority operates the Highland Lakes to maintain a highly regulated flow downstream of the City of Austin to supply water and hydroelectricity, and provide flood control for central Texas. Lakes Buchanan and Travis are operated as a system to supply interruptible water supplies for agriculture and environmental flows when available, and firm water supplies for municipal and industrial use. In addition to power plants operating on each of the major lakes, water from the Colorado River is used for cooling the South Texas Nuclear Project near Bay City.

Figure 3-2 shows the location of approximately 1,800 surface water rights for diversions from the Colorado River and its tributaries (Texas Commission on Environmental Quality, 2017a). The total amount of authorized diversions for these water rights is 4.1 million acre-feet per year. Approximately 74 percent of the total authorized diversion volume is for municipal supplies, 5 percent is for industrial purposes, and 20 percent is for irrigation (Texas Commission on Environmental Quality, 2017b).

3.2 Watersheds and River Gages

Across the Colorado River Basin, the geology, soils, climate, and human activities influence the river as it traverses the State. The spatial differences among these factors result in differences in the river flows and surface water-groundwater interactions. To help manage the different environmental and river conditions in the basin, the Colorado River Basin has been divided into ten watersheds (Figure 3-3). Figure 3-3 also shows the location of 35 stream gages used to monitor flow in the river. The 35 stream gages consist of 14 active and eight inactive United States Geological Survey streamflow gages and 13 gages that are cooperatively operated by the United States Geological Survey and the Lower Colorado River Authority. The river gages record the height of the water above the streambed and the quantity of water passing the gage, both of which are used to estimate the river flow.

Figure 3-3 shows the cumulative distribution function curves of streamflow (discharge) and stream height (stage) for four of the United States Geological Survey gages spaced across the

Colorado River Basin. The cumulative distribution function curves were developed from the data shown in Figure 3-4 and Figure 3-5. These data show that the magnitude and variation of the streamflow and stream height vary significantly among the gages. Table 3-1 provides the 10th and 90th percentiles for stream height and streamflow for the four gages.

Table 3-1. **Tenth and 90th percentiles for stream height and streamflow over the time period from 2000 to 2017 for four gages located on the Colorado River.**

Gage	County	Stream Height (feet)		Streamflow (cubic feet per second)	
		< 10th	< 90th	< 10th	< 90th
8117995	Borden	0.5	2.2	0.0	5.4
8147000	Lampasas	1.8	3.3	26	490
8158000	Travis	1.9	5.2	183	2,340
8162000	Wharton	8.2	15	272	2,530

One of the potentially important parameters that affects surface water-groundwater interaction is the temporal variability in the stream elevation. The greater the frequency of fluctuations in river stage, the more dynamic the exchange of water is between the stream and the aquifer. In addition, the larger the changes in the elevation of the river stage, the more important understanding and accounting for the process of bank storage is to properly quantify the net water exchange between groundwater and stream water.

3.3 Aquifers and Groundwater Wells

The interaction between streams and aquifers occurs in the aquifer outcrop area. An outcrop is where the aquifer is exposed at ground surface. Figure 3-6 and Figure 3-7 show outcrop locations in the Colorado River Basin for the major and minor Texas aquifers, respectively. Superimposed on the outcrop maps are surficial alluvium and terrace deposits as defined by the Geologic Atlas of Texas (Stoeser and others, 2007). Figure 3-6 and Figure 3-7 show that surficial alluvium and terrace deposits associated with the Colorado River are greatest in the southern portion of the basin (from southeastern Travis County to Matagorda County), the same area where the majority of the aquifer outcrops crossed by the river are located. The areas of narrow alluvium in the counties north of northwestern Travis County are predominately overlying geologic formations that are not aquifers.

Unlike the Brazos River alluvium, the alluvium associated with the Colorado River has not been designated by the TWDB as a minor aquifer. Saunders (1996) discusses qualifications for making such a designation, which include interaction with the Colorado River; its use as a source of groundwater for municipal, industrial, irrigation, domestic, and stock purposes; and the areal extent over which groundwater from the alluvium is used. Based on these qualifications, the alluvium is consistent with the TWDB's definition of a minor aquifer; that is, one that supplies relatively small quantities of water over large areas of the state. Designation as a minor aquifer has the benefit of protecting the water resource in the Colorado River alluvium, which has been negatively impacted with respect to both quality and quantity through over pumping, sand and gravel mining operations, and pesticide and fertilizer applications (Saunders, 1996). In addition, groundwater in the Colorado River alluvium is susceptible to pollution similarly to that for the Brazos River Alluvium Aquifer. In conclusion, Saunders (1996) states “The Colorado River alluvial aquifer is worthy of protection.”

Figure 3-8 gives the location of map areas shown in Figure 3-9 and Figure 3-10, which were developed in order to help identify the areas where shallow alluvium wells exist. Included on Figures 3-9 and 3-10 are wells located within a 2-mile buffer of the Colorado River, the footprint of the alluvium and terrace deposits, and the location of groundwater conservation districts. The wells of most interest are those that intersect the more permeable alluvium and terrace deposits, which have a good hydraulic connection to the river. In general, these wells have depths between 30 and 50 feet.

Four monitoring wells installed by the Lower Colorado River Authority as part of the Lower Colorado River Authority-San Antonio Water System Water Project (URS and Baer Engineering, 2006, 2007) are shown in Figure 3-8 and the map of Wharton and Matagorda counties (Map 8 on Figure 3-10). Two of these monitoring wells are by stream gages.

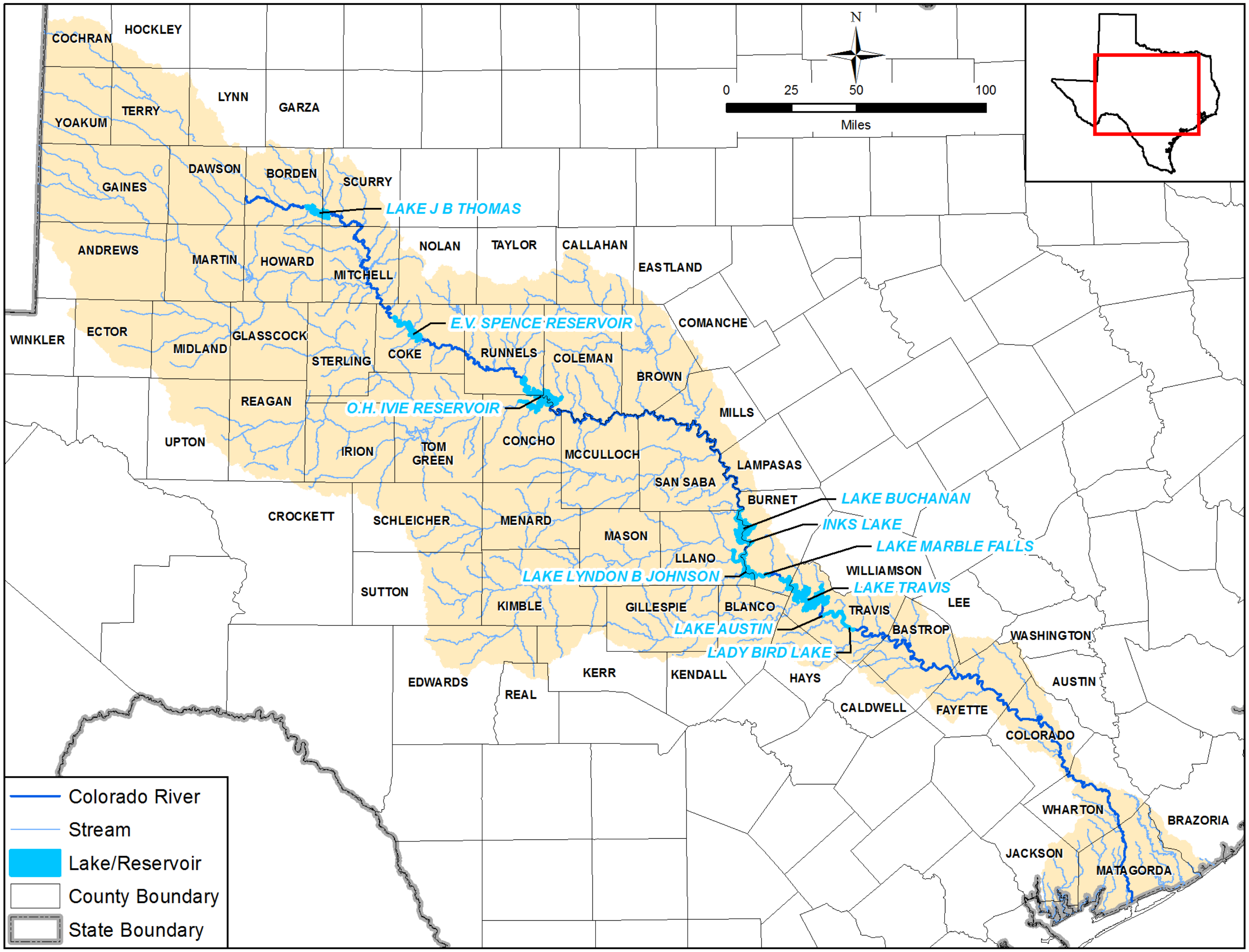


Figure 3-1. **Map of the Colorado River Basin showing the Colorado River, its tributaries, and lakes on the river.**

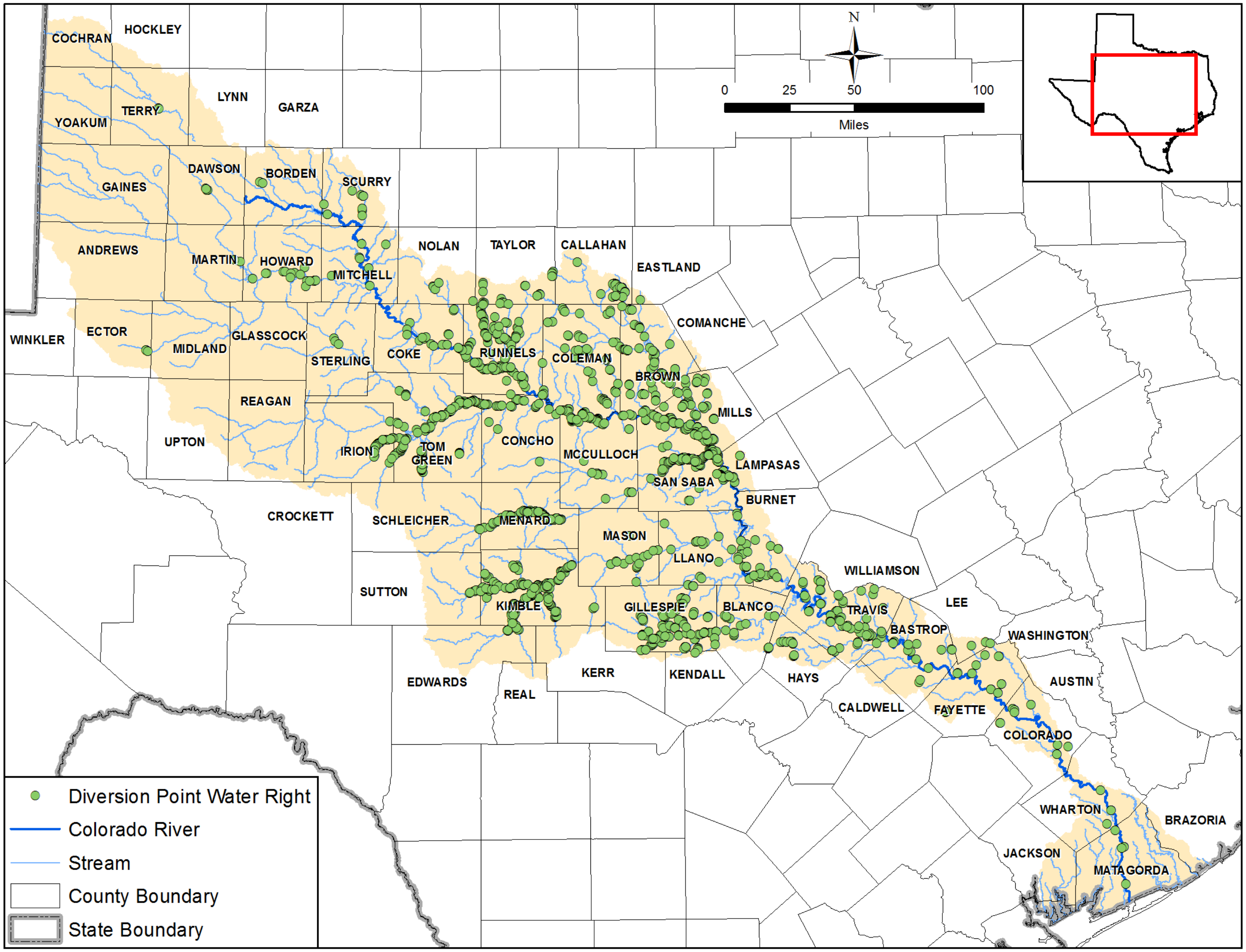


Figure 3-2. **Location of diversion points for surface water rights in the Colorado River Basin (Texas Commission on Environmental Quality, 2017a).**

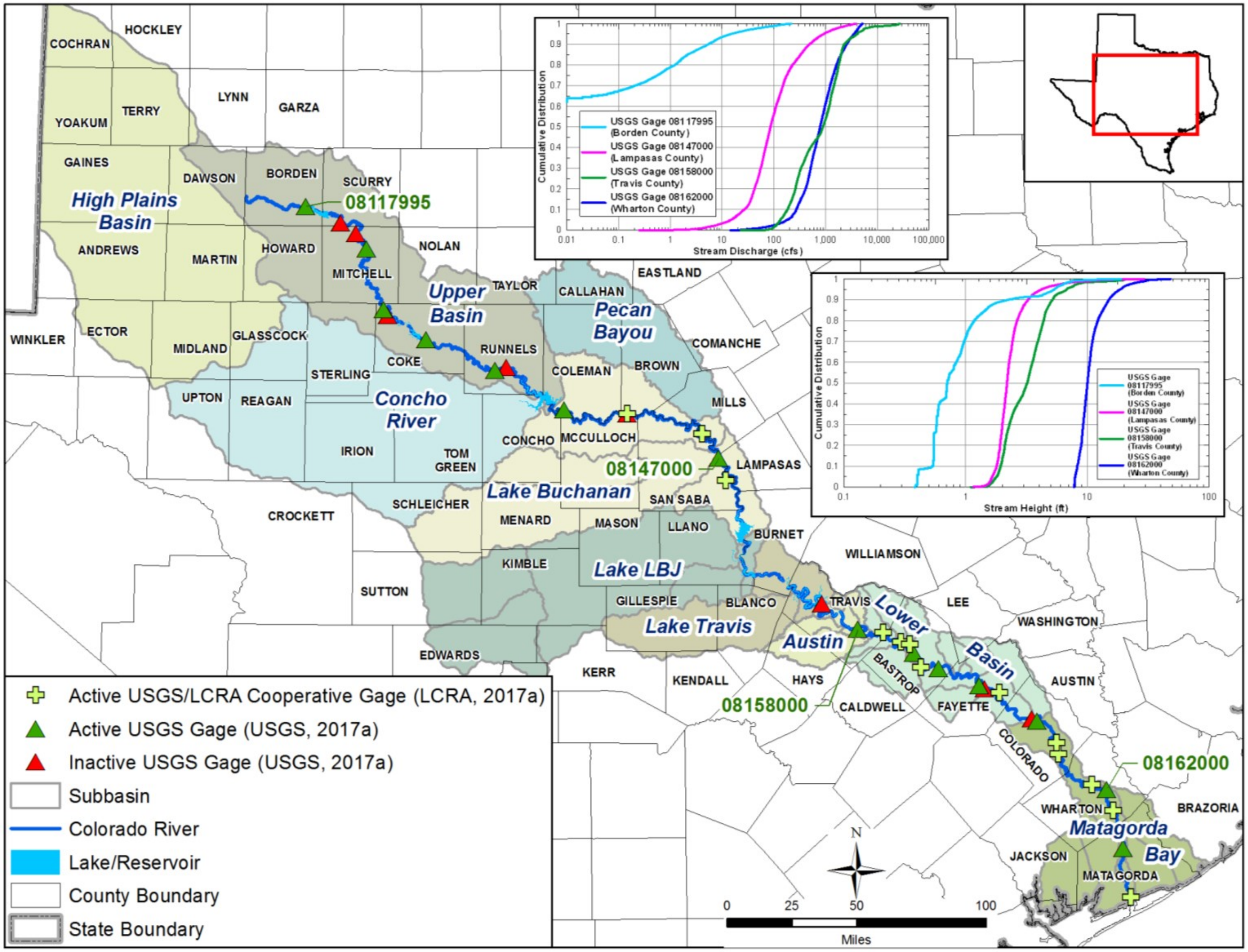
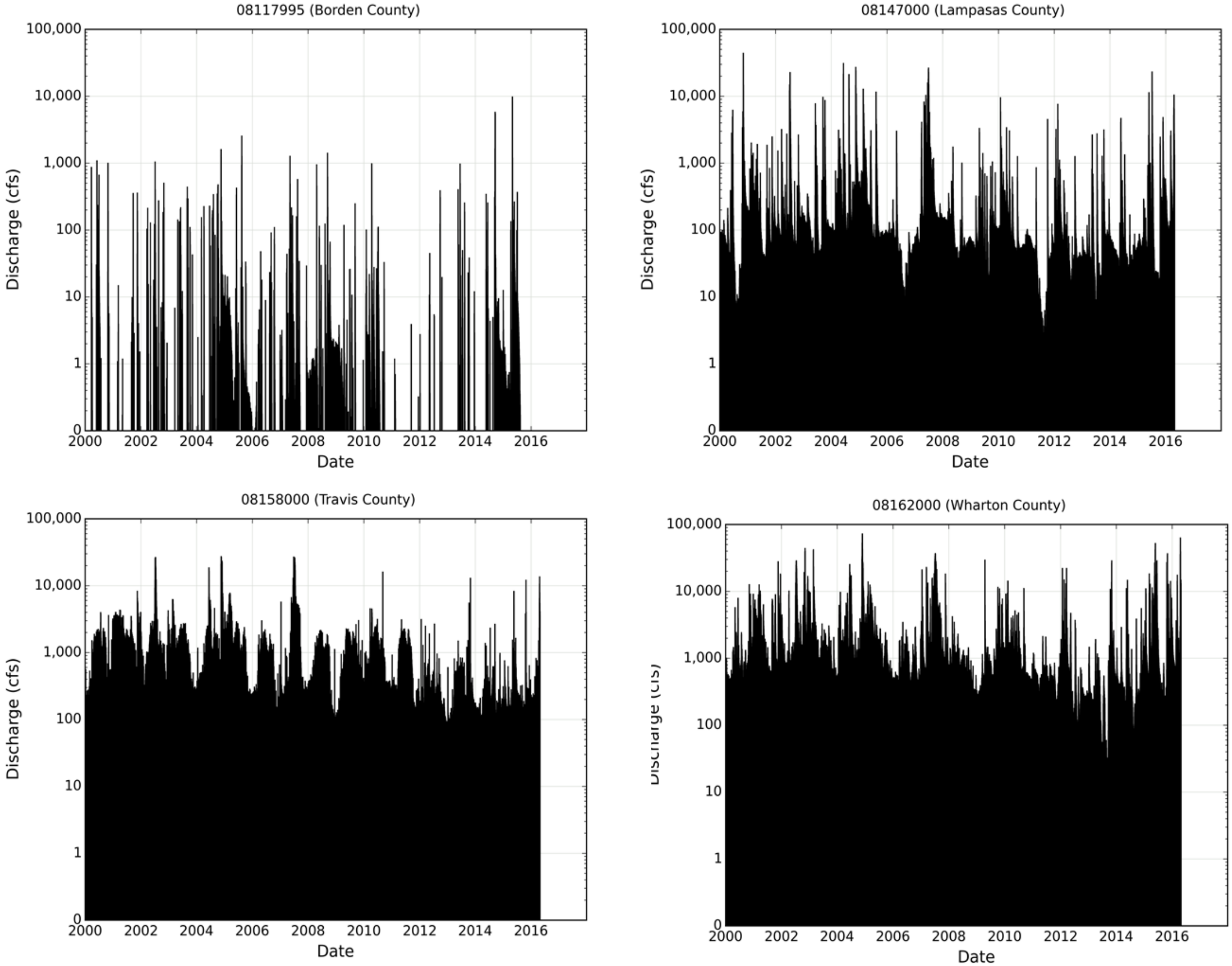


Figure 3-3. **Locations of watersheds and river gages and cumulative distribution function curves of streamflow (discharge) and stream height (stage) for gages 08117995, 08147000, 08158000, and 08162000.**

Note: LBJ = Lyndon B. Johnson; USGS = United States Geological Survey; LCRA = Lower Colorado River Authority; ft = feet; cfs = cubic feet per second


08117995 (Borden County)

08147000 (Lampasas County)

08158000 (Travis County)

08162000 (Wharton County)

Figure 3-4. **Measured streamflows available from 2000 to 2017 for gages 08117995 (Borden County), 08147000 (Lampasas County), 08158000 (Travis County), and 08162000 (Wharton County) (United States Geological Survey, 2017a).**

Note: cfs = cubic feet per second

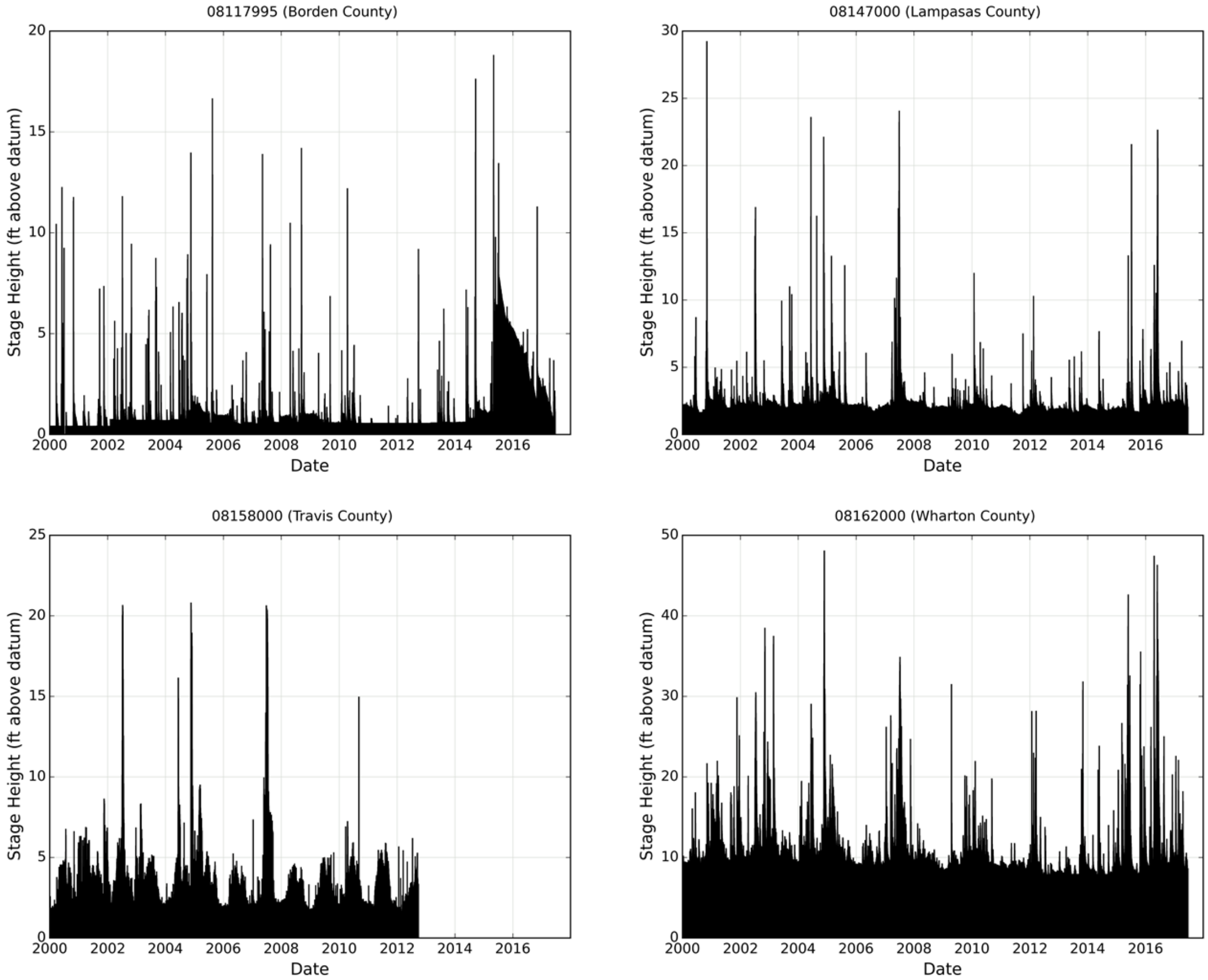


Figure 3-5. **Measured stream heights available from 2000 to 2017 for gages 08117995 (Borden County), 08147000 (Lampasas County), 08158000 (Travis County), and 08162000 (Wharton County) (United States Geological Survey, 2017a).**

Note: ft = feet

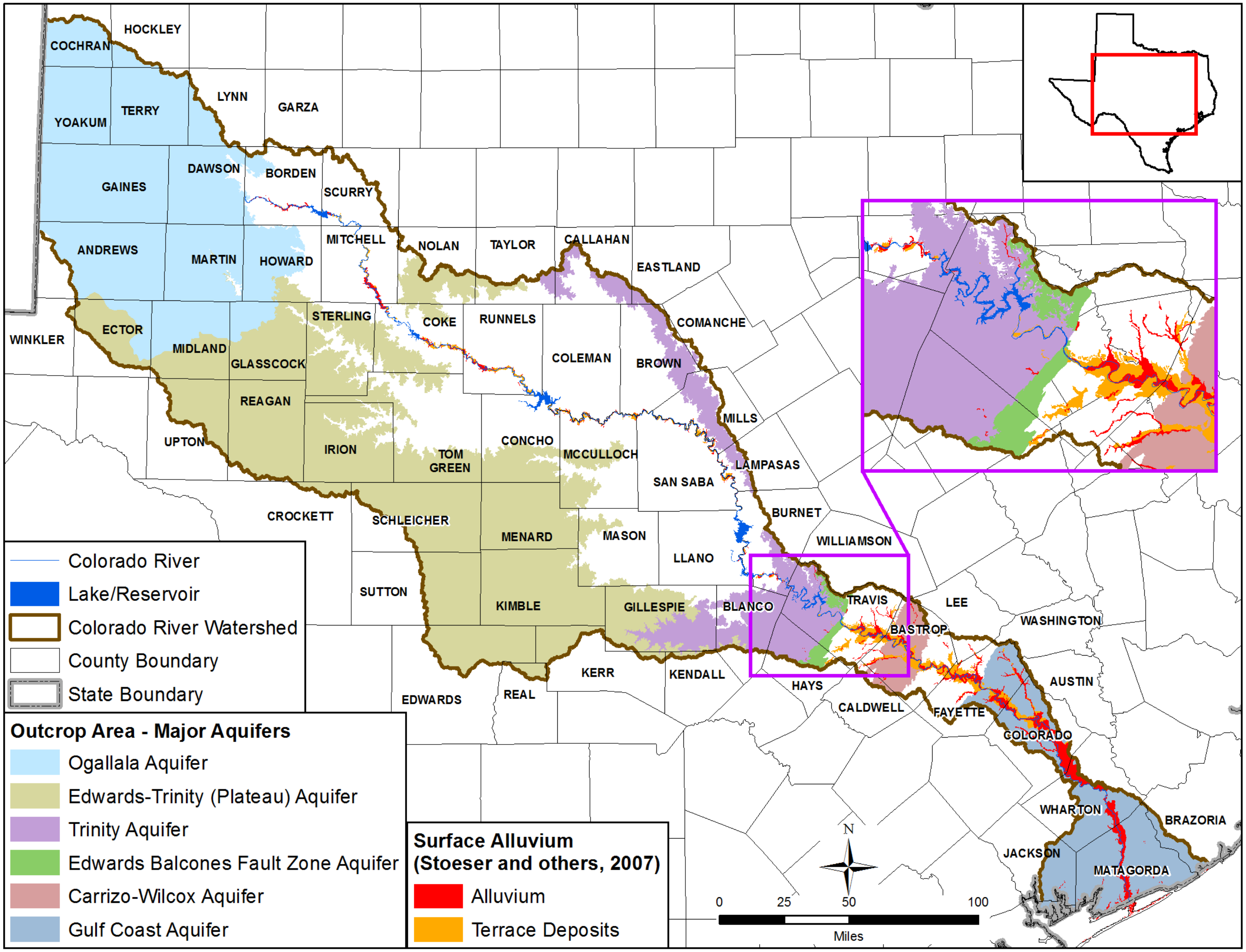


Figure 3-6. **Location of outcrops for major Texas aquifers in the Colorado River Basin and Colorado River alluvium and terrace deposits.**

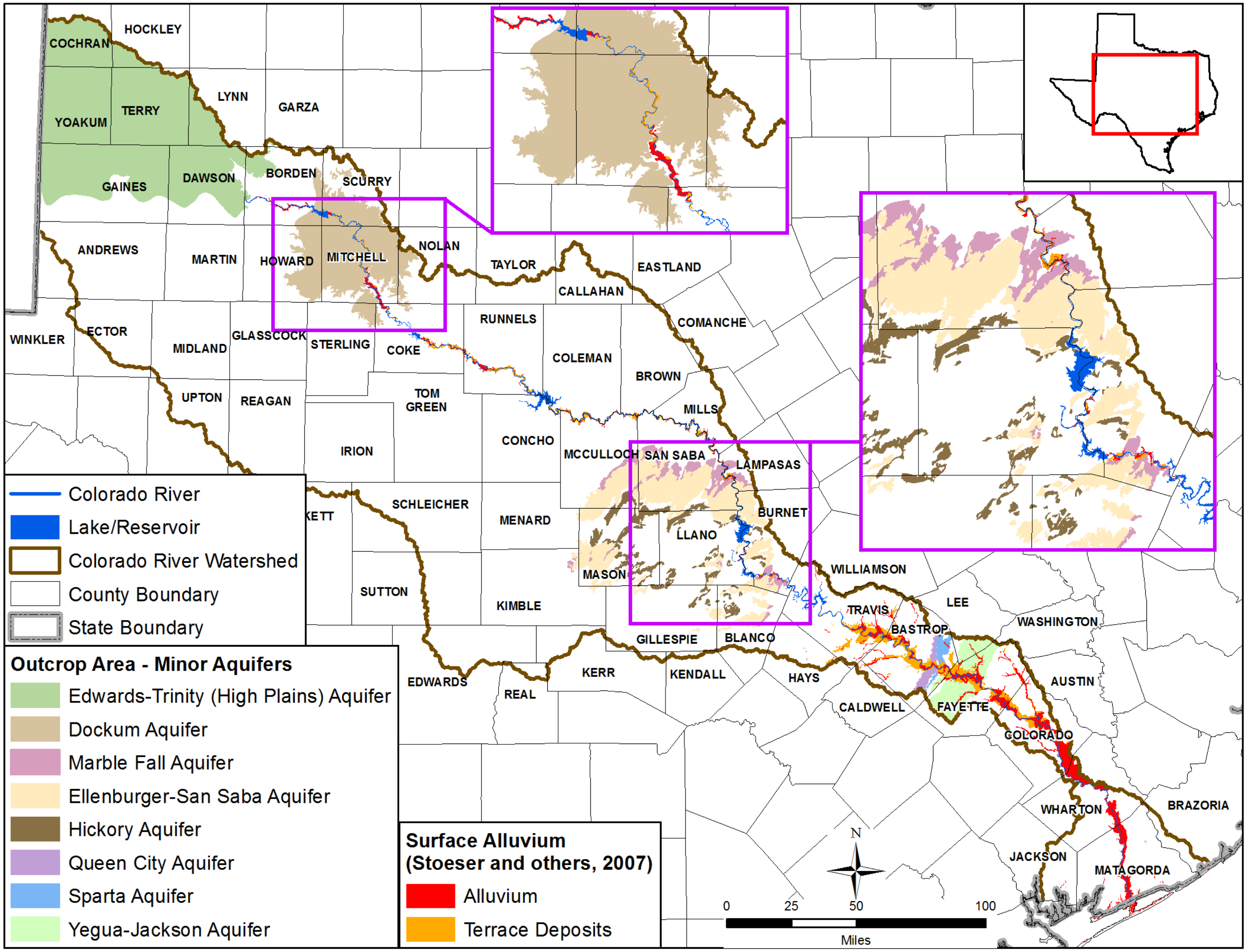


Figure 3-7. **Location of outcrops for minor Texas aquifers in the Colorado River Basin and Colorado River alluvium and terrace deposits.**

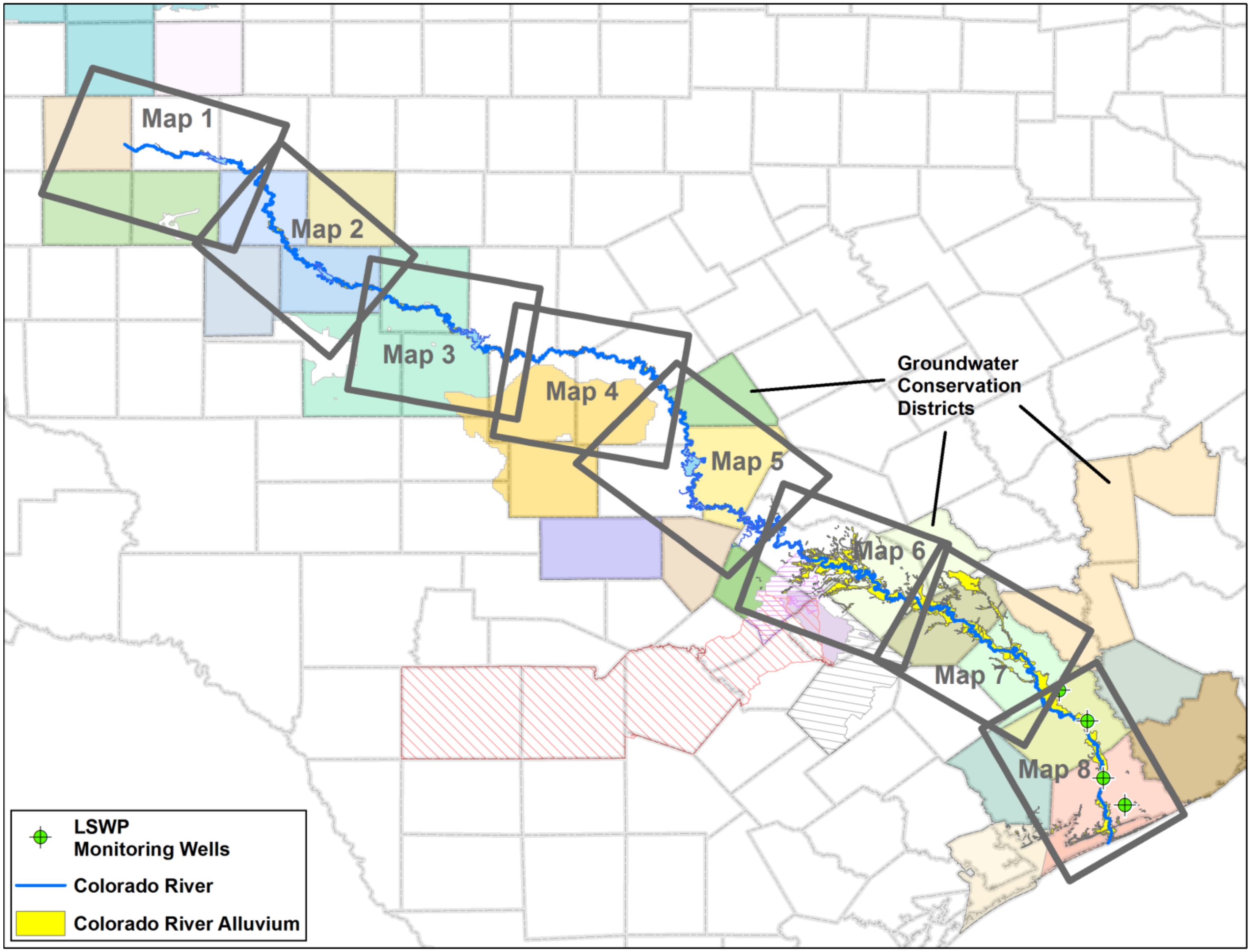


Figure 3-8. **Location of map areas in Figures 3-9 and 3-10 and the location of four monitoring wells installed by the Lower Colorado River Authority as part of the Lower Colorado River Authority-San Antonio Water System Water Project (LSWP).**

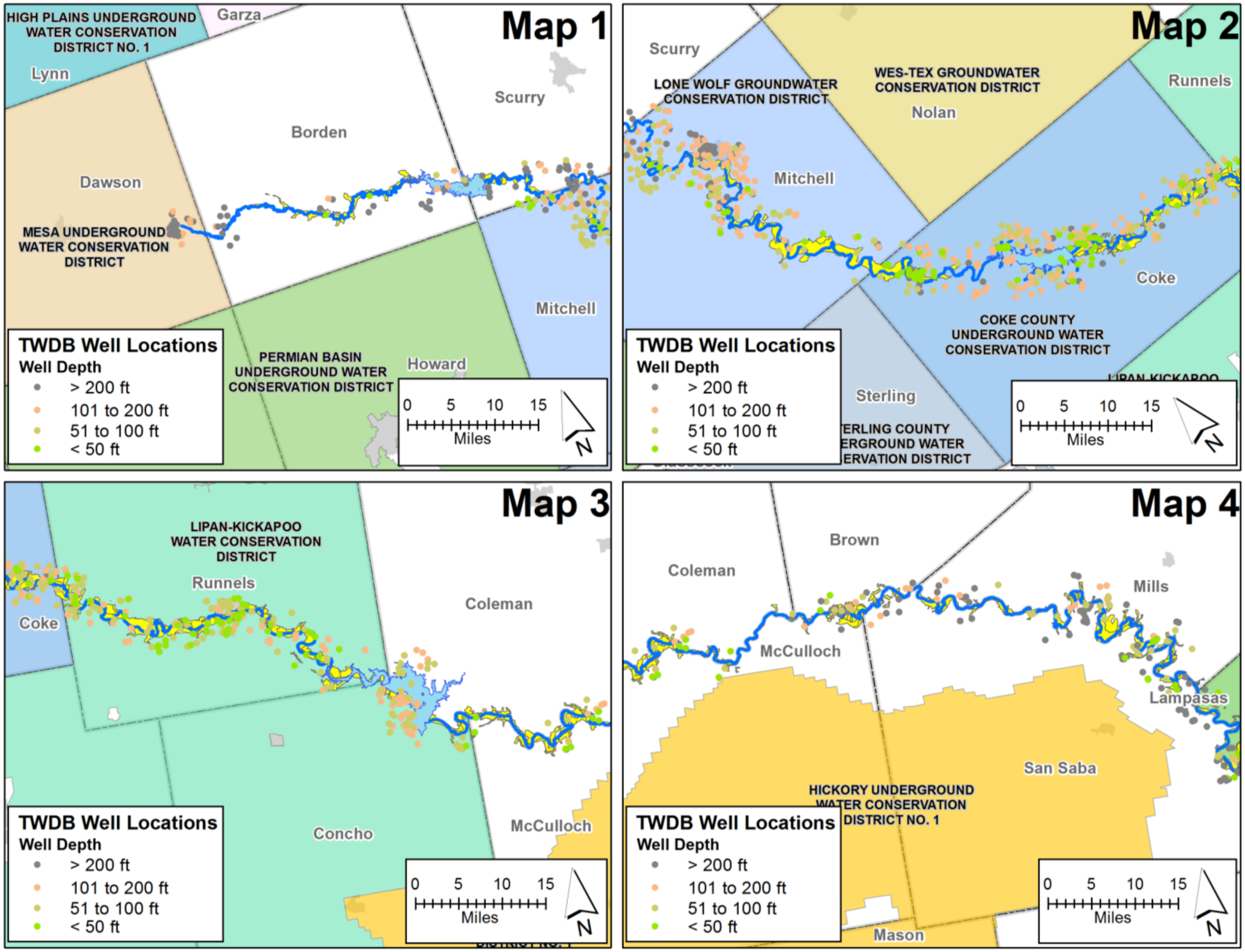


Figure 3-9. **Location of groundwater wells within a 2-mile buffer of the Colorado River and groundwater conservation districts in the areas defined by Maps 1, 2, 3, and 4 on Figure 3-8.**

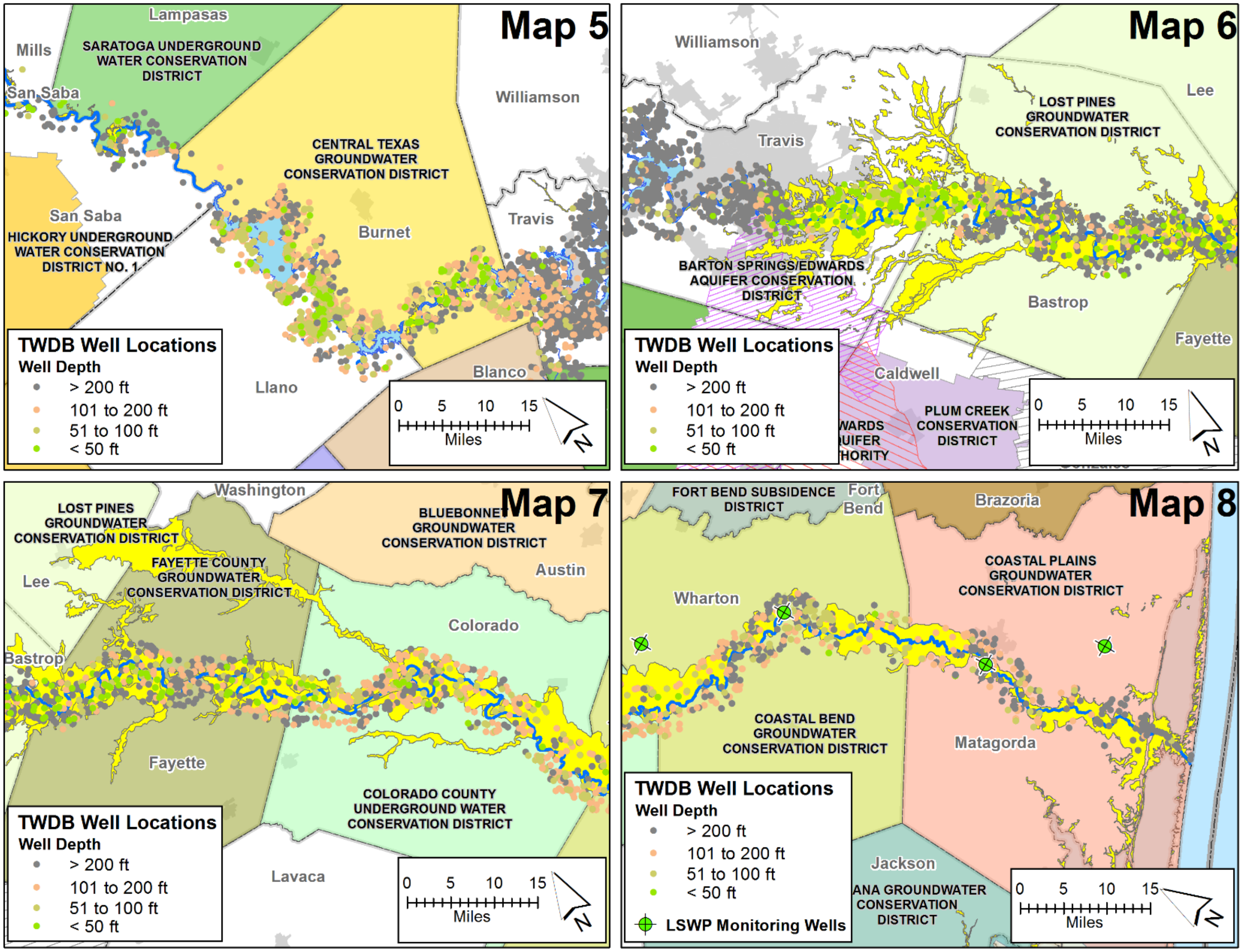


Figure 3-10. **Locations of groundwater wells within a 2-mile buffer of the Colorado River, the four LSWP monitoring wells, and groundwater conservation districts in the areas defined by Maps 5, 6, 7, and 8 on Figure 3-8.**

LSWP = Lower Colorado River Authority-San Antonio Water System Water Project

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4 Previous Colorado River Surface Water-Groundwater Studies

Several studies have been conducted to evaluate surface water-groundwater interaction and/or estimate base flow or gain/loss for the Colorado River (Table 4-1). This section provides a brief overview of these studies.

Table 4-1. Studies of surface water-groundwater interaction for the Colorado River.

Information Provided	Colorado River Basin Study Extent	Source
Identify sections of major streams that exhibit significant potential for surface water-groundwater interaction	all	Parson Engineering Science (1999)
Assembled a comprehensive compilation of river gain/loss studies in Texas	all	Slade and others (2002)
Base-flow characteristics from daily streamflow data for United States Geological Survey gages in the conterminous United States	all	Wolock (2003a, b)
Contribution of groundwater from major and minor aquifers to surface water	all	TWDB (2016)
Mass balance analysis and stream gain/loss studies	Austin to Bay City	Saunders (2005, 2006, 2009, 2012)
Spring flow from the Edwards BFZ Aquifer	Edwards BFZ Aquifer	Brune (1981)
Application of the Base Flow Index program and review of gain/loss studies	Gulf Coast Aquifer	Young and Kelley (2006); Young and others (2009)
Monitoring of water levels in paired river gage and nearby groundwater monitoring wells	Wharton and Matagorda counties	URS and Baer Engineering (2006, 2007)
Analysis of groundwater elevation data to determine the direction of hydraulic gradient in the vicinity of the Colorado River	Lower Colorado River Basin	Woodward (1989)
Extend of the Colorado River alluvium and location of major and minor aquifers underlying the Colorado River	all	Barnes (1979, 1981); Stoeser and others (2007)
Extent and thickness of the Colorado River alluvium	Fayette County	Standen (2017)
Description of the Colorado River alluvium	Bastrop County	Follett (1970)
Hydraulic properties of the Colorado River alluvium	Bastrop and Travis counties	Hibbs and Sharp (1993)
Hydraulic properties of the Colorado River alluvium	Travis County	Francis and others (2010); Gerecht and others (2011)

Note: BFZ = Balcones Fault Zone

4.1 Surface Water-Groundwater Interaction

The studies that have been conducted to evaluate surface water-groundwater interaction for the Colorado River are summarized in this section.

4.1.1 General Studies

Prior to initiation of the Water Availability Modeling Project conducted by the Texas Commission on Environmental Quality in response to Senate Bill 1 passed by the Texas Legislature in 1997, an investigation was conducted to "identify those sections of the major streams comprising 22 river basins that exhibit significant potential for interconnection with the underlying groundwater" (Parsons Engineering Science, 1999). In the Parsons study, they divided the Colorado River basin into three regions; an upper region from the Texas-New Mexico border to the boundary of Runnels and Coke counties, a middle region from the Runnels-Coke counties boundary to southern Travis County, and a lower region from southern Travis County to the Gulf of Mexico. Parsons Engineering Science (1999) concluded that groundwater discharge to the intermittent Colorado River in the upper region is insignificant, spring flow and base flow through groundwater discharge sustain the perennial river in the middle region, and the perennial condition of the river in the lower region is derived from groundwater discharge, wastewater discharge, dam seepage, and reservoir releases.

Brune (1981) documented over 24 springs that discharge from the Edwards Balcones Fault Zone Aquifer (see Figure 3-8) into the Colorado River. Barton Springs is the largest discharge point from the Edwards Balcones Fault Zone Aquifer to the Colorado River (Senger and Kreitler, 1984). Several of the springs (Bee, Mormon, Santa Monica, and Mount Bonnell springs) are beneath the surface of Lake Austin.

4.1.2 Gain/Loss Studies

Gain/loss studies involve performing a water balance along a designated stream reach. The stream reach is usually identified in terms of the distance on the stream channel between the upstream and downstream markers for the stream reach. The flow measurements include upstream and downstream streamflows for the stream reach and for sources and sinks of flow along the stream reach.

The flow mass balance can be computed using Equation 4-1 for a stream reach (Slade and Buszka, 1994; Slade and others, 2002). Rearrangement of terms in Equation 4-1 produces Equation 4-2. Equation 4-2 defines the amount of flow a stream has lost or gained because of its interaction with groundwater. Figure 4-1 illustrates the flow terms in Equation 4-2.

$$Q_{up} + Q_t + Q_r = Q_{down} + Q_w + Q_e + Q_{net} \qquad \text{Equation 4-1}$$

$$Q_{net} = Q_{up} + Q_t + Q_r - Q_{down} - Q_w - Q_e = Inflows - Outflows \qquad \text{Equation 4-2}$$

where:

Q_{up} = streamflow in at upstream end of subreach
Q_{down} = streamflow out at downstream end of subreach
Q_t = streamflow from tributaries
Q_r = anthropogenic return flows into subreach exclusive from groundwater interaction
Q_w = withdrawals and diversion from subreach exclusive from groundwater interaction
Q_e = evapotranspiration from subreach
Q_{net} = gain or loss in subreach

If inflows are greater than outflows (i.e., Q_{net} is positive), the river is losing and contributing water to the groundwater system. If outflows are greater than inflows (i.e., Q_{net} is negative), the river is gaining and groundwater is providing base flow to the river. Note that Slade and Buszka (1994) are consistent with this description of stream gain or loss based on the value of Q_{net}, but Slade and others (2002) incorrectly states the reverse.

Several potential sources of errors should be addressed as part of a gain/loss study. Three of these sources are proper accounting of diversions and return flows, changes in the flow rate entering the reach over time, and inaccuracies with measuring streamflows. Proper accounting of diversions can be difficult because the withdrawal may not be constant during the study period or the water users may not accurately report the water use. Unstable flow conditions can be caused by releases from upstream reservoirs or irregular water withdrawals. If gain/loss studies are performed during unstable flow conditions, then the flow measurements in the river should account for the time a pulse of water travels through the reach. Several sources of error exist with measuring the streamflow. The most important is the error associated with using stream height to calculate flow using discharge rating curves. Discharge rating curves change over time and especially after flood events. Saunders (2006) reports that the error associated with historical flows in the Lower Colorado River is approximately 8 percent.

A comprehensive compilation of river gain/loss studies in Texas completed by Slade and others (2002) includes 13 studies conducted on the Colorado River. Each study provided gain/loss estimates across a reach of the river. Table 4-2 summarizes the study date, the county in which the upstream and downstream location of the studied reach is located, the length of the river in the study, and the gain/loss per river mile estimated by the study. The upstream and downstream locations for the studies are illustrated in Figure 4-2. In general, both gaining and losing conditions were observed across the same reach of river for the various study dates, the river appears to be predominately losing in the upper portion, and the two studies across the middle and middle/lower portions of the river found gaining conditions, with the study that included the lower portion of the river having the largest gain.

Table 4-2. **List of stream gain/loss studies report by Slade and others (2002).**

Study Number	Study Date	Upstream End of Subreach County	Downstream End of Subreach County	Reach Length (miles)	Total Gain/Loss (cfs)	Gain/Loss per River Mile (cfs/mile)	Relative Portion of River[1]
42	Feb 1986	Scurry	Coleman	239.1	1.89	0.008	upper/middle
43	Jan 1987	Scurry	Coleman	239.1	-23.64	-0.099	upper/middle
44	Feb 1989	Scurry	Coleman	239.1	-5.41	-0.023	upper/middle
45	Feb 1975	Scurry	Mitchell	35.5	7.98	0.225	upper
46	Jan 1975	Scurry	Mitchell	35.5	4.96	0.14	upper
47	Jan 1976	Scurry	Mitchell	35.5	-2.24	-0.063	upper
48	Mar 1976	Scurry	Mitchell	35.5	-2.25	-0.063	upper
49	Aug 1985	Travis	Wharton	257.6	-1634.24	-6.344	lower
50	Dec 1966	Coke	Coke	34.7	-2.97	-0.086	upper
51	Mar 1967	Coke	Coke	34.7	-2.69	-0.078	upper
52	Apr 1968	Scurry	Coke	103.2	-0.28	-0.003	upper
53	Apr 1925	Coke	Travis	365	96.53	0.264	middle
54	Aug 1918	Coke	Matagorda	593	340.6	0.574	middle/lower

[1] Ranges for relative portion of river are: upper - Borden to central Coke counties, central - Coke to central Travis counties; lower - central Travis County to Gulf of Mexico

Note: cfs = cubic feet per second

The most comprehensive gain/loss study in Table 4-2 is Study 54. Table 4-3 lists the reported gain/loss for the 41 stream reaches (shown in Figure 4-3) for Study 54. The most substantial gains are reported for gages downstream from Lake Travis. In the Edwards Balcones Fault Zone and Trinity aquifers, the gains are attributed primarily to springs and fissure streams located in the Edwards Balcones Fault Zone Aquifer. The gaining stream condition that is prevalent in the Carrizo-Wilcox, Yegua-Jackson, and Gulf Coast aquifers in Study 54 conducted in 1918 is not present in Study 49 conducted in 1985. This difference is because Study 49 (United States Geological Survey, 1986) did not account for the large diversions from the river in the vicinity of the major and minor aquifers (Sanders, 2012) when solving Equation 4-2 for Q_{net} for each subreach.

Table 4-3. **Steam gain/loss for Study 54 reported by Slade and others (2002) for the Colorado River.**

No.[1]	Gain or Loss (-) (cfs)	Total Flow (cfs)	cfs/mile reach[2]	Aquifer(s)[3]	No.[1]	Gain or Loss (-) (cfs)	Total Flow (cfs)	cfs/mile reach[2]	Aquifer(s)[3]
1	0	0	0.00		22	-1.7	19.3	-0.43	TR
2	0	0	0.00		23	-0.9	17.6	-0.10	TR
3	0	0	0.00		24	1.4	16.7	0.11	TR
4	0	0	0.00		25	11.5	18.1	0.96	TR
5	0	0	0.00		26	3.7	29.6	3.70	ED, TR
6	0	0	0.00		27	0.4	33.3	0.20	ED
7	0	0	0.00		28	27.4	33.7	1.71	
8	0	0	0.00		29	-0.3	61.1	-0.15	
9	0	0	0.00		30	15.1	60.8	1.08	
10	3.8	0	0.13		31	20.2	75.9	1.01	CW
11	7.7	3.8	0.30		32	17.3	96.1	0.75	CW
12	-1.2	11.5	-0.40		33	1	113.4	0.08	
13	-0.1	10.3	-0.01		34	21	114.4	1.40	YG
14	3.5	10.2	0.15	EL-SS	35	9	135.4	0.53	GC
15	0	13.7	0.00	EL-SS	36	12	144.4	0.71	GC
16	-0.9	13.7	-0.13		37	27.2	156.4	1.13	GC
17	0.9	12.8	0.06		38	6.2	183.6	0.69	GC
18	-0.1	13.7	-0.02		39	50	189.8	2.38	GC
19	-0.6	13.6	-0.08		40	14.8	239.8	2.47	GC
20	6	13	0.21	TR, EL-SS	41	85.2	254.6	3.04	GC
21	0.3	19	0.05	TR	42	0.8	339.8	0.04	GC

[1] gage number on Figure 4-3

[2] gain/loss per river mile

[3] CW - Carrizo-Wilcox; EL-SS - Ellenburger-San Saba; ED - Edwards Balcones Fault Zone; GC - Gulf Coast; TR - Trinity; YJ - Yegua-Jackson

Note: cfs = cubic feet per second

Saunders (2005, 2006, 2009) published results from three stream gain/loss studies in the lower Colorado River Basin. The three studies used stream gage data collected in November 1999, 2005, and 2008, during which surface water diversion for the rice industry was not occurring, low stable flows were occurring, precipitation events were minimal, and the diversions and return flows could be determined. Table 4-4, Table 4-5, and Table 4-6 and Figure 4-4 present the results from these three studies, which indicate that, during the time of these studies, the Colorado River gained between 30 to 50 cubic feet per second across the Carrizo-Wilcox Aquifer in Bastrop County and gained between about 140 and 190 cubic feet per second across the Gulf Coast Aquifer in Colorado, Wharton, and Matagorda counties. The studies show the Colorado River gaining across the Yegua-Jackson Aquifer based on the 1999 data and losing across the aquifer based on the 2005 data.

Table 4-4. Stream gain/loss for the Saunders (2005) study of the Lower Colorado River using data from November 1999.

Reach Number	Reach Description	River Miles	Gain/Loss (cfs)	Aquifer(s)/Formation[1]
1	Austin to Bastrop	53.5	-9	CW
2	Bastrop to Smithville	24.8	+59	CW, RK, QS
3	Smithville to LaGrange	36.0	-22	YJ
4	LaGrange to Columbus	40.9	+81	GC
5	Columbus to Wharton	68.5	+10	GC
6	Wharton to Bay City	34.1	+98	GC
	Total	257.8	217	

[1] CW - Carrizo-Wilcox; RK - Reklaw; GC - Gulf Coast; QS - Queen City/Sparta; YJ - Yegua-Jackson
Note: cfs = cubic feet per second

Table 4-5. Stream gain/loss for the Saunders (2006) study of the Lower Colorado River using data from November 2005.

Reach Number	Reach Description	River Miles	Gain/Loss (cfs)	Aquifer(s)/Formation[1]
1	Utley to Bastrop	15.2	98	CW
2	Bastrop to Smithville	24.7	-48	CW, RK, QS
3	Smithville to LaGrange	37.3	22	YG
4	LaGrange to Columbus	32.8	71	GC
5	Columbus to Altair	27.7	-4	GC
7	Altair to Wharton	46.8	60	GC
8	Wharton to Lane City	10.7	47	GC
9	Lane City to Bay City	22.4	-36	GC
	Total	217.6	210	

[1] CW- Carrizo-Wilcox; RK- Reklaw; GC-Gulf Coast; QS- Queen City/Sparta; YJ-Yegua-Jackson
Note: cfs = cubic feet per second

Table 4-6. Stream gain/loss for the Saunders (2009) study in Bastrop County using data from November 2008.

Reach Number	Reach Description	River Miles	Gain/Loss (cfs)	Aquifer(s)/Formation[1]
1	Utley to Bob Byrant Park	13.4	34.5	CW
2	Bob Byrant Park to Colovista Country Club	11.5	-4	CW
3	Colovista Country Club to Smithville	15.1	-0.5	RK, QC
	Total	40	30	

[1] CW - Carrizo-Wilcox; RK - Reklaw; QC - Queen City
Note: cfs = cubic feet per second

A historical dry period in central Texas occurred from October 2010 to December 2011. During those 15 months, water flowing into the Highland Lakes was only 11.3 percent of the average flow. The dry months of November 2010 and November 2011 provided ideal low-flow conditions for evaluating gains and losses in the lower Colorado River. According to Saunders (2012):

> *"Streamflow in Bastrop and Columbus was very low and steady during those two months (400-450 cfs in November 2010; 200-250 cfs in November 2011). There were no significant releases from the Highland Lakes, and no irrigation diversions. Based on LCRA Hydromet gauge data, tributary inflows were minimal. Water balance calculations for the lower Colorado River were performed using daily average flows at USGS and LCRA gauges, accounting for wastewater return flows and withdrawals for industrial uses. The daily water balance calculations showed some variations, but overall a consistent pattern of gains was seen along the main stem of the river downstream from the Highland Lakes. In the reach from Tom Miller Dam in Austin to Bay City, the river was found to gain a total of 183 cfs in November 2010 and 177 cfs in November 2011."*

4.1.3 Hydrograph-Separation Studies

The hydrograph-separation method (sometimes called base-flow separation) aims to distinguish streamflow derived from surface runoff and that derived from groundwater, based solely on a stream hydrograph. A stream hydrograph is the time-series record of streamflow conditions. The hydrograph represents the aggregate of the different water sources that contribute to streamflow. The two main components that make up the streamflow hydrograph are:

1) Quickflow – flow in direct response to a rainfall event including overland flow (runoff) and direct rainfall onto the stream surface (direct precipitation).
2) Base flow – the steady flow derived from groundwater discharge to the stream and lateral movement in the soil profile (interflow).

Figure 4-5 illustrates that the relative contribution of quickflow and base flow changes over time during a flood event for a gaining stream. Initially, the low-flow conditions in the stream consist entirely of base flow at the end of a dry period. Then, as rainfall begins, an increase in streamflow is observed by the quickflow response dominated by runoff. This initiates the rising limb towards the crest of the flood hydrograph. The rapid rise of the stream level relative to surrounding groundwater levels reduces the hydraulic gradient towards the stream and is expressed by a reduction in the base-flow component at this stage. Eventually, the quickflow component passes, expressed by the falling limb of the flood hydrograph (also called the recession curve). With declining stream levels timed with the delayed response of a rising water table from infiltrating rainfall, the hydraulic gradient towards the stream increases (Brodie and others, 2005). At this time, the base-flow component starts to increase. At some point along the falling limb, quickflow ceases and streamflow is again entirely base flow.

The hydrograph-separation method relies on the principle that runoff events are of relatively short duration whereas groundwater responds more slowly to rainfall recharge. Empirical studies have determined that the duration of surface water flow following rainfall will be a function of the catchment area. The most widely used relationship is that of Linsley and others (1975):

$$t = 0.8278\, A^{0.2} \qquad \text{Equation 4-3}$$

where:

t = time between the storm crest and the end of surface runoff (in days)
A = catchment area (in square kilometers).

Based on Equation 4-3, the time for surface runoff to cease is estimated to be approximately 2.1 days for a catchment area of 100 square kilometers, increasing to 5.2 days for a catchment area of 10,000 square kilometers. Several base-flow separation routines use Equation 4-3 to determine the time after which streamflow is comprised solely of groundwater inflow. However, there is not a universally accepted approach for separating surface runoff from groundwater inflow within the streamflow peak.

Several potential sources of errors should be addressed as part of the evaluation and validation of a hydrograph-separation study. Hydrograph separation will be most accurate when surface runoff events are well-defined, but represent a relatively small proportion of the flow to the river. This is likely to be the case in small catchments, where travel times for surface runoff are short. The method is also most applicable to undeveloped catchments. If river losses occur within the catchment (due to pumping, evaporation, transpiration of riparian vegetation) then this water will not appear as flows at the gaging station and will not be included as groundwater inflow to the river. The method thus estimates net groundwater inflows within the catchment, rather than total inflows. The hydrograph-separation method is not appropriate for regulated streams where dam releases significantly influence the stream hydrograph response. Evans and Neal (2005) have also noted that flow releases from upstream reservoirs may produce a low flow signal that can be misinterpreted as base flow.

Many hydrograph-separation methods have been developed to estimate the base-flow and runoff components of streamflow and, in recent years, these methods have been implemented in a number of computer programs that facilitate the estimation process (Pettyjohn and Henning, 1979; Nathan and McMahon, 1990; Wahl and Wahl, 1995; Sloto and Crouse, 1996; Rutledge, 1998; Arnold and Allen, 1999; Eckhardt, 2005; Lim and others, 2005; Piggott and others, 2005). Although each of the methods is based on formalized algorithms for identifying the base-flow component of total streamflow, the methods are subjective and not based on mathematical solutions to groundwater- or overland-flow equations. As a result, it is advantageous to use more than one hydrograph-separation method to analyze a streamflow record and then compare the results from the multiple methods.

A hydrograph-separation method that has been widely used to estimate surface water-groundwater interaction in Texas is the Base Flow Index program (Young and Kelley, 2006; Young and others, 2009; Scanlon and others, 2012; Deeds and others, 2010; Kelley and others, 2014; Ewing and others, 2016). The Base Flow Index program (Institute of Hydrology, 1980a, b; Wahl and Wahl, 1995) executes a deterministic set of procedures to compute an annual base-flow index for multiple years of data at one or more gage sites. The base-flow index is the ratio of base flow to total flow volume for a given year and is defined by Equation 4-4.

$$BFI = \frac{V_b}{V_a} \qquad \text{Equation 4-3}$$

where:

BFI = base-flow index
V_b = volume of water calculated as base flow
V_a = total volume of streamflow

The Base Flow Index program algorithms are driven by two parameters, *N* and *f*. *N* represents the length of the intervals (measured in days) into which the period of record is divided. The parameter *f* is used to compare each minimum to the adjacent minimum blocks and derive base flow ordinates (Gustard and others, 1992). The Base Flow Index program uses default values of 5 and 0.9 for *N* and *f,* respectively. Wahl and Wahl (1995) suggest that the *N* value has the largest effect on the calculated base-flow value and can be estimated by plotting base-flow index versus *N* and locating the critical value where the slope of the line changes. Figure 4-6 shows an example application of the Base Flow Index program using data from year 2000 at gage 08164000 in the Lavaca River Basin.

Regarding the potential limitation of the Base Flow Index program, the United States Geological Survey (2017b) states:

> *"Users should be very cautious about using methods such as this for short-term storm events or for locations where streamflow is affected by upstream regulation, such as reservoir releases. In general, the method interprets most regulated releases as base flow. If the program is used for regulated streams, the effects of regulation must be carefully accounted for through manual adjustment of the program output."*

The Base Flow Index program has been applied to the Colorado River Basin to estimate base flow to support the development of regional groundwater models. At least two applications did not produce credible results for the lower Colorado River Basin because of problems related to the Colorado River being regulated through releases from Lake Travis and large diversion. These two applications are Young and Kelley (2006) and the analysis of stream hydrographs in Groundwater Management Area 12 as part of the updated of the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers.

Wolock (2003a) performed one of the most well know and widely cited applications of the Base Flow Index program. He created a geospatial dataset of base-flow characteristic through analysis of daily streamflow data over the period of record for about 19,000 United States Geological Survey streamflow gages in the conterminous United States (Wolock, 2003a). As part of his analysis of streamflow, Wolock (2003a) ignored whether or not a stream was regulated. The study developed data on a 1-kilometer grid for the United States by interpolating base-flow index values estimated at United States Geological Survey stream gages. The study provided base-flow index values for 21 stream gages on the Colorado River in Texas (Table 4-7). The tabulated data indicate that median base flow for the Colorado River is less than 100 cubic feet per second in the upper reaches of the river from Borden to Brown counties and typically above 1,000 cubic feet per second in the southern reaches of the river from Travis County south.

Table 4-7. Base flow and base-flow index values for the Colorado River from Wolock (2003a).

Gage Number	Colorado River Stream Gage	Period of Record	Base-Flow Index	Median Base Flow (cfs)	Average Base Flow (cfs)	Maximum Base Flow (cfs)	Base Flow Standard Deviation (cfs)
8117995	near Gail, TX	1988-2000	0.03	0	12	2,060	86
8119500	near Ira, TX	1947-1989	0.07	0.31	15	13,600	178
8120700	near Cuthbert, TX	1965-2000	0.16	4	32	8,770	246
8121000	at Colorado City, TX	1923-2000	0.05	0.62	41	16,000	333
8123850	above Silver, TX	1967-2000	0.14	8.5	76	15,900	430
8123900	near Silver, TX	1956-1970	0.05	3.8	105	17,400	697
8124000	at Robert Lee, TX	1923-2000	0.23	2	94	24,200	722
8126380	near Ballinger, TX	1907-2000	0.16	16	245	54,300	1,383
8126500	at Ballinger, TX	1907-1979	0.10	17	292	54,300	1,559
8136700	near Stacy, TX	1968-2000	0.36	45	181	31,300	753
8138000	at Winchell, TX	1923-2000	0.18	63	476	67,000	2,218
8147000	near San Saba, TX	1915-2000	0.28	226	1,086	191,000	4,507
8154510	at Austin, TX	1974-1990	0.60	1,260	1,460	25,300	1,837
8158000	at Austin, TX	1898-2000	0.48	1,130	2,239	323,000	5,974
8159200	at Bastrop, TX	1960-2000	0.63	1,540	2,238	65,800	3,645
8159500	at Smithville, TX	1930-2000	0.58	1,620	2,669	219,000	6,240
8160400	above La Grange, TX	1988-2000	0.61	1,440	2,676	84,000	5,465
8160500	at La Grange, TX	1938-1955	0.65	1,660	2,332	124,000	4,093
8161000	at Columbus, TX	1916-2000	0.54	1,620	3,106	164,000	6,517
8162000	at Wharton, TX	1938-2000	0.54	1,310	2,729	90,600	5,084
8162500	near Bay City, TX	1948-2000	0.40	895	2,590	79,300	5,544

Note: cfs = cubic feet per second; TX = Texas

Figure 4-7 and Figure 4-8 show the base-flow index and median base-flow values, respectively, from Wolock (2003a). These figures show a significant difference in the median base flow and base-flow index for the gages above and below the Highland Lakes. The average base-flow index value for the nine gages below the Highland Lakes is 0.56. Base-flow index values greater than 0.5 indicate groundwater contributes more total streamflow than does surface runoff.

In response to House Bill 1232 of the 84thTexas Legislature, the TWDB prepared a report that estimated the volume of flows from the aquifers to the surface waters of Texas (TWDB, 2016). As part of that study, the TWDB determined that the minimum flow rate for groundwater discharge to surface water is defined as a contribution of at least 0.1 percent of the mean annual surface water flow over any specified geographic area of any major or minor aquifer. To estimate the aquifer contributions to base flow, the TWDB combined the results from several studies performed by Wolock (2003a, 2003b) and Wolock and others (2004). The underlying data for the TWDB's analysis was the geospatial dataset of point base-flow characteristics and base-flow index from Wolock (2003a) and the geospatial dataset of hydrologic landscape regions broken out by watershed from Wolock (2003b). Using these data, TWDB (2016) first interpolated the average annual streamflow values and the average annual base-flow index within each of the hydrologic landscape regions. They then calculated the base-flow volume as a fraction of the average annual streamflow using the average base flow and base-flow index values from Wolock (2003a). The average annual base flow for each watershed was then obtained using the ArcGIS zonal statistics tool (TWDB, 2016). To obtain the groundwater discharge contributing base flow to surface water for each of the major and minor aquifers, the average annual base flow for each watershed was intersected with the aquifer outcrop areas. The TWDB (2016) geospatial data include the mean and median annual base flow by watershed and per square mile of watershed and the base-flow index for the major and minor aquifer outcrops. Figure 4-9 shows the estimated base-flow index for outcrops of major and minor aquifers in the Colorado River Basin as determined by TWDB (2016).

4.1.4 Studies Including Stream Gages and Nearby Alluvium Water Wells

The most direct approach to determine whether a stream is gaining or losing is to compare the water elevation in the stream to the elevation of the water table in the aquifer or alluvial adjacent to the stream. This type of study was performed as part of the Lower Colorado River Authority-San Antonio Water System Water Project in the lower Colorado River Basin. This project included installing an alluvium well approximately 300 feet from the stream gage at the city of Wharton and at Bay City (URS and Baer Engineering, 2006; 2007). The alluvium wells were drilled with hollow stem augers and consisted of 4-inch diameter Schedule 40 Polyvinyl Chloride casing with 40-foot screens.

Water-level data were collected in the alluvium wells at 15-minute intervals from April 11, 2006 to December 3, 2007 using pressure transducers. Figure 4-10 and Figure 4-11 show that, except for a few flood events, the hydraulic gradient indicates groundwater flow is entering the stream and that the stream is gaining. For approximately 10 flood events, the flood event caused a reversal of the hydraulic gradient. A portion of the URS and Baer Engineering (2007) analysis of the monitoring data is provided below:

> *"Except for brief periods during extreme high river stages (e.g. January 16, 2007, March 15, 2007, etc.), the elevation of the water table in the wells at Wharton and Bay City is higher than the elevation of the river. Over the period of record, the river elevation was higher than the water table elevation at the well less than 14 percent of the time at Wharton and less than 8 percent of the time at Bay City. The water table elevation averaged 1.39 feet higher than the river at the Wharton site and at least 7.28 feet higher than the river at the Bay City site.*
>
> *There is a relationship between the river elevation and the groundwater elevation at both the Wharton and Bay City locations… The correlation between river stage and the water table elevation is apparent not only for large scale fluctuations, but also for small scale features. When compared to fluctuations of river stage at Wharton, the water table fluctuations in the nearby well are attenuated by a factor of approximately 3 to 4, and the onset of steep rises are delayed by approximately 1 to 5 hours. At Bay City, the water table fluctuations are attenuated by a factor of approximately 6 to 12 and the onset of steep rises are delayed by approximately 0.5 to 2.25 hours. … The attenuation factor and*

> *the time delay between the river stage and the water table elevation is dependent on the distance between the river and the wells, the difference in elevation between the river and the water table, and the transmissivity of the saturated alluvial deposits. Differences among the attenuation factors at the two location is attributed to the differences in the different response times."*

4.2 Alluvium Characterization Studies

The Colorado River alluvium is a laterally continuous, hydraulically interconnected series of alluvial and terrace deposits. This section summarizes surface water-groundwater studies that involved hydrogeological characterization of the Colorado River alluvium.

4.2.1 History, Areal Extent, and Thickness of the Colorado River Alluvium

During most its Pleistocene and Holocene history, the Colorado River was a bedload-dominated fluvial system (Baker and Penteado-Orellana, 1977, 1978). This type of fluvial system typically produces good hydraulic interconnectedness in the alluvial deposits both vertically and horizontally. Today, the Colorado River is still a bedload-dominated fluvial system with a mostly coarse sand and gravel streambed (Hibbs and Sharp, 1993). Stoeser and others (2007) define the areal extent of the Colorado River alluvium as shown in Figures 3-6 through 3-10. Stoeser and others (2007) based the extent of their alluvium and terrace deposits on the studies by Barnes (1979, 1981). As shown in the figures, the Colorado River alluvium deposits do not become extensive until south of the Balcones Escarpment near Austin. South of the Balcones Escarpment, the ancestral Colorado River encountered a gently sloping area with low stream gradients, and the river deposited its sediment load in broad floodplain and terrace deposits.

The thickness and basal structure of the Colorado River alluvium is largely unknown, but it has been mapped in some areas. Garner and Young (1976) mapped the alluvium in the Austin area with an average thickness of about 30 feet and ranging up to 60 feet. In Bastrop County, Follett (1970) reports a maximum thickness of 50 feet for the alluvium. Standen (2017) mapped the thickness of the alluvium in Fayette County based on the analysis of driller logs. He reports maximum thicknesses greater than 60 feet.

4.2.2 Hydraulic Head Gradient

Woodward (1989) assembled and developed contours of hydraulic head data for the Lower Colorado River Valley using data from the files of the United States Geological Survey and the TWDB from 1970 to 1985. The study area focused on the Lower Colorado River Valley, which includes Travis, Bastrop, Fayette, Colorado, Wharton, and Matagorda counties. Woodward (1989) developed contour maps for regional aquifers to determine the groundwater flow direction in the vicinity of the Colorado River. Among his findings are:

- *Trinity Aquifer*: Flow in the lower Trinity Aquifer is toward the lower Colorado River and major tributaries of the river. The localized flow direction near Lake Travis is from the lake to the aquifer. Reliable water-level data in the upper Trinity Aquifer are sparse. Based on the available data and Brune and Duffin (1983), the groundwater flow direction is generally in the same direction as the slope of the land surface.
- *Edwards Balcones Fault Zone Aquifer*: The regional direction of flow in the Edwards Balcones Fault Zone Aquifer in the study area is easterly and toward the lower Colorado

River. In the outcrop area south of the Colorado River, the aquifer is recharged by Barton, Williamson, and Slaughter creeks.

- *Carrizo-Wilcox and Queen City Aquifers*: Water in the Carrizo-Wilcox and Queen City aquifers flows toward the lower Colorado River and the major tributaries of the river.
- *Sparta Aquifer*: Groundwater in the Sparta Aquifer moves easterly and toward the Colorado River and its major tributaries Pin Oak, Buckners, and Live Oak creeks.
- *Gulf Coast Aquifer System*: Generally, water in the Gulf Coast Aquifer flows southeasterly toward the Gulf and toward the lower Colorado River and its major tributaries. However, it appears that the regional groundwater flow pattern gradually changes from: (1) flow towards the lower Colorado River in central Colorado County, to (2) flow along and approximately parallel to the river in southern Colorado and northern Wharton counties, to (3) flow away from the Colorado River in central Wharton County upstream from the city of Wharton, to finally (4) flow back towards the river again in southern Wharton County. Groundwater pumping from rather closely spaced irrigation wells between the cities of El Campo and Wharton may have created a cone of depression that would cause water to move away from the Lower Colorado River Valley to the Gulf Coast Aquifer.

Figure 4-12 summarizes the findings of Woodward (1989) in a map that identifies the Colorado River from Lake Travis to Matagorda Bay as either a losing or gaining stream. All of the 318 miles in the Colorado River are mapped as gaining reaches, except for approximately 40 miles in the southwest region of Wharton County.

4.2.3 Hydraulic Properties

As a result of its bedload-fluvial deposition, the Colorado River alluvium consists primarily of sand with some gravel and cobbles and disconnect lenses or layers of silt and clay (Follett, 1970; Rogers, 1975; Hibbs and Sharp, 1993; Barnes, 1979). Across much of the alluvium and terrace deposits, and especially toward the base where bedload deposits of sands and gravels are preserved, the Colorado River alluvium is a highly transmissive aquifer.

Table 4-8 provides values for hydraulic properties of the Colorado River alluvium that were obtained from three field studies performed in Travis and Bastrop counties (Hibbs and Sharp, 1993; Gerecht and others, 2011; Francis and others, 2010). Hibbs and Sharp (1993) collected data to characterize and model stream bank storage. Gerecht and others (2011) collected data to characterize and model flow and heat transport in the hyporeic zone. Francis and others (2010) collected data to characterize and model the effects of dam operations on the hyporeic zone in a large fluvial island. The field data from these studies indicate that the average horizontal hydraulic conductivity of the alluvial deposits is likely 100 feet per day or greater (Table 4-8). In addition to characterizing the alluvium properties, Hibbs and Sharp (1993) and Gerecht and others (2011) characterize the hydraulic conductivity of the streambed though grain size analysis and modeling sensitivity analyses. Both studies concluded that the streambed was not impeding flow exchange between the stream and the aquifer.

Table 4-8. Summary of aquifer properties from surface water-groundwater studies on the Colorado River alluvium.

Source	Location	Aquifer Property
Gerecht and others (2011)	Hornsby Bend, Travis County	**Transmissive**: Horizontal hydraulic conductivity ranged from 33 to 164 feet per day from slug tests. Representative vertical hydraulic conductivity estimated at 50 feet per day. **Thermal:** Thermal conductivity ranged between 0.8 watts per meter-kelvin and 2.0 watts per meter-kelvin with average of 1.7 watts per meter-kelvin. Heat capacity ranged between 0.24 and 0.89 square millimeters per second with a mean of 0.61 square millimeters per second.
Francis and others (2010)	Hornsby Bend, Travis County	**Transmissive**: Average horizontal hydraulic conductivity of 150 feet per day based on grain size data. **Storage:** Average porosity of 38 percent.
Hibbs and Sharp (1993)	Near city of Webberville, Travis County	**Transmissive**: Average horizontal hydraulic conductivity values of 110, 95, and 135 feet per day from slug tests.
Hibbs and Sharp (1993)	Near city of Bastrop, Bastrop County	**Transmissive:** Average horizontal hydraulic conductivity values of 147, 173, and 104 feet per day from slug tests.

4.3 Water Quality Data

4.3.1 Surface Water Quality

Water quality data for the Colorado River are available for several stream gages from the United States Geological Survey and at several sites through the Colorado River Watch Network. The primary parameters available from the United States Geological Survey for gages on the Colorado River are temperature and specific conductance. Data are provided as daily values, current conditions, historical observations, and field/laboratory data. The largest dataset is available for daily values; however, those data are generally from the 1980s and 1990s, with few recent data.

A large variation in daily specific conductance is observed for the river from near the headwaters in Mitchell County to near the Gulf Coast in Wharton County (Figure 4-13). In the Upper Basin, the high salinity (frequently greater than 6,000 microsiemens per centimeter) is attributed to inflow from saline Beals Creek (Figure 4-14), seeps into the river related to oil and gas operations (abandoned wells, brine pits, disposal wells), and discharge of groundwater with high salinity due to dissolution of gypsum and pyrite (Scanlon and others, 2005). Two events resulted in the high specific conductance values of over 18,000 microsiemens per centimeter observed in mid-1988 (Slade and Buszka, 1994). First, full reservoirs precluded the usual diversion of low flows with high total dissolved solids concentrations during 1986 and 1987 resulting in highly saline flow entering the Colorado River from tributaries. Second, overflow of Natural Dam Lake on the Beals Creek tributary from September 1986 to August 1988 resulted in 3.5 times more loading of dissolved solids than typical into the river (Slade and Buszka, 1994). Originally a natural lake, a dam was constructed in 1989 to increase the capacity of Natural Dam Lake and for flood control (Texas Almanac, 2017).

Intermediate specific conductance values are observed at gages in the Lake Buchanan Basin. The data for gages 08136700 and 0814700 in this basin show higher values (typically greater than 2,000 microsiemens per centimeter) with a wider range prior to about mid-1990 and values less than 2,000 microsiemens per centimeter since that time. For gage 0814700 with values less than 1,000 microsiemens per centimeter, the lower values are a result of impoundment of O.H. Ivie Reservoir in 1990 (see Figure 4-14). The overflow of Natural Dam Lake also resulted in an increase in salinity at these two gages in mid-1988 (see Figure 4-15). Specific conductance values are lowest (consistently less than 1,000 microsiemens per centimeter) at gages located in the Lower and Matagorda Bay basins.

For the three United States Geological Survey gages below the Highland Lakes, the trend in specific conductance is very similar over the period of record (Figure 4-15). Short-term decreases in values are infrequent and small in magnitude at the Austin gage due to the diluting influence of reservoir releases on overall salinity at this gage. Decreases are slightly larger at the Bastrop gage and significantly larger at the Wharton gage. These short-term decreases are associated with freshwater runoff during rainfall events that act to dilute the salts in the river. The increase in the magnitude of observed fluctuations in specific conductance between the Austin and Wharton gages indicates that reservoir releases have less impact and storm runoff has greater impact on surface water salinity with increasing distance from the Highland Lakes. These data indicate that flooding and reservoir operations impact the salinity of the river.

The increase in specific conductance from 1987 to 1991 at the Austin, Bastrop, and Wharton gages (see Figure 4-15) is also the result of the increased dissolved solids load in the Upper Basin due to the reduction in diversion and overtopping of Natural Dam Lake. The increase was not as significant at these gages as it was at the gages above Austin due to dilution in the Highland Lakes. A 50-year flood event in 1992 flushed the Highland Lakes, which resulted in a significant reduction in specific conductance in 1992 (Hibbs and Sharp, 1993). These data indicate that the river is a very dynamic system affected by reservoir operations and climatic conditions.

The Colorado River Watch Network is a community-based network of volunteers who monitor water quality in the Colorado River approximately monthly. The Lower Colorado River Authority provides the volunteers with information, resources, and training, and the volunteers submit water quality data that provides early warning of potential water quality threats to the Lower Colorado River Authority. The water quality data for the Colorado River provided through the Colorado River Watch Network are available online (Lower Colorado River Authority, 2017b) for 17 sites in the Lower and Matagorda Bay basins (Figure 4-16 and Table 4-9). Sites are also monitored in the Lake Lyndon B. Johnson, Lake Travis, and Austin basins, but those data were not reviewed for this study. The monitored parameters are listed in Table 4-10

Table 4-9. Colorado River Watch Network surface water monitoring stations in the Lower and Matagorda Bay basins with online data.

Site Number	Site Name	First Year of Data	Last Year of Data	Count of Data
375	Colorado River at Little Webberville	2009	2017	58
379	Colorado River at Webberville	2009	2017	39
343	Colorado River at 969 Bridge Utley	2005	2017	117
337	CR at Bob Bryant Park Bastrop	2005	2017	132
53	CR at Fisherman's Park Bastrop	1995	2017	276
372	CR at Lost Pines Nature Trails	2009	2017	0
246	CR at Bus Hwy 71 LaGrange	2000	2017	170
210	CR at Brandt River Bottom Rd.	1998	2017	79
338	CR at Howell Canoe Columbus	2014	2017	0
59	CR at Beason's Park Columbus	1995	2017	217
60	CR at Riverfront Park Wharton	1996	2016	125
221	CR at Hwy 35 Bay City	2001	2017	39
395	CR at MBNC Bay City	2011	2017	0
304	CR at Riverside Park Bay City	2003	2014	0
312	CR at Hwy 521 LCRA Park	2003	2006	0
410	CR at Matagorda	2013	2014	0
360	CR at Matagorda Nature Center	2008	2017	0

Note: CR = Colorado River; Hwy = highway; Rd = road; MBNC = Matagorda Birding and Nature Center; LCRA = Lower Colorado River Authority

Table 4-10. Parameters monitored by the Colorado River Watch Network.

Monitored Parameter
Air Temp (degrees Celsius)
Water Temp (degrees Celsius)
Flow (cubic feet per second)
pH
Nitrates-N (milligrams per liter)
Dissolved Oxygen Average (milligrams per liter)
Dissolved Oxygen Percent Saturation
Specific Conductance (microsiemens per centimeter)
Days Since Rain
Field Rain Gage (inches.)
Secchi (meters)
Transparency (meters)
E.coli (colony forming units)

Water temperature and specific conductance for several of the gages are shown in Figure 4-17 and Figure 4-18, respectively. Water temperature varies over a fairly large range from about 10 degrees Celsius (50 degrees Fahrenheit) in the winter to about 30 degrees Celsius (86 degrees Fahrenheit) in the summer. Generally, specific conductance ranges between about 300 and 800 microsiemens per centimeter (see Figure 4-18). The reduction in specific conductance caused by rainfall runoff is greater for Sites 338 and 59 in Colorado County and Site 60 in Wharton County than for Sites 337, 53, and 372 in Bastrop County. For both temperature and specific conductance, data are very consistent between nearby gages.

Figure 4-19 shows consistency between the specific conductance from the United States Geological Survey gages in Bastrop and Wharton counties and nearby Colorado River Watch Network Sites 53 and 60, respectively (see Figure 4-15 for gage locations). Although greater detail is provided by the daily United States Geological Survey data, the fluctuations in specific capacity appear to be adequately captured by the approximately monthly data from the Colorado River Watch Network.

The nitrate concentrations from the Colorado River Watch Network data were reviewed and found to range from about 1 to 15 milligrams per liter for the sites in the Lower and Matagorda Bay basins, with the higher values observed at the sites where the river crosses the Carrizo-Wilcox Aquifer outcrop and the lower values observed at sites where the river crosses the Gulf Coast Aquifer outcrop.

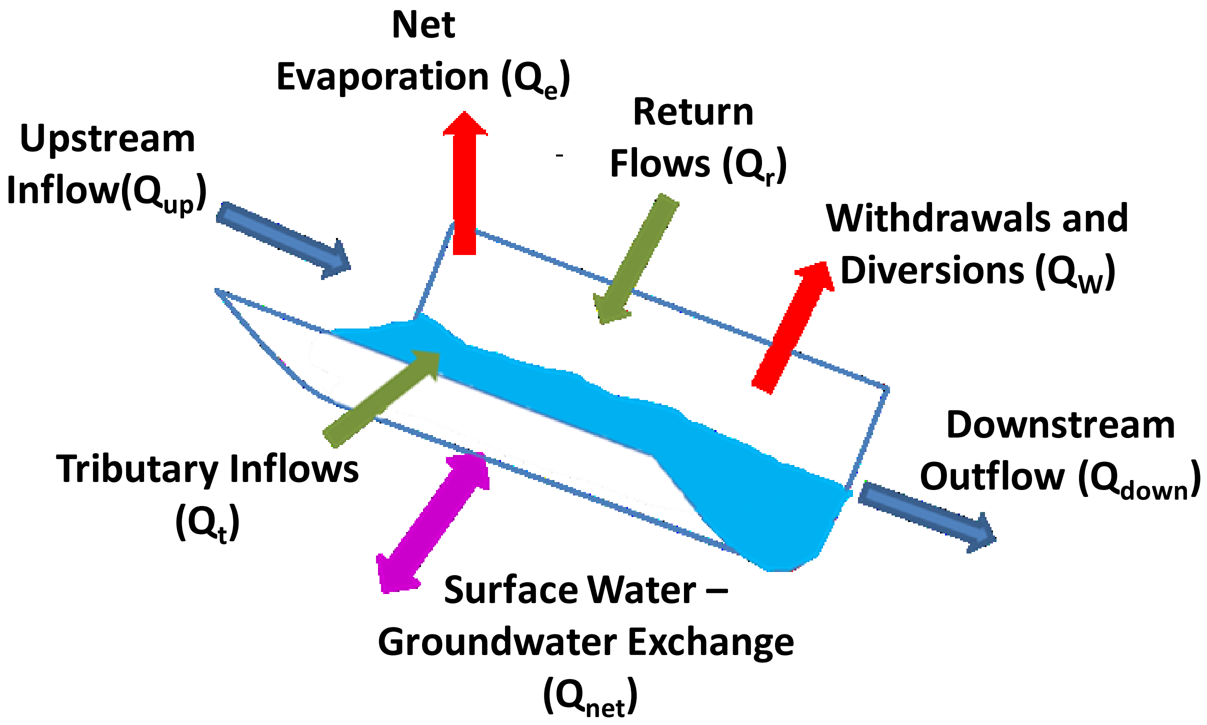
4.3.2 Groundwater Quality

Groundwater quality data in the TWDB Groundwater database are available for 43 alluvium wells located in the Lower Basin and the very northern portion of the Matagorda Bay Basin. The groundwater samples were collected between 1942 and 1989. For the vast majority of the wells, only one sample was collected and analyzed, and the maximum number of samples for any well was four. The average specific conductance for the groundwater samples ranges from 582 to

2,920 microsiemens per centimeter. A review of the data does not indicate any spatial or temporal trend (Figure 4-20). In the four wells with more than two measurements, the specific conductance increases with time in three of the wells but, due to the paucity of data and absence of recent data, a conclusion regarding trends for samples from a single well cannot be drawn.

Daily and seasonal fluctuations in groundwater temperature are relatively small compared to those in surface water, with the average temperature of shallow groundwater approximating the mean annual air temperature (Barlow and Leake, 2012). The nearly constant temperature of groundwater discharging to streams acts to regulate stream temperatures, by increasing the stream temperature in the winter and decreasing the stream temperature in the summer. Changes to groundwater discharge as a result of pumping can result in temperature changes in streams, which may impact aquatic life. Pumping may also result in changes to the groundwater temperature if the stream begins to recharge the aquifer as a result of the pumping. Based on a climate study for the years 1985 to 2003, Garbrecht and Schneider (2005) indicate that the mean annual temperature during that time period for south central Texas was about 69 degrees Fahrenheit (20.5 degrees Celsius). The groundwater in the Colorado River alluvium is expected to have a similar temperature.

Low concentrations of nitrate naturally occur in groundwater. A study of nitrate in rural wells conducted by the Environmental Protection Agency found that the concentration exceeded the maximum contaminate level of 10 milligrams per liter in only a few wells (Mahler and others, 2007). This suggests that the concentration of naturally occurring nitrate in groundwater is less than 10 milligrams per liter. Agricultural activities such as feedlots and nitrogen rich fertilizer application can increase groundwater nitrate concentrations. The water quality data for the wells completed in the Colorado River alluvium indicate nitrate concentrations ranging from about 0.5 to 700 milligrams per liter. The overall average concentration for all wells is 59 milligrams per liter. There is no spatial trend in the concentration but, in general, the highest values are observed in Fayette County.



Equation to Determine Whether Stream is Gaining or Losing

$$Q_{net} = Q_{up} + Q_t + Q_r - Q_{down} - Q_w - Q_e$$

$$Q_{net} = Q_{inflow} - Q_{outflow}$$

Positive Q_{net} (inflow > outflow) → Stream is Losing

Negative Q_{net} (outflow > inflow) → Stream is Gaining

Figure 4-1. **Water budget components and calculation used for a stream gain/loss study (equation from Slade and Buszka, 1994; Slade and others, 2002).**

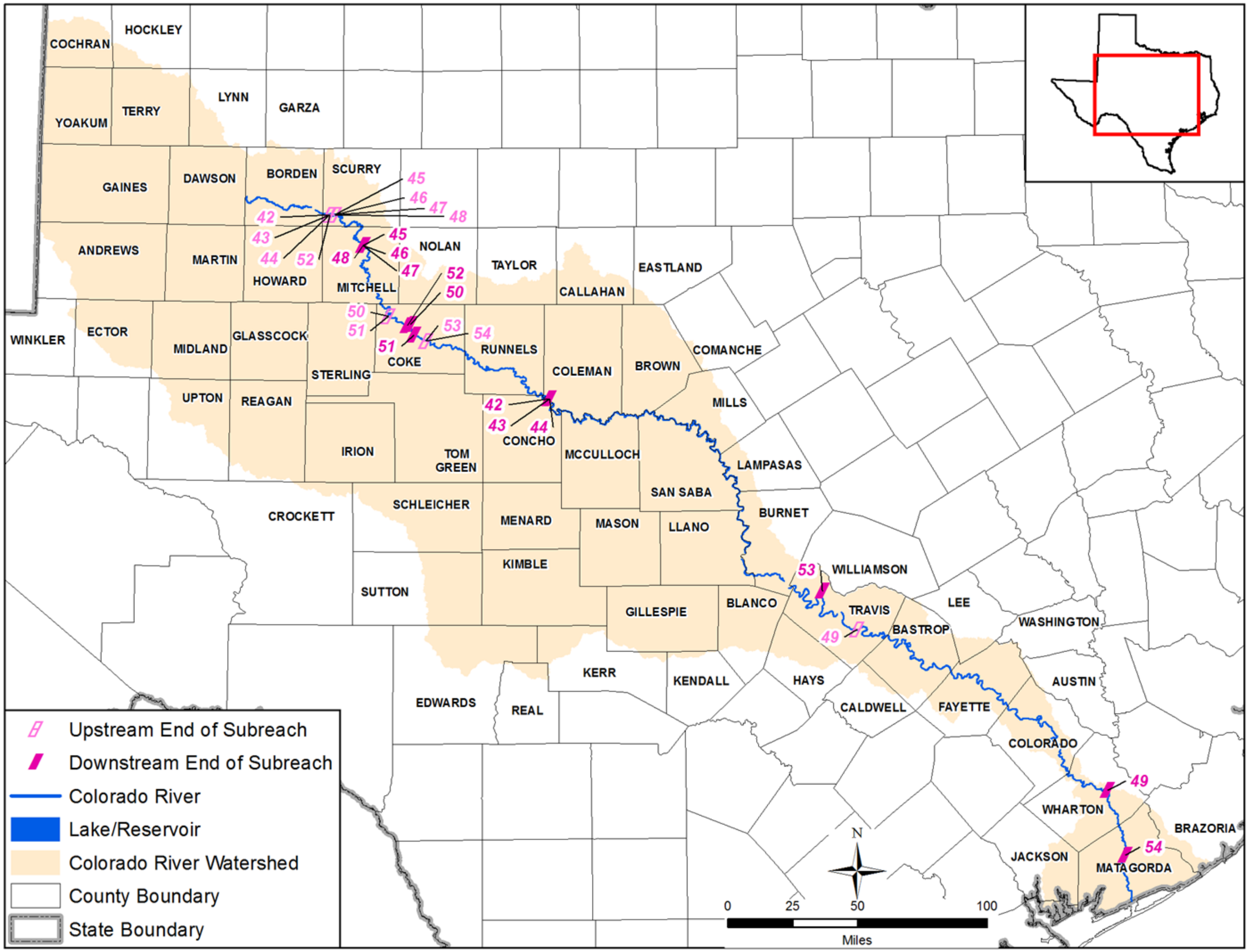


Figure 4-2. Upstream and downstream location for stream gain/loss studies reported by Slade and others (2002) for the Colorado River.

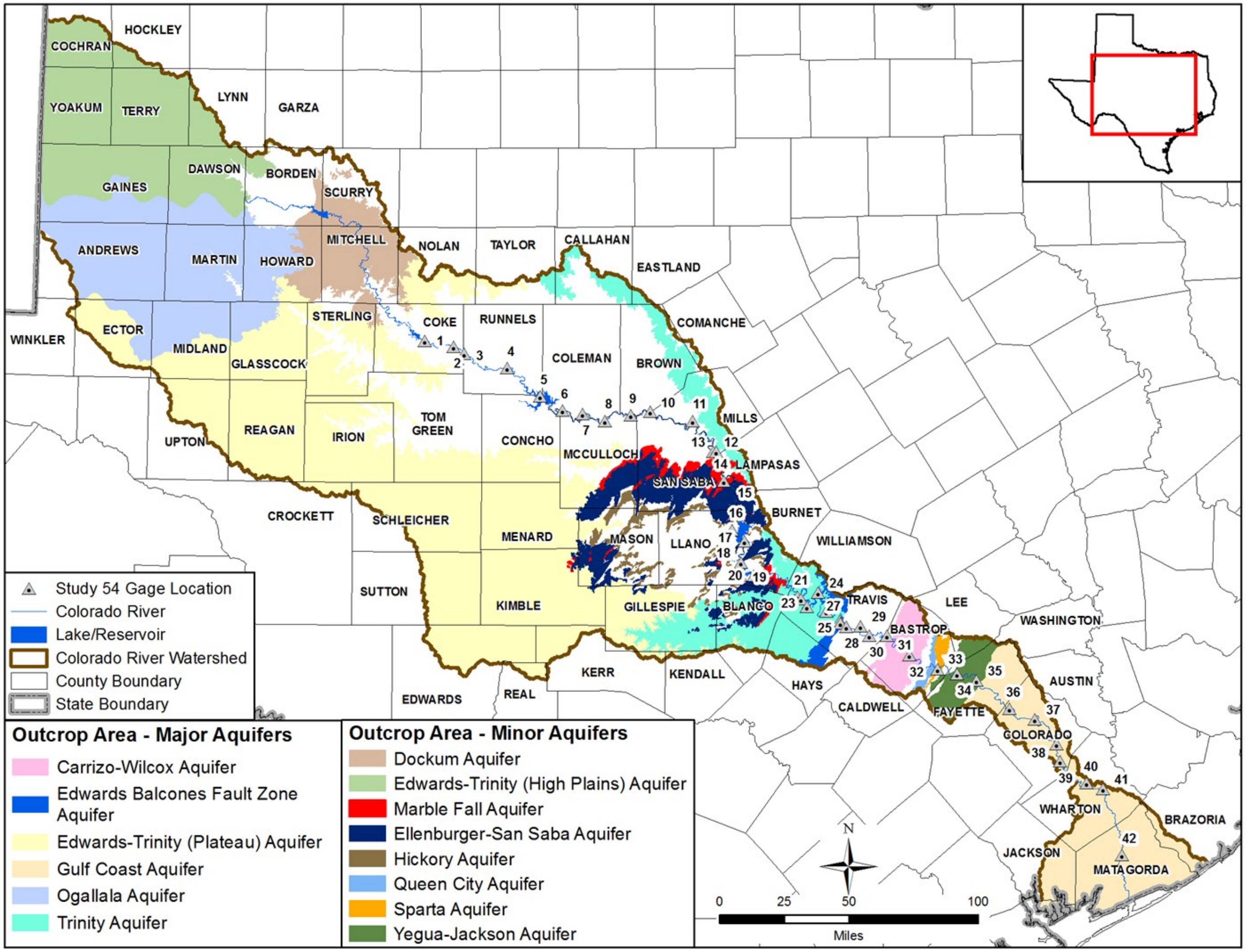


Figure 4-3. **The stream reaches from Coke to Matagorda counties for which the gain/loss were calculated as part of Study 54 reported by Slade and others (2002).**

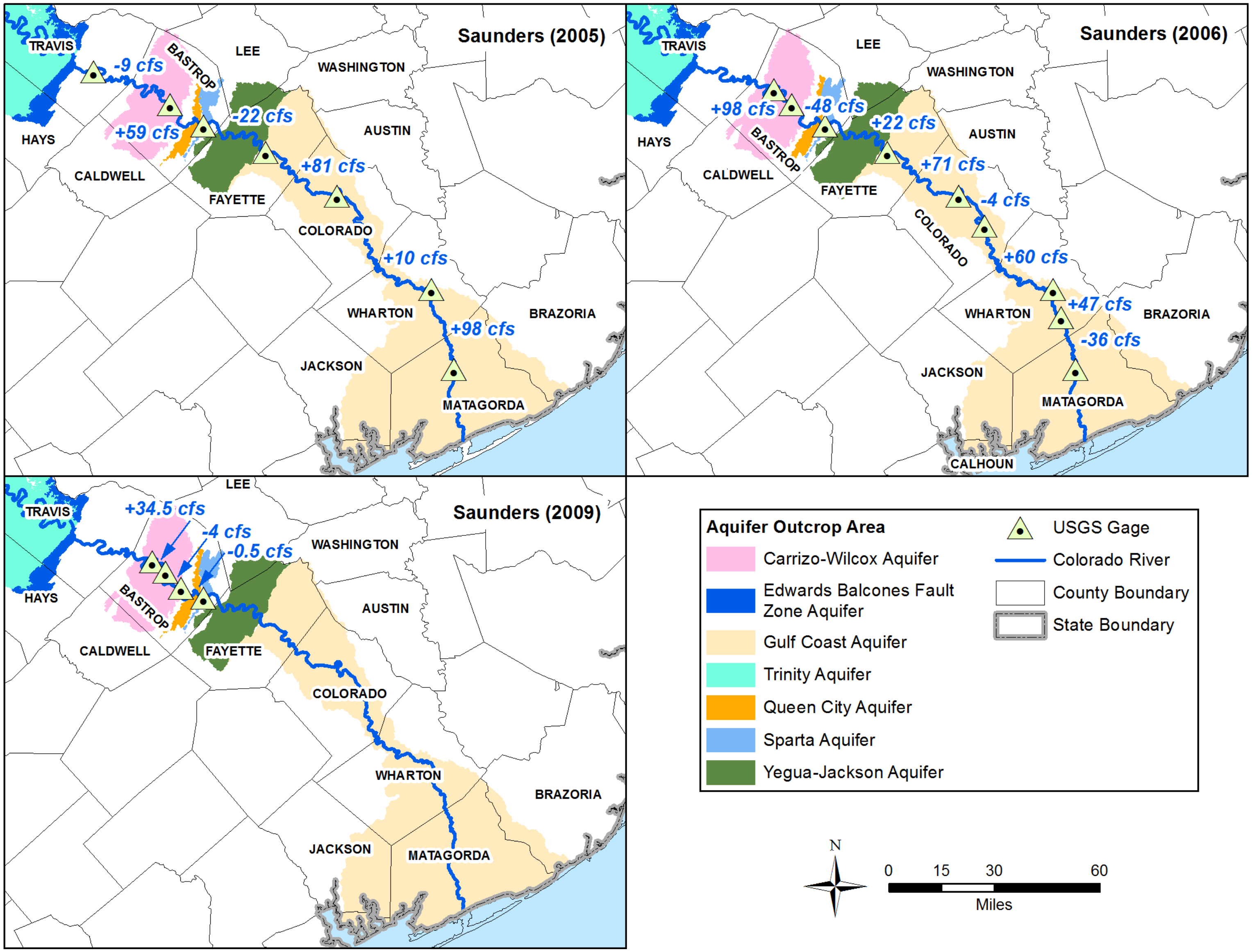


Figure 4-4. **Stream gain/loss determined for the lower Colorado River using data from November 1999 (Saunders, 2005) (top left), November 2005 (Saunders, 2006) (top right), and November 2008 (Saunders, 2009) (bottom left).**

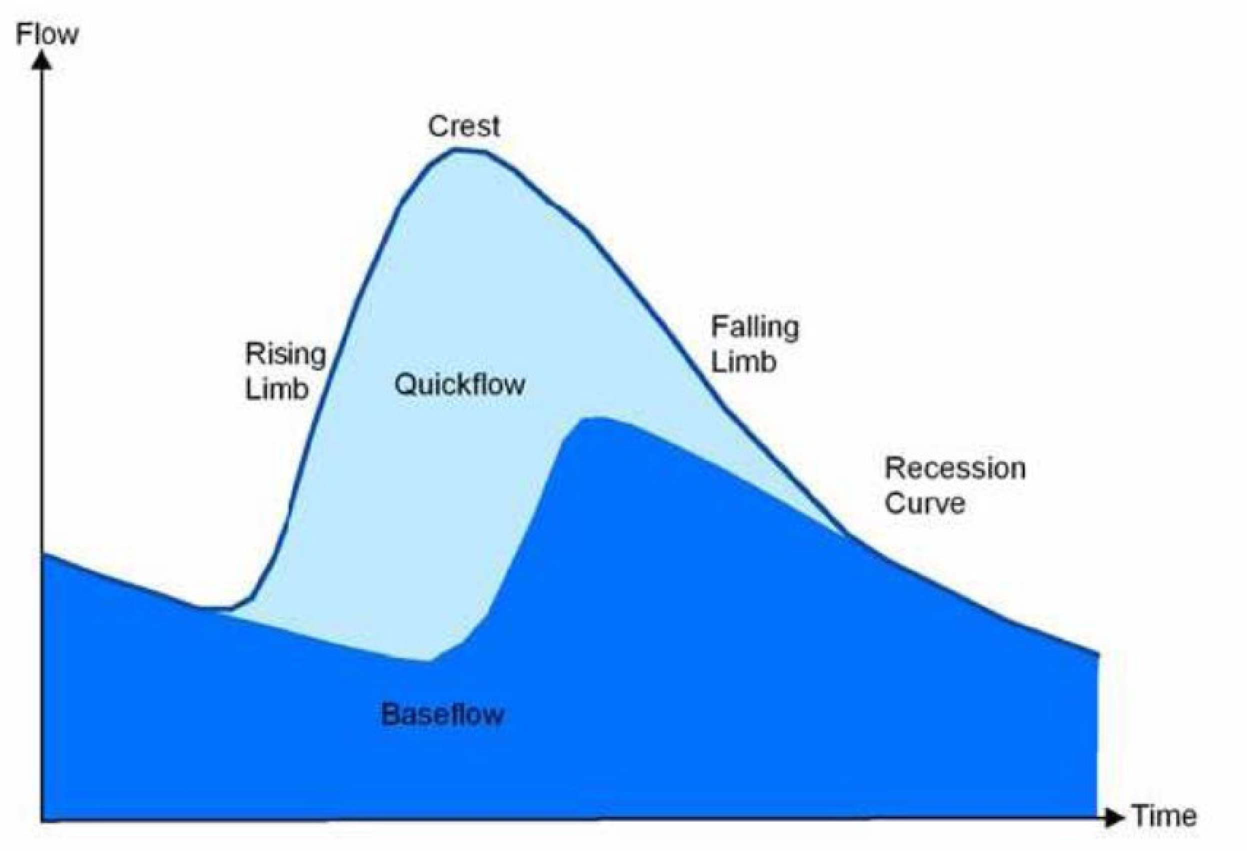


Figure 4-5. Flow components of a typical streamflow hydrograph (from Brodie and others, 2005).

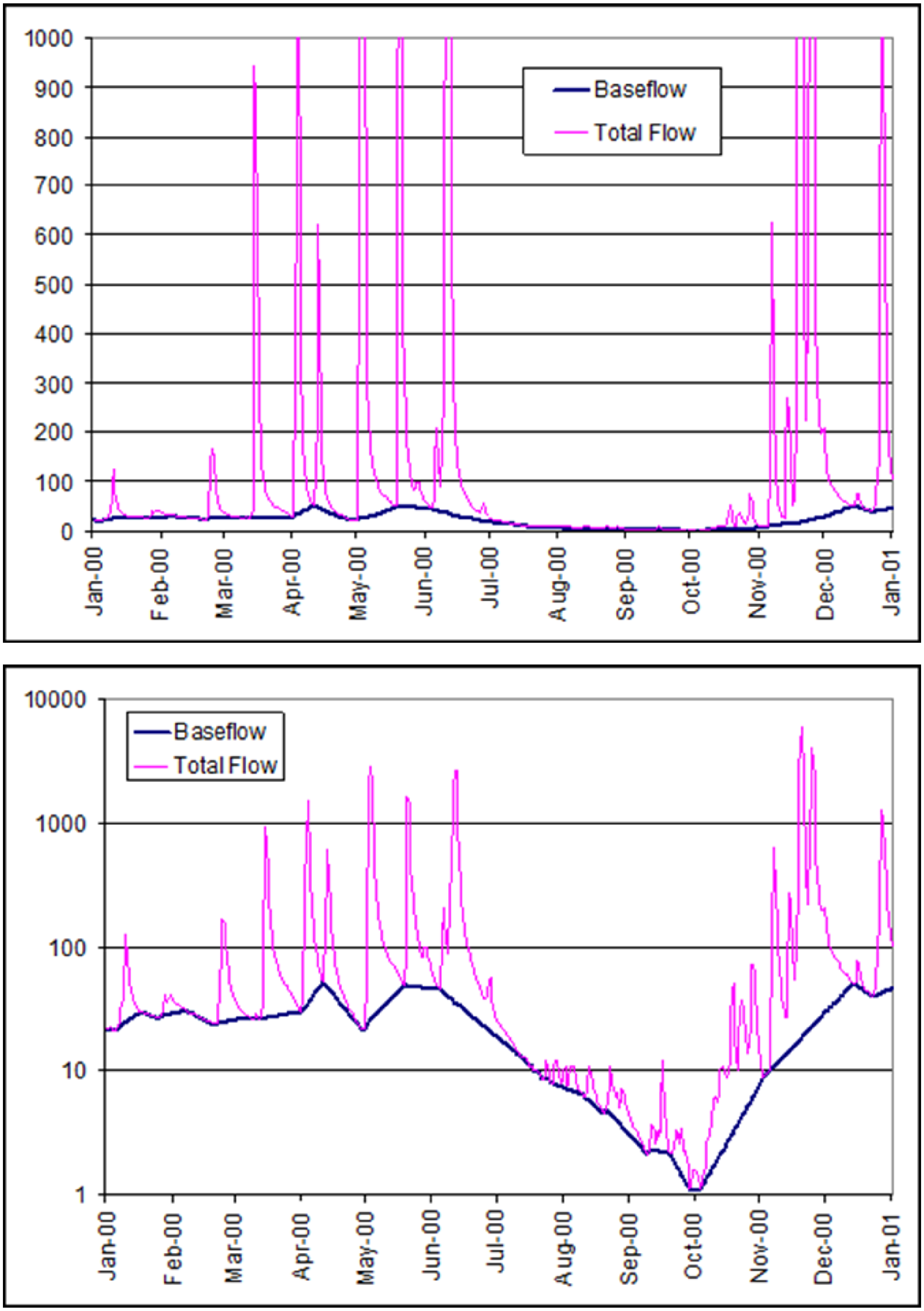


Figure 4-6. **Example application of the Base Flow Index program (Wahl and Wahl, 1995) from gage 08164000 in the Lavaca River Basin for year 2000 with a linear (upper plot) and log (bottom plot) y-axis (from Young and Kelley, 2006). Unit of flow on the y-axis is cubic feet per second (cfs).**

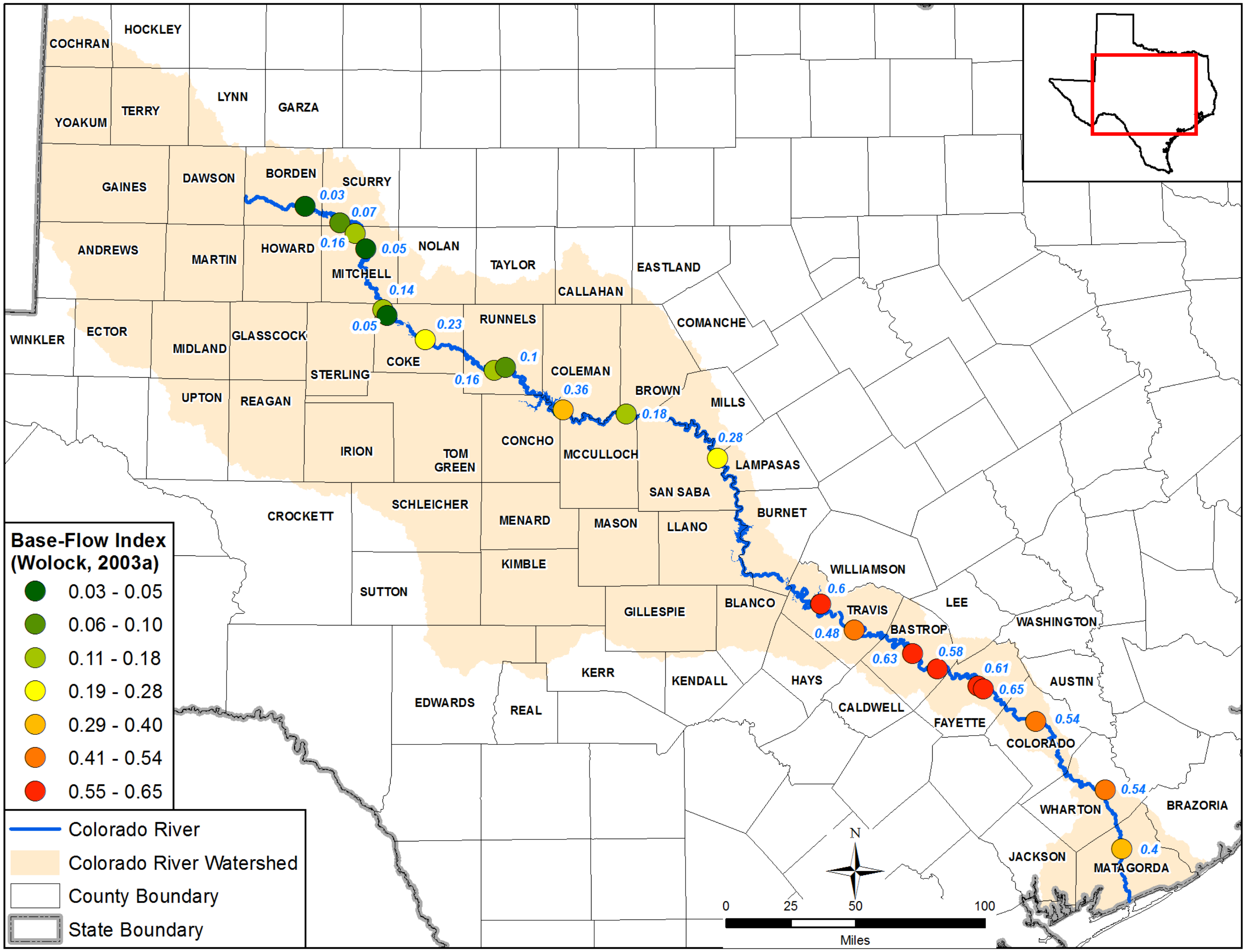


Figure 4-7. **Base-flow index from Wolock (2003a) for stream gages on the Colorado River.**

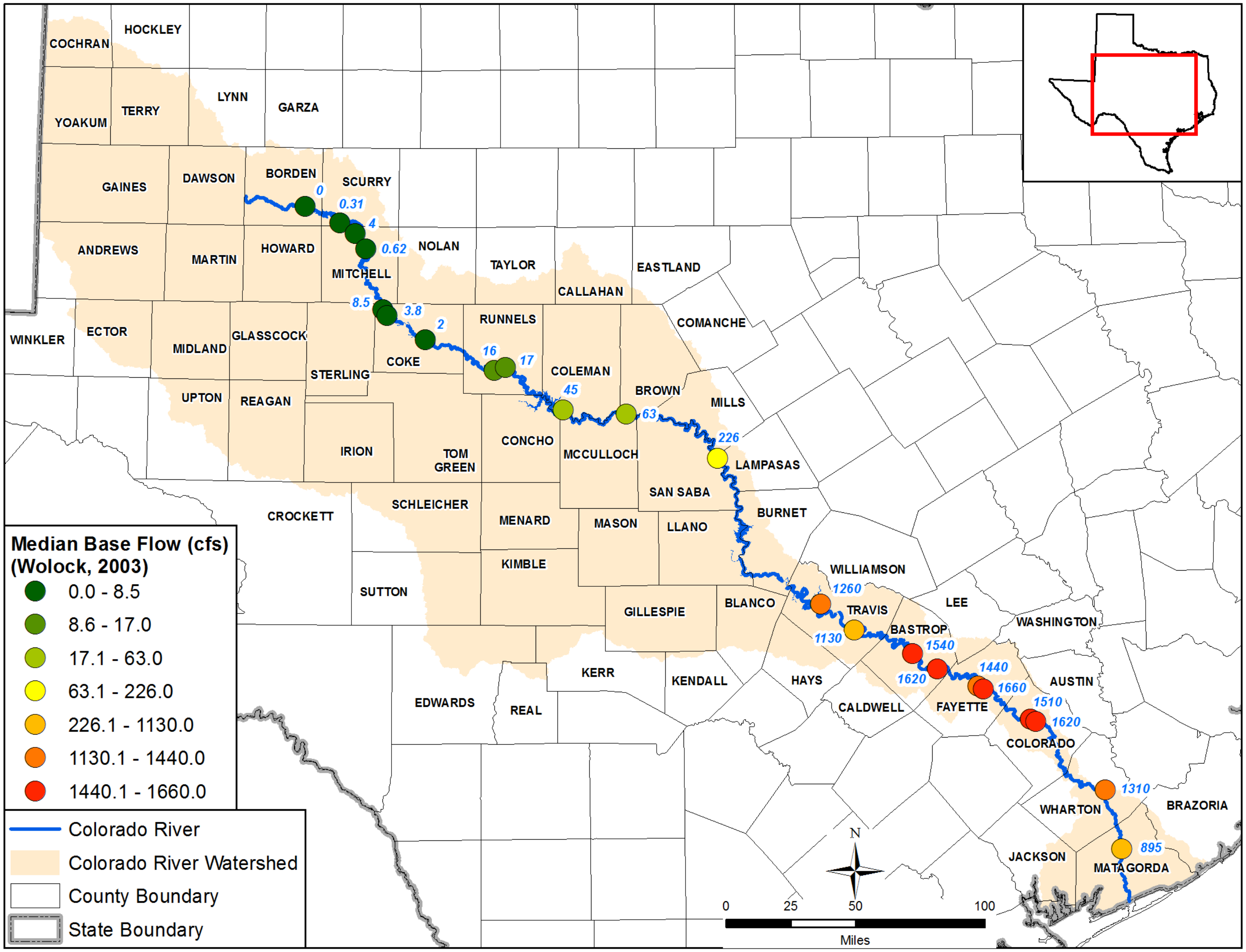


Figure 4-8. **Median base flow from Wolock (2003a) for stream gages on the Colorado River.**

Note: cfs = cubic feet per second

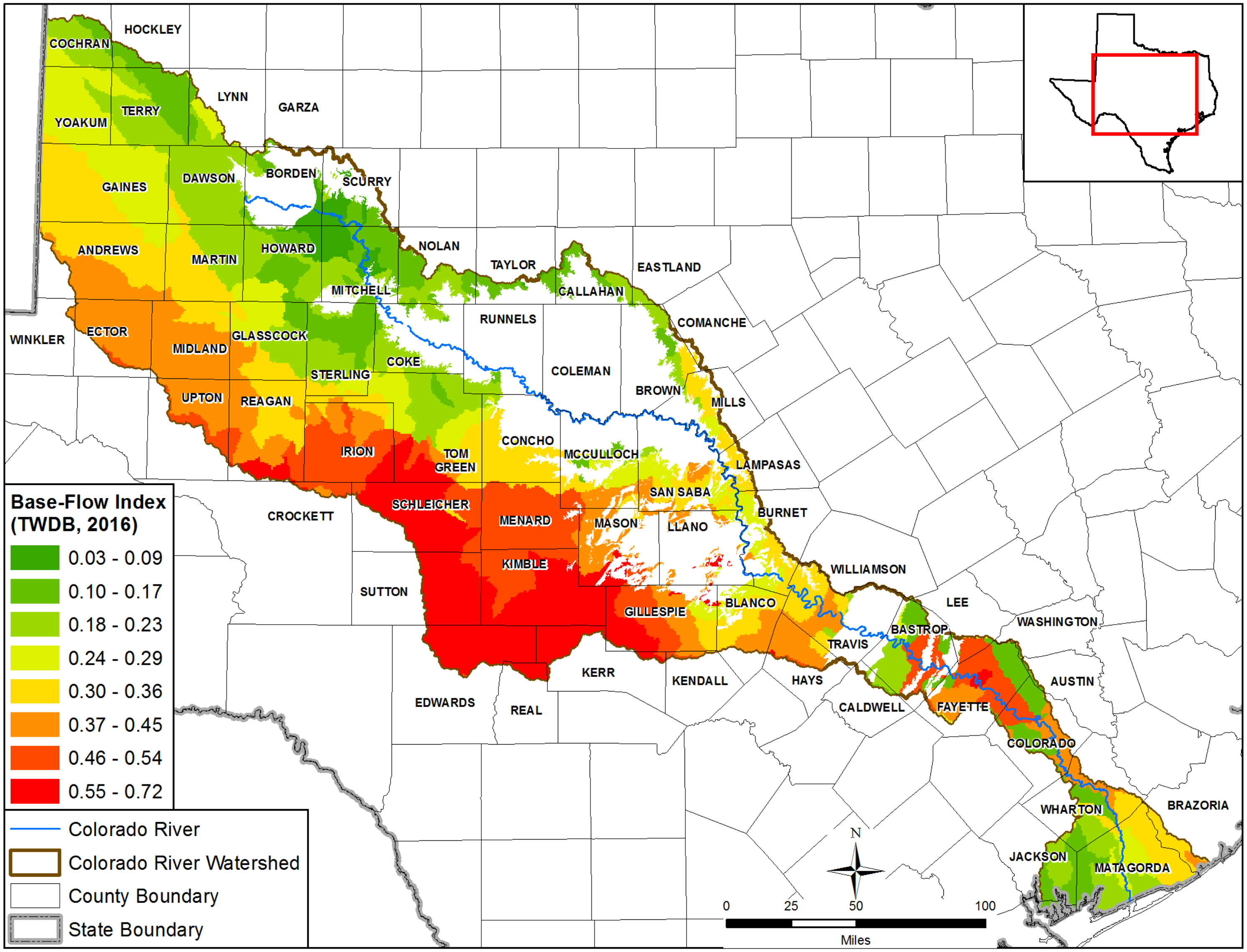


Figure 4-9. **Estimated base-flow index from major and minor aquifer outcrops in the Colorado River Basin as determined by TWDB (2016) using base-flow index values and hydrologic landscape regions from Wolock (2003a, b) and Wolock and others (2004).**

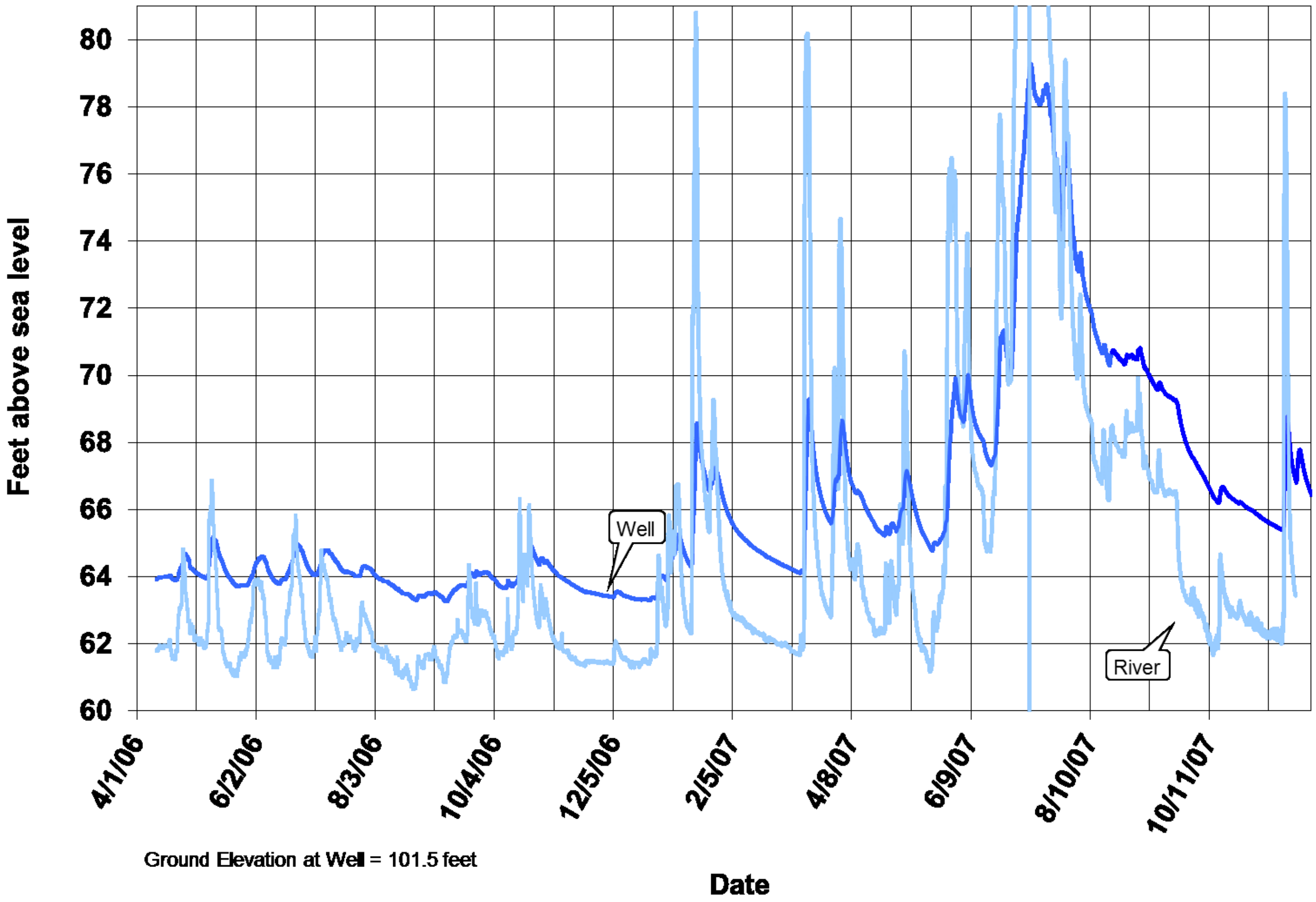


Figure 4-10. Data from the Wharton monitoring well and stream gage 08162000 at Wharton from April 11, 2006 to December 3, 2007 (from URS and Baer Engineering, 2007).

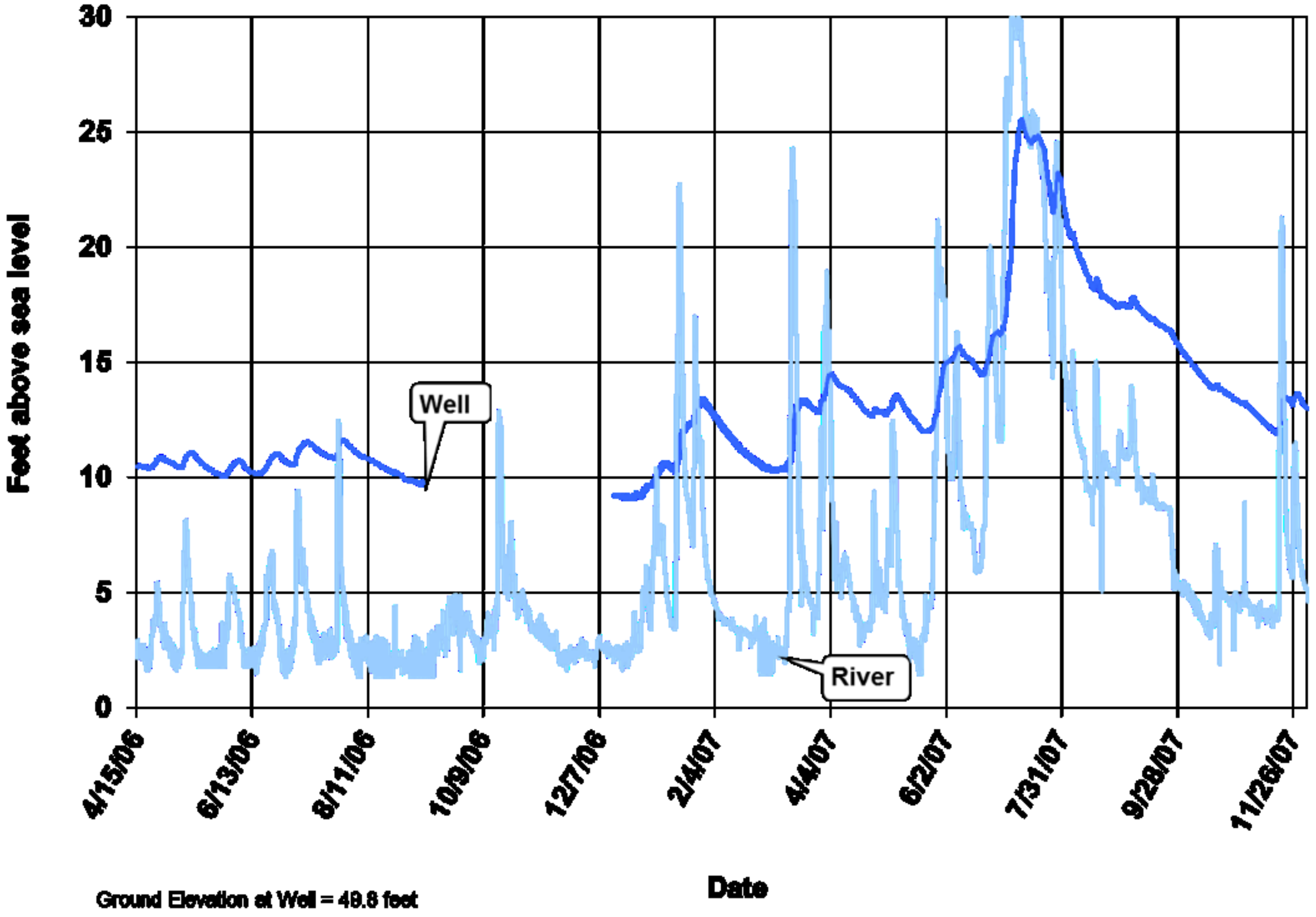


Figure 4-11. **Data from the Bay City monitoring well and streamflow gage 08162500 near Bay City from April 11, 2006 to December 3, 2007 (from URS and Baer Engineering, 2007).**

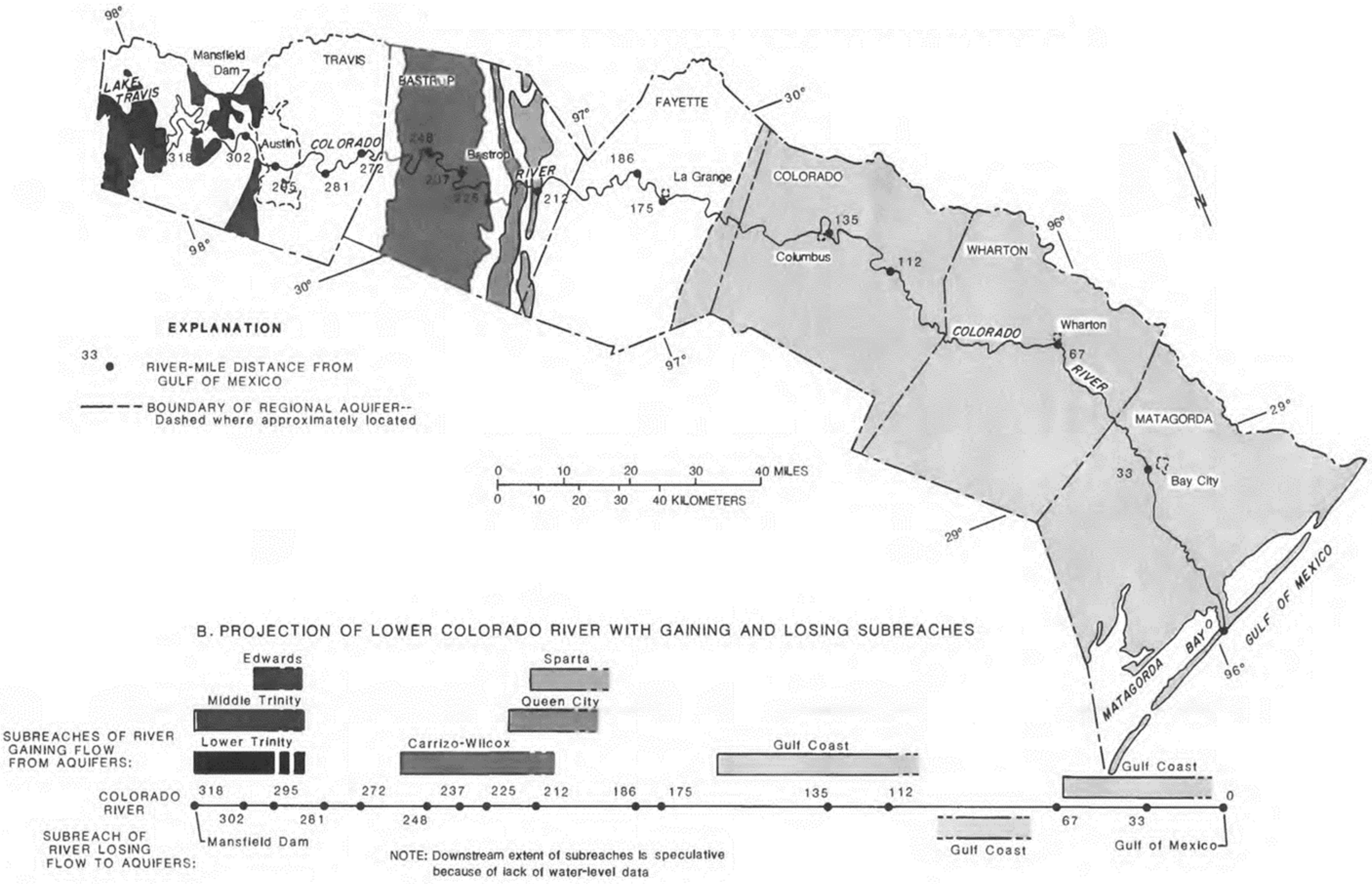


Figure 4-12. **Location of gaining and losing stream reaches along the Colorado River based on contours of water level developed using data from 1970 to 1985 and from regional aquifers in the lower Colorado River Basin (from Woodward, 1989).**

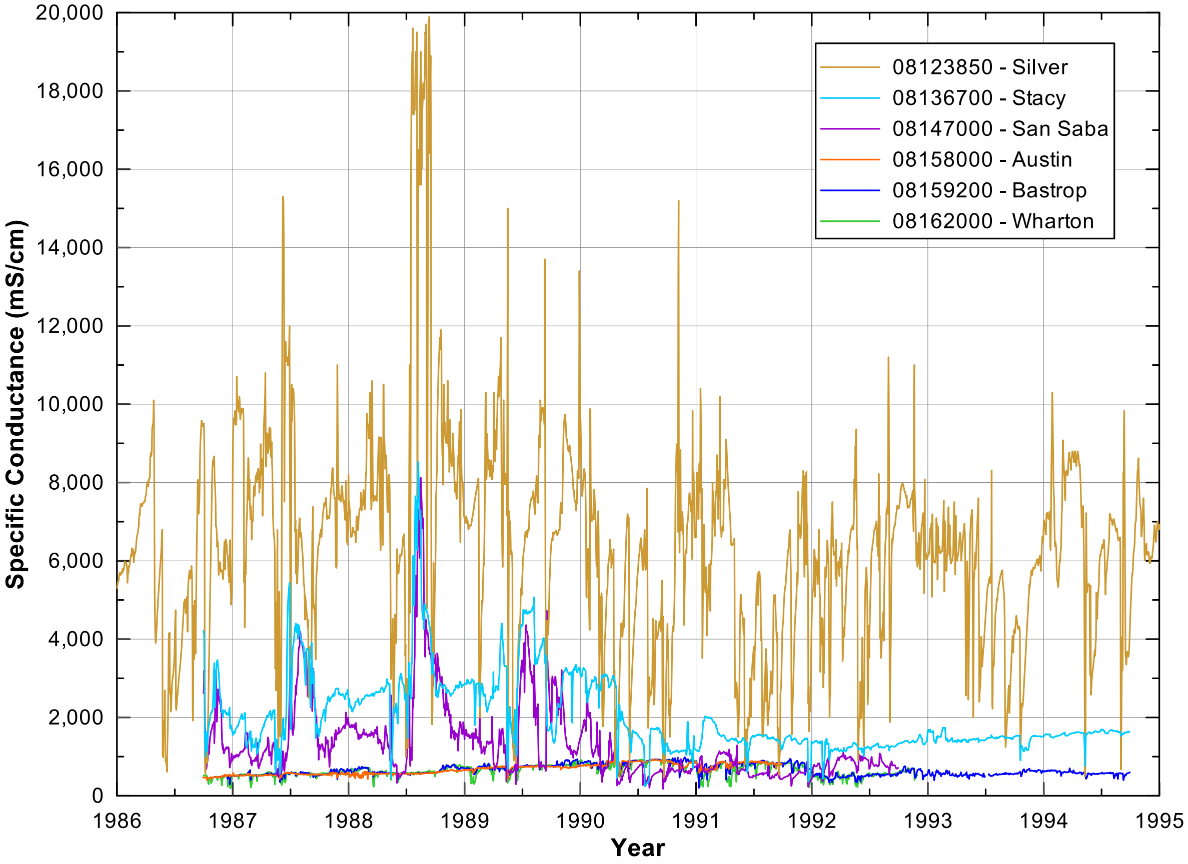


Figure 4-13. **Specific conductance at select United States Geological Survey gages on the Colorado River (United States Geological Survey, 2017a).**

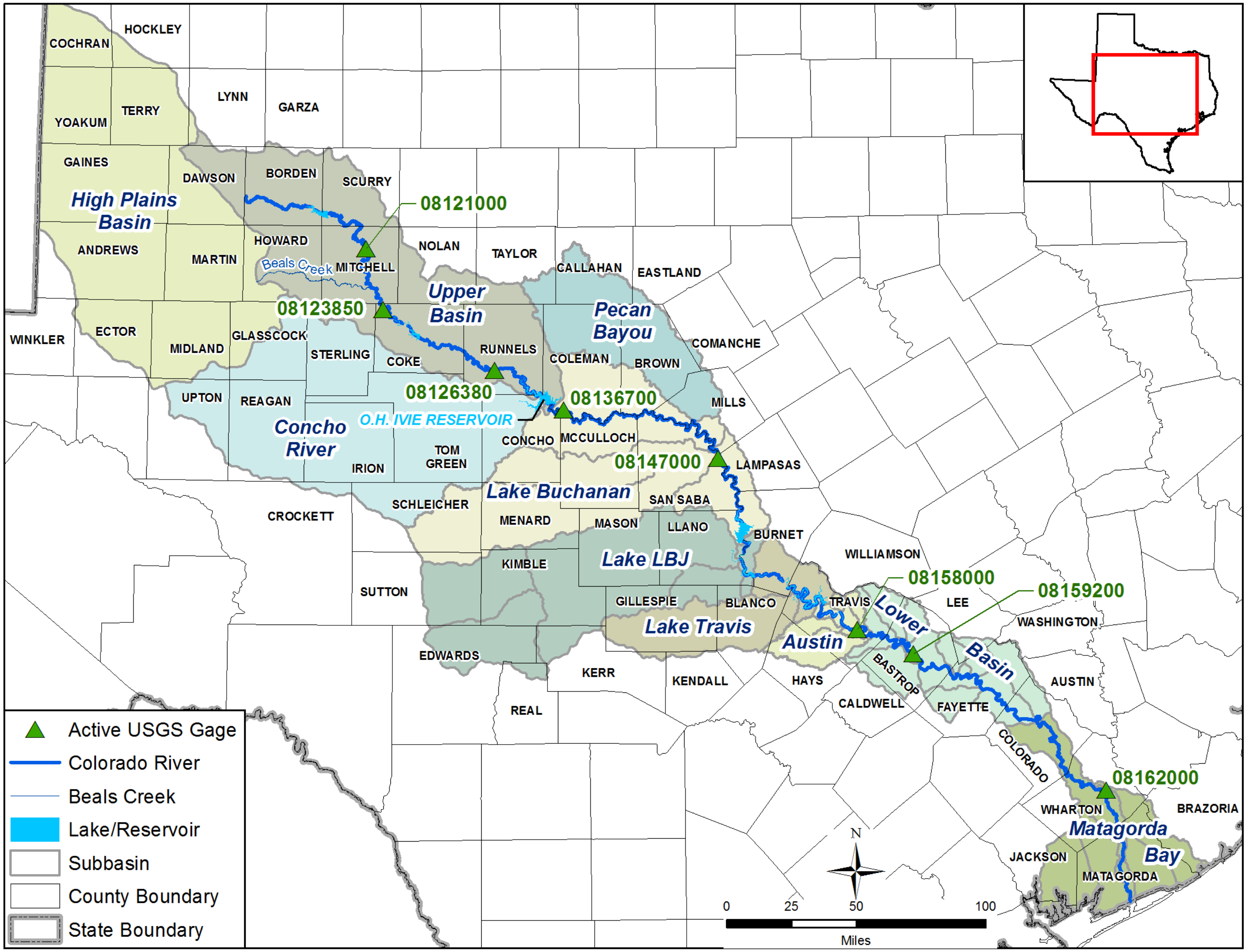


Figure 4-14. Location of select surface water features discussed in relationship to the specific conductance of water in the Colorado River.

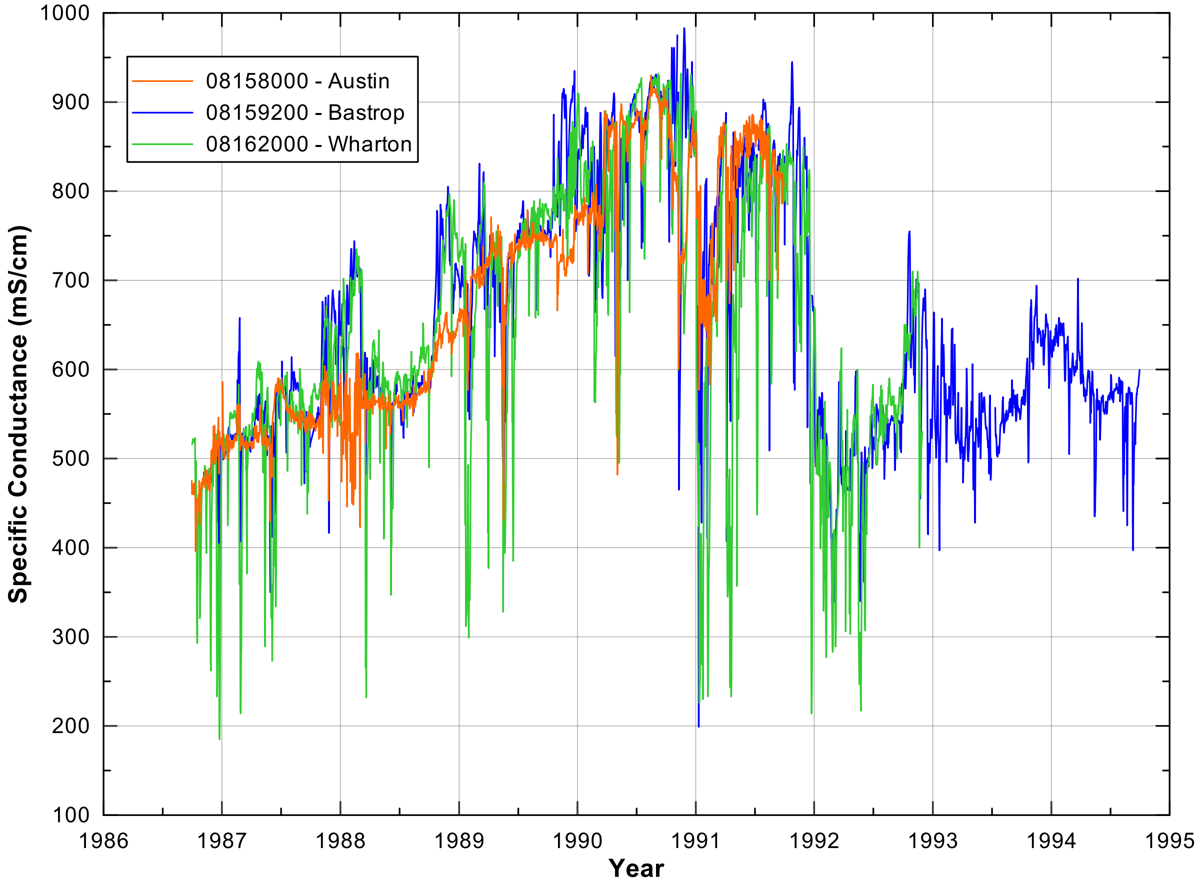


Figure 4-15. **Specific conductance for United States Geological Survey gages in the Lower and Matagorda Bay basins (United States Geological Survey, 2017a).**

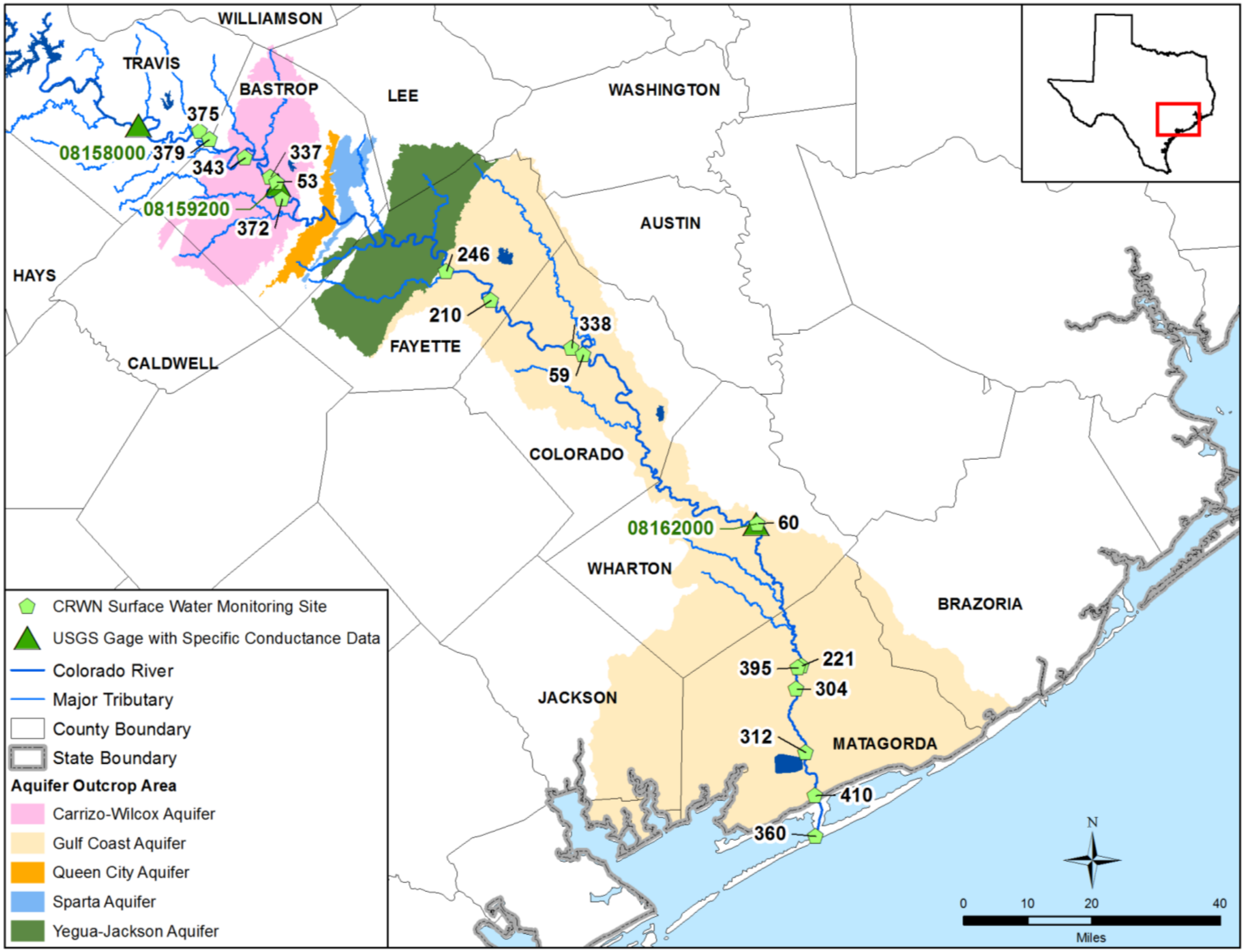


Figure 4-16. **Colorado River Watch Network (CRWN) surface water monitoring sites on the Colorado River in the Lower and Matagorda Bay basins.**

Note: USGS = United States Geological Survey

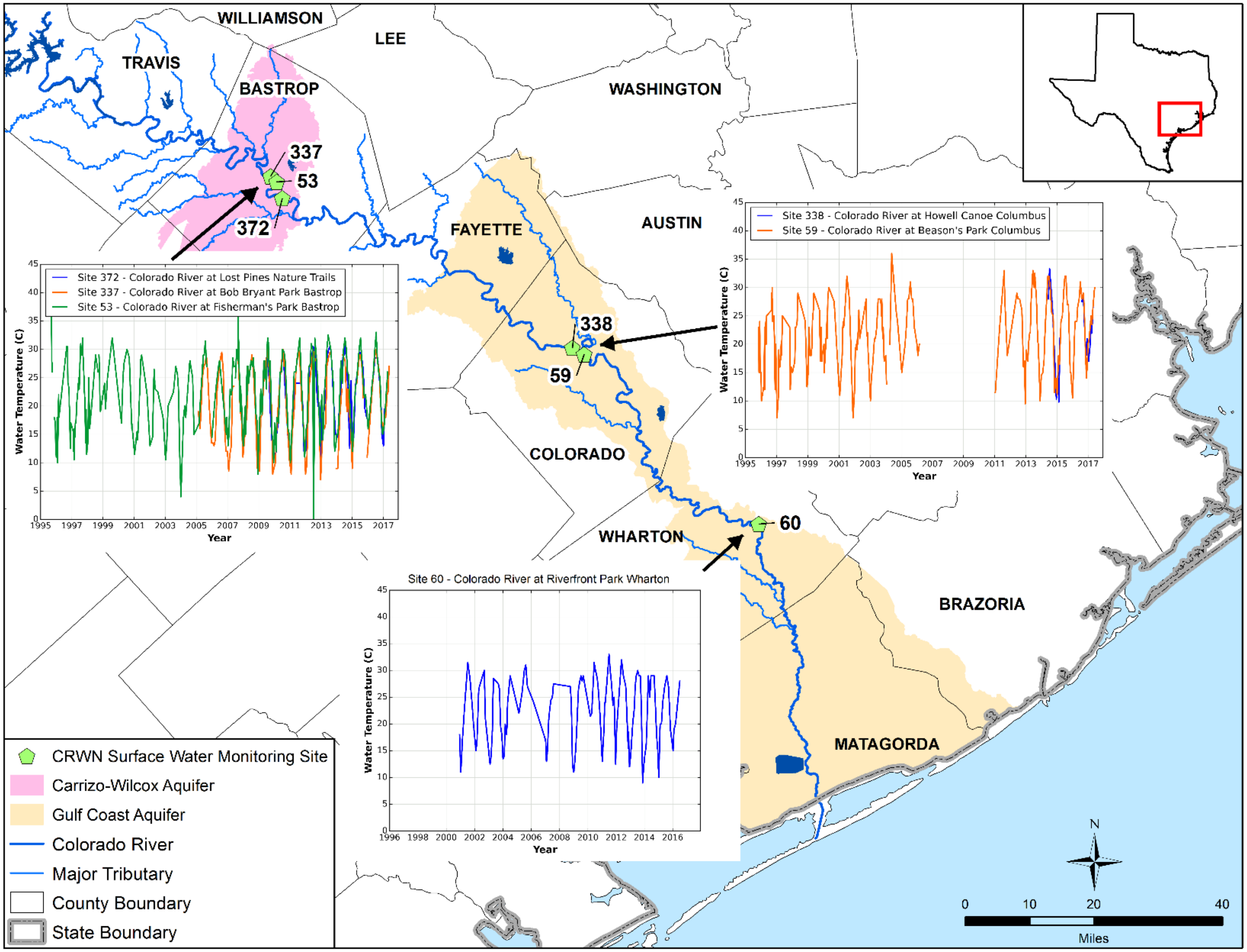


Figure 4-17. Water temperature in degrees Celsius for select Colorado River Watch Network (CRWN) sites (Lower Colorado River Authority, 2017b).

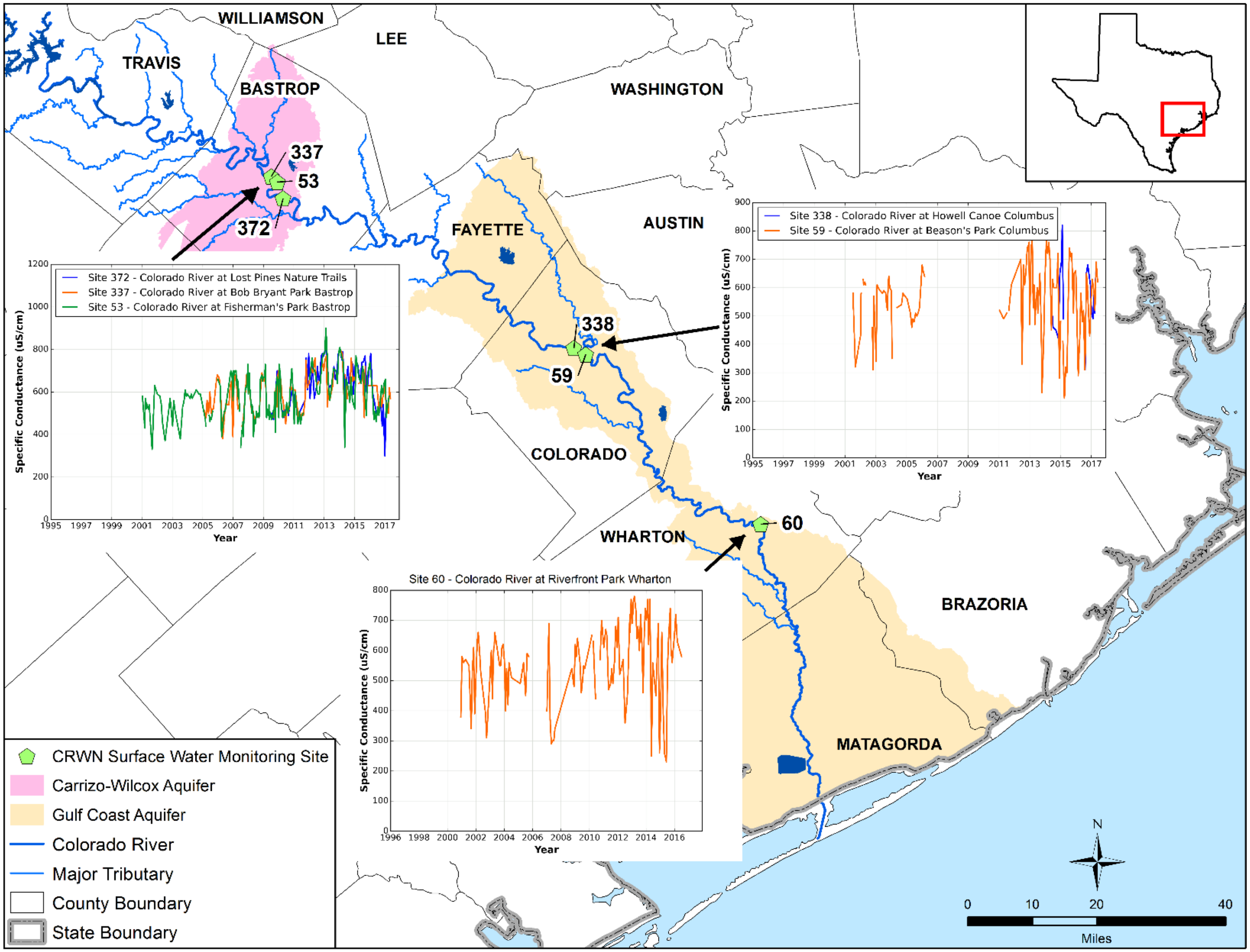


Figure 4-18. **Water specific conductance in microsiemens per centimeter for select Colorado River Watch Network (CRWN) sites (Lower Colorado River Authority, 2017b).**

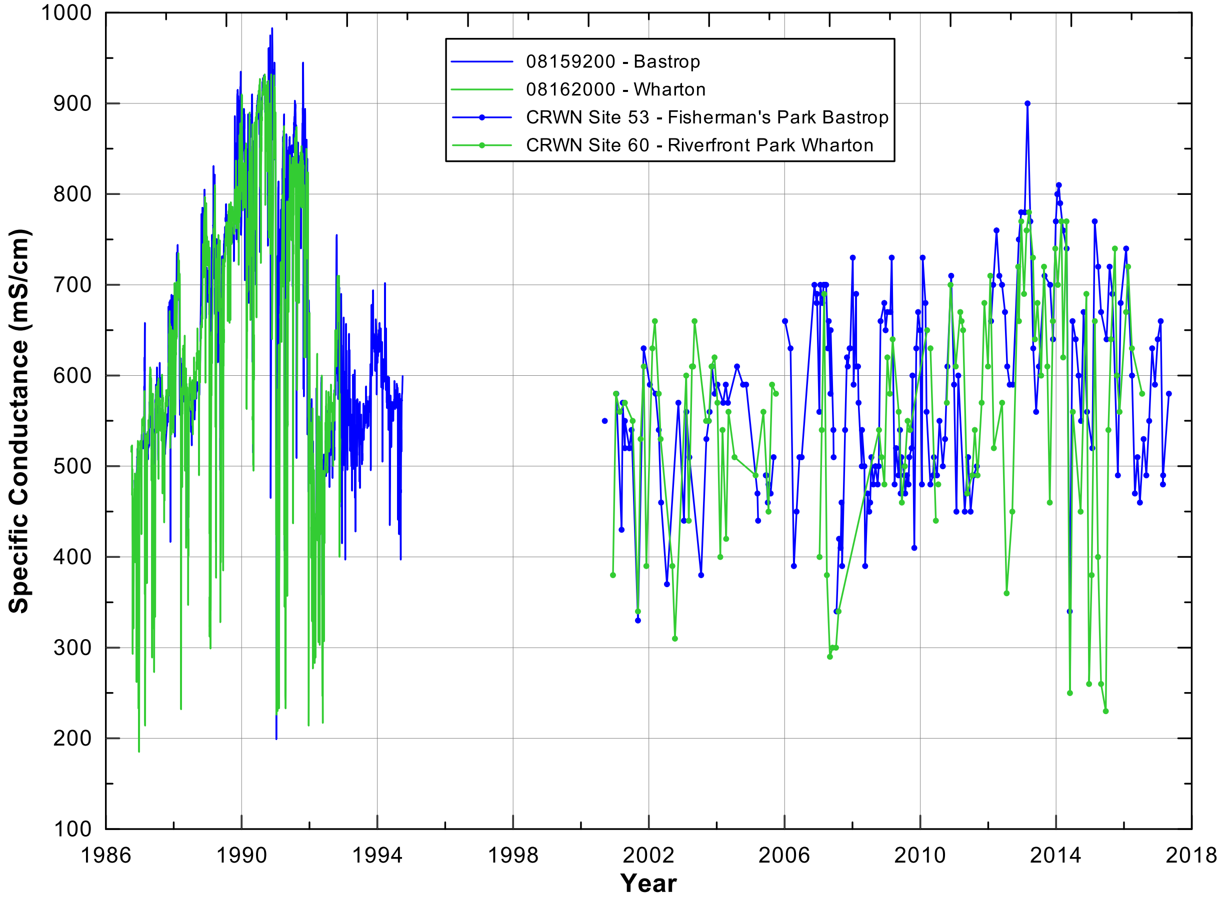


Figure 4-19. **Specific conductance data for United States Geological Survey gages and Colorado River Watch Network (CRWN) monitoring sites near the cities of Bastrop and Wharton (United States Geological Survey, 2017a; Lower Colorado River Authority, 2017b).**

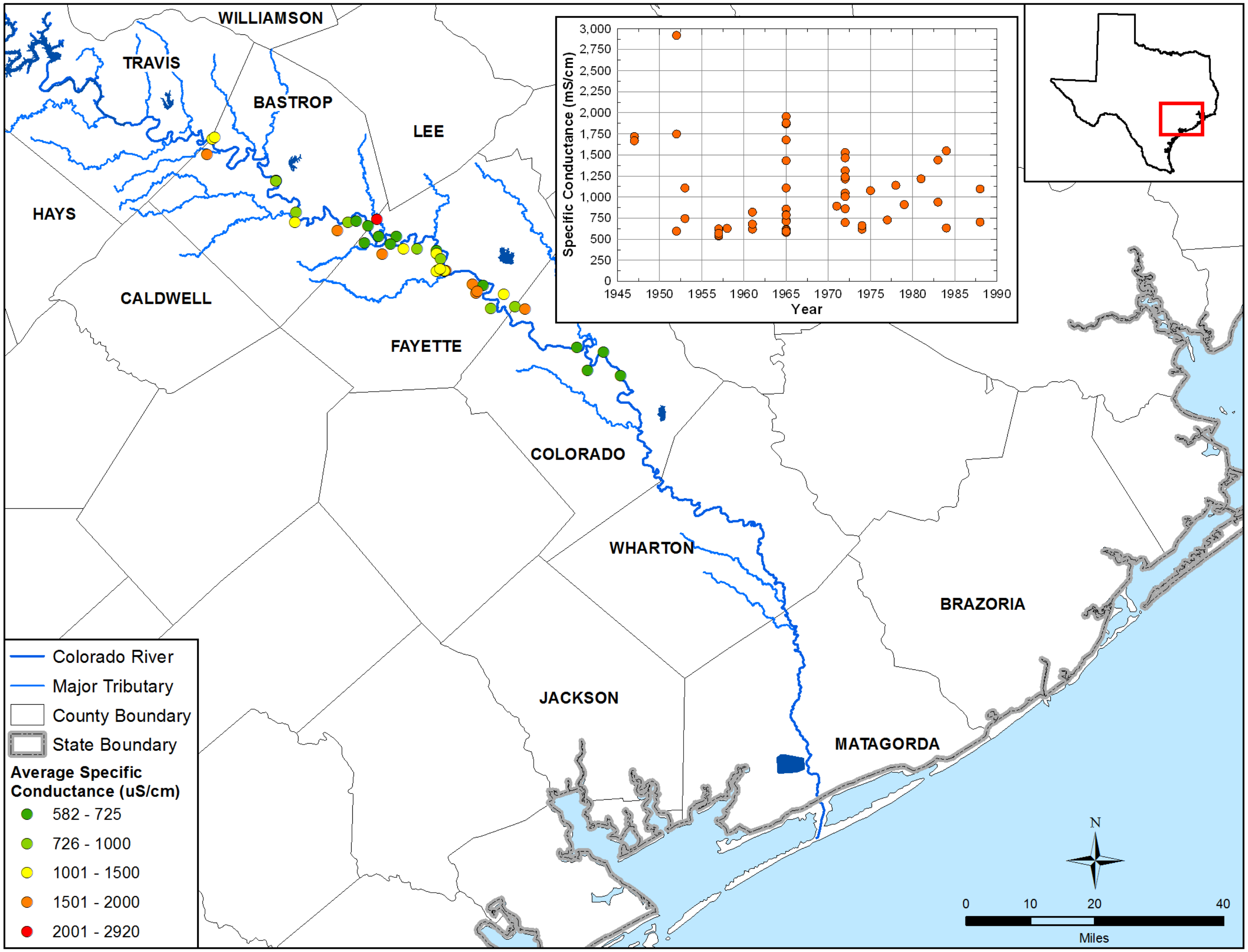


Figure 4-20. Spatial and temporal variation in groundwater specific conductance.

Note: µS/cm = microsiemens per centimeter

5 The Colorado River Alluvium in Groundwater Management Area 12

This section assembles data from previous studies of the Colorado River alluvium and from drillers logs in Travis, Bastrop, and Fayette counties to map the Colorado River alluvium and terrace deposits in Groundwater Management Area 12. In addition, transmissivity estimates for the alluvium and water levels and groundwater flow in the alluvium are discussed.

5.1 Mapping of the Colorado River Alluvium

Surface geology mapping by Barnes (1979, 1981) identifies alluvial material adjacent to the Colorado River and its tributaries in Groundwater Management Area 12. Interaction between the river and this alluvium occurs through discharge of groundwater into the river as base flow and recharge of the alluvium by the river. Deposition of the river's sediment load, in addition to erosion of underlying material during meandering in its floodplain, resulted in the development of broad floodplain and terrace deposits. Older terrace deposits may be isolated from the alluvium as a result of the river's meandering. Follett (1970) describes the alluvial deposits along the Colorado River in Bastrop County as consisting primarily of sand with some gravel and cobbles and disconnected lenses or layers of silt and clay. Increasing sand coarseness is typically observed with depth and gravel is frequently found at the base of the alluvial material. Sand, gravel, clay, sandy clay, and shale comprise the alluvium in Fayette County (Rogers, 1975).

The areal extent of the Colorado River alluvium is relatively easy to define based on surface geologic mapping, but the structure of the bottom of the alluvium has been largely unknown. In order to implement the alluvium associated with the Colorado River and its tributaries in Groundwater Management Area 12 in the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers, a study was conducted to delineate the areal and vertical extent of the alluvium. A similar type study was conducted by Standen (2017) for the alluvium in Fayette County.

Interaction between the alluvium and groundwater will occur where the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Gulf Coast aquifers outcrop (Figure 5-1). Study of the alluvium covered an extent from about 7 miles northwest of the active model boundary to about 10 miles southeast of the southern extent of the surficial outcrop layer in the model (Figure 5-2). Areas outside of the model extent were included in the study to help characterize the structure of the alluvium within the model extent. Evaluation of the alluvium structure consisted of:

- Reviewing lithologic logs from drillers reports to identify the presence of alluvium and, if present, selecting the depth to the bottom of the alluvium.
- Defining an areal extent of the alluvium for implementation into the model.
- Creating a raster of the bottom elevation and thickness of the alluvium.

Each of these components is described below.

5.1.1 Review of Lithologic Logs and Base of Alluvium Picks

The first task associated with mapping the Colorado River alluvium involved review of well lithology logs to both identify locations where alluvium is present and pick the depth to the base of the alluvium when present. Wells in the vicinity of the Colorado River and its major tributaries were compiled from the TWDB Submitted Drillers Reports and Groundwater databases. A lithology log is available for about 630 of the about 850 wells compiled (Figure 5-3). Wells from the Texas Commission on Environmental Quality well records were not considered by the study because specific locations for those wells are not available. Locating the wells at the center of the 2.5-mile grid in which they are contained results in significant uncertainty because the variability in the thickness of the alluvium within the grid is large and cannot be represented at a single point.

Typically, alluvium associated with the Colorado River or its tributaries was identified by the presence of gravel on the lithology log. The aquifers underlying the alluvium in Groundwater Management Area 12 consist of sand, some of which can be coarse, but are general devoid of gravel. Typically, the base of the alluvium was picked as the base of the deepest gravel or gravel mix (e.g., gravel and sand, gravel and clay) in a well. In many instances, this basal gravel is underlain by thick shale or clay. An example of the distinction between the alluvium and underlying Weches Formation in well 156938 in the TWDB Submitted Drillers Reports database is shown in Table 5-1. The alluvium could not be distinguished from the underlying geologic formation based on the lithologic log for some wells, so no pick was made for those wells. Locations of wells where the bottom of the alluvium could be picked, where it could not be picked, and where no alluvium is present are shown in Figure 5-4 along with the surficial alluvium and terrace deposits from the Geologic Atlas of Texas (Stoeser and others, 2007). The dataset of wells investigated for the report is provided in Appendix A, which includes the bottom of alluvium picks, the wells for which the alluvium bottom could not be differentiated from the underlying formation, and the wells for which a lithology log is not available. For coincident wells in Fayette County for this study and the study conducted by Standen (2017), the bottom of alluvium pick is the same with the exception of a few wells (see Appendix A).

Table 5-1. Example lithology log.

Well 156938[1]

Depth Interval (ft)	Description	Unit
0 - 11	Top Brown Sand	Alluvium
11 - 20	Coarse Sand / Brown Clay	Alluvium
20 - 45	Pea Gravel	Alluvium
45 - 60	Pea Gravel / Large Gravel	Alluvium
60 - 105	Gray Shale / Sandy Green Shale	Weches Formation
105 - 125	Gray-Brown Shale	Weches Formation
125 - 158	Gray-Brown Sand / Iron Rock	Weches Formation

[1] Tracking number in the TWDB Submitted Drillers Reports database

5.1.2 Areal Extent of Alluvium

A combination of information was used to develop the boundary of the Colorado River alluvium for its implementation into the model:

- The extent of alluvium and terrace deposits based on the Geologic Atlas of Texas surface geology (Stoeser and others, 2007) (Figure 5-5).

- The extent of the alluvium in Bastrop County from the surface geologic map in Follett (1970) (Figure 5-5).
- Locations of the Colorado River and its major tributaries (United States Geological Survey, 2014a) (see Figure 5-2)
- Detailed topographic and bathymetric data from the Lower Colorado River Authority (Figure 5-6).
- Locations of wells identified as having alluvium and not having alluvium based on review of lithologic logs (Figure 5-5).
- A buffer zone around the Colorado River and its major tributaries.

An initial boundary of the Colorado River alluvium was created using the location of alluvium and terrace deposits from Stoeser and others (2007), which are consistent with the alluvium mapped by Follett (1970) except at the main channel-tributary confluences. The boundary was modified based on the well lithology data to incorporate areas with wells where alluvium is observed and exclude areas with wells showing no alluvium. The boundary was further refined using detailed topographic and bathymetric data from the Lower Colorado River Authority to ensure inclusion of the Colorado River channel and floodplain. This was especially useful in areas with little or no well coverage. Final modification to the alluvium boundary consisted of extending it, if needed, to three-eighths of a mile from the Colorado River and its tributaries. This modification was most important around the tributaries with adjacent alluvium and where the Colorado River channel is narrow. The purpose for this final adjustment relates to implementation of the river and alluvium in the model. Figure 5-7 shows the boundary of the Colorado River alluvium developed for the model update.

5.1.3 Colorado River Alluvium Structure

The land surface is assumed to represent the top of the Colorado River alluvium, with the land surface developed base on the 10-meter (32.8-foot) Digital Elevation Model (United States Geological Survey, 2014b) rather than the coarser 30-meter Digital Elevation Model used by Dutton and others (2003) and 90-meter Digital Elevation Model used by Kelley and others (2004). The higher resolution Digital Elevation Model enables capture of small-scale elevation changes across the alluvium.

The bottom elevation of the alluvium was estimated through kriging using the software Surfer by Golden Software. At well locations with alluvium picks, the bottom elevation of the alluvium was calculated as the 10-meter Digital Elevation Model value at the well location minus the depth to the base of the alluvium at the well. Although a bottom elevation of the alluvium was available at numerous locations from well lithology logs (see Figure 5-7), these data were not sufficient to constrain the kriging. Additional control on the kriged surface was obtained through development of representative data points based on the following assumptions:

- Along its boundary, the thickness of the alluvium is zero.
- Along the Colorado River and the major tributaries located in the alluvium, the thickness of the alluvium underlying the river and tributaries is 2 feet.
- The thickness of the alluvium remains 2 feet for a distance of 700 feet on either side of the Colorado River.

The bottom elevation of the alluvium ranges from 215 feet in Fayette County to 545 feet in Travis County (Figure 5-8). Elevations are lowest along the Colorado River and generally increase toward the alluvium boundary. The thickness of the alluvium ranges from 0 to 95 feet, with most values between about 25 and 50 feet (Figure 5-9). The thickest area of alluvium is in Bastrop County slightly southeast of the active model boundary. The thicknesses determined here are consistent with those reported in the groundwater literature. Brune and Duffin (1983) and Duffin and Musick (1991) state that the Colorado River alluvium can be as thick as 60 feet in Travis County and Follett (1970) states thicknesses up to 50 feet in Bastrop County. The thicknesses determined by this study differ in Fayette County from those developed by Standen (2017) due to the additional control on the alluvium base along the Colorado River and major tributaries included in this study.

5.2 Transmissivity Estimate from Specific Capacity

Specific capacity is a measure of the productivity of a well and is calculated by dividing the total pumping rate by the drawdown (Freeze and Cherry, 1979):

$$SC = \frac{Q}{s} \qquad \text{Equation 5-1}$$

where:

SC = specific capacity (volume of water per time per length)
Q = pumping rate (volume of water per time)
s = drawdown in the well (length)

Specific capacity is generally reported as gallons per minute per foot. Productivity of a well is often evaluated after it is drilled through pumping the well at a specific rate and measuring the drawdown. Therefore, yield and drawdown data, from which specific capacity can be calculated using Equation 5-1, are frequently found on drillers logs. As discussed in Section 5.1.1, lithology logs on numerous drillers logs were reviewed in development of the structure for the Colorado River alluvium in Groundwater Management Area 12. During this review process, well yield and drawdown data were also captured and specific capacity values where calculated (Figure 5-10 and Appendix B).

Several researchers have shown that there is a theoretical linear relationship between specific capacity and transmissivity (Mace, 1997, 2001). Because specific capacity does not account for potentially important field variables, such as the condition of the well, the size of the well, and the partial penetration of the well into an aquifer, estimating transmissivity from specific capacity measurements is more uncertain than estimating transmissivity from aquifer pumping test data. In the absence of aquifer pumping test data, however, transmissivity estimates from specific capacity measurements provide some indication of aquifer characteristics where otherwise no data exists.

One approach for developing a relationship between specific capacity and transmissivity is through conversion of units. The conversion from transmissivity in units of square feet per day to specific capacity in units of gallons per minute per foot is:

$$1\,\frac{square\ feet}{day}\,x\,\frac{7.48\ gallons}{cubic\ feet}\,x\,\frac{1\ day}{24\ hours}\,x\,\frac{1\ hour}{60\ minutes} = 0.0052\,\frac{gallons}{(minute)\,(foot)} \qquad \text{Equation 5-2}$$

Using this conversion, the relationship between specific capacity and transmissivity is:

$$SC = T\ x\ 0.0052 \qquad \text{Equation 5-3}$$

where:

SC = specific capacity (gallons per minute per foot)
T = transmissivity (square feet per day)

Rearranging Equation 5-3, transmissivity is calculated from specific capacity as:

$$T = \frac{SC}{0.0052} \qquad \text{Equation 5-4}$$

The hydraulic conductivity is calculated from transmissivity as:

$$K = \frac{T}{b} \qquad \text{Equation 5-5}$$

where:

K = hydraulic conductivity (feet per day)
b = saturated thickness (feet)

For wells with a measured water level, the saturated thickness of the alluvium was calculated as the depth to the base of the alluvium minus the depth to water in the well. The median and average depth to water for alluvium wells with water-level data is about 25 feet. The saturated thickness was calculated using this assumed depth to water for wells with no water-level measurement.

Transmissivity values calculated using Equation 5-4 and hydraulic conductivity values calculated using Equation 5-5 are given in Table B-1. The average and geometric mean hydraulic conductivity for the alluvium in the area of the outcrop layer in the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers are 129 and 57 feet per day, respectively.

5.3 Water Levels and Groundwater Flow

Water-level data were obtained from the TWDB Groundwater and Submitted Drillers Reports databases and from measurements recorded on drillers reports downloaded from the TWDB Water Data Interactive Groundwater Data Viewer website. Water-level data are available for 86 wells completed into the alluvium in the entire area of study and 18 wells in the surficial outcrop layer of the updated model (Figure 5-11). Water-level elevation was calculated as the 10-meter Digital Elevation Model value minus the depth to water.

Only one water-level measurement is available for the majority of wells, and the greatest number of measurements for any well is 10. Measurement years range from 1940 to 2006, with 48 percent of the measurements prior to 1970 and 85 percent prior to 2000. A hydrograph for the well with 10 measurements, all taken in winter months, is shown in Figure 5-11. Data are too sparse to provide information regarding seasonal water-level trends, but do show that that the winter water level in the alluvium at this location varies from year to year with changes over several years of as much as about 10 feet.

The paucity of data precludes developing a surface representative of the water table in the alluvium. However, the water-level elevations are consistent with groundwater in the alluvium flowing towards the Colorado River.

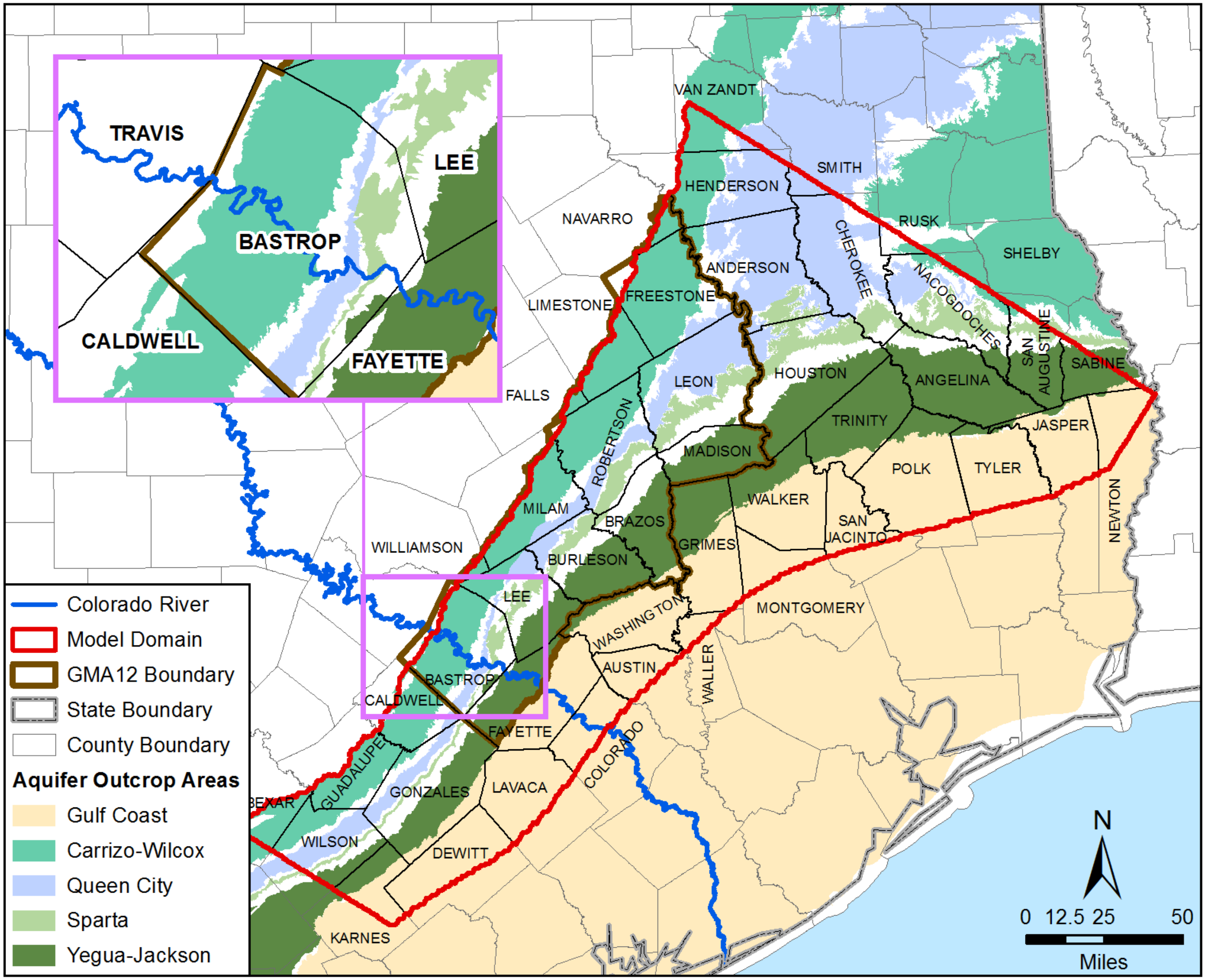
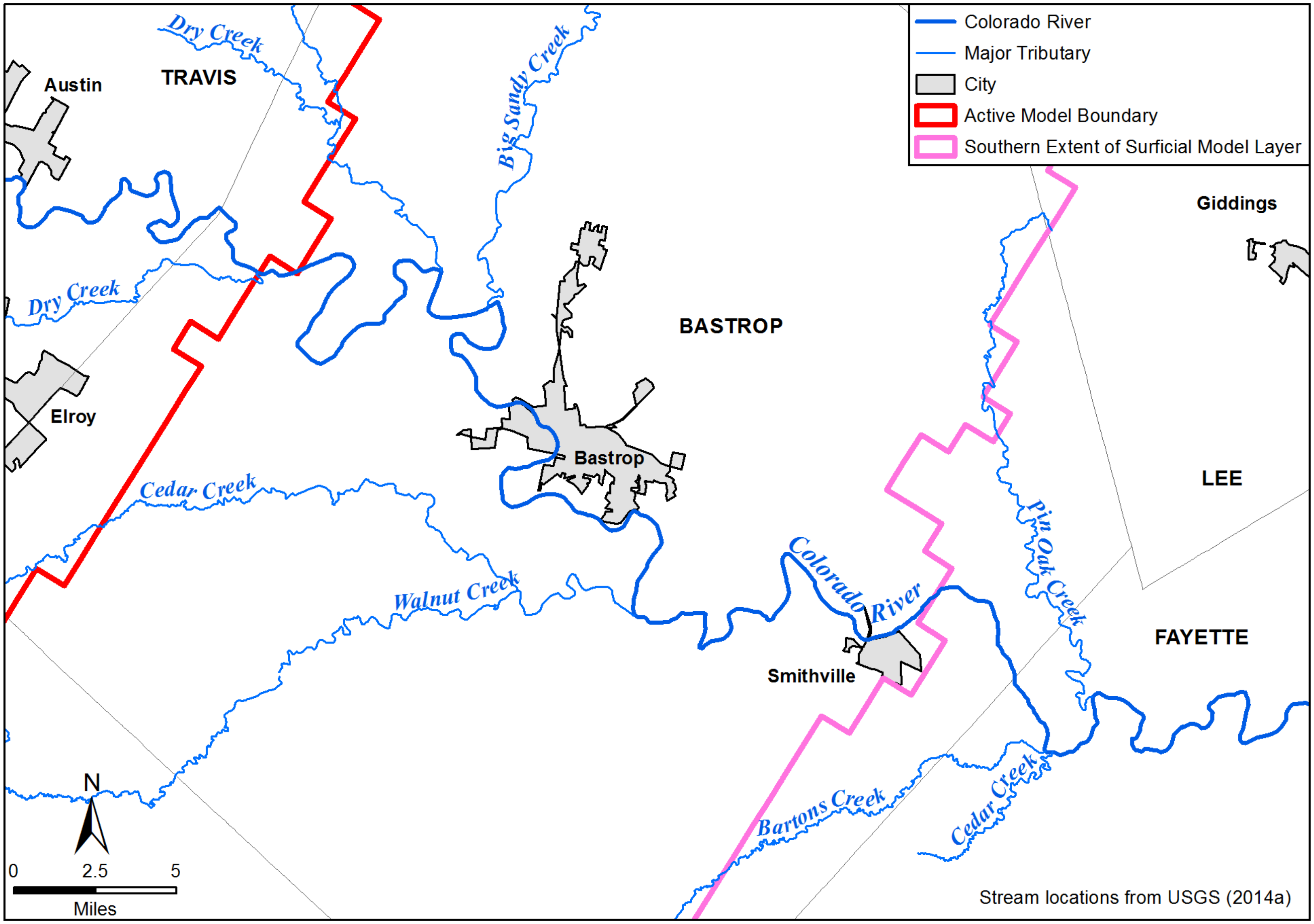


Figure 5-1. **Location of the Colorado River relative to Groundwater Management Area (GMA) 12, the active boundary of the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers, and aquifer outcrops.**



Stream locations from USGS (2014a)

Figure 5-2. **Area of study for the Colorado River alluvium.**

Note: USGS = United States Geological Survey

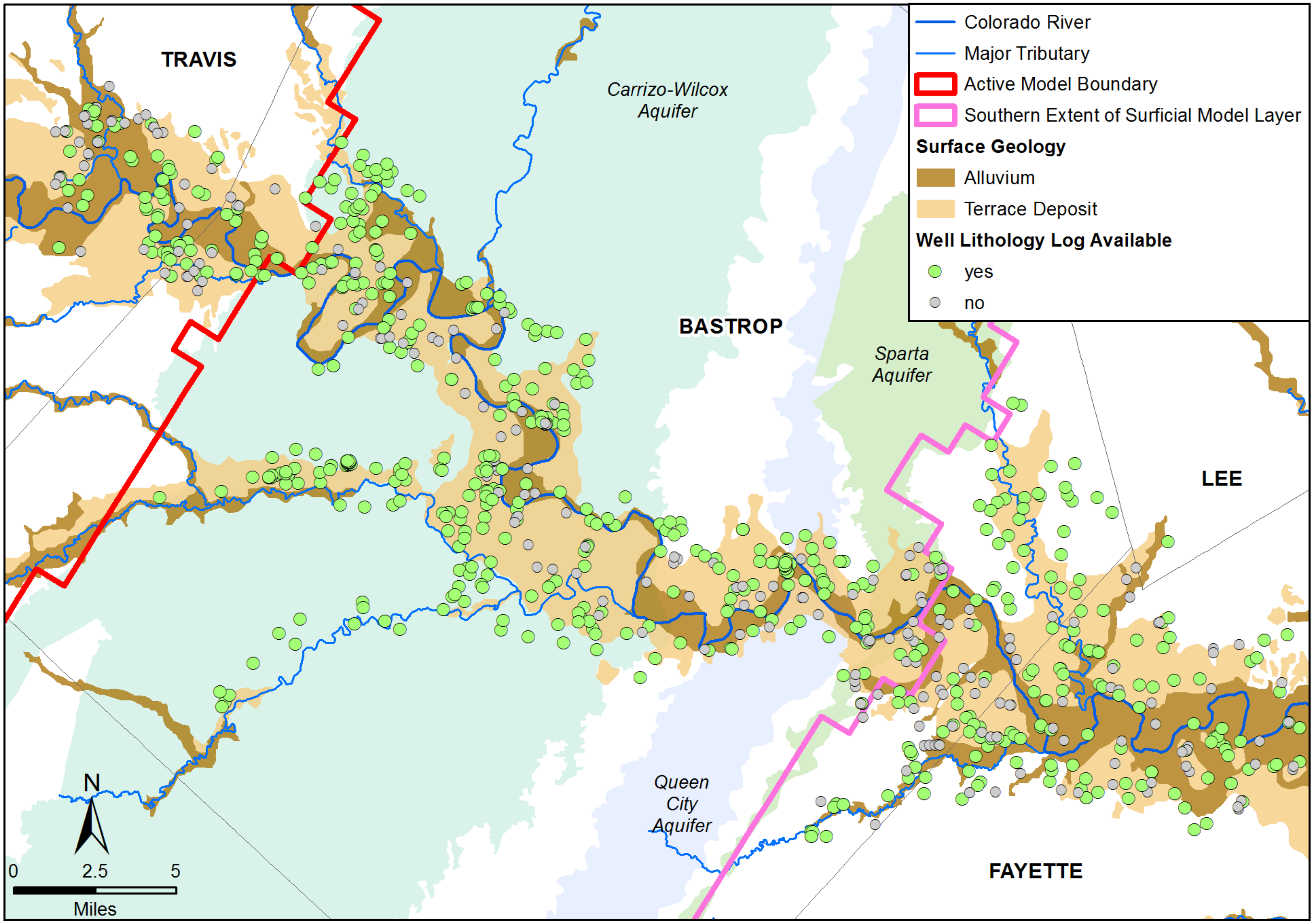


Figure 5-3. **Location of wells investigated for the Colorado River alluvium study and availability of lithology logs.**

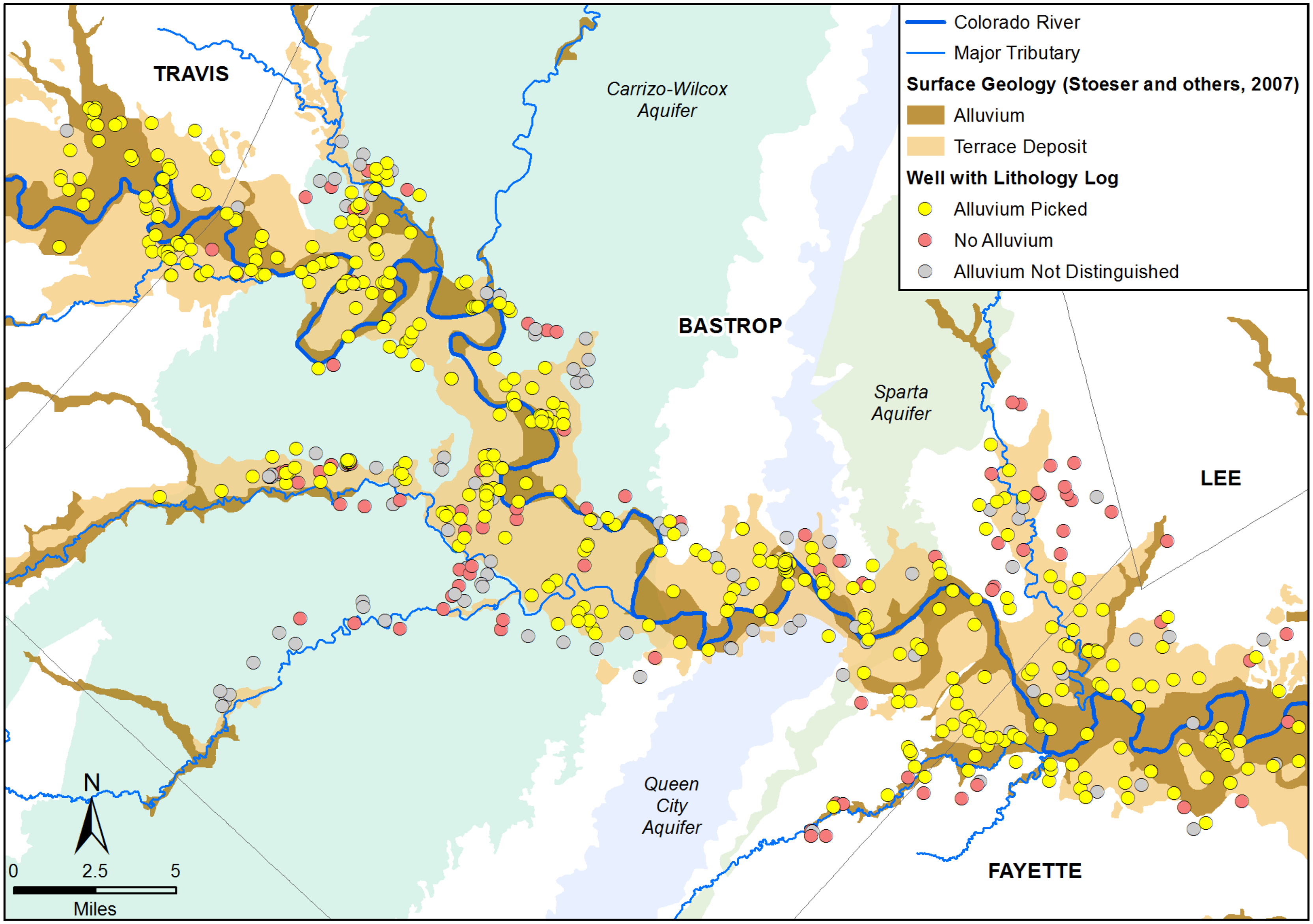


Figure 5-4. **Well locations where alluvium is present, absent, and indistinguishable from the underlying geologic formation.**

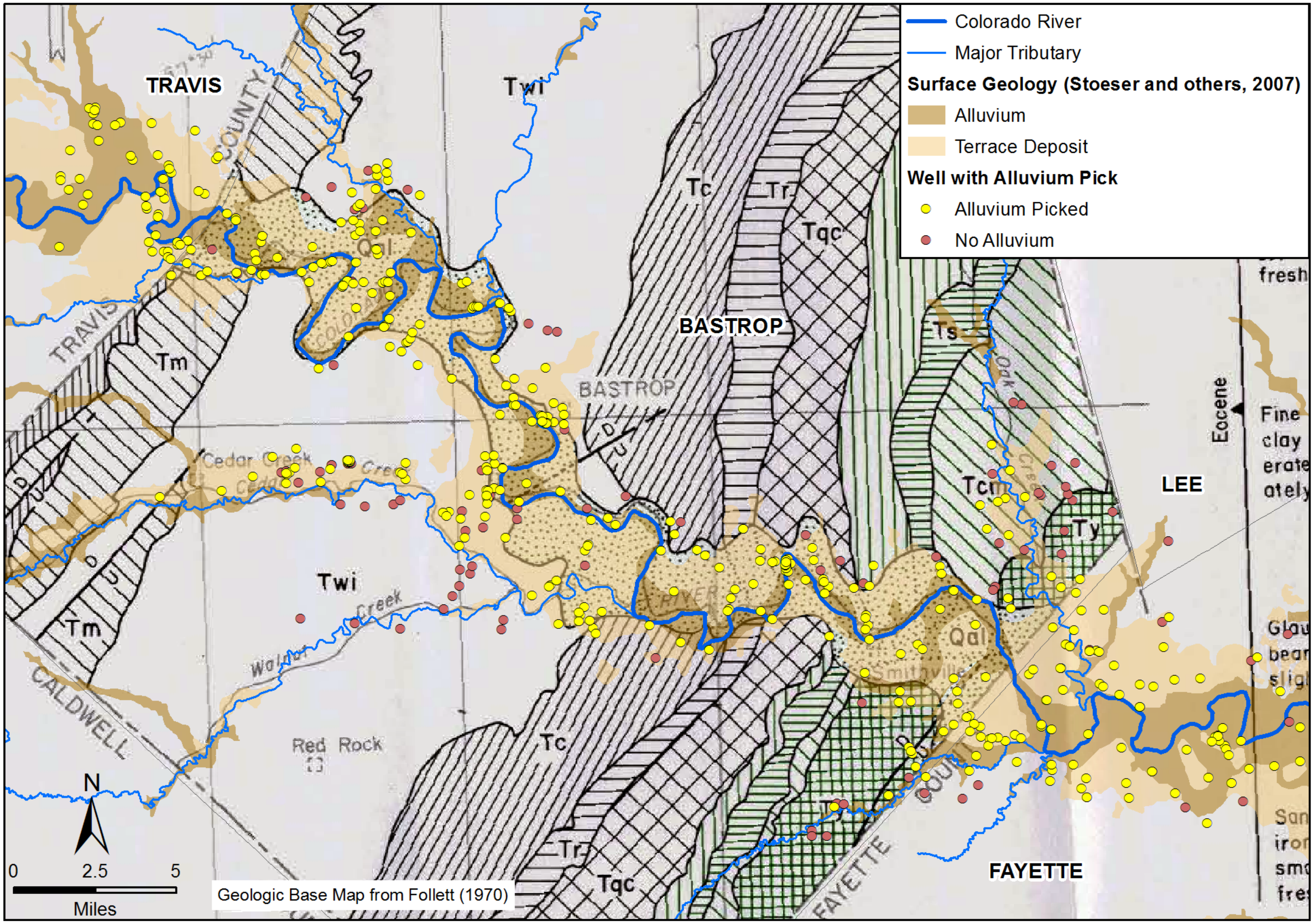


Figure 5-5. Geologic and well information used to inform the location of the Colorado River alluvium boundary.

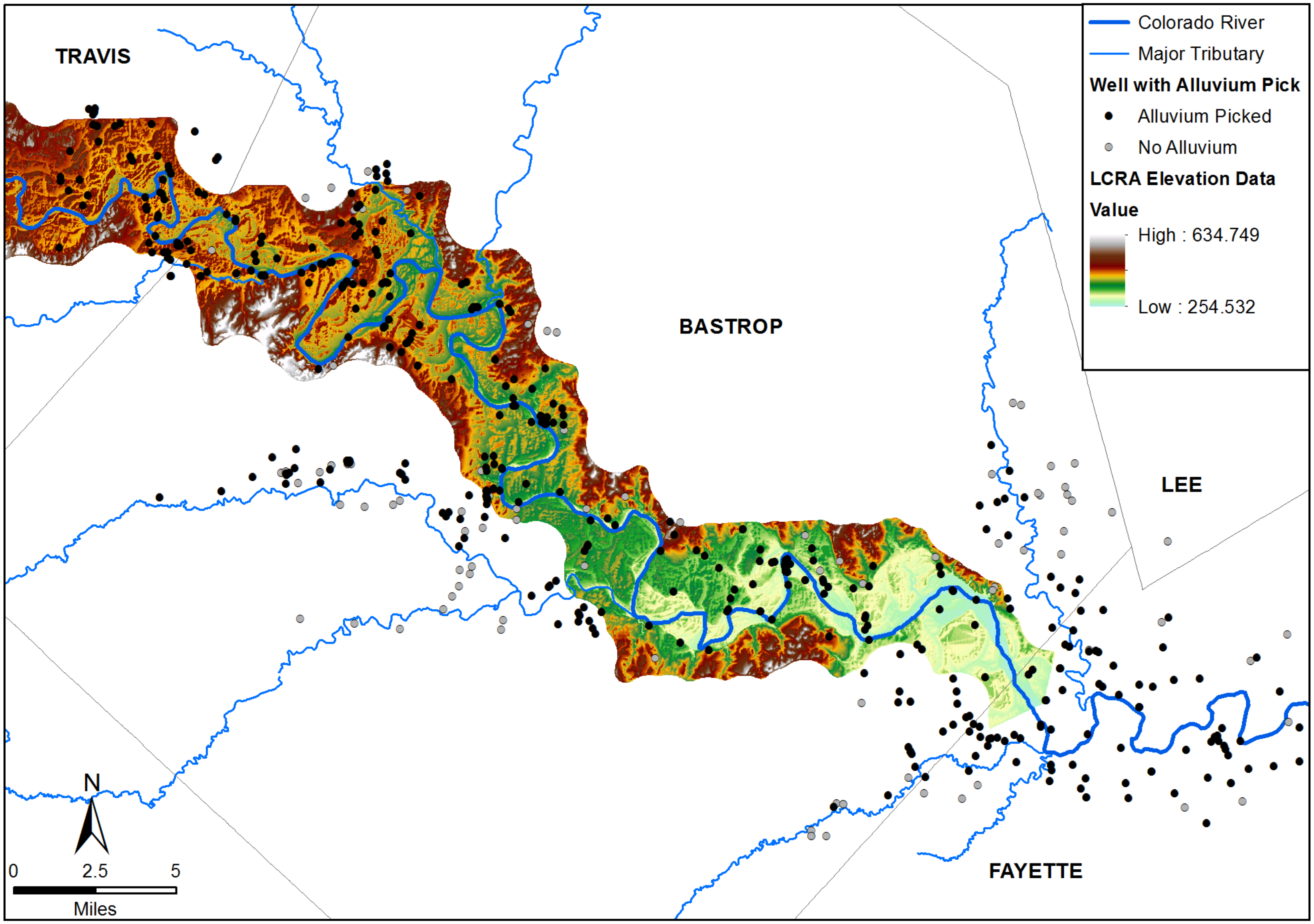


Figure 5-6. **Detailed topography from the Lower Colorado River Authority (LCRA). The topography extent is constrained by the extent of the detailed topography study conducted for the Lower Colorado River Authority.**

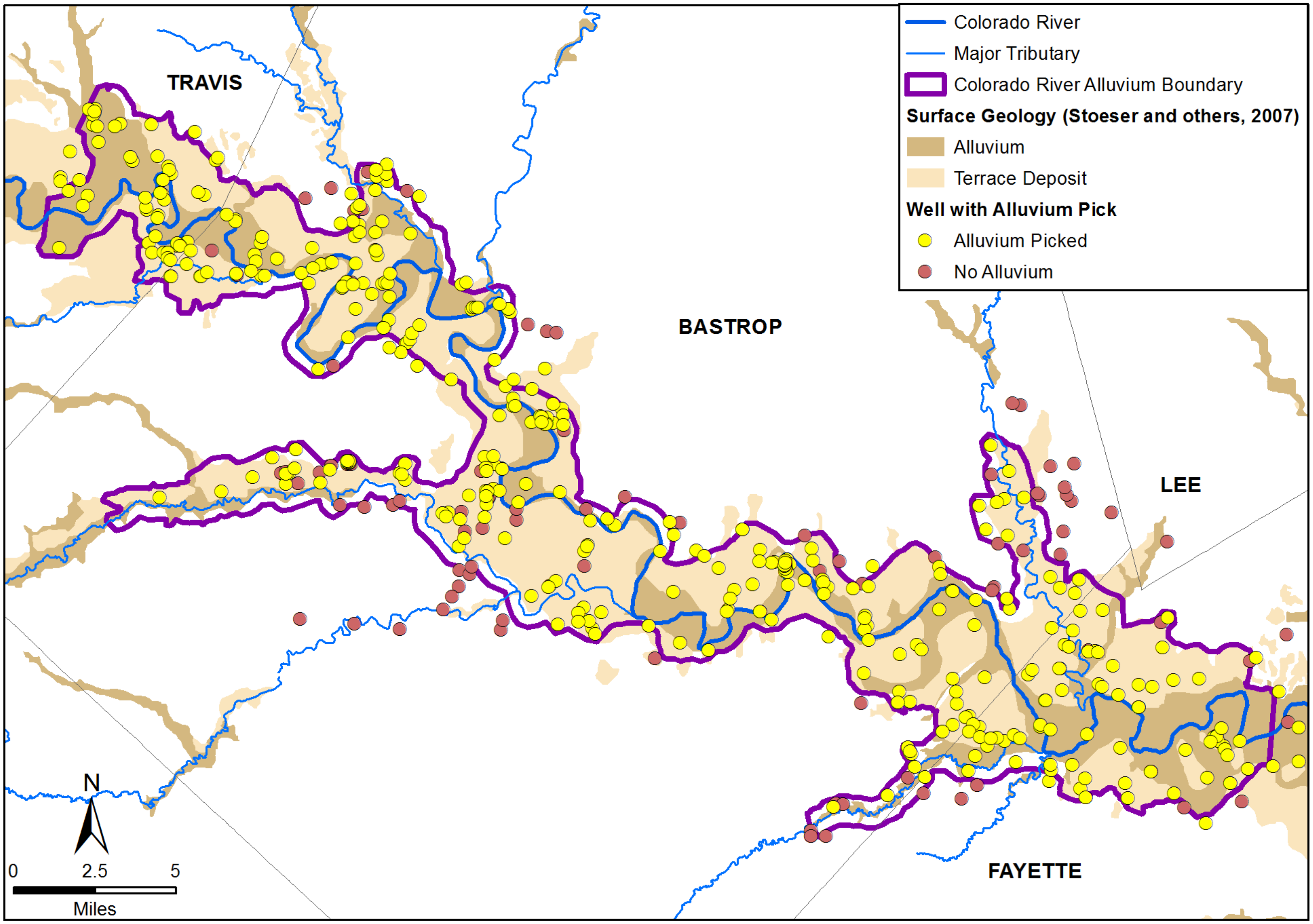


Figure 5-7. **Boundary for implementation of the Colorado River alluvium in the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers.**

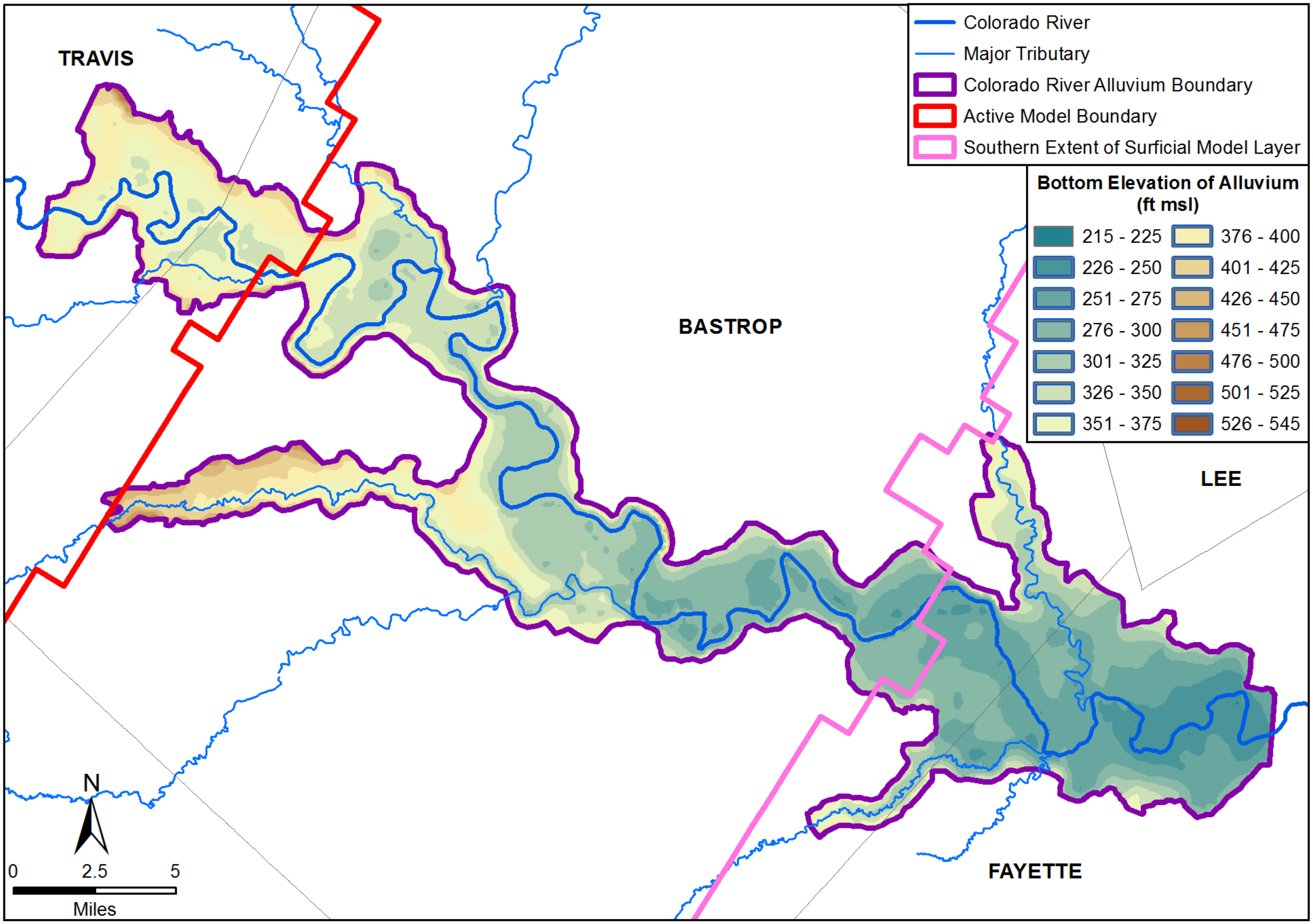


Figure 5-8. **Bottom elevation in feet above mean sea level for the Colorado River alluvium.**

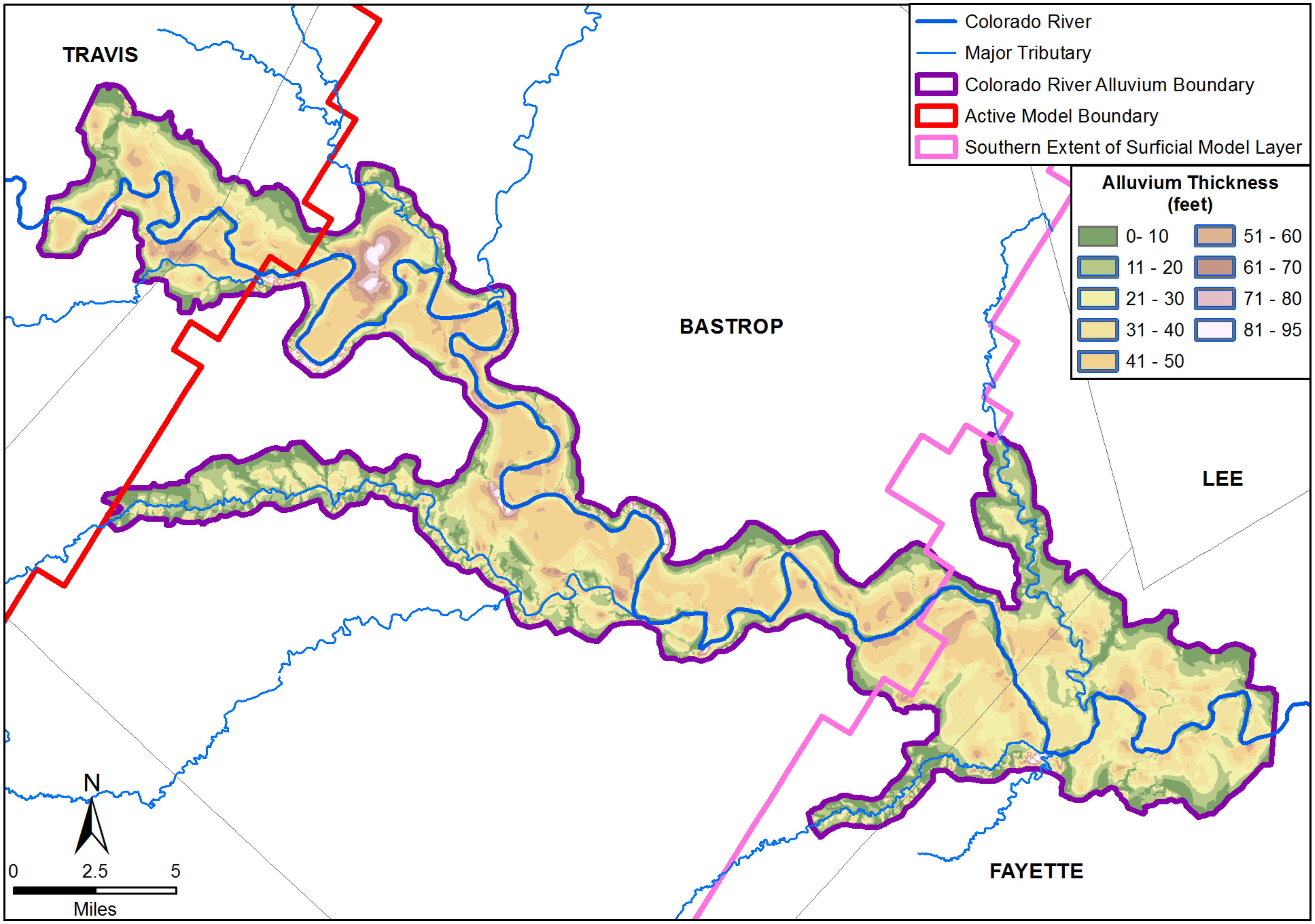


Figure 5-9. **Thickness in feet of the Colorado River alluvium.**

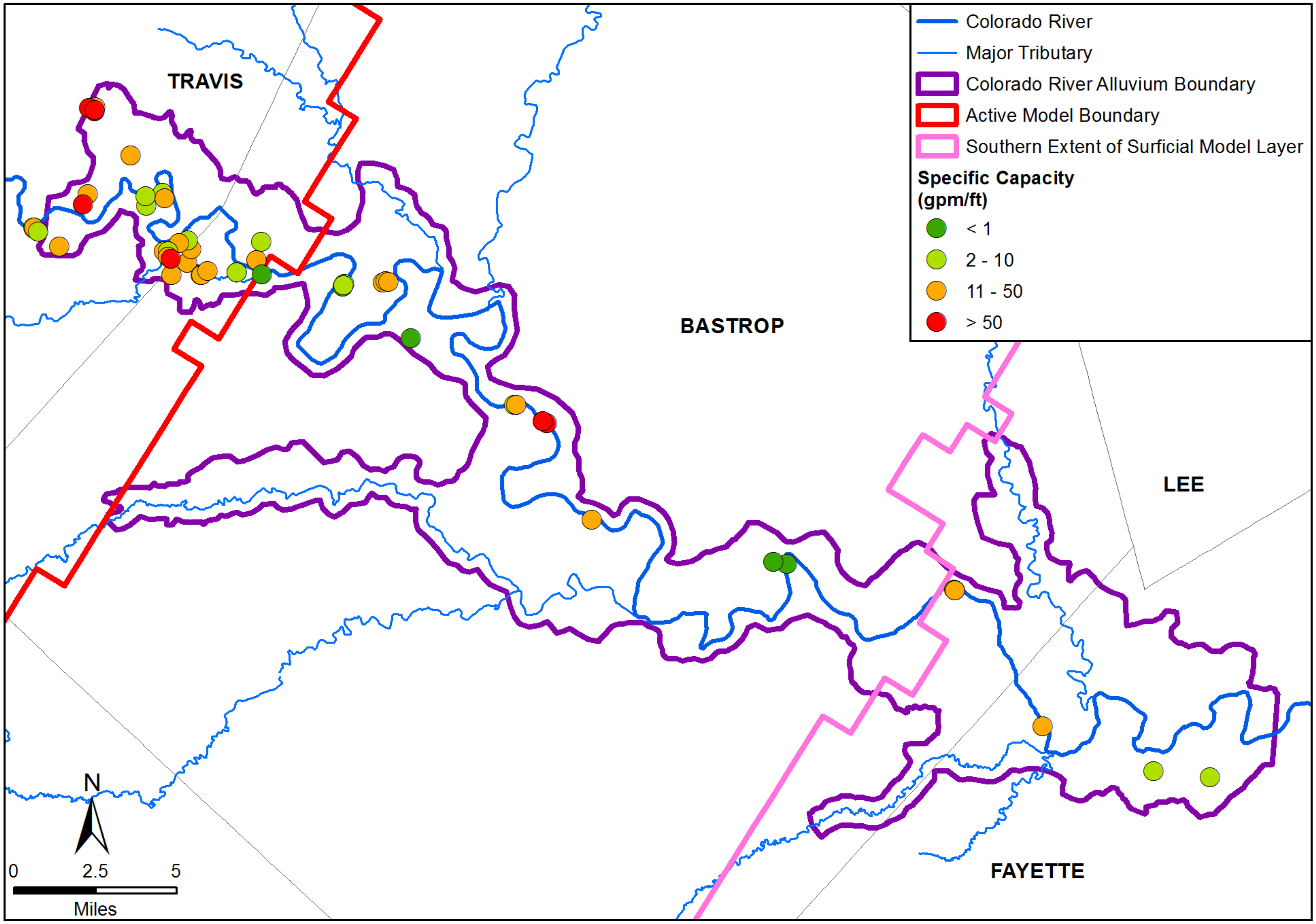


Figure 5-10. **Specific capacity data for the Colorado River alluvium.**

Note: gpm/ft = gallons per minute per foot

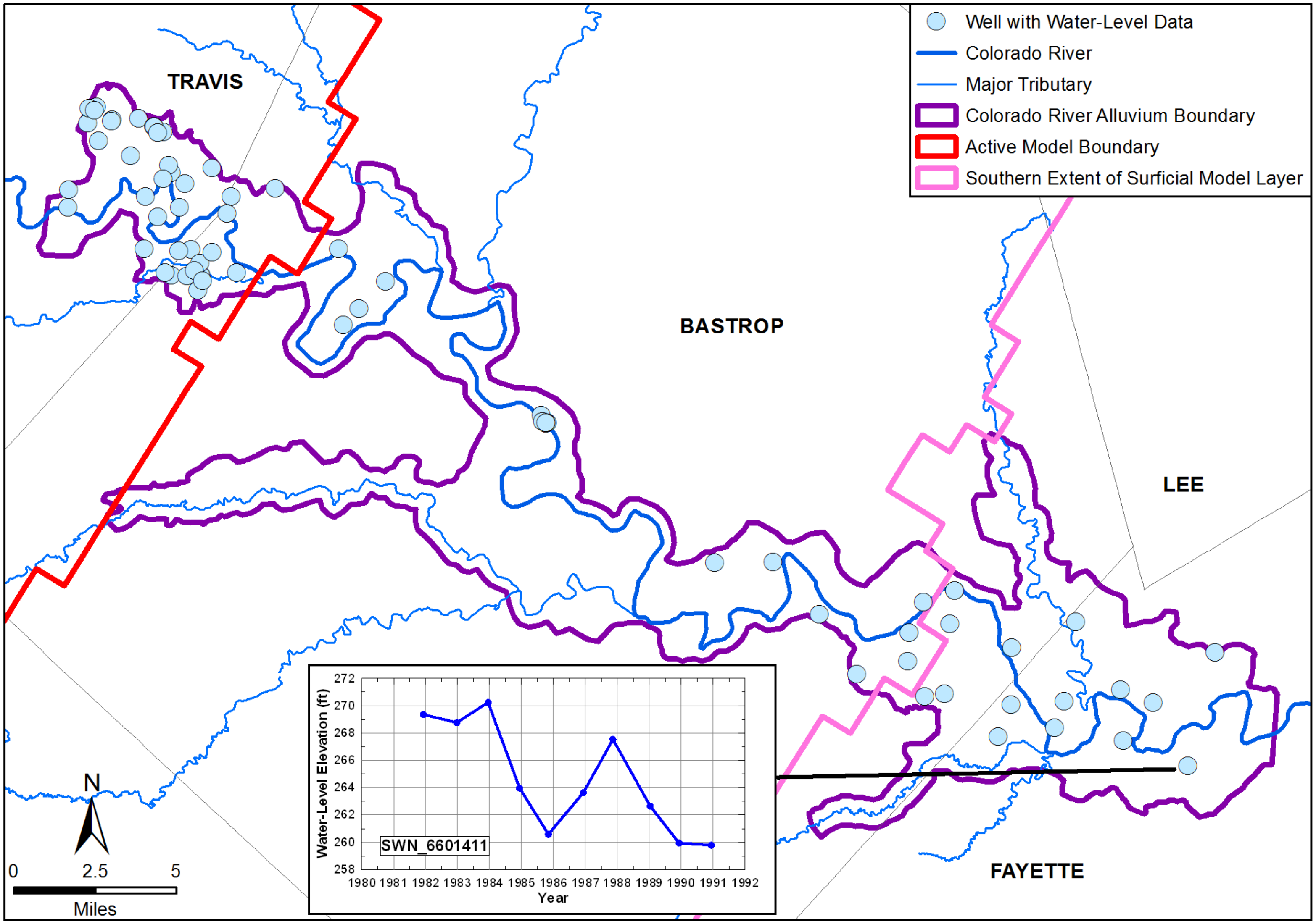


Figure 5-11. **Water-level data locations for the Colorado River alluvium and hydrograph of data for well 6601411 in the TWDB Groundwater database.**

Note: ft = feet

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6 Updates to the Central Carrizo-Wilcox, Queen City, and Sparta Groundwater Availability Model

6.1 Representing Local, Intermediate, and Regional Groundwater Flow Systems in Groundwater Models

As illustrated in Figure 6-1, groundwater moves along flow paths of varying lengths from areas of recharge to areas of discharge within a groundwater basin. In his landmark papers, Toth (1962, 1963) was among the first to conceptualize and demonstrate that large groundwater systems are comprised of groundwater flow paths of different spatial and time scales. Toth (1963) classified the different scales of groundwater flow paths as local, intermediate, and regional, which can be defined as:

- At the local scale, groundwater flow paths remain relatively shallow, recharge and discharge areas are adjacent to each other, and groundwater travel times are on the order of days or years.
- At the intermediate scale, groundwater flow paths can travel through multiple formations, recharge and discharge areas are separated by one or more topographic high and low, and groundwater travel times are on the order of decades or centuries.
- At the regional scale, groundwater flow paths can cross an entire basin, recharge areas are along groundwater divides, discharge areas lie at the bottom of major drainage basins, and groundwater travel times are on the order of millennia.

Among the three flow systems, the local flow system is the most important to surface water-groundwater interaction. However, where regional topographic lows serve as discharge locations for deep groundwater flow, surface water bodies could receive groundwater contributions from intermediate and regional groundwater flow systems. An important hydrogeological feature of Figure 6-1 is that the hydraulic head is three-dimensional and changes with depth. The three-dimensional aspect of the hydraulic heads becomes more important if pumping occurs at depth and causes large vertical hydraulic head gradients.

Figure 6-2 is a schematic that shows changes in hydraulic head in an aquifer beneath a stream as a result of deep pumping. At shallow depths and near the stream, the hydraulic head is greater than the stream elevation but, at the deeper depths, the hydraulic head is less than the stream elevation. The three wells are installed at different deeps such that Well A, Well B, and Well C are along groundwater flow paths associated with local, intermediate, and regional flow paths, respectively. With regard to representing the wells and the stream in a numerical groundwater flow model, the model layering can affect whether the stream is modeled as a gaining or losing stream. If the aquifer is divided into three model layers with each of the wells assigned to a different layer, the stream will be properly modeled as a gaining stream. If the aquifer is modeled as a single layer that is assigned the average hydraulic head in the three wells, the stream will be improperly modeled as a losing stream. Thus, where vertical hydraulic gradients are important to the flow system, groundwater models need to have sufficient model layer resolution near the ground surface to adequately represent the local flow system, if the local flow system is of interest to the modeler.

Besides the resolution of the model layers, another concern with representing surface water-groundwater interaction in groundwater models is grid cell size. Figure 6-3 illustrates the benefits of using small grid cells to represent a stream in the central Gulf Coast of Texas. Although smaller grid cell sizes provide the capability to better represent the location of streams and wells, they can lead to problems with long model run times and complex and large input and output files. Therefore, selection of the grid cell size should be balanced with the need to capture the important aspects of the hydraulic boundaries represented by wells and streams and the need to have a model that can be easily used.

Another potentially important consideration with selecting grid cell size is that recharge rates for some groundwater models will be affected by the cell size. Jorgensen and others (1989a, b) and Stoertz (1989) demonstrate that the recharge rate, which is appropriate for simulation of an aquifer system, is scale dependent. If the grid cell size in the model is larger than the length of shallow groundwater flow paths, both groundwater recharge and discharge occurs within the area represented by the grid cell. The result is a need to reduce the amount of net recharge applied at the water-table boundary of the model to simulate the aquifer system correctly at the desired scale.

6.2 Grid Cell Refinement Along the Colorado River

Figure 6-4a shows the grid cell spacing in the vicinity of the Colorado River in the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers (Kelly and others, 2004). All of the grid cells in this numerical grid are 1-mile by 1-mile square for an area of 1 square mile. Figure 6-4b shows the grid cells in the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers, which is currently under development by INTERA Incorporated. Across much of the model domain, the grid cells in the updated model have the same location and size as does the existing model except for near the Brazos and Colorado rivers. The updated model has 0.5-mile by 0.5-mile square grid cells near the Brazos River and 0.25-mile by 0.25-mile square grid cells in the vicinity of the Colorado River and its major tributaries.

The updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers is based on a version of MODFLOW called MODFLOW-USG (Panday and others, 2013). MODFLOW-USG provides the capability to use an unstructured numerical grid allowing for locally-refined grids. The options used to develop the locally-refined grid around the Colorado River is called Quadtree refinement. Quadtree refinement is based on the notion that any cell (normally a square cell) can be divided into four equal sized cells. Quadtree grids are often smoothed, which means that a cell connects to no more than two cells in any one direction.

The smaller grid cells provide the opportunity to improve the location of the Colorado River in the updated model. Figure 6-5 shows the grid cells, and the associated bottom elevation of the stream channel, used to represent the Colorado River and its major tributaries in the existing and updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. The smaller grid cells reduce the footprint of the river boundaries to a more appropriate size, and help to improve the resolution of tributary connectivity, especially in areas where more than one tributary connects with a larger river segment.

6.3 Addition of Shallow Model Layer to Represent the Colorado River Alluvium

Figure 6-6 shows the areal extent of the Colorado River alluvium superimposed on the numerical grid for the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. Development of the footprint and thickness of the Colorado River alluvium is discussed in Section 5.1. To incorporate the Colorado River alluvium in the updated model, an additional model layer was constructed to represent the alluvium. This approach was possible because MODFLOW-USG allows a model layer to be present over only a portion of the model domain.

Figure 6-6 shows two transects across the Colorado River alluvium. At the location of these transects, Figures 6-7 and 6-8 show the numerical grid and model layers for the upper 400 feet from the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. The Colorado River alluvium is represented as a separate model layer that pinches out at its lateral boundaries. The shallow model layer below the Colorado River alluvium layer represents the local flow system described by Toth (1962, 1963). The shallow flow model layer is represented by a portion of the aquifer beneath the Colorado River alluvium. The thickness of the Colorado River alluvium has been finalized and will not change during calibration of the updated model. However, the thickness associated with the shallow flow system has not yet been finalized and may change during calibration of the updated model.

6.4 Status of Central Carrizo-Wilcox, Queen City and Sparta GAM Update

The final report deadline for updating the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers is April 30, 2018. The refinement of grid cells near the Colorado River and the addition of vertical layers to represent the Colorado River alluvium discussed in Sections 6.2 and 6.3 are important components of the model update. In this section, other important components of the updated model are summarized.

6.4.1 Geological Faults

The groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers includes Horizontal Flow Barriers (Hseih and Freckleton, 1993) to represent geological fault. The locations and properties of the geological faults in the central portion of these aquifers have been revised as part of the model update process (Young and others, 2017). After review of more than 650 geophysical logs, Young and others (2017) adjusted the locations of the geological faults. The current model (Kelley and others, 2004) represents the faults as long, continuous sealing faults that extend across multiple counties. In contrast, Young and others (2017) represent the Milano Fault Zone as four grabens and one complex, and reduce the size of the area associated with geological faults. In addition, Young and others (2017) assign a vertical offset to the faults. In the updated model, the geological faults will still be represented by Horizontal Flow Barriers, but the hydraulic properties will vary as a function of the fault's vertical offset resulting in not all faults being sealing.

6.4.2 Aquifer Hydraulic Properties

To help guide the development of the hydraulic conductivity values for the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers, pumping test data have been collected and analyzed to estimate transmissivity values. The pumping test data were collected from Texas Commission on Environmental Quality files for Public Water Supply wells, from hydraulic consultants who have worked for lignite mines and water resource projects in Groundwater Management Area 12, and from the TWDB Submitted Drillers Reports database. Young and others (2017) presents transmissivity values calculated for 113 of these pumping tests. To help guide the development of specific storage values for the updated model, the groundwater and oil and gas literature were reviewed to develop relationships with depth of burial. The relationship is based on geomechanical considerations as shown by Equation 6-1, which was postulated by Shestakov (2002). Previous applications of the Shestakov model for estimating specific storage values include groundwater models developed for the Northern Trinity and Woodbine aquifers (Kelly and others, 2014), the Yegua-Jackson Aquifer (Deeds and others, 2010), the Gulf Coast Aquifer (Young and others, 2009) and the Carrizo-Wilcox Aquifer (Hamlin and others, 2016):

$$Ss = \frac{A}{D+Zo} \qquad \text{Equation 6-1}$$

where:

Ss = Specific storage (L-1)
D = Depth (L)
Zo = Calibrated parameter
A = Calibrated parameter based on aquifer type

6.4.3 Recharge

Recharge estimates have been determined based on streamflow hydrograph separation. This approach involves calculating recharge by dividing the base flow for a river reach by the watershed area associated with the river reach. Previous applications of this method in Texas include Scanlon and others (2012), Young and Kelley (2006), Ewing and Jigmond (2016), and Kelley and others (2014). Hydrograph separation was performed on streamflow data for 77 United States Geological Survey gages. The streamflow was divided into runoff and base flow using the codes Base Flow Index (Wahl & Wahl, 1995) and SWAT Bflow (Arnold & Allen, 1999).

6.4.4 Water Levels

Water-level data have been obtained from the TWDB Groundwater database and from databases maintained by groundwater conservation districts to support the model calibration period from 1950 to 2010. The calibration period for the current groundwater availably model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers is from 1974 to 2000. A master well file has been created and each well has been assigned to a grid cell based on the current model layers and grid refinement in the updated model.

6.4.5 Historical Pumping

Historical pumping data was developed through review of historical documents, accessing data available on the TWDB website, researching lignite mining documents at the Texas Railroad Commission, and corresponding with groundwater conservation districts and several municipal water providers. Development of the pumping dataset for irrigation, manufacturing, mining, municipal, and stock water uses was based on the following objectives:

- Collect data from the start of aquifer development through 2010
- Develop pumping on an annual basis
- Collect and integrate data from all available sources
- Maintain water user group specific pumping data when available

The primary source of pumping for municipal and industrial purposes was the TWDB, who maintains historical water use survey data for these uses with some records extending as far back as the mid-1950s. Historical reports provided information on groundwater development, which was used to inform when pumping of the aquifers began. Whenever possible, pumping for municipal, industrial, and power uses was assigned to specific wells. Well specific pumping was also developed using metered data from groundwater conservation districts and data from the Texas Railroad Commission for depressurization pumping associated with lignite mining. Based on current analysis, pumping has been assigned to about 3,300 specific wells.

6.4.6 Model Conversion and Construction

The groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers has been converted to MODFLOW-USG (Panday and others, 2013). One of the reasons for the conversion is the unstructured numerical grid capability of MODFLOW-USG that allows for locally-refined grids. As discussed in Section 6.2, refinement of the model grid has been performed for the Colorado River and its major tributaries and also for the Brazos River. Draft documentation explaining and evaluating the options in MODFLOW-USG for representing surface water-groundwater interaction for the updated model has been prepared. These options include the Drain package, the General Head Boundary package, the River package, the Stream package, the Streamflow Routing package, and the Connected Linear Network package.

The Connected Linear Network, Streamflow Routing, and Stream packages have the most sophisticated algorithms to model surface water-groundwater interactions because they can account for large changes in steam stage over short time periods. However, these packages are not well suited for use in the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers because this model uses yearly time steps, an estimated average annual river stage, and does not include detailed channel bathymetry. At the large temporal resolution of the model, the complex algorithms in these three packages are less numerically efficient than the other packages and could lead to unnecessary problems. Among the Drain, General Head Boundary, and River packages, the last provides the most robust capability for simulating surface water-groundwater interaction and was, therefore, selected for use in the updated model.

Although the use of the River package with refined grid cells and additional model layers for the Colorado River will provide the updated model with an improved capability to simulate surface water-groundwater interactions, these modifications will not provide all of the required capability to properly estimate all facets of surface water-groundwater interaction. Additional work that will be needed to address all aspects of surface water-groundwater interaction includes smaller times steps, estimated fluxes between streams and aquifers to serve as calibration targets, and a better understanding of the dynamic interaction between streams and groundwater, which can only be achieved by conducting appropriate field studies such as those proposed in Section 7.

6.4.7 Model Calibration

The model will be calibrated using the parameter estimating software PEST (Doherty, 2010). PEST is a widely accepted approach used and endorsed by the United States Geological Survey for calibrating groundwater models (Doherty and Hunt, 2010). The benefits of PEST are explained in the TWDB report that demonstrates how PEST was used to calibrate a groundwater model of the Edward-Trinity (Plateau) and Pecos Valley aquifers (Young and others, 2010). INTERA is currently in the process of adapting scripts to implement PEST for calibrating the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. INTERA has calibrated several recent groundwater availability models using PEST, including those for the High Plains Aquifer System (Deeds and Jigmond, 2015), the Brazos River Alluvium Aquifer (Ewing and Jigmond, 2016), and the Northern Trinity and Woodbine aquifers (Kelley and others, 2014). To expedite the calibration, INTERA will use a version of PEST that can be implemented on a computer cluster.

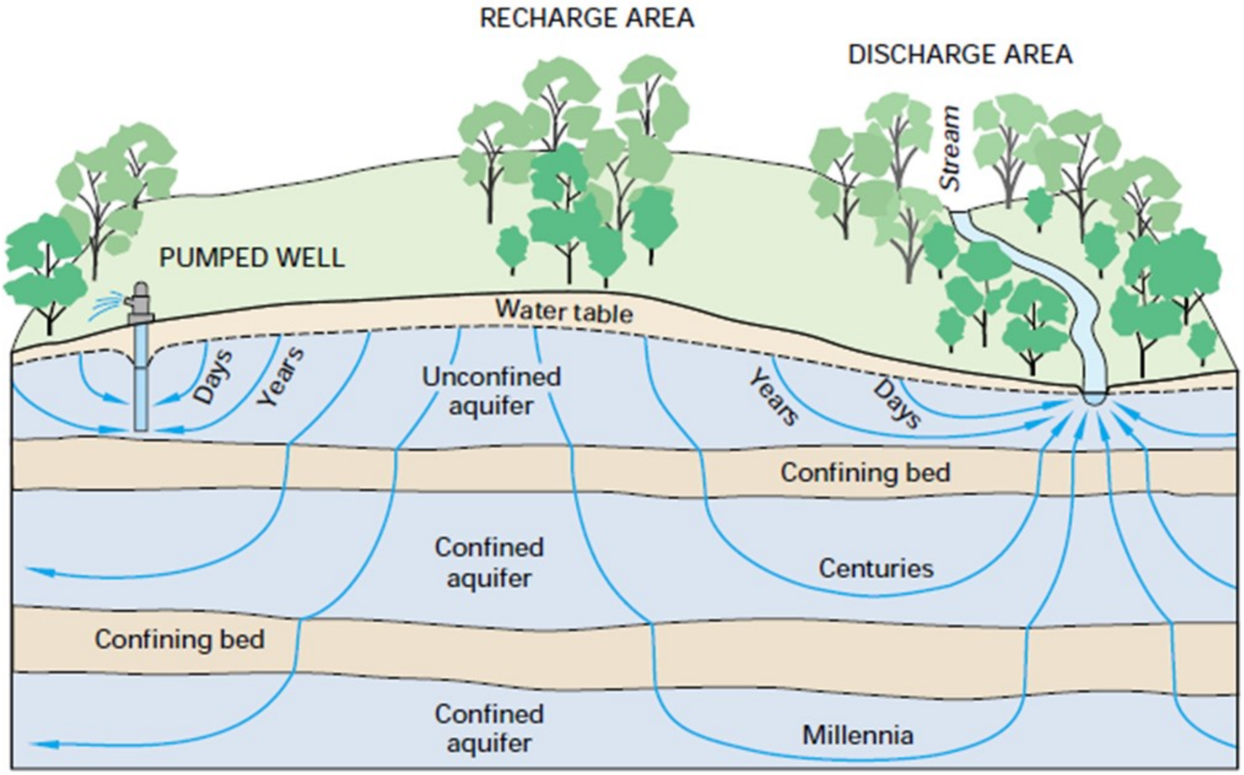
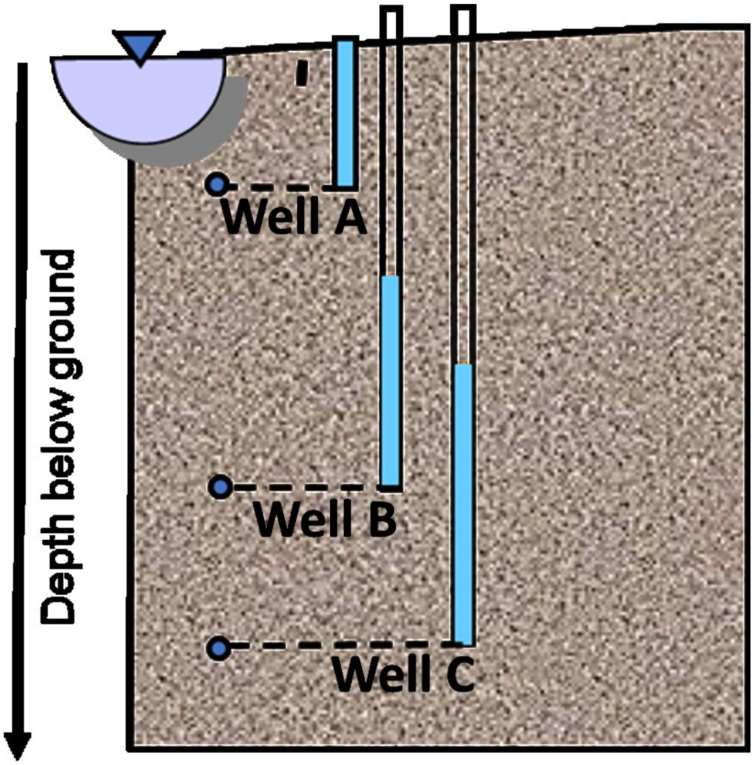


Figure 6-1. **Schematic illustration of the different spatial and time scales of groundwater flow paths (from Winter and others, 1998).**



Note: Low hydraulic head occurs at deeper wells because the deeper aquifer is being pumped

Figure 6-2. **Schematic showing the changes in hydraulic head in an aquifer beneath a stream as a result of deep pumping. Well A is located along a local groundwater flow path that discharges to the stream. Well B is located along an intermediate groundwater flow path that does not discharge to the stream. Well C is located along a deep, regional groundwater flow path that discharges at a nearby well field.**

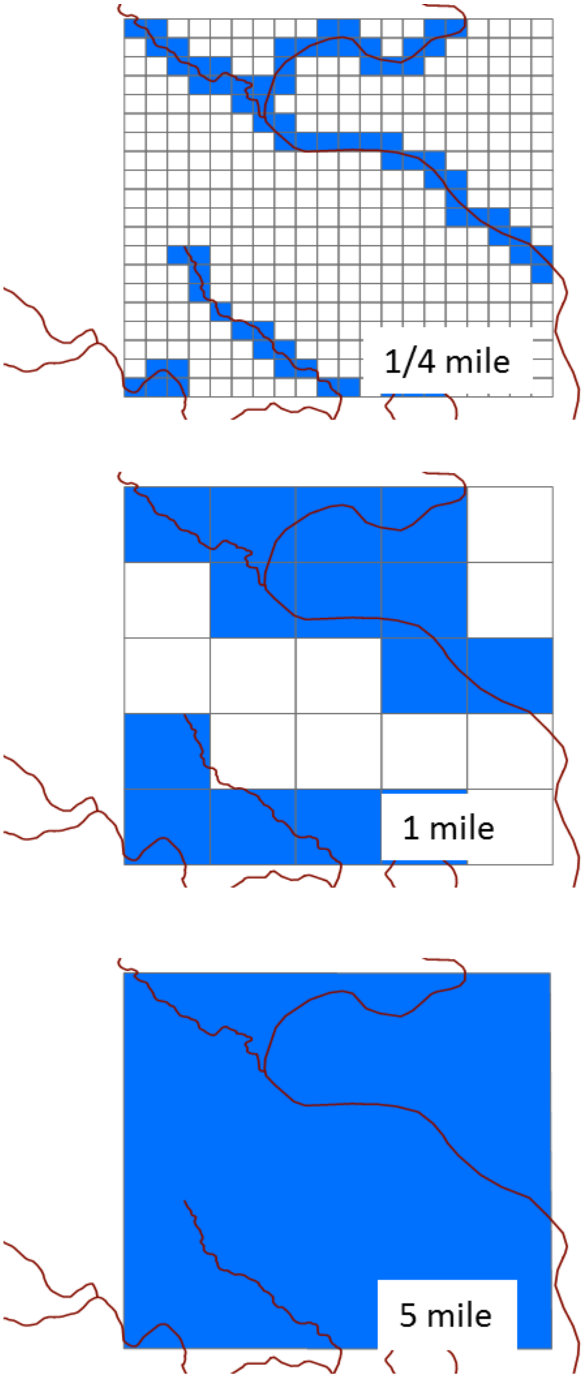


Figure 6-3. **Schematic showing the impact of grid cell size on the capability to accurately map the location of stream reaches onto a numerical grid.**

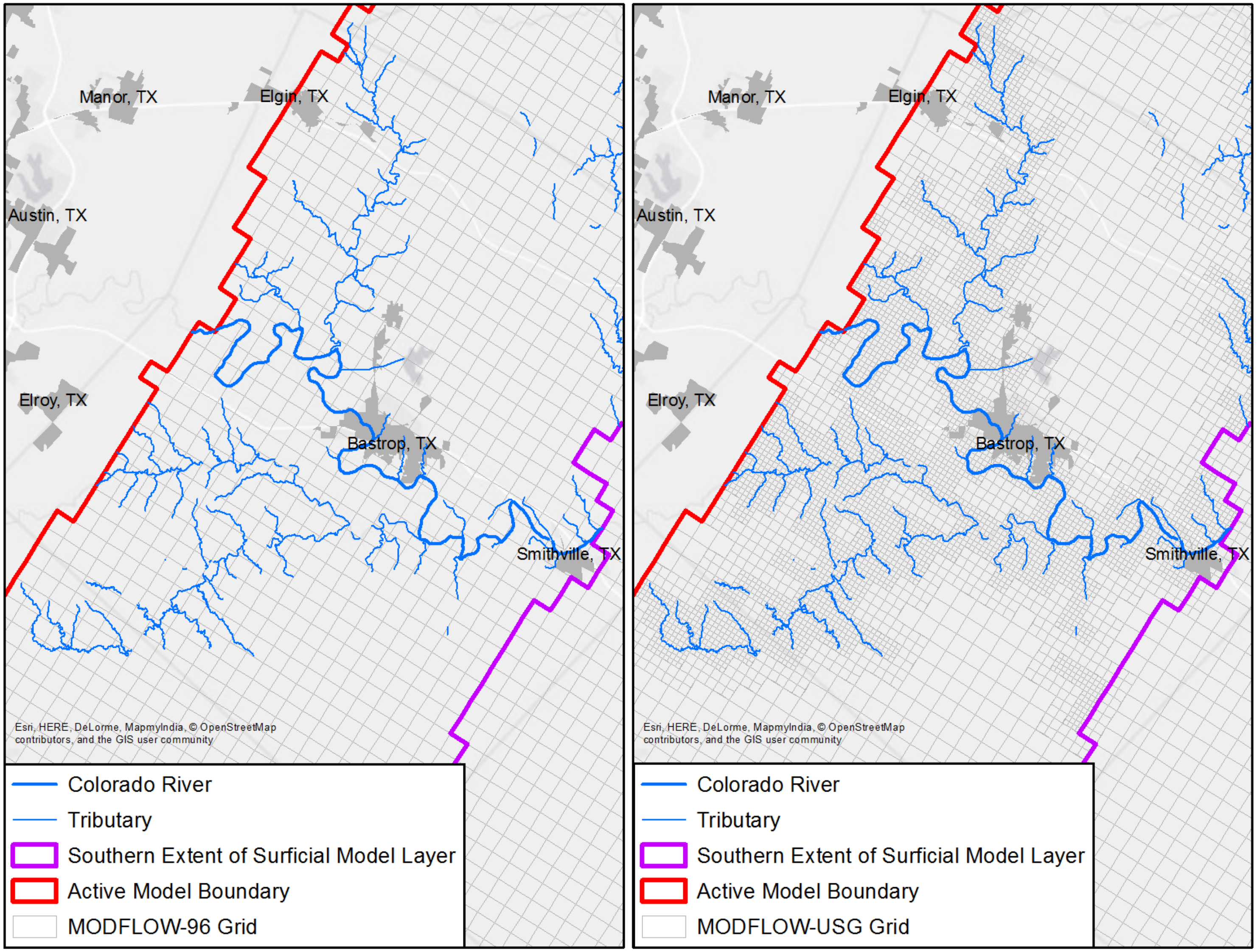


Figure 6-4. **Numerical grid showing the uniform 1-mile by 1-mile square grid cells in the existing groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers (A) and the locally-refined grid with 0.25-mile by 0.25-mile square grid cells in the vicinity of the Colorado River and it major tributaries in the updated model (B).**

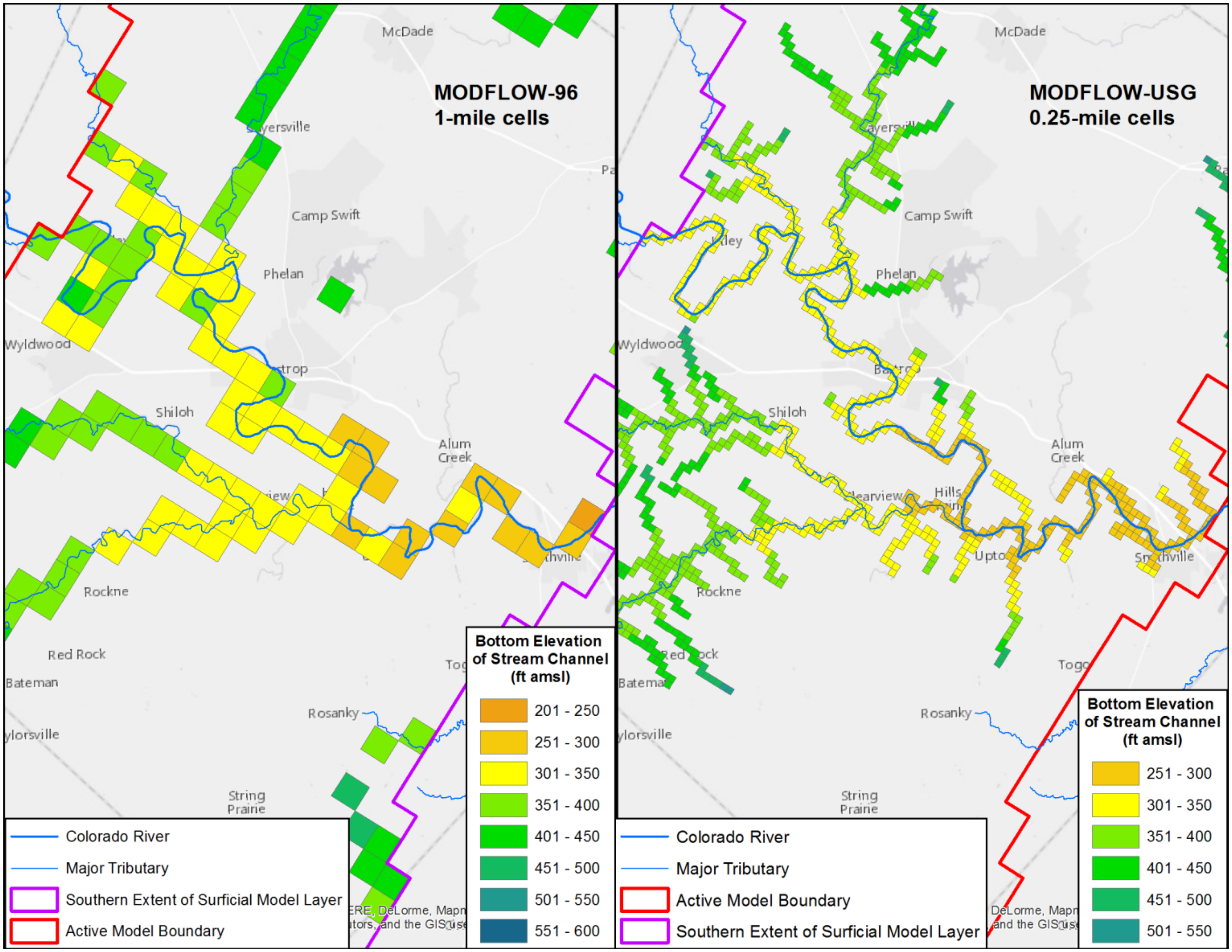
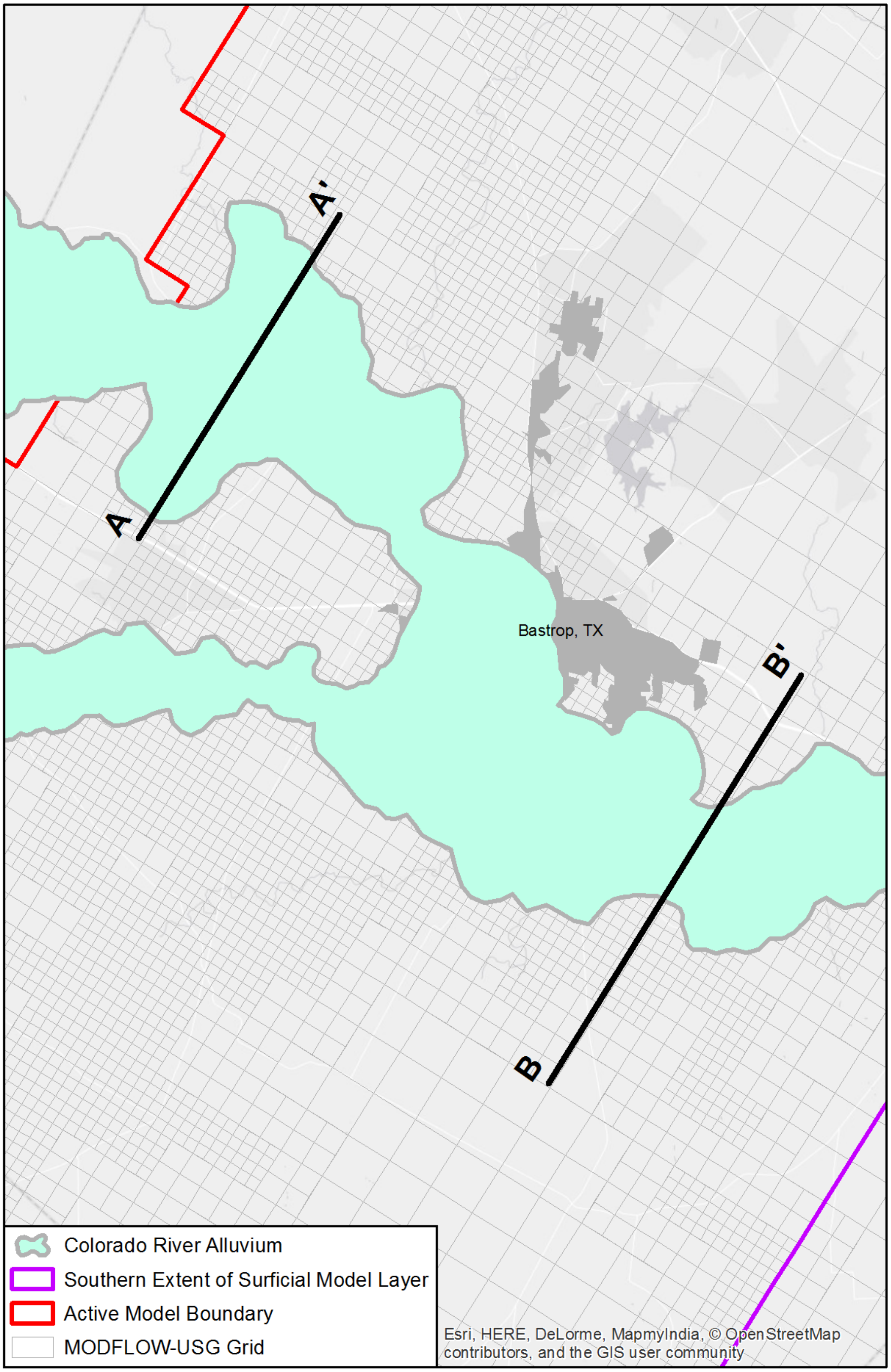


Figure 6-5. **Numerical grid and channel bottom elevations in feet above mean sea level for the uniformed grid cells used to represent the Colorado River and its major tributaries in the existing model (A) and the locally-refined grid cells used in the updated model (B).**



Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 6-6. **Areal extent of the Colorado River alluvium mapped onto the numerical grid for the updated groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers.**

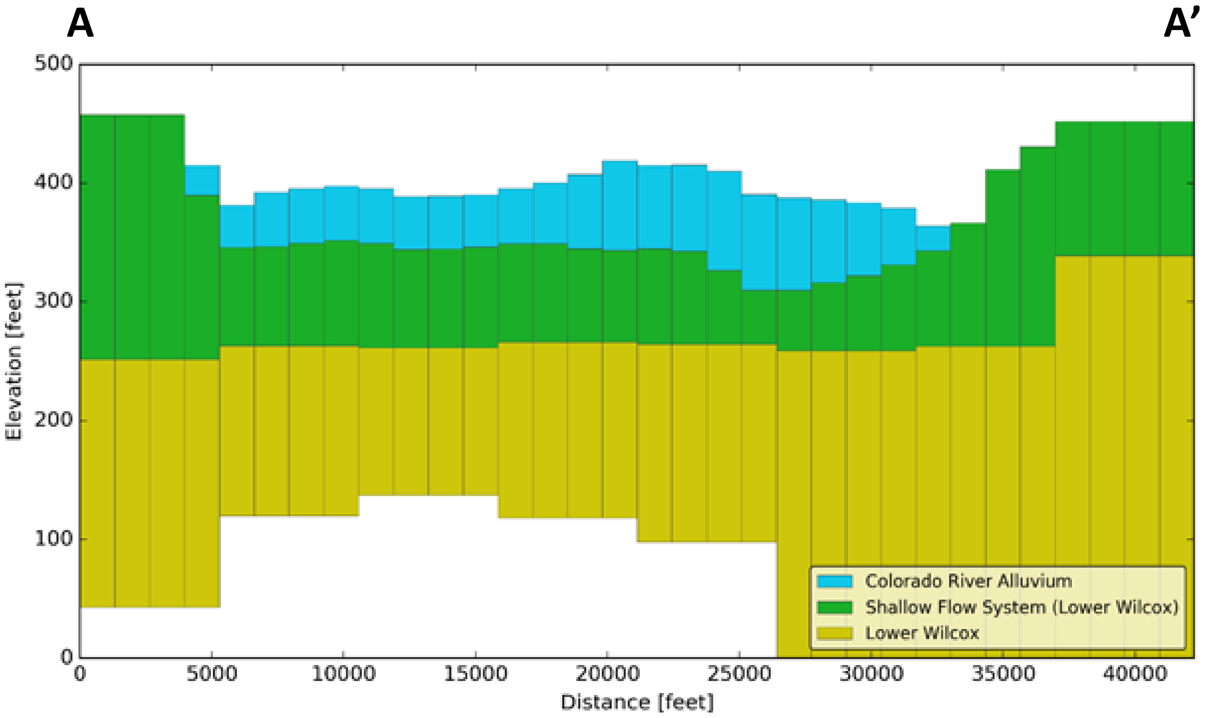


Figure 6-7. **Vertical cross-section for the updated model showing the model layers in the upper 400 feet along transect A-A' in Figure 6-6.**

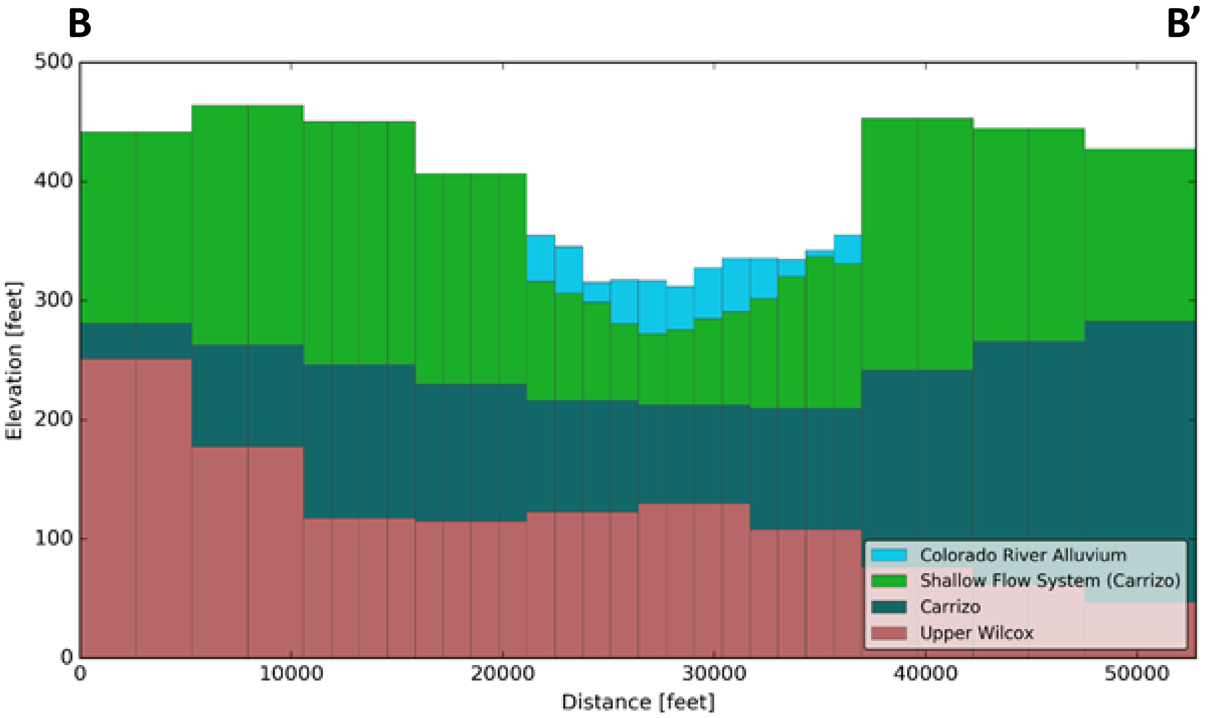


Figure 6-8. **Vertical cross-section for the updated model showing the model layers in the upper 400 feet along transect B-B' in Figure 6-6.**

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7 Field Study to Investigate Surface Water-Groundwater Interaction

This section provides a work plan for designing and implementing a data collection and analysis study to accomplish the following goals:

- Develop and demonstrate data collection and analysis methods that could (1) accurately determine stream gains and losses caused by interaction with the alluvium and (2) properly account for regulated stream conditions and bank storage.
- Quantify the exchange of water flux between the Colorado River and the alluvium over a range of different hydrological conditions.
- Estimate the net water flux exchange between the Colorado River and the alluvium at the field site locations for the length of the field data collection program.

7.1 General Approach to Data Collection and Analysis

The field study would assess surface water-groundwater interactions by monitoring collocated groundwater wells and surface water gages. Figure 7-1 shows a schematic of a fully built out field study site. The wells would be installed in the alluvium at varying distances from the river in a pattern that resembles the well array in Figure 7-2. In addition to alluvium wells, the monitoring program would include at least one well that intersects the river sediments and a few wells in the aquifer surrounding and beneath the alluvium. At a minimum, continual monitoring would occur in the river gage and in the alluvium wells. Continual monitoring would be performed by probes capable of measuring at 15-minute intervals for at least the following three parameters: hydraulic head (pressure head or water level), temperature, and specific conductance.

A numerical surface water-groundwater model would be used to interpret the field data and to develop estimates of the exchange of water between the stream and the alluvium over time. To complement and check the numerical predictions of stream gains and losses, a gain/loss analysis would be performed using assembled streamflow information. The best option for performing gain/loss analyses would be to use the Lower Colorado River Authority’s expertise and Daily Operational Routing Model (Carron and others, 2010) to estimate an upper and lower bound for stream gains or losses caused by flow between the stream and the alluvium.

Hydrograph separation would also be performed to investigate whether or not programs such as Base Flow Index (Wahl and Wahl, 1995) provide biased results for the regulated portion of the Colorado River. Results from the hydrograph-separation analysis could be used to help evaluate the findings of Wolock (2003a) and TWDB (2016), who present and discuss results obtained by using the Base Flow Index program to analyze river gages in a regulated portion of the Colorado River below the Highland Lakes.

7.2 Candidate Locations for the Field Study

Table 7-1 lists the factors that were considered in identifying and ranking sites to investigate the dynamics of water transfer between the Colorado River and the Colorado River alluvium.

Table 7-1. **Factors considered in identifying locations to investigate the dynamics of water transfer between the Colorado River and the Colorado River alluvium including bank storage.**

Factor	Importance	Explanation
Extensive alluvium	Essential	Extensive and permeable alluvium facilitates surface water-groundwater interaction.
Nearby river gage	Very High	A river gage is essential for the study. Installation of a new river gage would be approximately $50,000 and suitable location sites are limited.
Specific conductance changes significantly with increases and decreases in streamflow/stream elevation	Very High	The larger the solute concentration difference between the groundwater and the stream the greater the opportunity to estimate the water flux exchanged between the groundwater and the stream.
A wide range in seasonal stream temperatures	High	The larger the difference in the temperature between the groundwater and the stream the greater the opportunity to estimate the water flux exchanged between the groundwater and the stream.
Located above the outcrop of the Carrizo-Wilcox Aquifer	Moderately High	Significant increases in pumping are anticipated in the Carrizo-Wilcox Aquifer in the next 50 years. Groundwater conservation districts and environmental groups have expressed concerns regarding the effects of the higher pumping on water levels in the outcrops and on interactions between the Colorado River and groundwater.
Located at the up-dip or down-dip limit of a major or minor aquifer	Moderately High to Moderate	Determining the net impact of interaction between the Colorado River and groundwater in an aquifer requires monitoring of stream flow entering and leaving the aquifer outcrop.
Existing LSWP alluvium well or equivalent well that can serve as a monitoring well	Moderate	Using existing wells reduces the number of wells that would need to be installed for the study and provides historical water-level measurements that could be used to help determine appropriate spacing of monitoring wells.
Located above the outcrop of the Gulf Coast Aquifer System	Moderate	High pumping rates have traditional occurred in the Gulf Coast Aquifer System and are expected to continue. A site overlying the Gulf Coast Aquifer System would provide information on how the high pumping impacts the interactions between the Colorado River and groundwater.
Located in a groundwater conservation district	Moderate	Opportunity for assistance in funding or performing the field study.

Note: LSWP = Lower Colorado River Authority-San Antonio Water System Water Project

Six sites were identified and ranked using the criteria in Table 7-1. All six sites are located in the lower Colorado River Basin below Lake Travis. The primary reason for the absence of sites above Lake Travis is the lack of substantial alluvium deposits. Alluvium deposits are characterized by high permeability deposits that facilitate surface water-groundwater interactions. The sites are number from 1 to 6. The number of the site reflects its ranking relative to other sites. For instance, Site 1 is ranked as the most recommended and Site 6 is ranked as the least recommended. These rankings are based on a desktop study of very limited data and, therefore, may change after site visits have been performed. The term “site” refers to a general area and may contain several locations where a field study could be performed.

Figure 7-3 shows the areas associated with Sites 1, 2, and 3. Sites 1 and 2 include multiple river gages, but a field study would be performed at only one of the river gage locations. Site 1 includes four river gages, overlies the Carrizo-Wilcox Aquifer, is located in Bastrop County, is part of Groundwater Management Area 12, and its groundwater is managed by the Lost Pines Groundwater Conservation District. In addition, the Colorado River alluvium associated with Site 1 is mapped in Section 5. Site 2 includes three river gages, overlies the Gulf Coast Aquifer System, is located in Wharton County, is part of Groundwater Management Area 15, and its groundwater is managed by the Coastal Bend Groundwater Conservation District. Site 3 includes one river gage, overlies the Gulf Coast Aquifer System, is in Matagorda County, is part of Groundwater Management Area 15, and its groundwater is managed by the Coastal Plains Groundwater Conservation District. Site 2 includes the paired river gage and groundwater well used in the Lower Colorado River Authority-San Antonio Water System Water Project study (URS and Baer Engineering, 2007) for which water-level data are shown in Figure 4-10. Site 3 includes the paired river gage and groundwater well used in the Lower Colorado River Authority-San Antonio Water System Water Project study (URS and Baer Engineering, 2007) for which water-level data are shown in Figure 4-11.

Figure 7-4 shows the areas associated with Sites 4, 5, and 6. Each of these sites include two river gages, but the field study would be performed at only one of the river gage locations. The two river gages associated with Sites 4, 5, and 6 are located at the up-dip and down-dip extent of the outcrops for the Carrizo-Wilcox, Yegua-Jackson, and Queen City-Sparta aquifers, respectively, so that the net gain/loss between surface water and groundwater across the aquifer outcrop could be determined. Because there are two river gages associated with each site, each site consists of two parts - parts “a” and “b”. Part “a” includes the river gage located at the up-dip extent of the outcrop and part “b” includes the river gage located at the down-dip extent of the outcrop.

Site 4b uses an existing river gage to monitor flow in the Colorado River at the down-dip extend of the Carrizo-Wilcox Aquifer outcrop and Site 5b uses an existing river gage to monitor flow in the Colorado River at the down-dip extend of the Yegua-Jackson Aquifer outcrop. For both of these sites, a new river gage would need to be installed at the up-dip extent of the aquifer outcrop. To monitor the change in flow in the Colorado River across the outcrops of both the Queen City and Sparta aquifers, Site 6 would need to have both an up dip and down dip river gage installed. A concern with installing new river gages at an outcrop boundary is the potentially high cost to protect the gage during flooding if a secure structure, such as a bridge, is not available for supporting the river gage.

7.3 Data Analysis

Section 4 presents several low flow gain/loss studies that consistently show the Colorado River as gaining in the lower Colorado River Basin. Three potentially important questions that cannot be addressed by these gain/loss studies are:

- When stable low-flow conditions do not exist, what is the direction and magnitude of the water exchange between the alluvium and the stream?
- Does the majority of the water gained by the stream during low-flow conditions originate from bank storage or from the aquifer that surrounds the alluvium?
- How would pumping an aquifer or the alluvium near the stream affect the stream gains or losses over time?

- During persistent drought or extreme drought, is the quantity of groundwater sufficient to maintain critical/subsistence instream flows to get the river/stream through the drought in an ecologically sound condition?

With water supply becoming increasing more stressed as Texas's economy and population grows, the answers to these questions are important to develop informed management practices for both river authorities and groundwater conservation districts. For this reason, the data analysis method for the proposed field studies are designed to be robust and comprehensive. The study would incorporate the newest technologies associated with numerically modeling surface water-groundwater interaction along with current and historical analysis tools for river gage and well data.

Five methods would be used to analyze the data. Three of the methods are based on the application of a numerical model to simulate groundwater flow and transport along a vertical cross-section perpendicular to the stream. The model would include the stream, the stream bottom sediments, the underlying alluvium, and the aquifer encompassing the alluvium. The model would have the ability to (1) upload field measurement data, (2) perform a semi-automated calibration by adjusting the hydraulic boundary conditions and aquifer properties until best fits are achieved between measured and simulated values, and (3) calculate the direction and magnitude of the water exchanged between the stream and the alluvium and between the alluvium and the aquifer. Solute and transport modeling provide the means for understanding bank storage and determining how much of the water gained by a stream is original stream water sourced from bank storage or is actually groundwater from the alluvium.

The five data analysis methods are the hydraulic gradient method, the simulated solute concentration (or chemical separation) method, the simulated temperature method, the stream gain/loss or mass balance method, and the hydrograph-separation method.

7.3.1 Hydraulic Gradient Method

The hydraulic gradient method is based on Darcy's Law, which is used to calculate groundwater flow (Freeze and Cherry, 1979). Darcy's Law, which can be expressed as Equation 7-1, states that the direction of flow between the groundwater and a river can be determined by comparing the hydraulic heads within the groundwater with the water level in the river. If the river level is higher than the level in the adjacent groundwater, there will be a potential for the river to lose water into the groundwater. Conversely, if the river level is lower than the groundwater level adjacent to the river, then there is a potential for groundwater to flow into the river. It is possible to estimate the magnitude of the water exchange using Darcy's Law, which calculates flow as the product of the hydraulic gradient and transmissivity:

$$q = T\frac{\partial h}{\partial x} \qquad \text{Equation 7-1}$$

where:

q = flow rate into the alluvium perpendicular to the river
T = transmissivity of the alluvium
h = hydraulic head
x = distance

The hydraulic gradient method would be applied using both simple and advanced approaches. The simple approach would use a spreadsheet and the advanced approach would use the groundwater model. The Excel spreadsheet calculations would be based on an estimated transmissivity value for the alluvium and the difference in the elevations between the river height and the water levels in the wells. The advanced calculations would be conducted using a groundwater flow model that simulates groundwater along a vertical cross-section that intersects the groundwater wells and is perpendicular to the stream. An input to the model would be the measured stream height over time. The flow direction and magnitude of flow between the stream and the alluvium would be determined through a semi-automated procedure that adjusts aquifer parameters to obtain a best-fit between the measured and simulated water levels.

7.3.2 Simulated Solute Concentration Method

The simulated solute concentration method is based on a mass balance of solute exchange between the stream and the alluvium. There would be two advantages for using this method. One is that the method would provide an estimate of stream gain/loss that can be used to check the stream gain/loss estimate determined from the hydraulic gradient method. In addition, the method would help determine the origin (the alluvium, bank storage, or mixed) of the water gained by the stream during low-flow conditions. Numerous studies have successfully applied this approach using salinity (SKM, 2012; Porter, 2001; Stelfox and Western Australia, 2001; Brodie and others, 2005; Oxtobee and Novakowki, 2002; Boulton and others, 1999). These studies typically involve unregulated streams where the solute concentrations in runoff and groundwater are considered end members of the range in concentrations that are measured. In situations where the runoff component of a gage hydrograph is assumed to be a constant concentration, the simulated solute concentration method is referred to as chemical hydrograph separation.

Among the complicating conditions for the study would be that the difference in the salinity between the stream water and groundwater will be changing over time and, for some of the time, the difference between the two concentrations may not be large. Based on data provided in Section 4, during flood events, when significant changes can occur in the river solute concentrations, a groundwater flow and transport model could be used to estimate the chemical and solute flux that occurs between the stream and the groundwater.

7.3.3 Simulated Temperature Method

Besides salinity, another tracer that could be used to estimate the surface water-groundwater interaction is temperature. Among the reasons for using this method would be to provide a check on the stream gain/loss estimates from the hydraulic gradient method and the simulated solute method.

The data in Section 4 suggest that seasonal temperature variations are significantly different for stream water and groundwater. Large temperature differences in the heat of summer and the cold of winter provide for a prime opportunity to use temperature to evaluate surface water-groundwater interaction. Among the studies that have used temperature to determine water movement between streams and aquifers are Silliman and Booth (1993), Baskaran and others (2009), Gerecht and others (2011), Anibas and others (2009), Essaid and others (2008), Jensen and Engesgaard (2011), Lautz and Ribaudo (2012), and Schmidt and others (2006.)

A pioneering study performed by Silliman and Booth (1993) hypothesized temperature signals for both a gaining and losing stream. The first case (Figure 7-5a) shows signals for a stream that is strongly gaining groundwater. In this case, the temperature in the sediments is controlled by advection from the groundwater system. The sediments will reflect the temperature of the groundwater and would be expected to remain relatively constant over periods of days. In gaining conditions, shallow sediments show little variation as the influence of surface temperature is moderated by water flowing upward from depths where temperatures are constant (Baskaran and others, 2009).

The second case (Figure 7-5b) represents a losing condition with seepage flux from the stream to the aquifer, where the temperature in the sediments closely mimics the temperature of the surface water. In losing streams, the downward flow of water transports heat from the stream into the sediments, which propagates diurnal temperature fluctuations into the sediment profile (Baskaran and others, 2009).

To complement and expand on the graphical analysis methods like those illustrated in Figure 7-5, the groundwater flow model would be constructed so that it could simulate temperature. Heat transport in the subsurface is a combination of advective heat transport (i.e., heat transport by the flowing water) and conductive heat transport (i.e., heat transport by heat conduction through the solid and fluid phase of the sediment). Among the groundwater flow and heat codes that would be considered for this project is Hydrogeosphere (Therrien and others, 2010).

7.3.4 Stream Water Balance (or Gain/Loss) Method

The stream water balance is based on the type of measurements and calculations associated with the gain/loss studies discussed in Section 4.1.2. However, for this application, the method would not be performed manually but rather by using the Lower Colorado River Authority Daily Routing Operation Model (Carron and others, 2010). The Daily Routing Operation Model begins its simulation at Tom Miller Dam in Austin and routes streamflow downstream. The model includes gaged tributaries, return flows, releases from Lake Travis, releases from Lady Bird Lake, and known diversions. Its routing routine includes mass balance calculations and storage routines. The Daily Routing Operation Model is primarily a forecasting tool, but it can be used to develop a rough estimate of groundwater flows. When run to simulate historical flows, the Daily Routing Operation Model will predict ungaged flow at a stream gage. The ungaged flow is the difference between the observed streamflow at the gage and the model predicted streamflow. Ungaged flow represents flow not accounted for by the Daily Routing Operation Model routines, which include losses or gains from groundwater, rainfall/storm runoff, stream gage error, evapotranspiration, ungaged tributary flow, and inaccuracies in flow routing. A negative ungaged flow suggests that the stream is losing while a positive ungaged flow suggests that the stream is gaining.

Daily Routing Operation Model simulations would have limited but potentially valuable application, as they could be used as an independent check of the numerical predictions of stream gains and losses from the groundwater model simulation. The best opportunity to use the Daily Routing Operation Model to estimate surface water-groundwater exchange would be during times of low steady flow when there are no unaccounted tributary flows, no runoff, and diversions are small. For this discussion, the Lower Colorado River Authority identified periods of low flow in 2012, 2013, 2014, and 2015 and provided INTERA with spreadsheets of the simulated ungaged flows (Lower Colorado River Authority, 2017c). Using information from those spreadsheets, INTERA developed Figure 7-6 through Figure 7-9. For these time periods, the gains and losses appear reasonable based on the gain/loss results presented in Section 4, and indicate that gaining and losing conditions along the river vary both spatially and temporally. These types of data could be reviewed in context with field conditions at particular stream gages to help correlate what occurs at the study site with other regions of the Colorado River.

To help convey the information in Figure 7-6 through Figure 7-9, the plots in Figure 7-8 are discussed. The plots in Figure 7-8 report ungaged flows for a 25-day period beginning February 1, 2014 and ending February 25, 2014. The gages for the lower Colorado River Basin are ordered on the page from the most up-river gage, which is the Austin gage, to the most down-river gage, which is the Wharton gage. For this discussion, the assumption is made that the Daily Routing Operation Model did not include any gaged data between Austin and Wharton at locations other than those shown in Figure 7-8. The positive ungaged flow values for the Bastrop gage indicate that between the Austin and Bastrop gages, the Colorado River gained an average of about 35 cubic feet per second over the 25-day period. The near zero ungaged flow values for the Smithville gage indicate that between the Bastrop and Smithville gages, the Colorado River lost about as much as it gained during the 25-day period. The positive ungaged flow values for the LaGrange gage indicate that between the Smithville and LaGrange gages, the Colorado River gained an average of about 22 cubic feet per second over the 25-day period. Based on the ungaged flow values for the Columbus gage, the Colorado River lost an average of about 18 cubic feet per second from February 1st to 17th and then averaged a slight gain from February 17th to 25th between the LaGrange and Columbus gages. The ungaged values for the Wharton gage indicate that between the Columbus and Wharton gages, the Colorado River transitioned from gaining approximately 50 cubic feet per second on February 1st to losing approximately 20 cubic feet per second on February 15th.

7.3.5 The Base-Flow Separation Method Using the Base Flow Index Program

As discussed in Section 4, a stream hydrograph represents the aggregate of the different water sources that contribute to streamflow (Brodie and others, 2005). One type of approach to estimate base flow from groundwater contribution is base-flow separation. To efficiently and automatically determine the base-flow component of a stream hydrograph, Wahl and Wahl (1995) developed the Base Flow Index program for unregulated streams. The Base Flow Index program is widely used in the United States and is sometimes applied to regulated streams. The Base Flow Index program would be used to estimate base flow using the stream gage data to determine if errors would be introduced when applied to a regulated stream.

7.4 Approach for Conducting the Field Study

The approach for conducting the field study and associated costing assume the selection of two sites; a site at one of the river gages at Site 1 and one site at one of the river gages in either Site 2 or Site 3. The field study would be conducted in two phases. Phase I tasks are discussed in Table 7-2. Phase II tasks are discussed in Table 7-3.

Phase I is estimated to cost between $80,000 and $140,000 and last 6 months. The large range in the cost estimate results from a general lack of information regarding the sites, questions regarding the access for drill rigs, the willingness of the Lower Colorado River Authority to support the study, and uncertainty with the temporal variability in the specific conductance concentrations in the stream and the Colorado River alluvium. Among the options that would be explored to reduced field costs is the use of Geoprobe Rigs (Figure 7-10) instead of drill rigs to install wells and to place thermistors and specific conductance probes into the stream sediments without using wells or drive points.

Table 7-2. Major tasks and costs associated with Phase I for the field study performed at two locations.

Task	Description	Estimated Costs
1. Establish Project Objectives, Visit Sites, Site Reconnaissance and Selection	Establish project objectives and identify best potential sites. Visit sites to determine the best option for conducting the study. Key objectives would be to establish site security, availability of unrestricted access to site, good logistics for drilling, and possible opportunity to install drive points into stream sediments.	\$20K - \$40K
2. Exploratory Data Collection	Install temporary probes to continuously measure specific conductance in the river gages at Sites 1, 2, and 3, the LSWP alluvial wells in Wharton and Matagorda counties, and at an existing well in the alluvium at Site 1. Collect data for 4 months.	\$30K- \$50K
3. Exploratory Data Analysis	Construct a simple groundwater model to determine appropriate well spacing and frequency of monitoring. Perform preliminary analysis of available data.	\$10K - \$20K
4. Project Funding Sources and Potential Cooperators	Develop and execute a plan to obtain project funding and potential cooperators. Contact groundwater conservation districts, the USGS, universities, the TWDB, environmental organizations, and the LCRA.	\$10K - \$15K
5. Develop Detailed Work Plan for a Multi-Year Project	Design the field study based on results from Tasks 1 through 4. Contract vendors and contractors to secure bids. The field study would be planned at two sites and be scheduled to be completed in 2 years.	\$10K - \$15K
	Total	\$80K -\$140K

Note: K = thousand, LSWP = Lower Colorado River Authority-San Antonio Water System Water Project, USGS = United States Geological Survey, LCRA = Lower Colorado River Authority

Table 7-3 provides a summary of the major tasks and costs associated with Phase II. A cost range is given for each task. Phase II should collect field data for at least a 2-year period to include a range of field conditions. The largest unknown is the drilling costs. Drilling costs are dependent on site access and whether or not Geoprobe Rigs could be used to install some of the wells. The costs associated with drilling would be addressed as part of Phase I. The costs are based on a minimum of four wells installation at two sites. Other potentially important cost unknowns are the costs for installing probes in the streambed and the costs associated with security and building access roads.

Table 7-3. Major tasks and costs associated with Phase II for the field study performed at two sites.

Task	Estimated Costs
1. Install Monitoring Wells and Staged Piezometers in Alluvium, Aquifer, and Streambed	$60K - $100K
2. Purchase and Install Monitoring Equipment for Water Levels, Specific Conductance, and Temperature	$40K - $60K
3. Data Collection and Analysis	$85K - 125K
4. Reporting and Meetings	$30K - $50K
Total	$215 - $335K

Note: K = thousand

The collection and analysis of data in Task 3 in Table 7-3 would include rainfall and pumping information relevant to interpreting water levels from river gages and the groundwater wells. Groundwater pumping in the vicinity of the field study would be important if the pumping is sufficient to affect groundwater flow and water levels in the alluvium. As shown in Figure 7-1, the monitoring network would include measuring water levels in and beneath the alluvium to help identify changes over time in flow between the underlying aquifer and the alluvium. A possible good source for pumping data are local groundwater conservation districts. Project coordination with a groundwater conservation district should begin in Phase I. In Phase II, available information for all registered wells near the field site should be obtained from the groundwater conservation districts, including historical pumping, operational permits, and estimates of future pumping. After the pumping data have been obtained, an assessment should be made regarding whether nearby pumping outside of the study area should be monitored.

Precipitation data would provide useful information for helping to interpret water-level changes in the underlying aquifer and alluvium. When water levels rise in the monitoring wells, rainfall measurements would be used to help determine whether infiltration is partly responsible for the rise. Figure 7-11 shows the available rain gages in the lower Colorado River Basin. Reported precipitation from a subset of these gages would be monitored to evaluate whether regional rainfall was great enough to cause observed rises in groundwater levels and to evaluate whether runoff from the precipitation has contributed to flow in the Colorado River. For the proposed study, the most important location to measure rainfall would be at the field sites. At or near the field sites, a rainfall monitoring system, such as a tipping bucket, should be installed and connected to a datalogger to record rainfall at hourly intervals.

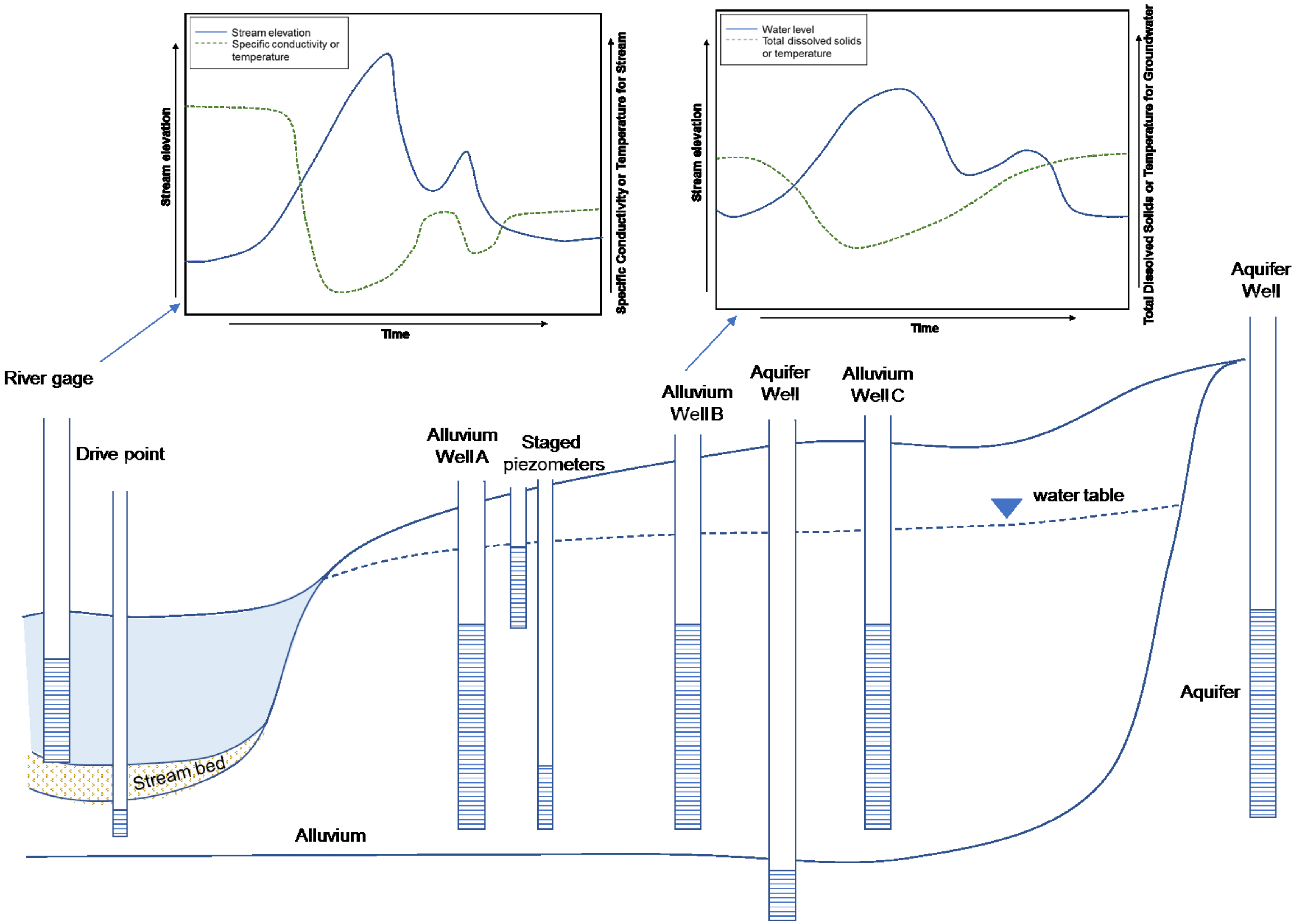

Figure 7-1. Schematic of comprehensive monitoring well network for field study.

Figure 7-2. Network of monitoring wells installed in the Colorado River alluvium at Hornsby Bend using a Geoprobe System under flow conditions (A) and after a 10,000-cubic-feet-per-second storm event (B) (from Barrera, 2015).

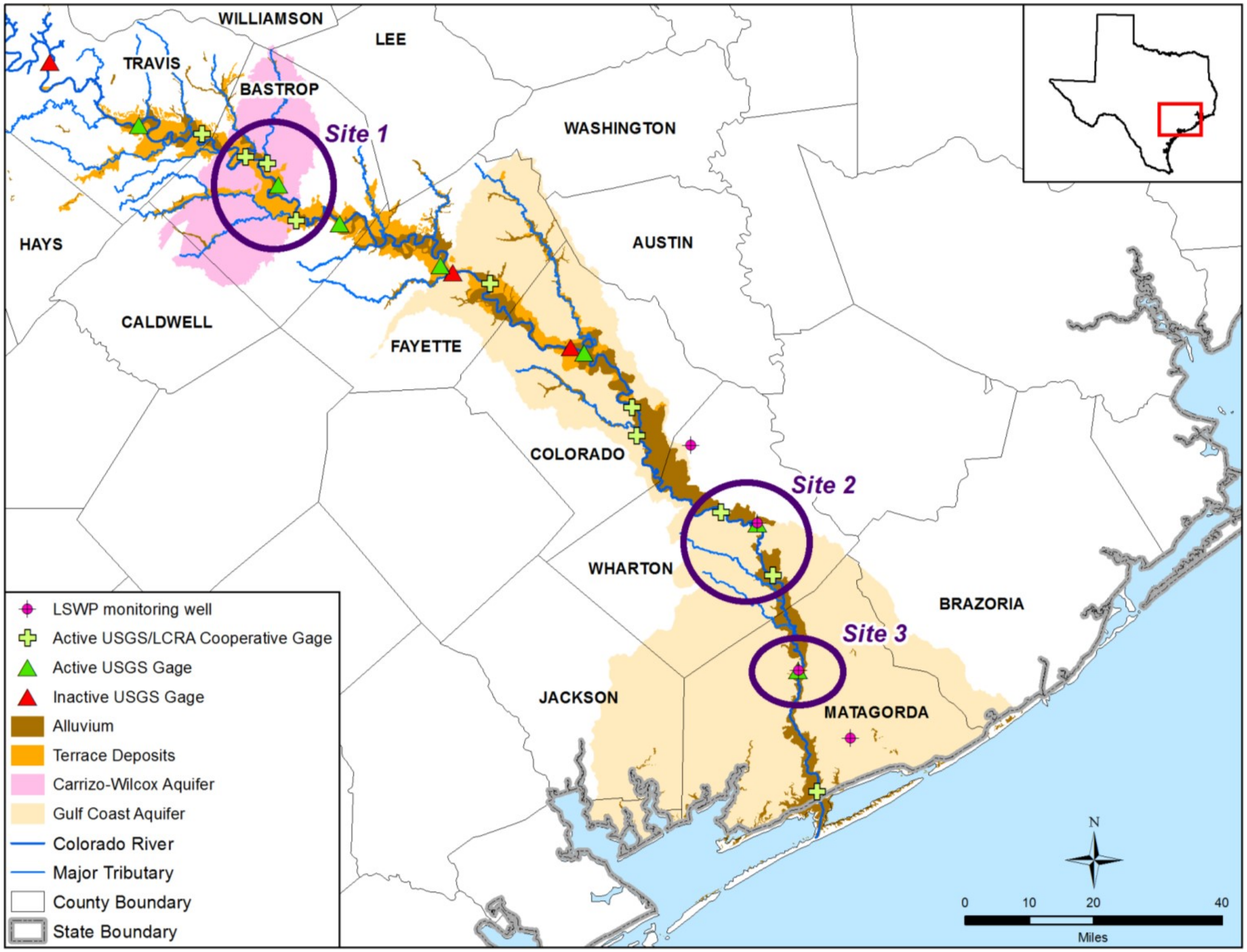

Figure 7-3. **Locations of Sites 1, 2, and 3 for the proposed field study.**

Note: LSWP = Lower Colorado River Authority-San Antonio Water System Water Project, USGS = United States Geological Survey; LCRA = Lower Colorado River Authority

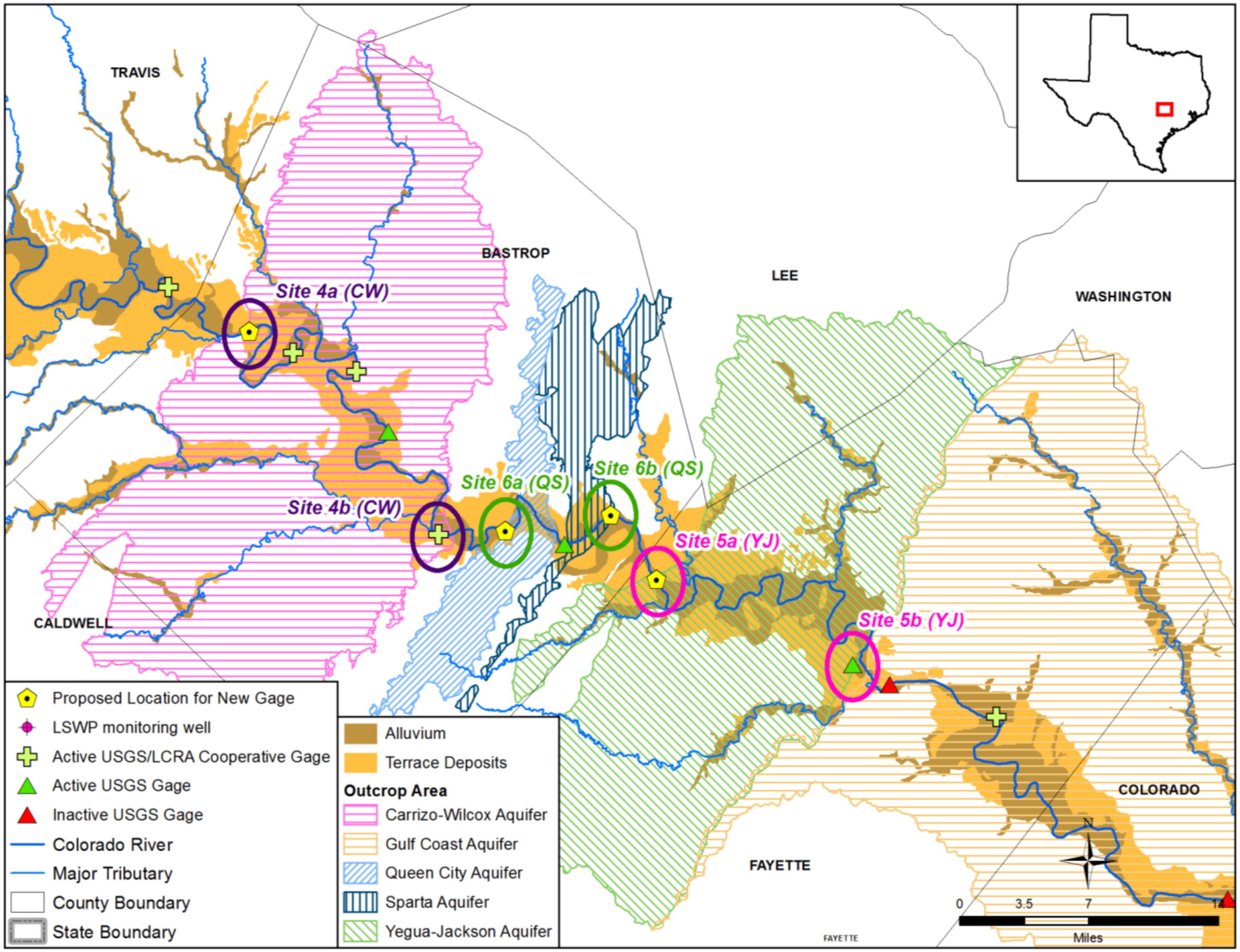

Figure 7-4. Locations of Sites 4, 5, and 6 for the proposed field study.

Note: LSWP = Lower Colorado River Authority-San Antonio Water System Water Project, USGS = United States Geological Survey; LCRA = Lower Colorado River Authority

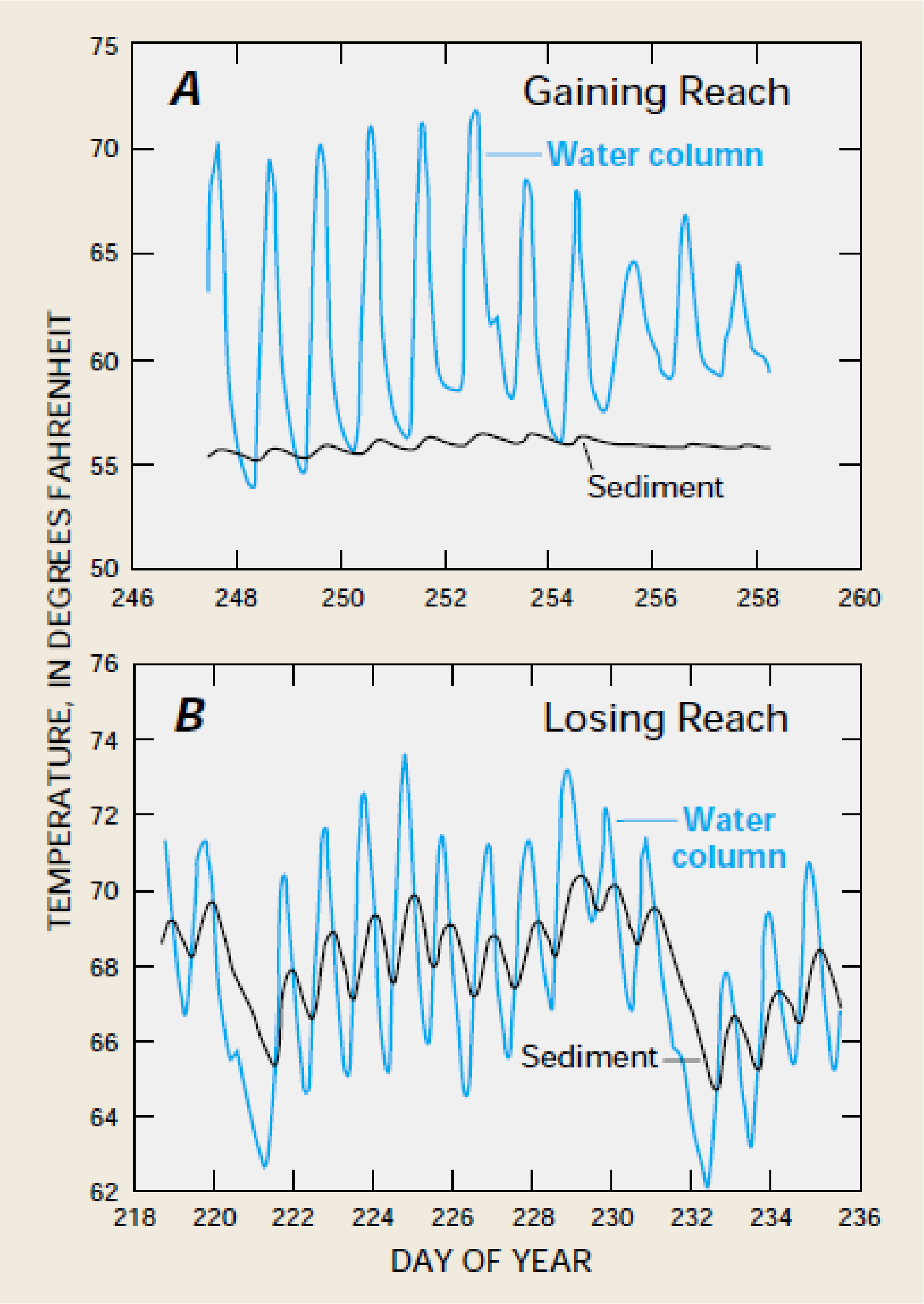

Figure 7-5. **Temperature profiles from field study on gaining reach (A) and losing reach (B) of Juday Creek in Indiana (Silliman and Booth [1993] as presented in Winter and others [1998]).**

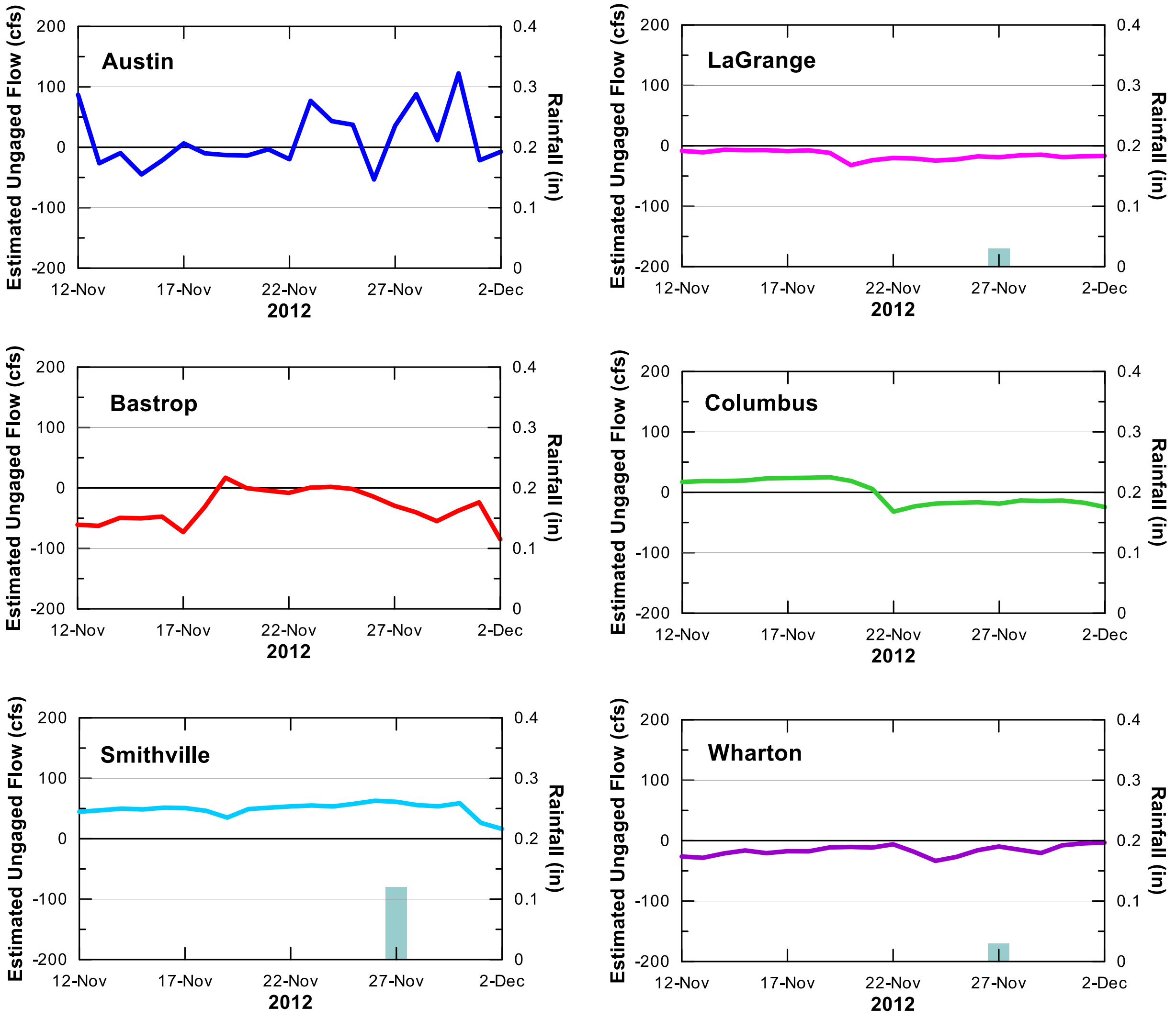

Figure 7-6. **Calculated ungaged flow (colored lines) from the Lower Colorado River Authority's Daily Operation Routing Model at six river gages for low-flow conditions in 2012. Ungaged flow estimates were produced by the Lower Colorado River Authority for its own use. Gage uncertainty, flow variability, and other issues can affect the accuracy of the estimates. Rainfall values (blue-green bars) were assembled by INTERA from rain gages located near the river gage.**

Note: cfs = cubic feet per second, in = inches

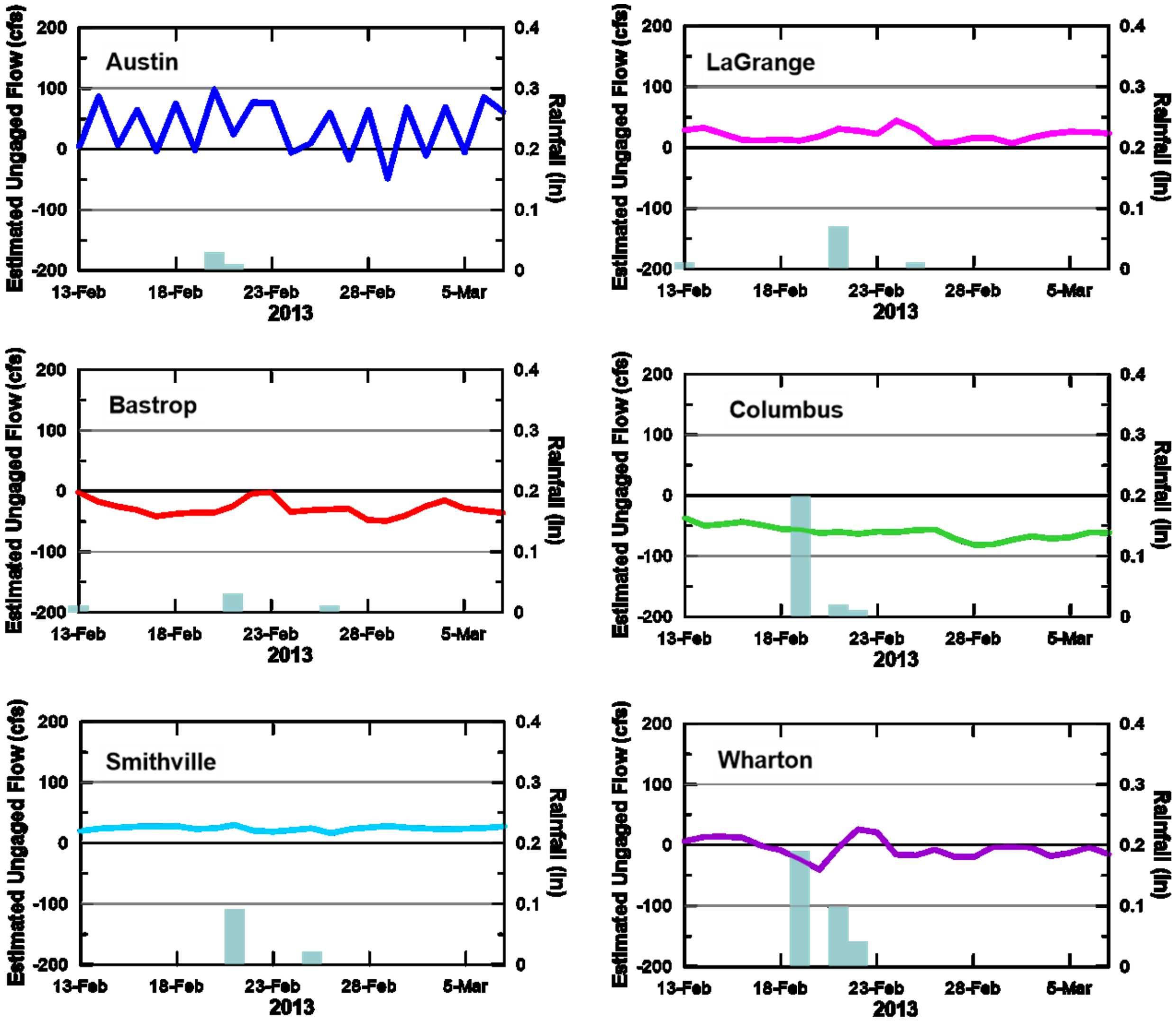

Figure 7-7. **Calculated ungaged flow (colored lines) from the Lower Colorado River Authority's Daily Operation Routing Model at six river gages for low-flow conditions in 2013. Ungaged flow estimates were produced by the Lower Colorado River Authority for its own use. Gage uncertainty, flow variability, and other issues can affect the accuracy of the estimates. Rainfall values (blue-green bars) were assembled by INTERA from rain gages located near the river gage.**

Note: cfs = cubic feet per second, in = inches

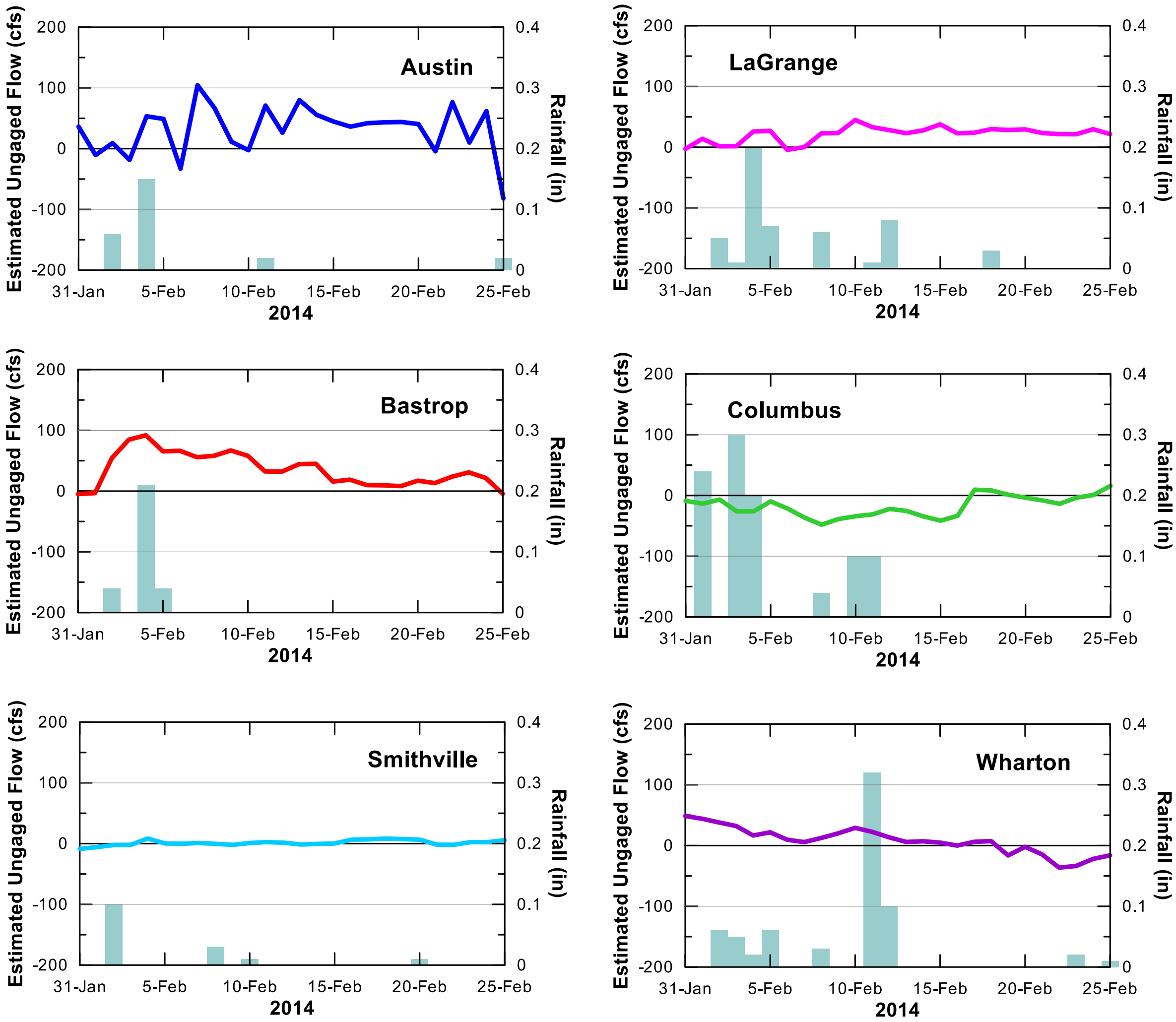

Figure 7-8. **Calculated ungaged flow (colored lines) from the Lower Colorado River Authority's Daily Operation Routing Model at six river gages for low-flow conditions in 2014. Ungaged flow estimates were produced by the Lower Colorado River Authority for its own use. Gage uncertainty, flow variability, and other issues can affect the accuracy of the estimates. Rainfall values (blue-green bars) were assembled by INTERA from rain gages located near the river gage.**

Note: cfs = cubic feet per second, in = inches

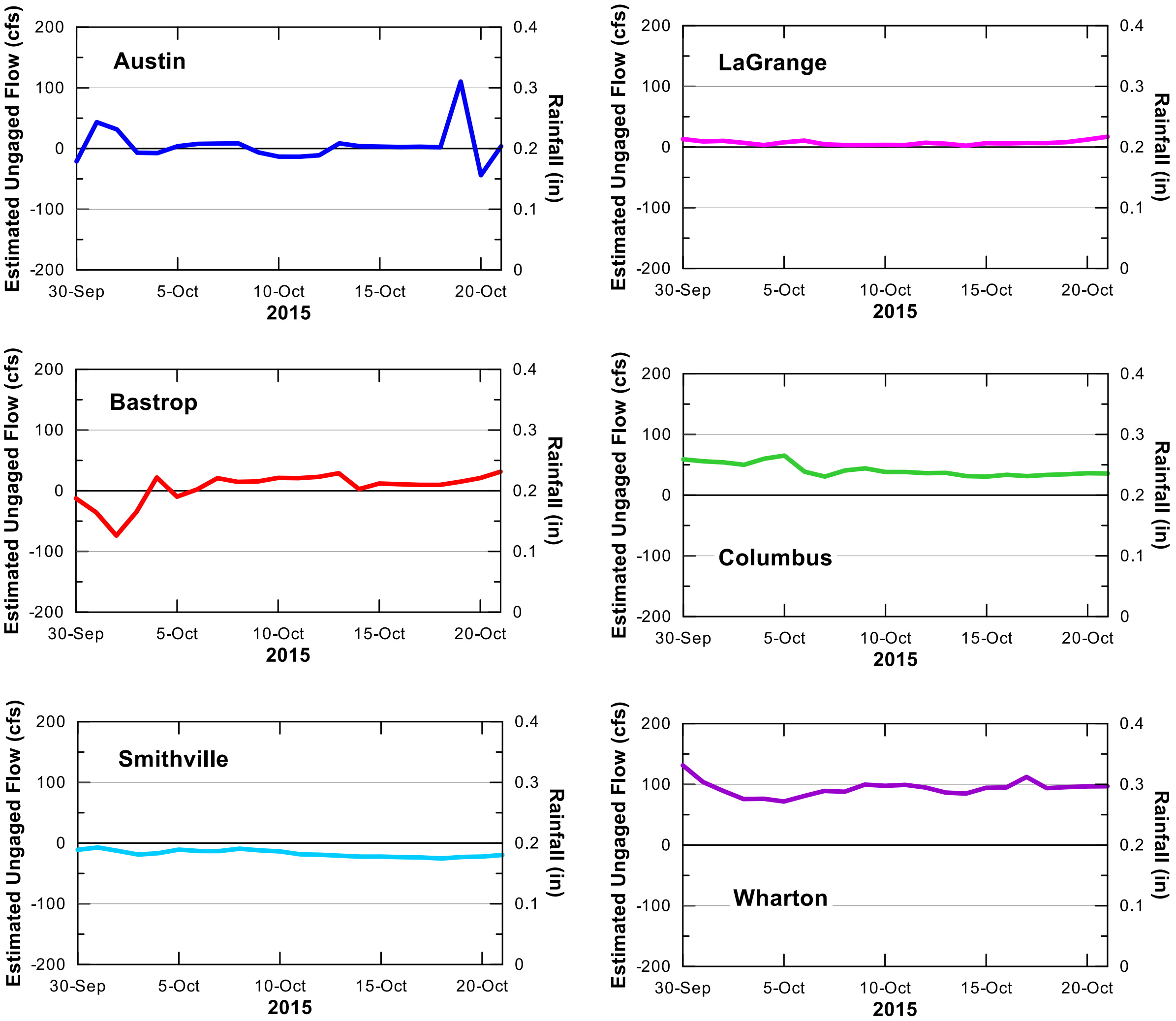

Figure 7-9. **Calculated ungaged flow (colored lines) from the Lower Colorado River Authority’s Daily Operation Routing Model at six river gages for low-flow conditions in 2015. Ungaged flow estimates were produced by the Lower Colorado River Authority for its own use. Gage uncertainty, flow variability, and other issues can affect the accuracy of the estimates. Rainfall values (blue-green bars) were assembled by INTERA from rain gages located near the river gage.**

Note: cfs = cubic feet per second, in = inches

Figure 7-10. Examples of Geoprobe Rigs (provided courtesy of Vortex Drilling, Inc in San Antonio, Texas and Pro-Tech in Baton Rouge, Louisiana).

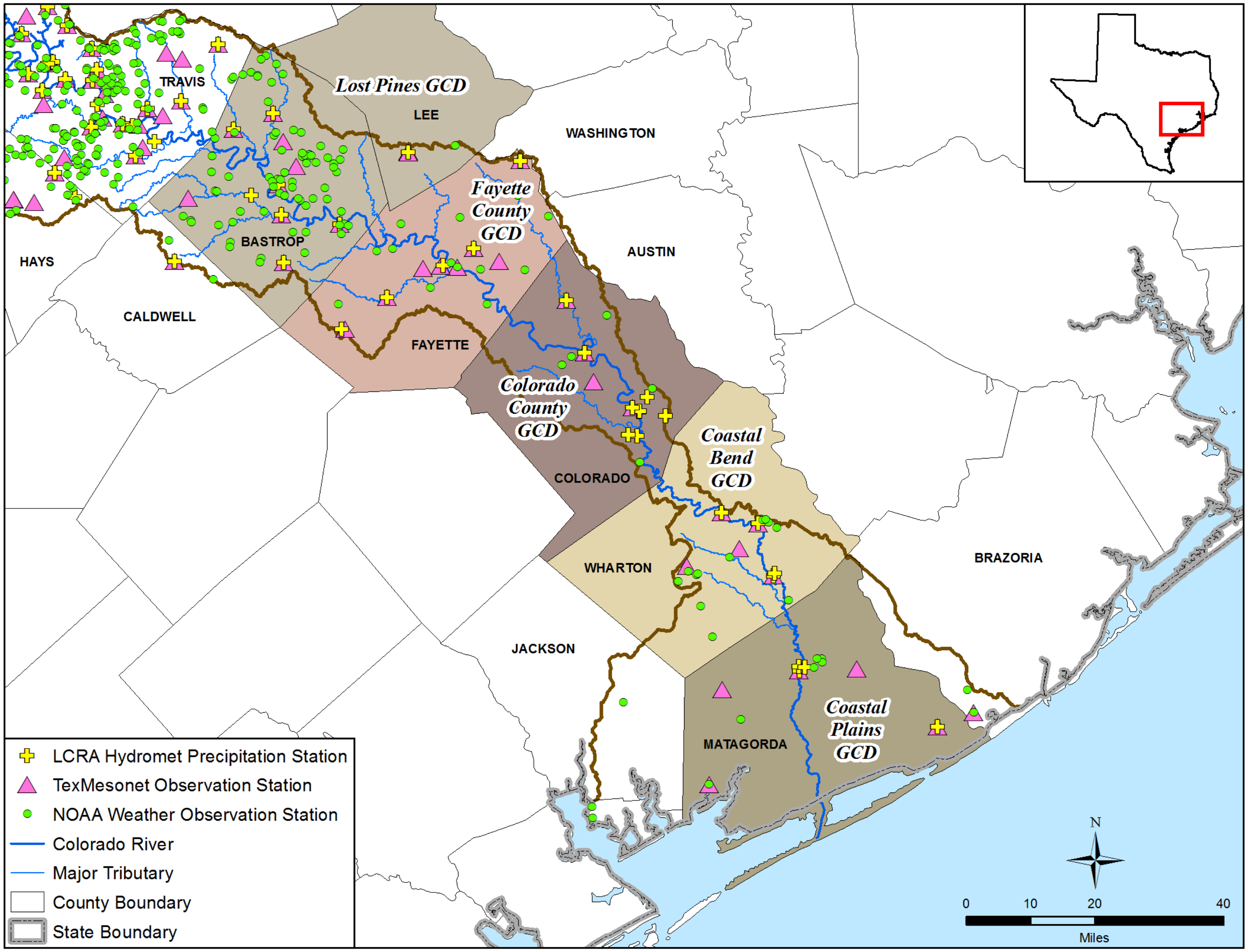

Figure 7-11. **Location of precipitation gages and groundwater conservation districts in the lower Colorado River Basin (Lower Colorado River Authority, 2017d; TexMesonet, 2017; National Centers for Environmental Information, 2017).**

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9 Appendix A – Well Dataset for Mapping the Colorado River Alluvium in and near Groundwater Management Area 12

Table A-1. Wells with base of alluvium pick.

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
5844806		5690674.71	19332142.22	Travis	Manville WSC	420	419.61	45	GWDB	41
5844807		5691558.82	19331756.77	Travis	Mansville WSC	418	417.70	48	GWDB	46
5852206		5687378.28	19318805.41	Travis	Claud Burgess	410	410.03	50	GWDB	40
5852213		5689178.39	19320566.16	Travis	Longhorn Sand and	400	405.10	37	GWDB	35
5852217		5692280.91	19326811.09	Travis	Unknown	415	416.41	55	GWDB	53
5852302		5704131.58	19321607.54	Travis	Edgar Fowler	410	410.58	60	GWDB	40
5852303		5703666.94	19322812.01	Travis	Colorado Lodges	415	410.82	48	GWDB	42
5852304		5699928.49	19317665.77	Travis	Garfield Water Supply	400	396.08	63	GWDB	56
5852307		5703853.50	19322309.90	Travis	J.B. Turner	400	410.91	70	GWDB	45
5852313		5702841.42	19320566.02	Travis	River Timbers	402	402.41	46	GWDB	40
5852314		5697501.12	19324395.78	Travis	Manville WSC	409	408.59	61	GWDB	57
5852505		5685831.29	19309456.76	Travis	Garfield Water Supply	405	403.89	48	GWDB	44
5853105		5713216.69	19314927.90	Bastrop		407	399.05	38	GWDB	22
5853502		5727348.09	19306138.62	Bastrop	Glen Harwell	395	407.47	86	GWDB	49
5853603		5739984.67	19305318.91	Bastrop	Crenshaw and Doguett	386	360.22	190	GWDB	64
5853901		5739724.72	19297719.50	Bastrop	Ted Deison	390	391.47	110	GWDB	55
5853912		5738792.14	19296381.44	Bastrop	James L. Broadhurst	390	391.00	153	GWDB	90

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
5854403		5751595.80	19303467.11	Bastrop	T. C. "Buck" Steiner	445	391.99	170	GWDB	8
5854404		5752374.08	19303890.60	Bastrop	Steiner Ranch	442	441.44	305	GWDB	15
5854705		5753961.87	19299777.46	Bastrop	C.D. McCall	360	363.11	170	GWDB	80
5854706		5754224.86	19299783.74	Bastrop	C. D. McCall	360	361.59	440	GWDB	85
5862113		5754774.74	19273066.78	Bastrop	Aqua WSC	362	359.90	490	GWDB	0
5862114		5755551.58	19273591.60	Bastrop	Aqua WSC	352	359.41	497	GWDB	13
5862115		5755653.81	19272986.44	Bastrop	Aqua WSC	370	367.44	496	GWDB	36
5862116		5756822.64	19275444.45	Bastrop	Aqua WSC	372	365.89	529	GWDB	32
5862117		5758276.18	19273353.17	Bastrop	Judge Jack Greisenbeck	360	361.74	206	GWDB	36
5862205		5765463.46	19280816.07	Bastrop	City of Bastrop	330	333.71	54	GWDB	48
5862206		5765378.19	19280712.68	Bastrop	City of Bastrop	330	330.88	52	GWDB	52
5862213		5764469.97	19282006.94	Bastrop	City of Bastrop	370	319.97	52	GWDB	28
5862214		5764735.52	19281912.39	Bastrop	City of Bastrop	371	336.50	34	GWDB	27
5862216		5764669.81	19280999.55	Bastrop	City of Bastrop	325	328.27	55	GWDB	48
5862508		5767663.65	19269630.49	Bastrop	Bastrop County WCID #2	365	364.78	524	GWDB	38
5862604		5784044.07	19259906.71	Bastrop	B. V. Brangus Ranch	350	426.88	512	GWDB	20
5863405		5793587.95	19257207.34	Bastrop	Floyd Martin	330	329.71	180	GWDB	40
5863606		5818764.77	19257541.32	Bastrop	TPWD	380	385.20	868	GWDB	30
5863902		5818111.49	19245374.83	Bastrop	City of Smithville	324	308.93	872	GWDB	36
6601103[2]		5881398.99	19242499.28	Fayette	Lee County W.S.C.	350	349.30	515	GWDB	5
6707313		5816881.96	19235117.22	Bastrop	City of Smithville	370	382.50	360	GWDB	0

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
6708307		5858909.92	19236421.35	Fayette	Mike Weth	313	307.38	850	GWDB	34
	361[2]	5836258.24	19229544.34	Fayette	Jack Page		305.00	460	SDR DB	25
	380	5842162.97	19225447.23	Fayette	Tim Larson		369.20	320	SDR DB	30
	620	5730285.01	19319268.28	Bastrop	Tom Rodes		514.40	200	SDR DB	0
	626	5735466.19	19303695.03	Bastrop	Mickey Malone		420.40	160	SDR DB	23
	733	5741895.53	19272458.54	Bastrop	Don Rucker		397.80	240	SDR DB	23
	895	5737572.11	19322273.22	Bastrop	Clarance Hendricks		432.50	196	SDR DB	46
	1084	5737659.72	19322275.28	Bastrop	Mauno Jaimes		432.90	196	SDR DB	0
	1085	5728999.73	19306683.47	Bastrop	Jack Anderson		405.60	75	SDR DB	41
	1115	5847819.56	19273791.76	Bastrop	Jill Metzger		400.90	535	SDR DB	0
	1126	5800356.56	19260212.37	Bastrop	Brad Hurda		337.20	140	SDR DB	25
	1268	5804872.36	19258605.13	Bastrop	Glynn Villerman		302.50	50	SDR DB	45
	1270	5730284.77	19273908.77	Bastrop	Phil Cook		431.80	300	SDR DB	0
	1271	5730284.77	19273908.77	Bastrop	Phil Cook		431.80	165	SDR DB	0
	1312	5847603.32	19222350.97	Fayette	Philipe Garcia		379.80	310	SDR DB	50
	1314[2]	5847906.18	19224181.43	Fayette	Ray Houston		371.80	340	SDR DB	15
	1435	5751208.37	19260731.45	Bastrop	Andy Fountain		363.30	340	SDR DB	81
	1852	5734336.68	19299517.39	Bastrop	Alan Stewart		391.70	250	SDR DB	42
	1857	5741777.87	19292401.55	Bastrop	Clifford Mcghee		438.28	275	SDR DB	22
	2060	5768237.84	19282098.49	Bastrop	Carl Spooner		374.30	213	SDR DB	87
	2062	5763135.35	19286430.00	Bastrop	W. C. Froelhich		364.60	235	SDR DB	31

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	2063	5736266.39	19321939.05	Bastrop	Karen Franks		424.10	200	SDR DB	0
	2478	5775401.43	19265263.05	Bastrop	Don Parr		380.60	210	SDR DB	31
	2480	5757806.11	19300274.36	Bastrop	Troy & Kay Graves		402.90	190	SDR DB	22
	2777	5733635.32	19318333.54	Bastrop	Greg Acosta		488.70	280	SDR DB	18
	2779	5739047.40	19296691.41	Bastrop	J.R. Broadhurst		389.70	205	SDR DB	72
	3037	5692049.78	19329337.83	Travis	Jimmy Johnson		414.60	70	SDR DB	52
	3058	5732997.67	19274174.37	Bastrop	Keith Dagenhart		423.00	205	SDR DB	0
	3059	5733525.75	19274085.32	Bastrop	Gary Jerome		419.20	220	SDR DB	0
	3821	5768274.65	19280580.89	Bastrop	Jim DeBaun		369.20	260	SDR DB	35
	4243	5744370.86	19290235.15	Bastrop	Jerry Freppan		412.60	275	SDR DB	55
	4456	5813304.03	19258313.09	Bastrop	David F. Johnston		458.25	340	SDR DB	0
	4781	5722859.56	19272624.06	Bastrop	Cleo Williams		428.90	490	SDR DB	21
	4951	5808652.82	19213342.73	Bastrop	Edmund Yeisley		412.70	600	SDR DB	0
	4997	5733255.83	19274382.66	Bastrop	Austin Loan Company		421.50	240	SDR DB	0
	4999	5732992.98	19274376.55	Bastrop	Austin Loan Company		423.10	230	SDR DB	33
	5000	5732990.62	19274477.82	Bastrop	Austin Loan Company		422.60	230	SDR DB	29
	5001	5733253.48	19274483.93	Bastrop	Austin Loan Company		421.10	230	SDR DB	25
	5002	5733336.50	19274688.52	Bastrop	Austin Loan Company		412.50	220	SDR DB	21
	5239	5791344.60	19259176.88	Bastrop	Dayton Thompson		326.77	350	SDR DB	99
	5494[2]	5838106.87	19229390.11	Fayette	James Wilson		311.10	470	SDR DB	32
	5596	5742381.15	19274191.07	Bastrop	Clayton Weaver		404.50	500	SDR DB	17

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	5932	5732810.47	19274676.29	Bastrop	Austin Loan Company		414.30	220	SDR DB	28
	5933	5733248.77	19274686.48	Bastrop	Austin Loan Company		414.70	205	SDR DB	26
	5934	5732985.91	19274680.37	Bastrop	Austin Loan Company		414.00	200	SDR DB	24
	6046[2]	5841870.09	19229893.92	Fayette	Raymond Montgomery		310.20	496	SDR DB	31
	6618	5840758.03	19252139.68	Bastrop	Gene Sampson		375.00	380	SDR DB	15
	6619	5817568.71	19249410.79	Bastrop	Catalino Soto		320.40	180	SDR DB	44
	6620	5817403.83	19249001.61	Bastrop	Lee Armstrong		320.00	170	SDR DB	37
	7618	5722852.59	19272927.51	Bastrop	Bobbi Williams		431.30	480	SDR DB	0
	7850[2]	5842851.65	19229312.54	Fayette	Brent Lloyd		289.00	470	SDR DB	35
	8198	5733804.43	19303554.96	Bastrop	Irma Jones		411.80	240	SDR DB	6
	8662	5708578.91	19318569.27	Travis	T B Turner		410.04	70	SDR DB	27
	9840	5734991.08	19316542.96	Bastrop	Adolf Viesel		406.10	155	SDR DB	38
	10197	5758185.70	19273452.70	Bastrop	Jack Griesenbeck		365.50	395	SDR DB	33
	12279	5723470.72	19272739.05	Bastrop	Robert Williams		419.60	480	SDR DB	37
	12283	5717834.16	19308350.61	Bastrop	Ricky Turner		380.60	60	SDR DB	47
	12284	5741540.18	19272652.48	Bastrop	Haddie Felia		396.90	235	SDR DB	25
	12337	5740346.51	19267460.79	Bastrop	Fred Sanders		423.30	320	SDR DB	0
	14322	5742533.02	19293836.84	Bastrop	Steve Hipe		387.50	270	SDR DB	47
	14323	5759589.32	19299001.29	Bastrop	Larry Mcgehee		391.30	225	SDR DB	17
	14327	5734130.57	19248079.54	Bastrop	Charlie Lunday		373.70	440	SDR DB	0
	15228	5817876.20	19247697.54	Bastrop	Ernest Grey		315.40	77	SDR DB	51

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	16438	5753268.12	19299457.65	Bastrop	Jo Goertz		363.90	540	SDR DB	68
	16440	5753523.56	19299767.37	Bastrop	Mike Goertz		367.80	550	SDR DB	58
	18452	5733622.06	19303854.35	Bastrop	Katisha Jones		417.00	260	SDR DB	0
	18711[2]	5857992.41	19241156.01	Fayette	James Raley		313.00	180	SDR DB	40
	19678	5837300.65	19263490.28	Bastrop	James Bryant		374.70	240	SDR DB	18
	20480	5843359.19	19260004.60	Bastrop	William Hector		336.30	205	SDR DB	0
	20855	5724825.28	19271049.10	Bastrop	JCG Land & Cattle Company, LLC		399.50	340	SDR DB	0
	21242	5733043.29	19294830.09	Bastrop	John Apostalo		350.20	270	SDR DB	41
	24022	5752203.08	19263185.11	Bastrop	Juan Lopez		386.60	280	SDR DB	0
	24514	5810673.08	19254803.36	Bastrop	Richard Chesebro		312.60	200	SDR DB	54
	25070[2]	5834566.80	19230411.35	Fayette	Jerry Hoskins		305.80	420	SDR DB	27
	32147	5714730.34	19313848.74	Bastrop	Greg Olson		391.30	41	SDR DB	40
	32670	5839290.77	19261213.69	Bastrop	Jed Barker		371.80	255	SDR DB	0
	35321	5785679.72	19264705.96	Bastrop	Bastrop Co. MUD #1		452.80	185	SDR DB	21
	35439	5849518.91	19259357.77	Bastrop	Hugh Tomlinson		362.00	360	SDR DB	0
	35464	5690547.05	19318065.60	Travis	Native Texas Nursery		398.60	34	SDR DB	33
	35479	5689709.43	19316325.97	Travis	O.C. Wimberly		400.20	50	SDR DB	49
	37720	5760581.52	19265005.17	Bastrop	Leonard Phillips		381.60	440	SDR DB	0
	37721	5760537.76	19266826.56	Bastrop	Leonard Phillips		375.10	340	SDR DB	0
	37822	5701928.88	19314369.84	Travis	James Samon		398.30	35	SDR DB	25
	38109	5730041.45	19307112.56	Bastrop	John Richardson		403.90	190	SDR DB	33

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	41270[2]	5860503.98	19219556.40	Fayette	Charles Sledge		361.77	288	SDR DB	15
	41291	5811601.44	19245917.34	Bastrop	Chris Hightree		429.90	708	SDR DB	19
	41293[2]	5840314.21	19228942.14	Fayette	Dean Selman		307.20	485	SDR DB	31
	41297[2]	5839072.14	19229415.43	Fayette	Stephen Colosky		310.50	465	SDR DB	31
	42032	5802225.73	19248717.06	Bastrop	Dora Hightower		320.60	345	SDR DB	36
	42109	5712400.11	19269752.93	Bastrop	Edward Ray Barrera		430.40	230	SDR DB	19
	42559	5804456.87	19257683.39	Bastrop	Tommy Odom		300.80	45	SDR DB	40
	42560	5802254.07	19258032.74	Bastrop	Ted Macon		305.70	40	SDR DB	40
	42561	5757802.08	19282150.54	Bastrop	Vasile Florin		372.90	300	SDR DB	42
	43979	5702361.40	19318530.46	Travis	Johnny Reed		400.00	52	SDR DB	49
	44337	5760861.67	19267947.86	Bastrop	Toby Tyler		350.40	80	SDR DB	61
	44339	5736907.25	19302007.14	Bastrop	Rudy Hernandez		388.70	80	SDR DB	73
	45272	5804464.55	19257379.60	Bastrop	Ted Macon (Bill Meyer)		300.40	70	SDR DB	41
	45273	5804459.43	19257582.13	Bastrop	Ted Macon (Danne Abcher)		300.70	65	SDR DB	41
	45274	5804459.43	19257582.13	Bastrop	Ted Macon (Donny Sovoda)		300.70	60	SDR DB	35
	45275	5804469.66	19257177.43	Bastrop	Ted Macon (Ilene Branscombe)		298.90	65	SDR DB	38
	45276	5804559.99	19257078.38	Bastrop	Ted Macon (Johnny Kettler)		295.80	60	SDR DB	38
	45277	5804438.98	19258391.52	Bastrop	Ted Macon Jr		299.20	60	SDR DB	40
	46559	5765616.21	19281731.37	Bastrop	Fred W. Hoskins		362.60	250	SDR DB	20
	46561	5830173.56	19230499.17	Bastrop	E. Lavonne Westbrook		297.30	306	SDR DB	40
	46583[2]	5852745.72	19250229.30	Fayette	Lonnie C. Wormley		336.70	528	SDR DB	23

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	46601[2]	5855561.28	19243419.74	Fayette	Phillip Wells		307.20	565	SDR DB	23
	51552	5748644.23	19250444.77	Bastrop	William Reese		381.00	430	SDR DB	0
	52423	5724331.08	19273467.75	Bastrop	Carl Kacures		422.30	210	SDR DB	31
	52798	5772173.03	19260932.12	Bastrop	Bobby Harriman		353.24	280	SDR DB	41
	54761	5752982.60	19256217.60	Bastrop	Don Gibson		445.40	315	SDR DB	0
	55972	5753304.45	19257440.08	Bastrop	Reed Lewis		381.20	235	SDR DB	0
	55974	5804838.34	19256477.81	Bastrop	Ted Macon Jr.		299.50	65	SDR DB	38
	55975	5730038.30	19273194.50	Bastrop	Nolan Johnson		417.50	335	SDR DB	24
	57432	5767120.82	19295639.28	Bastrop	Lee Cox		460.00	390	SDR DB	0
	60900	5730389.35	19307221.96	Bastrop	Dearl Croft		403.80	156	SDR DB	26
	61460	5762443.86	19296943.81	Bastrop	Tommy Odom		454.30	250	SDR DB	0
	64299[2]	5853476.50	19222810.63	Fayette	Patricia Topping		290.00	340	SDR DB	30
	64300	5853560.09	19219674.26	Fayette	Frank Haynie		311.41	390	SDR DB	0
	64755[2]	5869867.57	19227402.56	Fayette	Basil Ermis		295.80	230	SDR DB	30
	66385	5749999.85	19252501.93	Bastrop	Randy Ray		421.10	210	SDR DB	0
	66402	5850192.74	19270310.63	Bastrop	Wim Menzel		392.00	360	SDR DB	0
	67089	5804469.66	19257177.43	Bastrop	Ted Macon (Ilene Branscombe)		298.90	65	SDR DB	38
	67094	5804464.55	19257379.60	Bastrop	Ted Macon (Bill Meyer)		300.40	65	SDR DB	42
	67096	5804472.22	19257076.17	Bastrop	Ted Macon (Johnny Kettler)		294.90	65	SDR DB	41
	67097	5804374.23	19257478.64	Bastrop	Ted Macon (Donny Sovoda)		300.80	65	SDR DB	39
	67100	5804371.67	19257579.91	Bastrop	Ted Macon (Danny Abcher)		300.90	60	SDR DB	37

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	67101	5800229.71	19258285.38	Bastrop	Ted Macon Jr		306.30	65	SDR DB	38
	69158	5694940.19	19329300.51	Travis	Schwertner Farms		400.60	50	SDR DB	39
	70918	5706652.40	19306882.25	Bastrop	Dan Berdoll		391.54	52	SDR DB	52
	70919	5704156.10	19304901.98	Bastrop	Larry Mellenbruch		407.58	50	SDR DB	49
	70946	5707392.68	19309025.04	Bastrop	Larry Mellenbruch		411.00	66	SDR DB	65
	73919	5717436.28	19271993.75	Bastrop	Heidi Fysh		434.10	210	SDR DB	32
	73958	5697866.66	19323695.33	Travis	Travis County		399.50	80	SDR DB	55
	75641	5849945.33	19263115.52	Bastrop	Sherrell & Delores Moore		383.30	426	SDR DB	0
	76795	5734565.10	19316026.72	Bastrop	Chuck Joseph		419.50	230	SDR DB	19
	78597	5804446.65	19258088.09	Bastrop	Ted Macon Jr		301.00	65	SDR DB	33
	79620	5864252.20	19223909.76	Fayette	Edwin Muras		285.90	410	SDR DB	25
	80167	5770721.93	19248443.45	Bastrop	Jayson Arnold		370.31	340	SDR DB	14
	83438	5869680.72	19218082.52	Fayette	Robert Walsh		304.30	480	SDR DB	0
	88611	5853560.09	19219674.26	Fayette	Frank Haynie		311.41	180	SDR DB	12
	88871	5772090.51	19260727.82	Bastrop	Bobby Harriman		353.23	280	SDR DB	39
	89589	5810806.90	19252984.29	Bastrop	Joe Svoboda		291.30	190	SDR DB	23
	91201	5734251.90	19306906.78	Bastrop	Horace Henley		410.50	140	SDR DB	14
	91225	5835850.35	19221636.74	Fayette	Hugh Tucker		367.90	550	SDR DB	0
	98512[2]	5860087.67	19221974.91	Fayette	Assad Chowdory		313.90	285	SDR DB	10
	99340[2]	5853811.75	19230008.05	Fayette	Bryan Heck		285.60	143	SDR DB	36
	101338	5700146.01	19315747.52	Travis	Henry Chalmers		410.10	62	SDR DB	57

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	101341	5735792.40	19267152.02	Bastrop	Jason Bontrager		408.10	362	SDR DB	0
	101344	5773032.17	19247284.49	Bastrop	Ardelia Sessions		381.11	360	SDR DB	19
	103599	5802690.03	19258145.06	Bastrop	Ted Macon		306.00	65	SDR DB	36
	103600	5812821.59	19218713.54	Bastrop	Rod Langer		379.50	595	SDR DB	0
	103603	5768035.75	19283207.14	Bastrop	B I S D		374.99	400	SDR DB	34
	105979	5864252.20	19223909.76	Fayette	Jeremy Janda		285.90	420	SDR DB	45
	109392	5744680.23	19317985.25	Bastrop	Denny Denniston		432.14	260	SDR DB	17
	109431[2]	5855117.17	19243610.53	Fayette	Byron Seale		311.90	148	SDR DB	28
	111160	5770872.59	19249459.65	Bastrop	Todd Mueller		361.52	330	SDR DB	41
	111925	5797554.74	19263483.32	Bastrop	Steven Goerner		343.71	215	SDR DB	24
	111938	5808652.82	19213342.73	Bastrop	Edmund Yeisley		412.70	565	SDR DB	0
	112534	5765536.65	19295904.56	Bastrop	Pioneer Building		473.60	240	SDR DB	0
	116016	5829649.54	19257418.00	Bastrop	Peter Shaddock		340.40	335	SDR DB	50
	116019	5772476.15	19248486.13	Bastrop	Willie Shelton		381.45	515	SDR DB	30
	121249	5877217.08	19222033.92	Fayette	Brenda M. Ward		300.80	245	SDR DB	24
	125126	5723041.68	19272324.26	Bastrop	Manuel Aguiano		426.70	180	SDR DB	24
	125614	5797554.74	19263483.32	Bastrop	Steven Goerner		343.71	215	SDR DB	24
	125883[2]	5872096.36	19239106.64	Fayette	Raymond Schulz		284.50	45	SDR DB	30
	126079[2]	5874552.13	19229555.09	Fayette	Dennis Vacula		292.70	190	SDR DB	32
	129818	5739543.27	19320395.52	Bastrop	Mike Lamure		421.70	215	SDR DB	12
	129850	5734891.37	19313300.53	Bastrop	Andy Powlowski		393.10	260	SDR DB	9

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	130168	5737773.39	19321163.99	Bastrop	Mark Hubbard		412.30	200	SDR DB	16
	136154[2]	5837758.17	19229280.00	Fayette	Martin Rangle		311.20	440	SDR DB	30
	137284	5768384.45	19279672.31	Bastrop	Roy Mabry		366.10	385	SDR DB	0
	138211[2]	5827380.71	19223036.06	Fayette	Leonard Matura		328.30	560	SDR DB	20
	141003	5865875.46	19248354.21	Fayette	Magnum Producing & Operating		340.88	830	SDR DB	0
	151600	5805243.59	19257804.25	Bastrop	Ted Macon		300.40	60	SDR DB	36
	151638[2]	5846226.64	19231224.10	Fayette	Bryce Ramm		285.30	45	SDR DB	38
	151649	5737811.65	19308306.13	Bastrop	Ricky Turner		390.10	90	SDR DB	80
	151836	5755393.95	19265488.52	Bastrop	Corner Stone High School-Randy Ray		424.50	295	SDR DB	40
	153231	5742705.67	19293942.24	Bastrop	Steve Hipe		384.87	300	SDR DB	55
	156938	5823155.50	19236999.96	Bastrop	Bass Redd		320.80	400	SDR DB	40
	156946	5846102.12	19269088.49	Bastrop	Home Finders - Diane Clark		354.10	240	SDR DB	0
	156993	5818148.32	19254184.51	Bastrop	Dr. Karen S. Boehk		333.23	280	SDR DB	28
	157097[2]	5849399.16	19240724.15	Fayette	Juergen, Thomas		318.10	332	SDR DB	25
	157110	5850174.45	19244592.38	Fayette	Zoch, Alford		313.50	48	SDR DB	48
	157512	5687673.36	19325292.34	Travis	Jim Wisian		430.80	59	SDR DB	10
	159727	5759226.83	19299498.88	Bastrop	Gayle Connor		419.60	260	SDR DB	19
	159923	5742732.81	19318850.61	Bastrop	Raymond & Karla Mercieca		439.20	280	SDR DB	0
	160577	5706832.99	19310531.30	Travis	Larry Mellenbruch		410.30	36	SDR DB	32
	161318	5739251.95	19321603.97	Bastrop	Reese, Justin		415.40	242	SDR DB	28
	161635	5787308.38	19245003.38	Bastrop	Rothman, James		332.80	85	SDR DB	30

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	161636	5762985.68	19252610.01	Bastrop	Denton, Dale		364.60	285	SDR DB	38
	161685	5702248.93	19268714.62	Bastrop	Texas Roads & Utilities		438.00	195	SDR DB	21
	163773	5825668.58	19224713.19	Bastrop	Vernon Richards		323.30	545	SDR DB	7
	170096	5708005.02	19328478.90	Travis	Don Hartsfield		496.87	60	SDR DB	4
	171818	5824903.36	19227123.05	Bastrop	Mick, Christie		344.00	540	SDR DB	15
	173097	5709551.18	19318186.27	Travis	Manuel Elizondo		402.20	57	SDR DB	45
	174053[2]	5849311.35	19240721.81	Fayette	Juergen, Thomas		318.20	510	SDR DB	32
	176092	5751365.85	19265189.92	Bastrop	John Allen		401.70	320	SDR DB	21
	176107	5757058.11	19291245.19	Bastrop	Lauren Concrete (Ray Lauren)		402.40	295	SDR DB	53
	177413	5722068.31	19272706.87	Bastrop	BISD		431.90	220	SDR DB	0
	177550	5700443.30	19310286.68	Travis	Ted Wilson		410.10	59	SDR DB	58
	177560	5765202.77	19280708.80	Bastrop	City of Bastrop - Water Well G		321.30	52	SDR DB	41
	179731	5771643.09	19257476.63	Bastrop	David Sartain		354.14	315	SDR DB	0
	179760	5758026.63	19247124.69	Bastrop	Michael Waxman		449.00	280	SDR DB	0
	180614	5701877.61	19324493.83	Travis	Ray Leggett		401.40	70	SDR DB	27
	181056[2]	5880052.78	19224339.33	Fayette	Mark Zvonek		292.20	300	SDR DB	30
	181644	5810185.61	19256714.76	Bastrop	Terry Rosanky, J&T Trading Post		312.50	192	SDR DB	0
	186914	5886474.45	19246284.88	Fayette	Ruben Kappler		362.60	195	SDR DB	0
	188636	5838079.21	19277281.17	Bastrop	Frank Meuth		402.80	280	SDR DB	11
	188642	5842906.74	19283787.29	Bastrop	Earl Steinbach		439.00	250	SDR DB	0
	189255	5691722.17	19332266.68	Travis	Municipal Groundwater Solutions		419.50	53	SDR DB	43

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	192485	5760044.06	19283723.19	Bastrop	City of Bastrop		342.20	44	SDR DB	42
	192497	5760309.28	19283628.23	Bastrop	City of Bastrop		350.20	66	SDR DB	56
	192596	5810572.43	19255307.08	Bastrop	Terry Pearcy		312.50	215	SDR DB	42
	193456	5834498.10	19233041.89	Bastrop	Charlie Hilcher		310.63	380	SDR DB	30
	193461	5833979.68	19232724.73	Bastrop	Larry Richards		309.87	380	SDR DB	30
	194865	5807680.70	19255132.28	Bastrop	Clara Chronis		308.70	200	SDR DB	60
	194867	5807680.70	19255132.28	Bastrop	Phillip Brown		308.70	126	SDR DB	60
	194868	5811483.03	19254014.08	Bastrop	Ronald Pettit		307.80	120	SDR DB	60
	195531	5725159.54	19248884.19	Bastrop	John and Elaine Glass		459.90	500	SDR DB	0
	195842[2]	5854064.49	19243582.43	Fayette	United Resources, LP		303.70	620	SDR DB	50
	197323	5821221.01	19220042.10	Bastrop	Robert Vasek		353.30	645	SDR DB	14
	198940	5771542.57	19250792.09	Bastrop	Don Nixon; Richard Welch HMS.		354.94	495	SDR DB	35
	198965	5808862.68	19260427.43	Bastrop	Gay A. Wright		331.23	442	SDR DB	32
	199132	5743217.11	19294561.90	Bastrop	Mark Roemer		384.98	46	SDR DB	40
	199621[2]	5866163.17	19244211.01	Fayette	Neal Prestridge		312.38	158	SDR DB	38
	201009	5851793.06	19253039.03	Bastrop	Ruth Frost		349.50	515	SDR DB	31
	201450	5811111.52	19213405.18	Bastrop	Leslie Hurta		402.20	587	SDR DB	0
	201459[2]	5847884.74	19224990.75	Fayette	Richard Robinson		326.00	750	SDR DB	9
	202521[2]	5877217.08	19222033.92	Fayette	Brenda M. Ward		300.80	245	SDR DB	24
	204506	5755334.72	19275307.92	Bastrop	Reid Sharp		369.40	440	SDR DB	25
	204540	5728507.24	19271134.00	Bastrop	Paul Walhus & Dorothy Epp		414.80	350	SDR DB	32

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	204543	5728469.81	19272753.27	Bastrop	Paul Walhus & Dorothy Epp		418.00	300	SDR DB	0
	204550	5749498.01	19266259.46	Bastrop	Berry Vickers		405.40	295	SDR DB	30
	207651	5714635.49	19314150.21	Bastrop	Carol Hardy		393.60	54	SDR DB	53
	207695	5705622.98	19309795.13	Travis	Ron Epp		413.00	60	SDR DB	49
	208251	5705353.57	19310092.70	Travis	Micheal Klug		412.70	60	SDR DB	52
	208781	5695803.88	19329825.98	Travis	Betty R. Shaw		402.90	58	SDR DB	50
	209154	5705182.84	19309886.56	Travis	Michael Klug		413.00	70	SDR DB	52
	209221	5831902.65	19231556.70	Bastrop	David Evanicky		302.60	340	SDR DB	22
	209240	5749946.16	19288038.27	Bastrop	Diane Gregg		389.12	240	SDR DB	20
	209284	5702007.44	19314776.55	Travis	Bill Wilmont		396.90	45	SDR DB	42
	209899	5742443.00	19271560.19	Bastrop	Preston Frey		400.80	300	SDR DB	40
	211659	5710807.72	19309102.15	Bastrop	Hal Berdoll		390.30	61	SDR DB	0
	215576	5731749.97	19267462.93	Bastrop	B & W Ranches		460.80	310	SDR DB	0
	216683	5743247.47	19311876.17	Bastrop	Travis Turner		360.90	81	SDR DB	38
	217962	5732317.97	19303419.05	Bastrop	Harold Connet		380.50	65	SDR DB	60
	218767	5705173.75	19310291.32	Travis	Michael Klug		412.50	64	SDR DB	51
	219951	5829856.34	19256208.13	Bastrop	Marshall Munsell		299.80	300	SDR DB	42
	220521	5732831.48	19303937.28	Bastrop	Joe Miller		392.30	230	SDR DB	55
	221048	5804485.01	19256570.21	Bastrop	Barbara Lampley		291.30	60	SDR DB	38
	221049	5686103.49	19321005.25	Travis	Nick Biediger		412.70	42	SDR DB	35
	221264	5705622.98	19309795.13	Travis	Ron Epp		413.00	60	SDR DB	49

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	222855	5732831.48	19303937.28	Bastrop	Renee Miller Rangel		392.30	230	SDR DB	55
	223411	5824531.40	19227923.32	Bastrop	Robin Ramsay		344.30	560	SDR DB	28
	223461	5829655.47	19250431.80	Bastrop	Franklin Kasper		301.40	504	SDR DB	54
	223464	5825086.89	19226824.18	Bastrop	Diane & Ernest Hahn		329.70	674	SDR DB	18
	223490	5758722.97	19262024.63	Bastrop	M. Trigg Family Ltd Partnership		391.08	530	SDR DB	31
	224006[2]	5836213.24	19231264.28	Fayette	Robert M. Smith Jr.		310.28	428	SDR DB	31
	224128	5817453.12	19247079.08	Bastrop	Danny Schroeder		311.10	245	SDR DB	60
	225806[2]	5837524.12	19228160.36	Fayette	Impetro Operating LLC		294.60	490	SDR DB	40
	228049	5837057.22	19239285.13	Bastrop	Lama Energy		314.50	450	SDR DB	30
	229548	5720695.72	19275206.76	Bastrop	Jay Hoffman		440.90	210	SDR DB	6
	231592	5762106.20	19270914.14	Bastrop	David Greene		362.20	244	SDR DB	38
	236229	5743546.04	19295480.89	Bastrop	Mark Roemer		387.38	270	SDR DB	38
	236232	5733826.64	19313883.34	Bastrop	Kelly Hoag		398.00	240	SDR DB	20
	236236	5700049.67	19316150.33	Travis	David Dial		412.00	45	SDR DB	40
	236238	5702718.34	19318234.82	Travis	David Tucker		402.50	52	SDR DB	45
	237842[2]	5876085.54	19228078.06	Fayette	RLB Ventures Inc. Diehl & Brunson		289.50	42	SDR DB	25
	237843	5874985.49	19229769.20	Fayette	RLB Ventures Inc. Diehl & Brunson		287.30	42	SDR DB	10
	237845	5875273.52	19228865.81	Fayette	RLB Ventures, Inc		289.60	22	SDR DB	20
	237846[2]	5876362.88	19227579.35	Fayette	RLB Ventures Inc. Diehl & Brunson		291.20	40	SDR DB	31
	237847	5876741.58	19226577.12	Fayette	RLB Ventures Inc. Diehl & Brunson		290.40	23	SDR DB	22
	237848	5874988.24	19229668.31	Fayette	RLB Ventures Inc Diehl & Brunson		290.90	37	SDR DB	29

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	241942[2]	5834470.03	19224030.68	Fayette	Ken & Sher Brown		327.40	504	SDR DB	11
	242601[2]	5846130.78	19231525.18	Fayette	Jerry Domel		285.40	120	SDR DB	30
	243725	5738621.17	19303667.45	Bastrop	Kellis Berdoll		381.50	76	SDR DB	76
	243732	5708889.57	19304806.20	Bastrop	Hal Berdoll		400.53	60	SDR DB	59
	243733	5708977.22	19304808.18	Bastrop	Hal Berdoll		400.21	60	SDR DB	59
	243735	5739054.37	19303879.90	Bastrop	Kellis Berdoll		370.50	69	SDR DB	69
	243736	5739497.05	19303687.98	Bastrop	Dan Berdoll		367.40	76	SDR DB	76
	244004	5854059.09	19243784.58	Fayette	Weber Energy		305.20	650	SDR DB	0
	244206	5776656.21	19264180.23	Bastrop	David R Fuqua		331.40	214	SDR DB	27
	244281	5748536.16	19266135.34	Bastrop	Patrick Thomas		385.70	230	SDR DB	21
	244283	5691430.28	19329627.77	Travis	Billy Spears		416.60	60	SDR DB	55
	244899[2]	5864252.20	19223909.76	Fayette	Gary Janda		285.90	20	SDR DB	27
	248953	5817170.76	19254665.72	Bastrop	Walicek, Walt		369.68	255	SDR DB	0
	249073	5756941.52	19274131.48	Bastrop	Krischke, Dan		370.20	403	SDR DB	43
	249076	5791903.20	19243801.37	Bastrop	Williams, Craig		367.90	233	SDR DB	36
	250212	5714842.63	19305042.41	Bastrop	Mark Hayes		406.80	297	SDR DB	0
	250228	5828996.06	19258919.53	Bastrop	Rocky Hill Ranch		359.92	106	SDR DB	0
	250247	5824867.25	19235323.04	Bastrop	Bacon Crest Ltd.		362.50	444	SDR DB	58
	250261[2]	5835237.44	19231643.71	Fayette	Colorado River Cowboy Church		308.83	417	SDR DB	36
	250390	5827097.73	19220396.45	Fayette	Mitchell, Bernie		402.80	440	SDR DB	0
	250393	5756773.05	19270178.92	Bastrop	River Bend Farm		394.50	220	SDR DB	34

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	250656	5760017.32	19284836.09	Bastrop	Marcus Miles		360.80	300	SDR DB	8
	250966[2]	5873956.88	19228829.92	Fayette	Bobby Allen		288.30	347	SDR DB	30
	251300	5691562.98	19331554.56	Travis	Travis Co. Parks		417.90	50	SDR DB	46
	251304	5691394.52	19331247.21	Travis	Travis Co. Parks		419.20	50	SDR DB	45
	256650	5831769.44	19253524.18	Bastrop	Kieth Berdol		278.10	72	SDR DB	68
	256662	5831859.53	19253425.56	Bastrop	Kieth Berdol		279.80	72	SDR DB	71
	256672	5831859.53	19253425.56	Bastrop	Kieth Berdol		279.80	72	SDR DB	71
	257000	5754996.59	19263757.57	Bastrop	Aqua WSC		417.10	605	SDR DB	0
	257397	5710012.35	19305540.51	Bastrop	Hal Berdoll		388.04	58	SDR DB	58
	258108	5701002.72	19308780.32	Travis	Garfield WSC		411.20	80	SDR DB	64
	262853[2]	5866996.62	19249093.50	Fayette	Scott Hielscher		350.59	860	SDR DB	14
	262994	5738646.70	19313793.28	Bastrop	Texas Land & Hay Company		379.00	110	SDR DB	44
	262999	5737548.76	19312046.37	Bastrop	Texas Land & Hay Company		379.00	68	SDR DB	56
	263008	5718753.62	19310295.45	Bastrop	Ricky Turner		379.50	45	SDR DB	40
	263011	5718032.55	19307342.56	Bastrop	Ricky Turner		380.30	52	SDR DB	44
	264959[2]	5835547.68	19226488.49	Fayette	Weishuhn Farm		290.90	440	SDR DB	65
	265389	5838687.53	19254110.07	Bastrop	Sid Armer		339.70	612	SDR DB	0
	265952	5849398.05	19253987.94	Bastrop	Jeff Burns		332.10	450	SDR DB	18
	266000	5840329.42	19268429.82	Bastrop	Fred Cooper		376.40	360	SDR DB	14
	267026	5749073.99	19265641.81	Bastrop	Richard Williams		390.50	303	SDR DB	17
	268553	5718876.22	19304931.72	Bastrop	Jim & Judy Collins		376.40	40	SDR DB	35

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	268676	5807668.83	19262523.60	Bastrop	Gary Lehmann		340.88	555	SDR DB	0
	268677	5799183.77	19254512.82	Bastrop	Pecan Grove Plantation		310.03	438	SDR DB	43
	268929	5835428.21	19247848.58	Bastrop	Terri Taylor		315.00	405	SDR DB	25
	269077	5732064.41	19303008.20	Bastrop	David Petrie		382.10	50	SDR DB	44
	269079	5732235.01	19303214.82	Bastrop	David Petrie		382.30	60	SDR DB	52
	272321	5864492.58	19237787.12	Fayette	Ricky Schulze		300.90	100	SDR DB	100
	273376	5721440.49	19307724.18	Bastrop	James Glass		367.20	45	SDR DB	38
	276961	5752054.04	19262068.06	Bastrop	Douglas O'keefe		382.40	375	SDR DB	19
	276963	5804446.65	19258088.09	Bastrop	Bill Moore		301.00	50	SDR DB	39
	276966	5804456.87	19257683.39	Bastrop	Tracy Humphreys		300.80	52	SDR DB	39
	277730	5841085.96	19273006.13	Bastrop	Jerry Krchnak		373.30	347	SDR DB	11
	280395	5770687.50	19249860.09	Bastrop	Mary Jo Stickel - Kody Kleber		349.54	481	SDR DB	25
	282014[2]	5873414.54	19222942.76	Fayette	Cliff Giese		284.60	20	SDR DB	30
	282177	5737475.37	19318929.49	Bastrop	Jesse Banta		383.60	220	SDR DB	10
	282279	5714838.02	19305244.97	Bastrop	Hal Berdoll		407.40	52	SDR DB	45
	282283	5714838.02	19305244.97	Bastrop	Hal Berdoll		407.40	52	SDR DB	45
	282417	5758827.20	19286934.00	Bastrop	W. W. Oatman		389.30	350	SDR DB	10
	283472	5766016.30	19254302.90	Bastrop	James Harmon		389.20	200	SDR DB	3
	285862	5851668.28	19274197.72	Bastrop	Keith Cabeen		401.90	570	SDR DB	0
	286007	5848081.51	19247371.91	Bastrop	Jimmy Sherrill		323.42	455	SDR DB	54
	287288	5730608.23	19290216.98	Bastrop	Griffin Dewatering		472.90	470	SDR DB	0

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	287468	5702931.46	19308722.15	Travis	Brent Johnson		408.90	54	SDR DB	51
	288890[2]	5855701.90	19238158.31	Fayette	Karl Koch		302.90	140	SDR DB	25
	290530[2]	5888473.29	19231151.87	Fayette	Dorothy J. Elliott		275.00	180	SDR DB	36[3]
	292258	5778298.24	19268776.63	Bastrop	Bob Andrade		444.80	240	SDR DB	0
	295168	5812307.61	19218194.19	Bastrop	Terry Rittenhour		381.40	594	SDR DB	12
	295181	5737527.42	19309210.74	Bastrop	Kellis Berdoll		389.40	88	SDR DB	75
	295339	5841581.51	19284156.95	Bastrop	R. J. Nitsche		441.50	475	SDR DB	0
	296749	5822851.50	19235169.68	Bastrop	Sam Craig		365.80	460	SDR DB	45
	301604	5825942.72	19244665.78	Bastrop	Senen Baron		319.40	325	SDR DB	22
	302733	5886605.23	19232011.51	Fayette	Jeremy Finch		261.20	340	SDR DB	0
	303323	5839115.30	19267891.60	Bastrop	Raymond Nink		370.90	352	SDR DB	5
	304247	5686116.80	19320398.28	Travis	Native Texas Nursery		412.10	42	SDR DB	34
	304822	5873179.31	19215443.88	Fayette	Sam Wilson		373.50	380	SDR DB	20
	305659	5760396.98	19283630.34	Bastrop	City of Bastrop c/o Hardin & Assoc.		350.90	290	SDR DB	61
	305937	5726702.98	19303693.96	Bastrop	Trey Wyatt C C Tree Farm		407.20	150	SDR DB	30
	305939	5722899.05	19270903.51	Bastrop	Jeffery Voight		417.20	180	SDR DB	22
	305942	5739811.91	19301467.89	Bastrop	Barton Hills Farms		367.80	350	SDR DB	56
	305949	5700974.43	19329637.58	Travis	Auguse Krumm		423.80	41	SDR DB	38
	305977	5756015.51	19268844.27	Bastrop	Jason Alley		404.10	200	SDR DB	0
	305978	5755925.35	19268943.44	Bastrop	Will Jenkins		404.20	180	SDR DB	0
	305981	5756020.34	19268642.09	Bastrop	Clay Ingram		404.10	200	SDR DB	0

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	305983	5756100.82	19268947.63	Bastrop	Allen Kelley		403.80	200	SDR DB	0
	307118	5773493.02	19246384.53	Bastrop	Debbie Pearcy		385.94	500	SDR DB	47
	308198	5760117.35	19287977.19	Bastrop	Tim Hill		407.78	350	SDR DB	20
	310996	5879055.73	19219046.89	Fayette	Larry Harbers		307.30	305	SDR DB	0
	311725	5734235.79	19311361.38	Bastrop	John Lay		417.00	245	SDR DB	16
	313683	5813965.47	19218641.39	Bastrop	Johnny Sutton		370.80	610	SDR DB	0
	313784	5813965.47	19218641.39	Bastrop	Johnny Sutton		370.80	610	SDR DB	0
	316931	5850796.49	19244305.29	Fayette	Daniel J Bamsch		310.00	520	SDR DB	18
	316932[2]	5850796.49	19244305.29	Fayette	Daniel J Bamsch		310.00	520	SDR DB	18
	316971[2]	5846988.83	19235598.13	Fayette	Eddie L Schneider		301.60	520	SDR DB	30
	317052	5755674.53	19268431.17	Bastrop	Richard White		405.62	220	SDR DB	60
	317053	5755759.85	19268534.54	Bastrop	Pompeyo Chavez		405.10	220	SDR DB	40
	317569	5703631.94	19308737.85	Travis	Brent Johnson		410.50	65	SDR DB	58
	317574	5703564.72	19307825.10	Travis	Brent Johnson		390.60	57	SDR DB	50
	317581	5704009.42	19307531.44	Travis	Brent Johnson		401.20	62	SDR DB	55
	317614	5763004.29	19280959.73	Bastrop	Michael Allen		361.80	385	SDR DB	4
	317744	5726118.10	19317653.34	Bastrop	Charles Pertie		478.86	210	SDR DB	0
	318107	5751599.92	19266410.32	Bastrop	Bob Wilson		411.40	320	SDR DB	0
	318310	5838352.67	19253493.66	Bastrop	Maria Garza		348.20	355	SDR DB	0
	319018	5772030.10	19266800.94	Bastrop	Fil Valderrama		348.60	220	SDR DB	0
	319035	5847858.83	19255769.61	Bastrop	Cliff Burns		338.20	420	SDR DB	9

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	322157	5831882.97	19239048.64	Bastrop	L & R Partnership		303.80	305	SDR DB	20
	322340[2]	5856238.99	19237767.72	Fayette	Greg Deters		297.40	120	SDR DB	20
	323041	5832514.70	19235015.24	Bastrop	Theresa Ebner		312.30	332	SDR DB	40
	323189[2]	5851398.23	19224982.69	Fayette	Jason Riding		284.90	290	SDR DB	29
	323424	5833359.79	19219445.32	Fayette	Jeff Wise		383.20	380	SDR DB	0
	323433	5817371.28	19239989.83	Bastrop	Smithville ISD		315.60	200	SDR DB	39
	323435	5824571.91	19222963.40	Bastrop	Travis Hill		324.40	460	SDR DB	0
	323811	5766964.06	19255034.38	Bastrop	Randy Cunningham		377.94	230	SDR DB	38
	325584	5815525.34	19253813.66	Bastrop	David Fuqua		325.90	100	SDR DB	45
	326125	5845743.45	19269382.64	Bastrop	Republic Resources		360.70	450	SDR DB	0
	330247	5808717.60	19214255.55	Bastrop	David Corry		396.00	570	SDR DB	0
	330423	5851304.20	19268112.66	Bastrop	Jerrell Wolff		403.90	400	SDR DB	0
	334783[2]	5847819.78	19230760.00	Fayette	Robert Higgins Sr.		291.90	117	SDR DB	50[4]
	334797[2]	5847076.65	19235600.45	Fayette	Eddie Schneider		300.70	720	SDR DB	29
	334817[2]	5844156.37	19239775.44	Fayette	A. Martin Zoch		307.50	433	SDR DB	39
	334836[2]	5862288.16	19238132.67	Fayette	Edward R. Dykes		311.77	270	SDR DB	38
	338190[2]	5852729.54	19221170.95	Fayette	John Koether		292.50	182	SDR DB	45
	338198[2]	5867887.51	19238891.46	Fayette	Claudine Saunders		289.00	105	SDR DB	34
	340278	5735007.32	19312088.33	Bastrop	Turner Land & Hay		405.10	270	SDR DB	17
	341009	5823262.31	19243077.67	Bastrop	James Welch		319.64	280	SDR DB	25
	341032	5787348.21	19264645.95	Bastrop	Kenny and Faithe Evans		467.24	355	SDR DB	0

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	341490	5751189.37	19254150.27	Bastrop	Anthony Yoder		408.00	220	SDR DB	0
	342097	5774459.47	19249951.97	Bastrop	Dan Young		365.67	380	SDR DB	52
	343555	5724521.80	19276610.71	Bastrop	Julio Cruz		457.20	232	SDR DB	5
	343961	5737617.43	19309111.52	Bastrop	Kelles Berdoll		389.60	100	SDR DB	95
	345913	5836144.90	19267408.70	Bastrop	Republic Resources		380.00	530	SDR DB	12
	346511	5783245.19	19242472.94	Bastrop	Don Young		411.20	405	SDR DB	0
	346651	5766599.95	19280945.26	Bastrop	Reid Sharp		370.70	200	SDR DB	47
	347627	5838206.72	19272424.11	Bastrop	Michael & Lisa Willmon		394.80	530	SDR DB	0
	348041	5719401.48	19304943.73	Bastrop	Double Eagle Ranch - James Collins		374.50	50	SDR DB	34
	349919	5741559.70	19268096.86	Bastrop	Hoffman Ranch		422.50	347	SDR DB	0
	352088	5786345.95	19262596.36	Bastrop	Doug Granger		491.40	376	SDR DB	9
	354923	5765758.19	19254094.01	Bastrop	Thomas Krimbill		385.69	180	SDR DB	28
	358103	5843567.93	19268717.48	Bastrop	Gerardo & Cecilia Martinez		363.90	240	SDR DB	18
	358399	5739391.56	19323125.80	Bastrop	Ken Hallenburg		428.28	245	SDR DB	41
	358402	5782150.68	19247710.55	Bastrop	Terry Randal		356.40	550	SDR DB	71
	358661	5765247.85	19289721.06	Bastrop	Clyde Haywood		400.00	280	SDR DB	15
	359081	5852523.10	19255286.34	Bastrop	William Mitschke		354.60	540	SDR DB	31
	363000	5701556.70	19311425.47	Travis	Henry Chalmers		381.10	60	SDR DB	56
	364198[2]	5888363.97	19225580.37	Fayette	William Ring		286.10	1005	SDR DB	54
	365101[2]	5878787.01	19228860.87	Fayette	Beno Machala		238.80	95	SDR DB	23
	367854	5857845.88	19266262.57	Bastrop	Clayton Williams Energy		350.40	533	SDR DB	0

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	368367	5824900.74	19227224.31	Bastrop	Abigail David		344.80	536	SDR DB	26
	369127	5711438.64	19323797.89	Travis	David Shames		460.87	40	SDR DB	23
	369131	5711779.55	19324210.58	Travis	David Shames		492.70	50	SDR DB	45
	369808	5725437.48	19305385.94	Bastrop	Cedar Creek Tree Farms (Trey White)		403.70	151	SDR DB	50
	370343	5717193.69	19305703.58	Bastrop	Bettie Buchanan		406.70	350	SDR DB	42
	372056	5752852.19	19269072.80	Bastrop	Gary Butler		409.60	180	SDR DB	45
	372064	5755738.10	19269445.24	Bastrop	Dave Smith		402.90	200	SDR DB	30
	372068	5809001.86	19258405.82	Bastrop	Allan Seekatz		320.30	200	SDR DB	30
	372132	5755640.69	19269847.86	Bastrop	Christopher & Olivia Blankenship		401.00	200	SDR DB	36
	372142	5704070.71	19304799.10	Bastrop	Larry Mellenbruch		407.59	60	SDR DB	50
	372189[2]	5868037.40	19220366.73	Fayette	Gordon Westergren		325.20	700	SDR DB	14
	373295[2]	5875742.25	19231004.72	Fayette	Leonard Zbranek		272.60	135	SDR DB	40
	373371	5800435.89	19250089.49	Bastrop	Glenn Gilbreath		310.30	260	SDR DB	30
	373373	5766526.46	19283980.85	Bastrop	Michael Powell Kresge		370.90	320	SDR DB	50
	374022	5826753.25	19243876.86	Bastrop	Stewart Burns		314.80	440	SDR DB	48
	376248[2]	5862301.41	19234386.72	Fayette	Ben J Dusel		288.30	330	SDR DB	28
	376249	5862301.41	19234386.72	Fayette	Ben J Dusel		288.30	330	SDR DB	28
	376251	5862301.41	19234386.72	Fayette	Ben J Dusel		288.30	330	SDR DB	28
	376252	5862301.41	19234386.72	Fayette	Ben J Dusel		288.30	330	SDR DB	28
	376612[2]	5844839.52	19240502.42	Fayette	Webert Energy Corporation		306.90	630	SDR DB	40
	376966	5728166.94	19289654.19	Bastrop	Chip Wilkinson		380.10	440	SDR DB	12

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	376988	5841239.24	19250532.14	Bastrop	Virginia Garza		352.50	340	SDR DB	3
	377550	5835670.52	19252006.20	Bastrop	Elois Currivan		269.30	385	SDR DB	12
	378020	5772690.85	19264893.26	Bastrop	Gary Lehmann		336.30	66	SDR DB	65
	378545	5796134.43	19253626.45	Bastrop	Thomas Turf Grass - Seth Thomas		324.74	330	SDR DB	25
	378730	5739831.19	19293165.76	Bastrop	Robert Snider		484.64	370	SDR DB	15
	378849	5702999.01	19317431.19	Travis	Charles Perkins		399.30	51	SDR DB	45
	381611[2]	5849668.82	19237187.67	Fayette	Scott Rohloff		296.80	525	SDR DB	25
	382011[2]	5856342.09	19250325.34	Fayette	Wayne Smith		325.20	900	SDR DB	2
	384027	5727182.98	19309476.56	Bastrop	Larry Lay		401.70	235	SDR DB	30
	384433	5751211.93	19256884.42	Bastrop	Mike May		399.60	380	SDR DB	0
	384841	5850488.25	19269103.56	Bastrop	Delores Karisch		411.30	390	SDR DB	0
	384943[2]	5851516.05	19246956.86	Fayette	Weber Energy Corporation		303.90	550	SDR DB	35
	385501	5734049.12	19315609.73	Bastrop	Pedro Morales		420.10	260	SDR DB	0
	386070	5800435.89	19250089.49	Bastrop	Pecan Grove Plantation		310.30	220	SDR DB	33
	386533[2]	5885149.23	19237034.29	Fayette	Lazy Q Ranch		291.80	310	SDR DB	14
	388272	5840837.19	19262469.62	Bastrop	Brian Allen		351.50	240	SDR DB	5
	388636[2]	5884169.93	19224756.07	Fayette	Morgan Ranch		295.50	440	SDR DB	30
	389543	5880447.62	19241967.60	Fayette	Ken Stevenson		297.09	380	SDR DB	0
	390751	5718993.08	19311313.15	Bastrop	Rickey Turner		391.00	65	SDR DB	24
	390752	5718993.08	19311313.15	Bastrop	Rickey Turner		391.00	50	SDR DB	24
	390754	5735445.39	19315844.96	Bastrop	Josh Raymond		394.30	212	SDR DB	0

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	392533	5832464.60	19236937.72	Bastrop	Hancock Farms		312.20	370	SDR DB	38
	392736	5767310.75	19247955.77	Bastrop	Christopher Franklin		382.70	440	SDR DB	27
	393529	5753523.56	19299767.37	Bastrop	Goertz, Mary Jo		367.80	460	SDR DB	73
	394557	5765110.16	19280909.23	Bastrop	City of Bastrop		323.90	40	SDR DB	39
	394559	5765287.71	19280812.19	Bastrop	City of Bastrop		330.50	50	SDR DB	44
	394560	5765200.32	19280810.08	Bastrop	City of Bastrop		325.90	40	SDR DB	25
	394634	5789919.01	19260052.64	Bastrop	Joe Holub		404.06	407	SDR DB	10
	395840	5755693.87	19267621.74	Bastrop	Roger Blascky		407.32	170	SDR DB	36
	398838	5728644.79	19306877.92	Bastrop	Dale Accord		401.10	140	SDR DB	45
	401216	5741522.75	19247239.73	Bastrop	David Lackey		385.80	410	SDR DB	0
	401222	5758341.45	19248651.01	Bastrop	John R Ferguson 111		423.10	510	SDR DB	0
	401229	5731907.50	19313535.06	Bastrop	CMF Homes		438.57	255	SDR DB	19
	403703	5786138.20	19253276.29	Bastrop	CCW KASE Investments LLC		332.20	200	SDR DB	40
	404140	5771671.74	19259907.37	Bastrop	William Griesenbeck		353.64	260	SDR DB	25
	404464	5866925.56	19261444.44	Lee	Wayne Johnson		336.50	640	SDR DB	0
	405485	5804892.06	19254353.08	Bastrop	Malcolm Gunnel		315.80	365	SDR DB	36
	407865	5757834.95	19269799.02	Bastrop	Bill Stack		310.10	200	SDR DB	40
	410001	5744668.13	19296817.36	Bastrop	Brian Buckner		391.39	270	SDR DB	42
	410287	5755818.58	19269750.79	Bastrop	Jason & Sharon Rowe		401.60	200	SDR DB	32
	411999	5795136.41	19250440.62	Bastrop	Texas Rancho 40 Investments LP		332.00	402	SDR DB	60
	412073	5794995.03	19250054.38	Bastrop	Texas Rancho 40 Investments LP		332.20	420	SDR DB	60

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]	Depth to Alluvium Base (ft)
	412075	5795468.28	19252192.28	Bastrop	Texas Rancho 40 Investments LP		328.70	405	SDR DB	80
	413985	5755612.56	19268963.31	Bastrop	Cliff & Johnny Orsail		404.70	206	SDR DB	50
	414081	5859228.07	19227824.16	Fayette	Elbert Bradshaw III		299.70	880	SDR DB	42

[1] GWDB - TWDB Groundwater database; SDR DB - TWDB Submitted Drillers Reports database

[2] Well also in Standen (2017) study

[3] Depth to the alluvium base picked as 44 feet by Standen (2017)

[4] Depth to the alluvium base picked as 70 feet by Sanden (2017)

GAM = groundwater availability model, ft = feet, m = meter, LSD = land surface datum, m = meters; DEM = Digital Elevation Model

Table A-2. **Wells where the base of the Colorado River alluvium was not distinguishable from the underlying formation.**

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
5852209		5687079.52	19328417.66	Travis	C.L. Ferguson	430	430.07	65	GWDB
5854402		5755750.68	19301946.35	Bastrop	C. D. McCall	372	379.78	105	GWDB
5862119		5756116.65	19275630.22	Bastrop	Aqua WSC	385	367.15	495	GWDB
5862409		5756641.47	19268352.59	Bastrop	Aqua WSC	401	400.44	615	GWDB
5863901		5817770.99	19244961.15	Bastrop	City of Smithville	324	323.35	452	GWDB
5863919		5825639.28	19242835.10	Bastrop	City of Smithville	316	316.28	1,440	GWDB
5957804		5882634.41	19245469.71	Fayette	Clear Lake Pines	425	426.12	497	GWDB
6708604[2]		5862732.38	19221640.68	Fayette	Fayette WSC - West	342	342.86	1,197	GWDB
	619	5843265.36	19266886.95	Bastrop	Frank Pinn		340.30	300	SDR DB
	864	5727785.92	19275774.73	Bastrop	Richard Mayes		440.50	235	SDR DB
	1179	5740207.87	19321930.04	Bastrop	Earnest Nance		416.90	230	SDR DB
	1535	5721789.59	19246579.56	Bastrop	Richard Wicke		432.40	356	SDR DB
	2809	5752520.30	19257219.13	Bastrop	Anne Strohm		400.30	220	SDR DB
	3018	5757776.99	19301488.93	Bastrop	Billy Duty		348.80	365	SDR DB
	3020	5732741.56	19273864.43	Bastrop	Joey Chioco		422.20	220	SDR DB
	3021	5733175.16	19274077.17	Bastrop	Roy Jones		421.70	260	SDR DB
	3252	5804697.61	19262043.02	Bastrop	Neil & Laura Mixon		401.90	280	SDR DB
	4245	5748015.42	19273311.43	Bastrop	Catherine McMarion		461.90	320	SDR DB
	8948	5769898.50	19289530.17	Bastrop	ANDERSON		382.80	355	SDR DB
	8974	5755052.86	19254039.59	Bastrop	Rosamunda Findeisen		426.20	260	SDR DB

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
	13374	5740346.51	19267460.79	Bastrop	Mike Williams		423.30	380	SDR DB
	17019	5836273.45	19222255.03	Fayette	Tom Bridge		365.10	500	SDR DB
	19405	5795495.17	19244093.31	Bastrop	Tom Hatfield		421.30	340	SDR DB
	24520	5772050.73	19287557.38	Bastrop	Donald Barron		447.30	165	SDR DB
	27992	5768173.78	19244939.47	Bastrop	Dale Ringer		417.00	480	SDR DB
	29526	5712918.18	19235241.31	Bastrop	Steve Kirk		411.60	240	SDR DB
	30488	5736798.75	19317901.42	Bastrop	Jesse Banda		396.20	240	SDR DB
	31326	5755793.87	19256082.34	Bastrop	Joshua Simons		402.70	385	SDR DB
	32144	5713680.44	19236473.32	Bastrop	Gary Oppermann		409.80	243	SDR DB
	37024	5734509.73	19303368.73	Bastrop	Steve Boyd		416.80	260	SDR DB
	42198	5735451.77	19251653.71	Bastrop	Ken Kerner		398.60	215	SDR DB
	46451	5811733.34	19261411.72	Bastrop	Michael Psencik		339.62	80	SDR DB
	47462	5717601.74	19241624.83	Bastrop	Buddy Powell		423.00	240	SDR DB
	47824	5804838.34	19256477.81	Bastrop	Ted Macon		299.50	65	SDR DB
	47825	5773667.49	19264410.79	Bastrop	Eddie Robinson		352.40	330	SDR DB
	50667	5749394.79	19263219.75	Bastrop	Joe Townsend		379.80	300	SDR DB
	52723	5748370.81	19273117.56	Bastrop	Annie Baker		460.50	430	SDR DB
	52857	5773642.49	19243857.58	Bastrop	Tom Driver		403.10	280	SDR DB
	65689	5763691.93	19296062.65	Bastrop	Tommy Odom		449.50	235	SDR DB
	66386	5750518.70	19252817.85	Bastrop	Randy Ray		400.40	220	SDR DB
	70900	5712407.89	19234521.25	Bastrop	Steve Kirks		421.10	220	SDR DB

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
	71563	5730867.45	19320598.03	Bastrop	Guy Robinson		456.70	190	SDR DB
	72190	5735560.46	19250745.06	Bastrop	Delia Montesinos		383.60	205	SDR DB
	82665	5739035.66	19248497.57	Bastrop	Jimmie Hoffman		382.40	200	SDR DB
	91238[3]	5849862.08	19239825.20	Fayette	Howard McDonald		314.30	325	SDR DB
	98526	5806794.99	19248528.91	Bastrop	Arthur Kimbrough		421.38	285	SDR DB
	111155	5771880.58	19294539.69	Bastrop	Bruce Young		395.50	427	SDR DB
	111910	5797554.74	19263483.32	Bastrop	Steven Goerner		343.71	690	SDR DB
	115988	5871153.62	19231791.02	Fayette	Michael Penny		243.40	100	SDR DB
	125121	5814008.11	19258229.74	Bastrop	Steven Giles		442.07	340	SDR DB
	150551	5748673.46	19275149.47	Bastrop	Bastrop Church OF Christ		468.20	255	SDR DB
	157116	5871184.53	19214478.43	Fayette	St. James Baptist Church		380.20	85	SDR DB
	158125	5771322.72	19288653.57	Bastrop	Charles Schroeder		430.10	550	SDR DB
	159928	5756357.17	19258221.83	Bastrop	Henry Tomlin		369.60	405	SDR DB
	160526	5861829.00	19245410.34	Fayette	Hunter Industries		316.49	310	SDR DB
	161642	5770478.47	19287316.44	Bastrop	Chris Nutt		420.10	335	SDR DB
	176123	5723219.46	19272227.01	Bastrop	Dave Savage		425.70	180	SDR DB
	177405	5721286.33	19272385.33	Bastrop	BISD		427.60	220	SDR DB
	185426	5737661.95	19273472.83	Bastrop	Melvin Morris		403.60	260	SDR DB
	193470	5749946.16	19288038.27	Bastrop	Diane Greg		389.12	240	SDR DB
	194648	5841333.04	19230285.10	Fayette	Trish Vandiver		308.10	494	SDR DB
	207588	5732721.93	19316186.47	Bastrop	Eugene Hoskins		444.53	205	SDR DB

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
	224105	5805422.02	19247278.95	Bastrop	Doug Feick		446.20	583	SDR DB
	225091	5867259.81	19245860.89	Fayette	Zoch, Barry		340.12	430	SDR DB
	241925	5741523.54	19273361.02	Bastrop	Linda Wilson		391.00	127	SDR DB
	261199	5762442.04	19246015.87	Bastrop	Scott Hartzler		401.20	230	SDR DB
	268555	5724465.39	19244717.64	Bastrop	Michael Martin		423.30	440	SDR DB
	271281	5780775.67	19239374.92	Bastrop	James E. Pinkerton		445.40	400	SDR DB
	287253	5730608.23	19290216.98	Bastrop	Griffin Dewatering		472.90	427	SDR DB
	289849	5825205.66	19256188.85	Bastrop	George Dietrich		295.13	60	SDR DB
	295184	5715032.17	19315981.75	Bastrop	James Kitchen		402.60	63	SDR DB
	302039	5783933.81	19264359.18	Bastrop	JIM HALEY		435.70	320	SDR DB
	306041	5731951.87	19326698.53	Bastrop	Laurence Bernhardt		403.60	205	SDR DB
	306245	5752036.45	19251740.42	Bastrop	Dr. Shawn Taher		400.60	245	SDR DB
	319057	5795900.63	19255949.33	Bastrop	Dennis Ring		314.19	240	SDR DB
	324248	5845108.72	19236965.55	Fayette	Tom Hudson		306.70	490	SDR DB
	325580	5816036.73	19247549.07	Bastrop	David Fuqua		314.30	30	SDR DB
	330418	5837919.73	19266645.29	Bastrop	Roy Jones		382.20	360	SDR DB
	341008	5720419.24	19271960.54	Bastrop	Greg Guenther		427.70	240	SDR DB
	341016	5720497.39	19272367.27	Bastrop	Greg Guenther		428.50	180	SDR DB
	341017	5720156.04	19271954.52	Bastrop	Greg Guenther		436.40	94	SDR DB
	341019	5720153.73	19272055.80	Bastrop	Greg Guenther		437.80	94	SDR DB
	347145	5728423.31	19320237.75	Bastrop	William Lopez		519.00	310	SDR DB

State Well Number	SDR Tracking Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
	347743	5787556.00	19263335.28	Bastrop	Kerry And Becky Getter		440.00	330	SDR DB
	348040	5753772.96	19270917.18	Bastrop	Patti & Cleve Jacobs		402.90	530	SDR DB
	352081	5785010.88	19263373.23	Bastrop	P.G.I.		439.20	341	SDR DB
	354634	5808895.92	19214158.75	Bastrop	David Corry		400.20	540	SDR DB
	363561	5754777.78	19254539.29	Bastrop	Tim Kamrath		432.80	260	SDR DB
	367752	5712177.31	19236945.53	Bastrop	Wesley Brown		421.50	200	SDR DB
	368963	5855323.58	19268726.22	Bastrop	Clayton Williams Energy		367.60	533	SDR DB
	369933	5841674.52	19257327.72	Bastrop	Indian Hills Farm		356.90	320	SDR DB
	372150	5799108.82	19247018.49	Bastrop	Cree Land & Cattle		350.20	266	SDR DB
	372208	5763624.12	19295250.72	Bastrop	Grant Crump		440.50	440	SDR DB
	386068	5793111.23	19258714.64	Bastrop	Colorado Valley Pecan		336.32	200	SDR DB
	386824	5795760.78	19243998.99	Bastrop	Greg Hawes		424.80	400	SDR DB
	388275	5842609.08	19265148.78	Bastrop	Diego Cruz		337.30	380	SDR DB
	390421	5813957.54	19239598.87	Bastrop	Alan Hemphill		348.56	280	SDR DB
	397073[4]	5884685.57	19225175.23	Fayette	Ken Oden		272.80	164	SDR DB
	401339	5772314.83	19291107.88	Bastrop	Dr. James Elroy Whitworth		392.80	370	SDR DB
	402055	5735504.75	19324553.76	Bastrop	Tabb Improvements		433.86	195	SDR DB
	405584	5778493.55	19246507.17	Bastrop	Patrick Bailey		383.03	375	SDR DB
	410561	5735017.25	19322922.50	Bastrop	Aaron Gant		422.30	185	SDR DB
	410683	5740782.42	19271318.53	Bastrop	Dewey Overholser		394.80	420	SDR DB
	412074	5797731.03	19253646.04	Bastrop	Texas Rancho 40 Investments LP		326.07	400	SDR DB

State Well Number	**SDR Tracking Number**	**x GAM Coordinate (ft)**	**y GAM Coordinate (ft)**	**County**	**Owner**	**LSD (ft)**	**10-m DEM value (ft)**	**Well Depth (ft)**	**Well Data Source[1]**
	413727	5855480.76	19220601.00	Fayette	Fayette W.S.C.		318.83	2,150	SDR DB

[1] GWDB - TWDB Groundwater database; SDR DB - TWDB Submitted Drillers Reports database,

[2] Standen (2017) picked the base of the alluvium at 39 feet

[3] Standen (2017) picked the base of the alluvium at 21 feet

[4] Standen (2017) picked the base of the alluvium at 48 feet

GAM = groundwater availability model, ft = feet, LSD = land surface datum, m = meter, DEM = Digital Elevation Model

Table A-3. Well investigated for which a lithology log is not available.

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
5844801	5694482.70	19330201.26	Travis	Maclieb	410	410.96	38	GWDB
5844802	5694399.59	19329997.12	Travis	W. Davis	410	411.63	42	GWDB
5844803	5694009.31	19335759.34	Travis		440	443.31	40	GWDB
5844804	5691983.00	19332373.41	Travis	Elroy Brown	420	419.77	26	GWDB
5844805	5690465.87	19329707.45	Travis	R. Gilbert	410	416.21	33	GWDB
5844808	5690174.10	19331017.25	Travis	Mansville WSC	421	421.70	50	GWDB
5844809	5690001.48	19330912.11	Travis	Mansville WSC	421	420.90	48	GWDB
5844901	5696594.09	19329741.85	Travis	Maggie Burleson	420	406.83	1,690	GWDB
5844902	5698853.95	19330501.13	Travis	Coin Laurin	415	422.59	30	GWDB
5844903	5700065.62	19331135.44	Travis	James Burke	440	437.96	22	GWDB
5852203	5686103.81	19321004.89	Travis	H.L. Latham	410	412.74	26	GWDB
5852204	5687265.27	19315968.22	Travis	F.M. Oakley	400	402.38	60	GWDB
5852205	5689132.29	19326640.29	Travis	J.M. Glass	420	420.17	27	GWDB
5852207	5685930.82	19320899.77	Travis	Charles Hackett	415	412.35	28	GWDB
5852208	5685254.96	19319771.41	Travis	Charles Hackett	420	420.49	39	GWDB
5852210	5690004.78	19322811.83	Travis	Juan Paredes	420	421.18	31	GWDB
5852211	5690754.61	19324549.90	Travis	Jesse Trejo	415	411.24	30	GWDB
5852212	5690662.54	19324750.54	Travis	Fernando Robledo	415	412.78	27	GWDB
5852214	5686817.07	19328411.90	Travis	B.J. Temple	430	428.83	42	GWDB
5852215	5685241.72	19328377.35	Travis		430	424.94	35	GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
5852218	5692195.55	19326707.87	Travis	Unknown	416	416.52		GWDB
5852305	5705484.52	19315968.10	Travis	S.G. Edwards	400	401.05	39	GWDB
5852308	5702756.66	19328259.18	Travis	V.B. Lewis	410	412.68	26	GWDB
5852309	5706361.16	19319835.14	Travis	L.A. Turner	410	409.55	40	GWDB
5852310	5701248.53	19329136.68	Travis	August Krumm	420	423.42	30	GWDB
5852311	5701423.39	19329140.59	Travis	Leroy Roitsch	415	423.26	33	GWDB
5852312	5701883.66	19328138.66	Travis		410	410.78	27	GWDB
5852503	5689436.85	19308827.02	Travis	Republic Bank and	427	473.14	1,780	GWDB
5852601	5706700.57	19304756.50	Bastrop	W.B. Hinton	405	406.10	42	GWDB
5852602	5706963.20	19304762.41	Bastrop	W.B. Hinton	405	405.77	22	GWDB
5852603	5708756.56	19306827.98	Bastrop	Claude Berdall	400	401.70	46	GWDB
5852604	5707908.45	19305593.62	Bastrop	W.B. Hinton	407	404.51	41	GWDB
5852605	5708506.76	19302367.11	Bastrop	T.H. Caldwell	400	400.82	30	GWDB
5852606	5709258.45	19304004.26	Bastrop	T.H. Caldwell	405	402.33	26	GWDB
5852610	5706771.79	19313263.30	Travis	S.G. Edwards	400	385.41	53	GWDB
5852611	5699680.38	19309155.38	Travis	C.H. Buck	410	417.27	50	GWDB
5852614	5703096.51	19305283.18	Travis	Charles Strong	406	405.75	62	GWDB
5852615	5705381.18	19308878.08	Travis	Colorado River	409	410.35	68	GWDB
5853101	5713942.58	19317677.80	Bastrop	John T. Baker	390	422.65	36	GWDB
5853102	5714848.04	19316382.16	Bastrop	John T. Baker	420	390.76	46	GWDB
5853103	5721093.27	19319055.93	Bastrop	W.R. Rivers	420	417.05	35	GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
5853104	5710770.87	19322364.47	Travis	Neal McEachern	400	407.19	30	GWDB
5853106	5715200.50	19316289.21	Bastrop	River Oaks Trailer	395	392.33	40	GWDB
5853401	5710819.50	19308595.77	Bastrop	Claude Berdoll	400	407.84	40	GWDB
5853501	5727716.59	19312931.27	Bastrop	Ernest H. McDuff	425	427.50	54	GWDB
5853503	5731396.11	19309168.80	Bastrop	Mrs. E. Hatherly	425	420.22	30	GWDB
5853504	5734207.33	19305082.86	Bastrop	R.E. Barton	420	417.85	104	GWDB
5853505	5734200.26	19305386.33	Bastrop	W.A. Barton	420	416.54	720	GWDB
5853506	5735366.75	19300452.29	Bastrop	Colon E. McDonald	395	392.13	81	GWDB
5853507	5728756.17	19305867.54	Bastrop	W. Sommers	400	405.17	39	GWDB
5853601	5742737.95	19303763.76	Bastrop	J.G. Bryson	370	362.56	70	GWDB
5853602	5738297.25	19306291.95	Bastrop	John Barton	400	409.77	73	GWDB
5853802	5732210.51	19296733.82	Bastrop	John Allen	390	390.76	50	GWDB
5853807	5734689.68	19299424.29	Bastrop		390	391.55	52	GWDB
5853902	5741720.75	19298576.29	Bastrop	Carroll Rosanky	385	385.40	265	GWDB
5853903	5746806.84	19294747.58	Bastrop	Doyle Harkins	382	387.90	365	GWDB
5853904	5747785.01	19294163.11	Bastrop	Doyle Harkins	382	383.72	55	GWDB
5853905	5738306.72	19294648.54	Bastrop	M.A. Prokop	395	401.95	195	GWDB
5853906	5738482.06	19294652.65	Bastrop	M.A. Prokop	395	401.06	40	GWDB
5853907	5742095.28	19293826.18	Bastrop	M.A. Prokop, Jr	395	396.22	131	GWDB
5853908	5739878.84	19294888.04	Bastrop	Frank Spiller	398	394.62	131	GWDB
5853909	5743798.01	19292246.43	Bastrop	Earl Earhardt	385	388.02	46	GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
5854401	5751335.26	19303359.57	Bastrop	Buck Steiner	390	389.69	65	GWDB
5854701	5750284.52	19295943.56	Bastrop	Mrs. Addie Mae Powell	370	384.03	280	GWDB
5854702	5750743.41	19291398.20	Bastrop	E.L. Moore	370	367.31	185	GWDB
5854703	5757202.72	19296209.90	Bastrop	Powell well 1	370	366.37	3,638	GWDB
5854704	5752194.66	19285661.25	Bastrop	J.J. Hennesey	410	411.69	41	GWDB
5854707	5758628.72	19298876.53	Bastrop	TWDB	400	389.56	277	GWDB
5862101	5757974.96	19278611.06	Bastrop	Lloyd Ketha	362	368.36	192	GWDB
5862103	5757404.38	19273129.63	Bastrop	R.M. Hodgson	365	366.94	200	GWDB
5862105	5755673.15	19272177.00	Bastrop	R.M. Hodgson	355	360.75	23	GWDB
5862106	5762398.65	19273350.88	Bastrop	Sam Higgins well 1	355	364.97	3,368	GWDB
5862107	5756515.63	19273614.65	Bastrop	James Reed	340	367.88	332	GWDB
5862108	5761473.45	19282643.29	Bastrop	J.L. West	340	355.20	190	GWDB
5862109	5756844.43	19274533.74	Bastrop	Texas Tropical Fish	365	366.74	280	GWDB
5862110	5756929.73	19274637.11	Bastrop	Texas Tropical Fish	365	366.33	325	GWDB
5862111	5755139.29	19283504.01	Bastrop	Lloyd Ketha	375	393.79	340	GWDB
5862120	5760492.15	19279683.67	Bastrop	J & R Mobile Home Park	366	366.15	340	GWDB
5862202	5766792.02	19283885.58	Bastrop	Ben Johnson et al	362	371.14	3,735	GWDB
5862203	5765200.64	19280809.72	Bastrop	Texas Public Utility	382	325.85	650	GWDB
5862204	5765285.59	19280913.10	Bastrop	City of Bastrop	330	331.03	52	GWDB
5862207	5765288.04	19280811.83	Bastrop	City of Bastrop	347	330.56	58	GWDB
5862212	5765378.19	19280712.68	Bastrop	City of Bastrop	343	330.88	55	GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
5862215	5765468.34	19280613.89	Bastrop	City of Bastrop	327	332.15		GWDB
5862217	5765200.64	19280809.72	Bastrop	City of Bastrop	327	325.85	52	GWDB
5862402	5761884.72	19269187.31	Bastrop	E.M. Denman	350	351.23	39	GWDB
5862403	5760569.69	19265510.80	Bastrop	C-Bar Ranch	355	380.50	46	GWDB
5862404	5760830.18	19265618.38	Bastrop	C-Bar Ranch	380	368.96	208	GWDB
5862405	5760240.89	19264591.68	Bastrop	C-Bar Ranch	375	364.82	47	GWDB
5862406	5757579.33	19269488.91	Bastrop	K.M. Trigg	400	386.99	106	GWDB
5862408	5762435.11	19260898.61	Bastrop	Mildred Jenkins well 1	352	349.79	4,017	GWDB
5862501	5770354.89	19256331.44	Bastrop	Bettie Price well 1	351	337.23	6,425	GWDB
5862502	5766479.33	19256946.04	Bastrop	W.W. Craft	380	366.56	32	GWDB
5862503	5771742.58	19260617.66	Bastrop	Earl C. Erhard	355	350.42	160	GWDB
5862504	5763926.17	19257289.32	Bastrop	Tom Griffin	370	361.77	960	GWDB
5862505	5763548.04	19269328.71	Bastrop	E.M. Denman	350	358.00	47	GWDB
5862506	5768713.72	19266112.36	Bastrop	Kleberg Trigg	350	351.79	290	GWDB
5862601	5786885.00	19258559.47	Bastrop	Cecil Curry	394	371.16	396	GWDB
5862602	5786198.55	19257934.87	Bastrop	J. E. Price	355	364.38	54	GWDB
5862603	5786261.26	19258948.98	Bastrop	W. T. Higgins, Jr.	390	377.36	160	GWDB
5862801	5773945.74	19249432.80	Bastrop	J. S. Williams	360	381.23	60	GWDB
5862802	5774678.36	19251779.36	Bastrop	Jack Feregeson	360	364.98	38	GWDB
5862901	5781710.73	19254888.11	Bastrop	W. W. McAlister	330	334.64	44	GWDB
5862902	5788789.75	19252531.76	Bastrop	Mrs. Mark Young	320	329.50	23	GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
5862903	5781035.55	19246670.20	Bastrop	James Jackson	352	335.31	59	GWDB
5863403	5792690.71	19257994.85	Bastrop	John Mayes	370	330.42	15	GWDB
5863501	5807065.22	19258660.29	Bastrop	H.H. Wehmeyer	340	321.63	407	GWDB
5863602	5818677.00	19257539.06	Bastrop	TPWD	380	384.90	530	GWDB
5863603	5827901.03	19257169.56	Bastrop	Hill Estate	310	310.10	960	GWDB
5863604	5824779.33	19259113.87	Bastrop	Hill Estate	315	317.10	900	GWDB
5863605	5826235.98	19260467.78	Bastrop	Hill Estate	330	342.49	40	GWDB
5863701	5802439.12	19254189.44	Bastrop	Leonard Nut Co.	320	310.16	391	GWDB
5863702	5796477.95	19253938.31	Bastrop	H.W. Haisler	320	321.78	100	GWDB
5863703	5797691.68	19251032.76	Bastrop	Mrs. Bell Perkins	320	323.67	140	GWDB
5863704	5797525.24	19254167.21	Bastrop	Leonard Nut co	320	314.31	83	GWDB
5863705	5800375.13	19252517.29	Bastrop	Leonard Nut Co	310	310.18	29	GWDB
5863706	5791286.70	19243886.98	Bastrop	C.V. Williams	290	370.40	27	GWDB
5863707	5797109.20	19246259.76	Bastrop	C.A. Rosanky	350	358.86	365	GWDB
5863708	5801818.01	19247491.58	Bastrop	Monroe Inge	330	347.00	42	GWDB
5863801	5815461.20	19252900.05	Bastrop	B. G. Whitlow	325	323.11	715	GWDB
5863802	5809842.28	19249517.12	Bastrop	A.E. Miller	320	324.17	35	GWDB
5863803	5807139.06	19252283.15	Bastrop	W. Svoboda	325	324.23	230	GWDB
5863804	5807314.30	19252287.59	Bastrop	W. Svoboda	325	323.92	41	GWDB
5863903	5817760.62	19245365.83	Bastrop	City of Smithville	324	298.94	651	GWDB
5863904	5818031.49	19245068.80	Bastrop	City of Smithville	324	324.68	651	GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
5863905	5825319.74	19248395.20	Bastrop		277	326.76	180	GWDB
5863906	5818824.54	19255214.08	Bastrop	Mrs. --Douglas	315	326.40	34	GWDB
5863907	5825491.28	19245160.01	Bastrop	Jones Estate	320	324.68	180	GWDB
5863909	5821440.07	19245662.69	Bastrop	Elbert Thorn	315	332.46	190	GWDB
5863910	5824171.08	19241885.91	Bastrop	F.B. Barry	315	319.14	30	GWDB
5863911	5825755.57	19241724.22	Bastrop		315	316.27	300	GWDB
5863912	5826533.43	19252375.21	Bastrop	Woody Burns	310	291.15	265	GWDB
5863913	5826729.96	19251570.38	Bastrop	Woody Burns	310	282.91	37	GWDB
5863914	5824071.13	19255956.85	Bastrop	C.L. Gilbert	310	313.07	500	GWDB
5863915	5824243.75	19256062.28	Bastrop	C.L. Gilbert	310	312.28		GWDB
5863916	5824502.59	19246045.68	Bastrop		327	330.36	160	GWDB
5863917	5824401.72	19246549.36	Bastrop		323	328.95	25	GWDB
5863918	5818201.89	19245275.83	Bastrop	City of Smithville	322	324.44	1,100	GWDB
5864402	5829665.65	19256810.43	Bastrop	Roy Hoskins	310	333.67	44	GWDB
5864403	5830186.37	19257026.64	Bastrop	Virgil Hoskins	364	338.80	372	GWDB
5864702	5841104.01	19245668.35	Bastrop	Mrs. Gertrude	315	310.59	356	GWDB
5864703	5841061.47	19243946.08	Bastrop	Roy Thompson	315	309.39	36	GWDB
5864704	5841146.61	19244049.65	Bastrop	Roy Thompson	300	313.38	10	GWDB
5864705	5842159.77	19242253.84	Bastrop	C&Milton Meutsching	315	305.19		GWDB
5864706	5834455.85	19248126.43	Bastrop	M. Jones	310	315.96	322	GWDB
5864707	5834570.30	19250458.19	Bastrop	David Brummitt	290	281.91	350	GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
5864709	5829598.87	19245873.76	Bastrop	George Ramosek	319	319.29	200	GWDB
5864710	5829788.30	19248713.37	Bastrop	George Rainasek	290	289.52	350	GWDB
5864711	5831125.27	19247938.24	Bastrop		288	315.16	28	GWDB
5864808	5848033.55	19249192.41	Bastrop	Paul Gobel	315	311.39	35	GWDB
5864809	5851656.95	19248276.46	Fayette	J J Noack	325	323.91	40	GWDB
5864901	5865354.82	19248137.48	Fayette	Saint Michaels	345	345.07	175	GWDB
5864902	5861689.05	19257151.33	Fayette	R.C. Meier	335	335.42	638	GWDB
5864903	5860676.84	19252365.08	Fayette	Erwin Zoch	315	317.68	1,800	GWDB
5864904	5860159.41	19255287.65	Fayette	Mattie Johnson	321	320.57	46	GWDB
5864905	5865524.94	19248344.38	Fayette	Litheran Church	344	344.00	135	GWDB
5957701	5878530.78	19244648.49	Fayette	Motley	380	310.34	81	GWDB
5957702	5874333.66	19244027.50	Fayette	W U Williams Est.	360	350.03	195	GWDB
5957703	5874352.96	19243319.43	Fayette	W U Williams	337	334.30	65	GWDB
6601101	5873986.38	19237436.55	Fayette	Willis Koenig	281	272.66	290	GWDB
6601102	5870290.32	19228021.28	Fayette	Kermit Stolle	290	288.13	110	GWDB
6601104	5870043.27	19227406.96	Fayette	Emil Flath	293	296.17	88	GWDB
6601105	5881859.18	19228944.76	Fayette	Mary Zbonek	276	271.12	30	GWDB
6601201	5885549.26	19238462.52	Fayette	Paul Lehman	330	331.91	100	GWDB
6601401	5878877.87	19219142.99	Fayette	Charles Harburn	310	311.16	285	GWDB
6601402	5878387.00	19217813.01	Fayette	Henry Burtsch	353	345.31	68	GWDB
6601403	5878387.00	19217813.01	Fayette	Henry Burtsch	350	345.31	305	GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
6601405	5878378.70	19218116.40	Fayette	Saint Peter & Paul	350	334.70	84	GWDB
6601409	5881259.86	19225181.99	Fayette	Joe Belota	292	290.14	45	GWDB
6601410	5870402.89	19223873.11	Fayette	Ed Kraulik	291	292.26	25	GWDB
6601411	5869851.40	19224769.38	Fayette	Edwin Raschke	291	291.74	70	GWDB
6601501	5887347.40	19224235.71	Fayette	J.F. Morgan	280	280.15	1,000	GWDB
6601504	5887420.96	19224744.03	Fayette	Edward Morgan	282	282.95	42	GWDB
6707202	5815937.36	19237725.36	Bastrop	George Rohde	320	320.39	550	GWDB
6707203	5815826.24	19238633.73	Bastrop	J.D. Anderws	316	318.75	1,387	GWDB
6707205	5815885.57	19239749.12	Bastrop	George Rohde	320	320.84	30	GWDB
6707301	5817116.92	19232794.54	Bastrop	August Neumann	387	391.87	42	GWDB
6707302	5825422.98	19234223.17	Bastrop	R.R. Miller well 1	352	353.25	7,601	GWDB
6707303	5817150.31	19234921.44	Bastrop	City of Smithville	384	383.82	337	GWDB
6707304	5827074.61	19228090.07	Bastrop	Joe Ebner	340	329.20	300	GWDB
6707305	5828037.61	19228216.35	Bastrop	Joe Ebner	350	340.46	23	GWDB
6707306	5826955.40	19236085.27	Bastrop	L. Thomas	350	350.53	40	GWDB
6707307	5828827.54	19228236.84	Bastrop	Frank Keller	345	325.05	326	GWDB
6707308	5829439.17	19228354.05	Bastrop	Frank Keller	315	307.43	80	GWDB
6707309	5829617.48	19228257.35	Bastrop	Frank Keller	315	307.43	280	GWDB
6707310	5829150.14	19239483.48	Bastrop	G.L. Hill	315	311.45	310	GWDB
6707311	5819568.49	19236502.30	Bastrop	Mrs. Tom C. Machem	350	330.60	415	GWDB
6707312	5826376.24	19231311.53	Bastrop		313	341.44	490	GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
6707314	5816796.73	19235013.71	Bastrop	City of Smithville	370	379.07		GWDB
6707501	5810265.45	19219053.05	Bastrop	Frank Rundus	400	388.23	4,344	GWDB
6707601	5824194.69	19223965.83	Bastrop	Tom Mikulenka well 1	315	364.25	4,306	GWDB
6707603	5819148.43	19215229.87	Bastrop	M.H. Young well 1	343	342.85	4,248	GWDB
6708101	5839538.21	19235097.30	Fayette	Test Hole	305	313.49		GWDB
6708102	5836500.90	19230360.22	Fayette	Bobby Hoskins	308	308.28	520	GWDB
6708105	5837926.21	19229587.66	Fayette	Ann Valasta Horton	312	310.89	28	GWDB
6708106	5841303.75	19234738.77	Fayette	Richards	316	316.24	280	GWDB
6708107	5831732.57	19231349.62	Bastrop	Wm. Urner	300	301.85	300	GWDB
6708108	5829737.17	19237169.99	Bastrop	Yeager Hill Estate	305	321.79	640	GWDB
6708109	5834773.33	19239326.34	Bastrop	Yeager Hill Estate	305	305.80	650	GWDB
6708110	5836815.30	19238468.52	Bastrop	Yeager Hill Estate	310	314.81	36	GWDB
6708111	5835368.68	19236709.17	Bastrop	C.H. Winkler	310	312.25	26	GWDB
6708112	5830191.73	19236574.20	Bastrop	Yegar Hill Estate	305	295.65	29	GWDB
6708113	5833505.30	19240811.70	Bastrop	Yeager Hill Estate	300	315.16	1,000	GWDB
6708114	5838979.63	19229615.29	Fayette	Ralph Richards	311	310.34	26	GWDB
6708115	5841040.59	19234731.84	Fayette	Ralph Richards	316	317.09	26	GWDB
6708201	5849717.50	19235366.13	Fayette	Carl Fritsch	300	297.82	31	GWDB
6708202	5849974.59	19228994.70	Fayette	M.G. Heck	289	290.90	200	GWDB
6708203	5848165.77	19230971.09	Fayette	William Heirs	292	293.27	30	GWDB
6708301	5864920.18	19231723.21	Fayette	Test Hole	272	273.42		GWDB

State Well Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Owner	LSD (ft)	10-m DEM value (ft)	Well Depth (ft)	Well Data Source[1]
6708302	5857646.14	19237704.04	Fayette	Marvin Kipp	300	299.81	150	GWDB
6708303	5857915.77	19240748.63	Fayette	Arnold Killian	310	309.99	96	GWDB
6708304	5864300.73	19235148.80	Fayette	Elgin Hart	296	296.74	50	GWDB
6708305	5859373.90	19228941.60	Fayette	Jack Young	298	296.85	58	GWDB
6708306	5858976.02	19237233.40	Fayette	Mary Pietsch	291	314.28	40	GWDB
6708401	5834562.83	19220488.87	Fayette	W.R. Urner	360	359.63	62	GWDB
6708402	5842828.25	19223540.63	Fayette	Alfred Young	340	336.48	678	GWDB
6708403	5834562.83	19220488.87	Fayette	W.M. Urner	360	359.63	580	GWDB
6708405	5838776.96	19220599.16	Fayette	Test Hole	375	379.40		GWDB
6708501	5852309.75	19220450.48	Fayette	Yantis J Jacobs	304	302.00	45	GWDB
6708503	5849487.00	19220881.73	Fayette	A F Hayne	315	317.61	30	GWDB
6708601	5857895.87	19221814.45	Fayette	E.H. Luck	343	342.86	96	GWDB
6708602	5869261.54	19227082.14	Fayette	Robert Harbors	292	292.65	90	GWDB
6708603	5863552.44	19220549.25	Fayette	John H. Henderson	360	337.50	41	GWDB
6708605	5864211.37	19222186.80	Fayette	Rudolph Schmidt	340	336.25	110	GWDB
6708606	5858242.68	19225266.35	Fayette	A F Behrens	308	308.50	85	GWDB

[1] GWDB - TWDB Groundwater database

GAM = groundwater availability model, ft = feet, LSD = land surface datum, m = meter, DEM = Digital Elevation Model

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10 Appendix B – Specific Capacity, Transmissivity, and Hydraulic Conductivity for the Colorado River Alluvium in and near Groundwater Management Area 12

Table B-1. **Calculated specific capacities, transmissivities, and hydraulic conductivities for Colorado River alluvium wells.**

Well ID Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Depth to Base of Alluvium (ft)	Well Total Depth (ft)	Well Yield (gpm)	Draw-down (ft)	SC (gpm/ft)	T (ft^2/day)	DTW[1] (ft)	K (ft/day)	In Outcrop Layer of GAM
35464	5690547.05	19318065.60	Travis	33	34	600	15	40.0	7,692	25	962	
35479	5689709.43	19316325.97	Travis	49	50	1005	19	52.9	10,172	25	424	
42559	5804456.87	19257683.39	Bastrop	40	45	10	35	0.3	55	25	4	yes
42560	5802254.07	19258032.74	Bastrop	40	40	10	12	0.8	160	30	16	yes
70918	5706652.40	19306882.25	Bastrop	52	52	880	33	26.7	5,128	25	190	
70919	5704156.10	19304901.98	Bastrop	49	50	618	26	23.8	4,571	19	152	
70946	5707392.68	19309025.04	Bastrop	65	66	1253	30	41.8	8,032	30	229	
151638	5846226.64	19231224.10	Fayette	38	45	35	2	17.5	3,365	25	259	
160577	5706832.99	19310531.30	Travis	32	36	25	4.5	5.6	1,068	25	153	
188014	5681644.60	19312605.62	Travis	35	43	60	15.5	3.9	744	25	74	
189255	5691722.17	19332266.68	Travis	43	53	150	4	37.5	7,212	25	401	
192485	5760044.06	19283723.19	Bastrop	41.5	43.5	110	11	10.0	1,923	25	117	yes
192497	5760309.28	19283628.23	Bastrop	56	66	506	10.51	48.1	9,259	25	299	yes
199132	5743217.11	19294561.90	Bastrop	40.5	46	25	39	0.6	123	25	8	yes
208251	5705353.57	19310092.70	Travis	52	60	250	10	25.0	4,808	25	178	
217962	5732317.97	19303419.05	Bastrop	60	65	80	17	4.7	905	25	26	yes
236236	5700049.67	19316150.33	Bastrop	40	45	50	15	3.3	641	25	43	

Well ID Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Depth to Base of Alluvium (ft)	Well Total Depth (ft)	Well Yield (gpm)	Draw-down (ft)	SC (gpm/ft)	T (ft^2/day)	DTW[1] (ft)	K (ft/day)	In Outcrop Layer of GAM
236238	5702718.34	19318234.82	Bastrop	45	52	100	51	2.0	377	25	19	
243725	5738621.17	19303667.45	Bastrop	75.5	75.5	471	26	18.1	3,484	25	69	yes
243732	5708889.57	19304806.20	Bastrop	59	59.5	450	22	20.5	3,934	10	80	
243733	5708977.22	19304808.18	Bastrop	59	60	1059	45	23.5	4,526	10	92	
243735	5739054.37	19303879.90	Bastrop	69	69	423	26	16.3	3,129	39	104	yes
243736	5739497.05	19303687.98	Bastrop	75.5	75.5	823	31	26.5	5,105	25	101	yes
244899	5864252.20	19223909.76	Fayette	27	20	100	10	10.0	1,923	25	962	
251300	5691562.98	19331554.56	Travis	46	50	750	6	125.0	24,038	25	1,145	
256650	5831769.44	19253524.18	Bastrop	68	72	75	34	2.2	424	25	10	
256662	5831859.53	19253425.56	Bastrop	71	72	950	44	21.6	4,152	26	92	
256672	5831859.53	19253425.56	Bastrop	71	72	950	44	21.6	4,152	26	92	
257397	5710012.35	19305540.51	Bastrop	58	58	1207	51	23.7	4,551	25	138	
263008	5718753.62	19310295.45	Bastrop	39.5	45	160	17	9.4	1,810	25	125	
263011	5718032.55	19307342.56	Bastrop	44.5	52.5	260	18	14.4	2,778	25	142	
268553	5718876.22	19304931.72	Bastrop	35	40	5	27	0.2	36	25	4	
269077	5732064.41	19303008.20	Bastrop	43.5	50	10	10	1.0	192	25	10	yes
269079	5732235.01	19303214.82	Bastrop	52	60	75	12	6.3	1,202	25	45	yes
282014	5873414.54	19222942.76	Fayette	30	20	80	20	4.0	769	25	154	
282279	5714838.02	19305244.97	Bastrop	45	52	50	16	3.1	601	25	30	
282283	5714838.02	19305244.97	Bastrop	45	52	50	12	4.2	801	29	50	
287468	5702931.46	19308722.15	Travis	51	54	250	11	22.7	4,371	25	168	

Well ID Number	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Depth to Base of Alluvium (ft)	Well Total Depth (ft)	Well Yield (gpm)	Draw-down (ft)	SC (gpm/ft)	T (ft^2/day)	DTW[1] (ft)	K (ft/day)	In Outcrop Layer of GAM
305882	5681736.63	19312405.33	Travis	62	67	250	19	13.2	2,530	25	68	
305887	5681732.22	19312607.53	Travis	39	42	300	15	20.0	3,846	25	275	
305891	5682448.08	19311914.56	Travis	44	49	75	8	9.4	1,803	25	95	
317569	5703631.94	19308737.85	Travis	58	65	200	22	9.1	1,748	25	53	
317574	5703564.72	19307825.10	Travis	50	57	200	15	13.3	2,564	25	103	
317581	5704009.42	19307531.44	Travis	55	62	800	15	53.3	10,256	25	342	
378020	5772690.85	19264893.26	Bastrop	65	66	450	17	26.5	5,090	25	127	yes
378849	5702999.01	19317431.19	Bastrop	45	51	75	4	18.8	3,606	25	180	
5844806	5690674.71	19332142.22	Travis	41	45	750	7.5	100.0	19,231	10	620	
5844807	5691558.82	19331756.77	Travis	46	48	1050	9	116.7	22,436	9.3	611	
5852304	5699928.49	19317665.77	Travis	56	63	77	15	5.1	987	36	49	
5852314	5697501.12	19324395.78	Travis	57	61	668	21	31.8	6,117	31	235	
5852505	5685831.29	19309456.76	Travis	44	48	250	17.5	14.3	2,747	25	145	
5862206	5765378.19	19280712.68	Bastrop	52	52	500	9	55.6	10,684	25	396	yes
5862216	5764669.81	19280999.55	Bastrop	48.5	55	1381	15	92.1	17,705	11.5	479	yes

[1] A depth to water of 25 feet was assumed for wells with no water-level measurement.

GAM = groundwater availability model; SC = specific capacity; T = transmissivity; K = hydraulic conductivity; DTW = depth to water

ft = feet; gpm = gallons per minute; gpm/ft = gallons per minute per foot; ft/day = feet per day

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11 Appendix C – Water-Level Data for the Colorado River Alluvium in and near Groundwater Management Area 12

Table C-1. Water-level data for Colorado River alluvium wells.

Well Number[1]	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Aquifer Code	LSD (ft)	10m DEM value (ft)	Date of Water-Level Measurement	Measured Depth to Water (ft)	Water-Level Elevation[2] (ft)	Source of Water-Level Data[3]
5844801	5694482.70	19330201.26	Travis	100ALVM	410	410.96	5/25/1950	29.9	381.06	GWDB
5844801	5694482.70	19330201.26	Travis	100ALVM	410	410.96	1/21/1971	24.7	386.26	GWDB
5844802	5694399.59	19329997.12	Travis	100ALVM	410	411.63	1/21/1971	30.6	381.03	WDI
5844804	5691983.00	19332373.41	Travis	100ALVM	420	419.77	1/3/1940	14.7	405.07	GWDB
5844804	5691983.00	19332373.41	Travis	100ALVM	420	419.77	1/21/1971	11.8	407.97	GWDB
5844805	5690465.87	19329707.45	Travis	100ALVM	410	416.21	2/8/1971	27.2	389.01	GWDB
5844806	5690674.71	19332142.22	Travis	100ALVM	420	419.61	9/30/2003	10	409.61	GWDB
5844807	5691558.82	19331756.77	Travis	100ALVM	418	417.7	8/12/2004	9.3	408.4	GWDB
5844902	5698853.95	19330501.13	Travis	100ALVM	415	422.59	1/21/1971	24.6	397.99	GWDB
5852204	5687265.27	19315968.22	Travis	100ALVM	400	402.38	2/4/1971	35.4	366.98	GWDB
5852204	5687265.27	19315968.22	Travis	100ALVM	400	402.38	4/25/1978	35.25	367.13	GWDB
5852206	5687378.28	19318805.41	Travis	100ALVM	410	410.03	2/27/1969	19	391.03	GWDB
5852206	5687378.28	19318805.41	Travis	100ALVM	410	410.03	4/25/1978	24.7	385.33	GWDB
5852217	5692280.91	19326811.09	Travis	100ALVM	415	416.41	5/31/1985	39	377.41	GWDB
5852302	5704131.58	19321607.54	Travis	100ALVM	410	410.58	6/11/1968	28	382.58	GWDB
5852303	5703666.94	19322812.01	Travis	100ALVM	415	410.82	1/11/1971	31.8	379.02	GWDB

Well Number[1]	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Aquifer Code	LSD (ft)	10m DEM value (ft)	Date of Water-Level Measurement	Measured Depth to Water (ft)	Water-Level Elevation[2] (ft)	Source of Water-Level Data[3]
5852303	5703666.94	19322812.01	Travis	100ALVM	415	410.82	4/24/1978	34.9	375.92	GWDB
5852304	5699928.49	19317665.77	Travis	100ALVM	400	396.08	10/5/1966	36	360.08	GWDB
5852305	5705484.52	19315968.10	Travis	110TRRC	400	401.05	1/25/1971	25.6	375.45	GWDB
5852308	5702756.66	19328259.18	Travis	110TRRC	410	412.68	4/6/1971	22.1	390.58	GWDB
5852309	5706361.16	19319835.14	Travis	110TRRC	410	409.55	4/6/1971	31.5	378.05	WDI
5852310	5701248.53	19329136.68	Travis	110TRRC	420	423.42	4/5/1971	27.7	395.72	GWDB
5852311	5701423.39	19329140.59	Travis	110TRRC	415	423.26	4/5/1971	28	395.26	WDI
5852312	5701883.66	19328138.66	Travis	110TRRC	410	410.78	4/12/1971	26.5	384.28	GWDB
5852313	5702841.42	19320566.02	Travis	100ALVM	402	402.41	6/30/1972	26	376.41	GWDB
5852313	5702841.42	19320566.02	Travis	100ALVM	402	402.41	10/12/1973	28.2	374.21	GWDB
5852313	5702841.42	19320566.02	Travis	100ALVM	402	402.41	6/3/1975	22.88	379.53	GWDB
5852314	5697501.12	19324395.78	Travis	100ALVM	409	408.59	2/7/1990	31	377.59	GWDB
5852601	5706700.57	19304756.50	Bastrop	110ALVM	405	406.1	10/6/1966	20.1	386	GWDB
5852603	5708756.56	19306827.98	Bastrop	110ALVM	400	401.7	11/14/1952	43.5	358.2	GWDB
5852603	5708756.56	19306827.98	Bastrop	110ALVM	400	401.7	10/6/1964	41.4	360.3	GWDB
5852604	5707908.45	19305593.62	Bastrop	110ALVM	407	404.51	10/6/1964	22.3	382.21	WDI
5852605	5708506.76	19302367.11	Bastrop	110TRRC	400	400.82	11/27/1952	19.1	381.72	GWDB
5852605	5708506.76	19302367.11	Bastrop	110TRRC	400	400.82	10/6/1964	16.4	384.42	GWDB
5852606	5709258.45	19304004.26	Bastrop	110ALVM	405	402.33	11/14/1952	22.2	380.13	GWDB
5852606	5709258.45	19304004.26	Bastrop	110ALVM	405	402.33	10/6/1964	19.3	383.03	GWDB
5852611	5699680.38	19309155.38	Travis	100ALVM	410	417.27	11/5/1968	35	382.27	GWDB

Well Number[1]	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Aquifer Code	LSD (ft)	10m DEM value (ft)	Date of Water-Level Measurement	Measured Depth to Water (ft)	Water-Level Elevation[2] (ft)	Source of Water-Level Data[3]
5852614	5703096.51	19305283.18	Bastrop	100ALVM	406	405.75	10/3/1973	41	364.75	WDI
5852615	5705381.18	19308878.08	Travis	110TRRC	409	410.35	10/12/1973	44.2	366.15	GWDB
5853101	5713942.58	19317677.80	Bastrop	110ALVM	390	422.65	10/2/1964	24	398.65	WDI
5853103	5721093.27	19319055.93	Bastrop	110ALVM	420	417.05	10/2/1964	30.6	386.45	GWDB
5853104	5710770.87	19322364.47	Travis	110TRRC	400	407.19	5/25/1950	23.4	383.79	GWDB
5853104	5710770.87	19322364.47	Travis	110TRRC	400	407.19	1/25/1971	21	386.19	GWDB
5853105	5713216.69	19314927.90	Bastrop	100ALVM	407	399.05	8/19/1970	18	381.05	WDI
5853105	5713216.69	19314927.90	Bastrop	100ALVM	407	399.05	2/8/1971	20.5	378.55	WDI
5853401	5710819.50	19308595.77	Bastrop	110ALVM	400	407.84	11/14/1952	32.6	375.24	GWDB
5853401	5710819.50	19308595.77	Bastrop	110ALVM	400	407.84	10/6/1964	30.2	377.64	GWDB
5853503	5731396.11	19309168.80	Bastrop	110ALVM	425	420.22	3/26/1953	27.7	392.52	GWDB
5853503	5731396.11	19309168.80	Bastrop	110ALVM	425	420.22	10/2/1964	27.5	392.72	GWDB
5853802	5732210.51	19296733.82	Bastrop	110ALVM	390	390.76	10/5/1964	50.13	340.63	WDI
5853807	5734689.68	19299424.29	Bastrop	110ALVM	390	391.55	10/5/1964	46.8	344.75	GWDB
5862204	5765285.59	19280913.10	Bastrop	100ALVM	330	331.03	6/30/1943	38	293.03	GWDB
5862205	5765463.46	19280816.07	Bastrop	100ALVM	330	333.71	11/30/1949	22	311.71	GWDB
5862207	5765288.04	19280811.83	Bastrop	100ALVM	347	330.56	6/25/1942	16.8	313.76	GWDB
5862213	5764469.97	19282006.94	Bastrop	100ALVM	370	319.97	4/6/1991	12.65	307.32	WDI
5862213	5764469.97	19282006.94	Bastrop	100ALVM	370	319.97	5/15/1991	10	309.97	WDI
5862216	5764669.81	19280999.55	Bastrop	100ALVM	325	328.27	10/26/2000	11.5	316.77	GWDB
5862217	5765200.64	19280809.72	Bastrop	100ALVM	327	325.85	8/1/2006	13.75	312.1	GWDB

Well Number[1]	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Aquifer Code	LSD (ft)	10m DEM value (ft)	Date of Water-Level Measurement	Measured Depth to Water (ft)	Water-Level Elevation[2] (ft)	Source of Water-Level Data[3]
5863403	5792690.71	19257994.85	Bastrop	110ALVM	370	330.42	1/26/1953	10.3	320.12	GWDB
5863403	5792690.71	19257994.85	Bastrop	110ALVM	370	330.42	11/23/1964	12.4	318.02	GWDB
5863802	5809842.28	19249517.12	Bastrop	110ALVM	320	324.17	11/6/1952	30.3	293.87	GWDB
5863802	5809842.28	19249517.12	Bastrop	110ALVM	320	324.17	9/16/1964	30	294.17	GWDB
5863910	5824171.08	19241885.91	Bastrop	110ALVM	315	319.14	11/6/1952	26	293.14	GWDB
5863910	5824171.08	19241885.91	Bastrop	110ALVM	315	319.14	12/13/1952	26	293.14	GWDB
5863913	5826729.96	19251570.38	Bastrop	110ALVM	310	282.91	12/16/1952	35.3	247.61	GWDB
5863913	5826729.96	19251570.38	Bastrop	110ALVM	310	282.91	1/10/1966	32.9	250.01	GWDB
5863917	5824401.72	19246549.36	Bastrop	100ALVM	323	328.95	9/11/1972	21.5	307.45	WDI
5864704	5841146.61	19244049.65	Bastrop	110ALVM	300	313.38	9/29/1965	3.5	309.88	GWDB
5864711	5831125.27	19247938.24	Bastrop	100ALVM	288	315.16	9/11/1972	27.2	287.96	WDI
5864809	5851656.95	19248276.46	Fayette	110AVFV	325	323.91	7/20/1942	32.61	291.3	GWDB
5957703	5874352.96	19243319.43	Fayette	100ALVM	337	334.3	7/20/1942	57.16	277.14	WDI
6601202	5892156.97	19231354.93	Fayette	100ALVM	275	275.41	7/27/1942	21.67	253.74	GWDB
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	12/7/1981	22.39	269.35	GWDB
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	12/24/1982	22.98	268.76	GWDB
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	12/16/1983	21.5	270.24	GWDB
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	12/10/1984	27.77	263.97	GWDB
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	11/4/1985	31.15	260.59	GWDB
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	12/9/1986	28.1	263.64	GWDB
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	11/12/1987	24.2	267.54	GWDB

Well Number[1]	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Aquifer Code	LSD (ft)	10m DEM value (ft)	Date of Water-Level Measurement	Measured Depth to Water (ft)	Water-Level Elevation[2] (ft)	Source of Water-Level Data[3]
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	1/10/1989	29.08	262.66	GWDB
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	12/7/1989	31.79	259.95	GWDB
6601411	5869851.40	19224769.38	Fayette	100ALVM	291	291.74	12/10/1990	31.94	259.8	GWDB
6707205	5815885.57	19239749.12	Bastrop	110TRRC	320	320.84	11/20/1952	29.8	291.04	GWDB
6707306	5826955.40	19236085.27	Bastrop	110ALVM	350	350.53	11/18/1952	37.4	313.13	GWDB
6707306	5826955.40	19236085.27	Bastrop	110ALVM	350	350.53	1/5/1966	36	314.53	GWDB
6708112	5830191.73	19236574.20	Bastrop	110ALVM	305	295.65	1/6/1966	12.9	282.75	GWDB
6708114	5838979.63	19229615.29	Fayette	100ALVM	311	310.34	6/29/1942	21.8	288.54	GWDB
6708115	5841040.59	19234731.84	Fayette	100ALVM	316	317.09	6/29/1942	23.39	293.7	WDI
6708201	5849717.50	19235366.13	Fayette	100ALVM	300	297.82	8/25/1965	25.87	271.95	GWDB
6708203	5848165.77	19230971.09	Fayette	100ALVM	292	293.27	7/20/1942	25.18	268.09	GWDB
6708304	5864300.73	19235148.80	Fayette	100ALVM	296	296.74	8/24/1965	27.13	269.61	GWDB
6708305	5859373.90	19228941.60	Fayette	100ALVM	298	296.85	8/26/1965	35.6	261.25	GWDB
6708306	5858976.02	19237233.40	Fayette	100ALVM	291	314.28	7/20/1942	51.24	263.04	GWDB
37822	5701928.88	19314369.84	Travis			398.3	3/31/2004	12	386.3	SDR
42560	5802254.07	19258032.74	Bastrop			305.7	6/12/2004	30	275.7	SDR
70919	5704156.10	19304901.98	Bastrop			407.58	5/5/2004	19	388.58	SDR
70946	5707392.68	19309025.04	Bastrop			411	5/12/2004	30	381	SDR
177560	5765202.77	19280708.80	Bastrop			321.3	8/1/2006	13.75	307.55	SDR
243732	5708889.57	19304806.20	Bastrop			400.53	4/13/2005	10	390.53	SDR
243733	5708977.22	19304808.18	Bastrop			400.21	3/30/2005	10	390.21	SDR

Well Number[1]	x GAM Coordinate (ft)	y GAM Coordinate (ft)	County	Aquifer Code	LSD (ft)	10m DEM value (ft)	Date of Water-Level Measurement	Measured Depth to Water (ft)	Water-Level Elevation[2] (ft)	Source of Water-Level Data[3]
243735	5739054.37	19303879.90	Bastrop			370.5	4/6/2005	39	331.5	SDR
256662	5831859.53	19253425.56	Bastrop			279.8	6/5/2011	26	253.8	SDR
256672	5831859.53	19253425.56	Bastrop			279.8	6/5/2011	26	253.8	SDR
261199	5762442.04	19246015.87	Bastrop			401.2	6/16/2011	73	328.2	SDR
282283	5714838.02	19305244.97	Bastrop			407.4	3/16/2012	29	378.4	SDR

[1] State well number for wells with GWDB and WDI as source and tracking number for wells with SDR as source

[2] Calculated as the 10-meter Digital Elevation Model value minus the depth to water.

[3] GWDB =TWDB Groundwater database, WDI = TWDB Water Data Interactive Groundwater Data Viewer website, SDR = TWDB Submitted Drillers Reports database

GAM = groundwater availability model; ft = feet; LSD – land surface datum; m = meters; DEM = Digital Elevation Model

12 Appendix D – Draft Report Comments and Responses

Attachment 1
INTERA Incorporated
“GAM Improvements for Surface Water Groundwater Interaction”
Contract No. 1548301856
TWDB Comments to Draft Report

The following report and data review comments shall be addressed and included in the final deliverables pertaining to amendment 2 of the contract that is due August 31, 2018. Please note the items listed under suggestions are editorial in context and are not contractually required; however, adjustments noted may improve the readability of the report.

Colorado and Lavaca Basin and Bay Area Stakeholder Committee (BBASC) report comments:

The report is interesting and well written overall and the figures are very readable and informative.

General comments to be addressed

1. PURSUANT OT HOUSE BILL 1 AS APPROVED BY THE 84TH TEXAS LEGISLATURE, THIS STUDY REPORT WAS FUNDED FOR THE PURPOSE OF STUDYING ENVIRONMENTAL FLOW NEEDS FOR TEXAS RIVERS AND ESTUARIES AS PART OF THE ADAPTIVE MANAGEMENT PHASE OF THE SENATE BILL 3 PROCESS FOR ENVIRONMENTAL FLOWS ESTABLISHED BY THE 80TH TEXAS LEGISLATURE. THE VIEWS AND CONCLUSIONS EXPRESSED HEREIN ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF THE TEXAS WATER DEVELOPMENT BOARD.

   Response: Done.

2. Please review all reference citations against the reference section to make sure they are complete, accurate, and consistent.

   Response: Done.

3. Please ensure that all references in the reference section are formatted in a consistent reference style.

   Response: Done

4. Please ensure that all references in the reference section have citations in the report.

   Response: Done.

5. Please review all equations to ensure that all variables are accurately portrayed and that each equation is written properly.

   Response: Done

6. Please review and double-check the total cost range estimates in Tables 7-2 and 7-3. Additionally, please review the task and description text in these two tables.

   Response: Done

7. Please consider including a column for Well ID Number in Table C-1.

   Response: Done

8. Please provide an update on the progress of the whole model and the projected completion date.

   Response: Done

Specific comments to be addressed

9. Executive Summary, page xiii, first line: please clarify if the second site(s) is referencing the pre-existing study sites that were installed and analyzed for Lower Colorado River Authority – San Antonio Water System study.

   Response. Done. Two of the locations are in Wharton and Matagorda counties and are located where wells were installed by river gages as part of the Lower Colorado River Authority-San Antonio Water System Water Project.

10. Executive Summary, pages xi to xiii: please clarify in the report if the work plan is to just examine the flux between the river and the alluvium or to also evaluate the flux between the underlying geologic units and the alluvium.

    Response: Done

11. Section 2.2, page 4, first paragraph, last sentence: please verify if "inducing flow from the river into the stream" was intended, rather than "river into the aquifer".

    Response: Text revised as noted.

12. Section 3.1, page 9: please provide references for the facts stated.

    Response: We updated our reference for the facts and provided the reference.

13. Figure 3-2, page 12: please provide reference for water rights.

    Response: Done

14. Section 3.2, pages 9-10 and Figures 3-3, 3-4, 3-5 on pages 13, 14, and 15: please provide reference(s) for gauges.

    Response: Done

15. Figure 3-8, page 18 and Figure 3-10, page 20: please spell out LSWP in the legend or caption.

    Response: Done

16. Section 4.1.2, page 24, last two sentences: please rephrase that Study 49 did not account for large diversions in the Carrizo-Wilcox and Gulf Coast aquifers and please explain in more detail.

    Response: Done

17. Section 4.1.3, page 29: please ensure that the USGS, 2017 citation is included in the references section.

    Response: Done

18. Section 4.1.3, page 31 and Figure 4-9, page 47: please remove last sentence reference to Figure 4-9 or correct figure with appropriate data and reference correctly in the text. Please note that the figure does not agree with TWDB (2016) nor represent the approach or values determined from this study. Please remove figure or replace with data previously provided to INTERA from this study. The polygons shown appear to reflect only minor aquifers from Borden to Travis counties. It is unclear what the polygons represent from Bastrop to Matagorda counties.

    Response: The original figure in the draft report showed only those watersheds that intersect the Colorado River. The figure has been revised to show the BFI value from the study for all of the watersheds located in the Colorado River Basin. That is, the data received from the TWDB was clipped to the Colorado River Basin.

19. Section 4.3.1, page 35: please correct the reference to Figure 4-143.

    Response: Done

20. Figure 4-1, page 39: please consider altering this figure to show simply that Qnet = outflows – inflows, and that if Qnet is positive, a stream is gaining or if Qnet is negative, a stream is losing.

    Response: Equation 4-2 and subsequent text and Figure 4-1 have been modified to show the simplified equation in addition to the original equation. Note that the text was original incorrect. A positive Q_{net} indicates stream loss (inflow > outflow) and a negative Q_{net} indicates stream gain (outflow > inflow).

21. Figure 4-6 caption, page 44: please ensure that the reference for the Wahl and Wahl, 1998 citation is included in the references section.

    Response: Figure caption was corrected to say Wahl and Wahl (1995).

22. Figure 4-9, page 47: Section 5.1, page 57: please also discuss the interaction between the Colorado River Alluvium and the Yegua-Jackson Aquifer since previous tables indicate gaining reaches in this vicinity and figures indicate some analysis was completed for the alluvium in Groundwater Management Area 12 in Fayette County.

    Response: Done

23. Section 5.4, pages 59 to 60: please re-examine and please rephrase this section for clarity. For example, instead of using “base elevation” when referring to the bottom and top of the alluvium it may be clearer to state “top elevation of the alluvium” and “bottom elevation of the alluvium”. The three bullets in this section need clarification. The Lower Colorado River Authority gauge at Bastrop indicates the average depth of the Colorado River is around 3 feet deep. Please provide additional clarification and references for selecting 2 feet as the depth of the Colorado River and its tributaries. Please consider providing cross-section(s). Last sentence on page 59 needs to be re-written, “That is, the thickness of the alluvium is 2 feet directly underlying the Colorado River centerline and the tributaries in the alluvium”

Response: References to the base elevation of the alluvium have been changed to bottom elevation of the alluvium. The text for the three bullets has been clarified. The assumption of 2 feet thick is not the height of the water in the Colorado River (as indicated by the Bastrop gauge) but rather the thickness of the alluvium underlying the river and tributaries. Text has been clarified.

24. Section 5.5, page 60, bottom of page: please provide references and more background information for the relationship between specific capacity and transmissivity.

    Response: Done

25. Section 5.5, page 61, equation 5-4: please replace minus sign with equal sign, K = T/b.

    Response: Done

26. Section 5.5, page 61: please provide documentation for the selection of 7 feet for the assumed depth to water as opposed to using the depth to water in the well with specific capacity data.

    Response: The hydraulic conductivity calculations were revised to use the measured depth to water in the well for wells with a measurement. The average and geometric mean depth to water for all wells with a water-level measurement is about 25 feet. For wells with no water-level measurement, a depth to water of 25 feet was assumed rather than a depth to water of 7 feet originally used.

27. Figure 5-6, page 67: please discuss in text (page 59), figure caption, or figure legend why topography does not extend to the same footprint noted in the other figures in this section.

    Response: Done

28. Figure 5-11, Page 72: please change the well legend label to read “data” rather than “date”.

    Response: Done

29. Section 6.0: thank you for providing a summary of the implementation of surface water-groundwater interactions in the update to the groundwater availability model for the central part of the Carrizo-Wilcox, Queen City and Sparta aquifers. Per contract Amendment 2, Attachment 1 Scope of Work, Task 6 Deliverables, for the final report please provide an update for the progress of the entire model (all modeling tasks) along with the projected completion date.

    Response: Done. Section 6.4 has provided an update on progress with developing the updated model.

30. Section 6.0: please clearly state in the report that while the model update will refine the grid and representation of the river and alluvium in the model, because of the stress periods (annual) versus the dynamic response in surface water features needing daily, weekly, or monthly stress periods that the model will not be appropriate for estimating all facets of surface water-groundwater interactions. Surface water-groundwater interactions will be more realistic once the flux is understood and quantified through data analysis.

    Response: Done. We have address the comment in Section 6.4.

31. Section 7.2, Candidates (Sites) for Field Study: please consider including one site at the updip limit of the Carrizo-Wilcox outcrop and one site at the downdip limit of the Carrizo-Wilcox outcrop in order to evaluate the net volume of interaction across the outcrop (as discussed in contract Amendment 2, Attachment 1 Scope of Work Task 6, item 5b.).

    Response: Done. We have added an additional figure and text to discuss the candidate site.

32. As noted in Section 4.2.2 and in Figure 4-2, the Colorado River is projected to gain flow from the Sparta and Queen City aquifers. Please consider including areas where these aquifers outcrop as a potential field site. Additionally, please consider including outcrop areas of the Yegua-Jackson Aquifer in the field site. Ideally, field sites would coincide with upper and lower boundaries of an aquifer outcrop where the stream crosses over the outcrop area in order to evaluate the net volume of interaction between each unique aquifer and stream.

    Response: Done. We have added an additional figure and text to discuss the candidate sites.

33. Section 7.4: per contract Amendment 2, Attachment 1 Scope of Work Task 6, item 5c, the work plan should address precipitation estimates, as well as estimates of groundwater pumping in the vicinity of the field sites. Please include discussion of precipitation estimates and estimates of groundwater pumping in the vicinity of the field sites.

    Response: Done.

34. Section 7.4, Table 7-3, page 89: please check estimated cost totals and update as necessary.

    Response: Done

35. Appendix A, pages 107 to 132: please footnote the wells where the base of the alluvium does not match the picks by Standen (2017). In addition, please flag the wells associated with Standen (2017) study.

    Response: Done

Suggestions (optional):

36. Please proofread and correct the report for spelling and grammatical errors found throughout the report.

    Response: Done

37. Please consistently use the word “gauge” rather than “gage” in reference to river and stream gauges.

    Response: No change. Consistent with United States Geological Survey reports that use the word “gage” more frequently than the word “gauge”, the word gage was maintained in this report.

38. Please consistently use either “base flow” or “baseflow”.

    Response: Done

39. Please use “affect” when used as a verb meaning to impact or change and “effect” when used as a noun indicating the result of a change.

    Response: Done

40. Section 3.1, page 9: please spell out Lake Lyndon B. Johnson.

    Response: Done

41. Table 4-3, page 25: please correct the spelling of the Ellenburger in footnote 2.

    Response: Done

42. Section 4.3.1, page 35: please correct the spelling of Lake Lyndon B. Johnson.

    Response: Done

43. Table 4-9, page 36: please footnote or note in caption that CR refers to Colorado River.

    Response: Done

44. Figure 4-7, page 45: please consider rounding up base-flow index values in legend.

    Response: Done

45. Section 5.3, page 59: please change tributary to tributaries.

    Response: Done

46. Section 8, pages 99 to 105, formatting references: please remove “&” and replace with “and”, please remove parenthesis around dates, please be consistent with identification of pages (p. , pp., pgs, blank), and please consistently end references with a comma, a period, or no punctuation. If more than two authors, please use “and”.

    Response: Done

Public Comments:

When taken together, the Draft Report and the technical improvements to the GMA-12 GAM that it describes make an important advance in understanding and managing the surface water-groundwater interaction between the Colorado River and the Carrizo-Wilcox Aquifer Group.

By reviewing the historical studies, by incorporating the science (data) into the GAM, and by updating the model to include local and intermediate level groundwater flow systems, the tools will soon be in place to predict the groundwater and surface water interactions in this segment of the Colorado River Basin. Hopefully these tools, along with future field studies to enable monitoring, will be used to establish the scientific basis to inform the policy and management decisions that will guide adaptive management of these important natural systems while balancing the need for development of these water resources against the need to conserve these waters for future generations.

We want to take this opportunity to thank the Texas Water Development Board and the Texas Legislature for providing the funding and contract management support necessary to make these considerable improvements to the GMA-12 GAM. We look forward to participating as a stakeholder in the final phases of calibrating and installing the improved GAM into practice.

The following comments submitted by the Colorado and Lavaca Basin and Bay Area Stakeholder Committee have been summarized and edited as follows:

47. Section 2.1, Equation 2-1, page 4: please update equation to match Prudic and others (2004)

$$Q_L = \frac{KwL}{m}(h_s - h_a)$$

Response: Done

48. Section 3.1, paragraph 1, second to last sentence, page 9: please update text to include environmental flows; for example, "Lakes Buchanan and Travis are operated as a system to supply interruptible water supplies for agriculture [and_environmental flows]_when available, and firm water supplies for municipal and industrial use."

Response: Done

49. Section 3.3, paragraph 1**:** please consider adding a sentence or two to complete the history and recognize that attempts have been made to get the Colorado River Alluvium designated as a minor aquifer. For example, Saunders (1996) described the qualifications for the aquifer to be designated as a minor aquifer and Region K Water Planning Group considered, but did not designate it as a minor aquifer. Reference: Saunders, Geoffrey P. 1996. Qualification of the Colorado River Alluvium as a Minor Aquifer in Texas. TRANSACTIONS OF THE GULF COASTASSOCIATIONOF GEOLOGICAL SOCIETIES VOLUMEXLVI, 1996 363. Lower Colorado River Authority, Austin, TX 78767.

Response: Done

50. Figures 3-6 and 3-7, pages 16 and 17: please reposition the insert boxes to cover Groundwater Management Area 12 or include a separate figure that shows the major and minor aquifers in the model study area, as well as the alluvium and terrace deposits.

Response: Figure 5-1 was modified to show all aquifer outcrops in GMA 12 and the active model area.

51. Equation 4-2, page 23 and Figure 4-1, page 39: please re-evaluate the equation and please provide reference if applicable. For example, a simpler equation would be:

River Reach gain/loss or Qnet = outflows – inflows
where

Qnet is positive = baseflow and
Qnet is negative = stream loss.

Response: Equation 4-2 and subsequent text and Figure 4-1 have been modified to show the simplified equation in addition to the original equation. Note that the text was original incorrect. A positive Q_{net} indicates stream loss (inflow > outflow) and a negative Q_{net} indicates stream gain (outflow > inflow).

52. Section 4.1.3, last sentence page 31 and Figure 4-9, page 47: to be technically accurate, the last sentence should be revised to denote that Figure 4-9 shows the estimated base-flow index for outcrops of major and minor aquifers and for the Colorado River Alluvium in the Colorado River Basin as determined by TWDB (2016). Please revise the sentence: "Figure 4-9 shows the estimated base-flow index for outcrops of major and minor aquifers <u>and the Colorado River Alluvium</u> in the Colorado River Basin as determined by TWDB (2016)."

Response: No change. The analysis by TWDB (2016) assumed the contribution to baseflow originated from the minor and/or major aquifers and the contribution from alluvium surrounding the river was negligible in comparison.

53. Section 6.1, paragraph 2, sentence 3, page 74: for clarity, please rephrase sentence, “If the size of a model cell…”

Response: Done

54. Section 7, pages 83 to 89: please edit text and replace “will” to “would” or “should”. The section should be written more as a scope of work rather than a response to a request for qualifications.

Response: Done

55. Section 7.2, sentence 1, page 83: please clarify in the text of the report if there are other sites in the middle or upper Colorado River basin that would be suitable for such field studies.

Response: Done

56. Section 7.3, page 84, bullet point 2: please correct to “from bank storage **or** from the aquifer ..."

Response: Done

57. Section 7.3, page 84, new bullet point 4: suggest adding a new bullet point that raises the following question: “During persistent drought or extreme drought, is the quantity of groundwater sufficient to maintain critical/subsistence instream flows to get the river/stream through the drought in an ecologically sound condition.”

Response: Done

58. Table 7.1, page 84: please clarify the reasoning for listing a field study in the Carrizo-Wilcox as moderate in importance and please consider elevating the importance in Table 7.1

Response: Done

59. Section 7.3.1, page 85, second sentence after equation 7-1: please insert the word “simple”; for example, “The <u>simple</u> approach will use a spreadsheet and the advanced approach will use the groundwater model.”

Response: Done

60. Section 7.3.4, page 87, last paragraph**:** please discuss in more detail in the text of the report the significance of Figures 7-5 to 7-8. For example which of the figures indicate a gaining/losing segment? What is the implication of the trend line? What is the

implication of the change for Bastrop from 2012 to 2015? In addition, please update the figures with a legend that identifies blue columns for rainfall and the significance of the various colors used for the ungauged flow.

Response: We have modified the report to address several of the concerns. One of the modifications is the addition of a paragraph to discuss the calculated ungaged flows from 1 February to 25 February 2014.

61. Section 7.4, page 89: the text states that data will be collected for at least two years; however, long-term data collection is needed. Please include costs for transferring the monitoring and analysis to a third party.

Response: Comment not addressed because of the wide range of unknowns that would affect the costs.

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