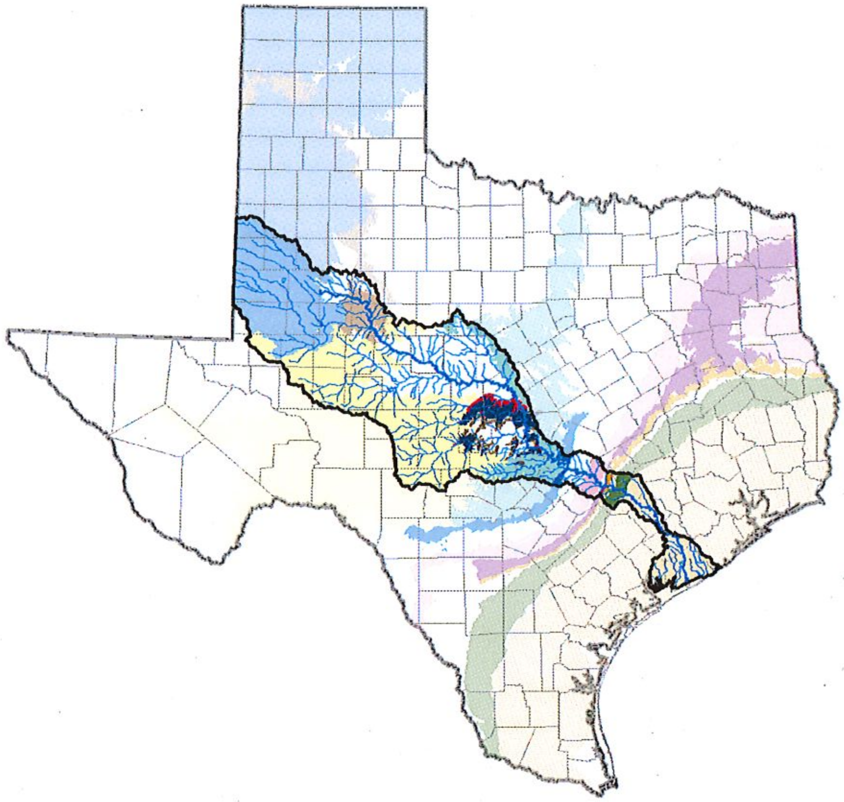
Final Report: Field Studies and Updates to the Central Carrizo-Wilcox, Queen City, and Sparta GAM to Improve the Quantification of Surface Water-Groundwater Interaction in the Colorado River Basin



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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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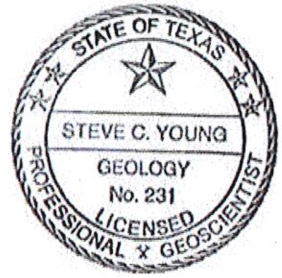
Geoscientist and Engineering Seal

Steven C. Young, P.E., P.G., Ph.D.

Dr. Steven Young was the technical lead and responsible for performing the technical analysis and writing the report.



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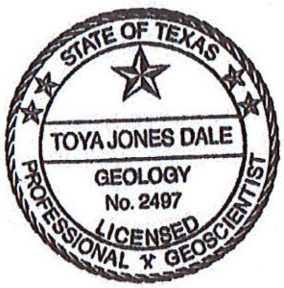
Toya Jones, P.G.

Ms. Toya Jones was responsible for mapping the base of the Colorado River alluvium in Travis, Bastrop, and Fayette counties and assisted with writing the report.



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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.

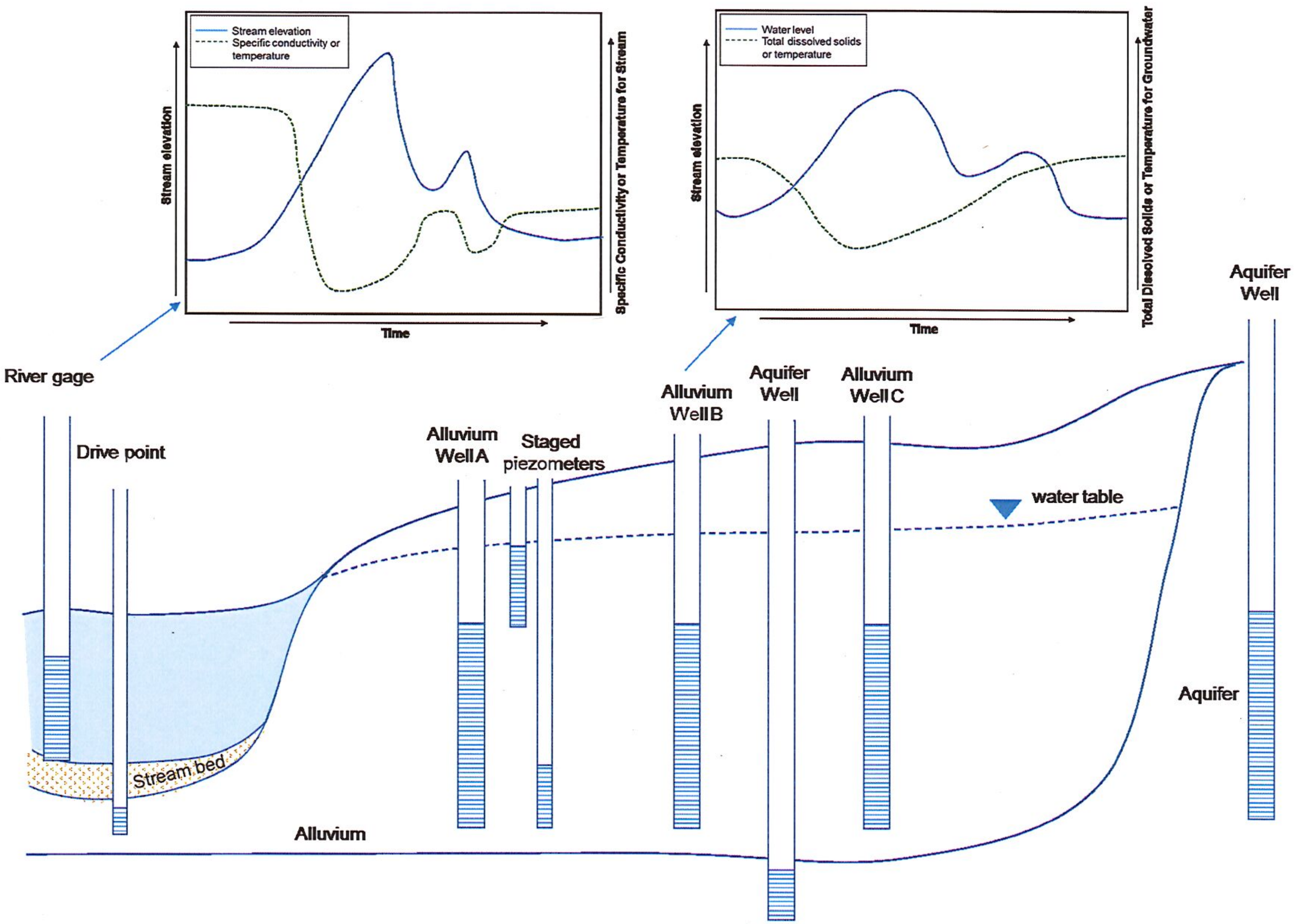

Figure 7-1. Schematic of comprehensive monitoring well network for field study.

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).**

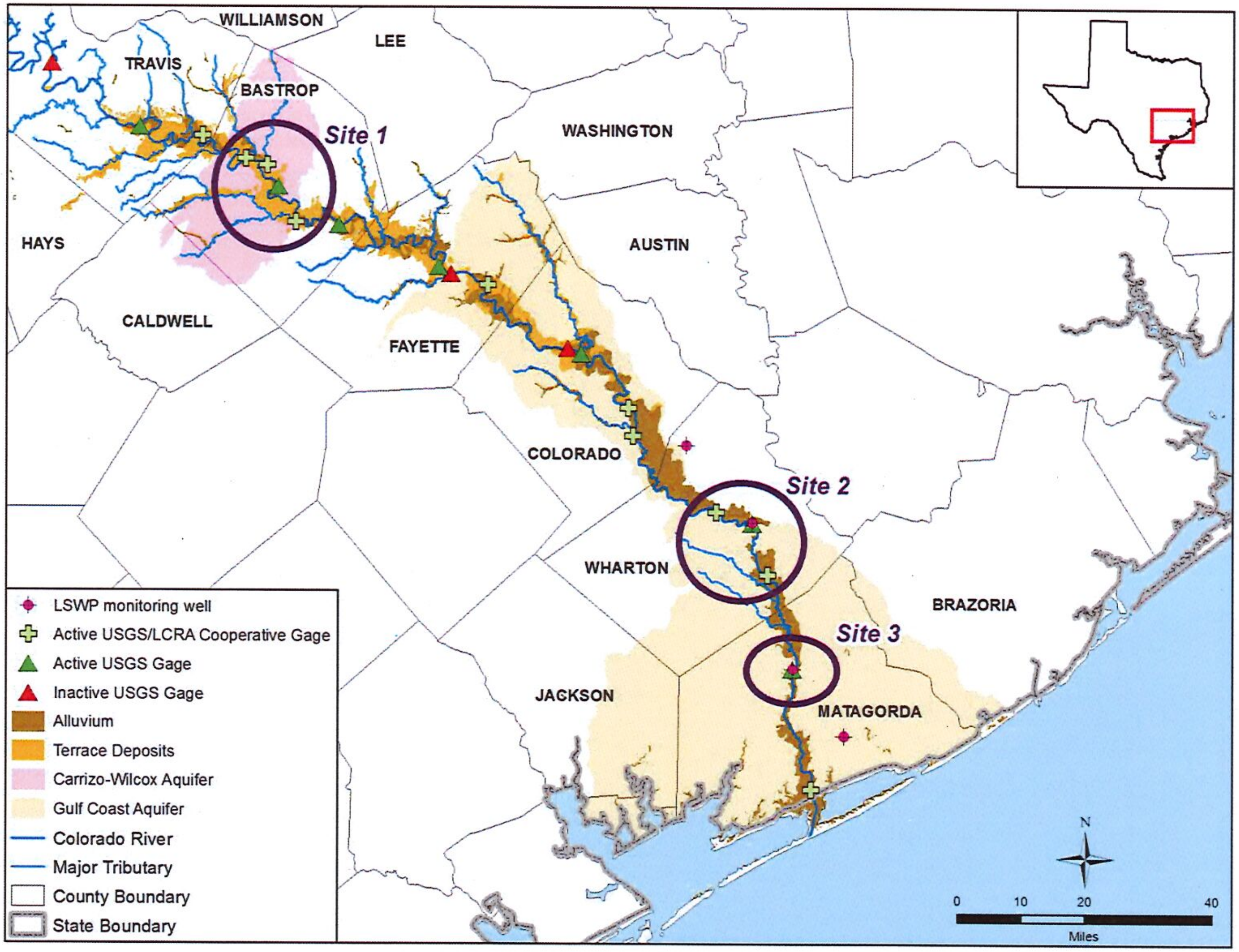

Figure 7-3. **Locations of Sites 1, 2, and 3 for the proposed field study.**

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

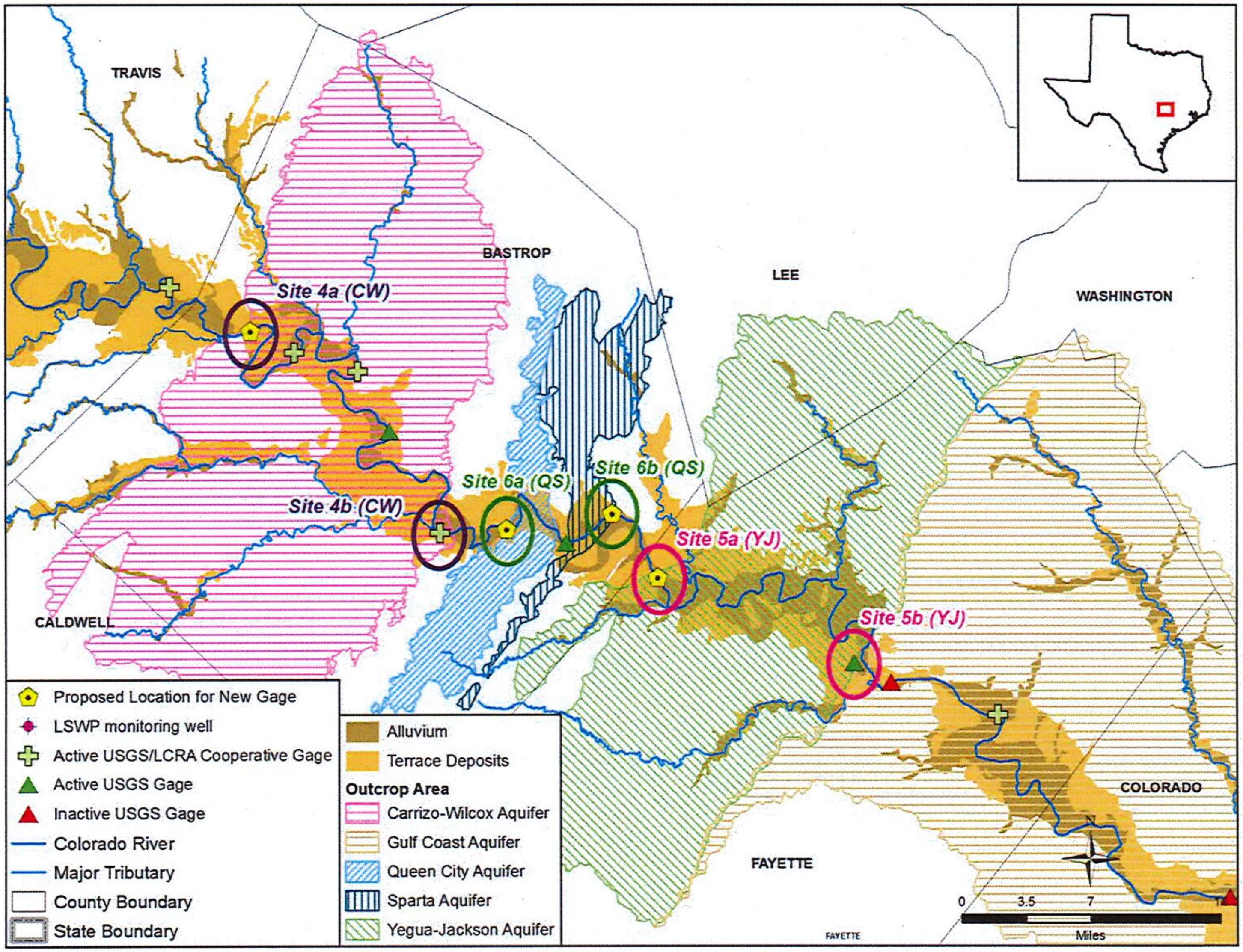

Figure 7-4. **Locations of Sites 4, 5, and 6 for the proposed field study.**

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

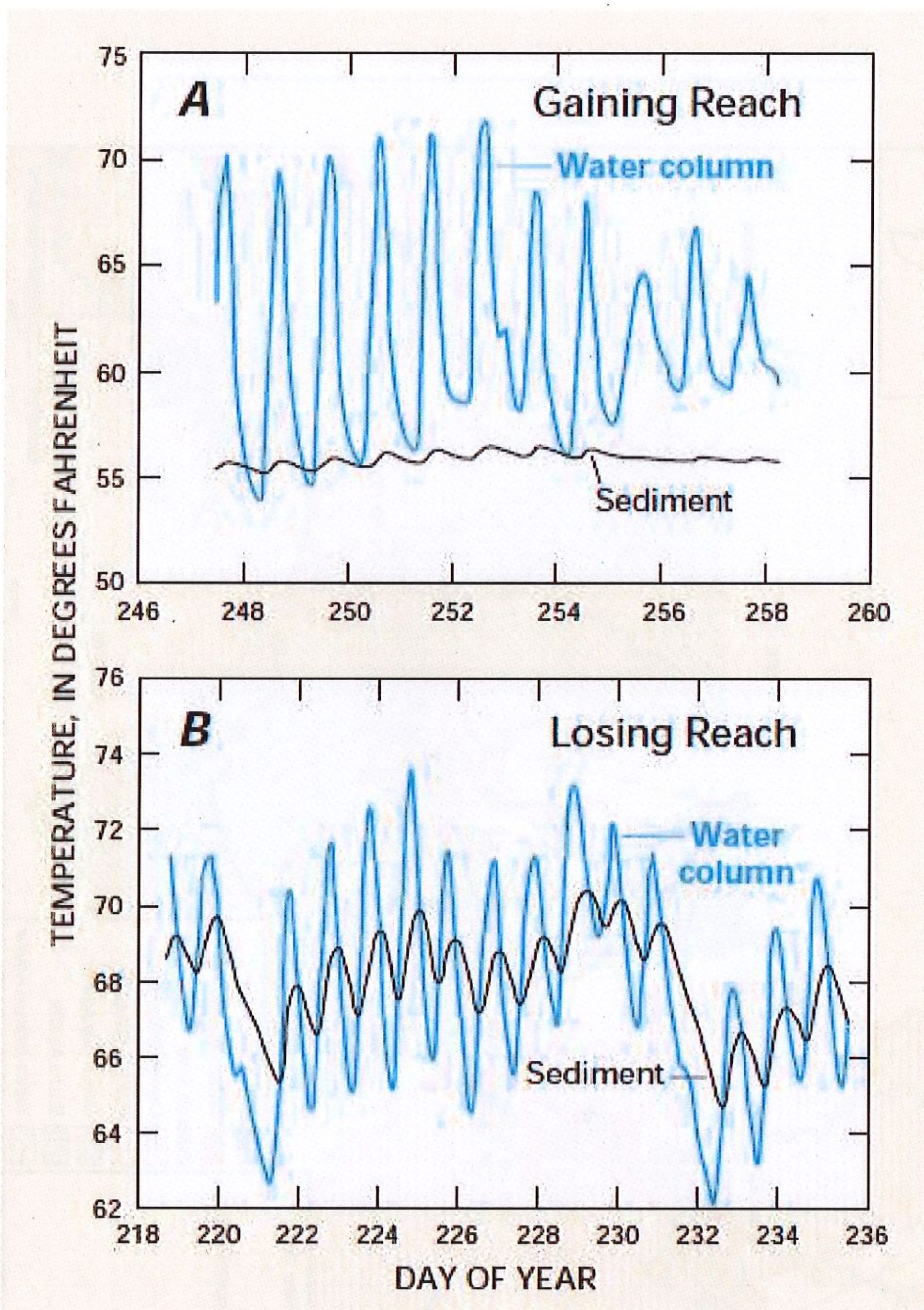

Figure 7-5. **Temperature profiles from field study on gaining reach (A) and losing reach (B) of Juday Creek in Indiana (Silliman and Booth [1993] as presented in Winter and others [1998]).**

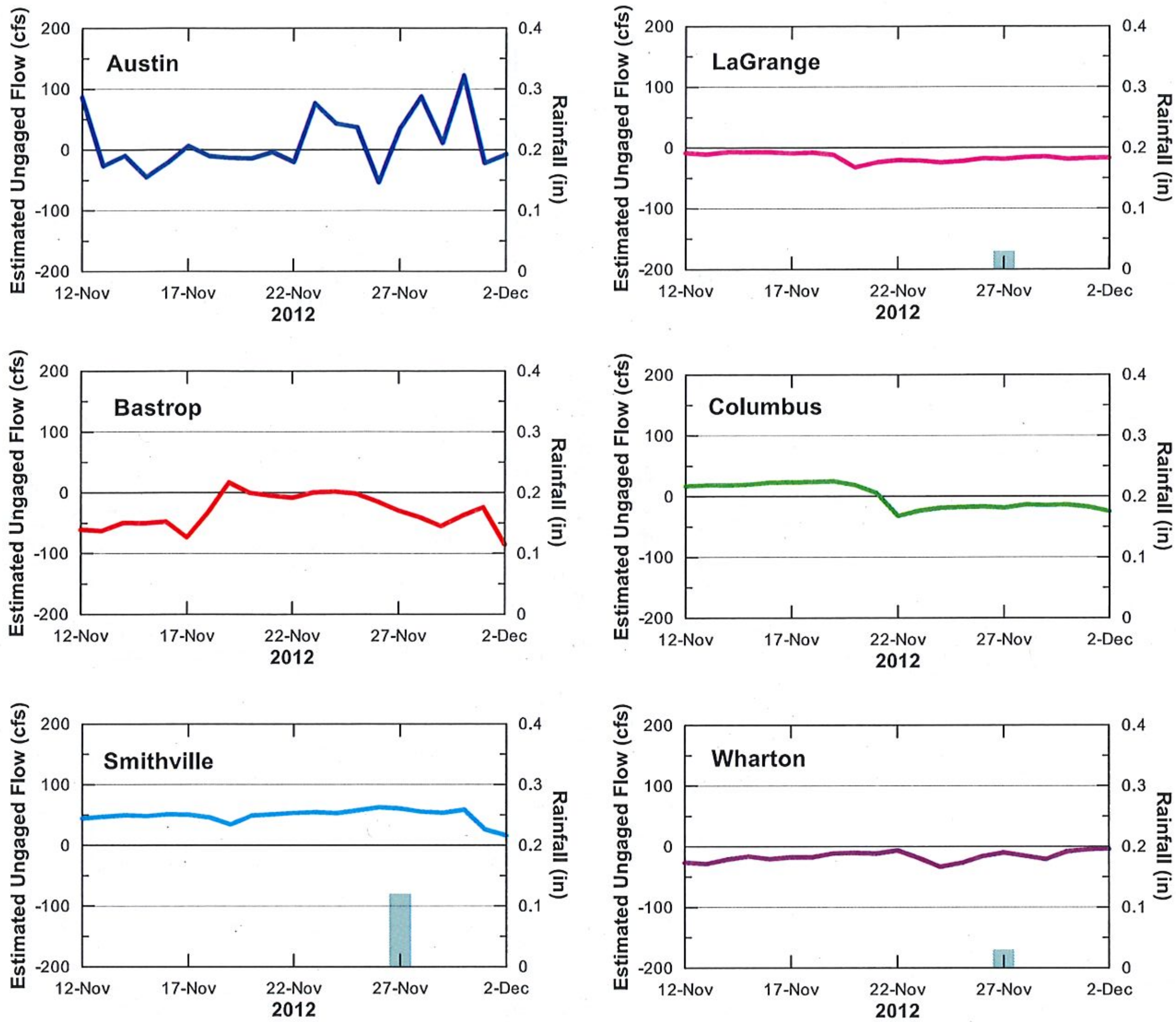

Figure 7-6. **Calculated ungaged flow (colored lines) from the Lower Colorado River Authority's Daily Operation Routing Model at six river gages for low-flow conditions in 2012. Ungaged flow estimates were produced by the Lower Colorado River Authority for its own use. Gage uncertainty, flow variability, 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

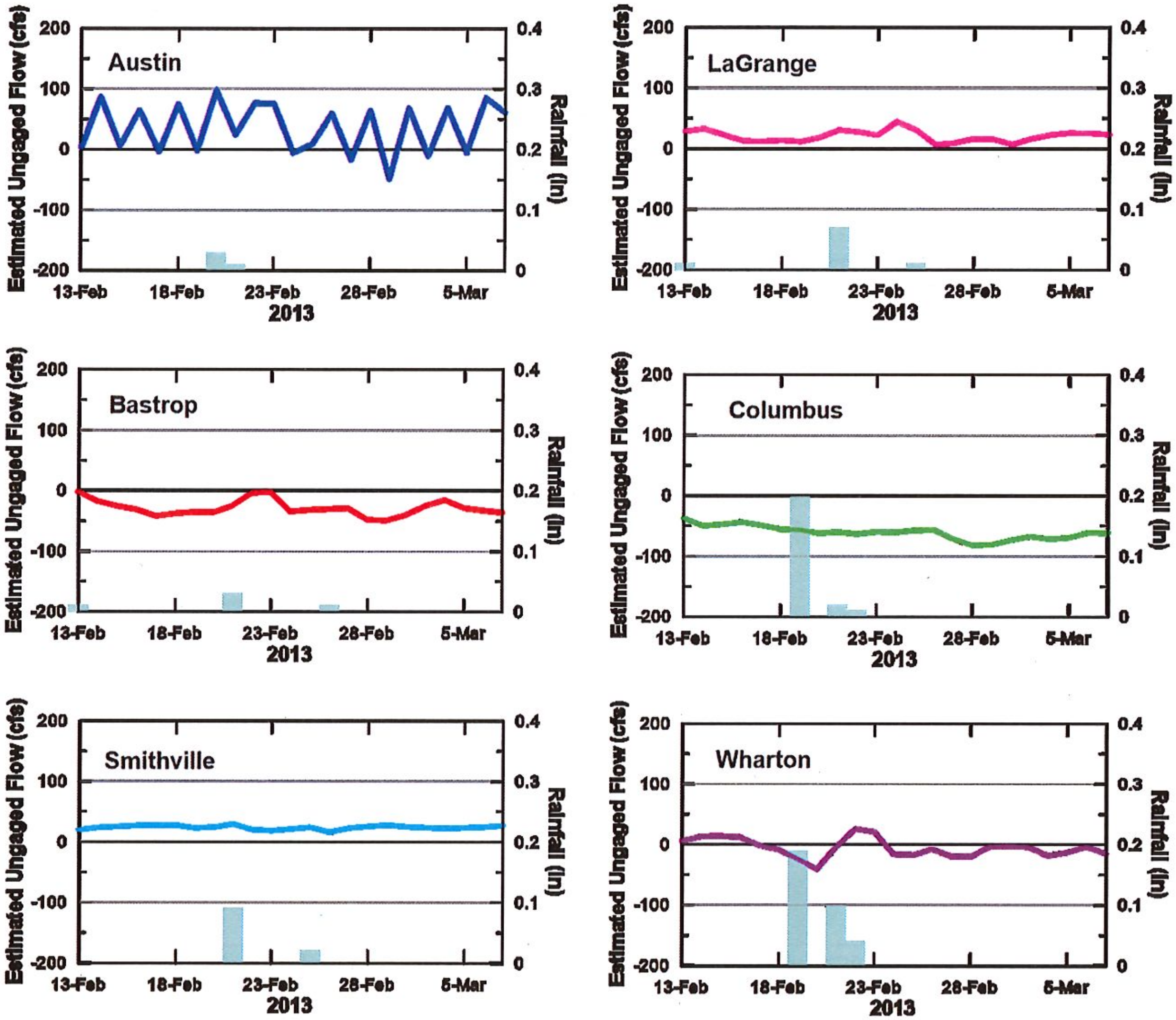

Figure 7-7. **Calculated ungaged flow (colored lines) from the Lower Colorado River Authority's Daily Operation Routing Model at six river gages for low-flow conditions in 2013. Ungaged flow estimates were produced by the Lower Colorado River Authority for its own use. Gage uncertainty, flow variability, 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

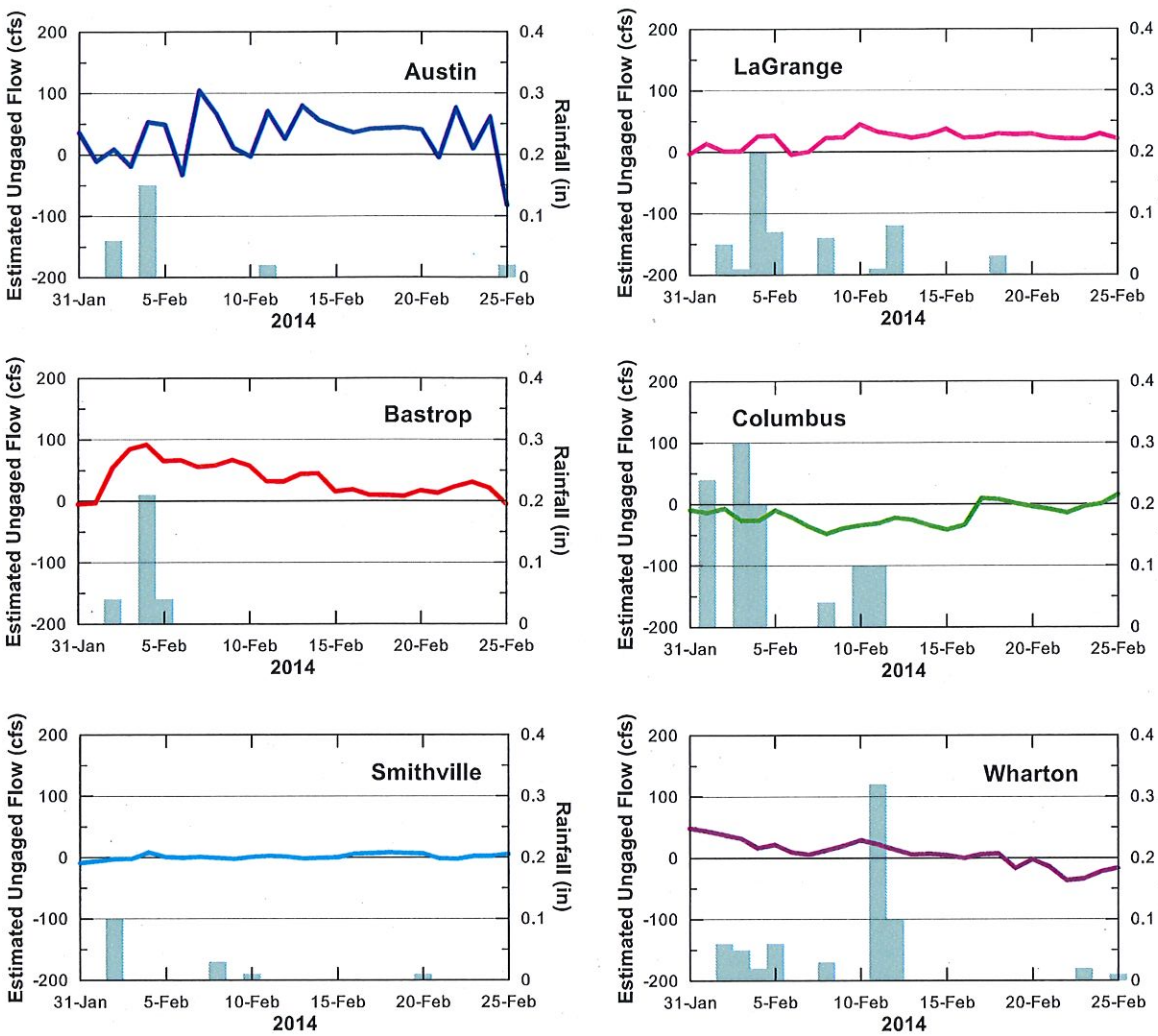

Figure 7-8. **Calculated ungaged flow (colored lines) from the Lower Colorado River Authority's Daily Operation Routing Model at six river gages for low-flow conditions in 2014. Ungaged flow estimates were produced by the Lower Colorado River Authority for its own use. Gage uncertainty, flow variability, 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

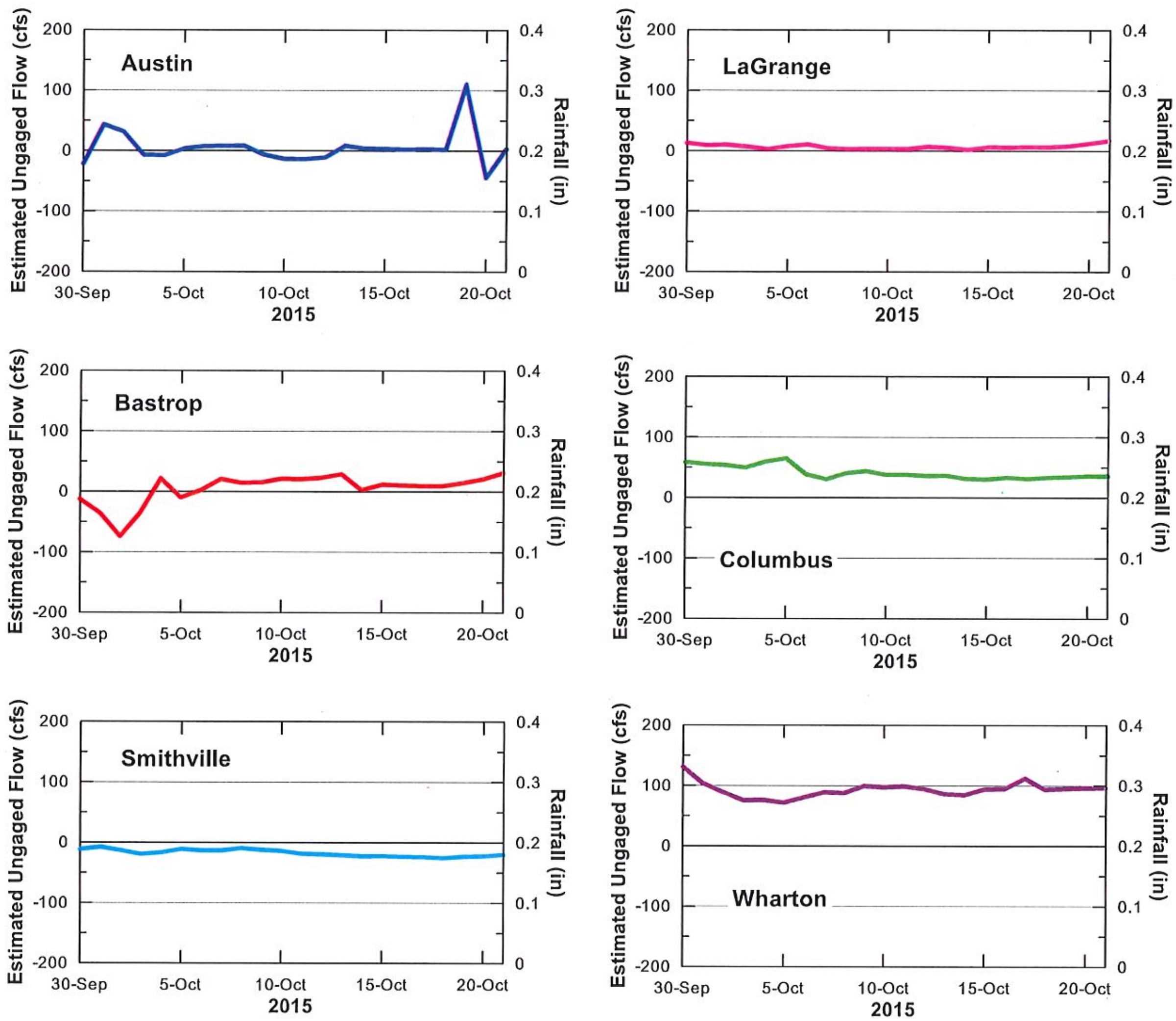

Figure 7-9. **Calculated ungaged flow (colored lines) from the Lower Colorado River Authority's Daily Operation Routing Model at six river gages for low-flow conditions in 2015. Ungaged flow estimates were produced by the Lower Colorado River Authority for its own use. Gage uncertainty, flow variability, 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).

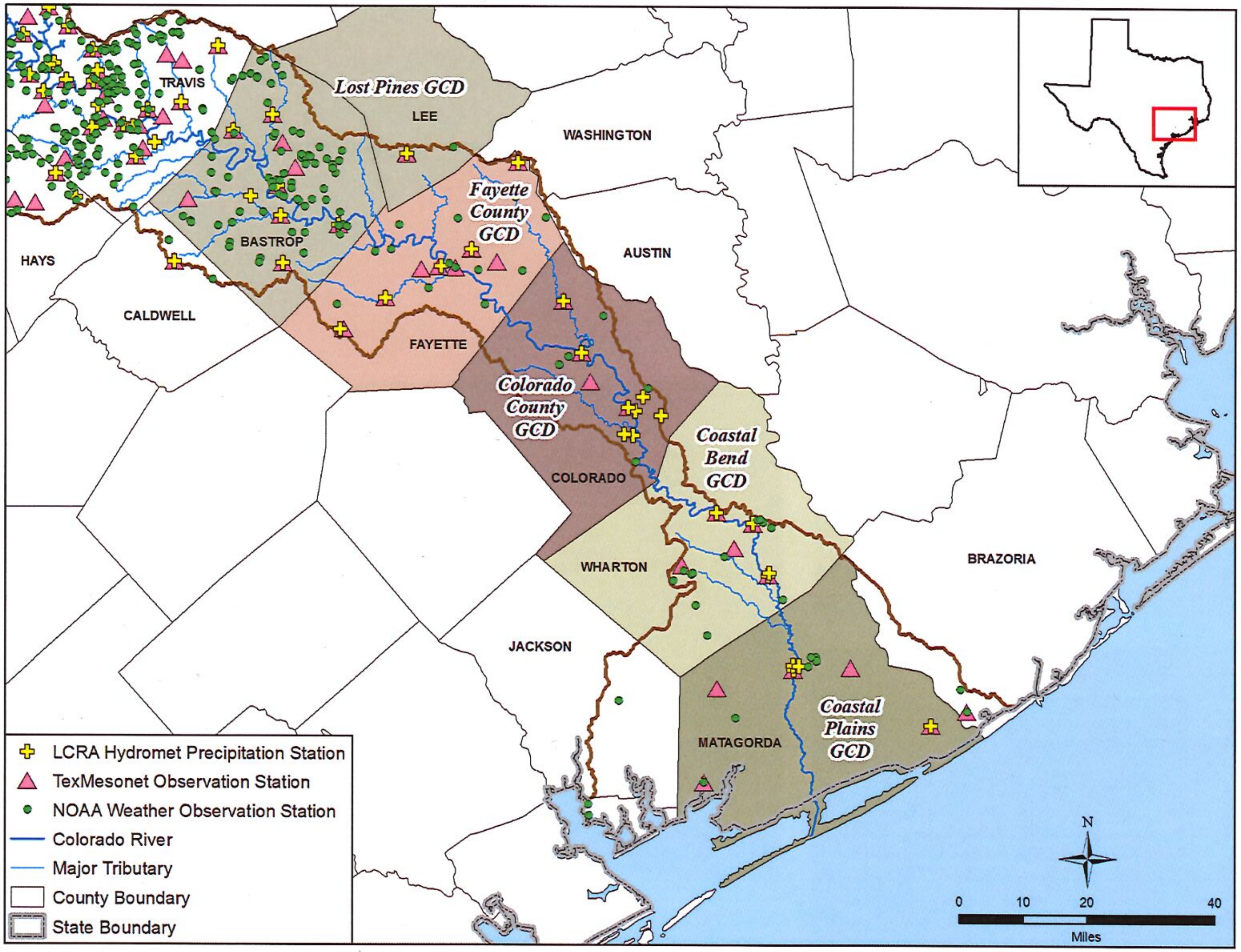

Figure 7-11. **Location of precipitation gages and groundwater conservation districts in the lower Colorado River Basin (Lower Colorado River Authority, 2017d; TexMesonet, 2017; National Centers for Environmental Information, 2017).**