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Surface Water-Groundwater Interaction Pilot Study

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LCRA
ENERGY • WATER • COMMUNITY SERVICES

BRAZOS RIVER AUTHORITY

POST OAK SAVANNAH GROUNDWATER CONSERVATION DISTRICT

TWDB Contract No. 1900012305

Prepared by

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GROUNDWATER RESOURCE PROFESSIONALS

INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS

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A PORTION OF THE FUNDING FOR THIS STUDY WAS PROVIDED PURSUANT TO SENATE BILL 1 AS APPROVED BY THE 85TH TEXAS LEGISLATURE 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.

GEOSCIENTIST SEALS

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Mr. Bené was the project lead and was responsible for pilot study design, technical analyses, and report writing.

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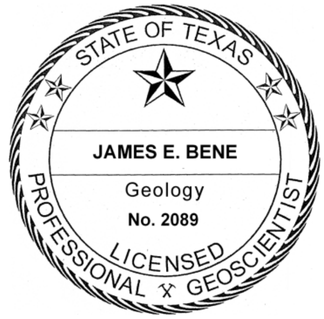
Date: ________July 9th, 2021_______________

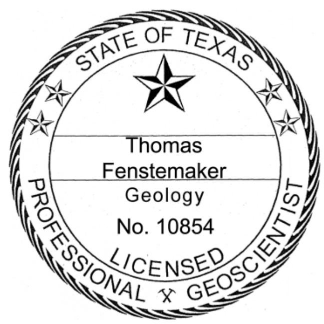


Tom Fenstemaker, P.G.

Mr. Fenstemaker acted as field operations manager and was responsible for coordination and oversite of monitor well drilling and construction, telemetry installation, and data compilation and evaluation. Mr. Fenstemaker also performed technical analyses associated with surface water- groundwater interactions, assisted in report writing, and assembled the report appendices.

Signature: ______________________________

Date: ________July 9th, 2021_______________



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Dr. Young conducted a review of the pilot study design, analyses, and results. Dr. Young also performed a review of the draft report and provided technical assistance throughout the project.

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Date: ________July 9th, 2021_______________

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EXECUTIVE SUMMARY

In 2019, R.W. Harden & Associates, Inc. (RWH&A) teamed with Intera, Inc. (Intera) to conduct a study focused on the evaluation of surface water/groundwater interactions. The goal of this study was twofold: 1) to establish a long-term monitoring system to document the hydrologic communication between the Colorado River and the adjacent alluvial aquifer in Bastrop County, Texas and 2) to evaluate, deploy, and test methods and technology that can be effectively used to document interactions between surface water bodies and groundwater systems across Texas. This project represents a pilot study that may be used in the future as a template for subsequent efforts, allowing for more-efficient development of additional monitoring sites. In addition, the methods developed during this study can be expanded to assess the effects of regional aquifers on shallow alluvial and surface water systems.

Alluvial sediments often act as a hydraulic buffer zone between rivers and underlying aquifers, but the highly heterogeneous nature of alluvial deposits presents unique challenges with respect to groundwater modeling and the interpretation of simulation results in State water planning efforts. In 2018, the central portion of the Carrizo-Wilcox Aquifer Groundwater Availability Model (GAM or model) (Young, et al., 2018) was updated to include layer and grid-cell refinements associated with alluvial aquifer deposits. However, while these refinements theoretically allow for more-accurate predictions of near-river fluxes, there are almost no data available describing the hydraulic properties of the river/alluvium interaction zone that can be used to configure the refined model cells. Improved understanding of hydraulic properties of alluvial sediments and variations in surface water-groundwater exchanges are essential for both establishing the accuracy of model predictions and evaluating the usefulness and limitations of the refined grid resolution in near-river hydrogeologic settings.

The information obtained during this study augments the work of other authors that have investigated surface water/groundwater interactions and bank storage. Citations for several more-pertinent published analyses are included herein for reference. Young et. al. (2017) provides an extensive discussion of surface water/groundwater studies that have been performed in the past.

Two study locations along the Colorado River in Central Texas were explored during this project. While there were many advantages to the initially-selected site at the LCRA Lost Pines Power Park River Intake Facility in Bastrop County, it proved to be unsuitable for the study because test drilling conducted in June 2019 indicated that no significant permeable alluvial sediments were present beneath the site. During subsequent months, alternate sites were identified and evaluated with respect to hydrogeologic considerations, as well as various logistical issues affecting long-term data acquisition such as landowner concerns, site security, drilling rig access, long-term site access, and likelihood of future flood damage to instrumentation.

The LCRA Pope Bend Vista (PB-Vista) boat ramp facility was ultimately selected as the alternate study site. Permeable alluvial materials were found during test drilling at PB-Vista in spring 2020. Three alluvium monitor wells and a river monitoring probe were constructed and subsequently outfitted with pressure, temperature, and electrical conductivity sensors/dataloggers in summer 2020. Hydraulic slug tests were performed at each monitor well to document the hydraulic conductivity of alluvial sediments at the site. Since installation, data recorded by the PB-Vista probes have been

transmitted by an on-site cellular telemetry station to a remote database that can be accessed via the internet.

The data recorded at the PB-Vista site indicate that alluvial water levels are directly influenced by river stage. Alluvial groundwater is under artesian pressure and rises above the top of the permeable sediments screened by the PB-Vista monitoring wells and rapid oscillations in river levels are followed closely by alluvial groundwater levels. Two general conditions are observed in the data:

- During short-term (hours to a few days), high-river-flow intervals driven by precipitation events, river levels exceed alluvium levels indicating groundwater flux from the river to the alluvium.
- Throughout the majority of the study period, alluvium artesian pressure levels were greater than river levels indicating a groundwater gradient toward the river.

In general, changes in artesian pressure are transmitted quickly through an aquifer, while migration of groundwater occurs at a comparatively slow pace. The data recorded during this study suggest that these conditions are present at the PB-Vista site; rapid artesian responses to changes in river stage were measured but the overall groundwater flux is relatively small. The conclusion that there is limited flux between the river and alluvium is supported by water temperature and conductivity measurements. The temperature of the river water varied with daily upstream dam releases, precipitation events, and seasonal and/or diurnal temperature variations. However, there was little change observed in the alluvial groundwater temperature throughout the recording period. Similarly, the conductivity of alluvial groundwater remained steady while river water conductivity generally fluctuated rapidly in response to changes in flow and environmental conditions.

Potential groundwater flux rates to/from the river were calculated through time using the recorded hydraulic gradients and alluvium hydraulic conductivity values derived from monitor well testing. The average hydraulic conductivity value for the alluvium was 4.9 ft/day, which is significantly lower than hydraulic conductivity values reported by Young and others (2017) for Colorado River alluvium in Travis and Bastrop counties and assigned to the Colorado River alluvium in the groundwater availability model for the central portion of the Sparta, Queen City, and Carrizo-Wilcox aquifers (Young and others, 2018).

The average groundwater velocity toward the river from summer 2020 through February 2021 at the PB-Vista site is estimated to be approximately 0.053 feet per day (ft/day). The estimated average volumetric flux is 0.19 cubic feet per day per lateral foot of alluvial sediments (ft^3/day/ft). When applied to the 4.5-mile length of the bank of the Pope Bend point bar structure, it is estimated that the alluvium contributes groundwater to the river at an average rate of approximately 4,460 ft^3/day [37.4 acre-feet per year (ac-ft/yr)] in that area.

ACKNOWLEDGEMENTS

Senate Bill 3 (SB 3) of the 80th Texas legislative session (2007) established a framework for identifying and promulgating environmental flow standards throughout Texas. As a result, the Texas Commission on Environmental Quality adopted environmental flow standards for the Colorado River and its associated tributaries effective August 8, 2012, based on recommendations from regional stakeholders and scientific experts. Under SB 3's provision for adaptive management, which calls for continued studies to validate and refine environmental flow analyses, recommendations, and standards, this project was initiated and partially funded during the 85th Texas legislature to assist the Texas Water Development Board (TWDB) and the Colorado and Lavaca Rivers and Matagorda Bay Basin and Bay Area Stakeholder Committee (BBASC) with understanding surface water-groundwater interactions along the Colorado River in Bastrop County in support of the SB3 e-flows process. Additional funds for this project were provided by the Lower Colorado River Authority, Brazos River Authority, and Post Oak Savannah Groundwater Conservation District.

The authors wish to acknowledge the LCRA for providing the study site and valuable logistical support that minimized project costs and facilitated site access. LCRA, TWDB, BRA, and POSGCD provided valuable review comments that improved the usefulness of this report.

This project was inspired by the widespread recognition of the need to develop methods and technology that can be deployed to document surface water/groundwater interactions throughout Texas. The recommendations contained within the report on the update to the Central Carrizo-Wilcox-Queen City-Sparta Groundwater Availability Model (Young et al., 2018) served as the initial framework to help define the scope and methods used by this study.

INTRODUCTION

Senate Bill 3 (SB 3) of the 80th Texas legislative session (2007) established a framework for identifying and promulgating environmental flow standards throughout Texas. As a result, the Texas Commission on Environmental Quality adopted environmental flow standards for the Colorado River and its associated tributaries effective August 8, 2012, based on recommendations from regional stakeholders and scientific experts. Under SB 3's provision for adaptive management, which calls for continued studies to validate and refine environmental flow analyses, recommendations, and standards, this project was initiated and partially funded during the 85th Texas legislature to assist the Texas Water Development Board (TWDB) and the Colorado and Lavaca Rivers and Matagorda Bay Basin and Bay Area Stakeholder Committee (BBASC) with understanding surface water-groundwater interactions along the Colorado River in Bastrop County in support of the SB3 e-flows process. Additional funds for this project were provided by the Lower Colorado River Authority, Brazos River Authority, and Post Oak Savannah Groundwater Conservation District.

In 2019, R.W. Harden & Associates, Inc. (RWH&A) teamed with Intera, Inc. (Intera) to conduct a pilot study of surface water/groundwater interactions in Central Texas. The primary goals of this project are: 1) to identify the important factors associated with selection and implementation of future monitoring systems, 2) establish a river/groundwater monitoring system at one site, 3) obtain field data documenting the direction and rate of flux between the Colorado River and the shallow alluvial sediments over which it flows, 4) evaluate the hydraulic relationships implied by the collected data and 5) compare the relative pros and cons associated with the various techniques for measuring and analyzing hydrogeologic field data. It is anticipated that the experience, methods, and equipment explored during this pilot study may be used to help plan future studies at additional sites in Texas.

Improved understanding of the relationship between regional aquifers and shallow hydrologic systems will become increasingly important as groundwater use in Texas expands in the future. Where alluvium is deposited on regional aquifer outcrop areas, alluvial materials act as hydrogeologic transition/buffer zones between rivers and underlying regional aquifers. While this study focused on the interactions between river flows and the adjacent alluvial groundwater system, the approaches discussed herein can be readily applied to document exchanges between regional aquifers and overlying shallow groundwater and surface water systems.

Alluvial aquifers represent a significant water resource for Texas' landowners and play an important role in the regional water planning process. However, there is uncertainty with respect to the volume of water contained within alluvial sediments and how that water is recharged and discharged through time. In many areas, "gaining stream" conditions exist where river flows are augmented by groundwater flux (baseflow) from the alluvium toward the river, while the reverse is true in other areas resulting in "losing stream" conditions. Gaining versus losing stream conditions can change due to variations in alluvial water levels and river stage.

The information recorded during this study will allow for improved accuracy of water planning models. Groundwater modeling is an important tool used by regulators to help develop Desired Future Conditions (DFC) and Model Available Groundwater (MAG) values for the aquifers in Texas. The recently-updated central portion of the Carrizo-Wilcox-Queen City-Sparta Groundwater Availability Model (GAM) (Young, et al., 2018) included refinement of the model grid resolution in regions where major river systems and associated alluvial deposits interact with underlying sediments. However, while the refined grid theoretically allows for more-accurate simulation of surface/groundwater interactions, there are almost no data available pertaining to the hydraulic properties of the river/alluvium interaction zone that can be used to configure the refined model cells. As a result, the hydraulic parameters assigned to the refined grid cells are not based on measured data, and the currently modeled surface water-groundwater fluxes produced by the GAM cannot be validated. Improved representation of hydrogeologic properties and calibration of surface water-groundwater exchanges in the GAM are essential for both establishing the accuracy of model predictions and evaluating the usefulness of the refined grid resolution in river/aquifer interaction zones.

Prior to selecting potential study locations, several methods of investigating the relationship between groundwater and surface water were considered. An overview of the approaches considered in selecting study sites and methods are presented in Gonzalez-Pinzón, et al (2015), Brodie et al. (2007), Kalbus et al. (2006) and Sophocleous (2002). In addition, the methods and findings of previous studies were reviewed. Hibbs (1993) obtained a variety of measurements from sensors installed in alluvium monitoring wells at two sites along the Colorado River in Bastrop County. Francis et al. (2010) investigated the effects of periodic dam releases on the hydraulic relationship between the Colorado River and Hornsby Bend Island using a total of eighteen piezometers and three to six water-level probes to monitor water levels in the shallow subsurface sediments of the study site. Using the water levels measured over a relatively short study period (mid-August to mid-September 2008), Francis calculated an estimated volumetric flux into and out of the sediments beneath the island during a single release of water from an upstream dam. Sawyer (2009) used four monitor wells located adjacent to the Colorado River and a river gauge to monitor groundwater pressure (depth), temperature and electrical conductivity at a site near Hornsby Bend Island. The wells and river gauge were measured and recorded every 15 minutes for seven days in September 2008 to investigate the surface water/groundwater interactions and estimate the volumetric flux into and out of the shallow sediments at the site.

After consideration of the approaches utilized for previous studies, it was determined that long-term, high-resolution (both spatial and temporal) measurements of groundwater and river temperature, electrical conductivity, and pressure (depth/stage) would allow for a quantitative determination of the relationship between the river and adjoining alluvial groundwater system. In spring 2020, three groundwater monitoring wells, river and aquifer monitoring instruments, and a telemetry station were installed at the Pope Bend site in Bastrop County. Transducers installed at the study site began recording data in summer 2020 and are intended to remain active for a minimum of five years. It is anticipated that previously-undocumented, long-term trends in alluvial groundwater flow systems will become apparent as data collection continues.

The following sections discuss various aspects of the project including, the study site design and selection processes, test drilling results, monitor well construction, aquifer testing, potential sensor types, instrumentation selection, data collection, and an evaluation of the groundwater gradients and fluxes derived from the study data.

STUDY SITE SELECTION

Selection of potential study sites involves an evaluation of several natural and logistical considerations, any of which may disqualify a given site. Future studies should initially consider the conditions at a potential study site through non-intrusive field reconnaissance and evaluation of publicly available information. As this study demonstrates, the usefulness of a site is ultimately dependent on subsurface conditions, which can only be investigated after a study site has been chosen and secured. The investigating team's creativity in devising mitigation measures for the selection criteria may provide additional site options.

The LCRA Lost Pines Power Park River Intake Facility (Intake Facility) was initially selected as the study site based on several pertinent factors discussed below. However, the Intake Facility proved to be unsuitable for the study because test drilling conducted in June 2019 indicated that little or no permeable alluvial or underlying regional aquifer (Simsboro Formation) sediments were present beneath the site. An alternate site within the LCRA Pope Bend Vista boat ramp facility (PB-Vista) was subsequently selected and utilized for this study. Figure 1 is a regional overview showing the locations of the two study sites explored during this project, the general extent of the alluvium, and the outcrop area of the underlying Hooper and Simsboro formations. Figure 2 is a cross-sectional diagram depicting the structure of the alluvium and subsurface geologic units.

The following sections discuss the pertinent issues affecting site selection and provide a summary of the relative pros and cons of the Intake Facility and the PB-Vista sites. Several factors must be considered when evaluating potential study sites:

- **Local hydrogeologic factors –** Surface water/groundwater interactions are heavily influenced by the distribution and characteristics of permeable sediments. Sites should be selected in depositional environments (such as a point bar) that increase the likelihood of laterally-extensive, permeable alluvial deposits adjacent to a river.
- **Regional hydrogeologic factors –** Of concern in water planning are potential reductions in groundwater contributions to rivers as increased pumpage of groundwater from regional aquifers lowers water table levels in aquifer outcrop zones. Sites where rivers or alluvial sediments overlie major aquifer outcrops will likely provide insights into the impacts associated with future groundwater use.
- **Drilling equipment access –** Monitor wells cannot be constructed in locations without suitable ingress/egress and topography appropriate for drilling equipment.
- **Drilling equipment selection –** To mitigate against ingress/egress/topographic limitations, selection of contractors with appropriate drilling equipment may provide more site selection flexibility.
- **Potential flood risk –** The topography of the site should limit potential damage from flood events.
- **Proximity to existing river gauges –** Accurate comparison of river stage and alluvial water levels is a key component in assessing the magnitude and direction of surface water/groundwater fluxes. Study sites that are directly adjacent to existing river gauges

may provide adequately detailed river level information, but evaluation of measurements recorded during this study indicates that more-distant river gauge measurements do not provide the site-specific data needed for accurate calculation of local hydraulic gradients.

- **Riverbank access for surface water monitoring equipment –** Measurement of site-specific surface water conditions are necessary for a refined analysis of river and alluvium interactions. Riverbank access is not practical at many otherwise-suitable locations.
- **Suitable location for telemetry equipment –** While measurements recorded by most data-logging equipment can be manually downloaded during a site visit, there are many advantages to continuous, automatic upload of data to internet-based storage. However, transmission of data typically requires a telemetry station that broadcasts data to a cellular phone network. Satellite-based telemetry may be employed in remote areas without cell coverage, but satellite telemetry is typically more expensive than the cellular-based telemetry.
- **Site preparation –** The effort and cost associated with site preparation must be consistent with project schedules and budgets. Typical tasks necessary to prepare a study site for construction include site grading, tree trimming, brush clearing, road construction, and installation of erosional controls.
- **Proximity to existing wells –** Study sites near existing wells completed in either the alluvium or underlying aquifer sediments may be beneficial or detrimental, depending on the circumstances. Unused wells with reliable construction records can augment study datasets and potentially reduce project costs by serving as a replacement for a monitor well that would have otherwise been constructed as part of the study. However, nearby wells that are pumped intermittently can dominate the response of the local groundwater system thereby masking or distorting the native flow patterns. In addition, data obtained from nearby wells with incomplete construction records should not be used unless the well completion interval and casing integrity can be confirmed by other means.
- **Site security –** The study site should be adequately protected from potential damage from trespassers, livestock, wildlife, etc.
- **Long-term site access –** Secure ingress/egress must be maintained throughout the study interval to facilitate repair/replacement and removal of monitoring equipment.

It should be recognized that finding a site that satisfies all pertinent factors is unlikely. Typically, it is beneficial to perform “fatal flaw” evaluations of each potential site before continuing more in-depth assessments. A variety of factors such as a lack of drilling rig or riverbank access, excessive flooding risk, or proximity to pumpage centers may represent fatal flaws for a given site. Evaluation of hydrogeologic factors, flood risk, groundcover, and proximity to existing gauges can usually be completed remotely in a relatively short amount of time. Assessing factors affecting construction equipment access and suitability for monitoring/telemetry equipment installation requires coordination and performance of an on-site inspection. Experience gained during this study suggests that obtaining landowner permission for well construction and long-term access represents the greatest hurdle in securing study locations. Landowner communications often require weeks to complete and are frequently unsuccessful. It is recommended that future projects perform an initial public outreach process to help identify landowners amenable to study site construction and long-term access.

Figure 1. Regional Overview Map

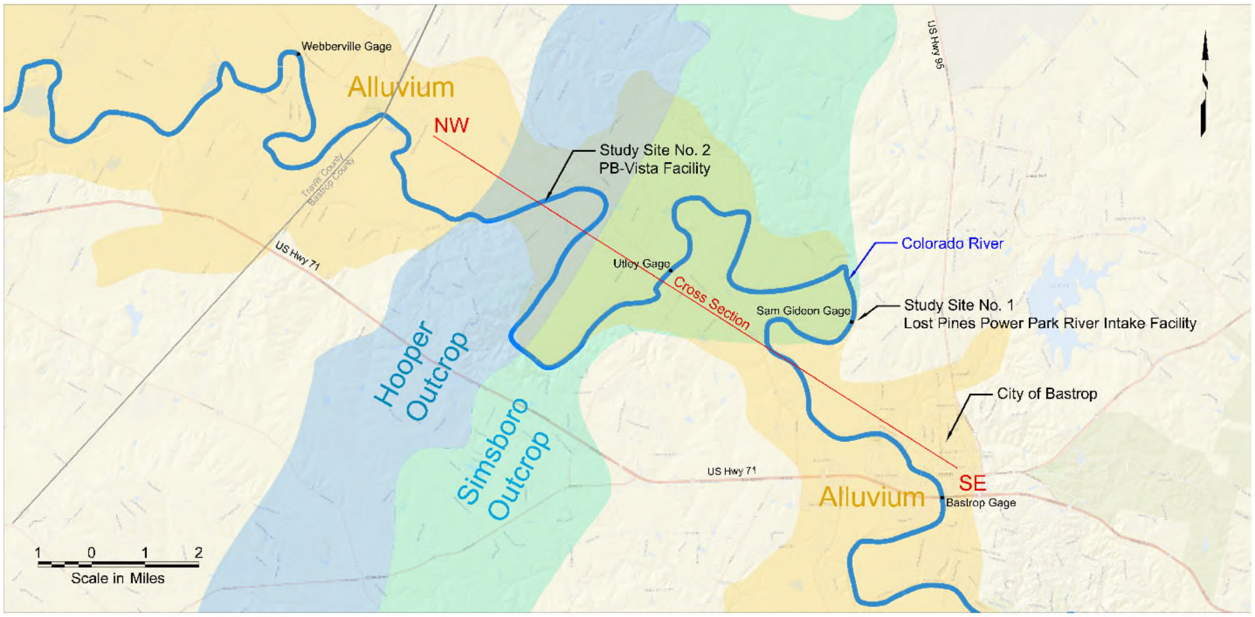
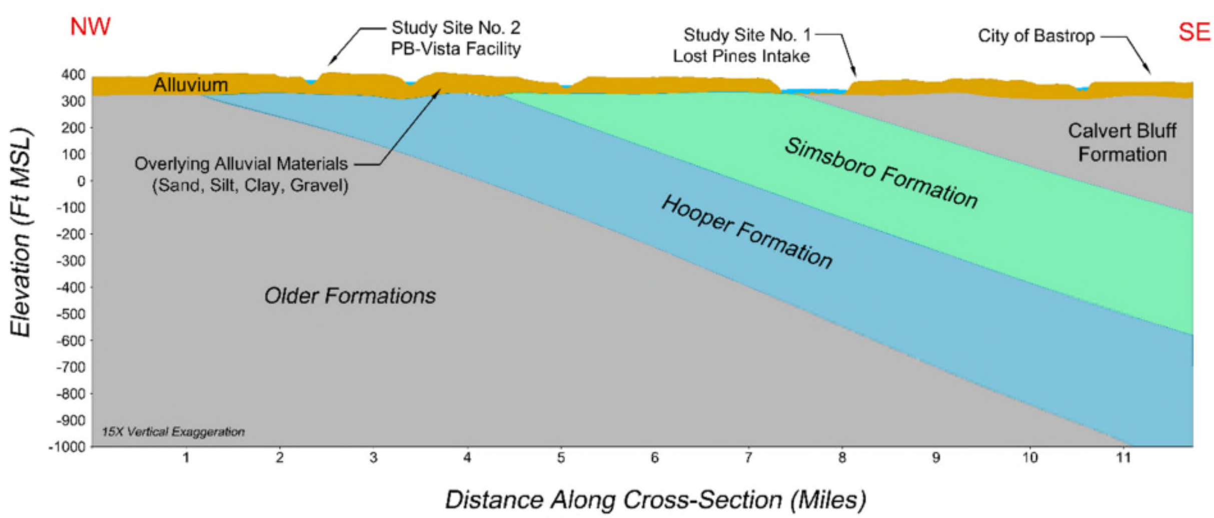


Figure 2. Regional Cross-Section Diagram



Study Site No. 1: Lost Pines Power Park Intake Facility

The LCRA Lost Pines Power Park River Intake Facility (Intake Facility) was initially chosen as the study location. Secure landowner access permissions, good rig ingress/egress to the proposed drill sites, and colocation with an existing river gauge made this a favorable location for a study site. The Intake Facility also has a High Accuracy Reference Network (HARN) monument to facilitate a professional topographic survey to accurately locate the position and elevation of installed monitoring equipment. Available geologic information indicated the potential presence of Simsboro aquifer sediments beneath the alluvium at the site. The existing riverbank intake structures provided good access for river monitoring equipment. Although the Intake Facility required some site preparation prior to construction of the monitoring system, the added costs were within the budget constraints of the project. However, while there appeared to be many advantages to the Intake Facility, test hole drilling conducted in June 2019 did not indicate the presence of significant permeable alluvial sediments beneath the site. Consequently, the test hole was plugged and abandoned in accordance with State regulations. Further work at the site was cancelled and the selection process for an alternate study location was initiated.

During subsequent months following abandonment of work at the Intake Facility, several alternative sites were identified and evaluated with respect to the factors listed above. Securing an alternate site proved effort-intensive primarily due to difficulties identifying landowners willing to allow construction and long-term access to monitoring wells and telemetry equipment. Because of the extended effort needed to secure an alternate study site, it is recommended that future projects include an initial phase during which multiple potential study locations are selected and confirmed.

Study Site No. 2: LCRA Pope Bend Vista Ramp Facility

The LCRA Pope Bend Vista Ramp Facility (PB-Vista) was ultimately selected as the alternative study site. Its location on the interior of the Pope Bend point bar depositional environment suggests the presence of laterally-extensive permeable alluvial sediments in hydraulic communication with the river. The Hooper Formation (Hooper), which is the lowermost member of the Wilcox Group underlies the alluvium at the site (Proctor et al., 1974). The Hooper is predominantly comprised of silt and clay layers but permeable sand layers of up to about 100 feet in thickness are not uncommon in Central Texas. While not predicted to undergo the pumping stresses forecasted to occur in the overlying Simsboro, some regional declines in the Hooper are predicted by the current GMA-12 Desired Future Conditions (DFC) simulation that have the potential to impact alluvial water levels in the Pope Bend area. The existing infrastructure at the site allows for good access to monitor well and telemetry unit locations. As the owner of the facility, LCRA provides assurance of long-term site security and accessibility.

Initial test hole drilling and logging at the site showed the presence of permeable alluvial sediments; based on the favorable test hole results, additional work at the PB-Vista site was authorized. Three alluvium monitor wells and a river monitoring sensor housing were constructed at the PB-Vista site. Figures 3 and 4 show aerial and cross-sectional views of the PB-Vista site and three monitor wells that were constructed in spring 2020, which were outfitted with pressure, temperature, and conductivity sensors/data loggers in summer 2020. Since that time, data from the PB-Vista transducers has been continuously transmitted by an on-site cellular telemetry station to a remote database that can be accessed via the internet. The following includes discussions of the methods and materials used during drilling and construction of the PB-Vista monitoring wells and ancillary equipment.

Figure 3. Vista Site Overview Map

Test Hole Drilling

In January 2020 a test hole was drilled at the PB-Vista site (approximately 5 to 10 feet from the location of PB-Vista 1) using hollow-stem auger drilling equipment to document the presence or absence of permeable alluvial sediments. A layer of alluvial sand, gravel, and cobbles (Figure 5) was encountered from a depth of approximately 18 feet to 32 feet below ground level (bgl). The test hole was extended to a depth of 80 feet bgl to determine whether permeable Hooper sediments may underlie the site; however, no other permeable materials were encountered between 32 and 80 feet bgl. While there may be permeable Hooper materials below 80 feet at the site, drilling was terminated because the 48-foot interval of relatively-impermeable sediments overlying the alluvium precludes significant hydraulic interaction between the Hooper and the alluvium. It should be noted that, because of the concern that drilling operations might have excessively disrupted the hydraulic properties of the alluvium near the well bore, the test hole was not used for monitor well construction.

Figure 4. Schematic Cross-Section of Vista Site

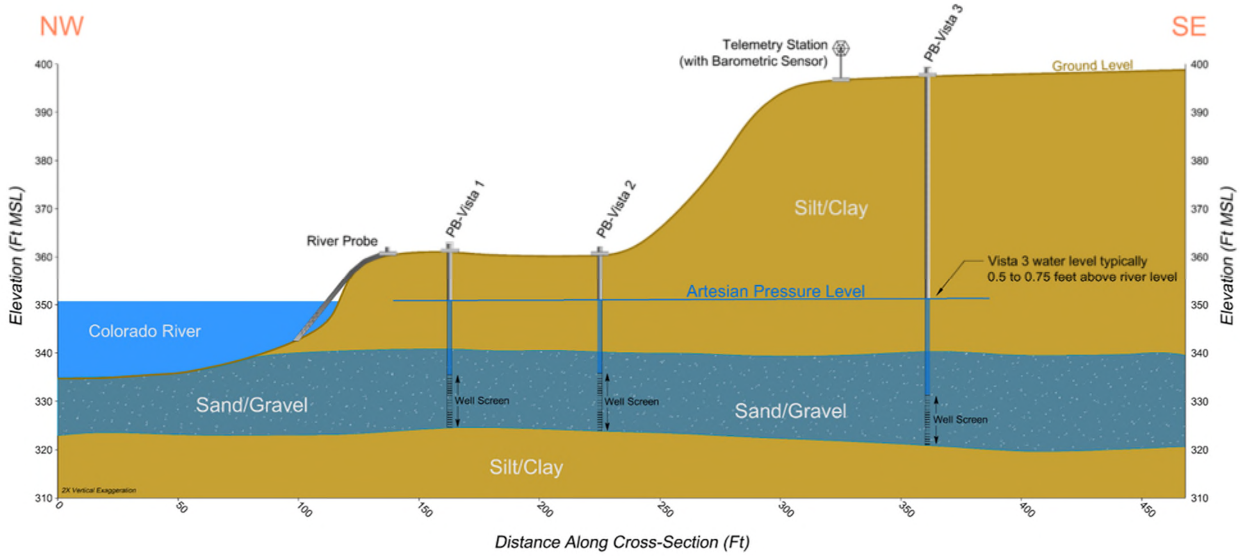
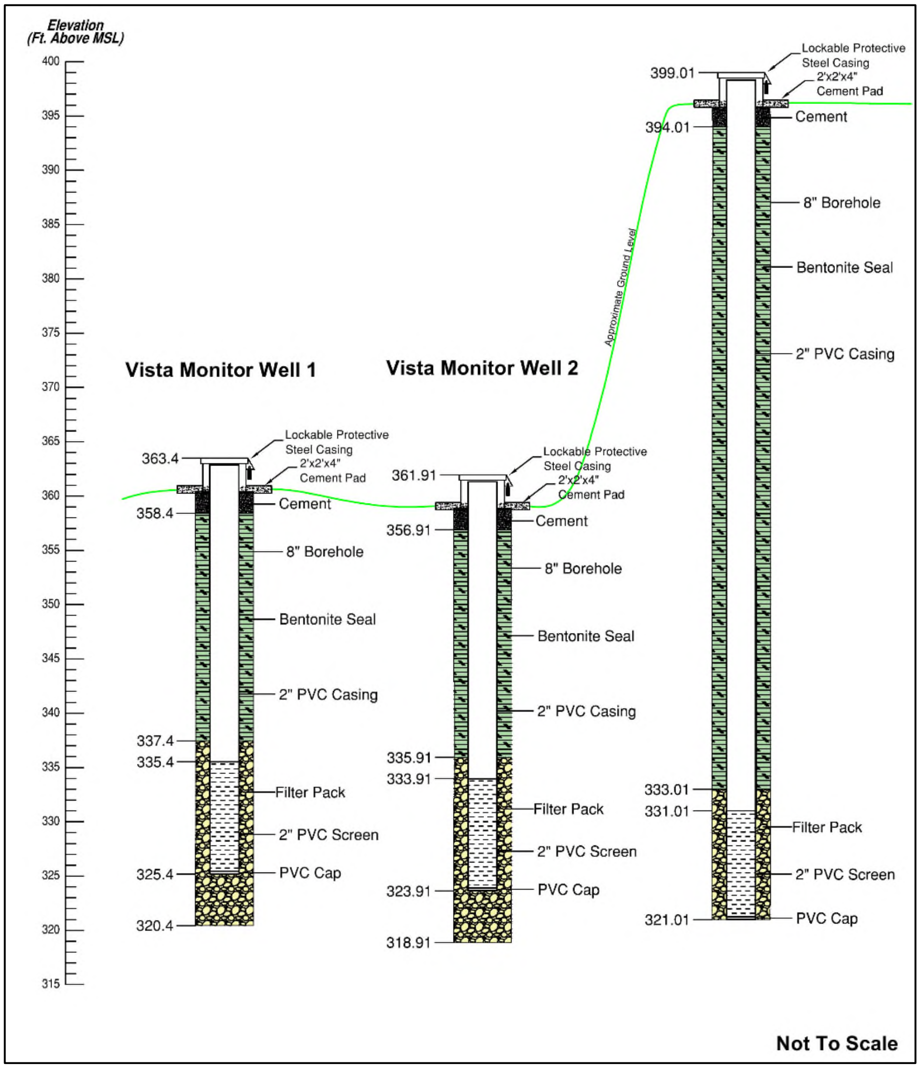


Figure 5. PB-Vista Test Hole Drilling.

Monitor Well Construction

Figure 6 is a cross-sectional diagram showing details associated with monitor well construction. Wells PB-Vista 1 and PB-Vista 2 are located near the river in the lower topographic area that is approximately 10 feet above normal river level. Well PB-Vista 3 and the telemetry station are in the upper topographic area of the site about 45 feet above the normal river stage. An eight-inch hollow-stem auger drilling rig was used to excavate boreholes for monitor well construction. After each hole was drilled through the full thickness of the permeable alluvial materials, a 2-inch diameter PVC monitoring well was completed.

Figure 6. Schematic Cross Section of Monitor Well Installation



The annular space between the PVC and the borehole was then filled with filter pack material to approximately two feet above the top of the slotted screen. The remainder of the borehole annulus above the filter pack was filled with bentonite chips to a depth of about two feet bgl. Each well was developed by repeated flushing of water from the well bore using temporary pumping equipment until the water was clear. After this material has settled at least 12 hours, the top two feet of the borehole was filled with neat cement. Concrete surface slabs conforming to State requirements were constructed at each well site. Following installation, a topographic survey was performed by James E. Garon & Associates, Inc. to document the locations and ground level elevations of the monitor wells. Appendix A includes a sequence of photographs and descriptions detailing the methods and materials used during construction/installation of the PB-Vista monitoring equipment.

River Gauge Installation

To determine the fluxes between the river and the alluvial aquifer requires accurate measurements of the river water level at the PB-Vista site. Because the nearest upstream and downstream LCRA river level gauges are located several miles away, a river gauge was installed the PB-Vista site. The river monitoring site consists of an electronic datalogger/pressure transducer submerged in a two-inch steel pipe installed into the riverbed and riverbank. The steel pipe was perforated on two sides (approximately 180-degrees apart) with the installed perforations oriented on the upstream and downstream sides of the steel pipe. A front-end loader and steel fence post driver were used to set the lower end of the pipe about four feet into the river sediments using a simple drive-point methodology (i.e., no drilling was performed in the river). For additional strength and stability, an additional ten feet of steel pipe was anchored into the riverbank material and connected to the subsurface telemetry conduit system described below.

INSTRUMENTATION OPTIONS AND SELECTION

The selection of measurement parameters for this study was based on their usefulness in characterization of hydrogeologic conditions as well as practical issues such as limitations on physical deployment (sensor size, cabling, etc.), reliability/suitability for long-term measurements, and budgetary constraints. Three primary measurement types were identified that may be used to study potential surface water/groundwater fluxes:

1. **Pressure –** When submerged in water, the sensor measures water pressure that can be converted to water depths and elevations. The water levels measured in adjacent monitoring sites can be used to accurately calculate hydraulic gradients beneath the study site. Because hydraulic gradient data can be used to determine the direction and magnitude of flows simply and quantitatively, pressure sensors represent a fundamental data source that should be included in all studies.
2. **Temperature –** River water temperatures fluctuate in response to oscillations in daily river flows due to upstream dam releases, seasonal changes, and longer-term environmental and/or surface water use patterns. In general, calculations of flux directions and magnitudes using temperature measurements are less accurate than those made with pressure measurements. Limitations on the usefulness of temperature data stem from the attenuation of groundwater temperature changes by the thermal capacity of the aquifer matrix, which comprises the bulk of the aquifer volume. However, temperature measurements can provide a useful and inexpensive source of support data that can be used to verify and supplement conclusions drawn from other data sources.
3. **Chemical Parameter Sensors –** The chemical composition of river water typically varies with both short- and long-term changes in dam operations and environmental parameters. Like temperature, sensors that measure chemical parameters such as pH, electrical conductivity, dissolved gasses, etc. are typically best used in combination with other data sources to verify flux directions and volumes. In general, electrical conductivity measurements are preferred over pH or dissolved gas measurements due to the ability of conductivity sensors to maintain calibration over longer periods of time.

For this study, sensors capable of recording pressure, temperature, and electrical conductivity were selected for deployment in monitoring wells and river transducer housing. Pressure and temperature sensors are standard equipment for most available transducers. In general, the added cost of including an electrical conductivity sensor in the datalogger is relatively small.

Conceptually, continuous measurements of the temperature of riverbed sediments using a linear string of fiber optic distributed temperature sensors (FODTS) placed in vertical profile could, in conjunction with monitoring well temperature data, provide information that could be used to determine groundwater influx areas. However, riverbed temperature profile measurements were not implemented because of the relatively high installation effort/cost and the potential for equipment damage during flooding events.

Electrical (resistivity) profiling methods were also considered for this study. Resistivity profiles can be useful for mapping the extent of permeable alluvial materials and other subsurface sediments, but the results generated by resistivity surveys typically require validation with a test drilling program. Because the cost of performing enough resistivity transects and test drilling to properly characterize the subsurface structure at PB-Vista is relatively high, resistivity surveys were not selected for this study.

Sensors/dataloggers are typically compact, self-contained electronic units that are lowered below the groundwater or river surface. An onboard, battery-powered electronic system records data measured at user-specified intervals. The recorded data can be accessed via an electronic cable leading to the surface or through direct download from the datalogger after lifting to the surface. The primary considerations used in selecting a specific datalogger are reliability, sensor accuracy, ease of installation, parameter monitoring options, and the cost of purchase and maintenance. Additional consideration was also given to the telemetry (remote reporting) options available from each manufacturer. In general, purchasing all system equipment from a single manufacturer is desired from ease of installation, configuration, and maintenance standpoints.

In-Situ AquaTROLL 200 series (100-psi, non-vented) dataloggers were installed in the riverbank housing and the three monitoring wells. An In-situ Cube 300S telemetry unit, which includes an onboard barometric pressure sensor, was selected to relay data from the installed dataloggers to a cellular network. The telemetry system is also capable of transmitting data from several different models of probes reporting a variety of water quality parameters, allowing for potential reequipping of sensor types in the future. The specification sheets for the selected equipment and other In-Situ transducers that may be deployed with this system are shown in Appendix B.

Monitoring Equipment Installation and Calibration

Installation of the transducers, cabling and telemetry system was completed in summer 2020. The dataloggers were installed in each well near the top of the screened interval and in the river within the perforated portion of the housing. The dataloggers are connected to the telemetry station using coaxial cables routed through a series of 1.5-inch diameter PVC conduits that were installed below grade using a trenching tool. The section of conduit connecting the upper and lower topographic areas was not placed in a trench to minimize the disturbance of the slope between these two areas, limiting the potential for future erosion and destabilization of the slope. Appendix A includes a series of photographs documenting the installation of the dataloggers, electrical conduits, and telemetry system.

Although the monitoring and telemetry system is designed to require little or no day-to-day attention, sensors may become coated or clogged with sediment and/or biological materials over time. Periodic cleaning and recalibration of transducers is required to ensure the accuracy of the measurements. A more detailed description of these cleaning and calibration procedures are presented in the operations manuals provided by In-Situ, Inc. (2021).

DATA COMPILATION AND EVALUATION

As described above, dataloggers installed in the three PB-Vista monitoring wells and the perforated housing set into the riverbank began recording pressure (water level), temperature, and water conductivity (specific conductance) in summer 2020. A fifth sensor contained within the on-site telemetry unit recorded barometric pressure over the same interval. Recorded data is stored by the onsite dataloggers and can be downloaded during an on-site visit by connecting a laptop computer to the electrical cable that extends from each probe to the surface slab/cap. Data is uploaded to the In-Situ, Inc. internet-based storage facilities and can be accessed using their HydroVu® website. A five-year subscription to the data storage facility and HydroVu access website was purchased as part of this study.

The raw data recorded by the dataloggers must be processed in order to properly evaluate it. Pressure measured by each probe is recorded in pounds per square inch (psi), which must be converted to feet of water above each sensor. Atmospheric pressure is then subtracted using the data recorded by the barometric transducer installed in the telemetry unit. Finally, rectification of the water height data to ground level elevation is necessary for proper assessment of the hydraulic gradients at the site.

Determination of Hydraulic Properties

On November 19, 2020, a series of slug tests were performed in the three monitoring wells to determine the hydraulic properties of the shallow alluvial aquifer. The slug tests were conducted by injecting a known volume of water into each monitoring well and measuring the water level response over time. Slug tests are widely used but, because the imposed hydrologic stress is relatively small and short-lived, the area characterized by a slug test is limited to the area near the well bore. Alternatively, data obtained from pump testing of wells can typically be used to define the aquifer conditions over larger areas. However, pump testing requires larger diameter wells to accommodate the installation of pumping/monitoring equipment, which increases costs significantly. In order to meet budgetary constraints, construction and testing of larger-diameter monitoring wells was not selected for this project.

The slug tests were analyzed using the following three methods: Bouwer and Rice (1976), Hvorslev (1951) and the Kansas Geological Survey Model (KGSM) with skin effects (Hyder and Butler, 1994). A commercial program AQTESOLV (Duffield, 2007) was used to perform the analyses. Table 1 provides the average hydraulic conductivity calculated using these three methods.

Table 1. Hydraulic Conductivity Values Calculated from Slug Tests

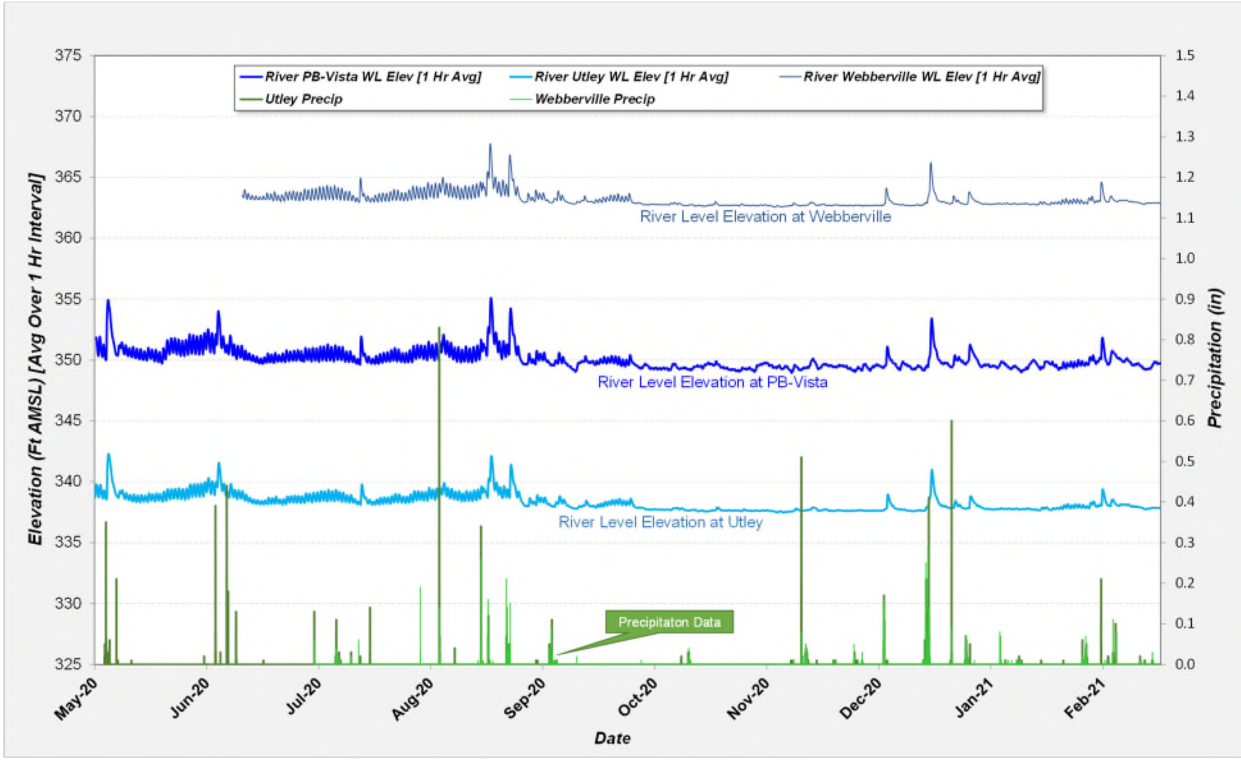
Monitor Well	Hydraulic Conductivity (ft/day)		
	Bouwer and Rice	Hvorslev	KGSM
PB-Vista 1	4.6	5.5	4.4
PB-Vista 2	4.7	5.5	4.9
PB-Vista 3	5.8	5.8	2.9

It should be noted that the hydraulic conductivity values in Table 1 are significantly less than the ranges reported by authors of previous studies. Young and others (2017) assigned alluvium conductivity values ranging from 50 ft/day to 140 ft/day, which were based on hydrogeologic studies performed by Hibbs and Sharp (1993); Gerecht and others (2011); Francis and others (2010). The values in Table 1 are also significantly less than the hydraulic conductivity of 75 ft/day used to represent the alluvium and terrace deposits in the GAM (Young and others, 2018). Because of the lack of measured hydraulic conductivity values in the Colorado River alluvium and terrace deposits, there is uncertainty as to whether the conductivities documented during this study are representative of Colorado River alluvium and terrace deposits in other areas.

River Stage

In addition to data recorded at the PB-Vista site, precipitation and river flow information is available for download from LCRA's Hydromet website (LCRA, 2021a; LCRA, 2021b; LCRA; 2021c; LCRA, 2021d). Rainfall data from two river gauge stations (Webberville and Utley) were used herein to provide a general representation of the magnitude and duration of precipitation in the PB-Vista area. Figure 7 graphs precipitation measured at Webberville and Utley with the changes in river stage recorded during this study. River levels typically oscillate on a daily basis as flows are dammed at night when electrical usage is low and released during the day when increased power production is needed. Dam operations also fluctuate on a seasonal basis; daily river level oscillations of one to two feet are common during warmer months, while changes in river levels are more subdued during colder portions of the year. As expected, precipitation also affects river levels, with observed short-term peaks of up to about five feet recorded after some rainfall events. The relationship between rainfall and river stage is highly dependent on rainfall location, intensity, and aerial extent. For purposes of this investigation, precipitation data is presented as a potential cause of elevated river stage.

Figure 7. Colorado River Elevation and Precipitation



Water Temperature

Figure 8 graphs water temperature through time. The temperature of river water varied with daily dam releases, precipitation events, and seasonal trends, while little change in alluvial groundwater temperature was observed throughout the recording period. River temperature varied from a high of approximately 33°C (91°F) to a low of about 3°C (37°F) recorded during the severe winter storm in February 2021. Changes in alluvial groundwater temperature were much more subdued. As shown in Figure 9, both PB-Vista 1 and PB-Vista 2 appear to exhibit annual temperature oscillations unrelated to river temperature change, although the recording interval is insufficient to conclude that the changes recorded thus far will repeat in the future. The lack of temperature correlation suggests that little or no infiltrated river water reached PB-Vista 1 or PB-Vista 2 monitoring wells or that river water that flowed into the alluvium equilibrated to the ambient temperature of the alluvial materials.

Figure 8. River and Groundwater Temperature

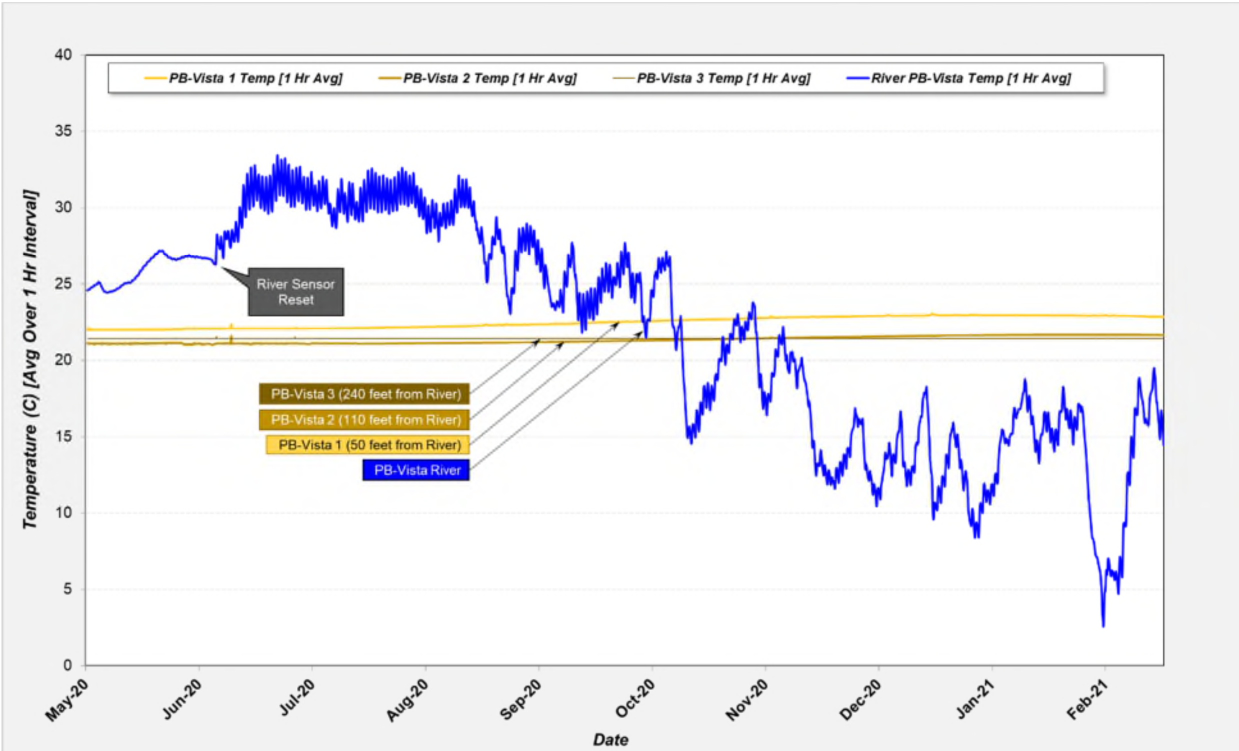
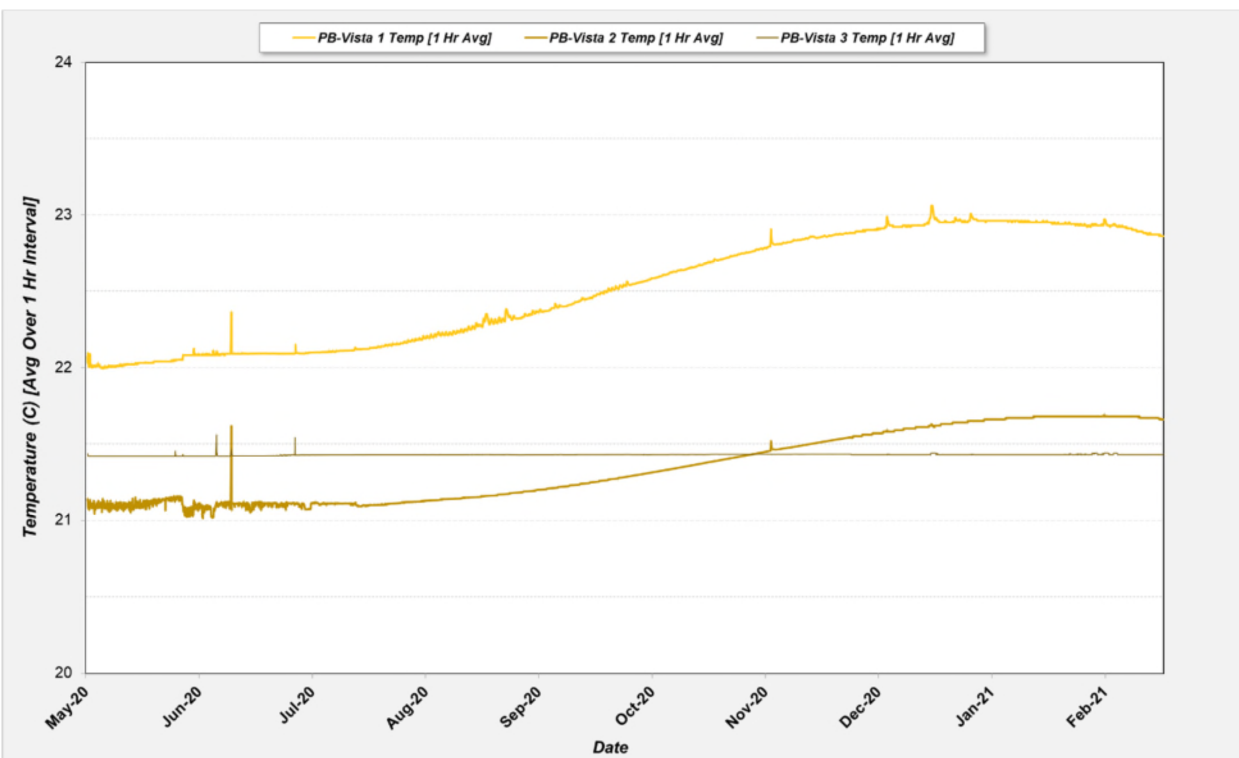


Figure 9. Groundwater Temperature



Much smaller changes in the temperature were measured in PB-Vista 3; an increase of approximately 0.1 degree was recorded in the interval between summer 2020 and December 2020. Temperature measurements recorded in PB-Vista 3 since that time have varied even less and are somewhat erratic, suggesting that there may be a failure of the temperature sensor. Given the small temperature responses recorded by the PB-Vista monitoring wells and the relative benefit of maintaining consistent, accurate water level measurements, it was determined that removing, diagnosing, and potentially repairing/replacing the PB-Vista 3 transducer was not desirable at this time.

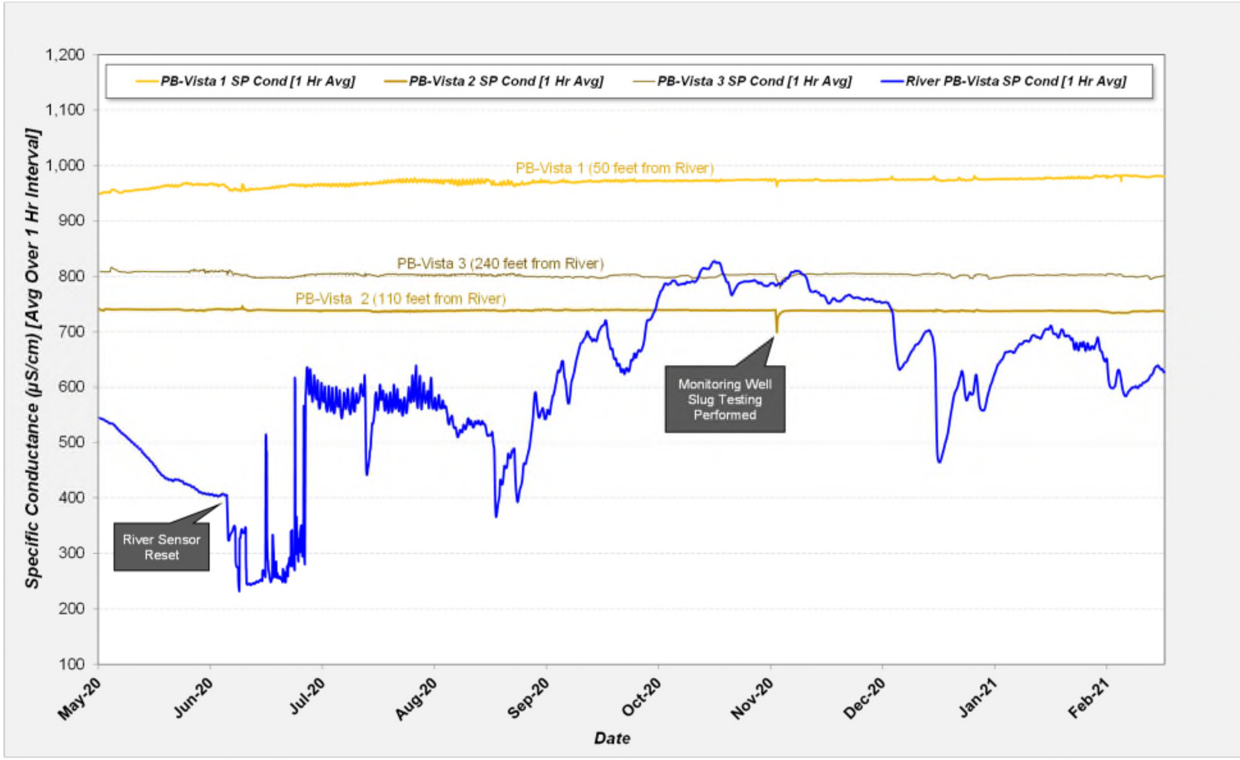
Electrical Conductivity (Specific Conductance)

The transducers installed at the PB-Vista monitoring sites include electrical conductivity sensors. The raw conductivity measurements are converted by the onboard electronics to specific conductance using the data recorded by the temperature sensor. Like water temperature, the conductance of alluvial groundwater remained relatively steady while river water conductance generally fluctuated rapidly in response to changes in flow and environmental conditions (Figure 10). River conductance values ranged from a low of approximately 250 microsiemens per centimeter (µS/cm) to 825 µS/cm from summer 2020 through February 2021. The lack of correlation between groundwater and alluvium specific conductance suggests that little or no infiltrated river water reached the PB-Vista monitoring wells.

The abrupt rise in river conductance recorded in mid-July 2020 was investigated and no cause was identified; no alterations in the physical conditions of the river probe/housing were observed and no changes in the configuration of the transducer software were made at the time of the increase.

While the conductance is generally consistent in all the monitor wells, small-scale variations were measured during the study period. Daily oscillations of up to approximately 8 µS/cm are apparent in the data recorded in PB-Vista 1 during summer months. Daily fluctuations of less than about 2 µS/cm were also measured in PB-Vista 2 and PB-Vista 3. Figure 10 shows a long-term increasing trend from approximately 950 µS/cm to 980 µS/cm in the PB-Vista 1 specific conductance, which is not observed in the other monitor wells. This trend may be a response to the generally-increasing trend in river conductance; however, the apparent increase may represent a measurement artifact resulting from the slow divergence of the transducer from a calibrated state.

Figure 10. Electrical Conductivity (as Specific Conductance)



Water Level Elevation

Figure 11 graphs water level elevations recorded by the PB-Vista transducers throughout the study period. Alluvial groundwater is under artesian pressure and rises approximately 15-20 feet above the top of the permeable sediments screened by the PB-Vista monitoring wells. Daily oscillations in river stage and alluvial groundwater levels are pronounced during warmer months, becoming less regular during colder periods. Figures 12 and 13 depict the daily responses recorded during summer and winter, respectively. As shown, rapid oscillations in river levels are followed closely by alluvial groundwater levels. Two general conditions are observed in the data:

- During short-term, high-river-flow intervals driven by precipitation events, river levels exceed alluvium levels indicating groundwater flux from the river to the alluvium.
- Throughout the majority of the study period, alluvium artesian pressure levels were greater than river levels indicating that groundwater flux is toward the river.

In general, there is a relatively consistent lag time between changes in river levels and the responses observed in the PB-Vista monitoring wells. Figure 14 graphs water level elevations over a two-day period in August 2020 during which typical summer river stage oscillations were recorded. As shown, river levels peak in the late morning and are generally at the lowest ebb in early morning before dawn. As expected, the interval between river level maximum/minimum values and corresponding monitor well groundwater levels increased with distance from the river, with full response lag times ranging from about 20-30 minutes at PB-Vista 1 to 1.25 to 2.25 hours at PB-Vista 3.

The hydraulic relationship between the alluvial groundwater level in Vista 3 and the other monitoring sites changed in response to both daily oscillations and longer-term trends in average river levels. As shown in Figure 15, the greater response lag time observed in PB-Vista 3 result in changes in the hydraulic relationship between the monitoring sites. During periods when average river stage is declining, the groundwater elevation at PB-Vista 3 remains above levels in the other monitoring sites throughout daily oscillation cycles. However, when average river levels are increasing over longer intervals, the groundwater level in PB-Vista 3 is below levels recorded at the other monitoring sites during daytime peaks but levels measured in the other monitoring sites fall below PB-Vista 3 levels at night.

Figure 11. PB-Vista Water Level Elevation – Seasonal Changes

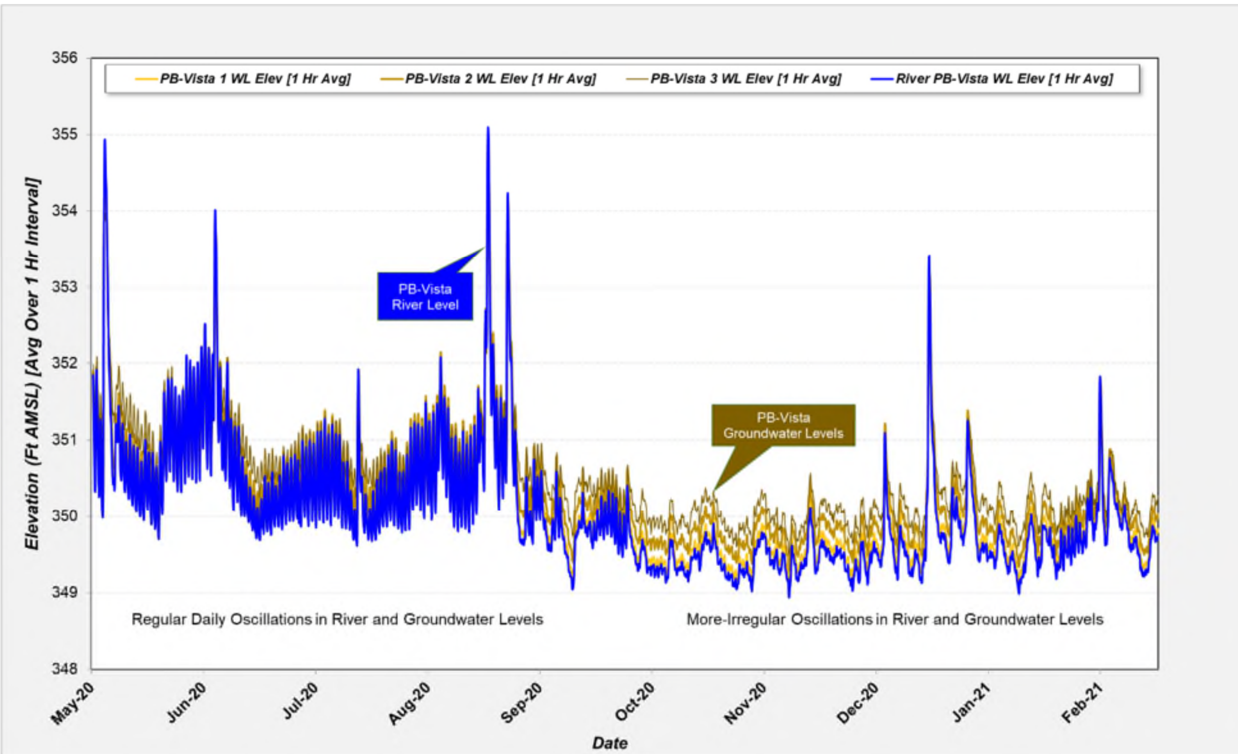


Figure 12. PB-Vista Water Level Elevation – Summer

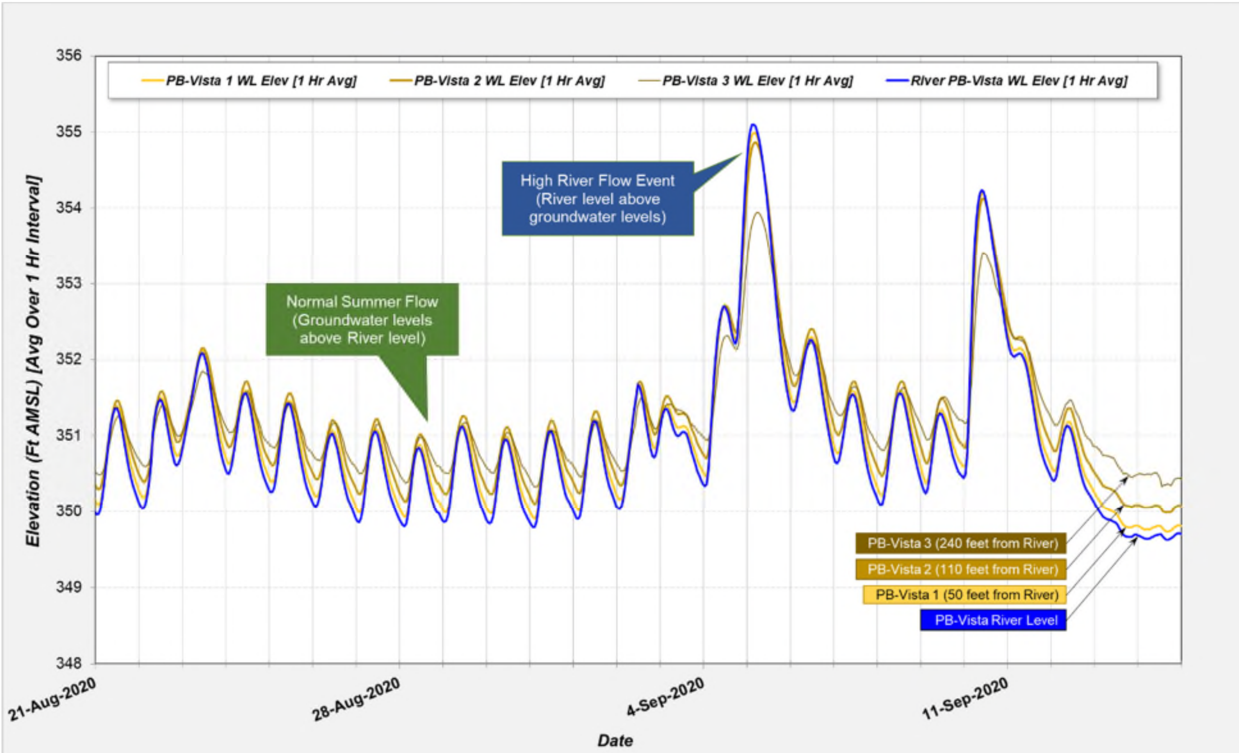


Figure 13. PB-Vista Water Level Elevation – Winter

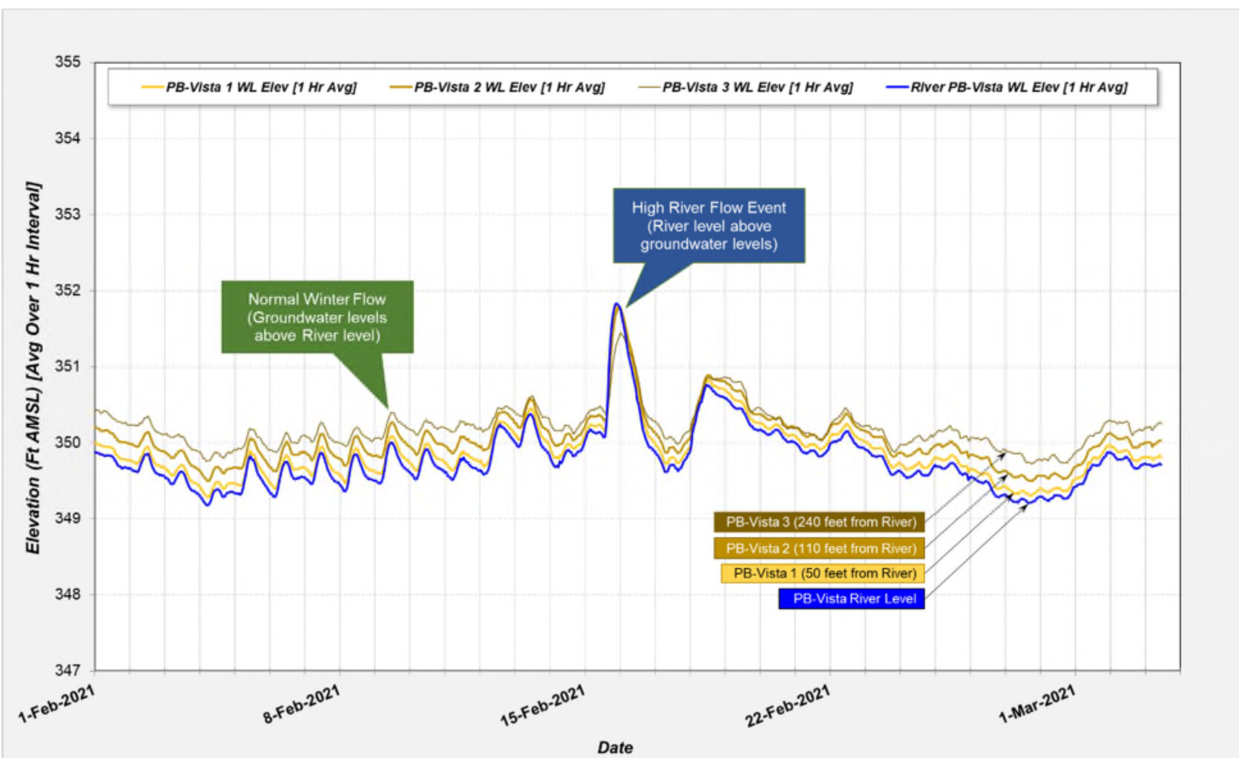


Figure 14. Water Level Elevation Response Delay

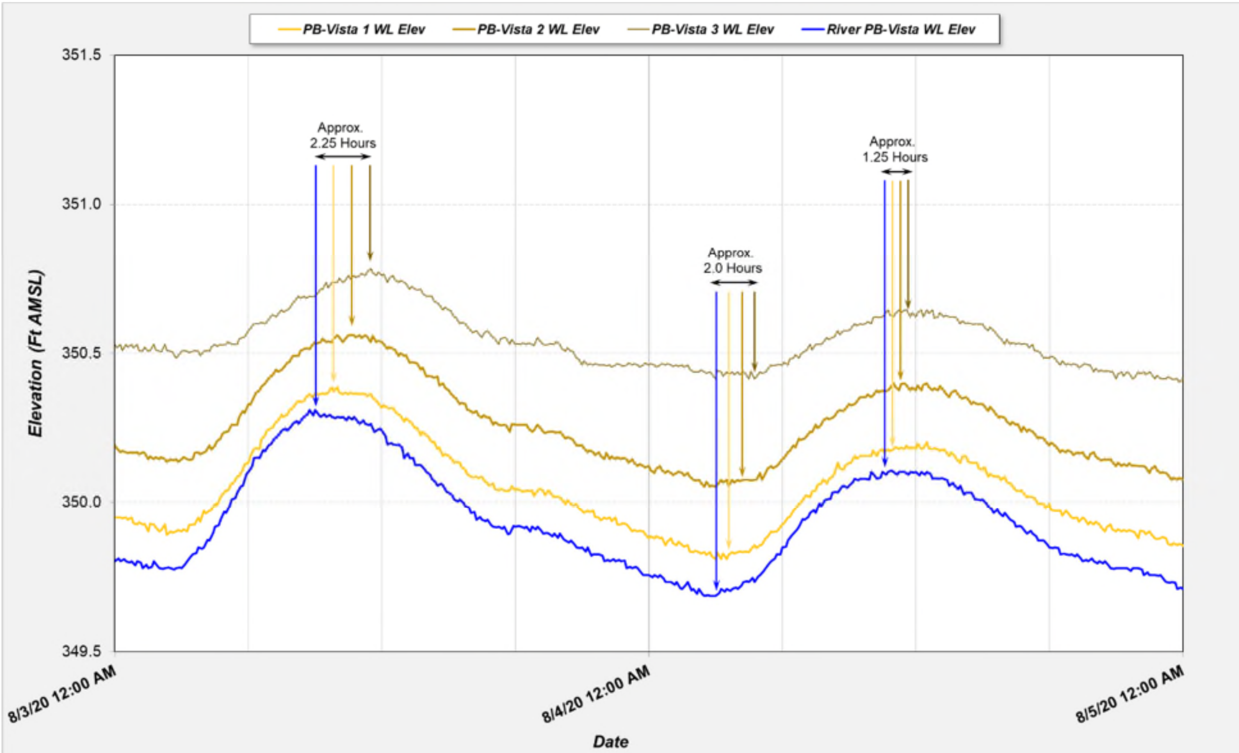
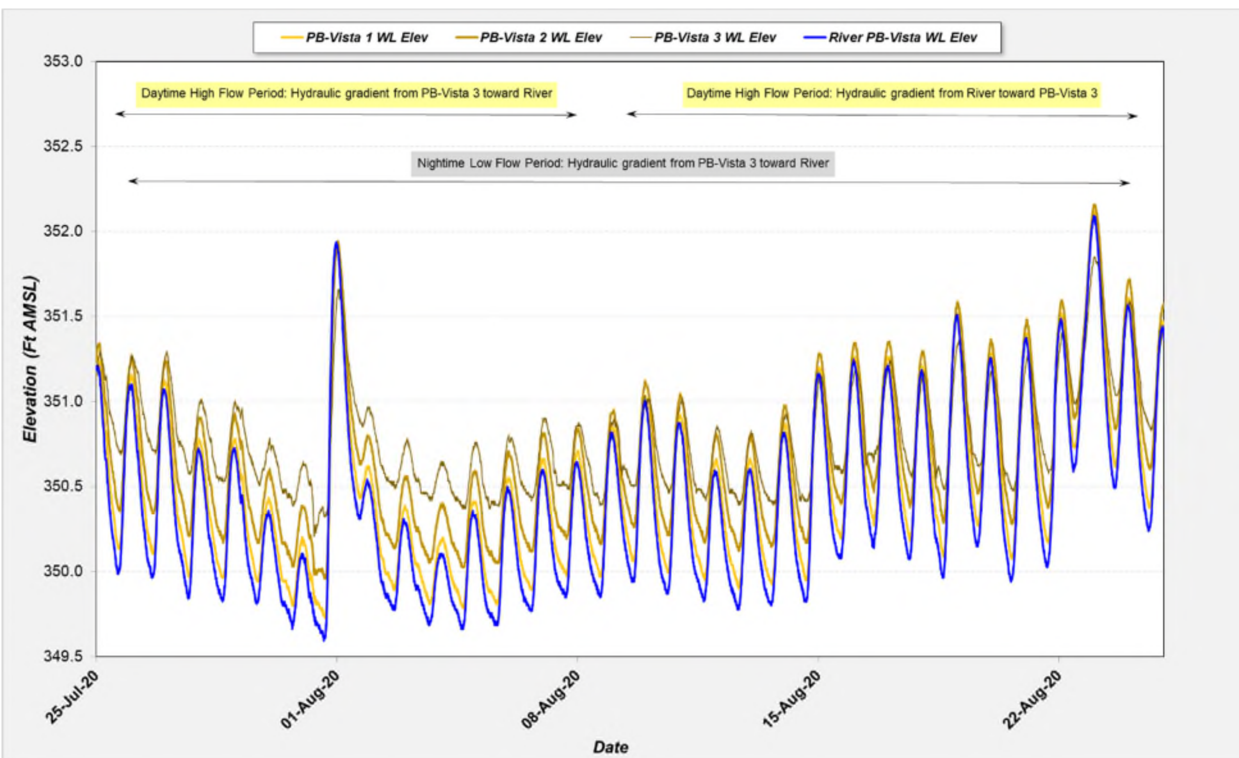


Figure 15. PB-Vista 3 Hydraulic Relationships



Hydraulic Gradient and Groundwater Flux

Figures 16 through 18 show the water level elevations and hydraulic gradient between each PB-Vista monitor well and the river through time. Hydraulic gradients exhibited both short and long-term variations in response to dam operations and precipitation events. During the majority of the study period, alluvial hydraulic gradients toward the river were observed, indicating "gaining stream" conditions throughout much of the year.

Seasonal changes in hydraulic gradients are also apparent, with relatively-consistent gradients toward the river during winter months and short-term reversals occurring during daily dam releases and precipitation events, which occur more frequently during warmer months. It should be noted that few high river stage events occurred during the 285-day study period which may bias results toward gaining stream conditions. As discussed above, the various lag times in the water level responses recorded in the wells affect whether groundwater levels are above or below river stage at a given time; consequently, both the magnitude and direction of the hydraulic gradients varied as river levels change throughout a typical day.

Groundwater velocity, flux rates, and discharge volumes were calculated from the measured hydraulic gradients using Darcy's Law: $Q = K\frac{dh}{dL}A$ and its variant: $V = K\frac{dh}{dL}({}^{1}\!/_{n_e})$

Where: Q is the volumetric flux rate (L^3/T)
dh/dl is the hydraulic gradient (unitless)
V is the average linear velocity (L/T)
K is hydraulic conductivity (L/T)
A is the area of flow (L^2)
n_e is the effective porosity (unitless)

The calculations are based on an average hydraulic conductivity value of 4.9 ft/day (derived from monitoring well slug tests), an average alluvium saturated thickness of 18 feet, and an assumed alluvium effective porosity of 0.2 (unitless). It should be stressed that the baseflow velocity and flux estimates discussed herein are heavily dependent upon the assumed structure and hydraulic parameters of the alluvium. Significantly different values could be obtained by altering the hydraulic conductivity, saturated thickness, and effective porosity values applied to the calculations described above.

Figure 19 shows the estimated average linear groundwater velocity toward the river and the cumulative distance traveled by a hypothetical groundwater particle between May 2020 and March 2021. Groundwater velocity toward the river varied significantly with daily oscillations in river level during summer, stabilizing to average values of approximately 0.05 to 0.1 ft/day during colder months. Summing the average hourly velocities calculated throughout the 285-day measurement interval, the cumulative distance traveled by a hypothetical groundwater particle is approximately 15 feet, which equates to an average linear groundwater velocity of 0.053 ft/day toward the river.

The term "baseflow" is commonly used to describe the amount of groundwater exchange with a surface feature. Figure 20 graphs the estimated average baseflow flux rate and cumulative baseflow volume of alluvial groundwater to the river along the entire interior perimeter of Pope Bend, which is approximately 23,500 feet in length. Assuming that the alluvium maintains a constant average thickness of approximately 18 feet and the hydraulic relationship between the alluvium and the river observed at PB-Vista is representative of conditions throughout Pope Bend, baseflow from the alluvium to the river is approximately 186 cubic feet per hour (ft^3/hr). A cumulative baseflow contribution to the river of approximately 29.2 acre-feet (1.272 million ft^3) is calculated over the 285-

day measurement interval, which equates to an annual baseflow volume of approximately 37.4 acre-feet from the alluvium along Pope Bend. It should be noted that, because Pope Bend represents a point bar alluvial structure, the volumetric flux was calculated for the alluvium within the interior of the bend; if similar hydrogeologic conditions are present in the exterior (cutback) portion of the point bar, the baseflow flux along Pope Bend would be approximately double the values discussed above.

Previous Study Findings

As discussed above, an average baseflow rate of about 186 ft^3/hr was calculated from the PB-Vista monitoring data, which equates to approximately 0.2 ft^3/day per foot of riverbank. These values are small in comparison to values generated by previous studies. In general, the values estimated by this study appear to be the result of applying the comparatively small alluvium hydraulic conductivity values calculated from the results of PB-Vista aquifer (slug) tests to the flux and velocity equations employed for this study. The following provides a brief overview of previous study findings.

Hibbs (1993) used information from monitor wells and river stage gauges at two locations to calculate hydraulic conductivities of the riverbank alluvium at both sites. These conductivities were included in numerical models to estimate the flux of groundwater/surface water along two reaches of the Colorado river. The first reach (Navarro-Taylor reach) extends approximately 31.1 miles from Austin to the eastern limit of the Navarro and Taylor Group outcrop in western Bastrop County. The second reach (Carrizo-Wilcox reach) extends approximately 51.5 miles from the eastern end of the Navarro-Taylor reach to Smithville. Model results estimate that flux of groundwater flowing into the river is 7.6 ft^3/day per foot of riverbank along the Navarro-Taylor reach and 8.0 ft^3/day per foot of riverbank along the Carrizo-Wilcox reach.

Both Sawyer, et al. (2009) and Francis, et al. (2009) investigated a reach of the Colorado river (Hornsby Bend) under the influence of water release operations at Longhorn Dam in Austin, Texas. Sawyer used a linear set of four piezometers and river stage recorder located on the riverbank to calculate a flux per foot of riverbank that ranged from 118.4 ft^3/day from the river into the aquifer and 58.1 ft^3/day from the aquifer into the river with an average daily flux of 37.7 ft^3/day from the river into the aquifer. Francis used fourteen piezometers to investigate the interaction between the Colorado river and a persistent island in the river near Hornsby Bend and found that an average flux of 67.4 ft^3/day per foot of riverbank flowed into and out of the island during a typical daily water release cycle of Longhorn Dam.

Figure 16. Hydraulic Gradient

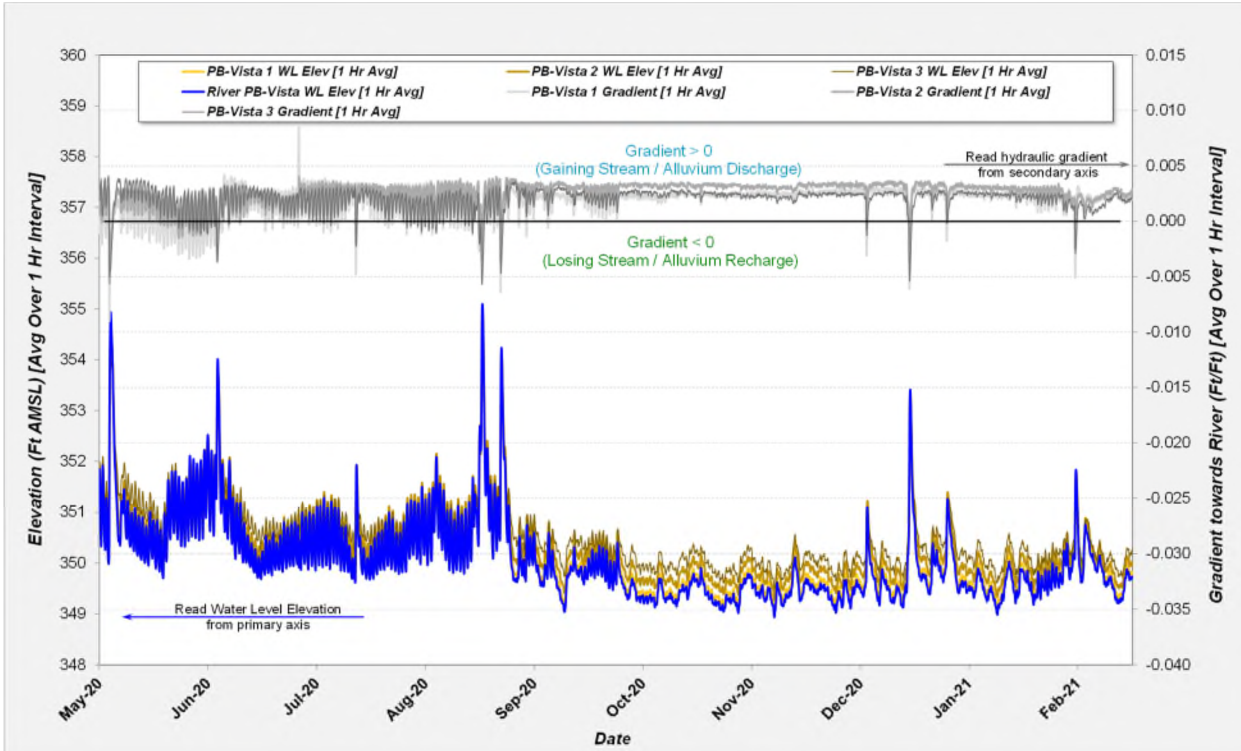


Figure 17. Hydraulic Gradient – Summer

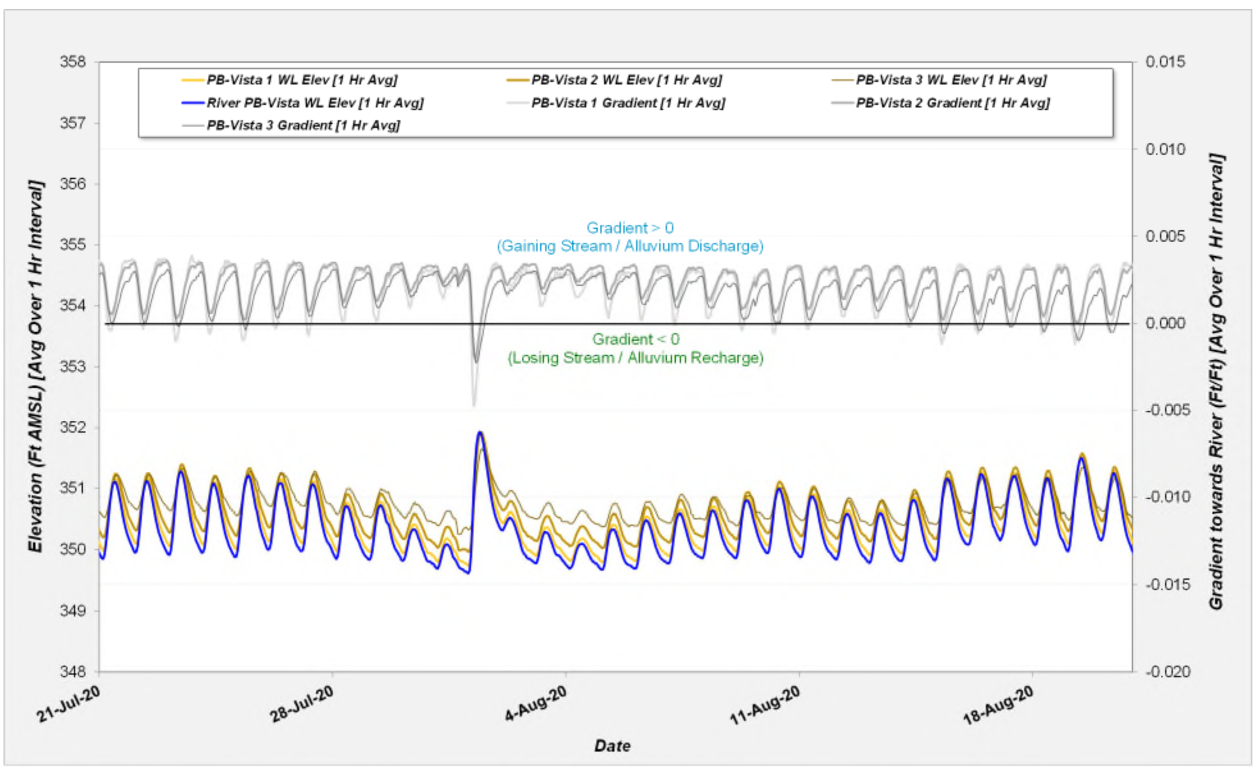


Figure 18. Hydraulic Gradient – Winter

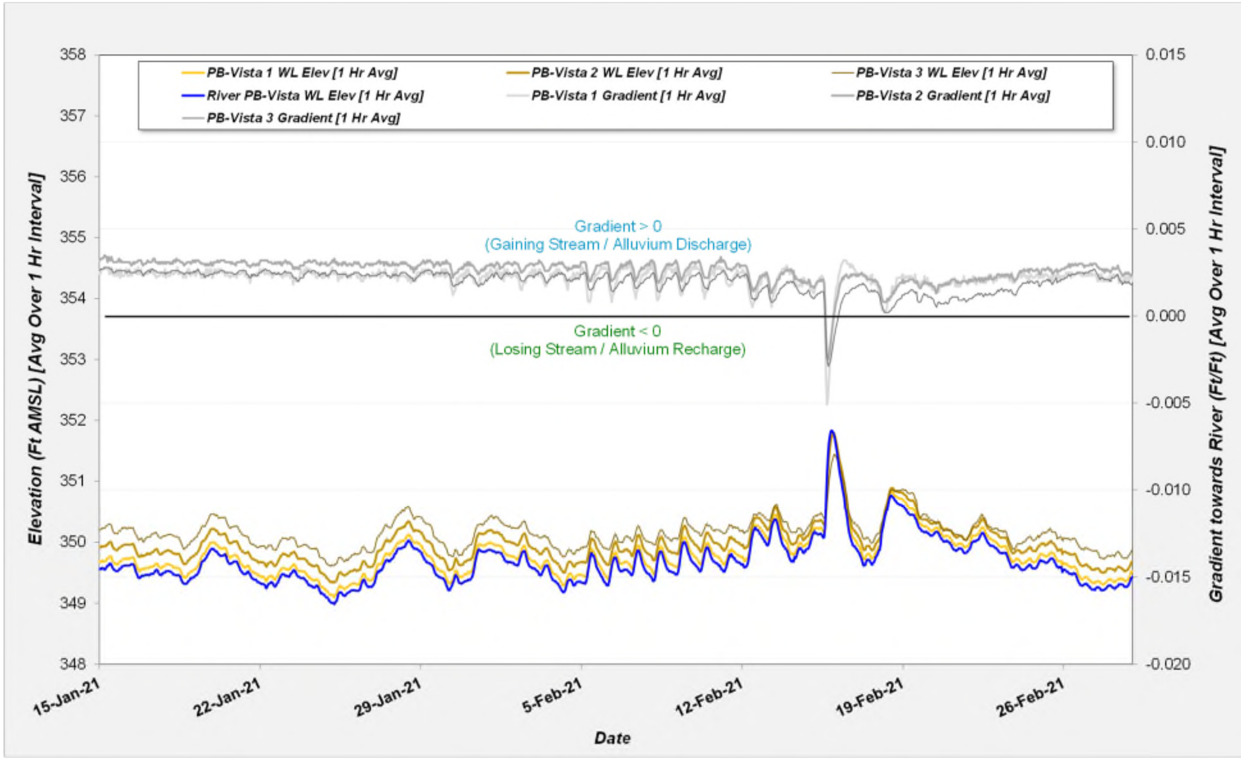


Figure 19. Average Groundwater Velocity and Migration Distance

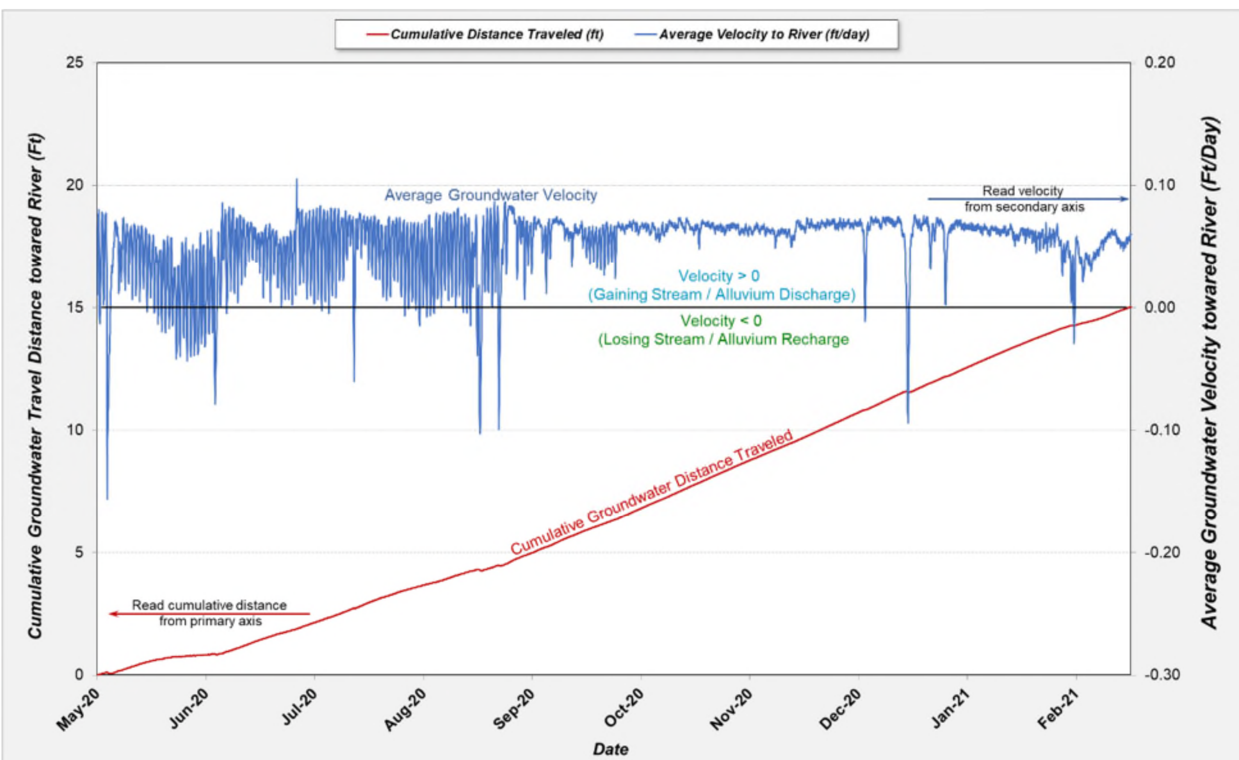
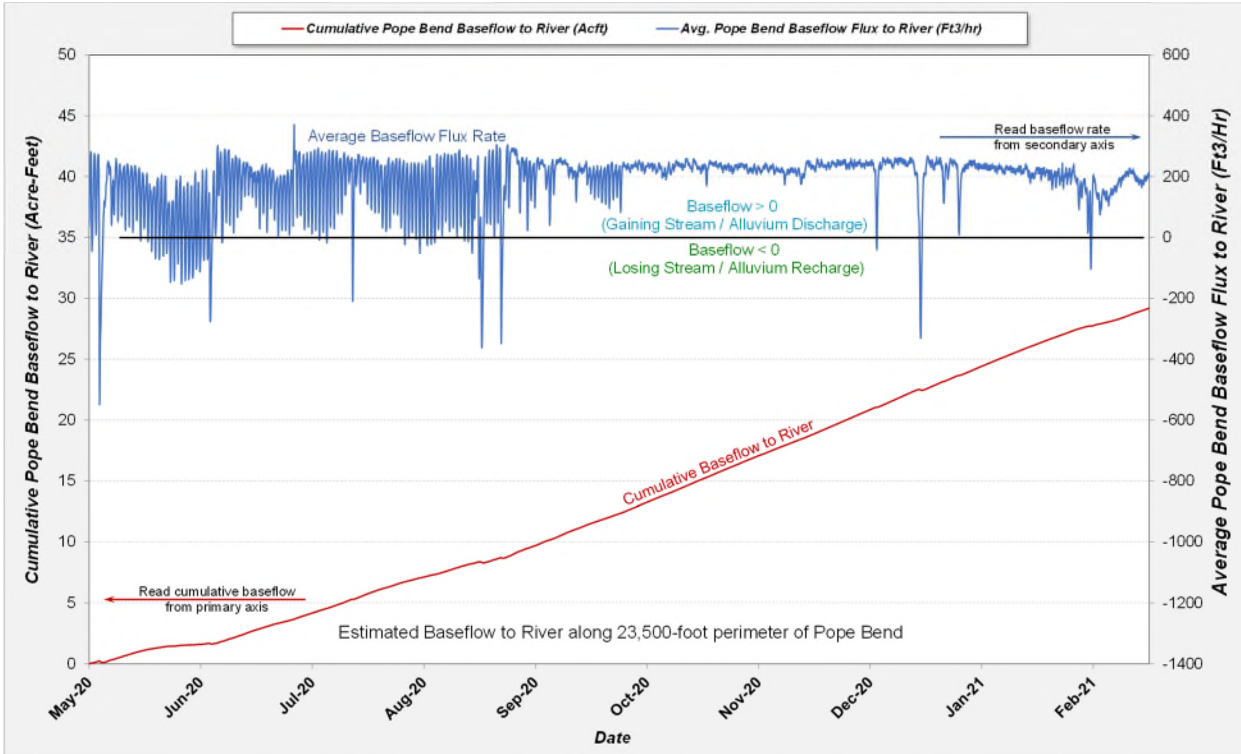


Figure 20. Estimated Baseflow to River Along Pope Bend



CONCLUSIONS

The information derived from the site selection process and from the drilling, well construction, and monitoring equipment installation efforts performed during this study provided valuable insights that can be used to refine and improve the methods used in future studies. From schedule and budgetary perspectives, it is extremely beneficial to select and secure multiple, potential study sites prior to performing field operations. Following the abandonment of the Intake Facility site, obtaining landowner agreements for monitor well construction and long-term access proved to be a time-consuming process. It is also recommended that initial public outreach processes be performed to help identify landowners amenable to study site construction and long-term access.

Evaluation of the various measurements and sensors utilized for this study suggest that pressure (water level elevation) data are the most useful for quantitatively determining surface water/groundwater fluxes. Temperature and chemical parameter measurements can provide data for corroborative analyses but generally do not allow for accurate, stand-alone calculation of baseflow rates or volumes. This study utilized precipitation information recorded by local river gauge stations but the rate and amount of precipitation that fell on Pope Bend was not measured. Equipping future study sites with precipitation gauges would potentially allow researchers to identify groundwater system responses that may be due to alluvium recharge via direct infiltration of rainfall on local outcrop areas.

The data collected during this study suggest several fundamental properties of the hydrologic system in the PB-Vista area:

- Alluvial groundwater levels rise above the top of the permeable alluvium materials screened by the PB-Vista monitor wells suggesting primarily artesian hydrogeologic conditions at the site. The data recorded from summer 2020 through February 2021 show that groundwater levels respond rapidly to changes in river levels, which indicates that there is a good hydraulic connection between the river and the alluvium at the site.
- Average groundwater flux is from the alluvium toward the river (gaining stream conditions); however, short-term reversals of the hydraulic gradient between the river and alluvium (losing stream conditions) were observed during and shortly after high river stage events.
- Groundwater levels are typically higher than river levels at PB-Vista, which indicates that recharge to the alluvium must be occurring either through infiltration of precipitation through overlying sediments or by upward migration of groundwater from deeper formations. Quantification of the amount of alluvial groundwater recharge that may occur via these modes requires extensive efforts that are beyond the scope of this study including: documentation of the structure and hydraulic properties of the alluvium and adjoining formations/sediments, as well as the various factors affecting potential evapotranspiration in the Pope Bend area. It is expected that direct recharge to the alluvium by infiltration of precipitation would result in a corresponding increase in groundwater levels, however; any rapid changes will be masked by the clear hydraulic link between groundwater levels and river stage, which is itself affected by precipitation events. The groundwater temperature and electrical conductivity values recorded during

this study do not show an apparent correlation to precipitation events, suggesting that any infiltration of precipitation likely occurs slowly and consistently through time.

- A relatively-large artesian response with comparatively little volumetric baseflow exchange is similar to the findings described by Hibbs (1993) and Sawyer (2009). Like this study, Hibbs obtained a variety of measurements from sensors installed in alluvium monitoring wells at sites along the Colorado River. While these studies recorded data over a relatively short intervals (days) the results suggested rapid, artesian responses with relatively small volumetric exchanges between the alluvium and the river.
- Water temperature and conductivity measurements suggest that only small exchanges in water volume between the river and alluvium occur in the PB-Vista area in response to fluctuations in river stage. Groundwater flow velocities and fluxes calculated from hydraulic gradient measurements and monitor well slug tests also suggest that relatively small increases in alluvial aquifer storage occur following high river flow events. The added groundwater storage rapidly returns to the river as baseflow once river levels drop.

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APPENDIX A

Regional aerial view of Study Site No. 1: Sam Gideon Power Plant Intake Facility, located just north of Bastrop, Texas.

Aerial view of Study Site No. 1: Sam Gideon Power Plant Intake Facility, showing the river gauge and drill locations (left) and an image showing the river gauge (right).

Auger-rig drill truck and support truck on drill location at Study Site No. 1.

Adding an auger section (or flight) to the drill string. The smaller diameter drill rod is used to drive the drill bit at the bottom end of the auger.

The additional auger flight and inner drill rod are connected to the drill rig and are ready to continue drilling operations.

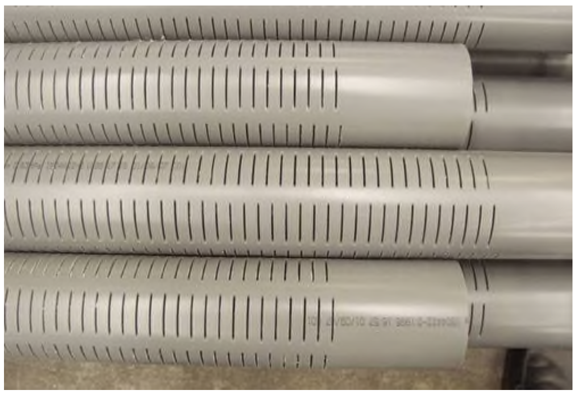
Drilling ahead with the auger rig. The rig had sufficient auger flights to drill to a depth of 55 feet below ground level. Drilling deeper than that required the use of mud rotary drilling methods.

The auger rig is also capable of drilling using mud rotary methods using a small above-ground trough for the drilling fluid.

The drill rod passes through a pipe passing through the bottom of the trough on the right. The pipe is inserted in the borehole and the annulus is sealed using bentonite. This contains the water within the borehole and trough.

The drilling fluid (mud) mobilizes the drill cuttings out of the borehole and deposits the in a chamber in the trough. Samples of the cutting materials are examined to determine the feasibility of installing a well. After drilling 120 feet below ground level, no suitable aquifer material was encountered, and the borehole was plugged in accordance with State and local regulations. After selecting the LCRA Pope Bend Vista Ramp Facility (PB-Vista) to be Study Site No. 2, the same drilling procedures were employed at that location.

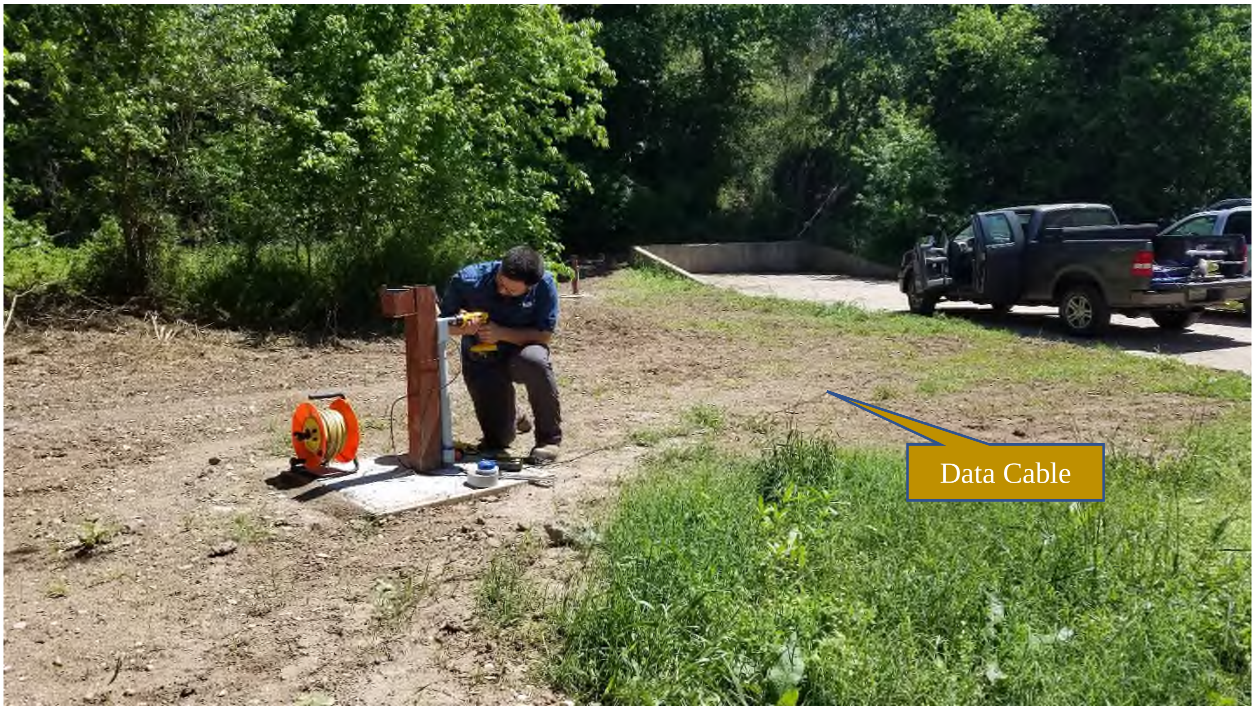
Drilling activities showed that an alluvial aquifer existed beneath Study Site 2. Three monitoring wells were subsequently constructed at the PB-Vista location.



The monitor wells were constructed using 2-inch PVC slotted pipe (shown in the lower picture) within the alluvial aquifer and solid 2-inch PVC pipe from the aquifer to the about 2 feet above ground level at each well location. The above-ground portion of the PVC pipe was protected with a 4-inch square lockable steel enclosure.

Each well then had a surface slab of cement installed and PVC conduit connections (grey pipe ends) for the transducer/telemetry system data cables. Monitor Well 2 is shown in this picture.

Monitor Well 2 after the concrete surface slab had been installed. The conduits for the transducer/telemetry system can be seen in the picture. The PVC conduits were buried below ground level for additional protection to the cables.

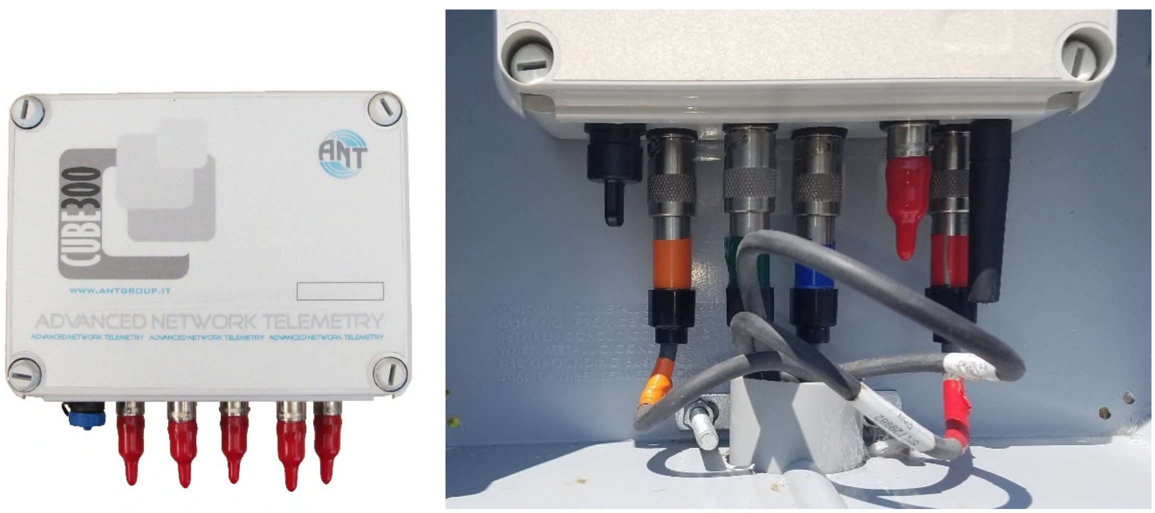


Additional above-ground conduits were installed at each well location to complete the installation of the transducer/telemetry system data cables. Monitor Well 1 is in the foreground and Monitor Well 2 is in the background.

The completed Monitor Well 1 is shown on the left. The opening in the trees behind the well is the location of the river gauge, shown on the right.

Monitor Wells 1 and two are on the lower portion of the PB-Vista site. This picture shows Monitor Well 3 and the telemetry station installed on the upper portion of the site. Pink flagging shows the location of the buried data cable conduit.

The installed telemetry system. The upper box contains the telemetry unit and the lower box houses excess lengths of installed system cables.



The In-Situ Cube 300 Telemetry unit which measure 7.87 inches wide, 7.1 inches high and 3.35 inches deep. This picture on the right shows the individual connections to each transducer. The connections are color-coded: Red – River Gauge; Orange – Monitor Well 1; Blue – Monitor Well 2 and Green – Monitor Well 3.

Each of the cables connects the telemetry system to an In-Situ AquaTROLL 200 transducer. This device measures, records, and reports water pressure (depth of water), temperature and conductivity (an indicator of water quality). More information on the telemetry unit and transduces can be found in Appendix B.

SPECIFICATION SHEETS
FOR INSTALLED EQUIPMENT

Aqua TROLL® CTD Data Loggers

CONDUCTIVITY, TEMPERATURE, PLUS WATER LEVEL LOGGING

MEASURE AND RECORD WATER LEVEL, WATER PRESSURE, CONDUCTIVITY, AND TEMPERATURE WITH THE AQUA TROLL 200, OR ONLY CONDUCTIVITY AND TEMPERATURE WITH THE AQUA TROLL 100. UNIQUE CONDUCTIVITY CELL ALLOWS FOR A WIDE, ACCURATE MEASUREMENT RANGE IN A NARROW DIAMETER INSTRUMENT (SUB-1 INCH).

ACCURATE RESULTS

- **Use dynamic density compensation** to collect accurate water level data in environments where salinity values may vary.
- **Receive 3D factory calibrated instruments** that are validated with NIST®-traceable standards.
- **Deploy for long-term monitoring**. Instruments operate with very low drift.

FLEXIBLE COMMUNICATIONS

- **Streamline data management:** Use the VuSitu Mobile App to consolidate all site information on your smartphone, and tag data with site photos and GPS coordinates. Simply connect the instrument to a Wireless TROLL Com or power pack, launch the mobile app, and start reading results. Simplify instrument setup, reduce log errors and get the most out of your data with Log Setup Assistant and Panoramic Live Data. Log data to your smartphone and download results in a Universal Data File.
- **Integrate into telemetry and SCADA systems and HydroVu™ Data Services** for real-time data and automatic event alerts. Outputs include standard Modbus/RS485, SDI-12, and 4-20 mA.
- **Streamline data collection and analysis.** Simplify instrument setup, automate site management, and generate reports with user-friendly VuSitu Mobile and Win-Situ® PC Software.

RUGGED, COMPACT DESIGN

- **Use in harsh environments** such as coastal, remediation, and mine water monitoring projects. Titanium construction resists fouling and is chemical- and corrosion-resistant.
- **Sub-1 inch design** fits narrow diameter, 1-inch wells.
- **Use RuggedCable® Systems** with titanium twist-lock connectors for quick, reliable connections. Integrate with the Rugged Cable Splitter to attach multiple In-Situ Shared Ecosystem instruments in a single water column with a single connector, allowing you to measure multiple parameters at various depths and simultaneously.

TOTAL FIELD SUPPORT

- **One-stop-shop for purchasing and support.**
- **Total Field Support**
- **24/7/365 technical support is just a phone call away.**
- **Guaranteed 7-day service for maintenance (U.S.A. only).**

Applications:

- **AQUIFER STORAGE AND RECOVERY SYSTEMS**
- **COASTAL DEPLOYMENTS–SALTWATER INTRUSION MONITORING, STORM SURGE ANALYSIS, AND ESTUARY/WETLAND RESEARCH**
- **REMEDIATION SITE AND MINE WATER MONITORING**
- **STORMWATER MONITORING PROGRAMS**

www.in-situ.com

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1-800-446-7488 (toll-free in U.S.A. and Canada)
1-970-498-1500 (U.S.A. and international)

In-Situ
YOUR EYES IN THE FIELD

Aqua TROLL® 100 and 200 Data Loggers

VUSITU MOBILE APP

Use the VuSitu Mobile App to access and manage data on your Android™ smartphone or tablet. Intuitive, free mobile app is an all-in-one software package that provides auto-configuration, simplified calibration, guided log setup, directed data analysis, automated report creation, Panoramic Live Data, Calibration Assistant and Log Setup Assistant. Tag data with site photos and GPS coordinates. View results in the field and email data on the spot. Download through the Google Play Store.

HYDROVU DATA SERVICES

Get decision-quality data anywhere, anytime, with cloud-based HydroVu Data Services. Integrate with In-Situ instruments and telemetry systems for real-time feedback on all your remote water monitoring sites.

[1] Temperature range for non-freezing liquids
[2] Typical battery life when used within the factory-calibrated temperature range, dependent on site conditions
[3] 1 reading = date/time plus all available parameters polled or logged from device
[4] 1 data record = date/time plus 3 parameters logged (no wrapping) from device
[5] External power or battery pack is recommended when using Linear Average or Event logging modes.
[6] Parameters derived from temperature at 25° C and actual conductivity range of 0 to 100,000 µS/cm with a ±0.5% + 1 µS/cm accuracy
[7] Derived from Standard Methods 2510B
[8] Defined by the Practical Salinity Scale 1978; Standard Methods 2520B
[9] Real-time level compensation based on water density
[10] Accuracy with 4-20 mA output option: ±0.25% FS
[11] Includes linearity and hysteresis over 1 year.
[12] Temperature response varies by temperature change and environmental conditions. Under typical field conditions, T95<5 min.

Specifications are subject to change without notice. Delrin is a registered trademark of E.I. du Pont de Nemours and Company. NIST is a registered trademark of the National Institute of Standards and Technology. Android is a trademark of Google Inc.

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1-970-498-1500 (U.S.A. and international)
221 East Lincoln Avenue, Fort Collins, CO 80524 USA

AQUA TROLL 100 AND 200 INSTRUMENTS		
TEMPERATURE RANGES[1]	Operational: -5 to 50° C (23 to 122° F) Storage: -40 to 65° C (-40 to 149° F) Calibrated: 0 to 50° C (32 to 122° F)	
DIMENSIONS & WEIGHT	Diameter (OD): 1.83 cm (0.72 in.) Length: 31.5 cm (12.4 in.) Weight: 188 g (0.41 lb)	
MATERIALS	Titanium body and sensors, Delrin® nose cone, and PVC conductivity cell	
OUTPUT OPTIONS	Modbus/RS485, SDI-12, and 4-20 mA	
BATTERY TYPE & LIFE[2]	3.6V lithium. 5 years or 200,000 readings3	
EXTERNAL POWER	8-36 VDC; Measurement current: 15 mA; Sleep current: 40 µA	
MEMORY Data records[4] Data logs	4.0 MB 190,000 50	
LOG TYPES[5]	Linear, Linear Average, and Event	
FASTEST LOGGING RATE	Linear: 1 per minute. Linear Average: 1 per minute. Event: 1 per second	
FASTEST OUTPUT RATE	1 per second	
ENVIRONMENTAL RATING	IP 68 with cable attached IP 67 without cable attached	
CONDUCTIVITY SENSOR – TYPE: Balanced 4-electrode cell		
METHODS	EPA Method 120.1; Standard Methods 2510	
RANGE, ACCURACY, & RESOLUTION	Range: 0 to 100,000 µS/cm Accuracy: ± 0.5% of reading + 1 µS/cm when reading less than 80,000 µS/cm ± 1.0% of reading when reading above 80,000 µS/cm Resolution: 0.1 µS/cm)	
PARAMETERS SUPPORTED[6] Actual conductivity Specific conductivity[7] Salinity[8] Total dissolved solids Resistivity Density (water salinity)	Range 0 to 100,000 µS/cm 0 to 100,000 µS/cm 0 to 42 PSU 0 to 82 ppt 10 to 200,000 Ohms-cm 0.98 to 1.14 g/cm3	Units µS/cm, mS/cm µS/cm, mS/cm PSU ppt, ppm Ohms-cm g/cm3
PRESSURE/LEVEL/SENSOR[9] – TYPE: Piezoresistive. Pressure/level are available only on the Aqua TROLL 200 Instrument.		
RANGE	Absolute (non-vented) 30 psia: 11 m (35 ft) 100 psia: 60 m (197 ft) 300 psia: 200 m (658 ft)	Gauged (vented) 5 psig: 3.5 m (11.5 ft) 15 psig: 11 m (35 ft) 30 psig: 21 m (69 ft) 100 psig: 70 m (231 ft) 300 psig: 210 m (692 ft)
BURST PRESSURE	Maximum 2x range; burst > 3x range	
MAX PRESSURE FOR AQUA TROLL 100	300 psi (692 ft))	
ACCURACY & RESOLUTION[10]	Accuracy: ±0.05%FS or better; Resolution: ±0.01%FS or better	
LONG-TERM STABILITY[12]	<0.1% FS	
UNITS OF MEASURE	Pressure: psi, kPa, bar, mbar, mmHg, inHg, cmH20, inH20. Level: in, ft, mm, cm, m	
TEMPERATURE SENSOR[13]		
METHOD	EPA Method 170.1	
ACCURACY & RESOLUTION	Accuracy: ±0.1° C. Resolution: 0.01° C or better	
UNITS OF MEASURE	Celsius or Fahrenheit	
WARRANTY	2 years. Up to 5-year (total) extended warranties available.	

Cellular Network Telemetry Systems

Quickly connect to remote monitoring stations by using cellular network technology. Economical, secure telemetry systems reduce data collection costs by providing real-time access to data, event notifications, and system status updates. Superior power supply management ensures long-lasting, independent operation at remote sites.

Real-Time Data

- Easily integrate systems into HydroVu data services for real-time evaluation of site data and conditions.
- Receive automatic data log uploads to your email, FTP site, or other current data management platform at customized intervals.
- Never miss a data point. The system recognizes missed data and sends that data on the next transmission.

Real-Time Decisions

- Integrate with HydroVu for up-to-date access to your data in the format you want, whenever and wherever you are, while simplifying the task of filtering the data for important results.
- Quickly respond to user-defined field events or to tampering. Automatic alarm notifications are sent to your email or phone via text message.
- Significantly reduce site visits. Receive system status updates, diagnose problems, and perform preventative and corrective maintenance from your office.

Tube Systems: For in-well deployments and low-profile installations, choose the battery-powered Tube 300R. For high-frequency sampling, choose the solar-powered Tube 300S.

Cube Systems: For sites that require multiple sensors, choose the battery-powered Cube 300R or the solar-powered Cube 300S. Connect up to five instruments to one Cube.

Both the Tube and Cube Systems offer data logging and transmission, and alarm notifications for parameter thresholds, instrument malfunction, and tampering detection.

Real-Time Support

- Receive free, 24/7 technical support and online resources.
- Order instruments and accessories from the In-Situ website.
- Troubleshoot deployment issues by using an external mode.
- Duplicate logs on the data logger and the telemetry system for confidence in the most remote locations.

Applications

- **Long-term groundwater and surface-water monitoring**
- **Event notification-crest stage gages, flood warning system, storm surge, slope stability**
- **Mine dewatering and acid mine drainage**
- **Stormwater management**
- **Tide gaging**

Cellular Network Telemetry Systems

Spec Sheet

In-Situ

General	Tube 300R	Tube 300S	Cube 300R	Cube 300S
Operating ranges [1]	Temp: -20-70° C (-4-158° F) Humidity: 95% max. n.c.	Temp: -20-70° C (-4-158° F) Humidity: 95% max. n.c.	Temp: -20-70° C (-4-158° F) Humidity: 95% max. n.c.	Temp: -20-70° C (-4-158° F) Humidity: 95% max. n.c.
Diameter, maximum	Tube: 5 cm (1.97 in.) Top cap: 5.2 cm (2.05 in.)	Tube: 7 cm (2.75 in.) Top cap: 7.5 cm (2.95 in.) (with solar panel)	NA	NA
Dimensions	Length: 48 cm (18.9 in.)	Length: 48 cm (18.9 in.)	20 x 18 x 8.5 cm (7.87 x 7.1 x 3.35 in.)	36 x 24 x 13 cm (14.2 x 9.4 x 5.1 in.)
Weight with battery	1730 g (3.81 lbs)	1670 g (3.68 lbs)	1345 g (2.965 lbs)	3100 g (6.83 lbs)
Materials	Stainless steel	Methacrylate, 5 mm thick	GW PLAST 75	GW PLAST 75
Ratings	IP68 (cannot operate submerged)	IP65	IP65	IP65
Power Internal Battery	Battery Lithium 10.8V / 19000 mAh	Solar panels integrated NiCd 7.2V / 1400 mAh	Battery Lithium 10.8V / 19000 mAh	Solar panels integrated NiCd 7.2V / 1400 mAh
Connectors	1 twist-lock connector	1 twist-lock connector	5 twist-lock connectors	5 twist-lock connectors
Operation Time	Up to 5 years when logging every 10 min. and uploading data 1/day	Solar panel power: Unlimited, depending on sunlight exposure and programmed activities	Up to 5 years when logging every 10 min. and uploading data 1/day	Solar panel power: Unlimited, depending on sunlight exposure and programmed activities

Common Specs	
Sensor compatibility	Aqua TROLL® 100/200 Data Loggers; Aqua TROLL 400 Multiparameter Instrument; Aqua TROLL 600 Multiparameter Sonde, BaroTROLL® Data Logger; Level TROLL 400/500/700/700H Data Loggers; Rugged Troll 200; RDO Pro-X
Communication Antenna	GSM quad band—850, 900, 1800, 1900 MHz (capable of GPRS, SMS, email, and FTP); 2G available SMA connector with stud antenna or optional external antenna for Tube 300R
Data access/storage Data access Data storage Data format	Via email or FTP; via cable; and real-time via GSM/GPRS direct call or HydroVu data services SD Flash memory, 512 MB (not replaceable) CSV file
Programming Programming mode Operation mode	Through ANT tool communication software, via cable, or remotely via landline or GSM modem Through communication software tool via direct connection to a PC or remotely though GSM modem or landline modem. 1. Up to 8 programmable events/day; data transmission; or SMS transmission 2. Automatic data logging (reading interval: 1 minute to 24 hours) 3. Alarm transmission (SMS) 4. Data logging and batch transmission of stored data. Connect up to 5 probes and log all available (includes data from internal barometric pressure sensor).
Interfaces Serial Interfaces	RS232 or RS485 software selectable (with automatic RS232 switching when a PC connection is detected)
Alarm capability Capacity Sources SMS limits	The unit can generate an alarm if tilted or disconnected; if exceeds critical temperature values or parameters threshold values; or if battery levels reach critical. Via SMS. 2 recipients Up to 8 alarm sources Can be programmed
Real-time clock/calendar	Built-in
Sensors	Built-in barometric pressure sensor included with non-vented systems, which automates barometric pressure compensation for non-vented water level sensors. Built-in temperature sensor
Warranty	**1 year**
Notes	* Refer to Alarms section in manual. Alarm sources: reset, temperature, tilt sensor, data send failure, low battery, probe reading out of range, tamper, log memory full or error, and probe reading error Specifications subject to change without notice

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APPENDIX C – REVIEW COMMENTS AND RESPONSES

The following are comments provided by the Texas Water Development Board following their review of the draft-final report documenting TWDB Contract No. 1900012305 (Surface Water-Groundwater Interaction Pilot Study). The author's responses are provided in italics immediately following each comment.

1) Title Page. Please remove Texas Water Development Board (TWDB) logo and please replace with, "Texas Water Development Board". The logo may not be used without agency approval in writing.

    TWDB logo removed and replaced with text on title page.

2) Title Page. Please refer to "TWDB Contract No. 1900012305" rather than "TWDB Order No. 109025, Contract No. 3916."

    Change made.

3) Title Page. Please insert the following paragraph on the lower half of the title page to acknowledge the nature of the project: "A PORTION OF THE FUNDING FOR THIS STUDY WAS PROVIDED PURSUANT TO SENATE BILL 1 AS APPROVED BY THE 85TH TEXAS LEGISLATURE 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."

    Text inserted.

4) Page ii, Geoscientist Seals: Please date and provide all signed seals for all professional geoscientists that are responsible for components of the report and study as required and appropriate.

    Appropriate seals and dates inserted.

5) Page 1, Executive Summary: Please preface the Executive Summary with the following paragraph to acknowledge the sources of funding and the relationship to the Environmental Flows process: "Senate Bill 3 (SB 3) of the 80th Texas legislative session (2007) established a framework for identifying and promulgating environmental flow standards throughout Texas. As a result, the Texas Commission on Environmental Quality adopted environmental flow standards for the Colorado River and its associated tributaries effective August 8, 2012, based on recommendations from regional stakeholders and scientific experts. Under SB 3's provision for adaptive management, which calls for continued studies to validate and refine environmental flow analyses, recommendations, and standards, this project was initiated and partially funded during the 85th Texas legislature to assist the Texas Water Development

Board (TWDB) and the Colorado and Lavaca Rivers and Matagorda Bay Basin and Bay Area Stakeholder Committee (BBASC) with understanding surface water-groundwater interactions along the Colorado River in Bastrop County in support of the SB3 e-flows process. Additional funds for this project were provided by the Lower Colorado River Authority, Brazos River Authority, and Post Oak Savannah Groundwater Conservation District."

Acknowledgement inserted.

6) Page 4, Introduction: Please preface the Introduction with the following paragraph to acknowledge the sources of funding and the relationship to the Environmental Flows process: "Senate Bill 3 (SB 3) of the 80th Texas legislative session (2007) established a framework for identifying and promulgating environmental flow standards throughout Texas. As a result, the Texas Commission on Environmental Quality adopted environmental flow standards for the Colorado River and its associated tributaries effective August 8, 2012, based on recommendations from regional stakeholders and scientific experts. Under SB 3's provision for adaptive management, which calls for continued studies to validate and refine environmental flow analyses, recommendations, and standards, this project was initiated and partially funded during the 85th Texas legislature to assist the Texas Water Development Board (TWDB) and the Colorado and Lavaca Rivers and Matagorda Bay Basin and Bay Area Stakeholder Committee (BBASC) with understanding surface water-groundwater interactions along the Colorado River in Bastrop County in support of the SB3 e-flows process. Additional funds for this project were provided by the Lower Colorado River Authority, Brazos River Authority, and Post Oak Savannah Groundwater Conservation District."

Acknowledgement inserted.

7) Page 10, Test Hole Drilling: Please discuss the reasoning for drilling to a depth of 80 feet below ground level for wells completed in the Hooper Formation when the majority of wells drilled in the past six years are around 140 to 160 feet below ground level.

Explanation inserted into text: While there may be permeable Hooper materials below 80 feet at the site, drilling was terminated because the 48-foot interval of relatively-impermeable sediments overlying the alluvium precludes significant hydraulic interaction between the Hooper and the alluvium.

Suggestions for the conceptual model report:

8) Throughout the report, please consistently reference the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. For example, the word Central is inconsistently capitalized. The Queen City and Sparta aquifers are sometimes used when referring to the model.

Capitalization of "central" changed for consistency.

9) Page 7, Study Site Selection: The authors recommend the use of "fatal flaw" evaluations of each potential site before continuing more in-depth assessments. Suggest that the report may

benefit from an example of what a "fatal flaw" might look like using one or more of the study sites described in the report.

Brief explanation of site-selection factors that may represent "fatal flaws" for a particular site added to text.

10) Page 9, Study Site Selection: Reviewers recognize the expediency of documenting what worked, rather than what didn't work, in final study reports. However, for this project it may be informative to more thoroughly document additional study sites that were considered after the abandonment of the Lost Pines Power Park site and before the selection of the Pope Bend Vista Ramp site. Suggest considering a more comprehensive documentation of all sites that were investigated but not selected for this project.

The authors acknowledge the suggestion that a detailed assessment of each potential test site may be helpful. However, because the excluded test sites are associated with private interests, it is inappropriate to include details regarding the reasons for the rejection in a publicly-available document.

11) Page 10, Test Hole Drilling, Sentence 2: Please remove "feet bgl" after "18" as the acronym is defined after "32" in the sentence.

Text removed.

12) Page 25, Previous Study Findings, 1st paragraph: The authors note that the baseflow rates calculated from the PB-Vista site are small in comparison to values generated from previous studies. They attribute this to the comparatively small alluvium hydraulic conductivity values calculated from the results of PB-Vista aquifer slug tests. Recommend further elaboration on how estimates of hydraulic conductivity from slug test results differ from those estimated from pump tests and why pump tests were not conducted as part of this study.

Text inserted into "Determination of Hydraulic Properties" section (page 16): Slug tests are widely used but, because the imposed hydrologic stress is relatively small and short-lived, the area characterized by a slug test is limited to the area near the well bore. Alternatively, data obtained from pump testing of larger-diameter wells can typically be used to define the aquifer conditions over larger areas. However, pump testing requires larger diameter wells to accommodate the installation of pumping/monitoring equipment, which increases costs significantly. In order to meet budgetary constraints, construction and testing of larger-diameter monitoring wells was not selected for this project.

13) Page 25, Previous Study Findings: The report provides a brief overview of previous study findings that includes Hibbs (1993), Sawyer *et al*. (2009), and Francis, *et al*. (2009). Recommend that they also consider comparing results to and providing overviews of estimates of groundwater discharges to the river resulting from gain-loss and other studies completed by the USGS in 1918 (results in TBWE 1960) and Saunders in 2005, 2008, and 2011 (results in Saunders 2006, Saunders 2009, and Saunders 2012, respectively).

Saunders, G.P., 2006, Low flow gain-loss study of the Colorado River in Texas: in Mace, R.E., Davidson, S.C., Angle, E.S., and Mullican, W.F., III, eds., Aquifers of the Gulf Coast of Texas, TWDB Report 365, p. 293-297.

Saunders, G.P., 2009, Low flow gain-loss study of the Colorado River in Bastrop County, Texas: in Hutchison, W.R., Davidson, S.C., Brown, B.J., and Mace, R.E., eds., Aquifers of the Upper Coastal Plains of Texas, TWDB Report 374, p. 161-165.

Saunders, G.P., 2012, Gain-loss studies in the Colorado River Basin of Texas: Drought of 2011- 2012 Update: Gulf Coast Association of Geological Societies Transaction, v. 62, p. 423-431.

TBWE (Texas Board of Water Engineers), 1960, Channel gain and loss investigations, Texas streams, 1918–1958: Texas Board of Water Engineers Bulletin 5807-D, 270 p.

The studies performed by Saunders represent evaluations of gains/losses to rivers and streams over large areas. The scope of this study is limited to evaluating the interaction between the Colorado River and adjoining alluvium at a single location. While this study discusses the potential contribution of alluvial groundwater to the Colorado River in the Pope Bend area, it does not discuss the various other factors affecting gains/losses in the area. Consequently, comparison of Saunders' findings to this study's findings is not appropriate.