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# LOWER COLORADO RIVER FLOOD PROTECTION PLANNING STUDY FINAL REPORT

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PO 00163

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## ACRONYMS

1D – One Dimensional
2D – Two Dimensional
AHPS – Advanced Hydrologic Prediction Service
DEM – Digital Elevation Model
EOC – Emergency Operation Center
FDST – Flood Decision Support Toolbox
FEMA – Federal Emergency Management Agency
FEWS – Flood Early Warning System
FPP – Flood Protection Planning
GIS – Geographic Information System
GIWW – Gulf Intracoastal Water Way
HGAC – Houston-Galveston Area Council
HWM – High-Water Mark
InFRM – Interagency Flood Risk Management
LCRA – Lower Colorado River Authority
LiDAR – Light Detection and Ranging
LAS – Log Ascii Standard
MCCRD – Matagorda County Conservation and Reclamation District
NAVD 88 – North American Vertical Datum 88
NLCD – National Land Cover Dataset
NOAA – National Oceanic and Atmospheric Admistration
NRCS – Natural Resource Conservation Service
NWS – National Weather Service
PMR – Physical Map Revision
QC – Quality Control
RMSE – Root Mean Square Error
Tc – Time of Concentration
TCEQ – Texas Commission of Environmental Quality
Tlag – Lag Time
TNRIS – Texas Natural Resource Information System
TR-55 – NRCS Technical Release 55
TWDB – Texas Water Development Board
TXDEM – Texas Department of Emergency Management
TxDOT – Texas Department of Transportation
UH – Unit Hydrograph
USGS – United States Geological Survey
USACE – U.S. Army Corps of Engineers

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## EXECUTIVE SUMMARY

During the Hurricane Harvey flood event, communities along the Lower Colorado River observed that the flooding along the river did not occur as estimated by National Weather Service (NWS) Advance Hydrologic Prediction Service (AHPS) website. This website provides real-time and forecast estimates at specific United States Geological Survey (USGS) gauges along the river and inundation limit estimates based on gauge heights. The inundation limits used by this NWS website are limited to one mile upstream and downstream of the gauge location. Flood stages were higher than the gauge rating curve at the Columbus gauge, therefore the maximum flood inundation could not be determined. Inundation limits were under-estimated in Wharton and over-estimated in Bay City. After Harvey, Wharton County along with Colorado County, Matagorda County, City of Columbus, City of Wharton, and City of Bay City partnered with the Texas Water Development Board (TWDB) through the Flood Protection Planning (FPP) program to develop updated hydraulic modeling and more accurate inundation mapping needed to improve on the existing NWS Advance Hydrologic Prediction Service website. This coalition of communities also began early discussions with the NWS on their Flood Decision Support Toolbox (FDST) website and developed a plan to incorporate new, more accurate inundation mapping with the recent release of this new website. A secondary goal of this project was the expansion of the real-time flood mapping capabilities of the FDST for the entire length of the Lower Colorado River studied (being from the Colorado/Fayette County line down to West Matagorda Bay). The expansion of this tool would require identification of new gauge locations and a long-term management plan for the new gauges.

The updated 1D/2D hydraulic model was derived from the original 2001 Flood Damage Evaluation Project (FDEP) hydraulic model by truncating one-dimensional (1D) cross-sections, adding two-dimensional (2D) meshes, and updating both with the most recent LiDAR elevation data. The LiDAR data was enhanced with bathymetric data collected as part of the study with multi-beam and single-beam sonar equipment. Adding bathymetric data along the channel enhanced the accuracy of the model. New hydrologic modeling was not included in the scope of this FPP study; therefore, hydrologic inputs were taken from the 2001 FDEP study hydrologic model with some minor updates to routing and loss methods. Calibration of the hydraulic model mainly focused on the Harvey event due to the collection of many Harvey high-water marks by both the USGS and Scheibe Consulting. Other events used for calibration purposes include the April 2016, November 2004, and October 1998 flood events. The new hydraulic model was used to develop inundation map libraries at 6-inch intervals for the lower 150 miles of the river. This model was also used to determine proposed locations for four new gauges along the Lower Colorado River as part of an effort to develop a continuous coverage of gauge data and real-time inundation mapping for use by the local communities. Zones were developed for each USGS, Lower Colorado River Authority (LCRA) and newly proposed gauge location for use in creation of a seamless set of flood inundation map libraries to be utilized as part of the new Flood Decision Support Toolbox (FDST) developed by the Interagency Flood Risk Management (INFRM) team of federal agencies including Federal Emergnency Management Agenct (FEMA), NWS, USGS, and U.S. Army Corps of Engineers (USACE). Inundation map libraries consisted of depth grids based on 6-inch intervals at each USGS and LCRA gauge location. It is recommended that map libraries for new gauge locations be completed when the new gauge locations are finalized, and new gauges are being installed.

Additional study is recommended for the most downstream portion of the river from the Wadsworth gauge to the mouth due to complexities associated with the interaction of both riverine and storm surge related flooding. Once an acceptable solution to represent the combined riverine and storm surge impacts is determined by USACE, Galveston District, flood inundation map libraries should also be completed for this downstream area. Finally, if desired, effort should be made to request that the LCRA and proposed new gauges be added as NWS flood forecast points. This project included the collaboration of all six local funding participants, Texas Water Development Board (TWDB), LCRA, USACE (Galveston and Fort Worth Districts), USGS, NWS, Houston-Galveston Area Council (HGAC), Matagorda County Conservation and Reclamation District (MCCRD), and the Port of Bay City. This project would not have been possible without the support and out-of-the-box thinking of all of these agencies

## 1.0 BACKGROUND

Hurricane Harvey slammed into the Texas Coast in late August of 2017 in the Rockport/Port Aransas area and then very slowly progressed northeasterly towards Houston, and ultimately to the lower Louisiana Coast. As Harvey progressed northeasterly, it left a wake of devastation through communities along its path including heavy sustained damage in Colorado, Wharton, and Matagorda Counties. These communities had large portions of major urban centers completely under water for days. The National Weather Service (NWS), US Army Corps of Engineers (USACE), Lower Colorado River Authority (LCRA), Federal Emergency Management Agency (FEMA), and Texas Department of Emergency Management (TxDEM) all collaborated to advise local Emergency Operations Coordinators (EOCs) to make decisions needed to help evacuate residences and businesses and help find shelter and access routes into and out of the various urbanized areas along the Lower Colorado River. The official (and some unofficial) flood projections under-predicted or over-predicted the effects of this large storm throughout this three County region, resulting in evacuating entire cities that did not flood (including Bay City), and not evacuating enough people in areas where very high velocity flooding occurred resulting in devastation and complete loss of residential structures (including portions of upper Peach Creek north of the City of Wharton).

The official flood projections developed by the NWS and its collaborating partners were based (all or in-part) on a FEMA current effective hydraulic (unsteady 1D) model of the Lower Colorado River, developed (circa 2001) by the LCRA and US Army Corps of Engineers. This historic model was developed and mapped using a digital surface based on LCRA (4-ft Contour) ortho-photogrammetry of the Colorado River. Furthermore, this hydraulic model had cross-sections that span 2-miles wide (in some areas) in an attempt to simulate flood inundation in wide flat overbank areas with a single water surface elevation. Post Harvey high-water marks collected by Scheibe Consulting, LLC proved that, in these wide flat areas, a constant water surface elevation is not reasonable, and actual overbank peak flood levels during Harvey varied as much as 2 feet vertically from that of peak water levels at the riverbanks along the Colorado River. Comparisons of the historic Colorado River model inundation projections and Harvey flood event aerial imagery (of the peak) along the river revealed that the current model does not replicate actual flood risks to the level of accuracy that the local communities need to make proper real-time emergency decisions in response to flooding.

In addition to the modeling enhancement needs, it was identified that some of the existing gauges along the Colorado River are completely by-passed by extreme flood waters (such as the gauge in Columbus), and thus the gauge readings may lack accurate estimates of flood volume going downstream, which is needed for reasonable real-time flood projections in Wharton and Matagorda Counties. Lastly, it was identified by local Emergency Operation Centers (EOCs) and community leaders that the available NWS real-time and flood projection inundation mapping was limited to about 1 mile upstream and downstream of the available USGS river gauges. During Harvey, vast flood damage occurred well outside these limits giving the local EOCs very limited real-time and future projection information needed to make proper decisions.

## 2.0 INTRODUCTION

The study area for the Lower Colorado River Flood Protection Planning (FPP) Study focuses on the Colorado River main channel from the Fayette/Colorado County line to the mouth of the river at the Gulf of Mexico (see **Figure 1**). Within the study area, three major tributaries enter the

Colorado River: Cummins Creek, Jones Creek and Blue Creek. The general terrain throughout the study area consists of flat coastal plain, which is ideal for farming as well as mining of gravel from the Colorado River alluvium. Within the project area, the river meanders with zones of erosion and deposition, which illustrate the everchanging nature of the river. This everchanging nature was very evident post-Harvey Flood, which caused significant morphological changes to the river channel resulting from increased erosion and lateral channel movement. The Cities of Columbus, Wharton, and Bay City lie along the Colorado River in Colorado, Wharton, and Matagorda Counties, respectively, and are greatly impacted by floodwaters from the Colorado River. Flooding from the Colorado River is expected by these communities and significant flood events have occurred several times over the last 25 years including floods in October 1998, November 2004, April 2016, and of course Hurricane Harvey (August 2017). During the Harvey flood event between 20 and 25 inches of rain fell within much the study area causing historic flood crests at the Columbus (48.13 ft.), Wharton (50.47 ft.), and Bay City (46.16 ft.) USGS gauges. Each of the three cities along the Colorado River discovered unique issues with real-time and predictive capabilities of the NWS Flood Forecast information. At Columbus, the peak flood stage was above the maximum flood stage for the flood forecast point, thus the Harvey flood extents could not be accurately depicted within the NWS tool. At Wharton, the flood forecast underpredicted the extents of flooding within the city, likely because the inundation tool did not consider overflows from the Colorado River that occurred further upstream and flooded the “backside” of Wharton along Peach Creek and Baughman Slough. Many residents where not evacuated in time due to this underprediction. Finally, at Bay City, the forcast flood depths provide by varying sources matched with NWS inundation maps resulted in an over-prediction of flooding extents resulting in evacuation of areas that did not flood. This may have been because the forecast tool did not consider the impacts of the Colorado River levees and other terrain features to prevent flooding within the city.

As a result of the issues described and the need for an updated hydraulic model of the Lower Colorado River, Wharton County applied to the Texas Water Development Board (TWDB) for an FPP grant. Other local stakeholders funding the project include Colorado County, Matagorda County, City of Columbus, City of Wharton, City of Bay City, and the Matagorda County Conservation and Reclamation District (MCCRD). The goals of the study are as follows:

- Create a 1D/2D dynamic hydraulic model for the Lower Colorado River from the Colorado/Fayette County line to the mouth of the river in Matagorda County and have this model reviewed by the USACE.
- Analyze the existing system of United Stated Geological Survey (USGS) and Lower Colorado River Authority (LCRA) gauges along the Lower Colorado River to determine where additional gauges should be located.
- Produce Map Inundation Libraries for all USGS and LCRA gauges for inclusion in the Flood Decision Support Toolbox (FDST) tool developed by the InFRM team and submit it to the USGS. The InFRM team is a collaborative effort between USACE, FEMA, USGS, and NWS to produce enhanced flood management data and tools.

To accomplish these goals, Wharton County contracted with Scheibe Consulting, LLC to complete the FPP study. Input on the study process and results was obtained through a series of stakeholder meetings as well as three public meetings. The first public meeting was held in March 2021 followed by a second public meeting in October 2021 and a final public meeting in January

2022 (in conjunction with Wharton County Commissioner's Court). Notices for these public meetings were published in local newspapers in Columbus, Wharton, and Bay City. Public meeting notices for each meeting are provided below in **Figure 2**. The following report details the analysis and results of the Lower Colorado Flood Protection Planning Study.

NOTICE TO PUBLIC

Wharton County, Matagorda County, Colorado County, City of Columbus, City of Wharton, and City of Bay City Announce a Virtual Public Meeting for the Lower Colorado River Flood Protection Planning Project

The Public Meeting will commence from 3:00 PM to 4:00 PM on Monday, March 8, 2021 via Zoom. The purpose of this meeting will be to update the various communities on the overall status of this project including the purpose, geographic area, schedule, and preliminary results. The public is invited to attend and provide feedback needed to enhance the overall quality of this project. Please register in advance for the virtual public meeting using the following link.

https://zoom.us/webinar/register/WN_DTRR1ZkAS_KE4APasyVlGQ

Connection information will be sent after registration is complete. For more information, please contact Eric Scheibe, PE (Scheibe Consulting, LLC) at (512) 263-0418 or escheibe@scheibeconsulting.com.

NOTICE TO PUBLIC

Wharton County, Matagorda County, Colorado County, City of Columbus, City of Wharton, and City of Bay City Announce a Virtual Public Meeting for the Lower Colorado River Flood Protection Planning Project

The Public Meeting will commence in person from 3:00 PM to 4:00 PM on Thursday, October 21, 2021, at the Wharton County Annex courtroom. The purpose of this meeting will be to update the various communities on the overall status of this project including the purpose, geographic area, schedule, and preliminary results. The public is invited to attend and provide feedback needed to enhance the overall quality of this project.

For more information, please contact Eric Scheibe, PE (Scheibe Consulting, LLC) at (512) 263-0418 or escheibe@scheibeconsulting.com.

Commissioners Court January 10, 2022
NOTICE OF A MEETING OF THE
COMMISSIONERS COURT OF WHARTON COUNTY, TEXAS

This Notice is posted pursuant to the Texas Open Meetings Act (VERNON'S TEXAS CODES ANN. GOV. CODE CH. 551). The Wharton County Commissioners Court will hold a meeting at 9:30 A.M. on the 10th day of January, 2022 in the Wharton County Commissioners Courtroom, Wharton County Courthouse Annex Building, 309 E. Milam Wharton, Texas. An Open Meeting will be held concerning the following subjects:

CALL TO ORDER
PLEDGE OF ALLEGIANCE - Pledge of Allegiance to the American Flag and Pledge of Allegiance to the Texas Flag
INVOCATION

PUBLIC COMMENTS
At this time comments will be taken from the audience on non-Agenda related topics. To address the Court, please submit a Public Participation/Witness Form to the County Clerk. Please Complete the Public Participation/Witness Form in its Entirety.
NO ACTION MAY BE TAKEN BY THE COURT DURING PUBLIC COMMENTS

PRESENTATIONS & PROCLAMATION

SAID COURT WILL AT SAID HOUR AND ON SAID DATE DISCUSS, CONSIDER AND ACT UPON THE FOLLOWING:

1. Provide update and take all appropriate action for County offices to respond to COVID-19 related situations. (County Judge)
2. Take all appropriate action regarding Wharton County's Local Policy related to employee leave for Coronavirus related issues. (County Judge)
3. Take all appropriate action to approve Employee Return to Work Form after testing positive for COVID-19. (County Judge)
4. Take all appropriate action to approve Resolution #22-02 - Adopt 2021 Wharton County Hazard Mitigation Plan. (County Judge)
5. Take all appropriate action regarding vinyl plank flooring installed in Crisis Center Building located at 116 E. Burleson. (County Judge)
6. Take all appropriate action to approve service agreement with Rise Broadband to provide fiber optic internet service to the Justice of the Peace Precinct 2 and Commissioner Precinct 2 offices. (County Judge)
7. Take all appropriate action to approve Statement of Work with GAIN Innovation, Inc., for emergency upgrade of Palo Alto firewalls at the Courthouse Annex, El Campo Annex, PCT 2 Commissioners office and Justice of Peace PCT 3 offices. (County Judge)
8. Take all appropriate action regarding positions in Wharton County Library. (County Judge)
9. Take all appropriate action to approve Interlocal Agreement between the Regional Public Defender Office for Capital Cases and Wharton County for the period October 1, 2021 through September 30, 2023. (County Judge)

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G.A. (Trey) Maffett
Wharton County Attorney

10. PUBLIC HEARING: Final presentation of results from the Lower Colorado Flood Protection Planning Study to be followed by public comments. (County Judge)

**CONSENT AGENDA ITEMS 11 – 17 (Unless removed from consent agenda, items identified within the consent agenda will be acted on at one time)**

11. Take all appropriate action to appoint Russell McDougall as a reserve deputy for the Wharton County Sheriff's Office effective March 1, 2022. (County Judge)
12. Take all appropriate action to approve Resolution #22-01 – Exempt License Plates. (County Judge)
13. Submit Local Government Code 113.901, Policy Compliance – approval of County Judge is waived, all claims must be approved in commissioners court. (County Judge)
14. Take all appropriate action to approve budget adjustments and amendments as presented and amended. (County Judge)
15. Take all appropriate action to ratify January 7, 2022 payroll, applicable benefits and time sensitive invoices. (County Judge)
16. Take all appropriate action to authorize County Treasurer and County Auditor to pay and release time sensitive invoices as presented and amended, cash payments to jurors and payroll and applicable benefits for January 21, 2022 to ratified by commissioners court January 24, 2022. (County Judge)
17. Accept Monthly Reports – Commissioners PCT 1-4-December; District Clerk-December; Theft-by-Check-August & September; Extension Office-C. Bowen-September, October & November; Veteran Services-December; Constable PCT 1 & 3-December; Permits/Inspections-December;

18. Permits
19. Pay claims.
20. Take all appropriate action regarding Southern Rock Energy Partners Tax Abatement Application. (County Judge)
21. Pursuant to Government Code Section 551.087 – Deliberation Regarding Economic Development Negotiations – the Commissioners Court will meet in executive session to discuss or deliberate regarding the commercial or financial information that the governmental body has received from a business prospect that the governmental body seeks to have locate, stay, or expand in or near the territory of the governmental body and with which the governmental body is conducting economic development negotiations.

    Tax Abatement with Southern Rock Energy Partners
22. Reconvene from executive session and consider taking action on the following matters:

    Take all appropriate action regarding Tax Abatement Agreement with Southern Rock Energy Partners.

ADJOURN

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G.A. (Trey) Maffett
Wharton County Attorney

**Figure 2: Public Meeting Notices**

## 3.0 TERRAIN DEVELOPMENT

Hydraulic models and floodplain delineations were developed using the most recent Light Detection and Ranging (LiDAR) elevation dataset. The primary sources of terrain data used were developed from the 2017 StratMap (Colorado County) and 2018 USGS (Wharton County), and 2018 StratMap/2019 USGS (Matagorda County). A map of the LiDAR datasets used in terrain development are shown in **Figure 3**. StratMap and USGS LiDAR datasets are available for download on the Texas Natural Resources Information System (TNRIS) website. These LiDAR datasets have an average point spacing of 70 cm and vertical accuracy meeting the FEMA standard 18.5 RMSE (root mean square error) criteria. The LiDAR data was received from TNRIS as log ascii standard (LAS) files, the standard open format for storing LiDAR point records.

The LAS data was processed by Scheibe Consulting to create a seamless topographic dataset for the study area. Where the datasets overlap, the newer LiDAR data took precedence over the older data. LAS files were processed to create Digital Elevation Models (DEMs) with a 3 ft. X 3ft. cell size for the entire study area. The DEMs were further enhanced in the Columbus area by incorporating an existing surface from survey data created for ongoing US 90 and I-10 TxDOT design projects.

LiDAR data consists of elevation data recorded when an emitted light beam bounces off an object and returns to a sensor usually mounted on an airplane. Because of this, LiDAR signals do not penetrate beneath the surface of water bodies resulting in a lack of accurate elevation data below water level in ponds, lakes, and streams. To add additional accuracy to the 1D/2D hydraulic models, bathymetric data was obtained from the U.S. Army Corps of Engineers (USACE) Galveston District or captured for the Colorado River channel using boat-mounted multi-beam or single-beam sonar. The USACE bathymetric data was used for the Gulf Intercoastal Water Way (GIWW) and old river channel. Multi-beam sonar data was collected for the Colorado River main channel from the mouth of the river to the Colorado/Fayette County line (see **Figure 3**). A technical memo containing further details of the multi-beam bathymetric survey for the Colorado main channel is included in **Appendix A**. During the collection process, limitations were encountered related to depth of water in the river as well as debris obstructing the boat path leaving some gaps in the multi-beam bathymetric data. Therefore, additional cross-section survey within the gap areas was collected using single-beam sonar equipment to create a continuous representation of the channel bathymetry within the hydraulic model. The best multi-beam coverage was within Matagorda County where the channel is deepest. An example of a surface created by merging the multi-beam bathymetric data with LiDAR data is shown in **Figure 4**. Advantages of enhancing LiDAR data with bathymetric data were investigated during the course of this study and were shown to reduce the 100-yr floodplain by approximately 7.6% and 100-yr water surface elevations by up to 4.3 ft. A memo containing further details of the comparison of model results with and without bathymetry was submitted to TWDB in December 2020 and is also included in **Appendix A**.

## 4.0 HYDROLOGY

Hydrologic data utilized for the Lower Colorado FPP Study was derived from the 2001 Flood Damage Evaluation Project (FDEP Study) completed by the Lower Colorado River Authority (LCRA) and USACE Fort Worth District in 2001. The hydrologic modeling from the FDEP study is also considered the FEMA effective hydrologic model for the Lower Colorado River. It was not within the scope of this FPP study to upgrade the FDEP model with Atlas 14 rainfall data or reevaluate the overall layout and assumptions used to develop this original hydrologic model. The USACE Fort Worth district is conducting an independent and concurrent update of the FDEP hydrology model with Atlas 14 rainfall data, which was not complete at the time of this FPP study but may be worth incorporating into an update for this study in the future. For modeling of frequency events (10-yr, 100-yr, and 500-yr), frequency rainfall data from the 2001 FDEP study was utilized as-is. For further explanation of the development of the frequency rainfall data please refer to the final report for the 2001 FDEP Study. Historic flood event rainfall data for the Harvey, April 2016, and November 2004 flood events was obtained from the National Weather Service (NWS) as gridded rainfall (XMRG format) and processed using HEC-METVue software to produce basin averaged hyetographs. Rather than rerunning with NWS data, rainfall data already included in the 2001 FDEP model was utilized for the October 1998 event.

The original FDEP model was upgraded to HEC-HMS version 4.3, but sub-basin delineations and Snyder's unit hydrograph parameters were not updated from values in the original FDEP hydrology model. To produce a better calibrated comparison to observed hydrographs for the various flood events, the initial and constant loss parameters and routing methodology were updated for the model sections that are coincident with the FPP study area (i.e., La Grange to Columbus, Columbus to Garwood, Garwood to Wharton, Wharton to Bay City, and Bay City to the mouth sections). Initial estimates of Lag and K values were based on travel time through the reach as calculated from reach length and average flood wave celerity through the reach. The Lag and K values were further optimized through several iterative runs focused on the Columbus section of the hydrology model and then applied with similar calculation methodology to the routing reaches of the remaining model sections. Initial and constant losses were increased uniformly by 50% to better calibrate to the volume represented by observed gauge data for the various flood events and applied to all sub-basins within the study area. Adjusted initial and constant losses and Lag and K routing data are provided in **Tables 1 and 2**, respectively.

**Table 1: Initial and Constant Losses**

| Model Section | Sub-basin ID | FDEP Parameters | | | Updated Parameters | | |
|---|---|---|---|---|---|---|---|
| | | Initial Loss (in.) | Constant Rate (in/hr) | % Imp. | Initial Loss (in.) | Constant Rate (in/hr) | % Imp. |
| La Grange to Columbus | CC-29 | 0.59 | 0.10 | 9.08 | 0.89 | 0.15 | 9.08 |
| | CC-31 | 0.61 | 0.11 | 1.15 | 0.92 | 0.17 | 1.15 |
| | CC-32 | 0.69 | 0.12 | 5.63 | 1.04 | 0.18 | 5.63 |
| | CC-33 | 0.78 | 0.14 | 2.49 | 1.17 | 0.21 | 2.49 |
| | CC-34 | 0.72 | 0.13 | 2.20 | 1.08 | 0.20 | 2.20 |
| | CC-38 | 0.79 | 0.14 | 1.12 | 1.19 | 0.21 | 1.12 |

| Model Section | Sub-basin ID | FDEP Parameters | | | Updated Parameters | | |
|---|---|---|---|---|---|---|---|
| | | Initial Loss (in.) | Constant Rate (in/hr) | % Imp. | Initial Loss (in.) | Constant Rate (in/hr) | % Imp. |
| Col. to Garwood | LC-01 | 0.75 | 0.2 | 6.99 | 1.13 | 0.3 | 6.99 |
| | LC-02 | 0.83 | 0.21 | 3.75 | 1.25 | 0.32 | 3.75 |
| Garwood to Wharton | LC-03 | 0.46 | 0.08 | 13.38 | 0.69 | 0.12 | 13.38 |
| | LC-04 | 0.49 | 0.08 | 8.35 | 0.74 | 0.12 | 8.35 |
| | LC-05 | 0.50 | 0.09 | 7.73 | 0.75 | 0.14 | 7.73 |
| Wharton to Bay City | LC-06 | 0.46 | 0.08 | 13.38 | 0.71 | 0.12 | 10.44 |
| | LC-07 | 0.49 | 0.08 | 8.35 | 0.75 | 0.14 | 5.43 |
| | LC-08 | 0.50 | 0.09 | 7.73 | 0.77 | 0.14 | 4.4 |
| | LC-09 | 0.46 | 0.08 | 13.38 | 0.74 | 0.14 | 3.38 |
| | LC-10 | 0.49 | 0.08 | 8.35 | 0.71 | 0.12 | 11.78 |
| | LC-11 | 0.50 | 0.09 | 7.73 | 0.78 | 0.14 | 7.36 |
| | LC-12 | 0.46 | 0.08 | 13.38 | 0.74 | 0.12 | 4.59 |
| | LC-13 | 0.49 | 0.08 | 8.35 | 0.72 | 0.12 | 10.21 |
| | LC-14 | 0.50 | 0.09 | 7.73 | 0.77 | 0.14 | 7.63 |
| Bay City to Mouth | L-15 | 0.022 | 0.004 | 2.72 | 0.033 | 0.006 | 2.72 |
| | L-16 | 0.022 | 0.004 | 7.07 | 0.033 | 0.006 | 7.07 |
| | L-17 | 0.017 | 0.003 | 33.89 | 0.017 | 0.003 | 33.89 |
| | L-18 | 0.018 | 0.003 | 60.91 | 0.027 | 0.005 | 60.91 |

**Table 2: Lag and K Routing**

| Model Section | Reach ID | Constant Lag (hr.) | Constant K (hr.) |
|---|---|---|---|
| La Grange to Columbus | R1670 | 3.58 | 4.08 |
| | R630 | 3.24 | 1.00 |
| | R780 | 0.42 | 0.92 |
| | R790 | 2.88 | 3.38 |
| | R800 | 4.36 | 4.86 |
| | R860 | 4.19 | 4.69 |
| Col. to Gar. | R870 | 9.59 | 10.09 |
| Garwood to Wharton | R1270 | 6.43 | 6.93 |
| | R1710 | 1.46 | 1.46 |
| | R1720 | 4.71 | 4.71 |
| Wharton to Bay City | R1280 | 3.07 | 3.07 |
| | R1310 | 3.15 | 3.15 |
| | R1730 | 1.69 | 1.69 |
| | R890 | 2.23 | 2.23 |
| | R900 | 7.82 | 7.82 |

| Model Section | Reach ID | Constant Lag (hr.) | Constant K (hr.) |
|---|---|---|---|
| | R910 | 2.58 | 2.58 |
| | R920 | 4.42 | 4.42 |
| Bay City to Mouth | R1760 | 2.88 | 3.38 |
| | R1780 | 2.2 | 2.7 |
| | R1790 | 3.5 | 4 |
| | R930 | 3.5 | 4 |

It should be noted that the complex flow dynamics within the study area result in a significant amount of flow being diverted around the Columbus and Wharton USGS gauge locations. The hydrology model does not consider these complex flow dynamics, which are more accurately reflected in the unsteady 1D/2D flow routing inherent in the hydraulic modeling described in the following section. It is recommended that the USACE Fort Worth District consider these complex dynamics as they update the Lower Colorado Hydrology to reflect Atlas 14 rainfall data. With that in mind, the hydrologic model produced reasonable results at the Columbus gauge when considering the amount of flow diverted on the upstream side of Columbus and the amount and timing of flow coming in from Cummins Creek just upstream of the gauge. A comparison of the updated HMS hydrograph to the gauge results for the Harvey event are provided in **Figure 5** and show a 6% difference in peak flows and a 2% difference in total volume. Additional calibration was performed as part of the hydraulic modeling and is discussed in the calibration section of this report. Additional details of hydrologic model development are provided in the modeling notebook in **Appendix B**.

## 5.0 HYDRAULIC MODEL DEVELOPMENT

A HEC-RAS 1D/2D hydraulic model was created for 158 miles of the Colorado River mainstem through Colorado, Wharton, and Matagorda counties. The original HEC-RAS model created during the 2001 FDEP Study was used as a starting point for model development. The FDEP model was modified by trimming the 1D cross-sections down to the channel, reorienting some sections where needed, and adding additional channel cross-sections where needed to better model meander bends and other features. 2D meshes were then added in the overbank areas where significant overbank flow was known to occur. The project area was originally split into five sections with each section centered on a respective gauge location (Columbus, Garwood, Wharton, Bay City, and the Mouth). During the model development process, the Columbus and Garwood sections were combined resulting in four final hydraulic model sections. Bridge survey data from the FDEP models was adjusted to the truncated channel sections and utilized in the 1D/2D models. The FM 521 bridge in Matagorda County was the only bridge configuration that had been substantially changed since the FDEP model was finalized. Texas Department of Transportation (TxDOT) plan sets were used to update the FM 521 bridge in the 1D/2D hydraulic model. The Mouth section is a full 2D model with downstream boundary conditions taken from the National Oceanic and Atmospheric Administration (NOAA) tidal gage near the town of Matagorda for the Harvey and April 2016 flood events with normal depth being used for all other modeled events in the absence of tidal gage data. Figures showing the hydraulic model layout details for each model section are provided in **Appendix C**.

Manning's roughness values (i.e., n-values) play a significant role in hydraulic model calibration and accuracy. Overbank n-values within the 2D hydraulic meshes are associated with different land uses within the study area, while channel n-values are based on condition of the channel with respect to vegetation and sediment size. Development of a land use dataset for association with overbank n-values began with searching for existing land use datasets within the study area. The National Land Cover Dataset (NLCD) covers the entire study area, but the resolution and accuracy of the data was not detailed enough for use with 2D modeling. The Brazos-Colorado Land Use/Land Cover dataset from the Texas Commission on Environmental Quality (TCEQ), contains more detailed land use data based on the Anderson land cover classification system. However, it only covered approximately 50% of the study area and was therefore expanded to cover the remainder of the study area based on current aerial imagery (ArcGIS base map imagery and Google aerial imagery). Over bank n-values assigned to the various land uses ranged from 0.03-0.14. Land use descriptions and associated n-values are provided in the modeling notebook in **Appendix B**. Channel n-values range from 0.04-0.07 and were adjusted at some locations to improve the hydraulic calibration as discussed in the calibration and results section below.

General set up of the 2D portion of the hydraulic models consisted of creating meshes with additional break lines and connectors. The 2D meshes were delineated in GIS based on levees, major roads, and railroads as mesh boundaries and have a base cell size of 100 ft. by 100 ft. Break lines were drawn in the 2D meshes and enforced with a smaller cell size to add detail related to stream channels, depressions from gravel mines, and other significant drainage features. 2D connectors were added between meshes to maintain continuity and to represent the weir effect on water flowing over the bounding roadways. At significant culvert crossings in the overbank areas either culvert data was added to the connector at the appropriate location, or a simplified notch was added to the roadway to represent the passage of water through the culverts (see **Figure 6**). Bridge openings in the 2D areas were generally represented within the LiDAR terrain datasets as openings in the roadway embankments allowing water to continue flowing downstream. Additional details of model set up and modeling assumptions are provided in the modeling notebook provided in **Appendix B**.

The final component of hydraulic model set up was to place boundary conditions at locations where flow enters and exits the model. Boundary conditions for the 1D portions of the models consist of inflow hydrographs at the upstream end and stage hydrographs at the downstream end. The downstream boundary stage hydrographs for the Columbus/Garwood, Wharton and Bay City sections were taken from the hydraulic model results of the next downstream section. Downstream boundary conditions for the Mouth section varied depending on the event being modeled. Tidal surge elevations for the April 2016 and Harvey events were available from the NOAA tidal gauge near the City of Matagorda and the mouth of the river and were applied as stage hydrographs to the 2D mesh boundaries at the downstream end of the Mouth model section. No tidal or stage data was available for the October 1998, November 2004, and all frequency events; therefore, a normal depth boundary condition was applied to the 2D mesh boundaries at the downstream end of the Mouth model section for those runs. Sub-basin inflows were applied to the 1D portions of the model as lateral or uniform lateral inflows. External normal depth boundary conditions were used where portions of the flow left the model system for neighboring watersheds beyond the limits of the study. Additional details regarding internal and external boundary conditions are provided in the modeling notebook provided in **Appendix B**.

## 6.0 HYDRAULIC MODEL CALIBRATION AND RESULTS

Calibration of the hydraulic models was performed to ensure accuracy of model results for flood warning and floodplain management purposes. Similar to the calibration effort for the hydrology, four flood events were utilized for hydraulic calibration: Harvey, April 2016, November 2004, and October 1998. Rainfall data sources for these events were described previously in the Hydrology section of this report. The focus of the hydraulic calibration was on the 2017 Hurricane Harvey flood event due to the intense effort to collect and document high-water marks by the USGS as well as by Scheibe Consulting. Peak stages for the other three events were available at existing gauge locations and were used for further model validation.

High-water mark (HWM) or peak stage data was obtained for all calibration events and was taken from USGS/LCRA gauge data, USGS collected data (Harvey only), or Scheibe Consulting collected data (Harvey only). The USGS Harvey data was marked in the field by data collection teams, but it was unclear if the HWM elevations were collected with survey grade GPS equipment or field estimated. This introduced some uncertainty into the accuracy of the USGS collected Harvey HWM data. The Scheibe Consulting collected data was marked and surveyed in the days after the Harvey event during the same visit with survey grade GPS equipment (average vertical accuracy +/- 0.15 ft.). Appropriate adjustments were made to all data so that all final HWM elevation data was set to the North American Vertical Datum 1988 (NAVD 88). **Figure 7** illustrates the Harvey HWMs from both sources as well as USGS and LCRA gauge locations that provided data for hydraulic calibration.

The calibration process for the Harvey event began by applying the hydrographs from the Harvey hydrology model run to the four hydraulic model sections. The hydraulic models were then run sequentially starting with the Columbus/Garwood section then proceeding downstream to the Mouth section. In the initial runs, the downstream boundary condition for each section was set to normal depth with an appropriate friction slope. The models were then run proceeding upstream from the Mouth section back up to the Columbus/Garwood section with stage hydrographs set as the downstream boundary conditions, where appropriate. An initial comparison to HWMs along the Colorado channel was made to determine the need for channel n-value adjustments. Channel n-values were adjusted at several locations mainly in the Wharton section to better match HWMs as well as the Wharton gauge rating curve. This included adding a vertical variation in n-values for several cross-sections downstream of the Wharton gauge location. The final Harvey calibration produced results along the main channel within 0.5 feet of HWM elevations at 71% of comparison points and within 1 foot at 86% of comparison points. Values greater than 1 foot represent locations where there are known issues with gauge readings at Lane City and Bay City gauges. For example, the Lane City gauge may be impacted by subsidence issues per conversations with LCRA, and per anecdotal evidence from the Matagorda Conservation and Reclamation District board members, the Bay City gauge readings are routinely off. These issues are currently being investigated to determine the source of errors at these gauges. Overbank n-values were not changed as 90% of overbank high-water marks for Harvey within 1 foot of the HWM elevation and 55% were within 0.5 feet of the HWM elevation with a few outliers greater than 1 foot. The other flood events were also run and compared to elevations available at USGS and LCRA gauges. Results of the main channel HWM comparisons for all four events is presented in **Table 3**. Overbank HWM comparisons for the Harvey event are presented in **Table**

**4**. A series of maps showing the maximum inundation for the calibrated Harvey event is available in **Appendix D**.

**Table 3: Main Channel HWM Comparison for all Flood Events**

| Source | Location | HWM WSEL | Model WSEL | Diff (Model-HWM) |
|---|---|---|---|---|
| **Harvey** | | | | |
| USGS Survey | U/S Bus 71 (Columbus) | 202.96 | 203.07 | **0.11** |
| USGS Survey | Bus 71 (Columbus) | 201.40 | 201.43 | **0.03** |
| USGS Gauge | US 90 (Columbus Gauge) | 193.69 | 194.13 | **0.44** |
| USGS Survey | US 90 Alt | 172.74 | 173.75 | **1.01** |
| LCRA Gauge | Near Garwood | 156.76 | 157.57 | **0.81** |
| USGS Survey | FM 950 (Garwood) | 145.56 | 145.67 | **0.11** |
| USGS Survey | Near Camp Pryor Rd. | 134.90 | 135.23 | **0.33** |
| USGS Survey | Near Wharton CR 459 | 124.84 | 125.51 | **0.67** |
| LCRA Gauge | Glen Flora Gauge (FM 960) | 118.09 | 118.28 | **0.19** |
| USGS Survey | Upstream of US 59 | 106.04 | 106.17 | **0.13** |
| USGS Gauge | US 59 (Wharton Gauge) | 102.89 | 102.89 | **0.00** |
| Scheibe Survey | Bus 59 | 102.57 | 102.47 | **-0.10** |
| USGS Survey | Los Cucos | 102.62 | 102.47 | **-0.15** |
| USGS Survey | Near CR 132 | 90.59 | 90.2 | **-0.39** |
| LCRA Gauge | Lane City Gauge | 82.75 | 81.23 | **-1.52** |
| USGS Survey | Near CR 444 | 73.96 | 73.59 | **-0.37** |
| USGS Survey | SH 35 (Bay City) | 48.04 | 48.32 | **0.28** |
| USGS Gauge | Bay City Gauge | 46.16 | 45.55 | **-0.61** |
| USGS Survey | D/S of FM 521 | 19.30 | 20.96 | **1.66** |
| USGS Gauge | Wadsworth Gauge | 19.55 | 19.32 | **-0.23** |
| USGS Survey | Boat Ramp near CR 257 | 3.75 | 3.99 | **0.24** |
| **April 2016** | | | | |
| USGS Gauge | US 90 (Columbus Gauge) | 191.19 | 191.08 | **-0.11** |
| LCRA Gauge | Near Garwood | 155.24 | 155.83 | **0.59** |
| LCRA Gauge | Glen Flora Gauge (FM 960) | 117.34 | 117.44 | **0.10** |
| USGS Gauge | Bus 59 (Wharton Gauge) | 100.72 | 101.50 | **0.78** |
| LCRA Gauge | Lane City Gauge | 79.53 | 80.17 | **0.64** |
| USGS Gauge | Bay City Gauge | 40.36 | 42.48 | **2.12** |
| **November 2004** | | | | |
| USGS Gauge | US 90 (Columbus Gauge) | 189.08 | 190.92 | **1.84** |
| USGS Gauge | US 59 (Wharton Gauge) | 100.74 | 101.82 | **1.08** |
| USGS Gauge | Bay City Gauge | 41.73 | 43.49 | **1.76** |
| **October 1998** | | | | |
| USGS Gauge | US 90 (Columbus Gauge) | 189.12 | 190.38 | **1.26** |

| Source | Location | HWM WSEL | Model WSEL | Diff (Model-HWM) |
|---|---|---|---|---|
| USGS Gauge | US 59 (Wharton Gauge) | 101.12 | 101.74 | **0.62** |
| USGS Gauge | Bay City Gauge | 41.00 | 43.24 | **2.24** |

**Table 4: Overbank HWM Comparison for Harvey Event**

| County | Source | Location | WSEL | Model WSEL | Diff (Model-HWM) |
|---|---|---|---|---|---|
| Wharton | Scheibe Survey | CR 232 | 115.99 | 116.89 | **0.90** |
| | Scheibe Survey | FM 102 #1 | 121.24 | 121.81 | **0.57** |
| | Scheibe Survey | FM 102 #2 | 119.40 | 120.92 | **1.52** |
| | Scheibe Survey | CR 228 | 121.02 | 121.24 | **0.22** |
| | Scheibe Survey | CR 247 #1 | 115.12 | 115.34 | **0.22** |
| | Scheibe Survey | CR 247 #2 | 114.73 | 115.30 | **0.58** |
| | Scheibe Survey | FM 640 #1 | 113.67 | 114.47 | **0.80** |
| | Scheibe Survey | FM 640 #2 | 113.76 | 114.79 | **1.03** |
| | Scheibe Survey | CR 239 | 107.58 | 110.92 | **3.34** |
| | Scheibe Survey | CR 102 Behind Walmart | 107.16 | 107.16 | **0.00** |
| | Scheibe Survey | Wilke Rd. (CR 231) | 104.35 | 104.20 | **-0.15** |
| | Scheibe Survey | FM 102 near TxDOT | 105.34 | 104.71 | **-0.63** |
| | Scheibe Survey | Wilke Rd. nr Old Bolton Pl. | 103.27 | 103.24 | **-0.03** |
| | Scheibe Survey | Intersection Wilke Rd/Halford Rd. | 103.18 | 102.95 | **-0.23** |
| | Scheibe Survey | US59 at Bus59 | 101.94 | 101.92 | **-0.02** |
| | Scheibe Survey | Bus 59 near CR220 | 100.84 | 101.46 | **0.62** |
| | Scheibe Survey | CR 137 near Maude St. | 97.12 | 97.70 | **0.58** |
| | Scheibe Survey | Fulton St. North of Gail Ave. | 99.22 | 98.02 | **-1.20** |
| | Scheibe Survey | Bus 59 South of Joan St. | 99.45 | 99.69 | **0.24** |
| | Scheibe Survey | Joan St. near TNT Western Wear | 99.51 | 98.98 | **-0.53** |
| | Scheibe Survey | Los Cucos | 102.58 | 102.64 | **0.06** |
| | Scheibe Survey | N Fulton St. btwn Caney and Hawes | 102.66 | 101.73 | **-0.92** |
| | Scheibe Survey | Santa Fe Ditch nr Hodges Ln. | 98.87 | 98.93 | **0.06** |
| | Scheibe Survey | At Dalmas and Milam Sts. | 99.64 | 99.92 | **0.28** |
| | Scheibe Survey | Bus 59 south of river | 101.14 | 101.3 | **0.16** |
| | Scheibe Survey | US 59 at Carroll Rd. | 101.71 | 102.05 | **0.34** |
| | Scheibe Survey | US 59 at CR 423 | 102.18 | 101.88 | **-0.30** |
| | Scheibe Survey | US 59 near Pierce | 100.99 | 101.22 | **0.23** |
| | Scheibe Survey | US 59 near Pierce | 100.59 | 101.20 | **0.61** |
| | USGS Survey | Near Gulf Coast Med Center | 105.96 | 105.98 | **0.02** |
| | USGS Survey | U/S of 59 near Pierce Pump Rd. | 106.72 | 106.93 | **0.21** |
| | USGS Survey | Bus 59 South side of River | 102.23 | 102.52 | **0.29** |
| | USGS Survey | CR 423 | 97.86 | 97.48 | **-0.38** |
| | USGS Survey | Peach St. @ FM 950 Glen Flora* | 100.08 | 119.58 | **19.50** |

| County | Source | Location | WSEL | Model WSEL | Diff (Model-HWM) |
|---|---|---|---|---|---|
| | USGS Survey | CR 228 West of Glen Flora | 121.73 | 121.73 | **0.00** |
| | USGS Survey | River Valley Rd. near CR 459 | 124.76 | 125.28 | **0.52** |
| | USGS Survey | CR 257 | 129.16 | 129.68 | **0.53** |
| | USGS Survey | CR 263 S | 132.84 | 133.38 | **0.54** |
| | USGS Survey | CR 263 North of CR 238 | 131.80 | 133.88 | **2.08** |
| | USGS Survey | FM 2614 @ CR 267 | 137.32 | 137.46 | **0.14** |
| | USGS Survey | Camp Pryor Road | 135.91 | 135.43 | **-0.48** |
| Colorado | Scheibe Survey | Columbus Crockett @ Back | 198.86 | 199.63 | **0.77** |
| | Scheibe Survey | Columbus Overflow @ US 90 | 199.38 | 198.95 | **-0.43** |
| | Scheibe Survey | Columbus Spring @ Fannin | 200.22 | 200.15 | **-0.07** |
| | Scheibe Survey | Columbus Overflow @ Montezuma | 197.76 | 196.97 | **-0.79** |
| | Scheibe Survey | Columbus Milam nr Industry State Bank | 193.17 | 193.2 | **0.03** |
| | Scheibe Survey | Columbus @ I-10 Frontage | 192.32 | 192.84 | **0.52** |
| | Scheibe Survey | Columbus SH 71 south of New World Dr. | 192.13 | 192.75 | **0.62** |
| | Scheibe Survey | Calhoun Rd. (CR 281) nr Parker Rd. | 163.26 | 163.45 | **0.19** |
| | Scheibe Survey | Calhoun Rd. (CR 281) S. of Patos Ln. #1 | 165.36 | 165.50 | **0.14** |
| | Scheibe Survey | Calhoun Rd. (CR 281) S. of Patos Ln. #2 | 163.66 | 163.50 | **-0.16** |
| | Scheibe Survey | Gravel Pits near Eagle Lake #1 | 165.53 | 165.64 | **0.11** |
| | Scheibe Survey | Gravel Pits near Eagle Lake #2 | 163.07 | 163.34 | **0.27** |
| | USGS Survey | FM 2614 @ Foote Ln. | 142.50 | 143.25 | **0.75** |
| | USGS Survey | FM 950 East of Garwood | 144.71 | 144.75 | **0.04** |
| | USGS Survey | CR 79 East of River | 155.02 | 156.18 | **1.16** |
| | USGS Survey | FM 102 near CR 307 | 186.69 | 187.54 | **0.85** |
| | USGS Survey | CR 216 near Miller Lake | 187.68 | 187.96 | **0.28** |
| | USGS Survey | CR 101 near Miller Lake | 188.65 | 188.17 | **-0.48** |
| | USGS Survey | Columbus Overflow nr Ann Derr Dr. | 194.82 | 194.16 | **-0.66** |
| | USGS Survey | Columbus Crockett @ Fannin | 202.09 | 202.63 | **0.54** |
| | USGS Survey | Back of Coldwell Banker Bldg. | 200.17 | 200.84 | **0.67** |

*This USGS HWM is assumed to be a bad value as it is not consistent with nearby HWM elevations

After hydraulic model calibration was completed, runs for synthetic events were set up for the 10-yr, 100-yr and 500-yr events. The results for the 100-yr and 500-yr events were compared to effective FEMA floodplains for further model validation. The results compared well except where the 1D/2D model contained more accurate results where lateral overflows and overbank flooding was not appropriately accounted for in the effective 1D hydraulic model. Maps containing a floodplain comparison of 100-yr model results to FEMA effective floodplains is contained in **Appendix E**. A comparison of maximum water surface elevation profiles for the 100-yr frequency event (modeled vs. FEMA effective) is provided for each model section in **Figures 8 through 11**.

## 7.0 FDST MAP LIBRARY DEVELOPMENT

After completion of the 1D/2D hydraulic model and calibration effort, the model results were then used in the development of data for use within the recently created Flood Decision Support Toolbox or FDST tool. The FDST tool is set up to allow users to select an inundation map from a map library based on a known gauge's reading. The goal of this project was to develop a seamless set of inundation maps for the entire 158 mile of river encompassed by this study. It was determined through extensive discussions with USGS, that to achieve this goal, it would be necessary to identify the "influence zone" of a particular gauge and then determine if additional gauges are needed. Scheibe collaborated with LCRA and USGS to determine if the four LCRA gauges could be used to enhance the FDST tool with a denser gauge network. These discussions revealed that this was feasible and that only stage readings are needed from the LCRA gauges. LCRA and USGS then collaborated to develop an automated way to pull LCRA real-time data into the FDST system.

As a result of this collaboration, all existing USGS and LCRA gauge locations will be added to the FDST tool with inundation map libraries derived from the new 1D/2D hydraulic model results with the ultimate goal of having a continuous coverage within the FDST tool from Columbus to the mouth of the river. As part of this effort, it was determined that some additional gauges would be needed to achieve the goal of seamless inundation mapping. These new gauge locations were approximated and total four (4) new locations. LCRA has agreed to maintain in perpetuity all new gauges installed as part of this project (up to 5 total). This study does not fund the installation of these new gauges but does establish need and quantity. The first step to accomplishing this goal includes dividing the river into zones based on existing and proposed gauge locations. The following methodology was used to determine where the new gauges should be located (approximately) as well as determining the associated gauge "influence zones" for all existing and proposed gauge locations.

The gauge "influence zones" were determined by comparing the water surface elevation profiles for the four actual flood events (Harvey, April 2016, November 2004, and October 1998) and the three synthetic events (10-yr, 100-yr, and 500-yr events) corresponding to the maximum water surface elevation at each existing LCRA and USGS gauge location. For example, **Figure 12** shows, for the 100-yr event, the corresponding profiles when the Glen Flora gauge and Wharton gauge are at their maximum water surface elevations, respectively. These two profiles occur at different time steps because Glen Flora reaches its maximum water surface elevation before Wharton. The red dot shows the point at which the "gauge influence" switches from the Glen Flora gauge to the Wharton gauge. This same procedure was carried out for the reaches between all existing gauges (both LCRA and USGS) for all seven events. The points were then plotted in plan-view to determine the best locations for additional gauges. Maps illustrating the "gauge influence" points between each gauge are provided in **Appendix F**. A wide spread of points representing the seven events indicated the need for additional gauge locations between the Columbus and Altair gauges, Garwood and Glen Flora gauges, Lane City and Bay City gauges, and Bay City and Wadsworth gauges. Maps illustrating the improvement in the spread of "gauge influence" points are also included in **Appendix F**. Note that the gauge influence points are much closer together with proposed hypothetical gauges in-place indicating a well-spaced proposed gauge network. It is likely that the driving factors for a gauge's particular "zone of influence" are significant lateral overflows draining from and major tributaries draining into the Colorado River.

The proposed hypothetical locations for new gauges were determined based on accessibility and are subject to agreement with property owners. The final gauge zones for use in developing the map inundation libraries are shown in **Figures 13 through 15**. Since the final placement of the four proposed new gauges is subject to negotiation with property owners, inundation map libraries were only created for the existing USGS and LCRA gauges. Discussions have already taken place regarding bringing the LCRA gauge data online for the USGS to access and display within the FDST tool and future funding is currently being sought.

Inundation map libraries were developed according to the "InFRM Flood Decision Support Toolbox: Executive Summary and Submittal Guidance" document for all LCRA and USGS gauges. The map libraries consist of depth grids from the hydraulic modeling based on 0.5-foot intervals at each gauge location. Minimum stage for the USGS gauges corresponds to NWS flood stage, while minimum stage for LCRA gauges was determined based on guidance in "Resources for Setting Flood Stage and Flood Severity Categories" supplied by NWS. The minimum stage at each gage location represents the trigger point at which overbank flooding begins. Maximum stages were set at each gauge to the maximum 500-yr stage based on the required 0.5-foot interval. The map libraries contain between 10 and 40 depth grids depending on location. Currently, the Altair and Lane City LCRA gauges are at temporary locations pending completion of separate construction projects; therefore, map libraries for these gauges will be submitted to USGS for inclusion in the FDST when the LCRA re-establishes the gauges at their permanent locations. Per the FDST submittal guidelines, the hydraulic model rating curve results were compared to the USGS/LCRA rating curves for the remaining five (5) USGS/LCRA gauge locations and have a root mean squared error (RMSE) of less than 1.5 at each location except for the LCRA gauge at Glen Flora. The overall RMSE for the Glen Flora gauge rating was 3.34, which is lies outside the acceptable range for a Tier A (detailed) hydraulic model but within the tolerance for Tier B (base level engineering) models represented within the FDST. **Figures 16 through 20** show the graphic comparison of model rating to USGS/LCRA rating for each of the five (5) USGS/LCRA gauges and **Tables 5 through 9** show the RMSE calculations. Additional GIS data was also created as required by the FDST submittal guidelines including mapping limits for each gauge and metadata files. The models and inundation map libraries for the Columbus, Garwood, Glen Flora, Wharton and Bay City gauges will be submitted to the InFRM team for review and implementation concurrently with this FPP Study final report. It should be noted that inundation map libraries for the Wadsworth gauge and the mouth of the river were not developed as part of this FPP study due to the complexities of combining storm surge and riverine flooding into one consistent map library dataset.

**Table 5: Columbus Gauge RMSE Calculation**

| Discharge (cfs) | Model Stage | USGS Stage | Error | Squared Error |
|---|---|---|---|---|
| 39573 | 34.00 | 34.22 | -0.22 | 0.05 |
| 41153 | 34.50 | 34.79 | -0.29 | 0.09 |
| 42708 | 35.00 | 35.29 | -0.29 | 0.09 |
| 44340 | 35.50 | 35.76 | -0.26 | 0.07 |
| 45906 | 36.00 | 36.19 | -0.19 | 0.04 |
| 47733 | 36.50 | 36.69 | -0.19 | 0.04 |
| 49700 | 37.00 | 37.19 | -0.19 | 0.04 |
| 52139 | 37.50 | 37.78 | -0.28 | 0.08 |

| Discharge (cfs) | Model Stage | USGS Stage | Error | Squared Error |
|---|---|---|---|---|
| 54506 | 38.00 | 38.31 | -0.31 | 0.10 |
| 56993 | 38.50 | 38.83 | -0.33 | 0.11 |
| 60215 | 39.00 | 39.48 | -0.48 | 0.23 |
| 63366 | 39.50 | 40.06 | -0.56 | 0.31 |
| 66112 | 40.00 | 40.54 | -0.54 | 0.30 |
| 69204 | 40.50 | 41.07 | -0.57 | 0.33 |
| 72751 | 41.00 | 41.67 | -0.67 | 0.44 |
| 75700 | 41.50 | 42.15 | -0.65 | 0.42 |
| 79351 | 42.00 | 42.72 | -0.72 | 0.52 |
| 83296 | 42.50 | 43.29 | -0.79 | 0.62 |
| 87579 | 43.00 | 43.88 | -0.88 | 0.77 |
| 92028 | 43.50 | 44.26 | -0.76 | 0.58 |
| 97541 | 44.00 | 44.72 | -0.72 | 0.52 |
| 103083 | 44.50 | 45.11 | -0.61 | 0.38 |
| 107606 | 45.00 | 45.40 | -0.40 | 0.16 |
| 113611 | 45.50 | 45.76 | -0.26 | 0.07 |
| 120026 | 46.00 | 46.13 | -0.13 | 0.02 |
| 127221 | 46.50 | 46.51 | -0.01 | 0.00 |
| 134652 | 47.00 | 46.87 | 0.13 | 0.02 |
| 143517 | 47.50 | 47.29 | 0.21 | 0.05 |
| 151844 | 48.00 | 47.65 | 0.35 | 0.12 |
| 160439 | 48.50 | 48.00 | 0.50 | 0.25 |
| 169418 | 49.00 | 48.36 | 0.64 | 0.42 |
| 178541 | 49.50 | 48.70 | 0.80 | 0.64 |
| 187976 | 50.00 | 49.04 | 0.96 | 0.92 |
| 196307 | 50.50 | 49.33 | 1.17 | 1.38 |
| 204929 | 51.00 | 49.62 | 1.38 | 1.91 |
| 214085 | 51.50 | 49.93 | 1.57 | 2.46 |
| 222582 | 52.00 | 50.22 | 1.78 | 3.17 |
| 230473 | 52.50 | 50.49 | 2.01 | 4.05 |
| 235936 | 53.00 | 50.67 | 2.33 | 5.42 |
| | | | **RMSE** | **0.83** |

**Table 6: Garwood Gauge RMSE Calculation**

| Discharge (cfs) | Model Result | USGS Rating | Error | Squared Error |
|---|---|---|---|---|
| 33654.29 | 150.4 | 149.08 | 1.31 | 1.71 |
| 35321.45 | 150.9 | 149.57 | 1.33 | 1.76 |
| 37136.41 | 151.4 | 150.09 | 1.32 | 1.74 |
| 39038.83 | 151.9 | 150.64 | 1.26 | 1.59 |
| 41316.03 | 152.4 | 151.19 | 1.20 | 1.43 |
| 43525.57 | 152.9 | 151.66 | 1.26 | 1.58 |
| 45610.62 | 153.4 | 152.09 | 1.31 | 1.72 |
| 48043.11 | 153.9 | 152.60 | 1.33 | 1.76 |

| Discharge (cfs) | Model Result | USGS Rating | Error | Squared Error |
|---|---|---|---|---|
| 51208.68 | 154.5 | 153.21 | 1.29 | 1.65 |
| 55634.77 | 154.9 | 153.96 | 0.95 | 0.90 |
| 65367.22 | 155.4 | 155.30 | 0.08 | 0.01 |
| 79657.95 | 155.9 | 156.37 | -0.47 | 0.22 |
| 100565.9 | 156.5 | 157.14 | -0.64 | 0.41 |
| 114861.3 | 156.9 | 157.30 | -0.41 | 0.17 |
| 132863 | 157.4 | 157.44 | -0.04 | 0.00 |
| 150077.1 | 157.9 | 157.55 | 0.35 | 0.12 |
| 168293.5 | 158.4 | 157.67 | 0.71 | 0.51 |
| 190077.2 | 158.9 | 157.81 | 1.12 | 1.25 |
| 212581.5 | 159.4 | 157.95 | 1.44 | 2.07 |
| | | | **RMSE** | **1.04** |

**Table 7: Glen Flora Gauge RMSE Calculation**

| Discharge (cfs) | Model Result | USGS Rating | Error | Squared Error |
|---|---|---|---|---|
| 30779 | 104.9 | 99.7 | 5.19 | 26.97 |
| 32146 | 105.5 | 100.4 | 5.07 | 25.68 |
| 34147 | 106.3 | 101.3 | 4.94 | 24.39 |
| 34647 | 106.7 | 101.6 | 5.10 | 25.99 |
| 36008 | 107.2 | 102.2 | 5.01 | 25.07 |
| 38433 | 108.2 | 103.3 | 4.90 | 23.99 |
| 40213 | 108.9 | 104.2 | 4.74 | 22.47 |
| 43416 | 110.0 | 105.7 | 4.30 | 18.53 |
| 44862 | 110.5 | 106.4 | 4.10 | 16.78 |
| 46540 | 111.0 | 107.2 | 3.86 | 14.87 |
| 48558 | 111.7 | 108.1 | 3.55 | 12.57 |
| 51990 | 112.7 | 109.7 | 3.00 | 9.00 |
| 55561 | 113.6 | 111.0 | 2.56 | 6.56 |
| 57583 | 114.1 | 111.7 | 2.30 | 5.31 |
| 60075 | 114.6 | 112.6 | 1.93 | 3.73 |
| 62197 | 115.0 | 113.2 | 1.78 | 3.18 |
| 64298 | 115.4 | 113.8 | 1.61 | 2.61 |
| 65740 | 115.7 | 114.2 | 1.50 | 2.25 |
| 67952 | 116.0 | 114.7 | 1.34 | 1.78 |
| 70858 | 116.5 | 115.3 | 1.12 | 1.24 |
| 74626 | 116.9 | 116.0 | 0.83 | 0.69 |
| 78536 | 117.2 | 116.7 | 0.45 | 0.20 |
| 84665 | 117.6 | 117.7 | -0.15 | 0.02 |
| 97833 | 118.0 | 119.0 | -0.99 | 0.98 |
| 152505 | 118.4 | 120.4 | -1.96 | 3.85 |
| | | | **RMSE** | **3.34** |

**Table 8: Wharton Gauge RMSE Calculation**

| Discharge (cfs) | Model Stage | USGS Stage | Error | Squared Error |
|---|---|---|---|---|
| 39628 | 39.00 | 38.00 | 1.00 | 0.99 |
| 40682 | 39.50 | 38.54 | 0.96 | 0.91 |
| 41763 | 40.00 | 39.09 | 0.91 | 0.82 |
| 43046 | 40.50 | 39.74 | 0.76 | 0.58 |
| 44484 | 41.00 | 40.45 | 0.55 | 0.30 |
| 45790 | 41.50 | 41.09 | 0.41 | 0.17 |
| 46861 | 42.00 | 41.61 | 0.39 | 0.15 |
| 48036 | 42.50 | 42.18 | 0.32 | 0.10 |
| 49167 | 43.00 | 42.72 | 0.28 | 0.08 |
| 50512 | 43.50 | 43.35 | 0.15 | 0.02 |
| 51625 | 44.00 | 43.87 | 0.13 | 0.02 |
| 53024 | 44.50 | 44.51 | -0.01 | 0.00 |
| 54186 | 45.00 | 45.04 | -0.04 | 0.00 |
| 55741 | 45.50 | 45.68 | -0.18 | 0.03 |
| 56984 | 46.00 | 46.12 | -0.12 | 0.01 |
| 58262 | 46.50 | 46.57 | -0.07 | 0.00 |
| 59487 | 47.00 | 46.99 | 0.01 | 0.00 |
| 60367 | 47.50 | 47.28 | 0.22 | 0.05 |
| 61406 | 48.00 | 47.57 | 0.43 | 0.19 |
| 62234 | 48.50 | 47.80 | 0.70 | 0.50 |
| 63014 | 49.00 | 48.01 | 0.99 | 0.99 |
| 64728 | 49.50 | 48.44 | 1.06 | 1.11 |
| 66978 | 50.00 | 48.88 | 1.12 | 1.25 |
| 78024 | 50.50 | 50.15 | 0.35 | 0.12 |
| 92663 | 51.00 | 50.46 | 0.54 | 0.29 |
| 108460 | 51.50 | 50.62 | 0.88 | 0.77 |
| | | | **RMSE** | **0.60** |

**Table 9: Bay City Gauge RMSE Calculation**

| Discharge (cfs) | Model Stage | USGS Stage | Error | Squared Error |
|---|---|---|---|---|
| 62593 | 40.00 | 40.93 | -0.93 | 0.86 |
| 64096 | 40.50 | 41.42 | -0.92 | 0.85 |
| 65950 | 41.00 | 42.02 | -1.02 | 1.05 |
| 67748 | 41.50 | 42.56 | -1.06 | 1.13 |
| 69629 | 42.00 | 43.09 | -1.09 | 1.20 |
| 71496 | 42.50 | 43.61 | -1.11 | 1.24 |
| 73513 | 43.00 | 44.17 | -1.17 | 1.36 |
| 75757 | 43.50 | 44.69 | -1.19 | 1.42 |
| 78072 | 44.00 | 45.11 | -1.11 | 1.23 |
| 80250 | 44.50 | 45.33 | -0.83 | 0.69 |
| 82367 | 45.00 | 45.54 | -0.54 | 0.29 |
| 84739 | 45.50 | 45.76 | -0.26 | 0.07 |
| 87262 | 46.00 | 46.00 | 0.00 | 0.00 |

| Discharge (cfs) | Model Stage | USGS Stage | Error | Squared Error |
|---|---|---|---|---|
| 89754 | 46.50 | 46.23 | 0.27 | 0.07 |
| 92154 | 47.00 | 46.45 | 0.55 | 0.31 |
| 94246 | 47.50 | 46.64 | 0.86 | 0.74 |
| 95101 | 48.00 | 46.71 | 1.29 | 1.65 |
| | | | **RMSE** | **0.91** |

## 8.0 RECOMMENDATIONS FOR FUTURE EFFORT

This study was an initial and critical step forward in developing accurate, real-time flood map data for the Lower Colorado River. At the conclusion of this study there are still additional steps to be completed in the development of a continuous system of flood warning and real-time flood mapping tools on the Lower Colorado River. The following are recommendations for future effort needed to take this flood warning project to full completion:

- New gauge locations should be finalized, and gauges should be installed per agreement with LCRA. This effort will require negotiation with property owners at the various proposed locations to ensure access for installation and future maintenance. At a minimum, gauges should be able to record and transmit stage readings accessible by the USGS for use with the FDST tool. Funding for this effort may be realized through CBDG-MIT or future TWDB funds.
- Once new gauge locations are finalized, inundation map libraries for those locations should be completed and submitted to USGS for approval and inclusion in the FDST tool. This effort can proceed simultaneously to the new gauge installation effort.
- After new gauges and map libraries are added to the FDST tool, it is recommended that inundation map libraries be developed for the mouth of the river that is highly affected by storm surge as well as riverine flooding. Additional analysis is recommended to determine the combined impacts of storm surge and riverine flooding and how to best represent that in the FDST tool format. It is recommended that one or more map libraries should then be created for the downstream area including the Wadsworth gauge and the mouth of the river. This additional effort should be executed in close collaboration with USGS and the USACE Galveston District.
- If desired, it is recommended that requests be submitted to NWS to add flood forecast points at any of the LCRA or proposed new gauge locations where rating curve and flow data can be accurately estimated. This will require developing some additional information including required flood stages at each proposed forecast point and meeting all NWS standards for flood forecast points.
- Once the USACE Fort Worth District finalizes the development of the Atlas 14 hydrology updates, it may be worthwhile to reevaluate the 100-yr and 500-yr flood risk limits to ensure the inundation map libraries extend to the full expected probability limits of a flood that may realistically occur in this watershed. Such updates may also warrant a Physical Map Revision (PMR) by FEMA to enhance flood risk understanding in the region.

## 9.0 REFERENCES

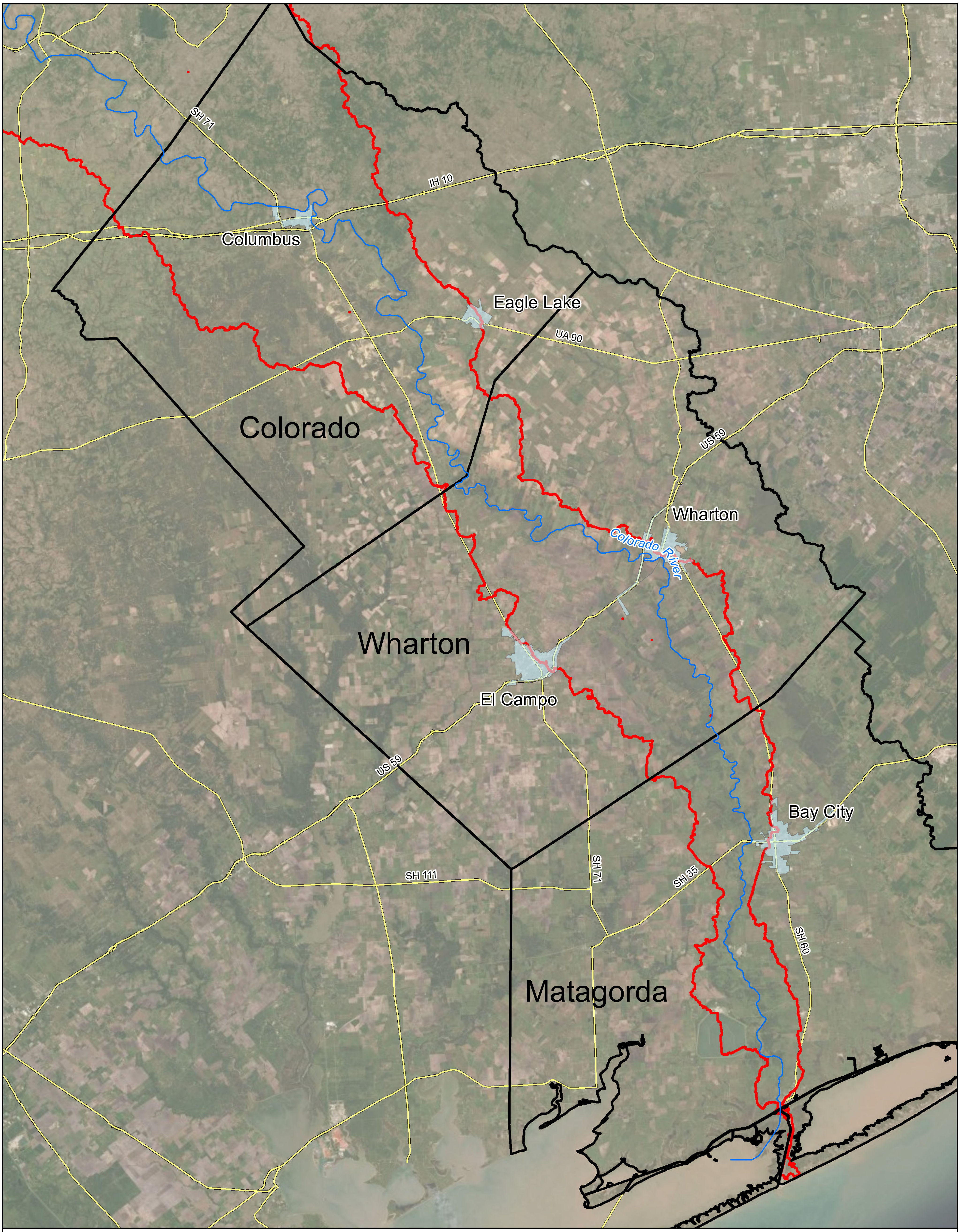
U.S. Army Corps of Engineers Hydrologic Engineering Center, February 2016, HEC-RAS River Analysis System: 2D Modeling User's Manual.

U.S. Army Corps of Engineers (FW District), July 2002, Hydrology – Hydraulics Appendix to the Corps' Information Paper on Colorado River Flood Damage Project – Phase 1.

InFRM (Inter Agency Flood Risk Management), December 2020, InFRM Flood Decision Support Toolbox: Executive Summary and Submittal Guidance.

Nation Weather Service Central Region IHOP Team. April 2016, Resources for Setting Flood Stage and Flood Severity Categories.

# FIGURES




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure 1: Lower Colorado FPP Study Area**

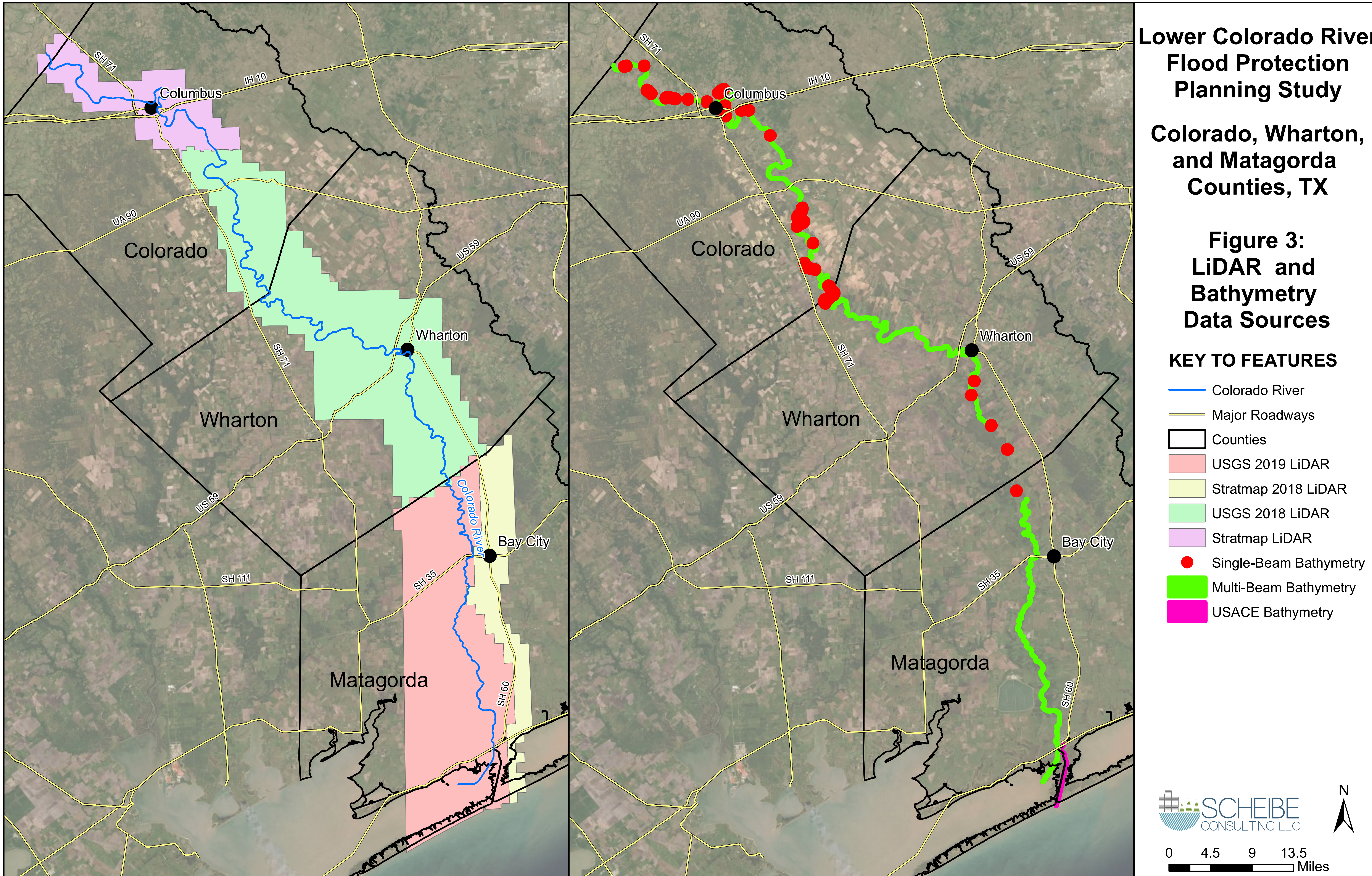
**KEY TO FEATURES**

- Colorado River
- Cities
- Counties
- Colorado Watershed
- Major Roadways

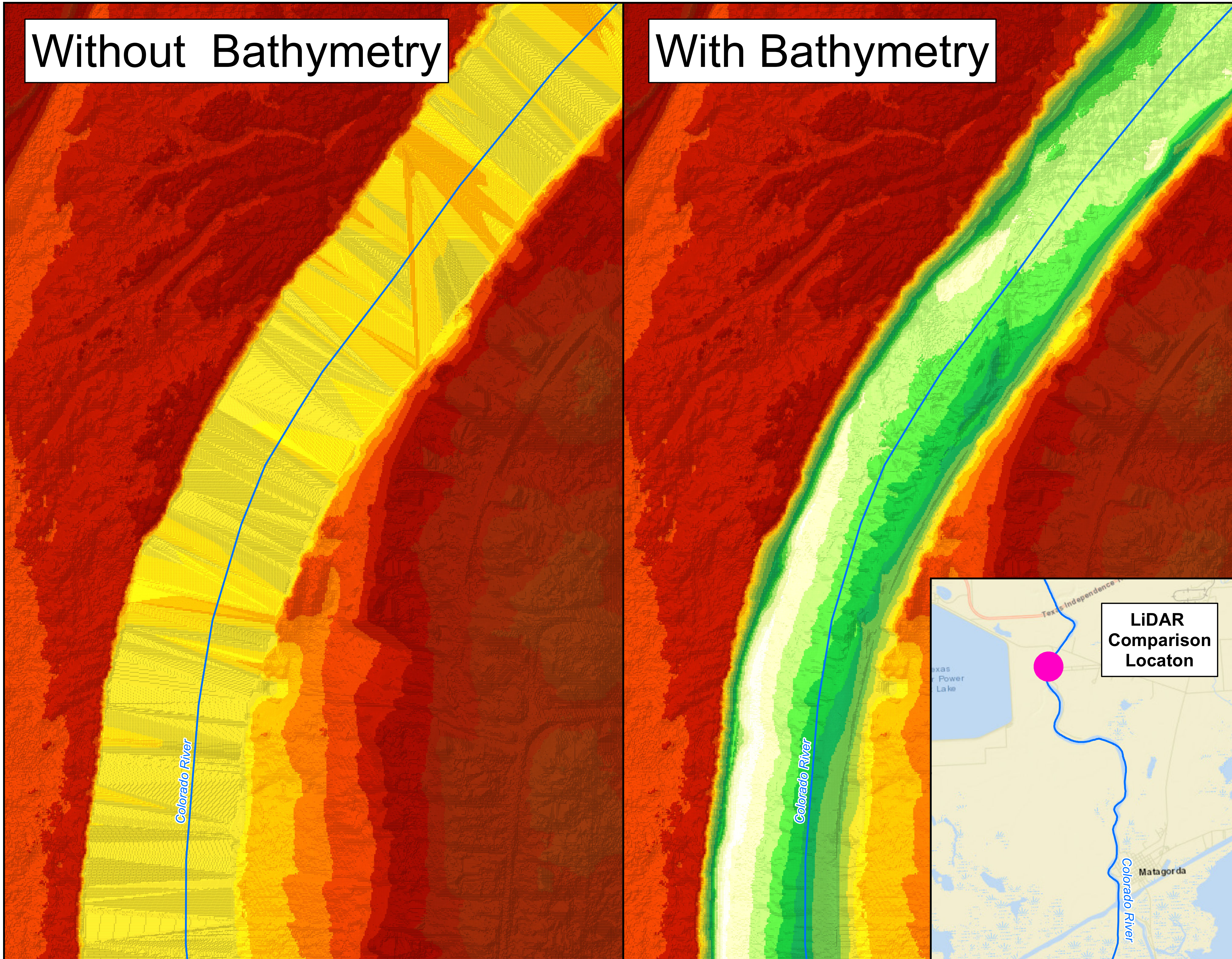
SCHEIBE CONSULTING LLC

N

0 7 14 21 Miles



Lower Colorado River Flood Protection Planning Study
Colorado, Wharton, and Matagorda Counties, TX
Figure 3: LiDAR and Bathymetry Data Sources
KEY TO FEATURES
Colorado River
Major Roadways
Counties
USGS 2019 LiDAR
Stratmap 2018 LiDAR
USGS 2018 LiDAR
Stratmap LiDAR
Single-Beam Bathymetry
Multi-Beam Bathymetry
USACE Bathymetry
SCHEIBE CONSULTING LLC
N
0 4.5 9 13.5 Miles
Columbus
Wharton
Bay City
Colorado
Wharton
Matagorda
Colorado River
SH 71
IH 10
UA 90
US 59
SH 111
SH 35
SH 60




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure 4: River Channel with and without Bathymetry**

**KEY TO FEATURES**

Colorado River

SCHEIBE CONSULTING LLC

N

0 100 200 300 400 Feet

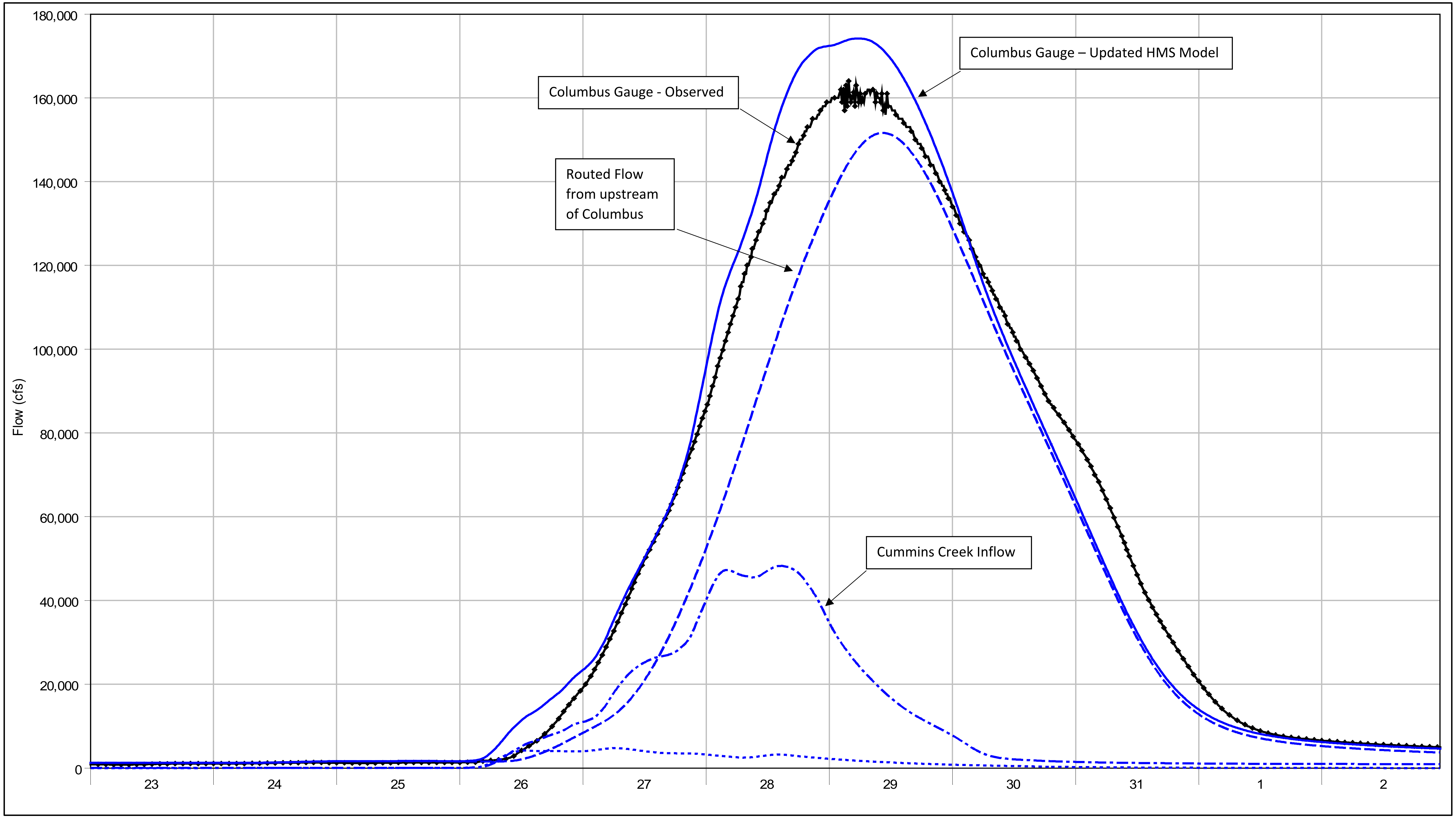



**Figure 5: Hydrology (Updated HMS) Results at Columbus Gauge for Harvey Event**

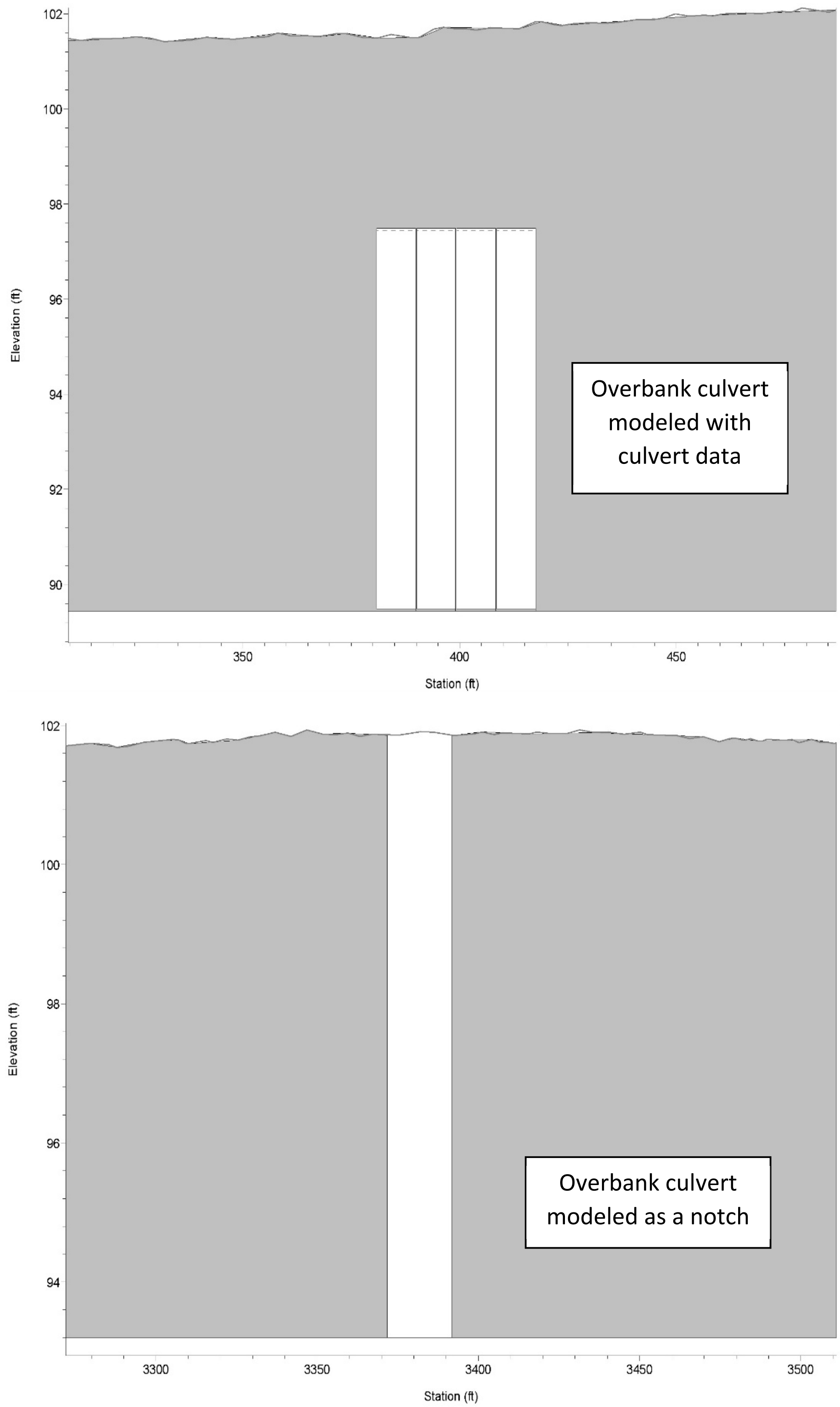
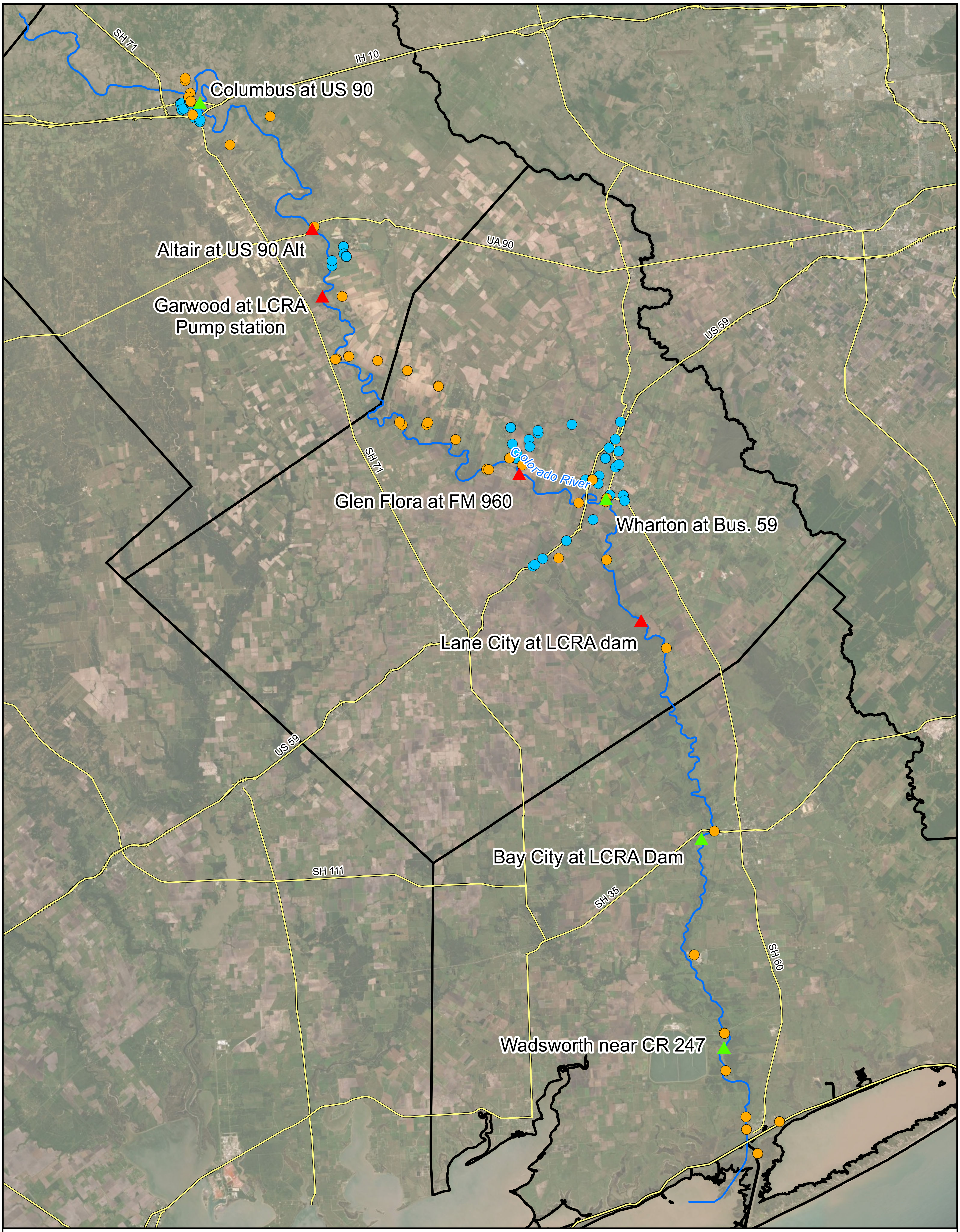



Figure 6: Overbank Culvert Modeling Methods




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure 7: Harvey HWM and Gauge Locations**

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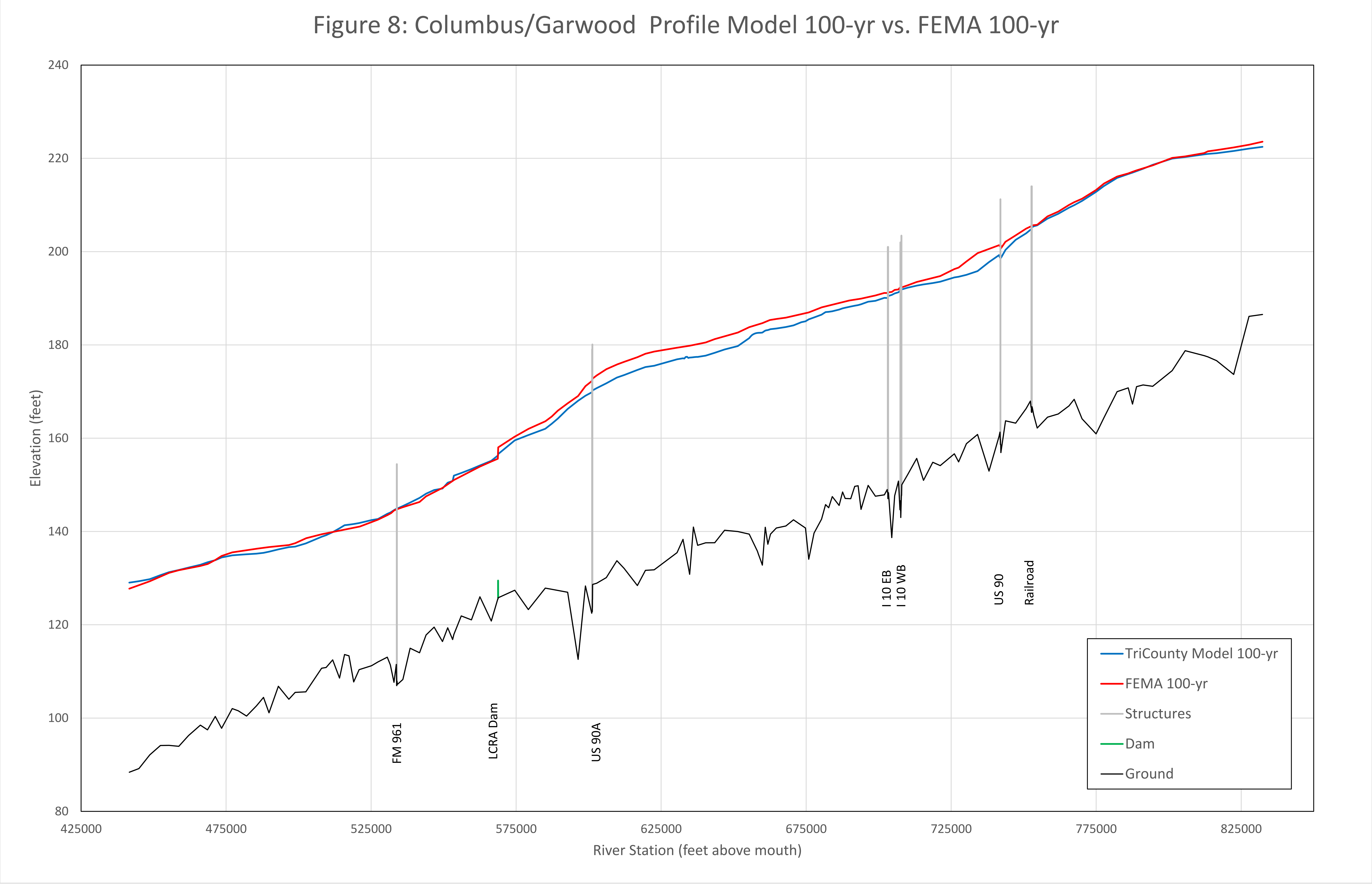
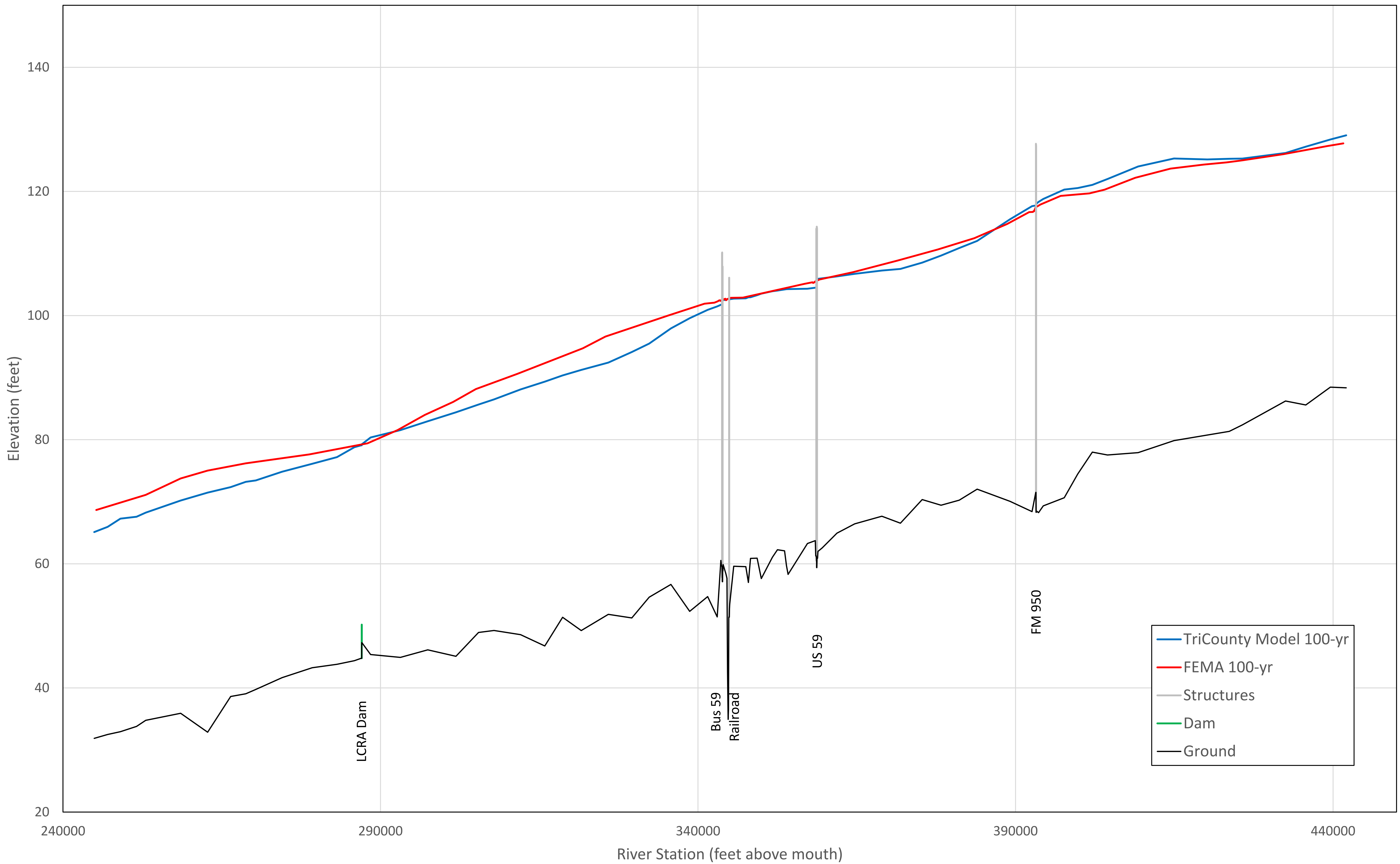


Figure 8: Columbus/Garwood Profile Model 100-yr vs. FEMA 100-yr
Elevation (feet)
River Station (feet above mouth)
240
220
200
180
160
140
120
100
80
425000
475000
525000
575000
625000
675000
725000
775000
825000
FM 961
LCRA Dam
US 90A
I 10 EB
I 10 WB
US 90
Railroad
TriCounty Model 100-yr
FEMA 100-yr
Structures
Dam
Ground

# Figure 9: Wharton Profile Model 100-yr vs. FEMA 100-yr



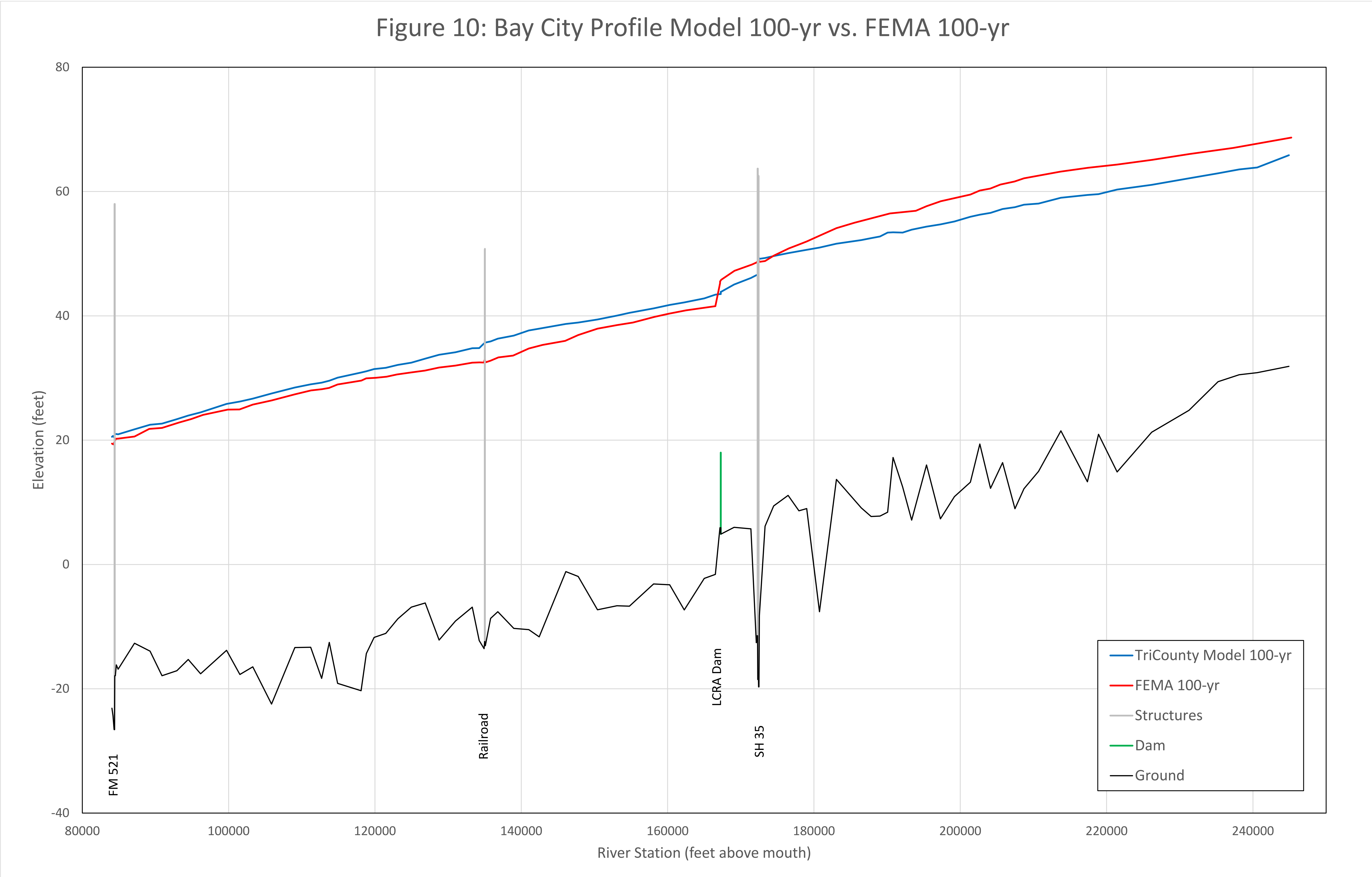


Figure 10: Bay City Profile Model 100-yr vs. FEMA 100-yr
80
60
40
20
0
-20
-40
Elevation (feet)
80000
100000
120000
140000
160000
180000
200000
220000
240000
River Station (feet above mouth)
FM 521
Railroad
LCRA Dam
SH 35
TriCounty Model 100-yr
FEMA 100-yr
Structures
Dam
Ground

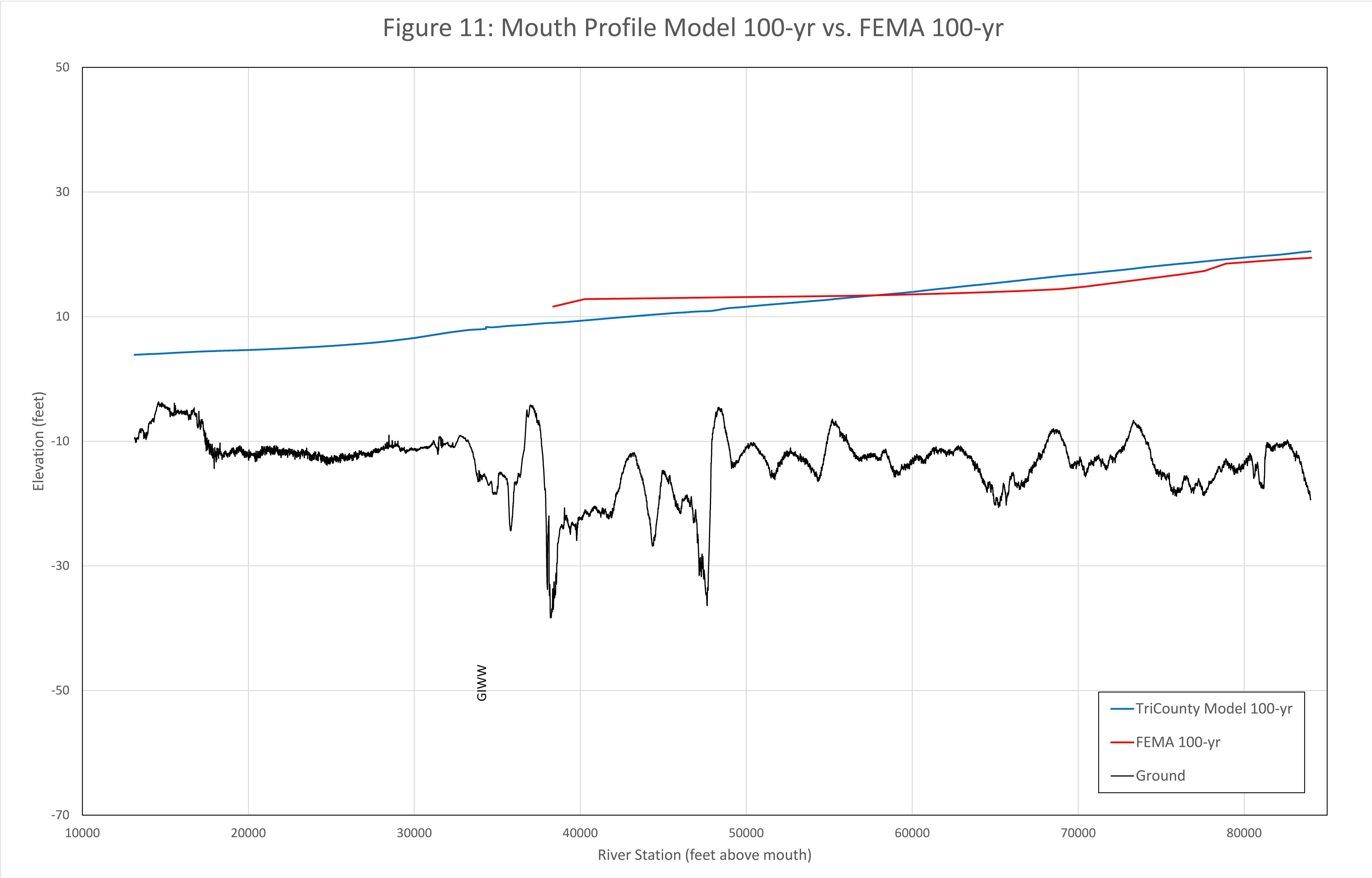
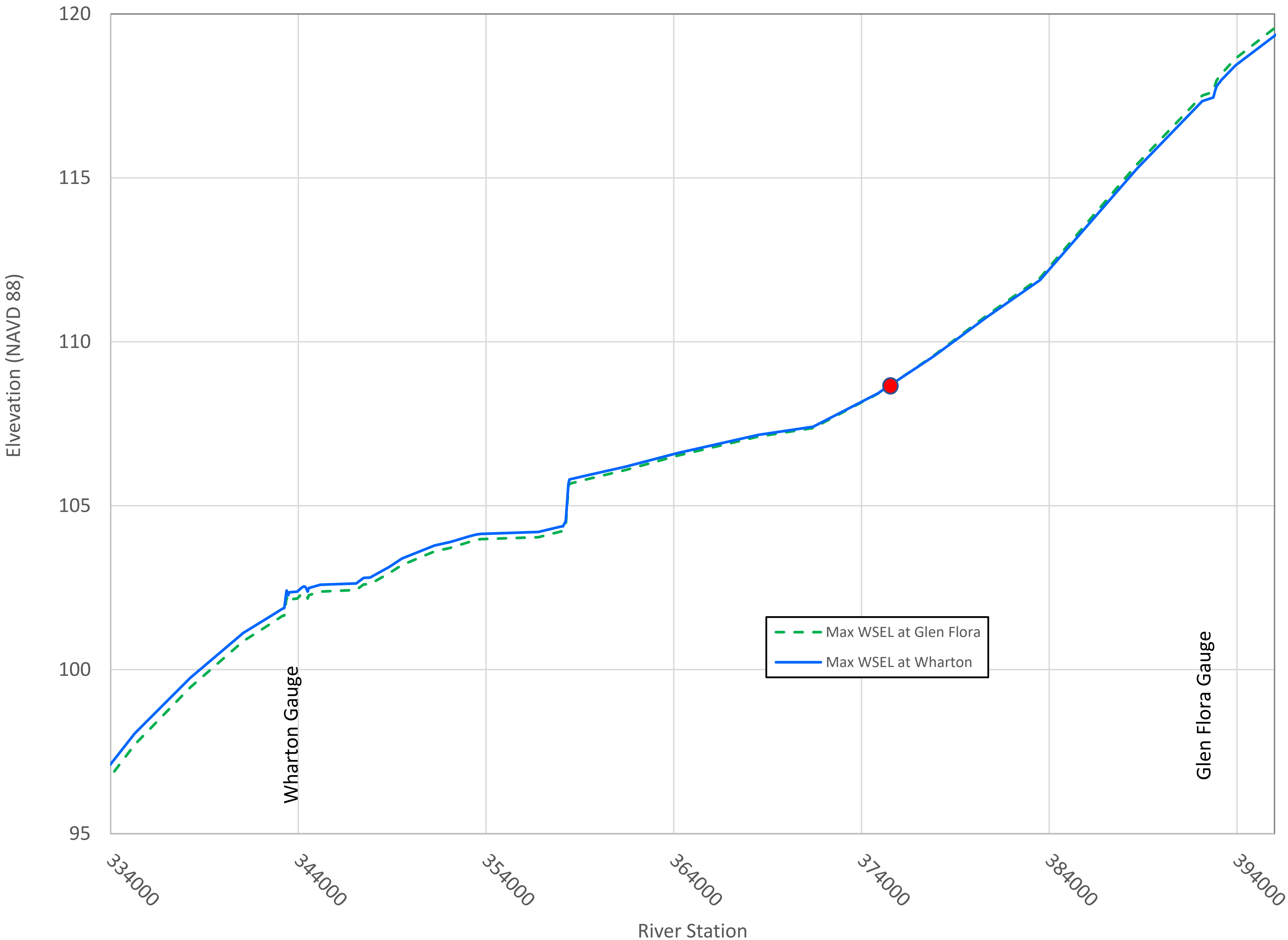


Figure 11: Mouth Profile Model 100-yr vs. FEMA 100-yr
Elevation (feet)
50
30
10
-10
-30
-50
-70
10000
20000
30000
40000
50000
60000
70000
80000
River Station (feet above mouth)
GIWW
TriCounty Model 100-yr
FEMA 100-yr
Ground

# Figure 12:  100-yr Gauge Influence  between Wharton and Glen Flora




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure 13: Final Gauge Zones Colorado County**

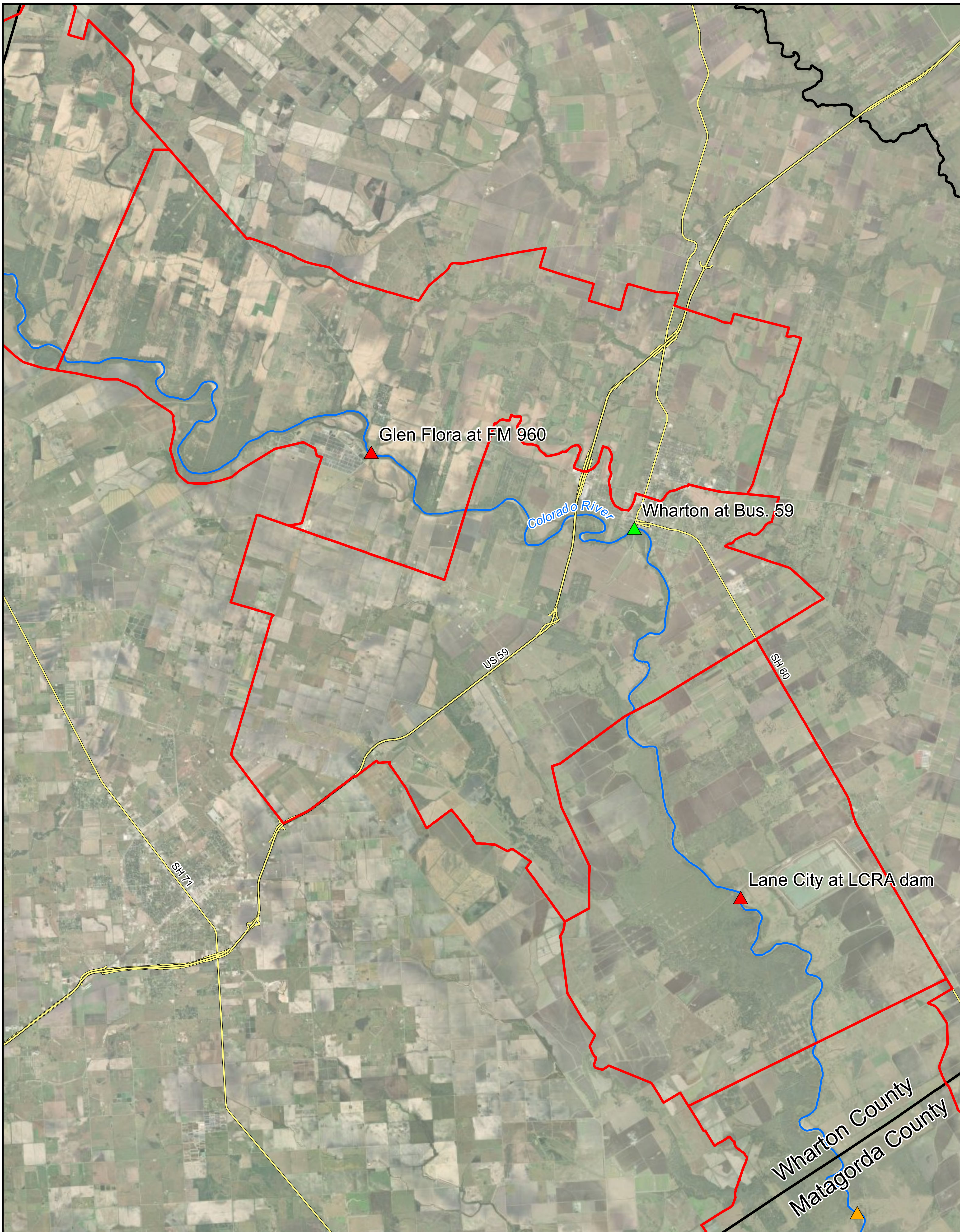
**KEY TO FEATURES**

- Proposed Gage Zones
- USGS Gage
- LCRA Gage
- Proposed Gage

SCHEIBE CONSULTING LLC

N

0 2 4 6 Miles




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure 14: Final Gauge Zones Wharton County**

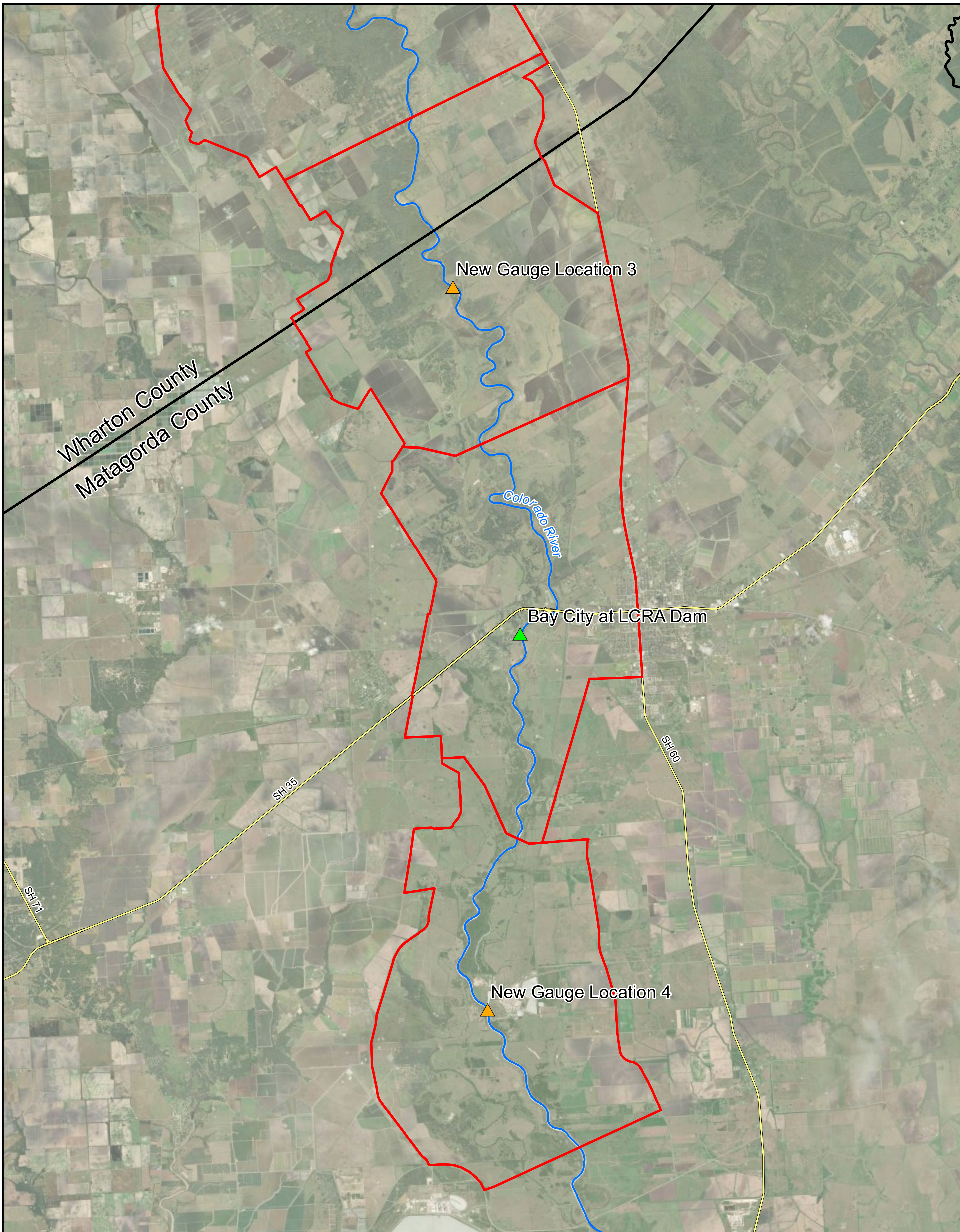
**KEY TO FEATURES**

- Proposed Gage Zones
- USGS Gage
- LCRA Gage
- Proposed Gage

SCHEIBE CONSULTING LLC

N

0 2 4 6 Miles




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure 15: Final Gauge Zones Matagorda County**

**KEY TO FEATURES**

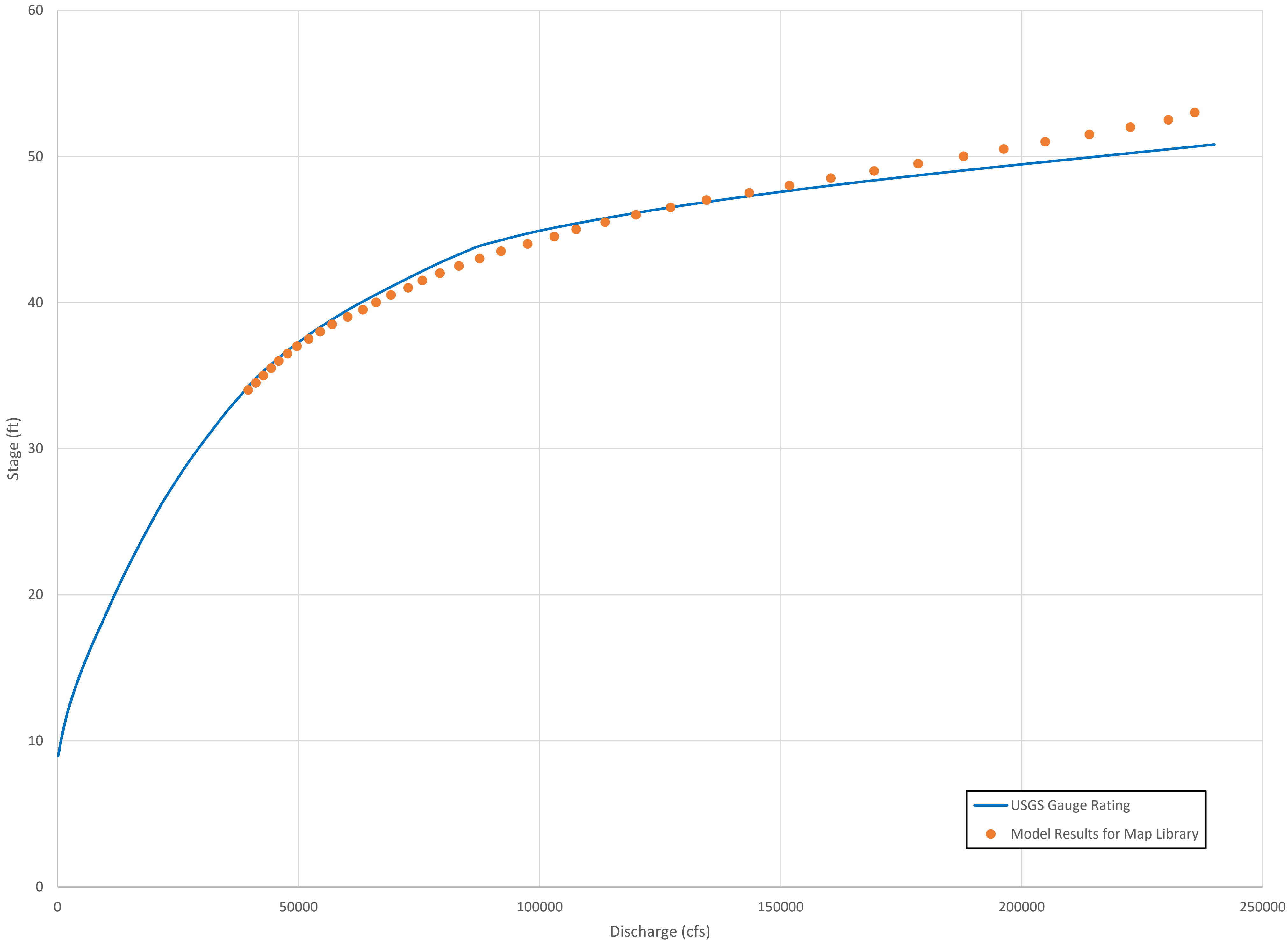
- Proposed Gage Zones
- USGS Gage
- LCRA Gage
- Proposed Gage

SCHEIBE CONSULTING LLC

N

0 2 4 6 Miles

Figure 16: Columbus Gauge Rating Comparison



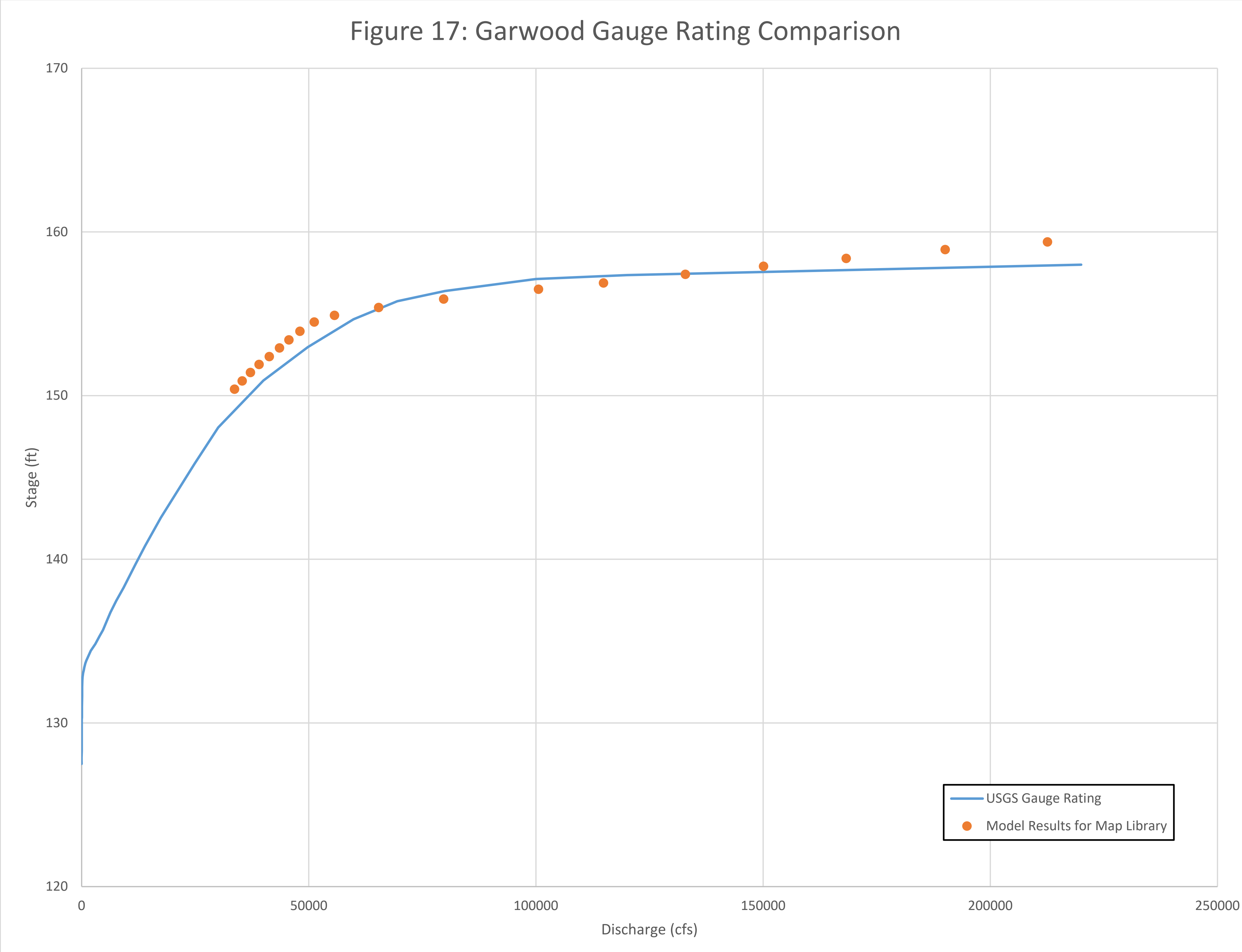


Figure 17: Garwood Gauge Rating Comparison
Stage (ft)
170
160
150
140
130
120
0
50000
100000
150000
200000
250000
Discharge (cfs)
USGS Gauge Rating
Model Results for Map Library

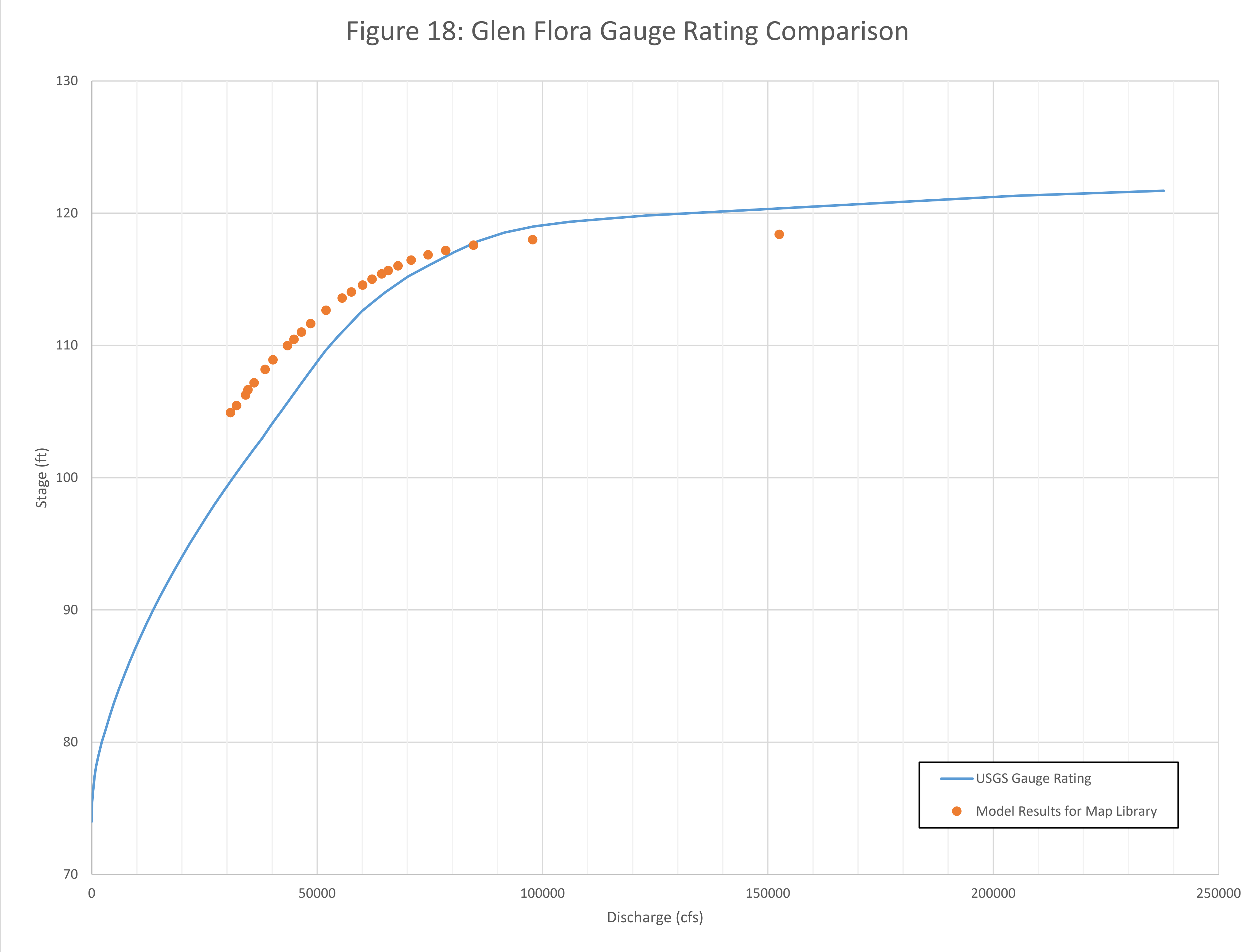


Figure 18: Glen Flora Gauge Rating Comparison
Stage (ft)
130
120
110
100
90
80
70
0
50000
100000
150000
200000
250000
Discharge (cfs)
USGS Gauge Rating
Model Results for Map Library

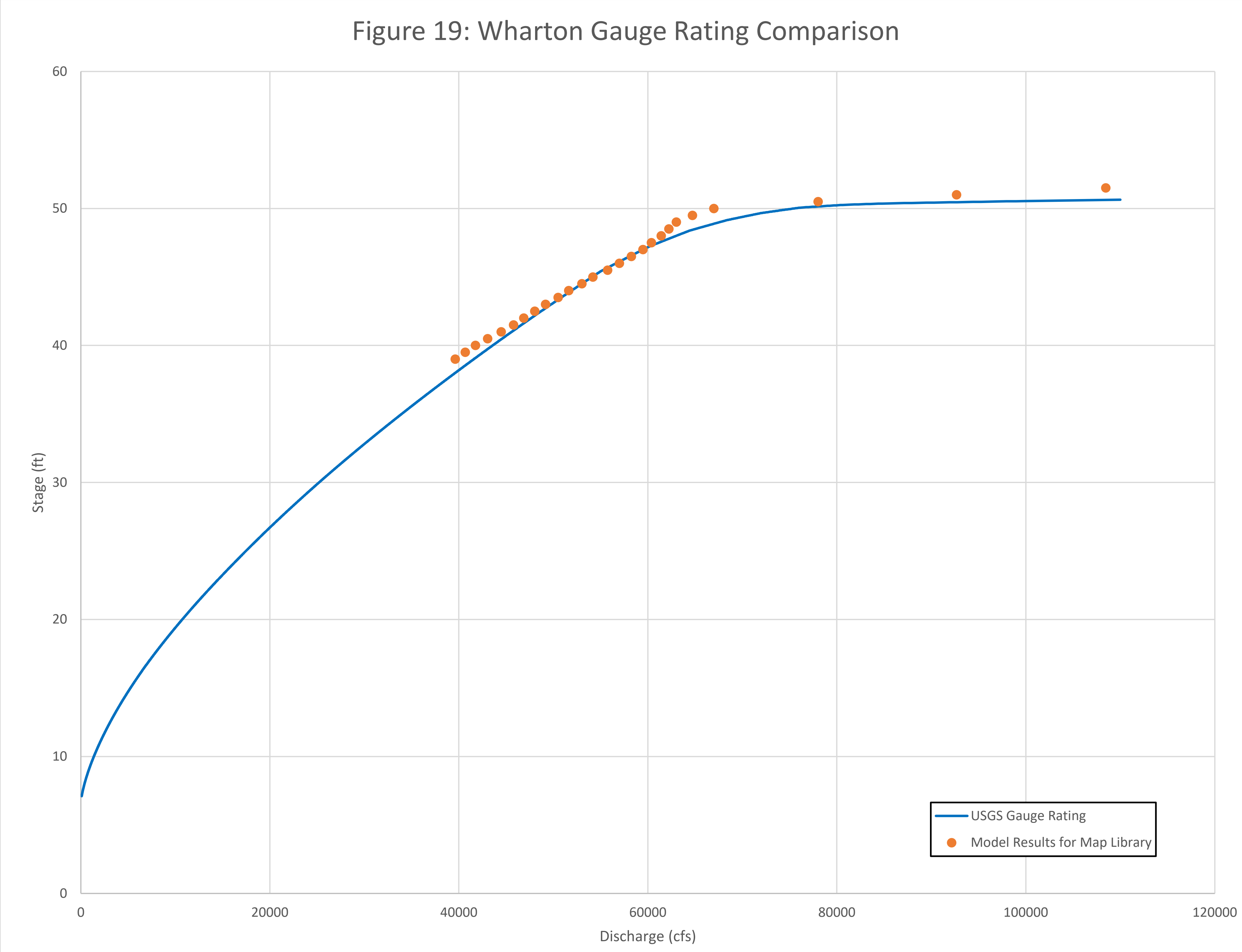


Figure 19: Wharton Gauge Rating Comparison
Stage (ft)
Discharge (cfs)
0
10
20
30
40
50
60
0
20000
40000
60000
80000
100000
120000
USGS Gauge Rating
Model Results for Map Library

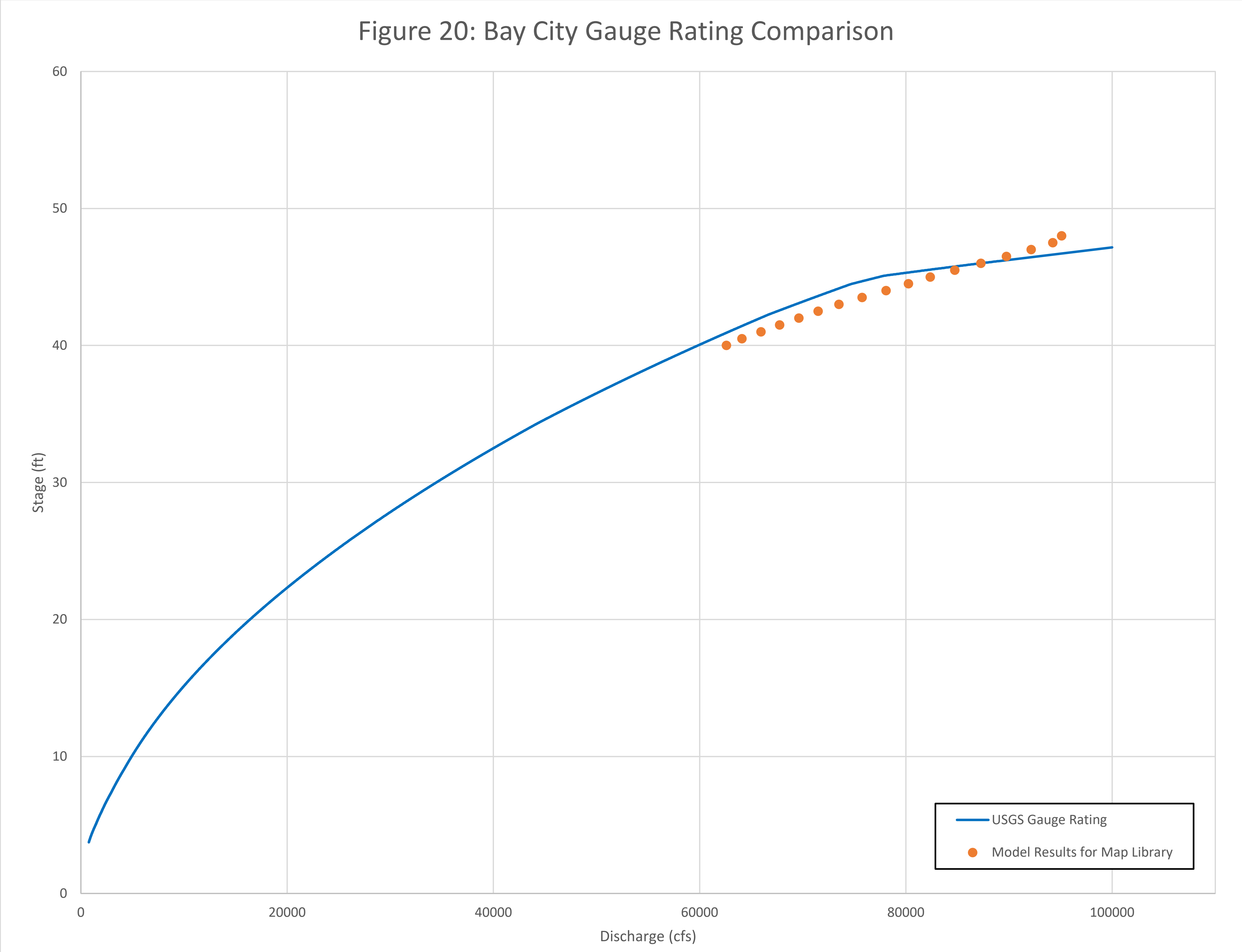


Figure 20: Bay City Gauge Rating Comparison
Stage (ft)
Discharge (cfs)
0
10
20
30
40
50
60
0
20000
40000
60000
80000
100000
USGS Gauge Rating
Model Results for Map Library

# APPENDIX A:

# BATHYMETRIC SURVEY MEMORANDA

# Technical Memorandum

To: FishViews

From: Ryan McEliece, Shawn Hinz—Gravity Marine LLC

Date: July 26th, 2019

Subject: *Lower Colorado River MBES Survey Data Summary*

Project: LCRA MBES Survey

# Overview

Gravity Marine, LLC (Gravity) was contracted by Fishviews (FS) to perform a multibeam echosounder (MBES) hydrographic survey of the Lower Colorado River in Texas. The project's objectives were to collect bathymetry data from the mouth of the River near Matagorda, TX, up to the approximate area of the Ellinger area County Line. The survey covers approximately 150 miles of river. Data was collected over 18 days in June and July of 2019.

The MBES survey was executed in accordance with scope of work provided to Gravity Marine LLC.

The following memo summarizes the survey methodology, data QA/QC, and processing methods for the MBES survey.

**SURVEY Summary**

The survey was conducted in 4 main sections based on available boat launches:

1. The River mouth near Matagorda to Bay City Dam
    - This entire section was surveyed
    - Deeper water in this section made it possible to survey 3 passes, centerline or thalweg, and both banks.
    - No Major obstacles found in this section.

2. Bay City Dam to Lane City Dam
    - Deeper water in the lower section and gradually shallower upriver
    - Survey crew was stopped by shallow water approximately 10 miles downstream of the lane city dam and could travel no further upriver.
    - This section was mostly surveyed with 3 passes (Thalweg and both banks)

3. Lane City dam to Garwood Dam
    - The downstream half of this section was surveyed with 3 passes, the upper section was surveyed with 1 pass down the thalweg.
    - Many hazards, obstacles and shallow spots exist in this section. Some gaps in the data exist due to sections being too shallow for sonar.

4. Garwood dam to Ellinger (Furthest North of Survey area)
    - The majority of this section was surveyed with 1 pass down the thalweg
    - Many shallow spots, obstacles and hazards in this section of river exist. Some gaps in the data exist due to being too shallow or hazardous for survey to be completed safely.
    - The section from the Garwood dam upriver approximately 5 miles was not surveyed due to vessel being unable to safely access this section (low water levels).

***Survey Vessel and Crew***

The MBES survey was conducted on R/V Mazama, a 24-ft aluminum survey vessel owned and operated by Gravity Marine, LLC. Lead surveyor for the MBES acquisition was Marine Scientist, Ryan McEliece, with vessel navigation and support from Gravity's USCG Captain's Michael Duffield and Peter Jenkins.

***Survey Equipment***

The following survey equipment was used to conduct the MBES survey;

- Echosounder
  - Norbit Wideband Multibeam Sonar (WBMS)
  - 400 kHz
- Inertial Navigation System
  - SBG Ekinox E
  - Set to collect TSS data at 100 Hz
- Heading Sensor (integrated)
  - Trimble BD982
  - Dual Antenna Heading Sensor
  - Set to collect data HDT data at 50 Hz
- GPS Receiver (integrated)
  - Trimble BD982 GNSS Receiver
  - Positioning Set to 20 Hz
  - Receiving Real Time Kinematics (RTK) Corrections via Trimble's RTX
  - Trimble DHL 450 radio modem
  - Synced PPS (rising edge)
- Sound Velocity Profiler
  - Integrated sound velocity probe on WBMS head
  - YSI Cast Away Sound Velocity Profiler

***Survey Datums and Projections***

The following horizontal and vertical projections were used for the survey:

- Ellipsoid: WGS-84
- Horizontal Datum;
  - Grid: NAD 83 (2011) State Plane
  - Zone: Tx-4204 TEXAS SOUTH CENTRAL
- Vertical Datum: NAVD88
- Geoid Model: G2012-B CONUS
- Distance Unit: International Foot
- Depth Unit: International Foot

***Data Acquisition***

MBES data was acquired through the survey and navigation software package HYPACK 2018, using the SURVEY and HYSWEEP modules to facilitate the MBES sonar data acquisition. This acquisition software also collects all INS, GPS, and sound velocity data.

***Sensor Alignment Verification***

A patch test was conducted to confirm alignment of the INS system with the sonar transducer and to verify angular and delay offsets applied to the time-tagged sensor data. The patch test consisted of a series of lines run in a specific pattern, then used in pairs to analyze roll, pitch and heading alignment bias angles, as well as latency (time delays) in the time tagging of the sensor data. The patch test data was evaluated in the following order: latency, pitch, roll, and heading.

Pitch bias was determined by running reciprocal lines over a smooth slope, perpendicular to the depth curves. Roll alignment was determined by running reciprocal lines over a flat bottom. Heading bias was determined from running reciprocal lines, made on each side of a submerged feature, in relatively shallow water. Patch test lines were conducted at a speed allowing for forward overlap.

Final angular offset values were input into HYPACK and a confidence check was performed to verify accuracy requirements.

## MBES QA/QC

### *System Assessment*

Prior to commencing MBES survey activities, a full system assessment was conducted to ensure all proper checks and procedures were in place to execute a successful MBES survey. This includes assessment of the following items;

- Confirm MBES system is powered and transmitting/receiving data
- Confirm GPS system is powered and transmitting/receiving position data, and position data seems reasonable given the geographic location
- Confirm INS is powered and transmitting/receiving data. Check that IMU responds to vessel movement, and angle measurements are accurate
- Check survey acquisition software is running properly, and all sensors are communicating properly with software
- Check survey computer that it has sufficient hard drive space and memory to conduct survey and run current version of acquisition software.

### *Sound Velocity Profiles*

Sound velocity data at the sonar head is collected instantaneously during the MBES survey which is used for beam steering and bending calculations. Sound velocity profiles were conducted routinely during the MBES survey. These are conducted using the YSI Cast Away, a conductivity-temperature-depth sensor lowered through the entire water column. This sensor uses these data to create a sound velocity profile as a function of depth for the entire water column.

Sound velocity profiles are vital to MBES data collection and dictate the angles of acoustic beam transmission and return. These data were used in final MBES processing to calculate accurate sounding data.

### *Position Accuracy Verification*

Horizontal and vertical positions were corrected via Trimble's RTX system, a Real-Time Kinematic (RTK) broadcast through satellites to the INS GPS receiver. During the survey, the error calculations were closely monitored to ensure the position corrections were meeting the project requirements.

Periodic position checks were carried out at both known survey monuments and one set by the survey team. These periodic checks both confirm the horizontal and vertical accuracies of the survey equipment and the setup of the survey instrumentation.

## MBES PROCESSING

MBES data processing was conducted using the MBMAX64 toolbox of the HYPACK 2018 survey software. MBES data processing was conducted using a three-phase processing strategy;

1. Phase 1 = Review and editing of position, tide, heading, roll, pitch, and heave data.
2. Phase 2 = Review of swath data from each discrete survey data file.
3. Phase 3 = Area based editing of all data, and removal of spurious/erroneous data points.

Final data was exported as a gridded 3x3 foot XYZ file, including individual grid soundings northing coordinate, easting coordinate, and elevation referenced to NAVD88.

## DELIVERABLES

The following DRAFT deliverables were provided to Fishviews and/or LCRA:

- Memo
  - Colorado_River_Texas_MBES_Survey_07262019
- XYZ
  - *Mouth_to_BayCity_NAVD88.XYZ*
  - *BayCity_to_LaneCity_NAVD88.XYZ*
  - *LaneCity_to_Garwood_NAVD88.XYZ*
  - *Garwood_to_Ellinger_NAVD88.XYZ*

# Technical Memorandum

Date: December 21, 2020

To: Saul Nuccitelli (Texas Water Development Board)

From: Daniel Harris, PE, CFM (Scheibe Consulting, LLC, TBPE Firm 13880)

Subject: **Impact of bathymetric data on 2D hydraulic model results – Lower Colorado Case Study**

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There has been much recent discussion regarding the impact of riverine bathymetric data on floodplain modeling results. This has been especially relevant with respect to large scale modeling efforts such as FEMA base level engineering and development of the National Water Model. The impact of bathymetric data on flood modeling has also been a subject of recent academic research as exemplified by the recent findings of Cook and Merwade (2009) focused on 1D modeling of the Brazos River in Fort Bend County. Their study showed a decrease of 18% in inundated area when bathymetric data was added to detailed LiDAR data utilized in the Brazos River 1D HEC-RAS model. This memo provides an additional case study showing the impact of bathymetric data on the results of a 2D HEC-RAS hydraulic model covering a portion of the Lower Colorado River in Matagorda County.

Scheibe Consulting, LLC (Scheibe) is currently developing detailed 1D/2D hydraulic models as part of the Lower Colorado Flood Protection Planning Study funded by the Texas Water Development Board (TWDB). The modeling is split into five sections stretching across Colorado, Wharton, and Matagorda Counties south of Houston. Topographic data for the models is derived from LiDAR data sources including 2017 and 2018 Stratmap datasets from Texas Natural Resources Information System (TNRIS) and 2018 and 2019 datasets from United States Geological Survey (USGS). LiDAR data does not penetrate water well, therefore it does not contain any bare earth returns below water level in the Colorado River channel. To supplement this missing data, Scheibe contracted a bathymetric survey of the main Colorado River channel from the mouth of the river to the Colorado/Fayette County line. Due to flow conditions in the river and physical limitations of the collection equipment, the most complete bathymetric data was collected for the most downstream portion within Matagorda County. Bathymetric data for the old Colorado River channel between the intracoastal waterway and the Gulf of Mexico was supplied by the USACE Galveston District. The bathymetric data was used to enhance the LiDAR topography by adding definition below the water line during the creation of the final digital elevation models used in the hydraulic modeling.

Of the five sections, four of them are set up as 1D channels with 2D overbanks. Only the most downstream section in Matagorda County from FM 521 to the mouth of the river (i.e. the mouth section) was setup and run as a full 2D model. **Figure 1** shows the mouth section including the extents of 2D modeling and the coverage of LiDAR and bathymetric datasets. The mouth section model consists of several 2D meshes connected with 2D connectors reflecting the underlying LiDAR terrain. The base cell size for all meshes is 100 ft. by 100 ft. with break lines along many existing stream and ditch flowlines to enhance the detail of the mesh by creating smaller cells with a minimum 20 ft. by 20 ft. cell size. The model was calibrated to three major flood events, which include Hurricane Harvey, April 2016, and October 1998 events. The focus of calibration was on the Harvey event as it was the most recent and included many documented high-water marks to calibrate results to. Downstream boundary conditions for the Harvey and April 2016 events are stage hydrographs taken from the NOAA tidal gage located at Matagorda, TX near the mouth of the river. Tidal gage data was not available for the October 1998 event. Other boundary conditions were set to normal depth with a minimum slope of 0.0005 ft./ft. Inflows at the upstream end of the mouth section were taken from the results of the upstream Bay City section.

For a comparison of with and without bathymetric data, the mouth section was set up to run on a terrain consisting of LiDAR data with incorporated bathymetric data as well as a terrain without bathymetric data incorporated. Flow data for the comparison reflects a 1% annual chance event (ACE) as derived from the effective FEMA hydrology model for the Colorado River. The effective FEMA model was created as part of the 2001 LCRA FDEP study of the Colorado River that included creation of a basin-wide hydrology model as well the previous 1D unsteady Colorado RAS HEC-RAS model. Since the LCRA FDEP study was completed in 2001, it does not reflect the new Atlas 14 frequency rainfall data. **Figure 2** illustrates the decrease in the 1% ACE inundation area that occurs when bathymetric data is incorporated with the LiDAR data. The comparison resulted in an overall 7.6% decrease in 1% ACE inundation area when bathymetric data is incorporated. This corresponds to reductions of water surface elevation along the channel of up to 4.3 ft. **Figure 3** shows a comparison of channel water surface profiles for the with and without bathymetry scenarios. **Figure 4** shows the spatial distribution of water surface elevation reduction when bathymetric data is incorporated revealing that 59% of the inundation area shows a water surface elevation decrease of at least 1 foot. This amount of water elevation decrease is very significant in the flat coastal plain near the mouth of the Colorado River.

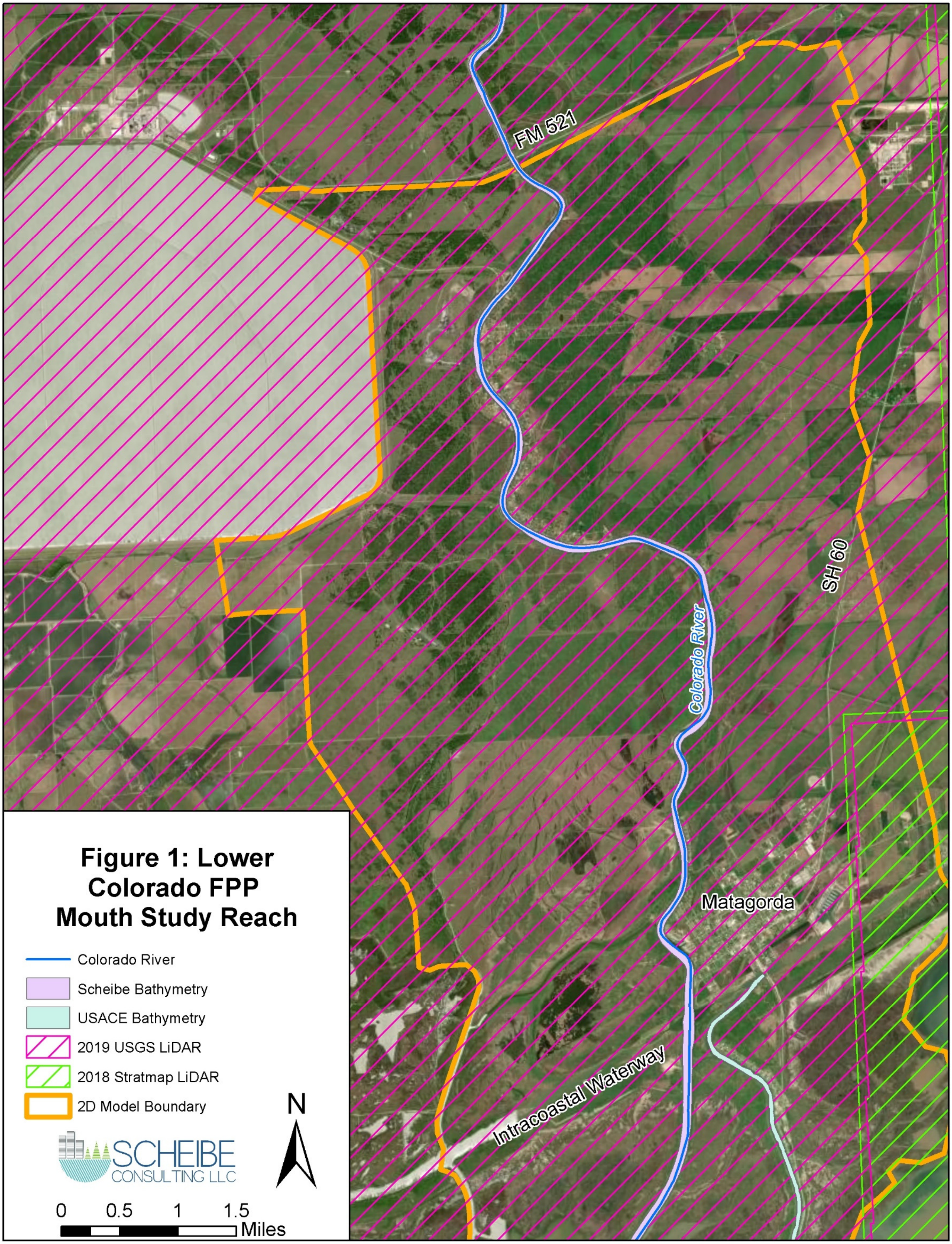



Figure 1: Lower Colorado FPP Mouth Study Reach

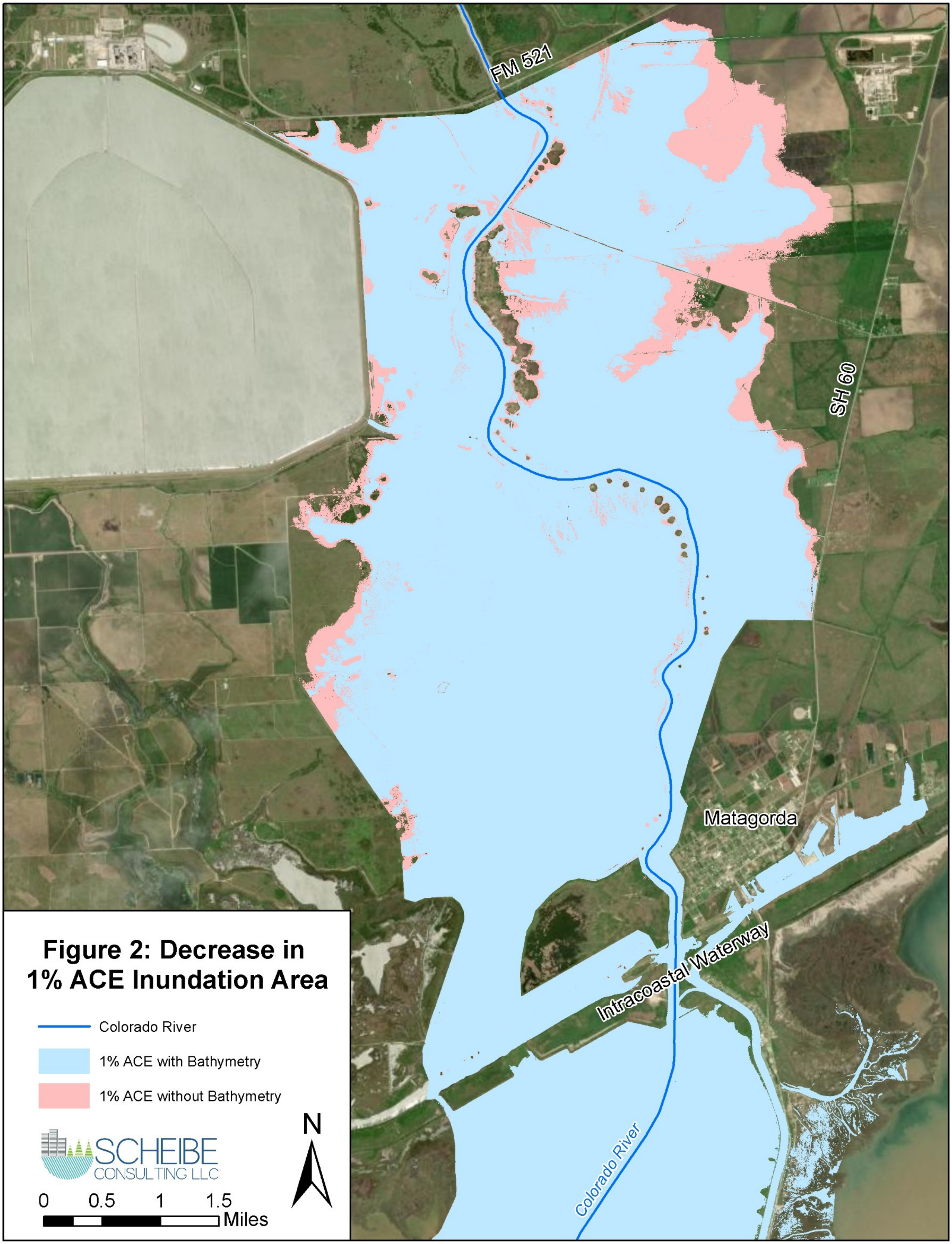



**Figure 2: Decrease in 1% ACE Inundation Area**

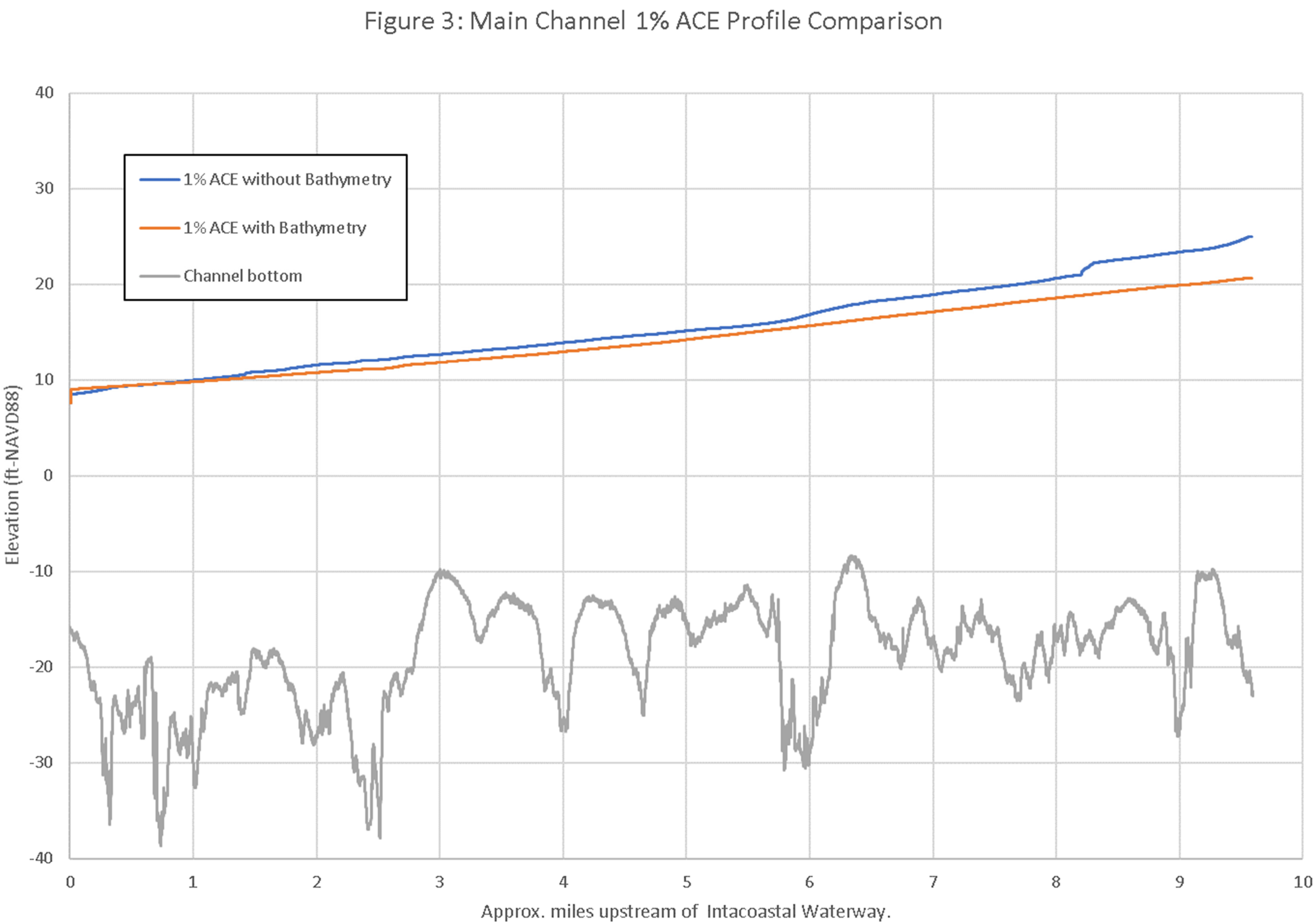
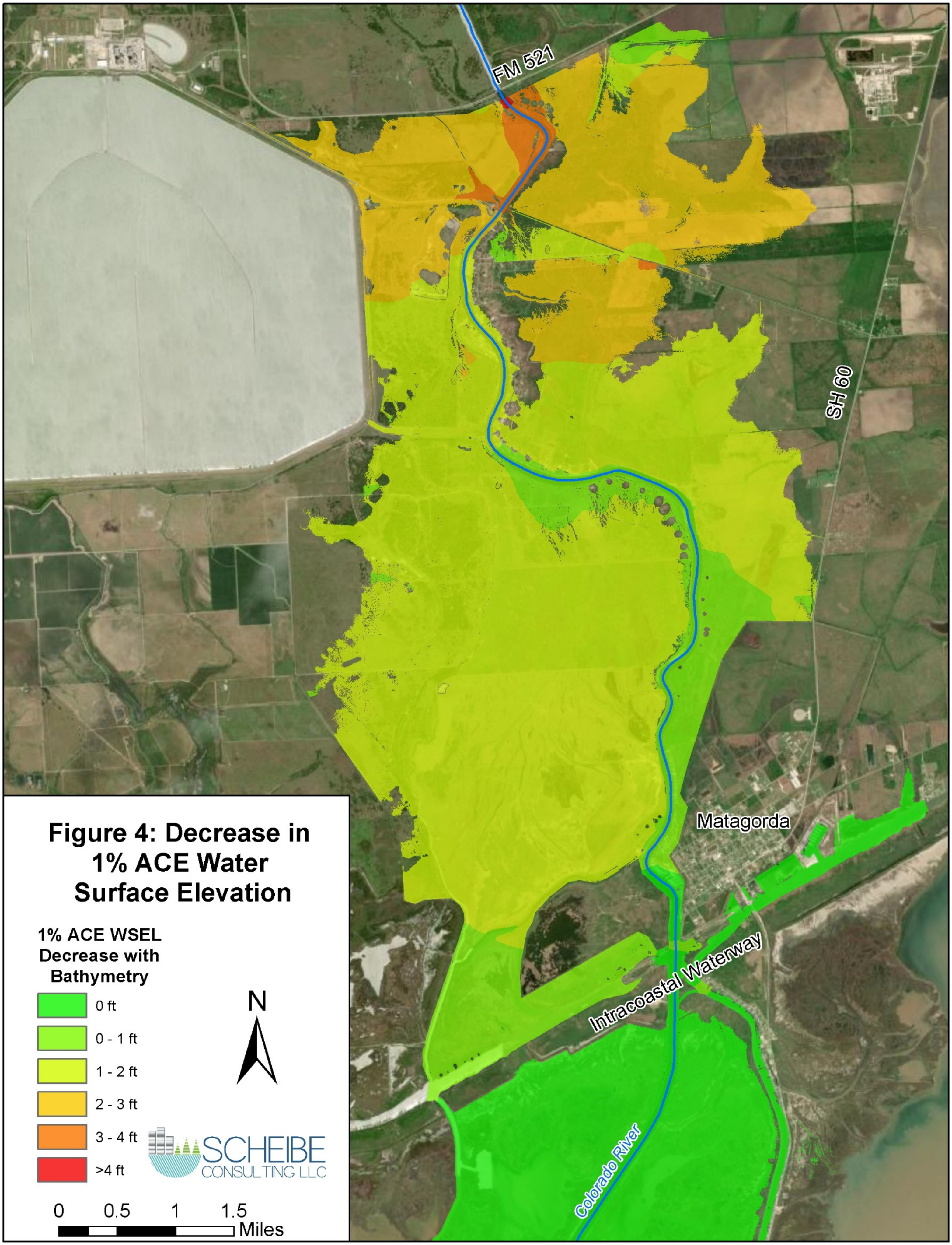


Figure 3: Main Channel 1% ACE Profile Comparison
1% ACE without Bathymetry
1% ACE with Bathymetry
Channel bottom
Elevation (ft-NAVD88)
40
30
20
10
0
-10
-20
-30
-40
0
1
2
3
4
5
6
7
8
9
10
Approx. miles upstream of Intacoastal Waterway.


FM 521
SH 60
Matagorda
Intracoastal Waterway
Colorado River
Figure 4: Decrease in 1% ACE Water Surface Elevation
1% ACE WSEL Decrease with Bathymetry
0 ft
0 - 1 ft
1 - 2 ft
2 - 3 ft
3 - 4 ft
>4 ft
N
SCHEIBE CONSULTING LLC
0
0.5
1
1.5
Miles

# APPENDIX B:
# MODELING NOTEBOOK

# Lower Colorado River FPP Modeling Notebook

**Entry #: 1**
**Modeler: Daniel Harris**
**Date: 10/18/2019 (updated 8/20/2020)**
**Subject: LiDAR data sources**

LiDAR data sources are listed below by model section:

Columbus – StratMap 2017 and USGS 2018 at the most downstream area.

Garwood –USGS 2018

Wharton – USGS 2018

Bay City – USGS 2018 and USGS 2019

Mouth – USGS 2019

Accuracy standards for the different datasets are as follows:

StratMap 2017 – 50 cm resolution, 19.6 cm vertical accuracy (non-vegetated)

USGS 2018 – 70 cm resolution, 19.6 cm vertical accuracy (non-vegetated)

USGS 2019 – 70 cm resolution, 19.6 cm vertical accuracy (non-vegetated)

Project reports downloaded from TNRIS for each dataset indicate that these standards have been met or exceeded.

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**Entry #: 2**
**Modeler: Daniel Harris**
**Date: 10/18/2019**
**Subject: Bathymetric and survey data sources**

Bathymetric data has been obtained for the main channel of the Colorado River including the current and former mouths. The bathymetric/survey data comes from four different sources as described below.

Corps of Engineers bathymetric survey – Survey data is from the USACE Galveston District hydrographic survey program and covers the old mouth of the Colorado River (downloaded in 5/16/2019). This data was incorporated into the terrain data set for the Mouth section RAS model. Data consists of single beam cross-sections taken approximately every 250 feet. The elevation data was delivered in Mean Lowest Low Tide (MLLW) datum and was converted to NAVD88 for use in the FPP study.

Fishviews bathymetric survey – Fishviews and its subcontractor were contracted to collect multi-beam bathymetric survey data for the main channel of the Colorado from the new mouth to the Fayette County line. Bank to bank data was collected to a point just downstream of the Matagorda County line. Shallow water and debris prevented the field crew from collecting a full dataset upstream of this point. There are a few large gaps with no data and large stretches with only thalweg data (mainly in Colorado county). This data was incorporated into terrain datasets for all sections.

AquaStrategies bathymetric survey- AquaStrategies was contracted to acquire single-beam cross-section data at several locations throughout Colorado and Wharton Counties to add detail to the modeling.

Single beam data was also collected to fill some of the data gaps left by Fishviews. This data was incorporated into individual RAS XS or terrain data as needed.

Original 2001 model bridge/cross-section survey – Bridge survey data collected in 2001 as part of the LCRA FDEP modeling effort was reincorporated where needed into the current RAS models. It is assumed that the bridges have not been significantly structurally reconstructed or updated since the 2001 FDEP study. 2001 XS survey was given lowest priority for use after the newly collected bathymetric data. It was only used if it still appeared to be valid given the everchanging nature of the Colorado River channel. Notes have been added to the RAS models where 2001 survey data was reincorporated.

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**Entry #: 3**
**Modeler: Daniel Harris**
**Date: 10/18/2019**
**Subject: Model Sections**

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The 2001 FDEP model was divided into sections from one gage location to the next. The FPP model is split into section centered on each gage within the study area. Ultimately, the FPP model will be used to develop inundation maps for the INFRM team flood information tool. In the tool the inundation zones must be centered on a gage location and extend to the upstream and downstream limits of influence. For this reason, it made sense to adjust the model splits as follows.

Columbus Section – centered on Columbus gage and extends from Fayette County line about 6 1/3 miles upstream of US 90A.

Garwood Section – centered on Garwood gage and extends from about 6 1/3 miles upstream of US 90A to about 9 ¼ miles upstream of the Glen Flora overflow.

Wharton Section – centered on Wharton gage and extends from about 9 ¼ miles upstream of the Glen flora overflow to just upstream of Matagorda County line.

Bay City Section – centered on Bay City gage and extends from just upstream of the Matagorda County line to FM 521.

Mouth Section – a full 2D section that extends from FM 521 to the mouth of the Colorado.

*08/09/2021 Update – The Columbus and Garwood sections have been combined to resolve modeling issues at the boundary of the two sections. There are now 4 model sections.*

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**Entry #: 4**
**Modeler: Daniel Harris**
**Date: 10/18/2019**
**Subject: General model development assumptions**

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- RAS models are a combination of full 1D, 1D/2D, or full 2D sections. Full 1D unsteady modeling is used in less populated areas and/or areas not highly impacted by 2D overbank flows. 1D/2D sections are utilized for areas with significant/complex 2D overbank flows combined with 1D main channel flows. Full 2D flow modeling is only used in the Mouth Section to capture the complex nature of interaction between riverine flows and coastal storm surge data.
- 1D cross-section location and layout is derived from the 2001 FDEP model. Effort was made to keep cross-sections in the same locations, but tweaks were made throughout to adjust the cross-sections

to match the current LiDAR data where needed. Additional cross-sections were also added where needed to ensure proper hydraulic transitions.

- 2D meshes were delineated in ArcGIS where needed and were general divided by major roadways or raised canals. More detail in the layout of 2D meshes was used in the Cities of Columbus, Wharton and Bay City. The base mesh cell size for all 2D meshes is 100 ft. by 100 ft. Breaklines were added where necessary where smaller cell size was needed to define changes in topography such as stream channels and roadway and canal crests. Minimum cell sizes for breaklines ranged from 10-30 ft. and maximum cell sizes ranged from 40-60 ft depending on the level of detail needed.
- Lateral Weirs were added to transition from the 1D to 2D sections. Weir station and elevation data was taken from RAS terrain data used in each section. Weir coefficients of 0.5 were entered for all lateral weirs and adjusted as needed for model stability and accuracy.
- 2D area connectors were drawn in ArcGIS and added to the models. Weir station and elevation data for the connectors was taken from RAS terrain data used in each section. Weir coefficients of 2.6 were entered for all connectors and adjusted as needed for model stability and accuracy. This coefficient is standard for road crossings, which most of the connectors represent.
- Bridge and inline weir data were incorporated from the 2001 FDEP model as discussed in Entry #2 above.
- Ineffective areas were set at appropriate locations to model overbank areas of ineffective flow as well as transitions into and out of bridge openings. Permanent ineffective areas were used as needed to model overbank ponds and gravel pits in 1D sections as they do not provide any flood conveyance but do provide significant storage.

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**Entry #: 5**
**Modeler: Daniel Harris**
**Date: 10/18/2019**
**Subject: Land use/Manning's N development**

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The only land use dataset that covers the entire study area is the latest NLCD dataset, however, the raw NLCD dataset is derived from remote sensing satellite data and is not accurate enough for developing a Mannings's N layer for use in 2D hydraulic modeling. The Brazos - Colorado land use dataset obtained from TCEQ is a much cleaner and more accurate dataset based on the Anderson land cover classification system. However, the data set only partially covers the study area. The dataset was extended to cover the remainder of the study area using recent aerial images to determine the land use classifications. N-values were then populated in the dataset based on land use classification as indicated in the table below. The range of n-values used was deemed acceptable when compared to guidance provided by HCFCD.

| CODE | Description | N Value |
|---|---|---|
| 111000 | Stream/River | 0.04 |
| 112000 | Canal/Ditch | 0.035 |
| 113000 | Lake/Pond | 0.03 |
| 114000 | Reservoir | 0.03 |
| 115000 | Bay/Estuary | 0.03 |
| 116000 | Sea/Ocean | 0.03 |
| 211000 | Single-Family Residential | 0.12 |

| CODE | Description | N Value |
|---|---|---|
| 212000 | Multi-Family Residential | 0.12 |
| 221000 | Commercial/Light Industry | 0.14 |
| 222000 | Heavy Industry | 0.14 |
| 223000 | Communication/Utilities | 0.11 |
| 224000 | Institutional | 0.12 |
| 225000 | Agricultural Business | 0.1 |
| 226000 | Transportation | 0.03 |
| 227000 | Entertainment/Recreation | 0.09 |
| 230000 | Mixed Urban | 0.13 |
| 300000 | Bare | 0.04 |
| 310000 | Transitional | 0.04 |
| 320000 | Quarries/Gravel Pits | 0.05 |
| 330000 | Bare Rock/Sand | 0.04 |
| 340000 | Flats | 0.065 |
| 350000 | Disposal | 0.05 |
| 410000 | Woody Vegetation | 0.085 |
| 411000 | Forested/Trees | 0.1 |
| 412000 | Shrubland | 0.09 |
| 413000 | Orchards/Vineyards | 0.09 |
| 421000 | Natural Herbaceous | 0.07 |
| 422000 | Cropland | 0.05 |
| 422211 | Rice Fields | 0.065 |
| 422410 | Pasture/Hay | 0.06 |
| 422421 | Grass Farms | 0.045 |
| 430000 | Wetlands | 0.07 |
| 431000 | Woody Wetlands | 0.08 |
| 432000 | Emergent Wetlands | 0.07 |

**Entry #: 6**
**Modeler: Daniel Harris**
**Date: 06/18/2020**
**Subject: Modeling of overbank culvert crossings**

Culvert crossings through roads located in the 2D overbank areas of the models were represented using one of three different methods depending on the situation. Descriptions of the methods are as follows:

Method 1: This method was used for culvert crossings through 2D connectors where previous model data available to model culverts through the connector. This method was specifically used in the Wharton section where previous model data was available associated with the Colorado overflow through the City of Wharton.

Method 2: This method was used for culvert crossings through 2D connectors located along the top of major roads where no previous model information existed. Culvert sizes were determined from aerial images or other external sources. One specific source in the Bay City section was data from the

Matagorda Drainage district documenting the culvert locations and sizes along the river levees. A notch was added to the 2D connector at the culvert location representing the total width of the culvert opening allowing water to flow from mesh to mesh.

Method 3: this method was used for culvert crossings located internally within 2D meshes. The culvert was modeled by drawing a break line on top of the road in such a way that water was passed from the upstream cells to the downstream cells as if water were passing through the culvert. This method is likely the least accurate of the three methods but provides a way for water to pass through critical culvert crossings.

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**Entry #: 7**
**Modeler: Daniel Harris**
**Date: 08/03/2020**
**Subject: Initial Model Calibration**

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Model calibration was focused mainly on the USGS and LCRA gage locations. Many highwater marks (HWMs) were collected for the Harvey event by the USGS as well as Scheibe Consulting. Scheibe HWMs were focused mainly within Wharton County. USGS collected data at several bridge crossings and other key locations along the river as well as at overbank locations that saw flooding. HWMs for April 2016 and June 1998 events were limited to gage locations.

Minor changes were made to channel n-values as well as some bridge modeling methods with the goal of producing model water surface elevation results within +/-0.5 feet of gage and HWM survey results. Most of the n-value adjustments were within the Wharton section downstream the Glen Flora and Wharton Gauge locations. Initial channel n-values where set at 0.4 and after calibration where raised to 0.5-0.6 at these locations. The bridge modeling method for the Business 59 bridges at the City of Wharton where set to use energy low flow method only. It appears that the momentum low flow method produced losses through the bridges that were too high. This helped with calibration to the Wharton gage which is on the downstream side of the bridges.

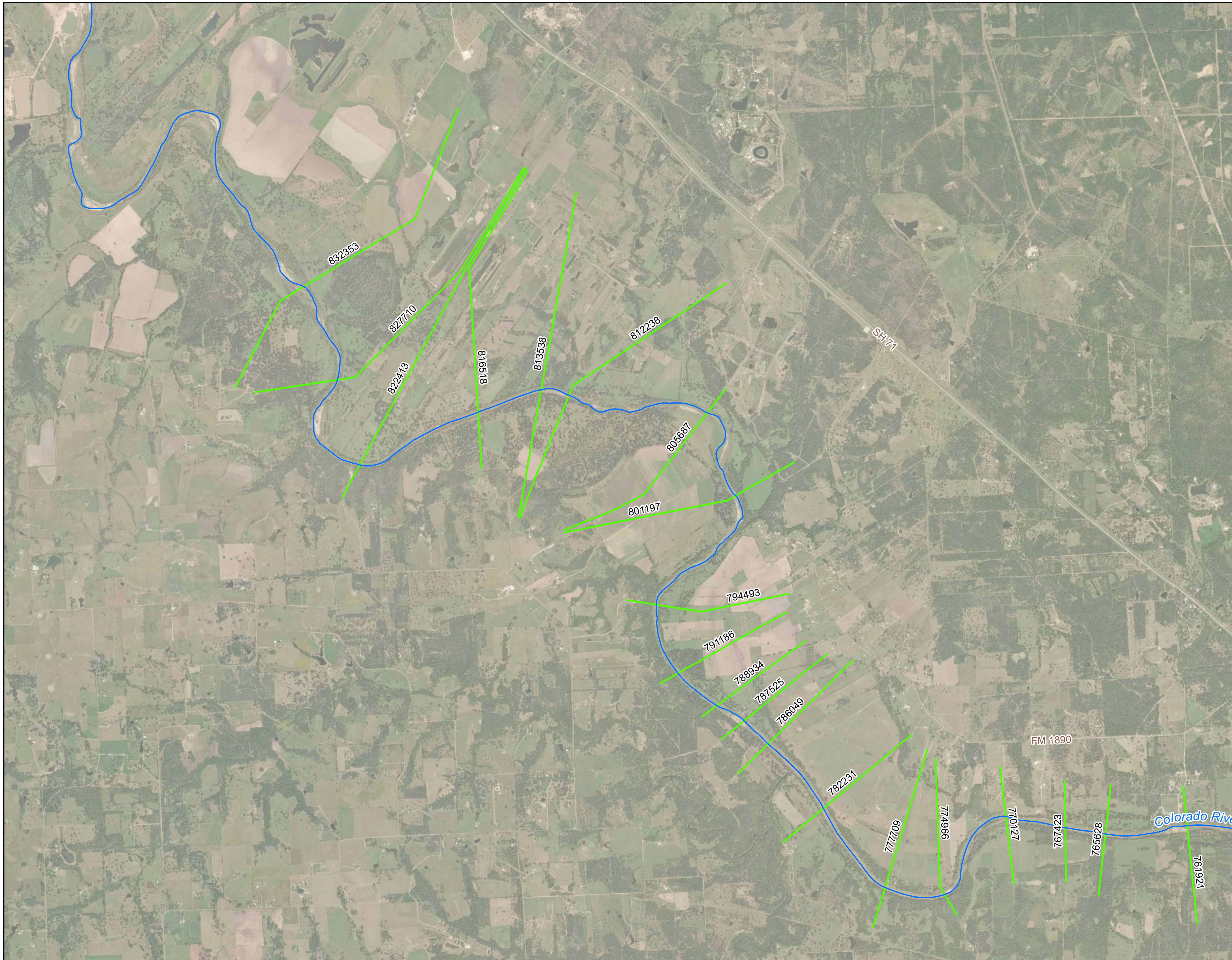
Downstream boundary conditions were left as normal depth due to known mass balance issues associated with stage boundary conditions as the downstream end of a 2D mesh. The normal depth results produce more consistent and reasonable hydrographs used as input into the downstream sections. Friction slopes for the normal depth boundary conditions were initially based on channel invert slope at model boundary locations. The slopes were adjusted in an effort to match the max water surface elevation results between adjacent models at boundary condition locations for each calibration event. The boundary WSELs are generally within +/-1.5 feet at the Mouth/Bay City and Bay City/Wharton boundaries. Wharton/Garwood boundary WSELs are within +/- 3 feet. Garwood/Columbus boundary results remain about 5 feet different for the Harvey event despite several slope adjustments. However, the Garwood/Harvey boundary WSELs for the other two calibration events are within +/- 2 feet.

*08/09/2021 Update – Per USACE review comments the downstream boundary conditions between sections were set to stage hydrograph for the channel section and connected to the upstream stage hydrograph for the next downstream section. Also, a vertical variation in n-value was used for several cross-sections at and downstream of the Wharton gage to create a better match to the official USGS rating curve for the Wharton gage. This was done so that the results met the root mean square error requirement for the FDST when compared to the USGS rating curve.*

**Entry #: 8**
**Modeler: Daniel Harris**
**Date: 08/18/2020**
**Subject: Hydrologic inputs**

Hydrographs for input into the hydraulic models were produced using gridded hourly rainfall data from NWS. The gridded rainfall data (XMRG format) for the Harvey, April 2016, and November 2004 events was obtained from NWS and processed using HEC-MetVue software to produce basin averaged hyetographs. The sub-basin data and HMS model from the 2001 LCRA FDEP Study was used to produce the required input hydrographs. No changes were made to the original Snyder's unit hydrograph parameters (lag time and peaking coefficient) developed during the FDEP study. However, initial and constant losses and routing methodology were updated to better calibrate hydrologically to the modeled storm events. Initial and constant loss parameters were increased by 50% to better match the volume represented by observed hydrographs for the modeled storm events. The original Modified Puls routing was replaced with Lag and K routing parameters developed by calibrating the Columbus gage section of the hydrologic model to the Harvey, April 2016, and November 2004 events. The "Lag and K" routing method was not available within HEC-HMS at the time of the 2001 FDEP study and allows for more accurate adjustment of lag and attenuation of the routed hydrographs to better match gage data. Lag and K parameters were calculated with similar methods for the remaining routing reaches for the Garwood, Wharton, and Bay City and Matagorda sections. Rather than rerunning with NWS data, original FDEP meteorology already included in the LCRA HMS model for the October 1998 event was used.

# APPENDIX C:
# HYDRAULIC MODEL LAYOUT




# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C1: Hydraulic Model Layout- Columbus/Garwood Section

**Key To Features**

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

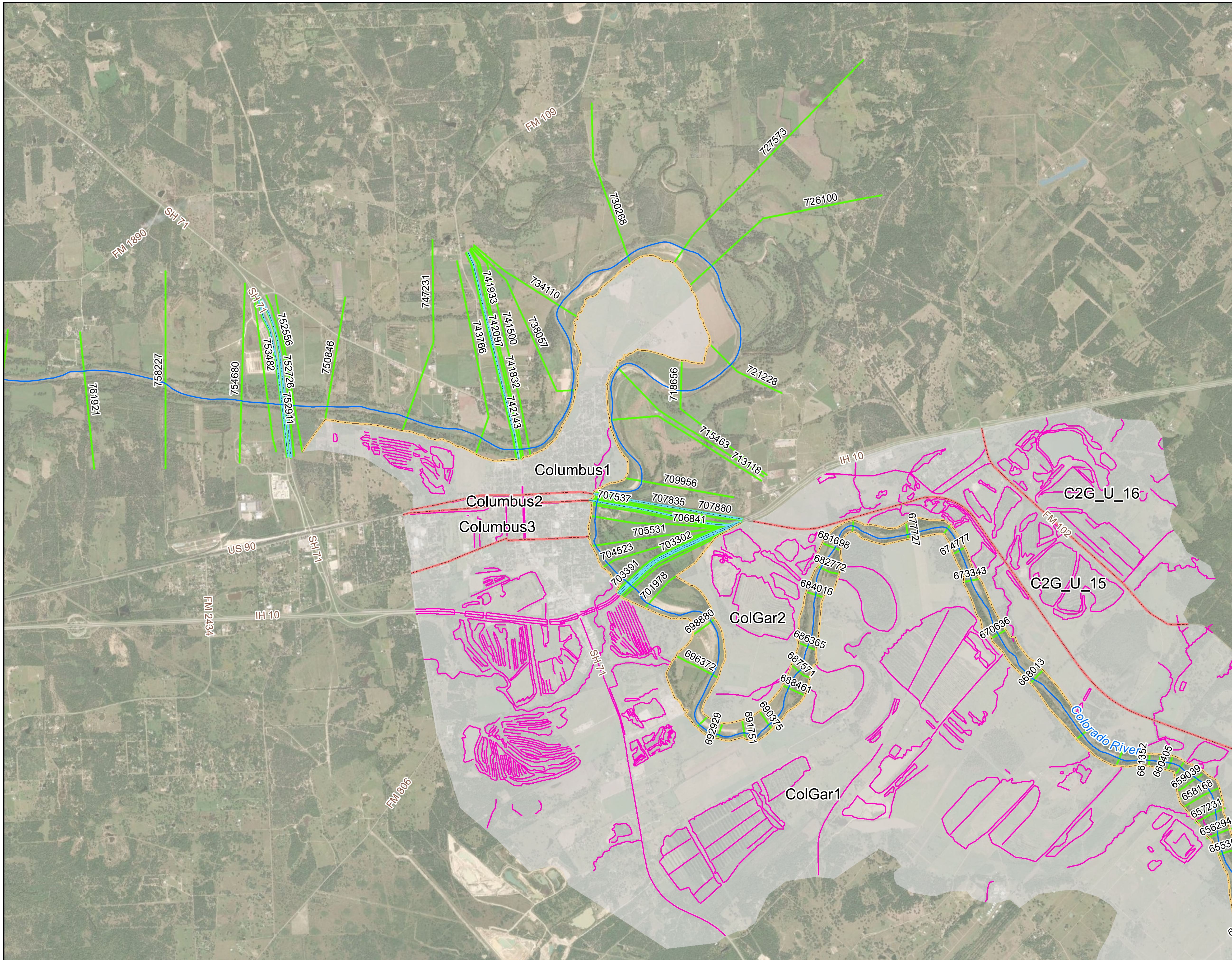
N

0 4,000 8,000 Feet

# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C2: Hydraulic Model Layout- Columbus/Garwood Section




**Key To Features**

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

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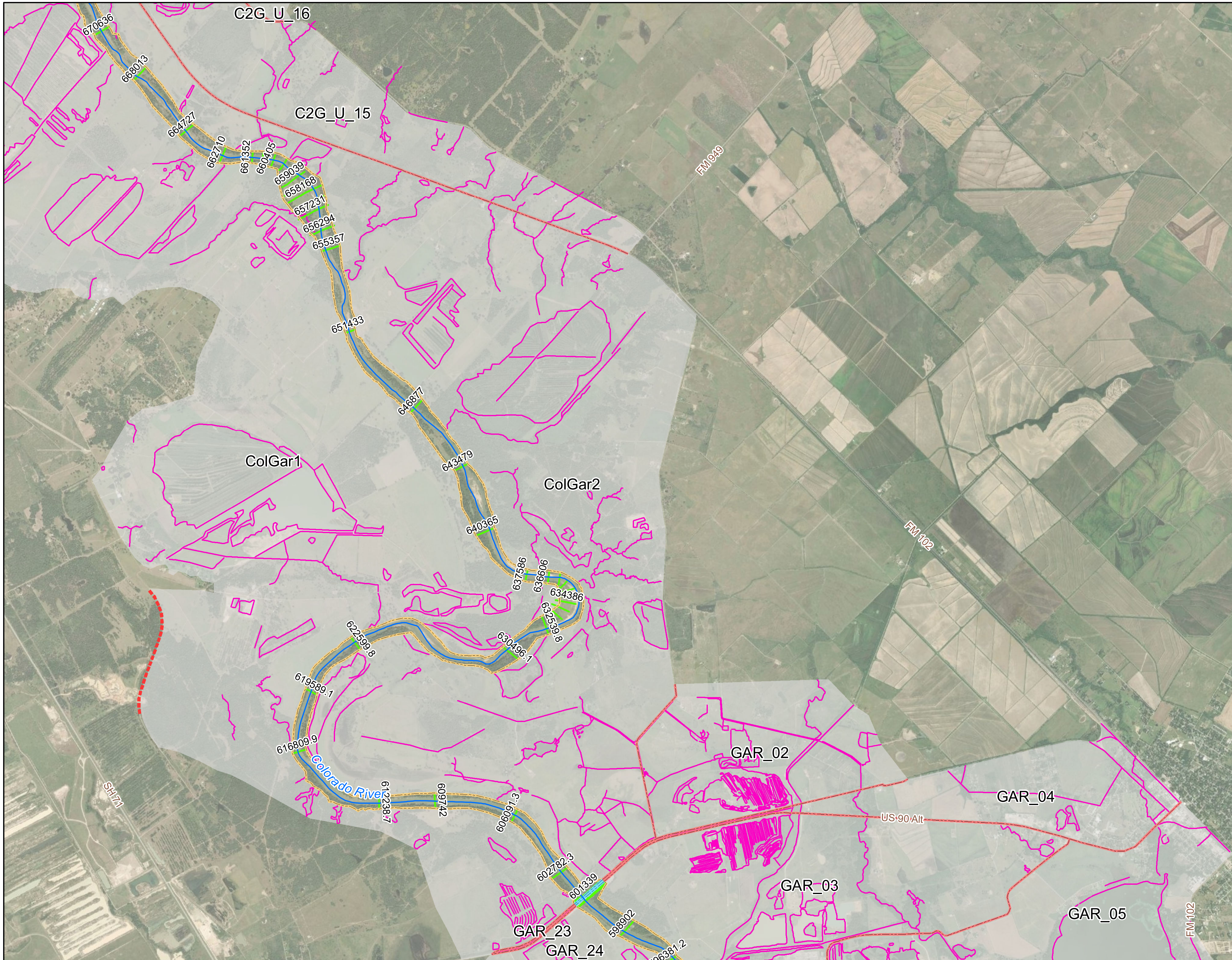
# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C3: Hydraulic Model Layout- Columbus/Garwood Section




### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

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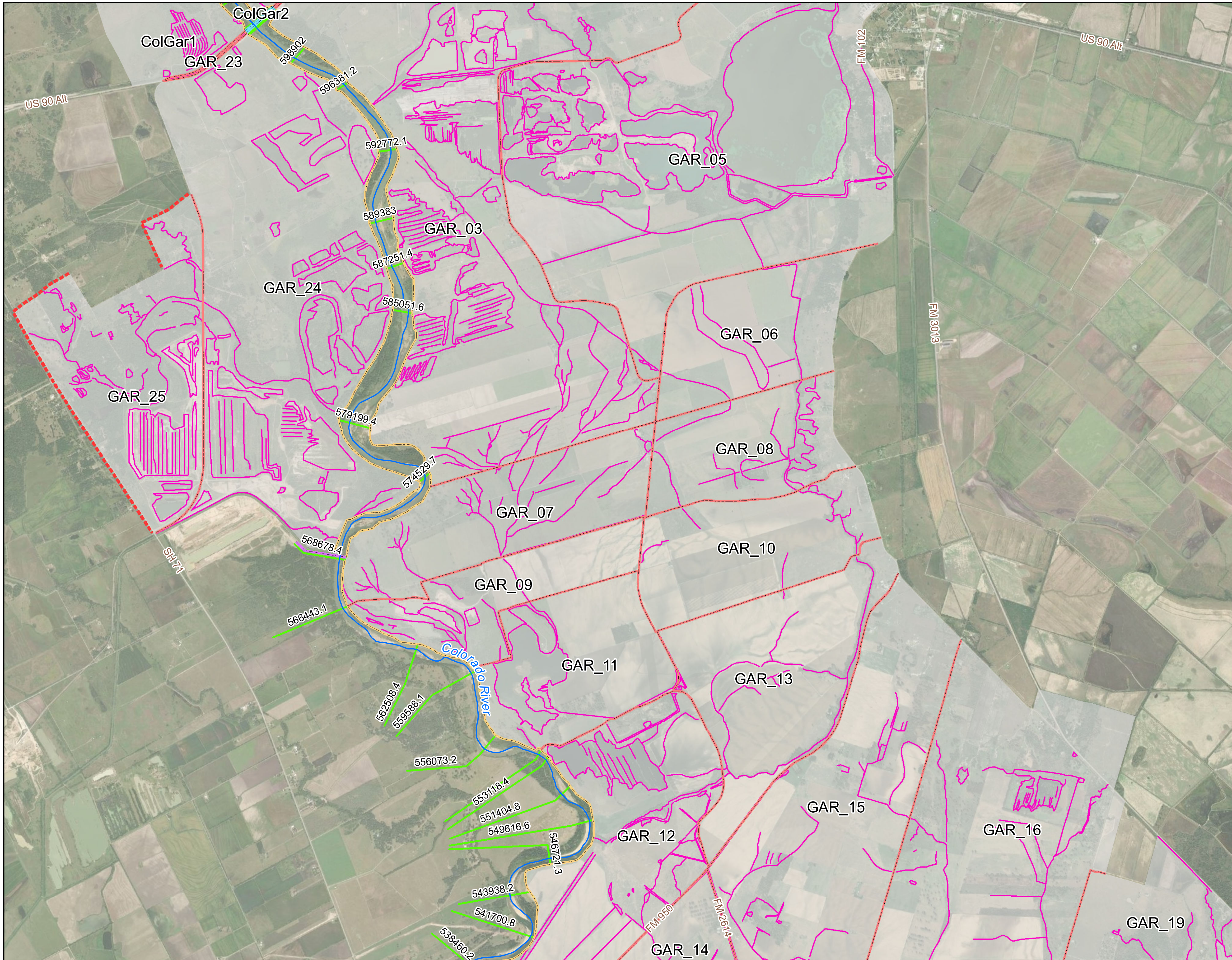
# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C4: Hydraulic Model Layout- Columbus/Garwood Section




### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

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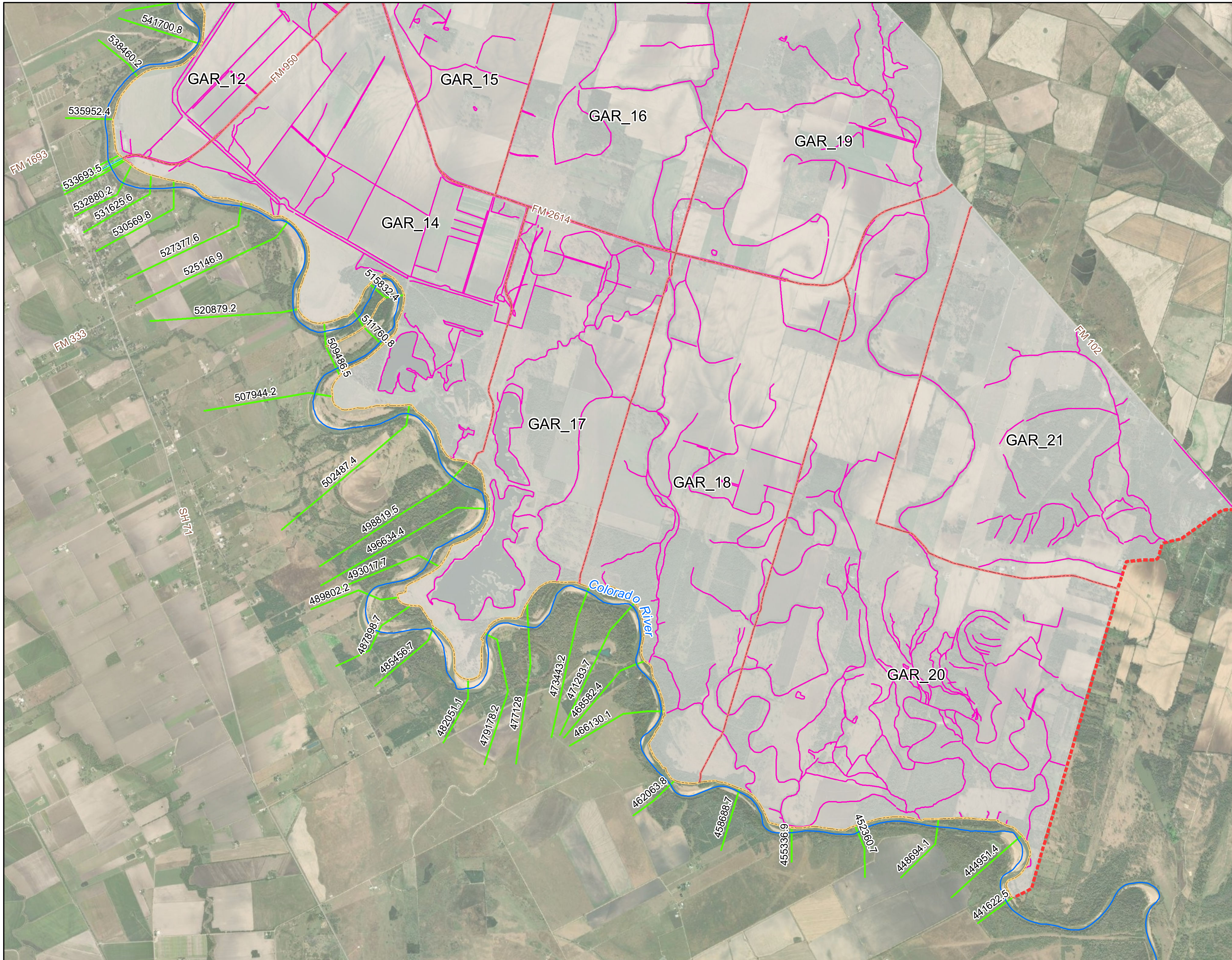



# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C5: Hydraulic Model Layout- Columbus/Garwood Section

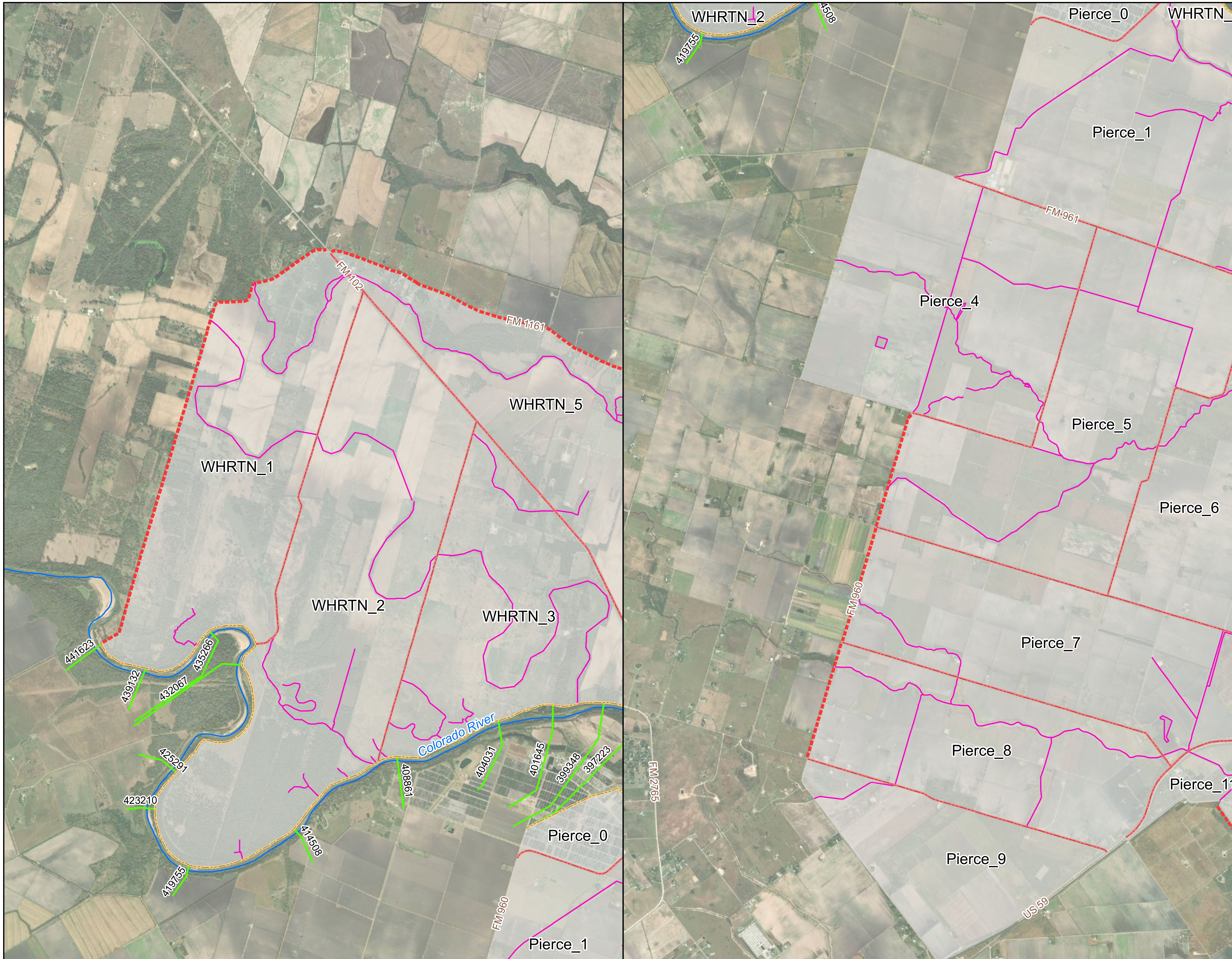
### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

N

0 4,000 8,000 Feet




# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C6: Hydraulic Model Layout- Wharton Section

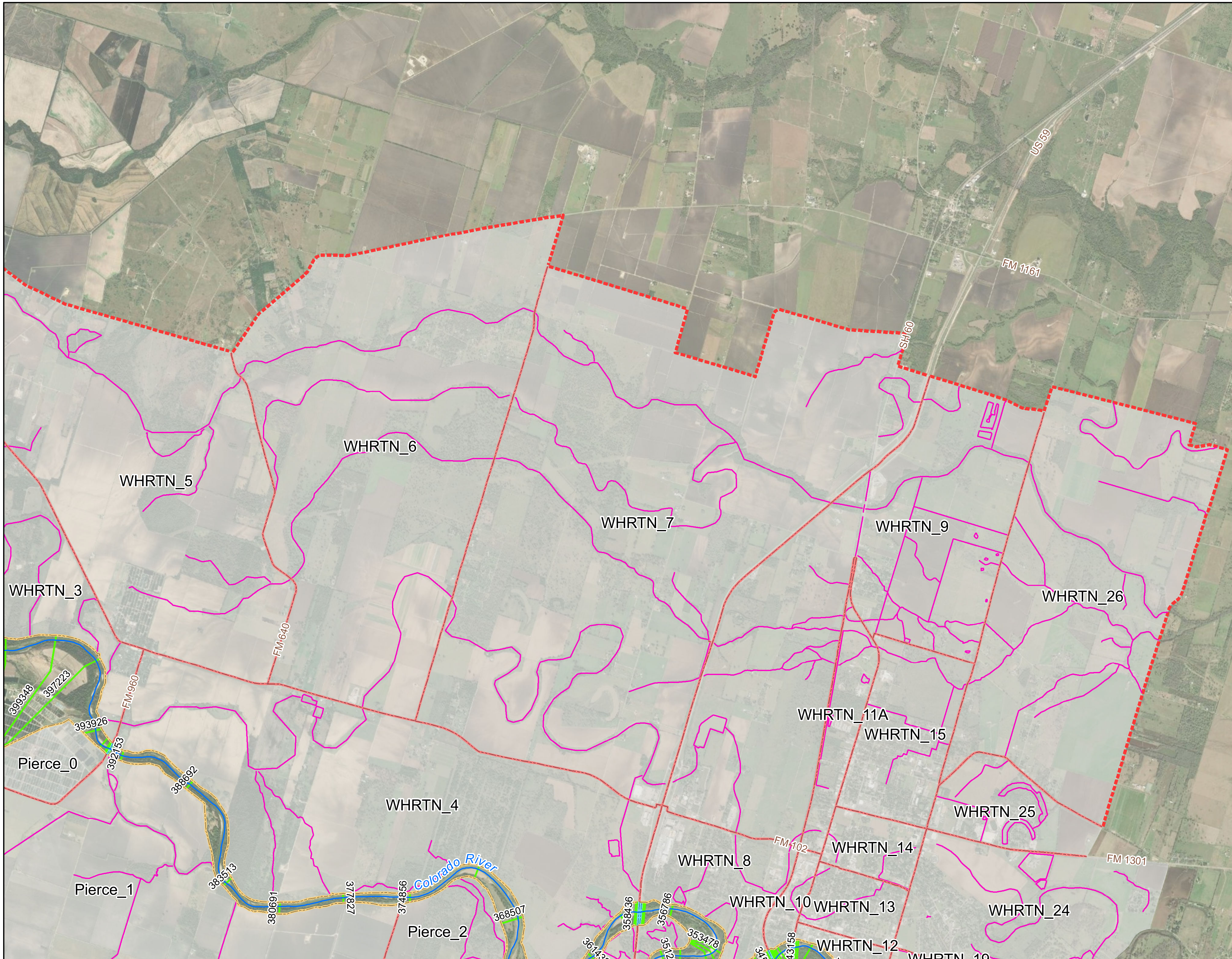
### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

N

0 4,000 8,000 Feet




# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C7: Hydraulic Model Layout- Wharton Section

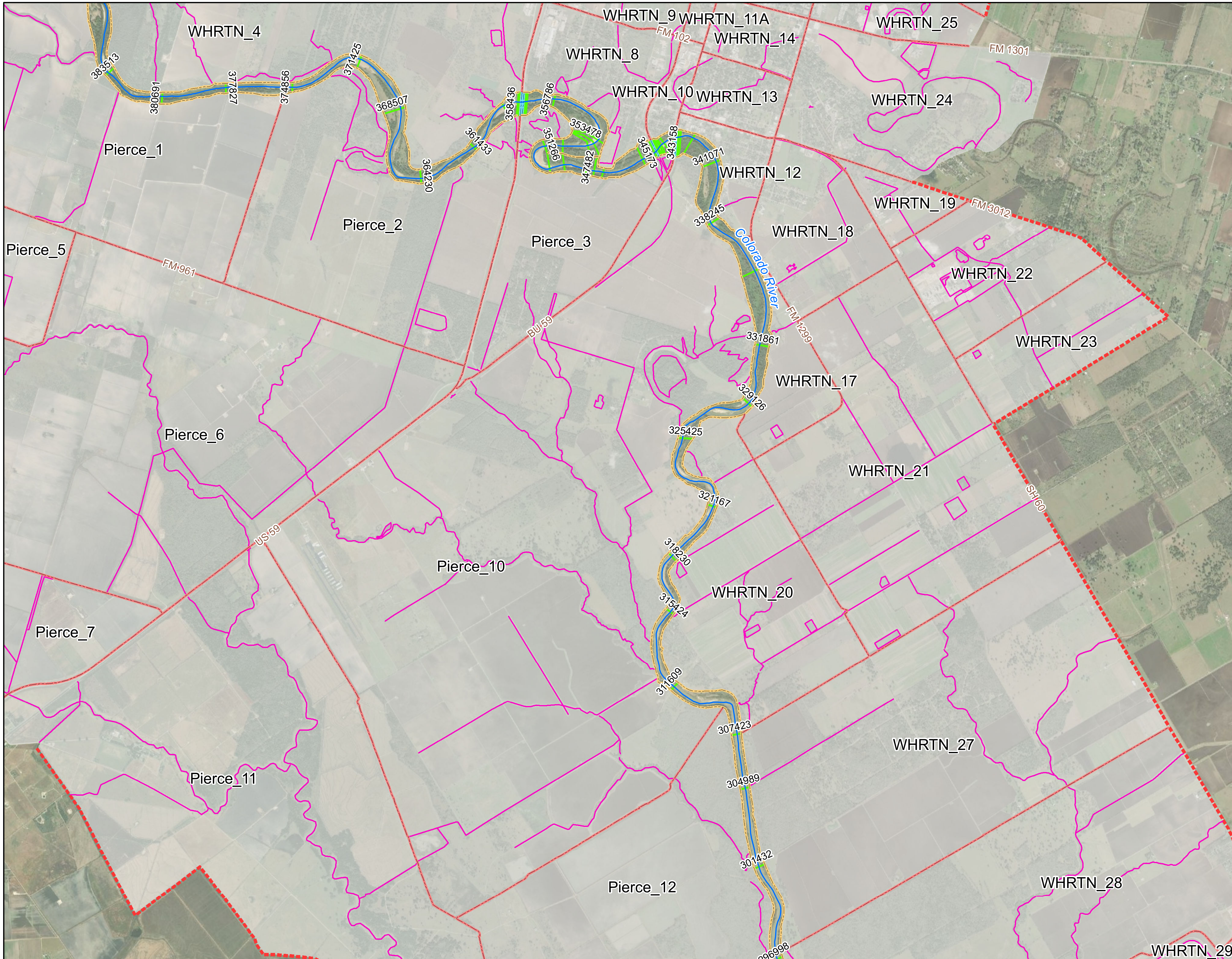
### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

N

0 4,000 8,000 Feet




# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C8: Hydraulic Model Layout- Wharton Section

**Key To Features**

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

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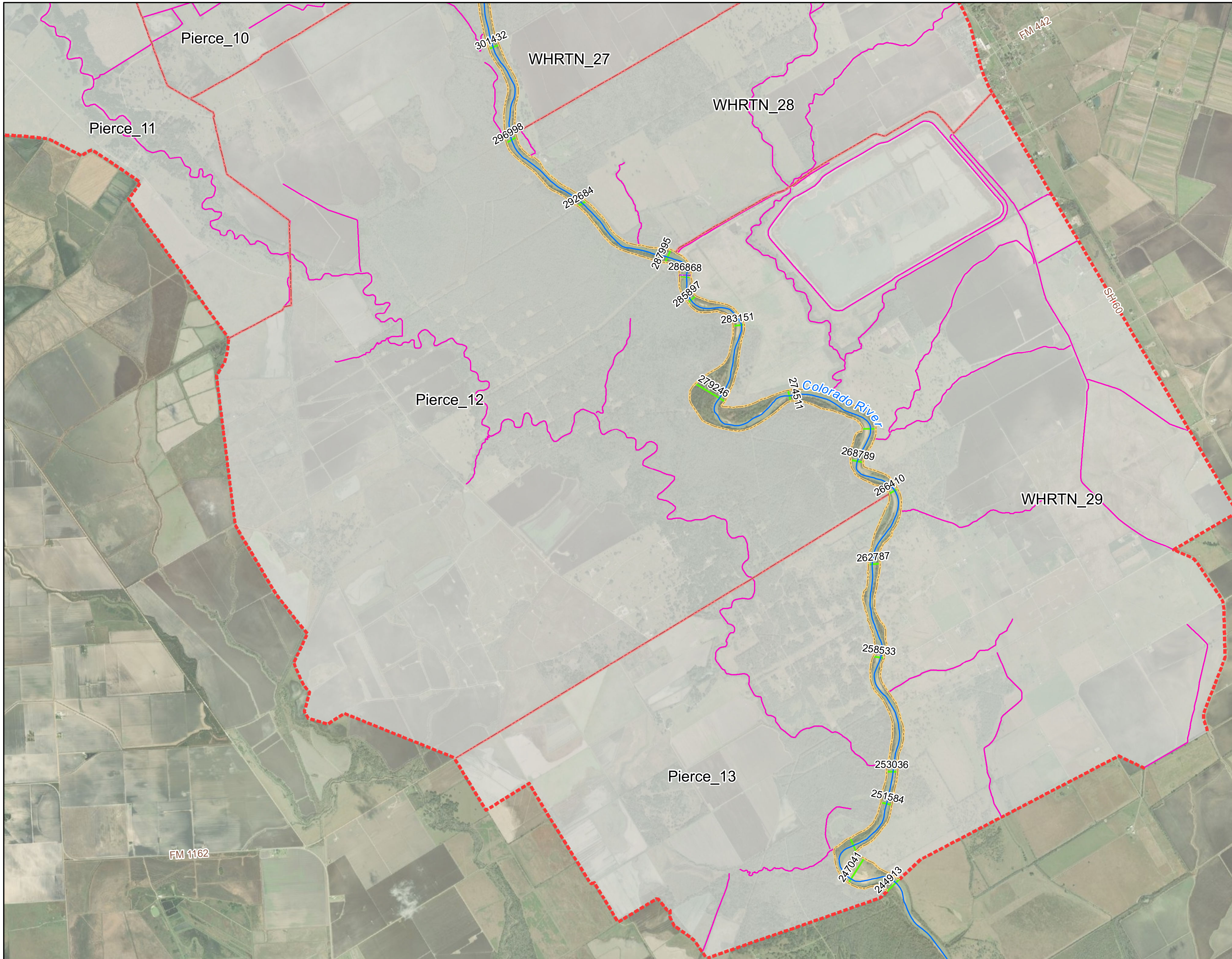


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C9: Hydraulic Model Layout- Wharton Section

### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

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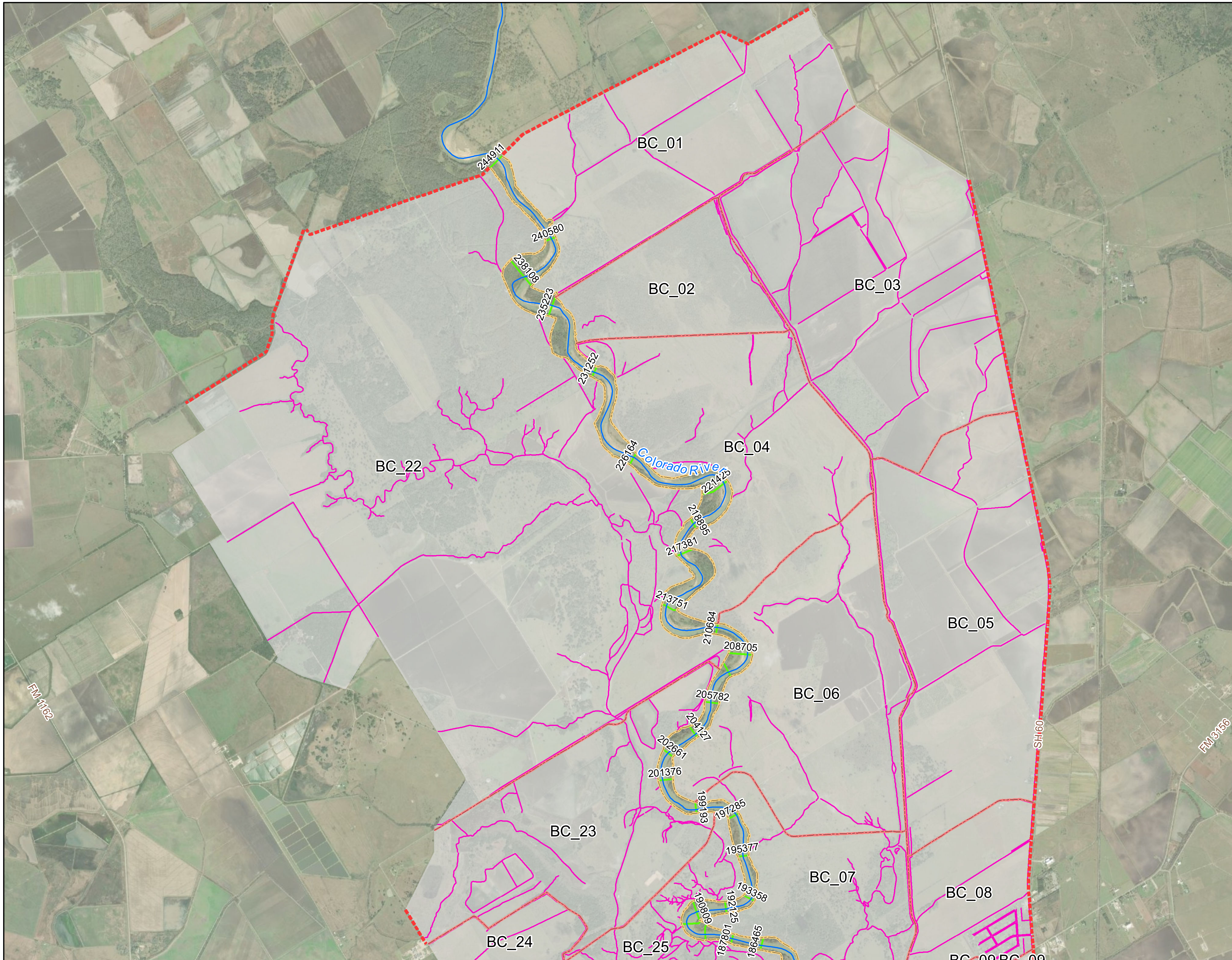
0 4,000 8,000 Feet




# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C10: Hydraulic Model Layout- Bay City Section

### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

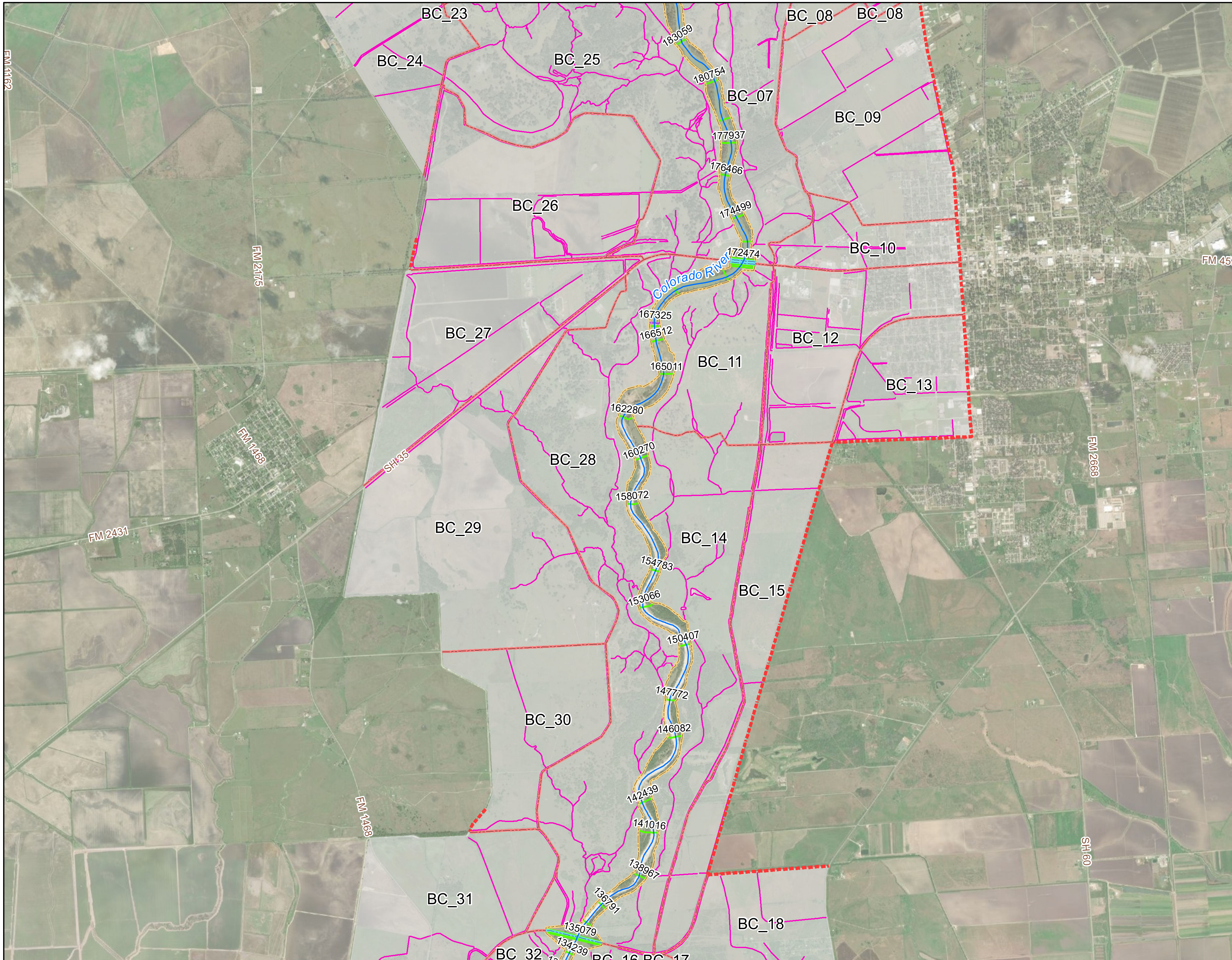
N

0 4,000 8,000 Feet

# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C11: Hydraulic Model Layout- Bay City Section




### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

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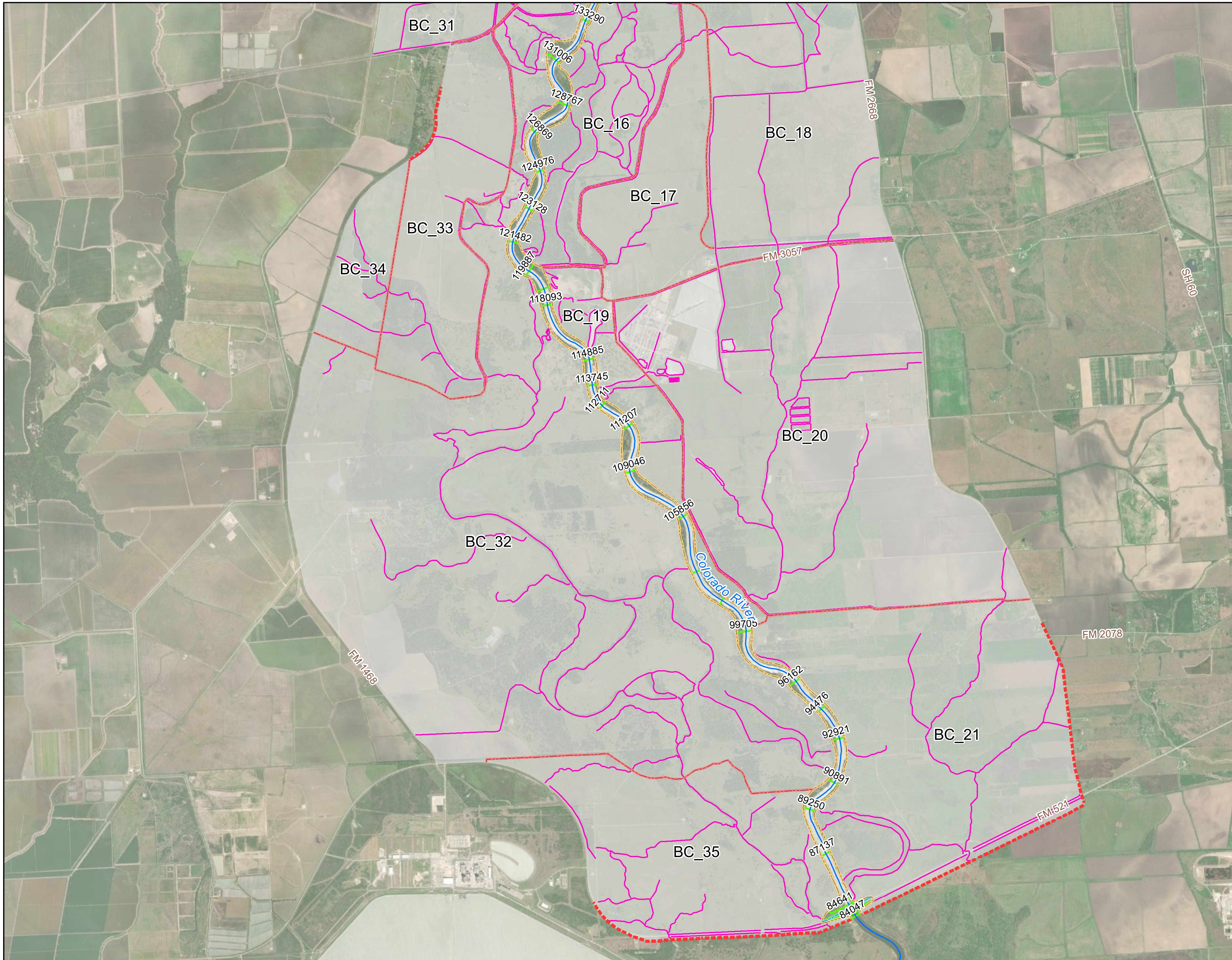


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C12: Hydraulic Model Layout- Bay City Section

### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

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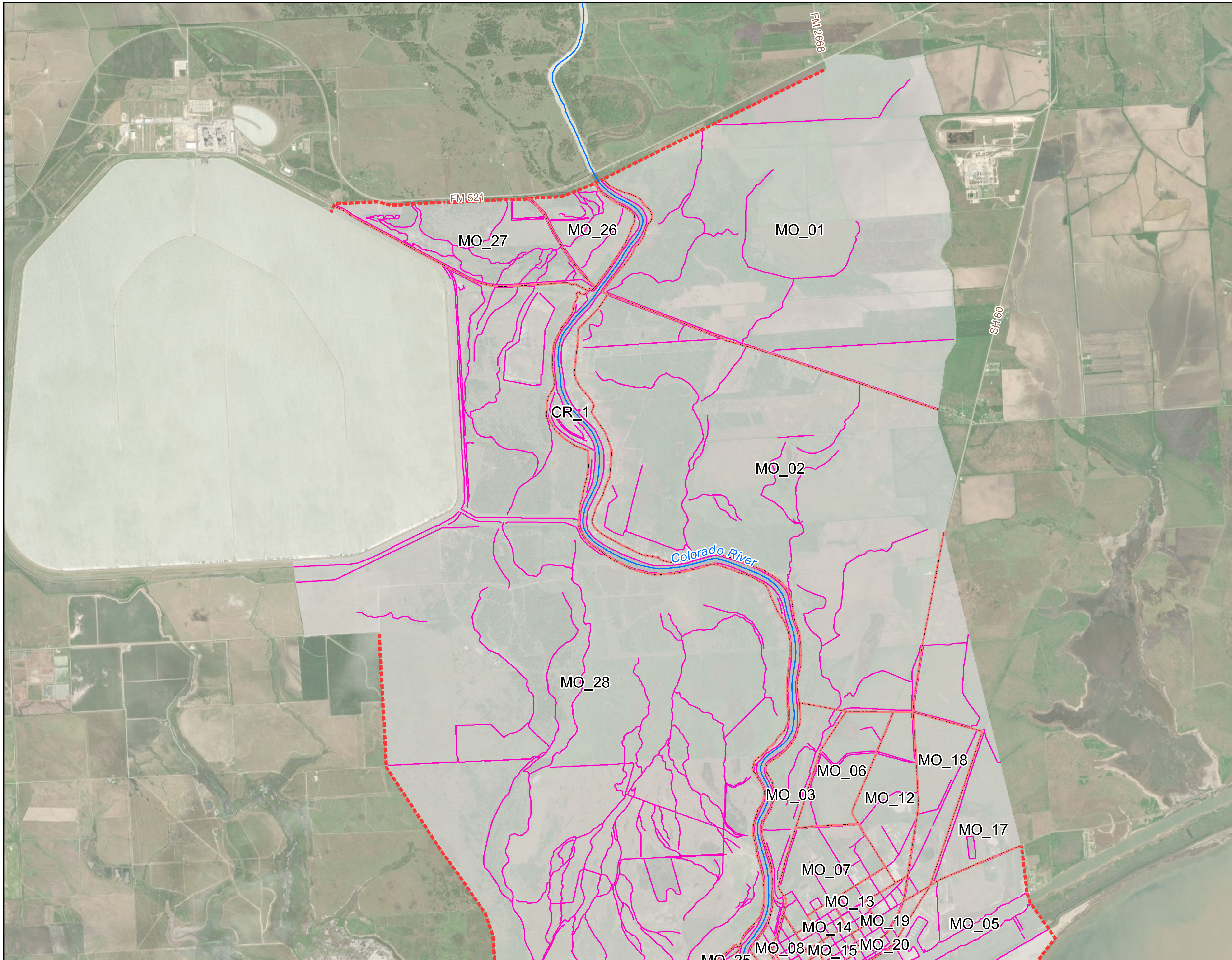


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C13: Hydraulic Model Layout- Mouth Section

### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

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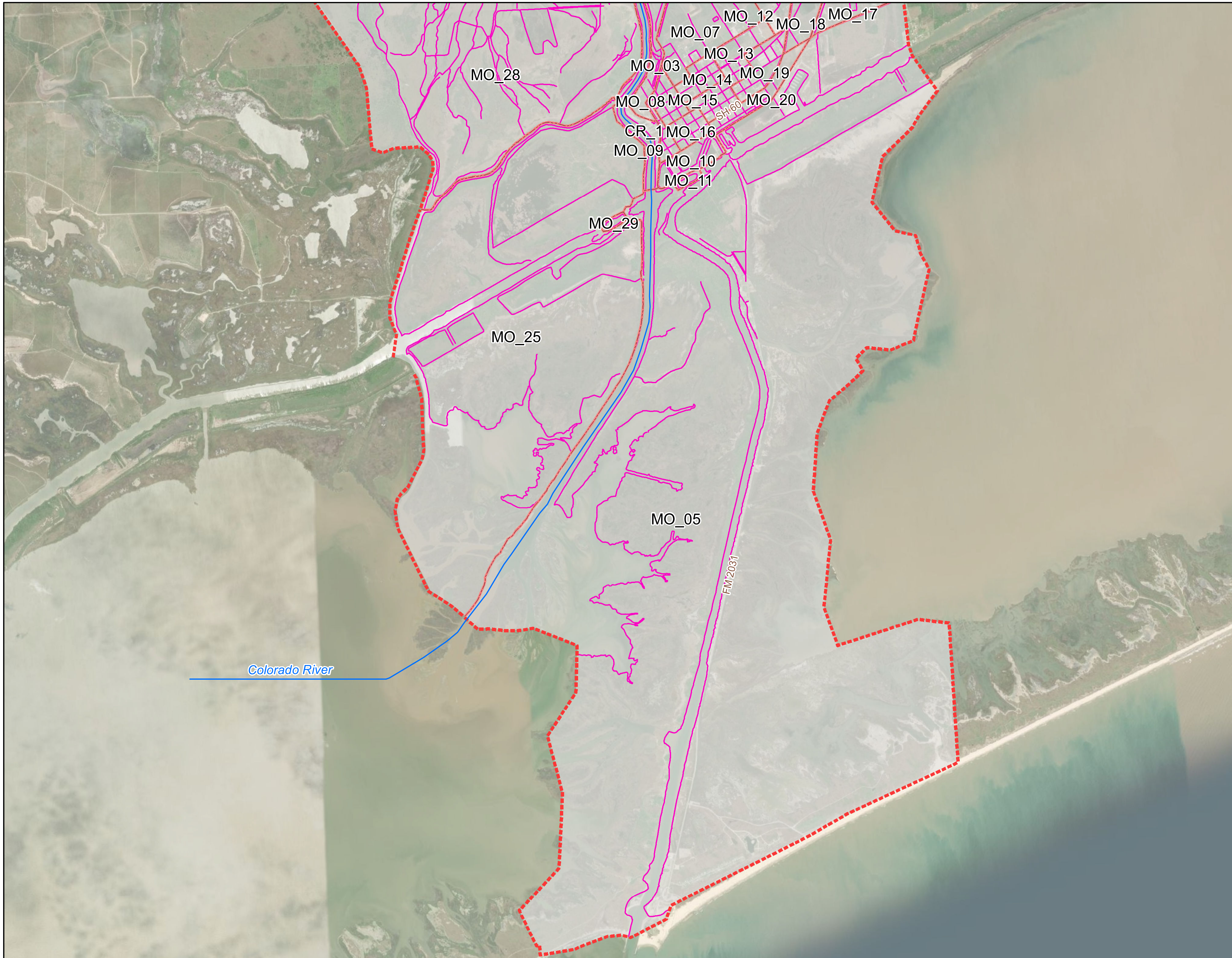


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure C14: Hydraulic Model Layout- Mouth Section

### Key To Features

- Bridges
- 2D Connectors
- Inline Structures
- Lateral Weirs
- 1D Cross-Sections
- 2D Break Lines
- 2D Boundary Conditions
- 2D Meshes
- Colorado River

SCHEIBE CONSULTING LLC

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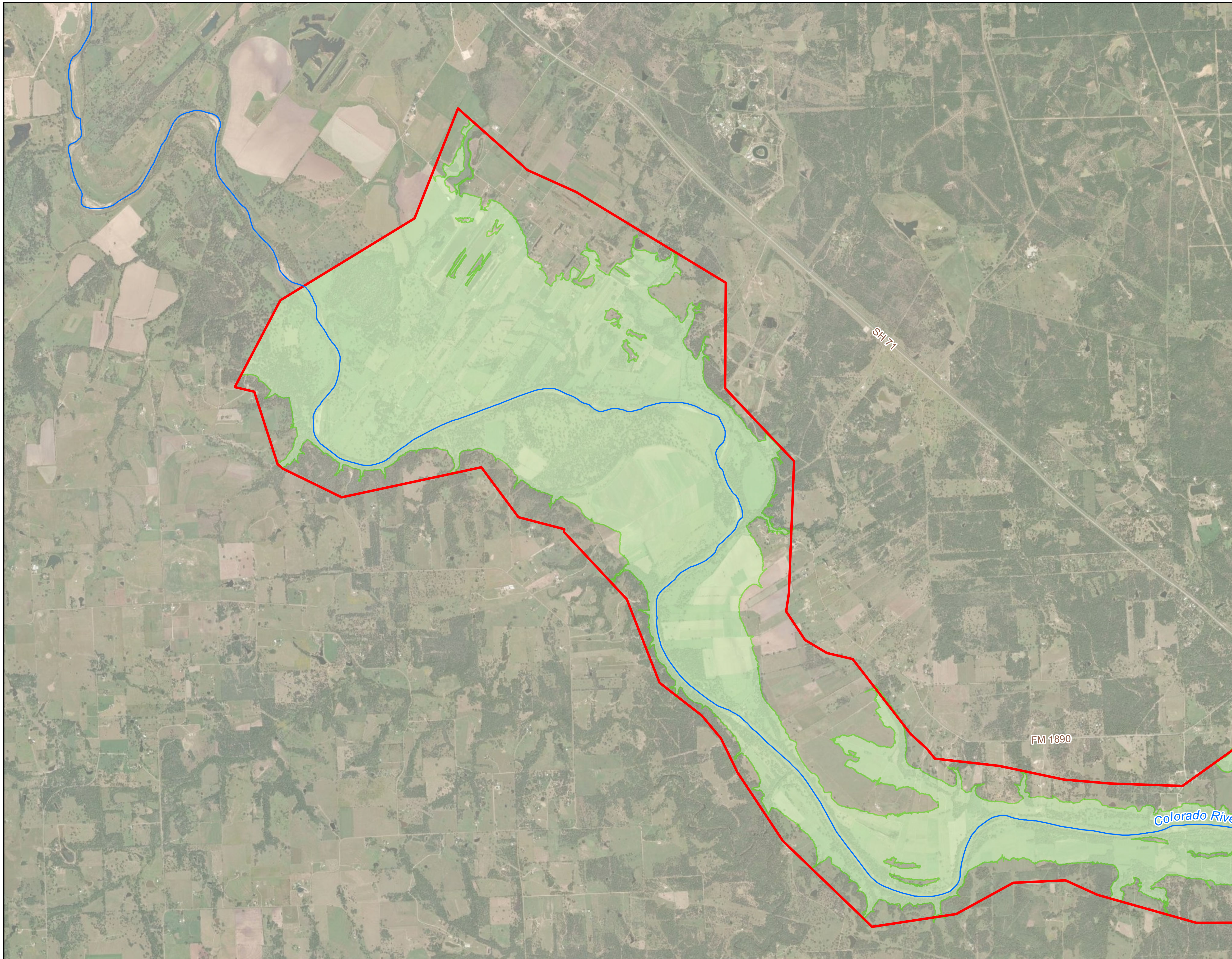
# APPENDIX D:
# HARVEY INUNDATION




# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D1: Harvey Inundation- Columbus/Garwood Section

### Key To Features

- Colorado River
- Study Limits
- Harvey Inundaton

SCHEIBE CONSULTING LLC

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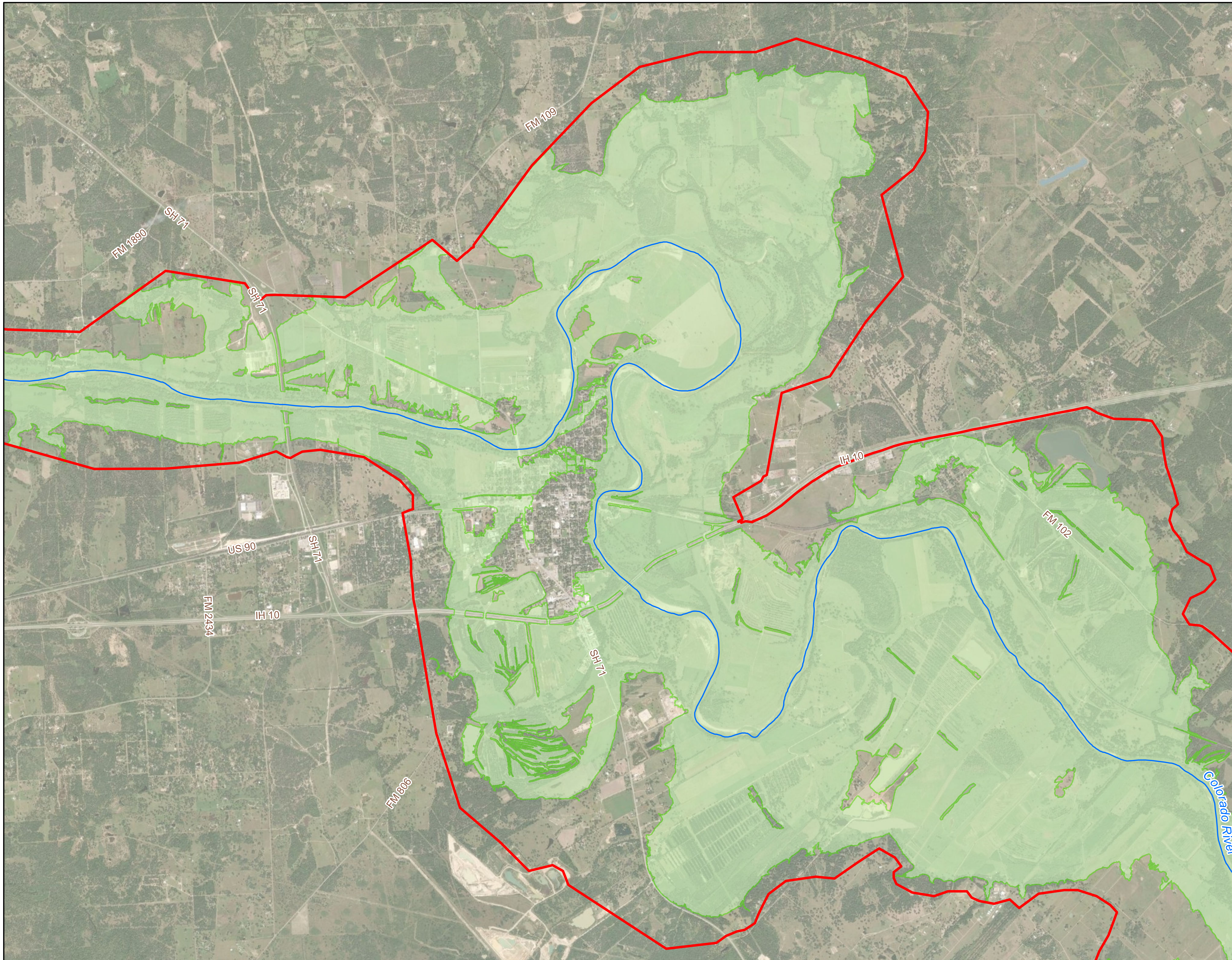


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D2: Harvey Inundation- Columbus/Garwood Section

**Key To Features**

- Colorado River
- Study Limits
- Harvey Inundaton

SCHEIBE CONSULTING LLC

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# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D3: Harvey Inundation- Columbus/Garwood Section

**Key To Features**

- Colorado River
- Study Limits
- Harvey Inundaton

SCHEIBE CONSULTING LLC

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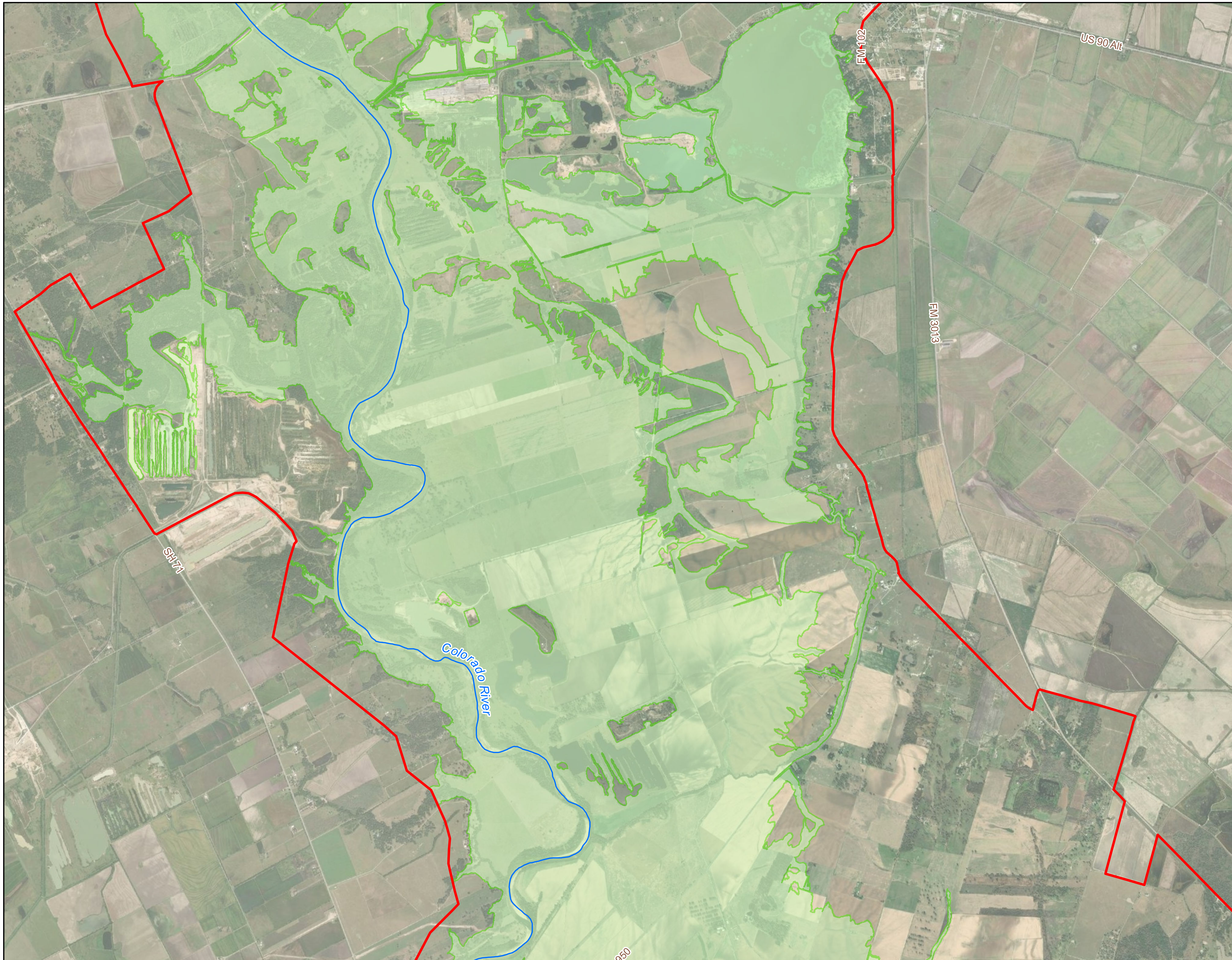
## Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D4: Harvey Inundation- Columbus/Garwood Section




**Key To Features**

- Colorado River
- Study Limits
- Harvey Inundaton

SCHEIBE CONSULTING LLC

N

0 4,000 8,000 Feet


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D5: Harvey Inundation- Columbus/Garwood Section

### Key To Features

- Colorado River
- Study Limits
- Harvey Inundaton

SCHEIBE CONSULTING LLC

N

0 4,000 8,000 Feet


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D6: Harvey Inundation- Wharton Section

### Key To Features

- Colorado River
- Study Limits
- Harvey Inundation

SCHEIBE CONSULTING LLC

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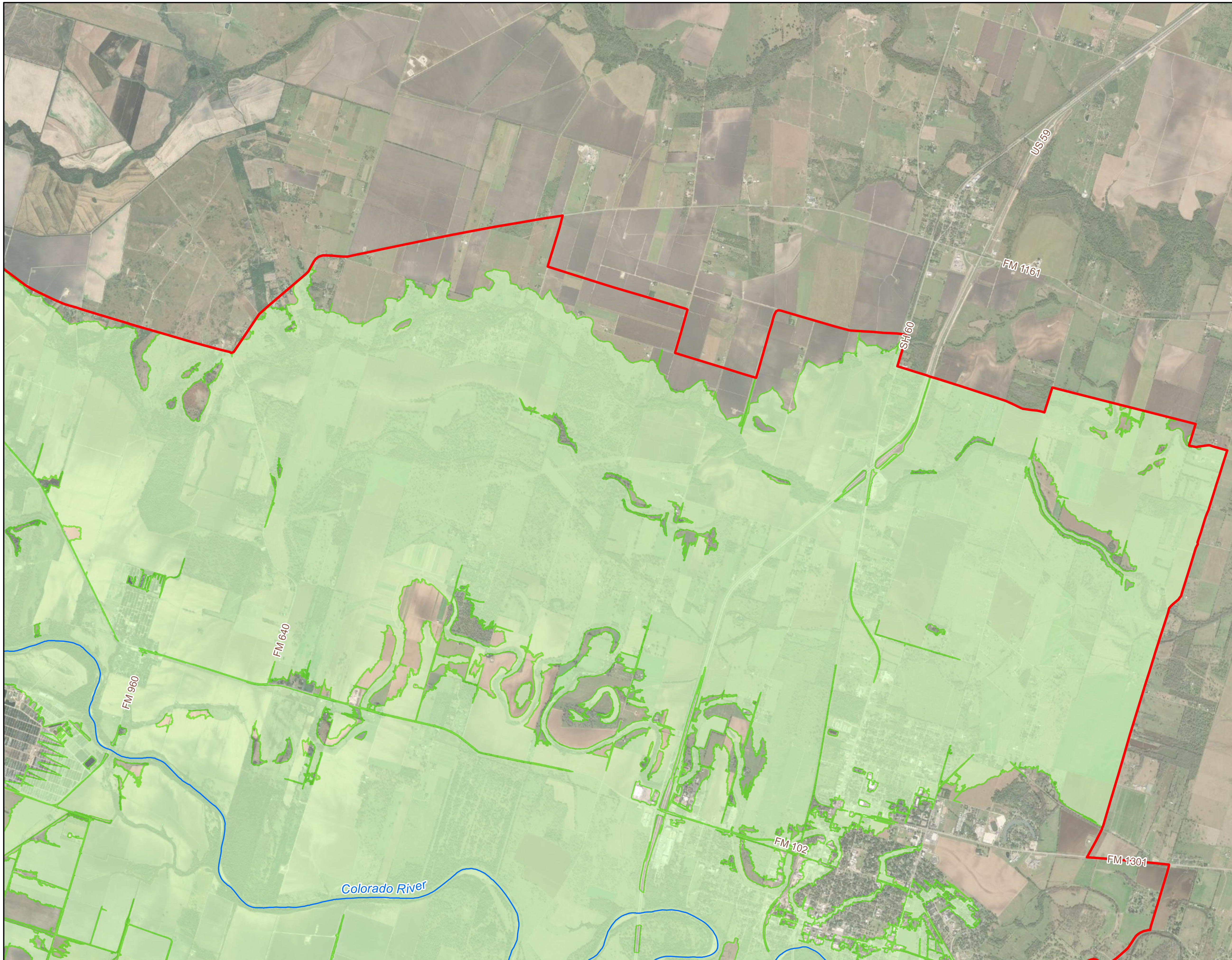


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D7: Harvey Inundation- Wharton Section

### Key To Features

- Colorado River
- Study Limits
- Harvey Inundation

SCHEIBE CONSULTING LLC

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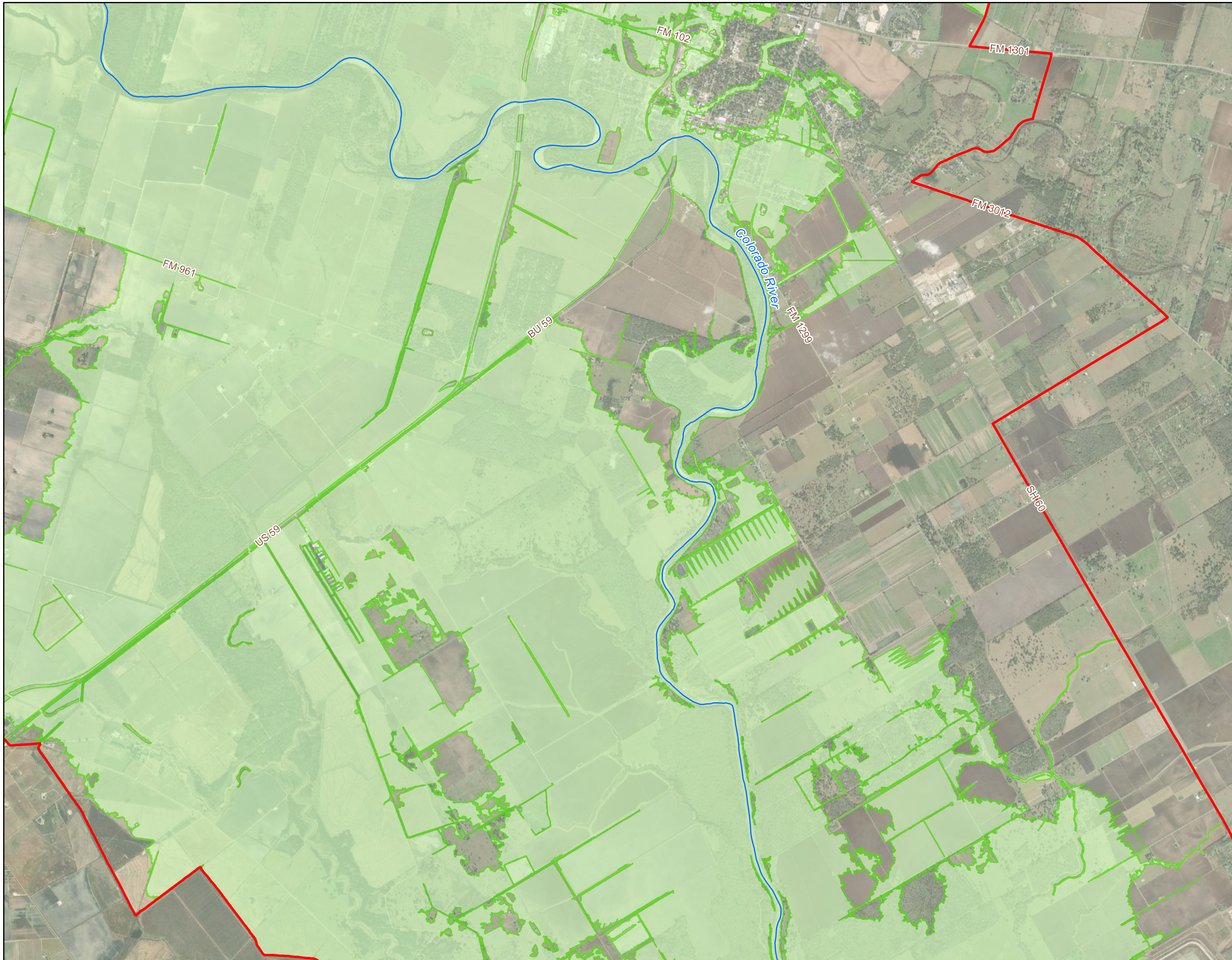


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D8: Harvey Inundation- Wharton Section

### Key To Features

- Colorado River
- Study Limits
- Harvey Inundation

SCHEIBE CONSULTING LLC

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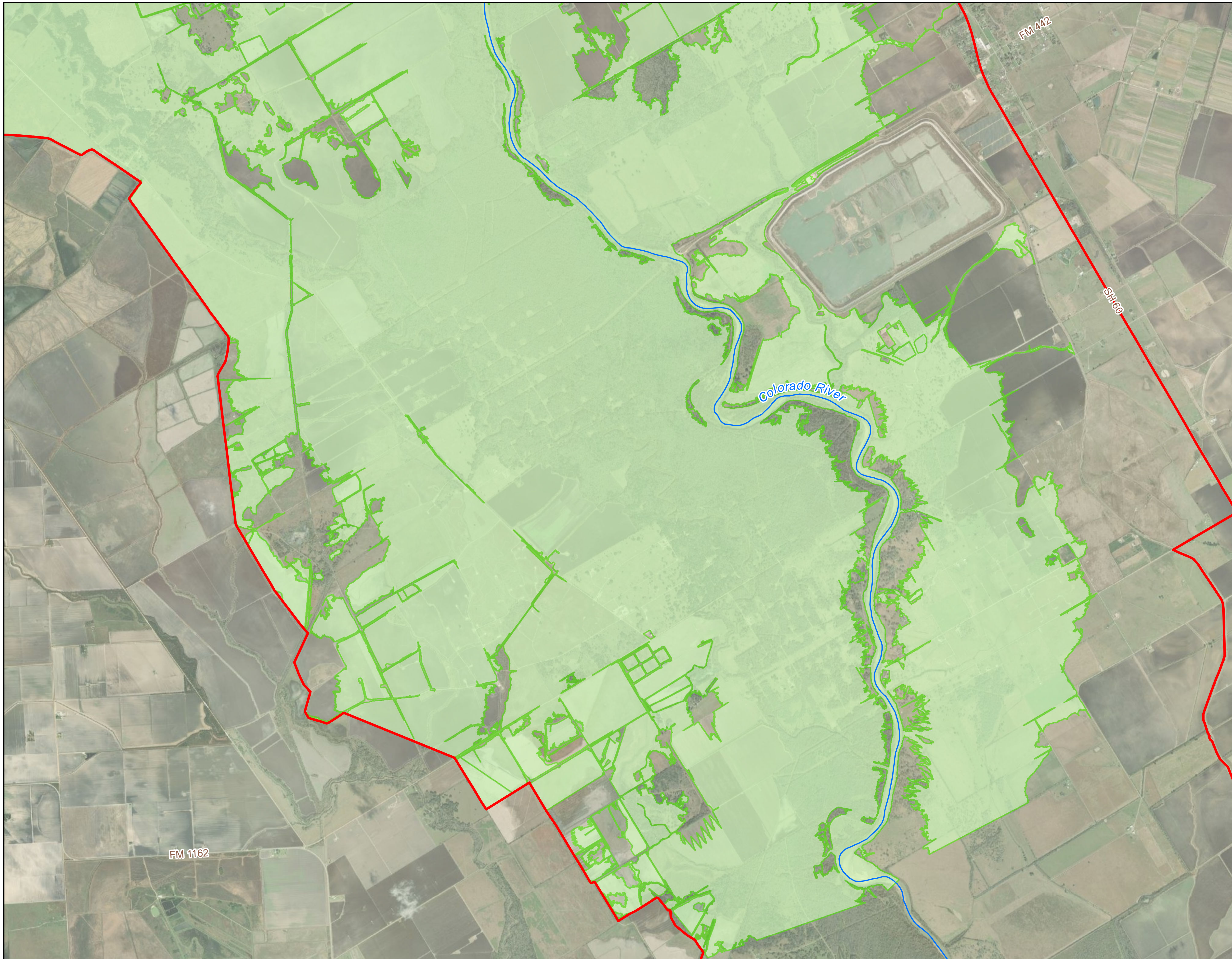


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D9: Harvey Inundation- Wharton Section

### Key To Features

- Colorado River
- Study Limits
- Harvey Inundation

SCHEIBE CONSULTING LLC

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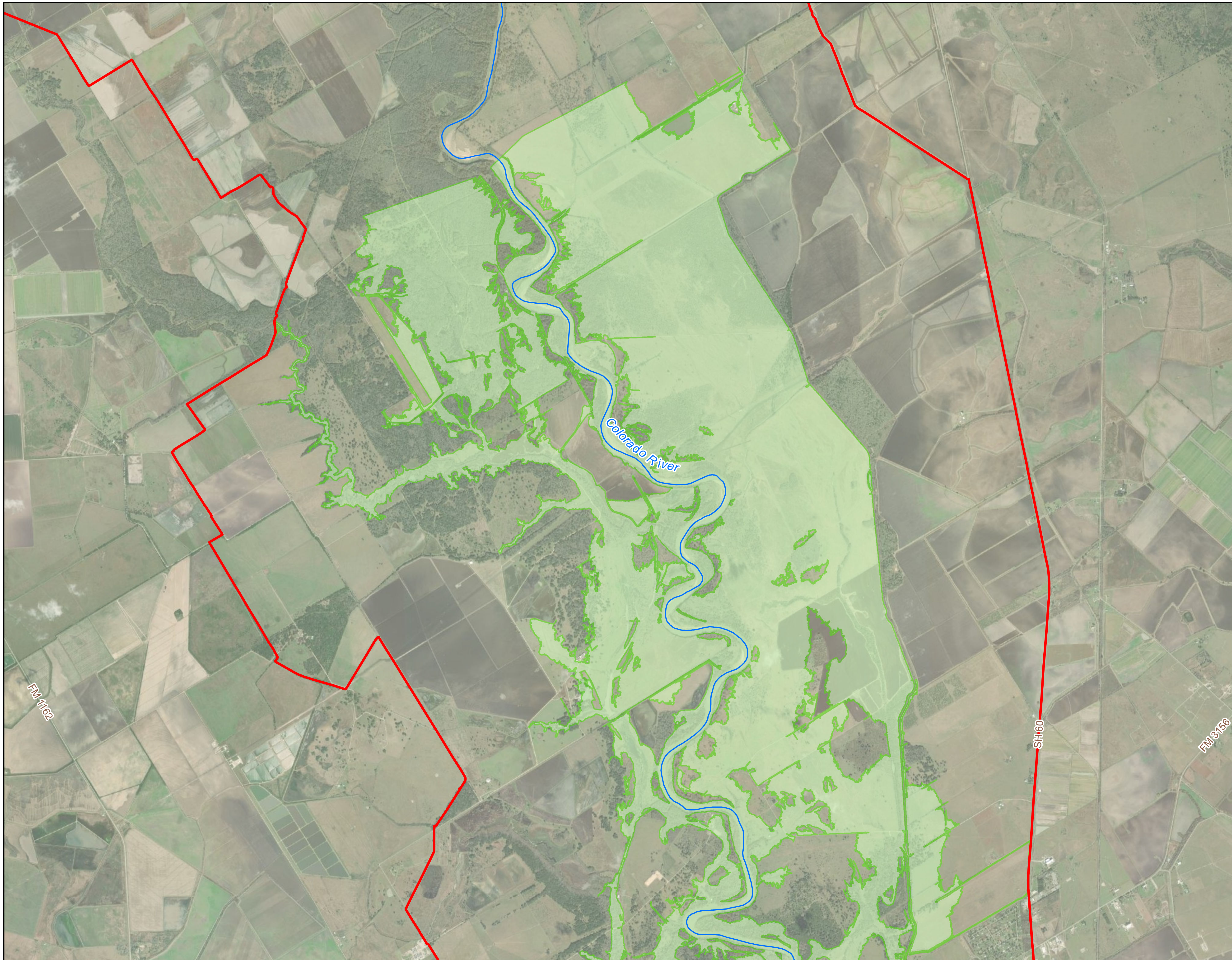
0 4,000 8,000 Feet

# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D10: Harvey Inundation- Bay City Section




**Key To Features**

- Colorado River
- Study Limits
- Harvey Inundation

SCHEIBE CONSULTING LLC

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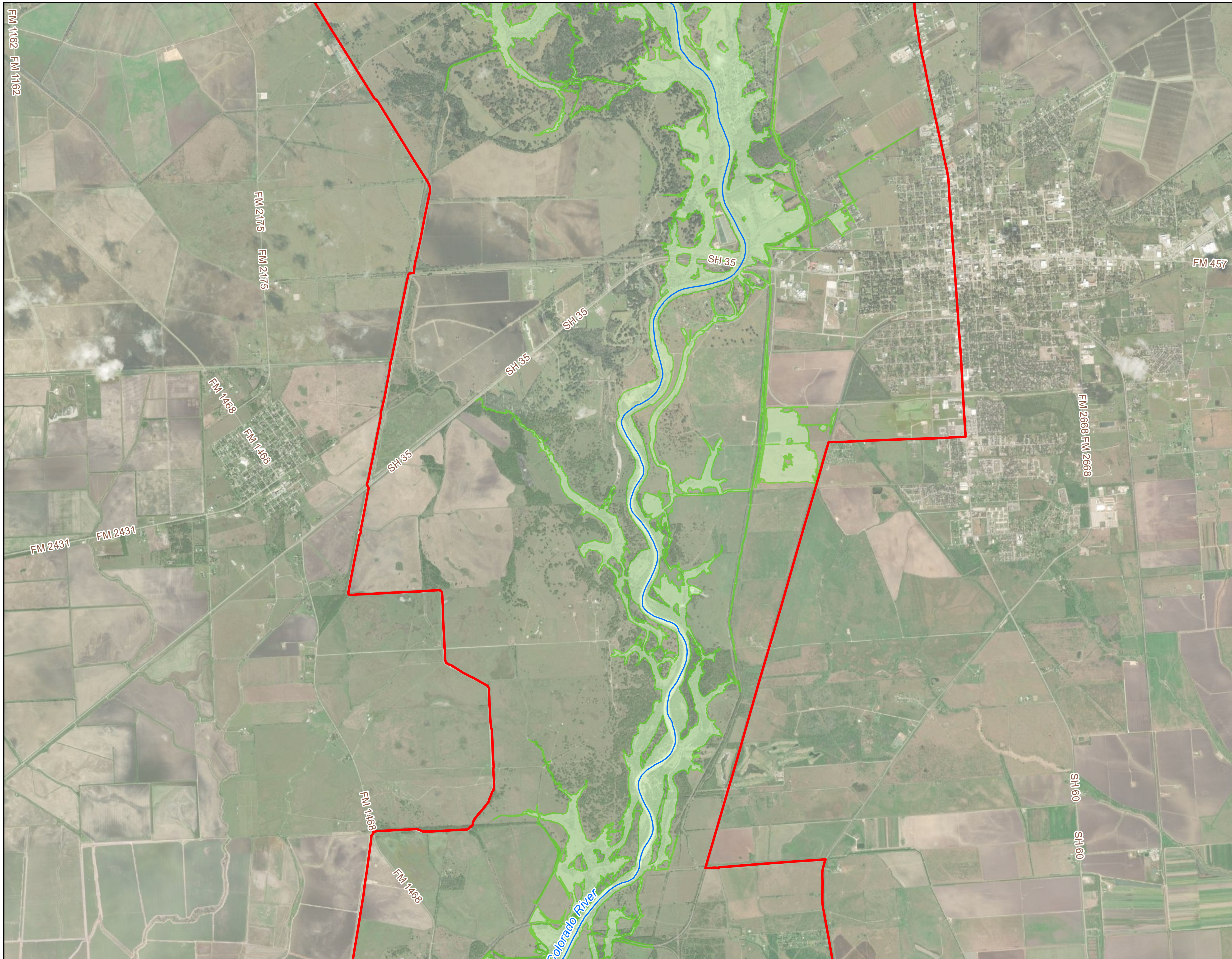


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D11: Harvey Inundation- Bay City Section

**Key To Features**

- Colorado River
- Study Limits
- Harvey Inundation

SCHEIBE CONSULTING LLC

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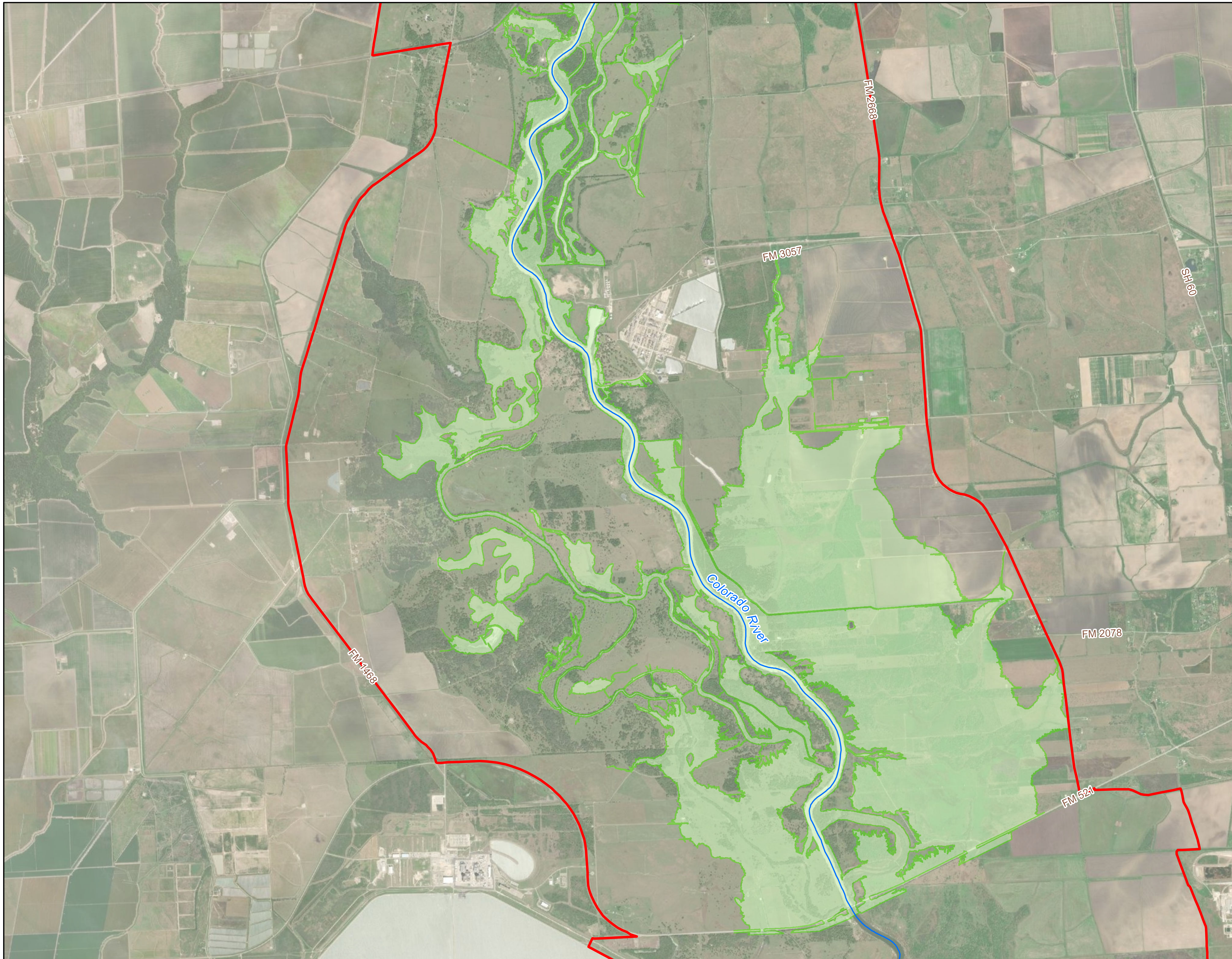


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D12: Harvey Inundation- Bay City Section

### Key To Features

- Colorado River
- Study Limits
- Harvey Inundation

SCHEIBE CONSULTING LLC

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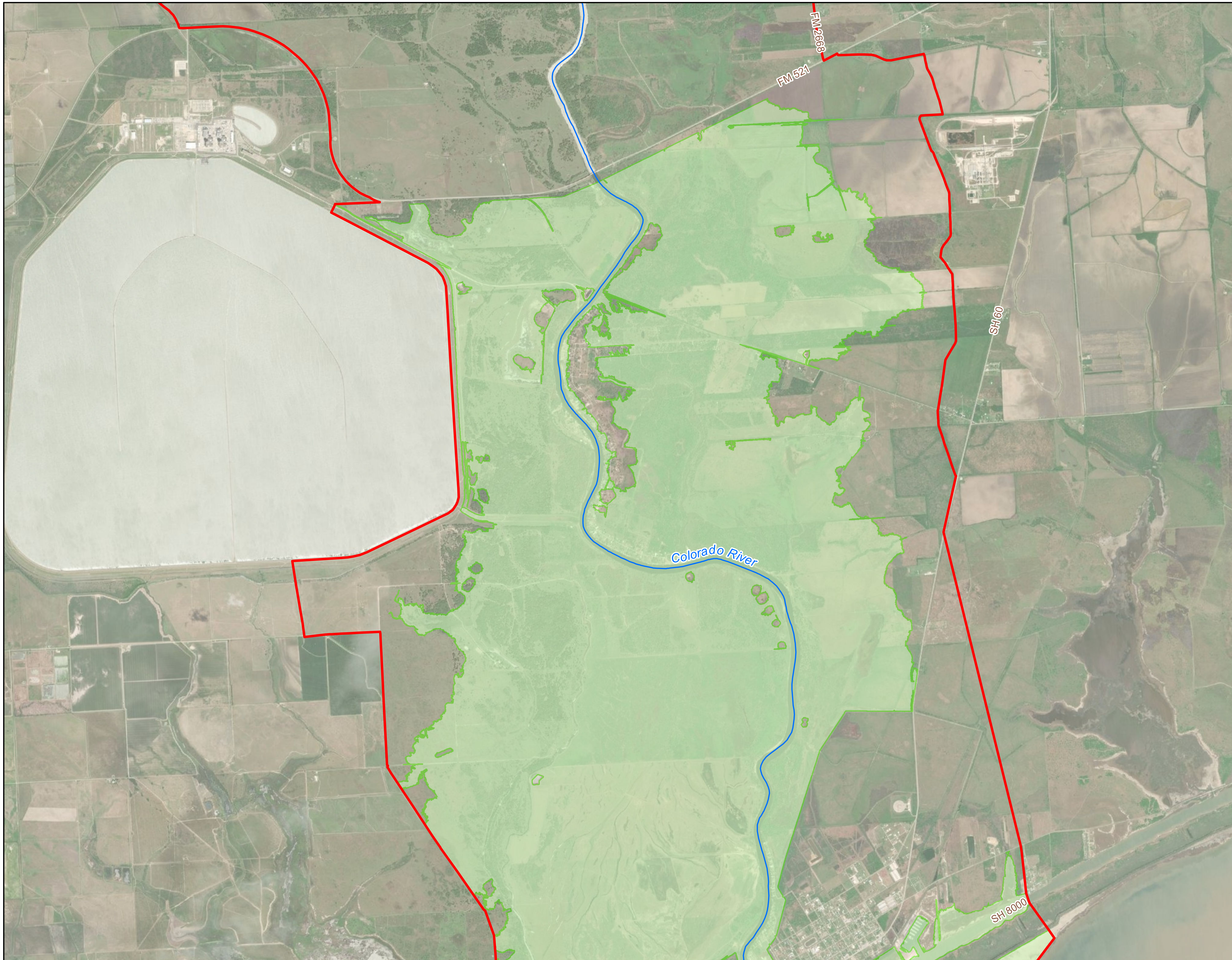


## Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D13: Harvey Inundation- Mouth Section

**Key To Features**

- Colorado River
- Study Limits
- Harvey Inundation

SCHEIBE CONSULTING LLC

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# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure D14: Harvey Inundation-Mouth Section

### Key To Features

- Colorado River
- Study Limits
- Harvey Inundation

SCHEIBE CONSULTING LLC

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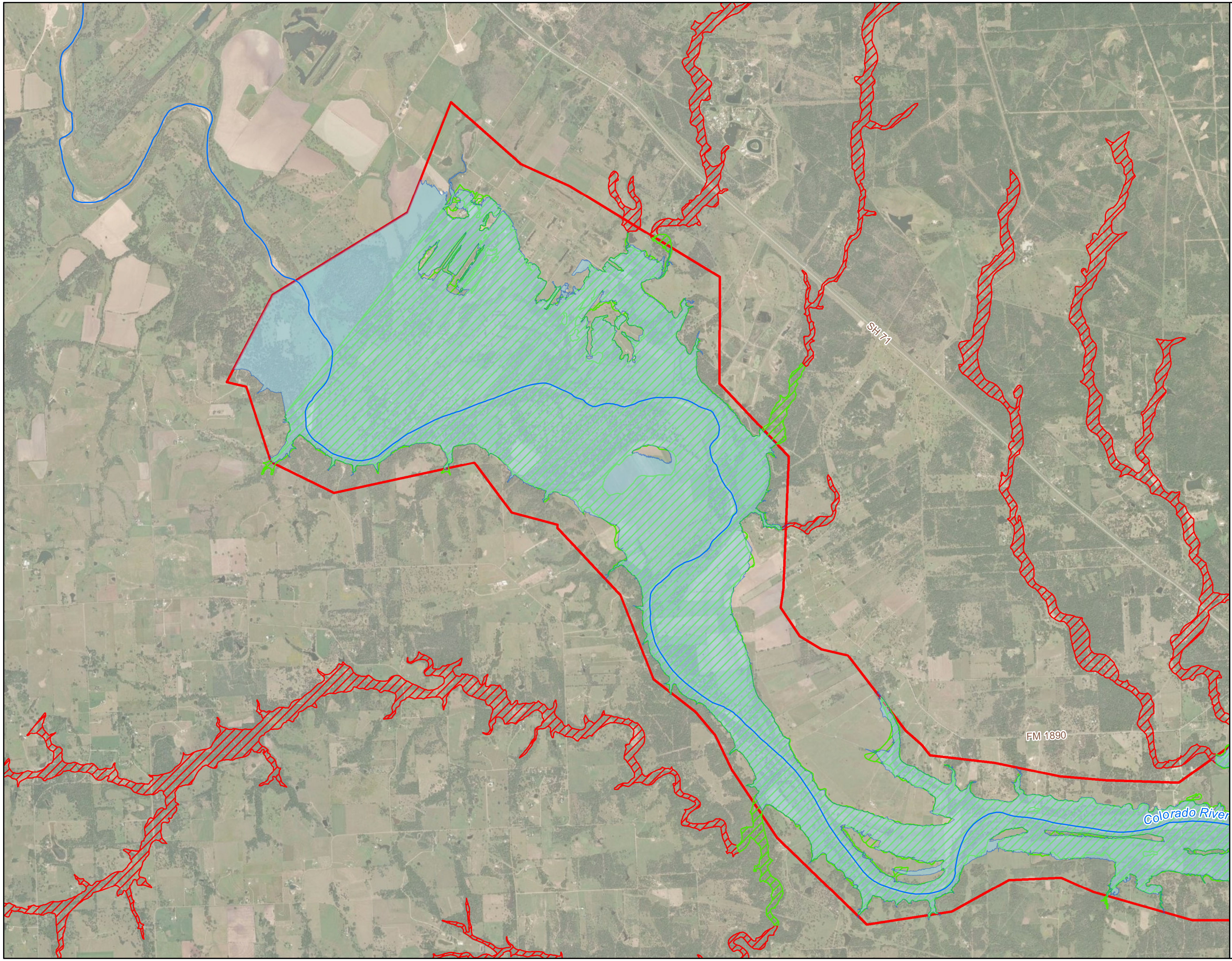
# APPENDIX E:

# 100-YR INUNDATION COMPARISON TO FEMA




# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E1: 100-YR Inundation- Columbus/Garwood Section

**Key To Features**

- Colorado River
- TriCounty100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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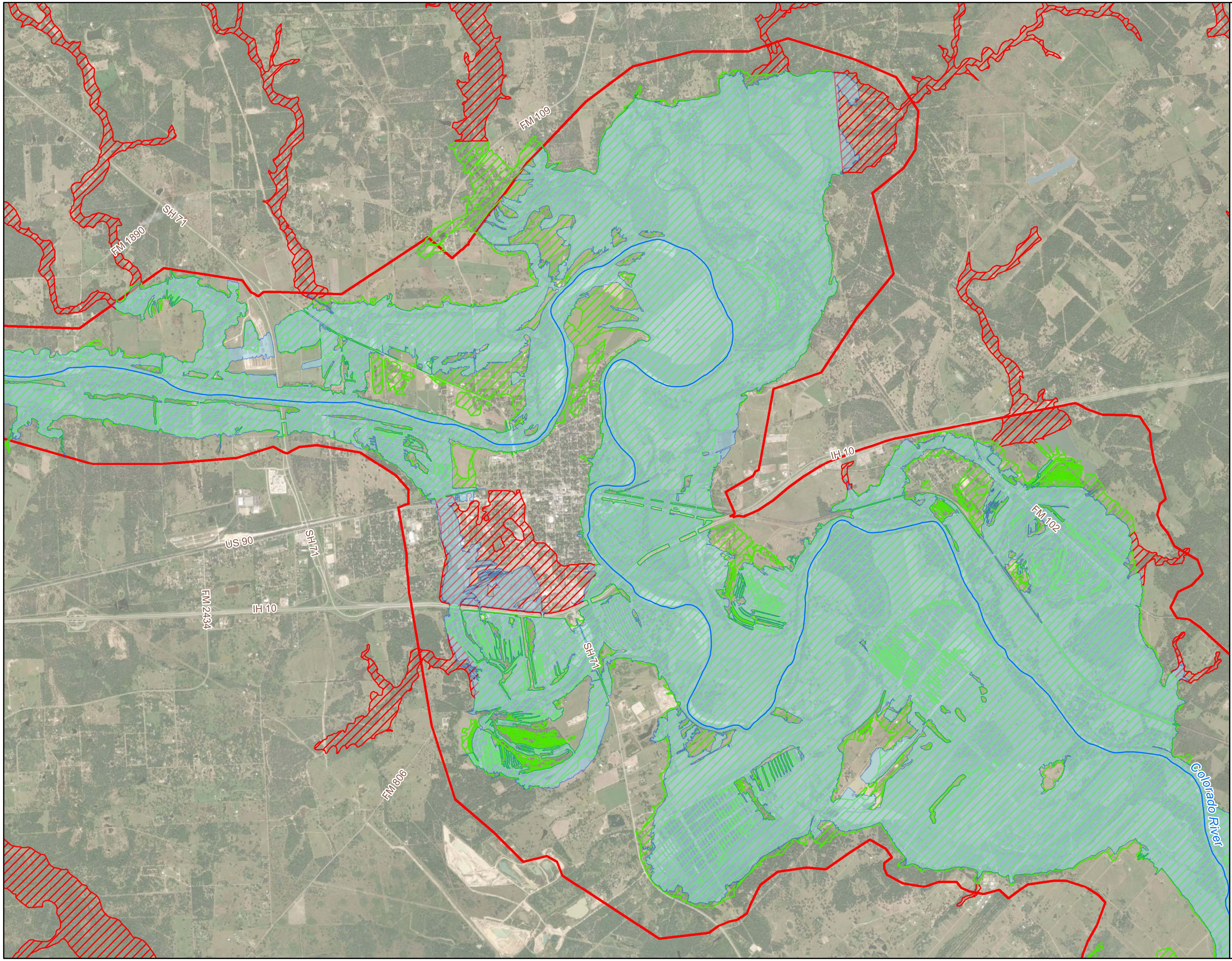


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E2: 100-YR Inundation- Columbus/Garwood Section

### Key To Features

- Colorado River
- TriCounty100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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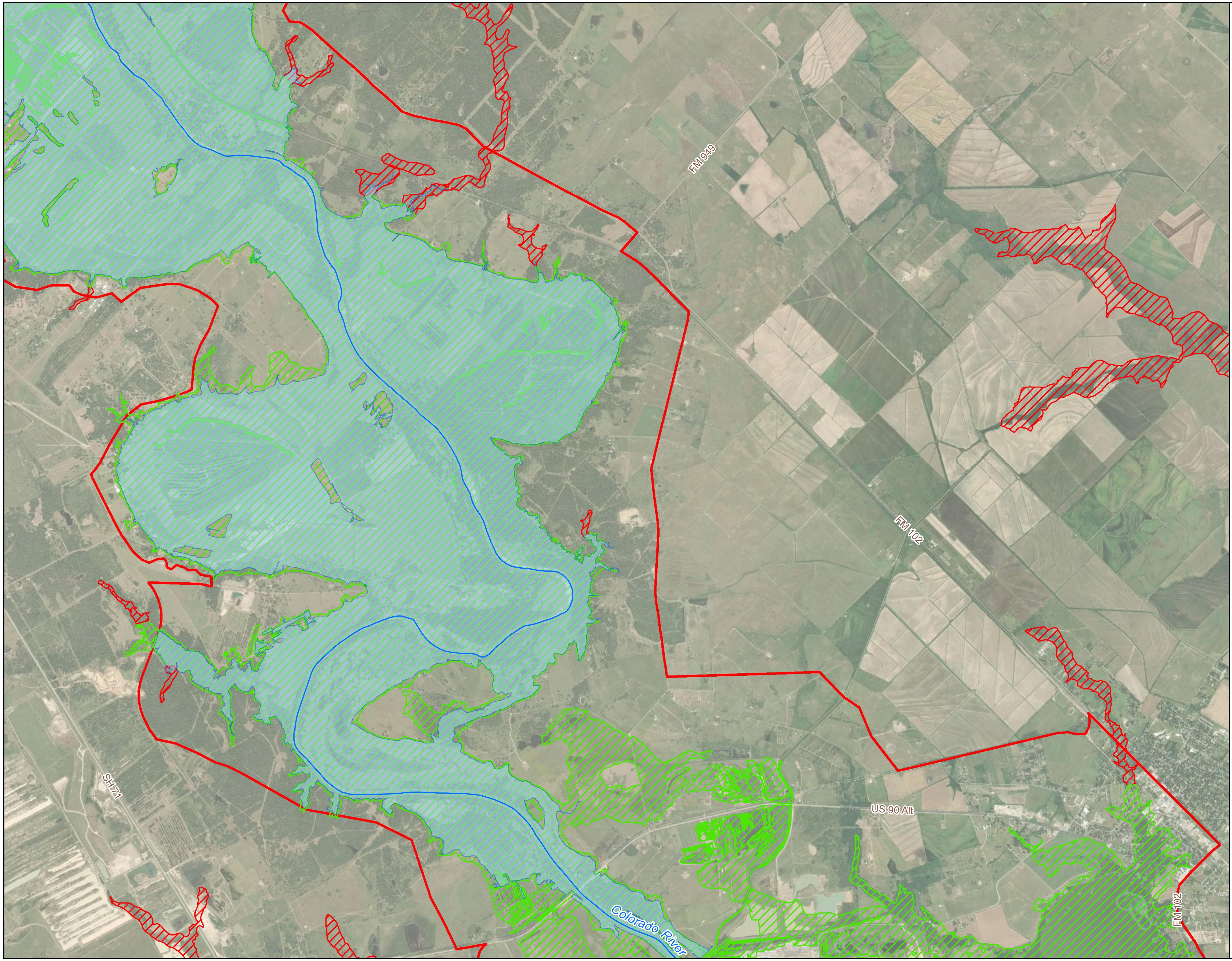
# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E3: 100-YR Inundation-Columbus/Garwood Section




**Key To Features**

- Colorado River
- TriCounty100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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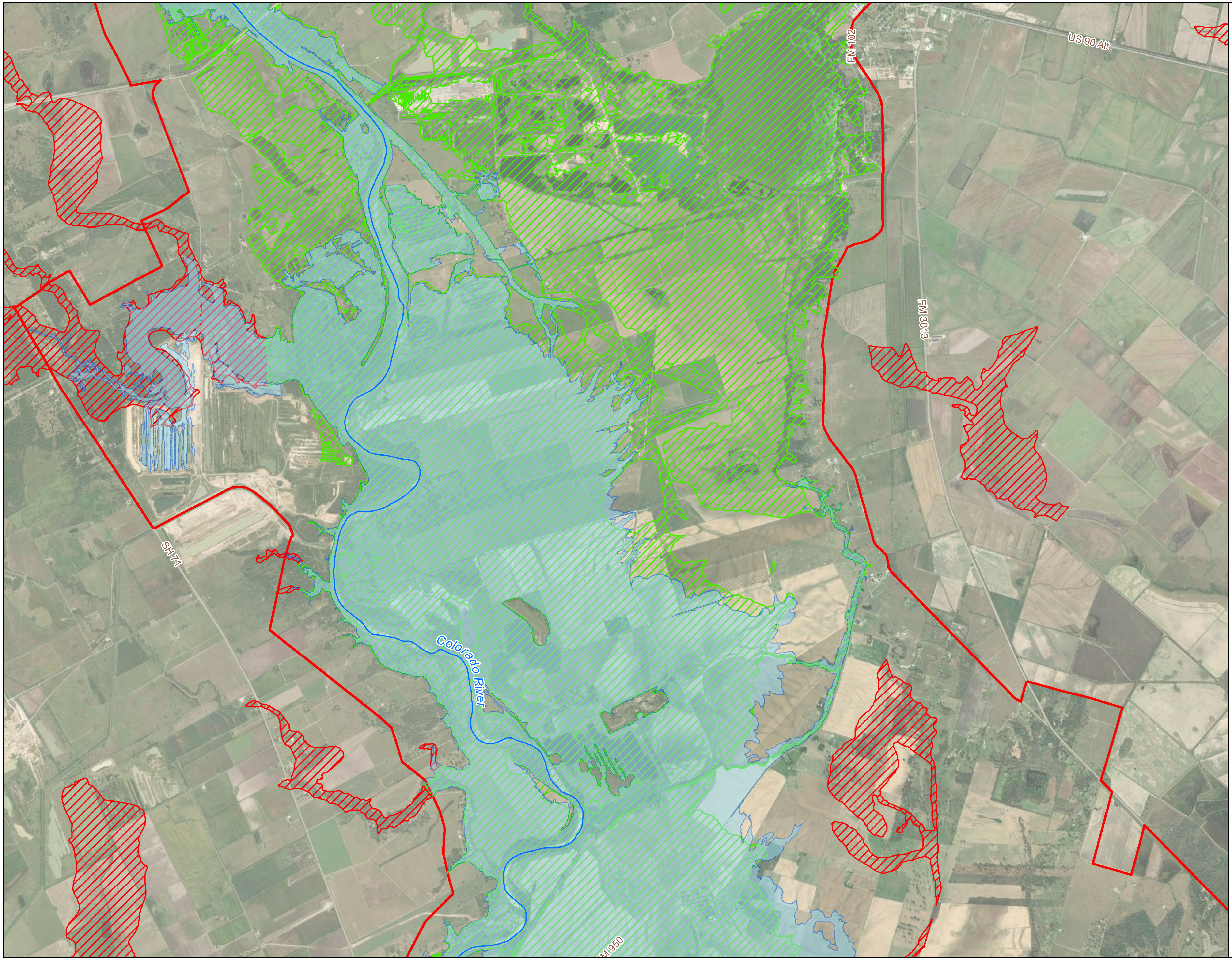


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E4: 100-YR Inundation-Columbus/Garwood Section

### Key To Features

- Colorado River
- TriCounty100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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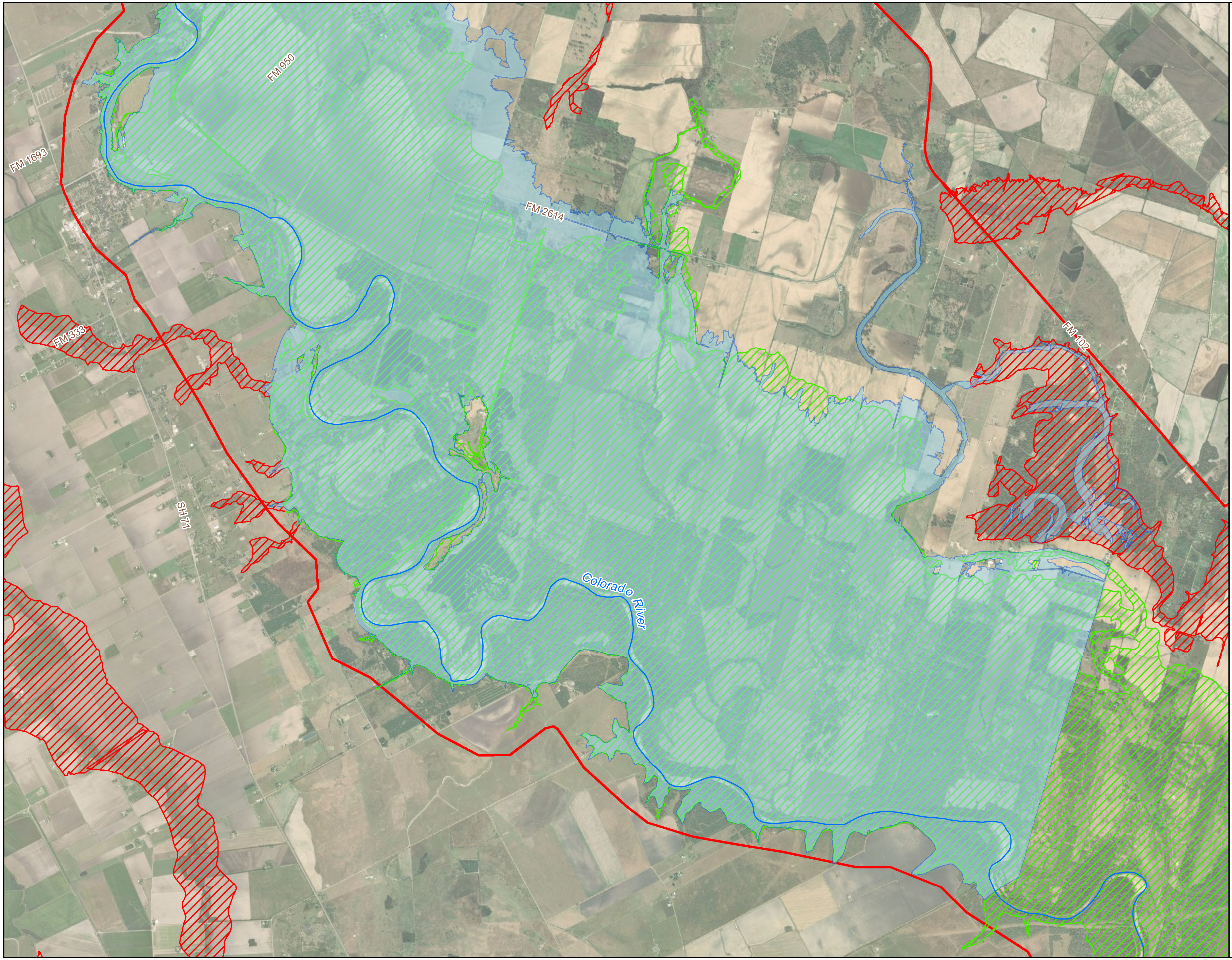


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E5: 100-YR Inundation- Columbus/Garwood Section

### Key To Features

- Colorado River
- TriCounty 100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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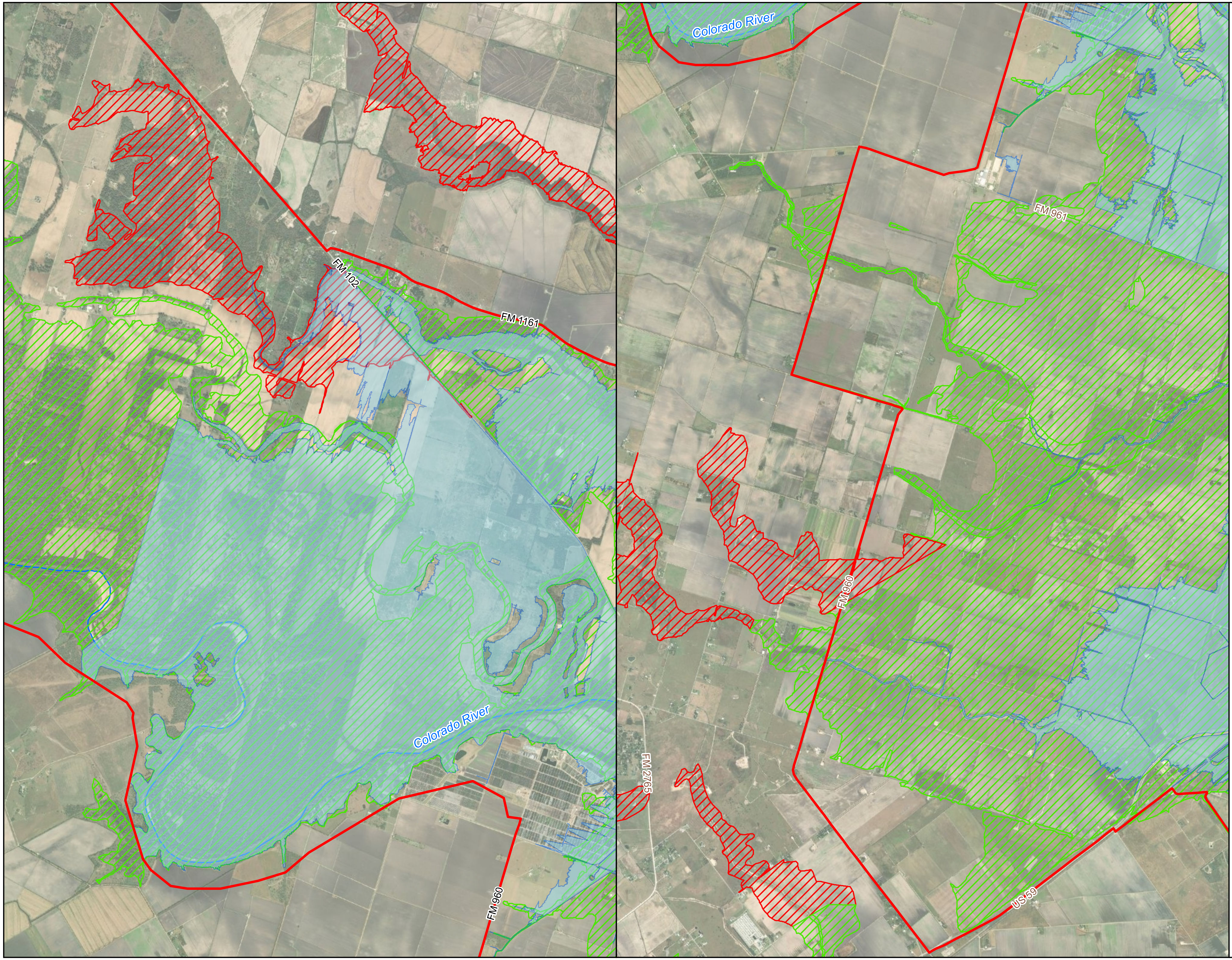


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E6: 100-YR Inundation- Wharton Section

### Key To Features

- Colorado River
- TriCounty100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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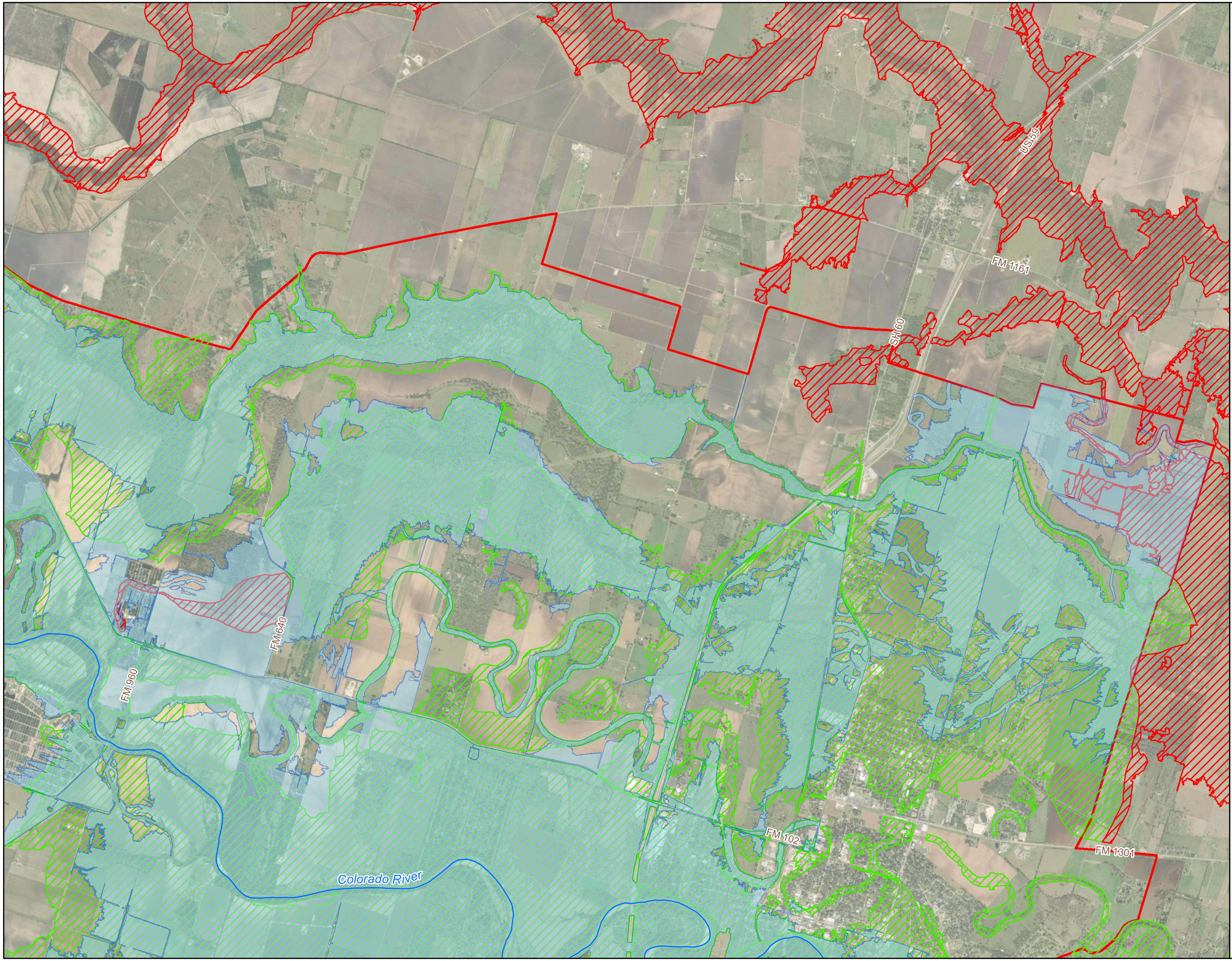


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E7: 100-YR Inundation- Wharton Section

### Key To Features

- Colorado River
- TriCounty100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

N

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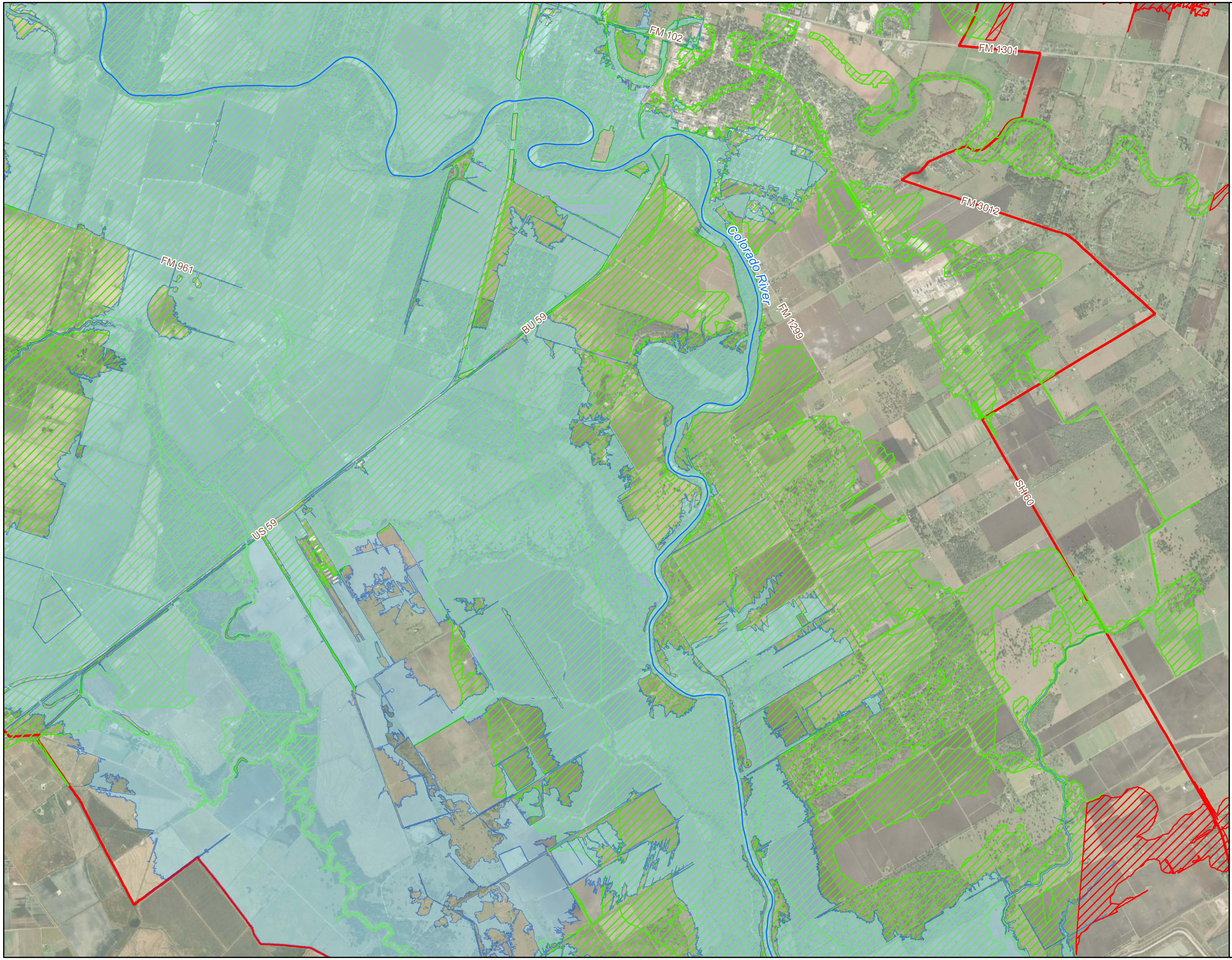


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E8: 100-YR Inundation- Wharton Section

**Key To Features**

- Colorado River
- TriCounty100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

N

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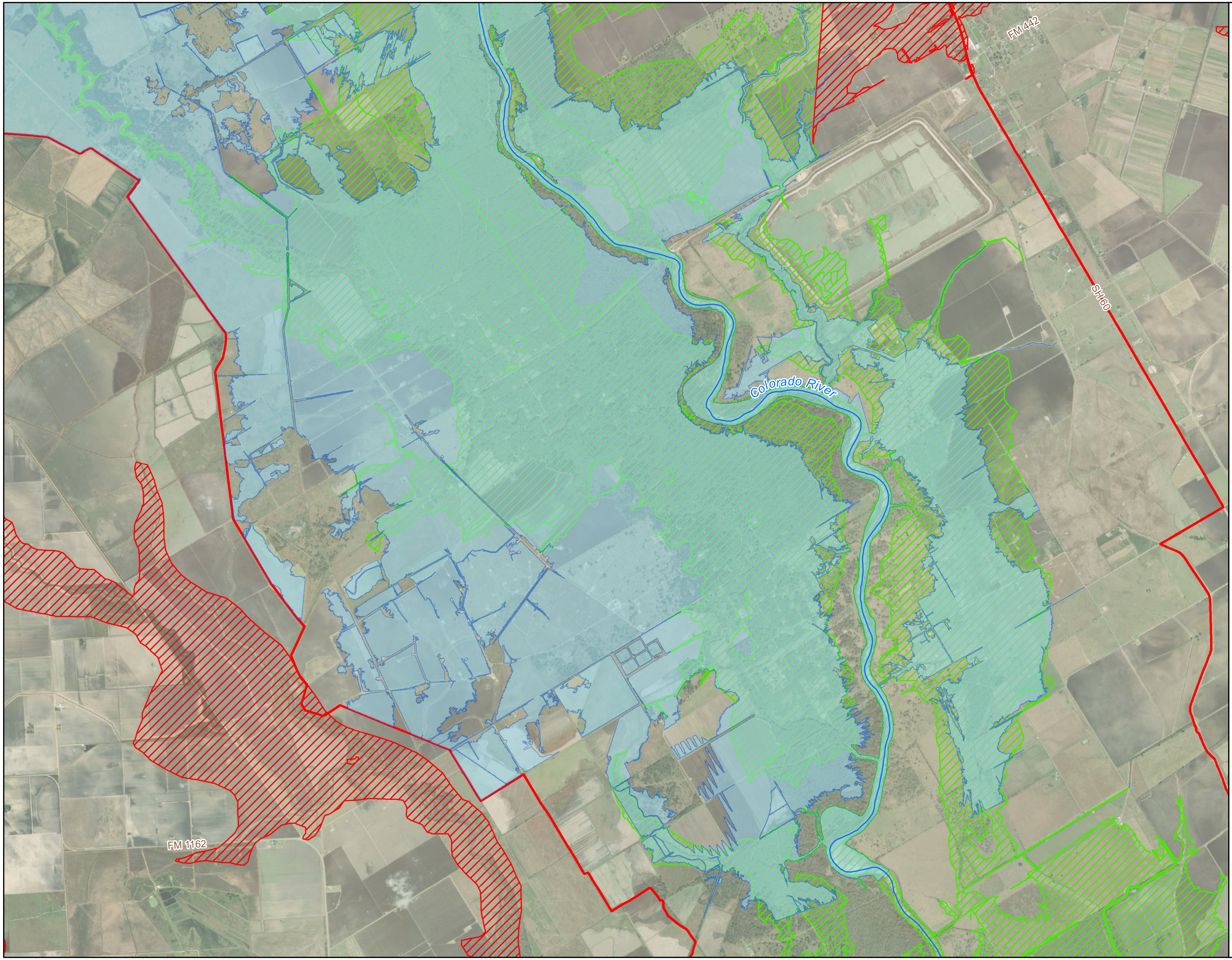


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E9: 100-YR Inundation- Wharton Section

### Key To Features

- Colorado River
- TriCounty100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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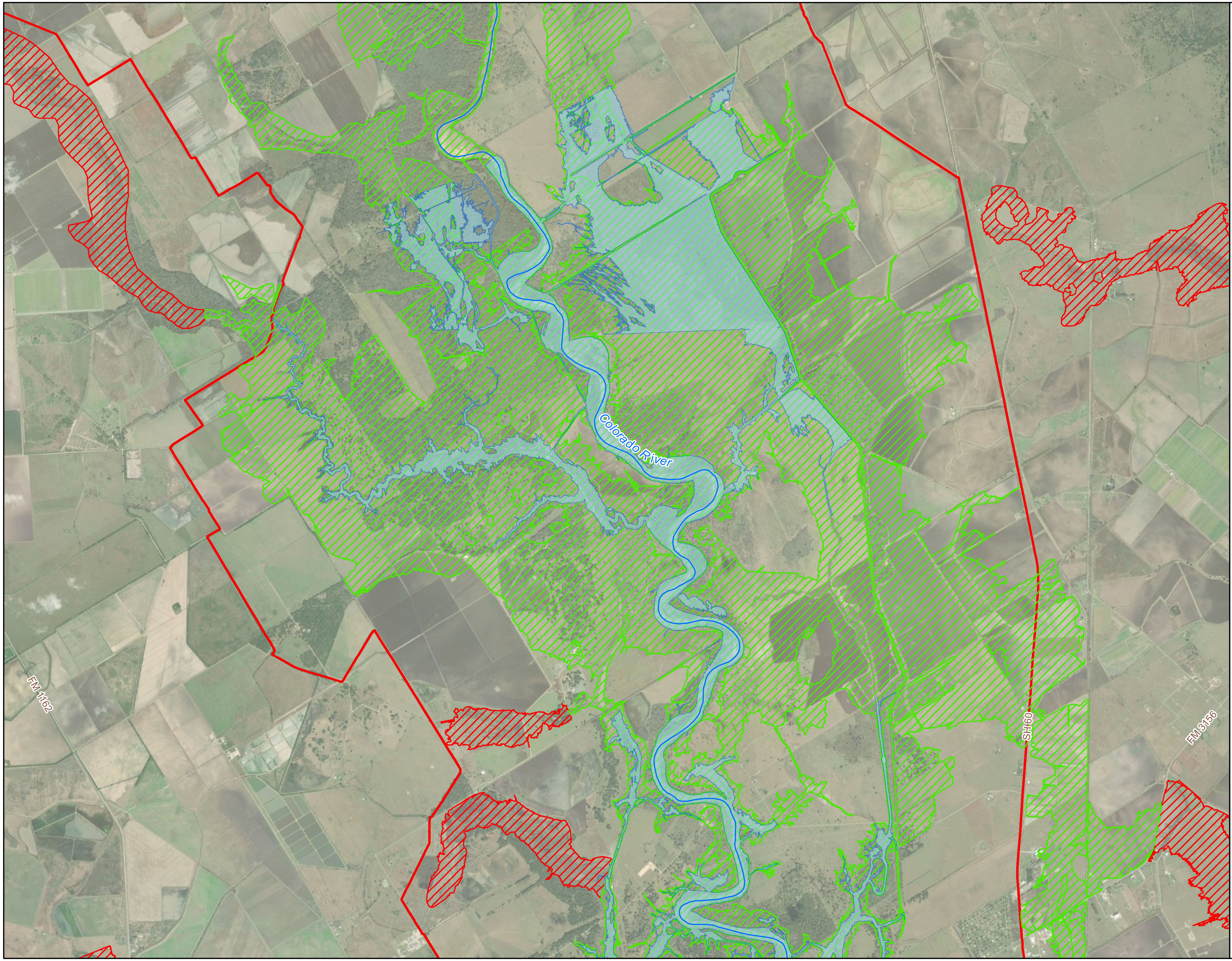
0 4,000 8,000 Feet

# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E10: 100-YR Inundation- Bay City Section




**Key To Features**

- Colorado River
- TriCounty 100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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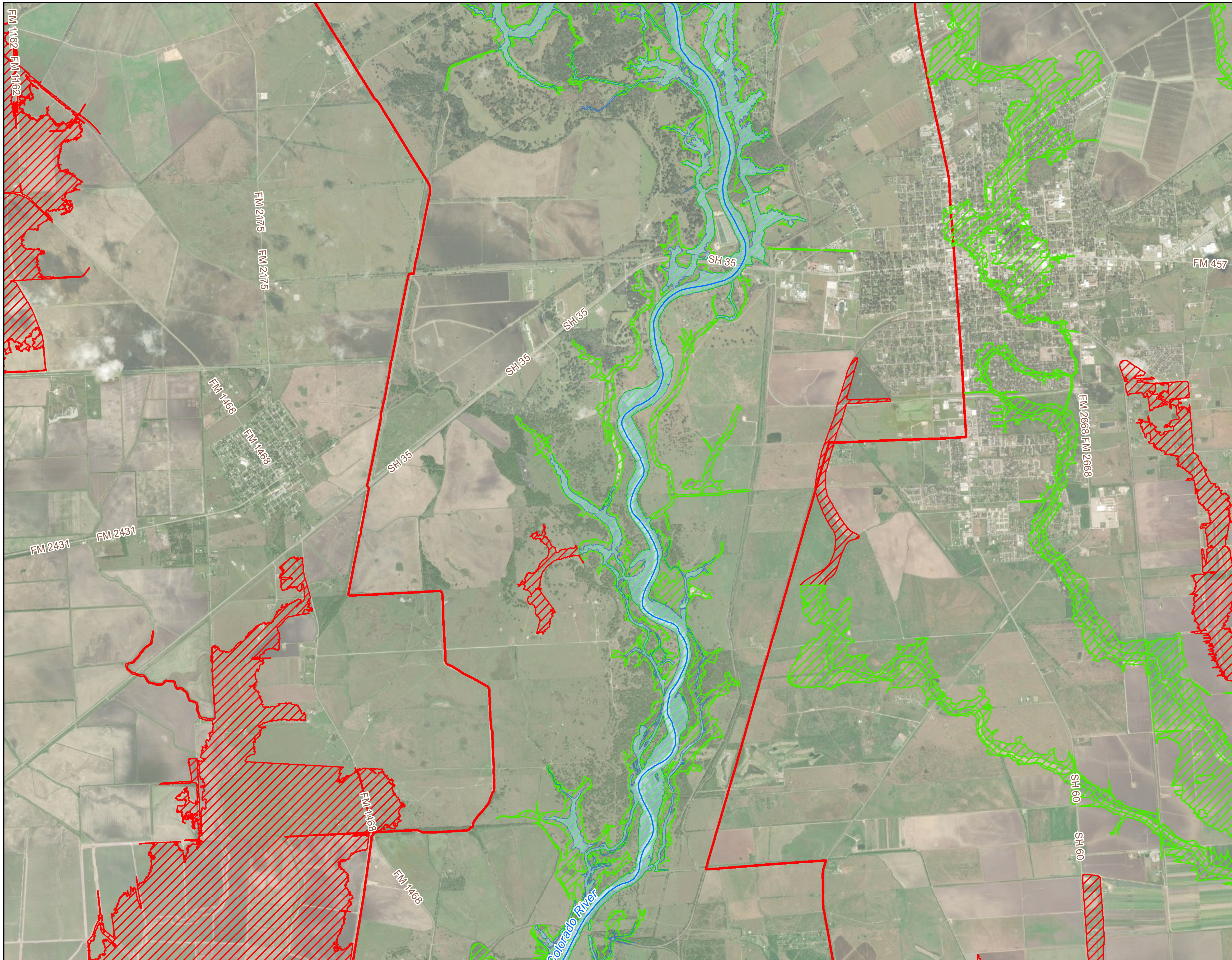


# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E11: 100-YR Inundation- Bay City Section

### Key To Features

- Colorado River
- TriCounty 100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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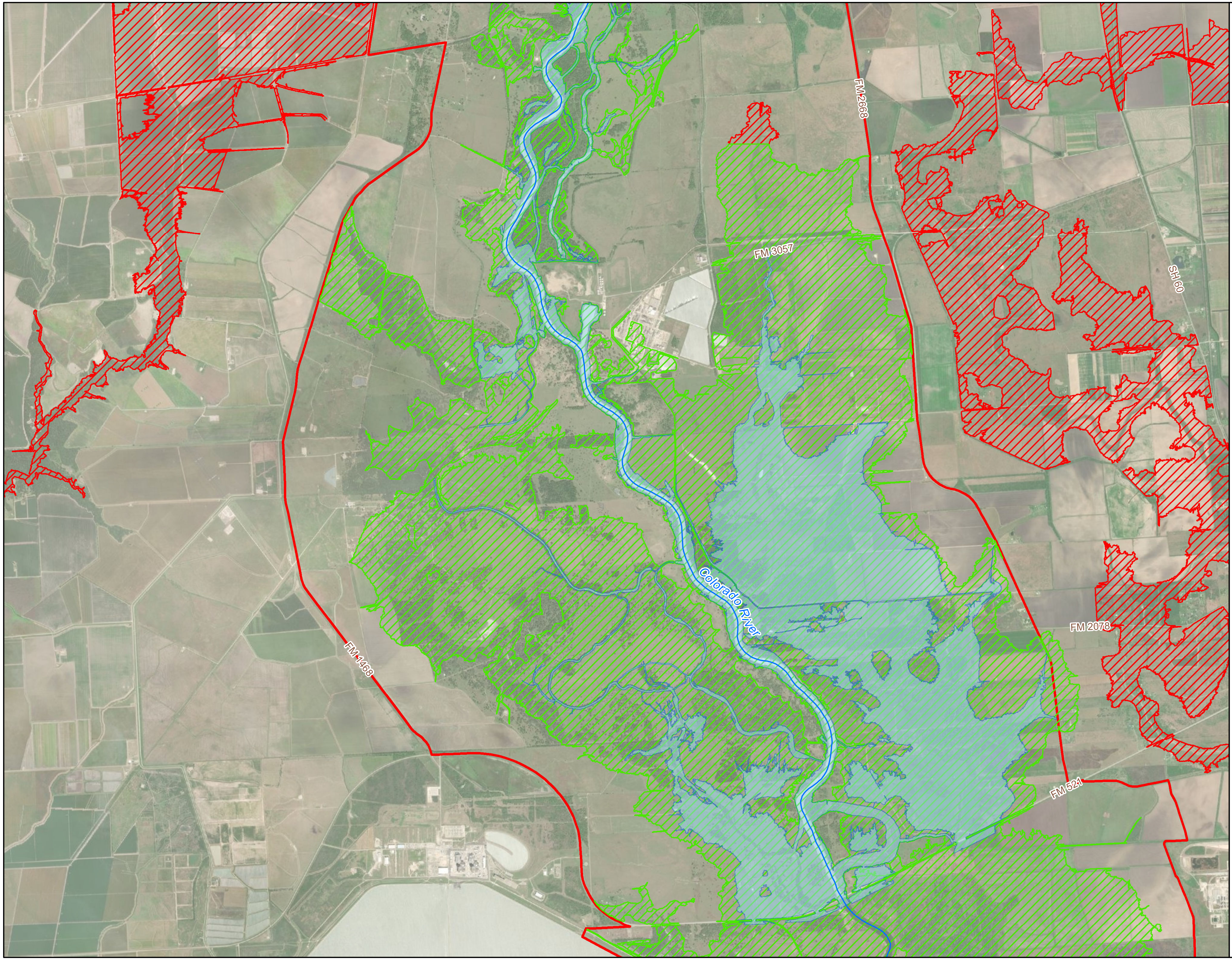



# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E12: 100-YR Inundation- Bay City Section

**Key To Features**

- Colorado River
- TriCounty 100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

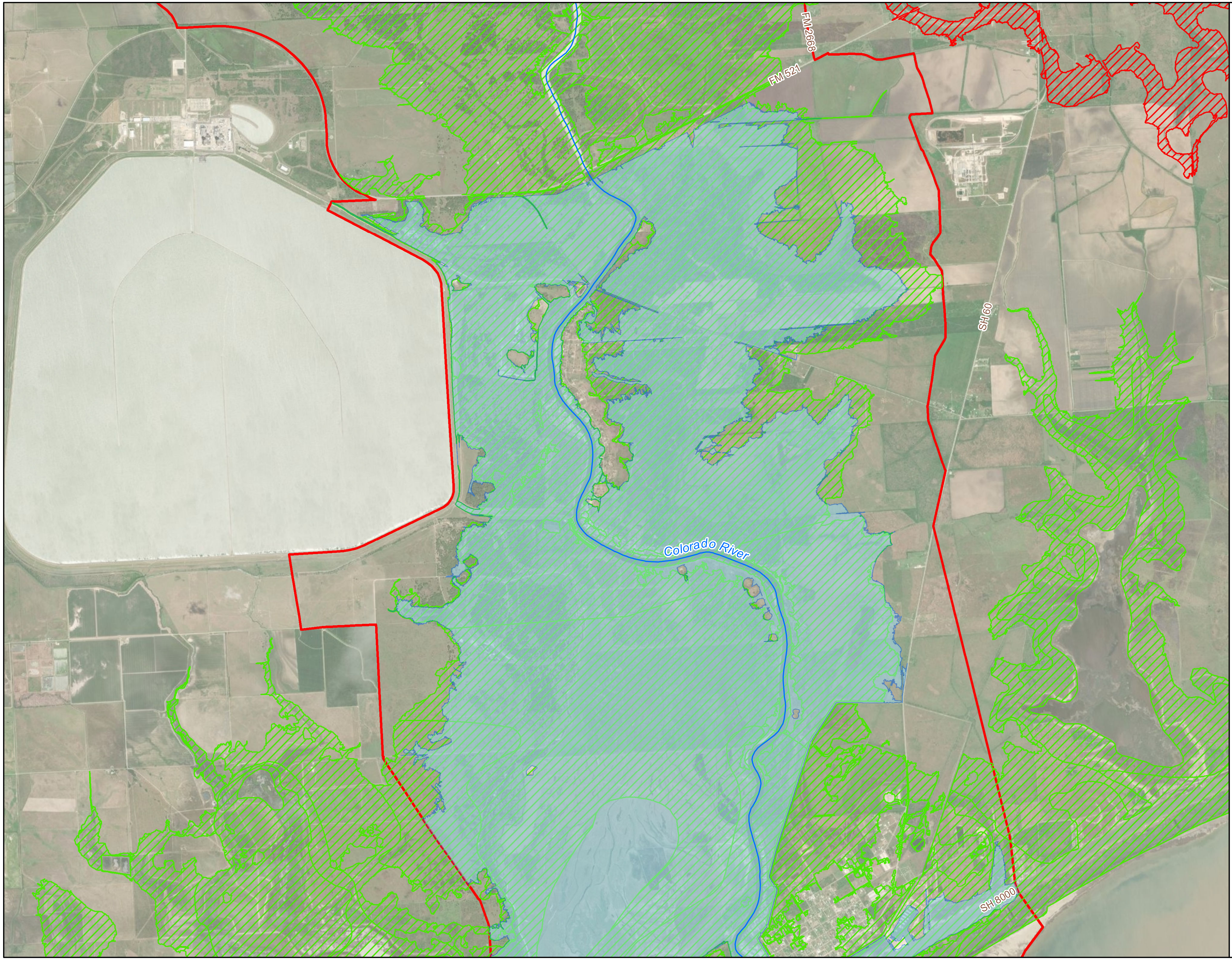
N

0 4,000 8,000 Feet

# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E13: 100-YR Inundation- Mouth Section




### Key To Features

- Colorado River
- TriCounty 100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

N

0 4,000 8,000 Feet

# Lower Colorado River Flood Protection Planning Study

## Colorado, Wharton, and Matagorda Counties, TX

## Figure E14: 100-YR Inundation- Mouth Section


**Key To Features**

- Colorado River
- TriCounty 100-yr Floodplain
- FEMA Zone A
- FEMA Zone AE
- Study Limits

SCHEIBE CONSULTING LLC

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0 4,000 8,000 Feet

# APPENDIX F:
# “GAUGE INFLUENCE” POINT MAPS


**KEY TO FEATURES**

| | | |
|---|---|---|
| USGS Gauge | Harvey | 10yr |
| LCRA Gauge | Apr2016 | 100yr |
| Major Roadways | Nov2004 | 500yr |
| | Oct1998 | |

0 1 2 3 Miles

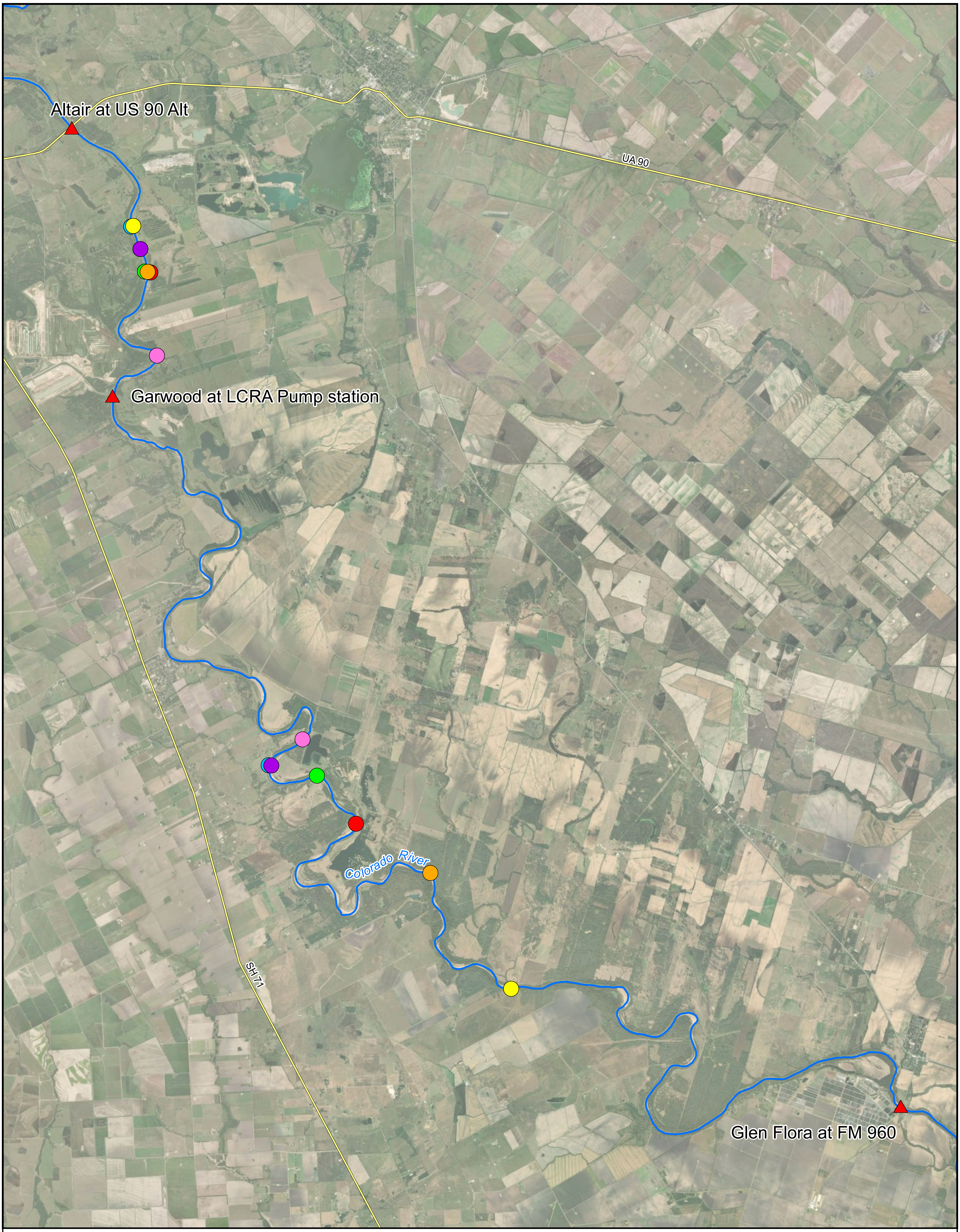
N

**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure F1: Gauge Influence Points Columbus to Altair**

SCHEIBE CONSULTING LLC




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure F2: Gauge Influence Points Altair to Glen Flora**

**KEY TO FEATURES**

- USGS Gauge
- LCRA Gauge
- Major Roadways
- Harvey
- Apr2016
- Nov2004
- Oct1998
- 10yr
- 100yr
- 500yr

SCHEIBE CONSULTING LLC

N

0 1.5 3 4.5 Miles


**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure F3: Gauge Influence Points Glen Flora to Lane City**

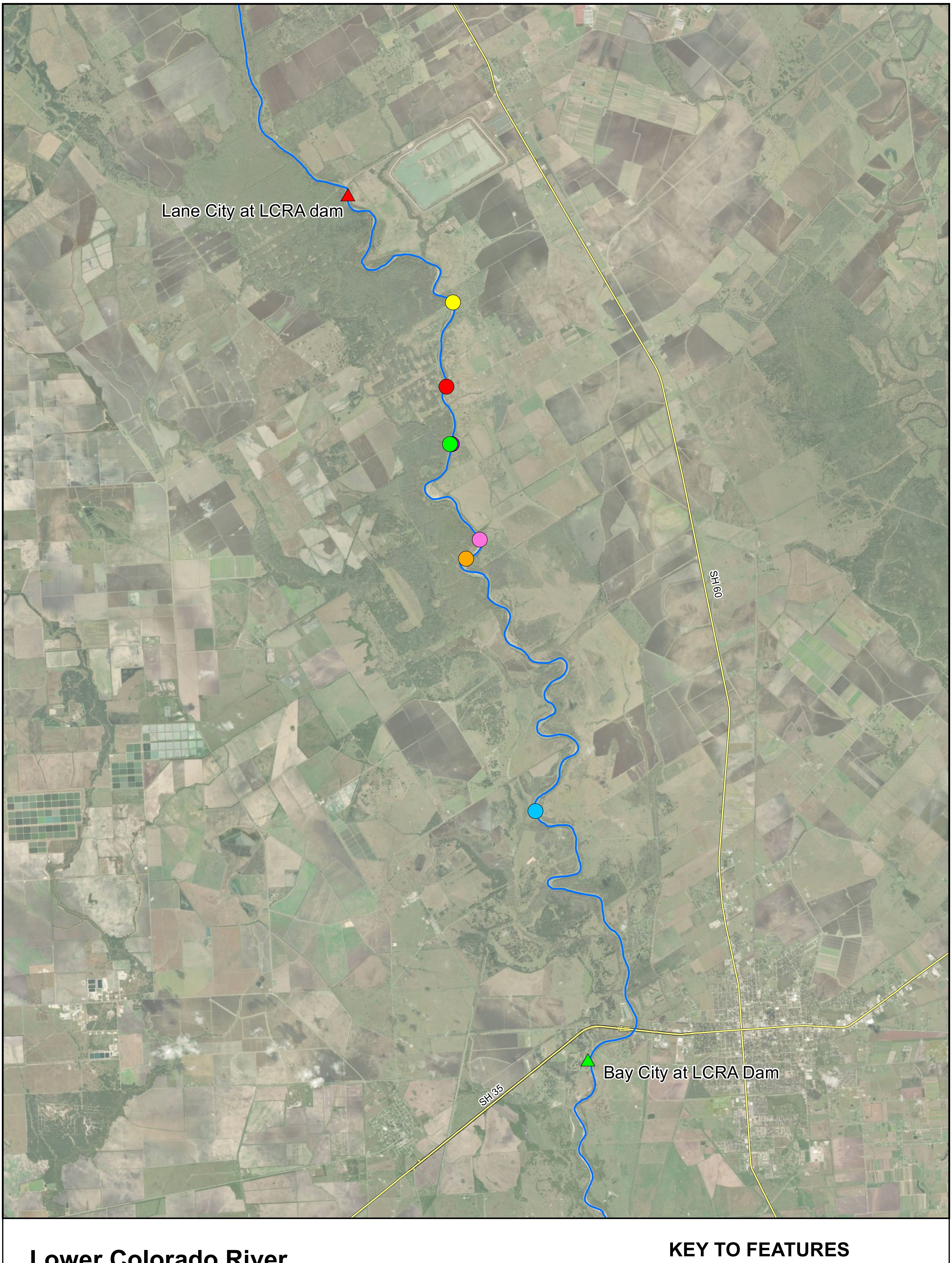
**KEY TO FEATURES**

USGS Gauge
LCRA Gauge
Major Roadways
Harvey
Apr2016
Nov2004
Oct1998
10yr
100yr
500yr

SCHEIBE CONSULTING LLC

N

0 1 2 3 Miles

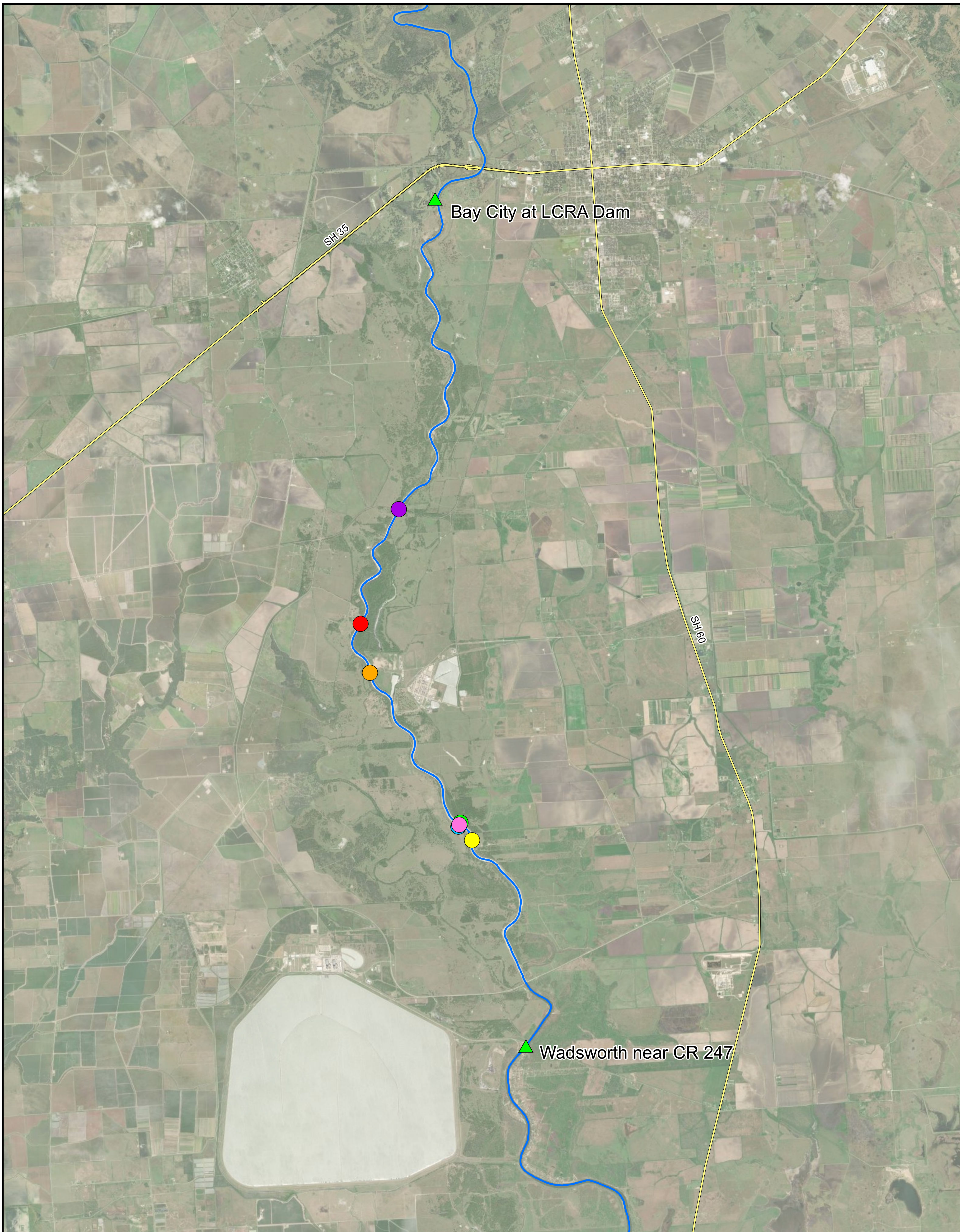



**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure F4: Gauge Influence Points Lane City to Bay City**

SCHEIBE CONSULTING LLC




**KEY TO FEATURES**

- USGS Gauge
- LCRA Gauge
- Major Roadways
- Harvey
- Apr2016
- Nov2004
- Oct1998
- 10yr
- 100yr
- 500yr

0 1.5 3 4.5 Miles

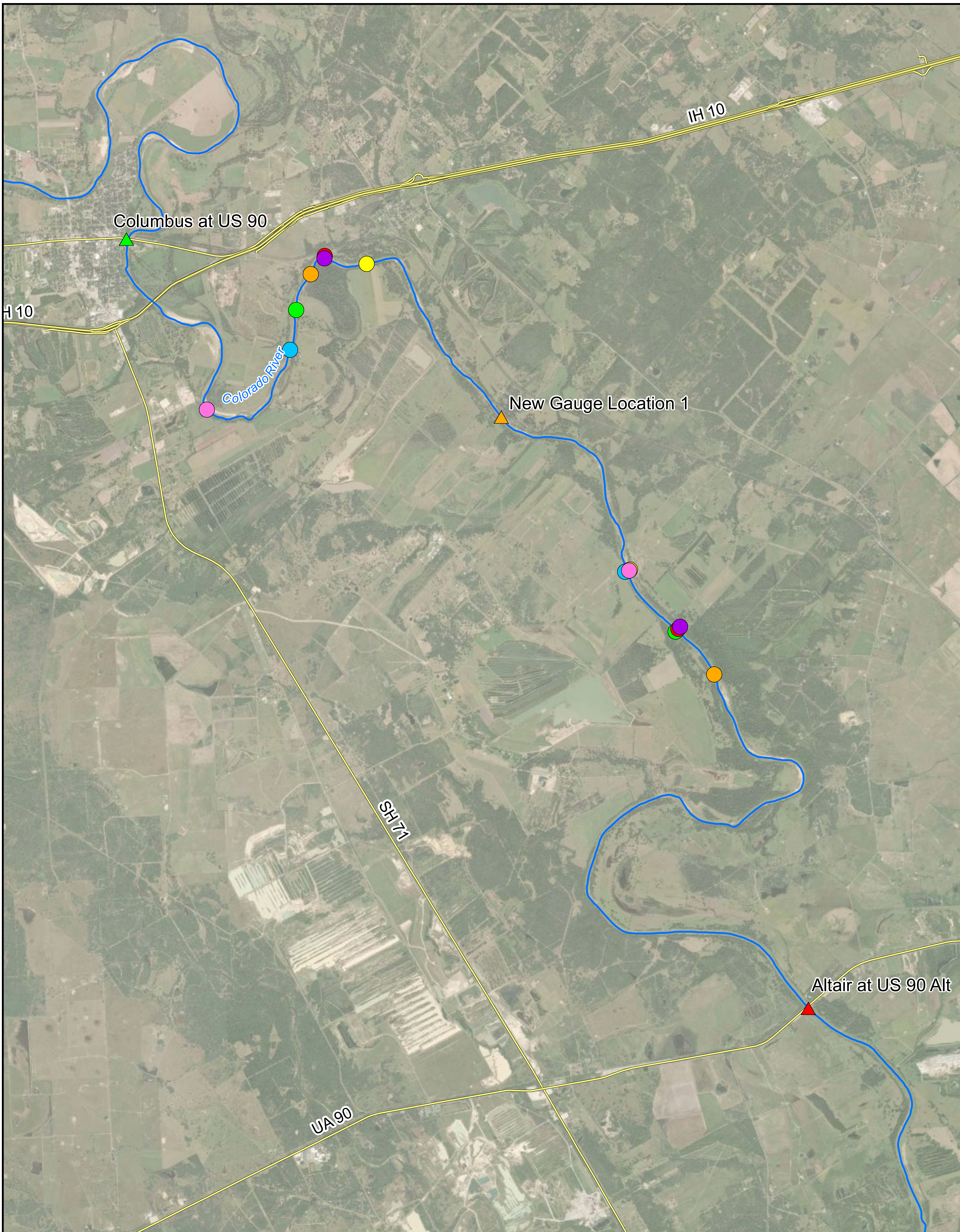
N

SCHEIBE CONSULTING LLC

**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure F5: Gauge Influence Points Bay City to Wadsworth**




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure F6: Gauge Influence Points Columbus to Altair with Proposed New Gauge**

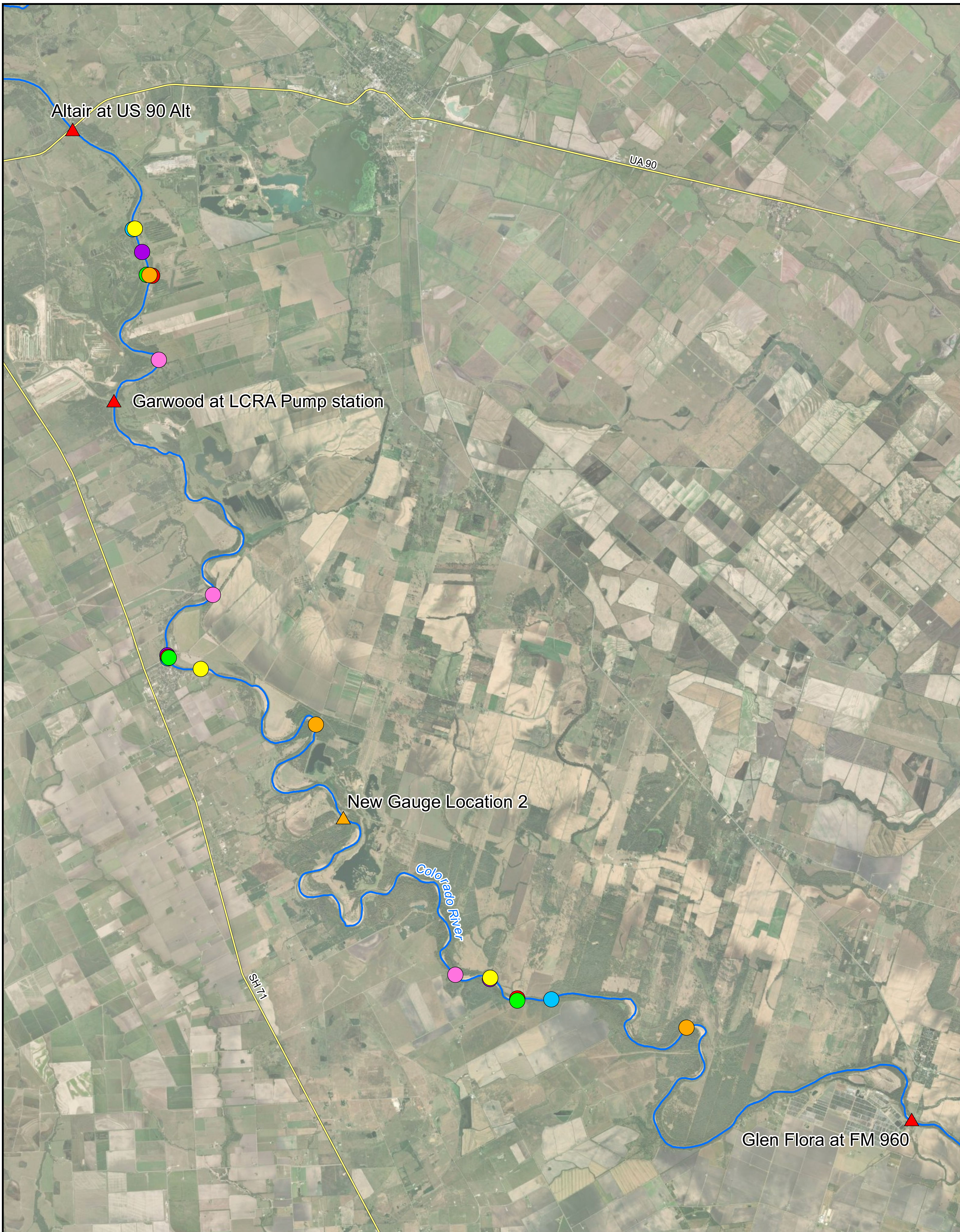
**KEY TO FEATURES**

| | | |
|---|---|---|
| USGS Gauge | Harvey | 10yr |
| LCRA Gauge | Apr2016 | 100yr |
| Proposed Gauge | Nov2004 | 500yr |
| Major Roadways | Oct1998 | |

SCHEIBE CONSULTING LLC

N

0 1 2 3 Miles




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure F7: Gauge Influence Point Altair to Glen Flora with Proposed New Gauge**

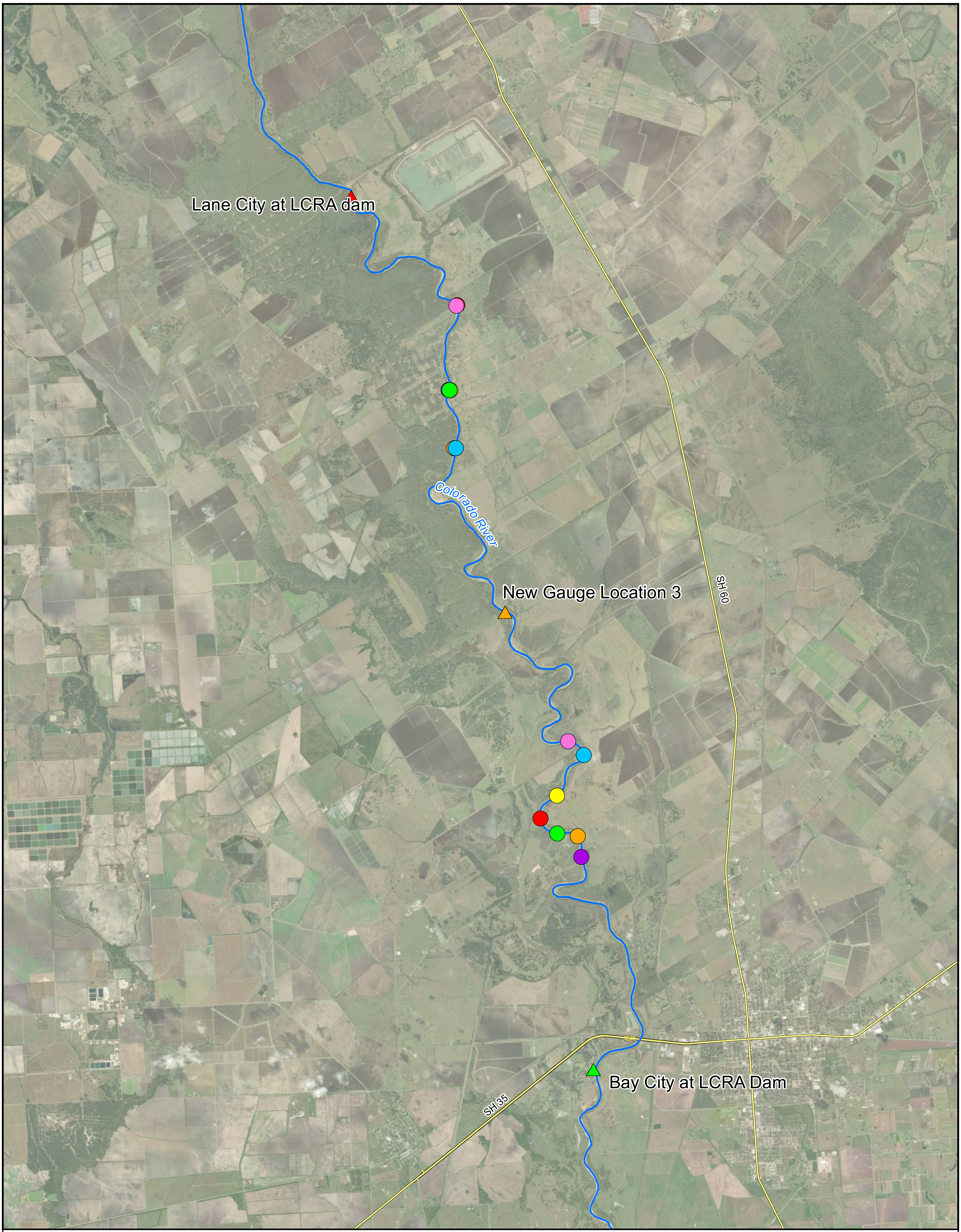
**KEY TO FEATURES**

USGS Gauge
LCRA Gauge
Proposed Gauge
Major Roadways
Harvey
Apr2016
Nov2004
Oct1998
10yr
100yr
500yr

SCHEIBE CONSULTING LLC

N

0 1 2 3 Miles




**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure F8: Gauge Influence Points Lane City to Bay City with Proposed New Gauge**

**KEY TO FEATURES**

- USGS Gauge
- LCRA Gauge
- Proposed Gauge
- Major Roadways
- Harvey
- Apr2016
- Nov2004
- Oct1998
- 10yr
- 100yr
- 500yr

SCHEIBE CONSULTING LLC

N

0 1.5 3 4.5 Miles


**Lower Colorado River Flood Protection Planning Study**

**Colorado, Wharton, and Matagorda Counties, TX**

**Figure F9: Gauge Influence Points Bay City to Wadsworth with Proposed New Gauge**

**KEY TO FEATURES**

USGS Gauge
LCRA Gauge
Proposed Gauge
Major Roadways
Harvey
Apr2016
Nov2004
Oct1998
10yr
100yr
500yr

SCHEIBE CONSULTING LLC

N

0 1.5 3 4.5 Miles