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CENTER FOR TRANSPORTATION RESEARCH

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Streamflow Measurement at TxDOT Bridges: Final Report

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16. Abstract
A transect of 20 radar streamflow gages has been installed on TxDOT bridges located on or near Interstate Highway 10, with gages located from west of San Antonio to the Louisiana border. The highest concentration of gages is east of Houston where I-10 is particularly flood prone. A cloud-based big data system is used to combine streamflow data from the TxDOT gages with real-time forecasts from the National Water Model to provide real-time flood forecasting along I-10 and a foundation for flood risk assessment of the regional transportation system.

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Research Supervisor: David Maidment

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Executive Summary

The National Weather Service has developed a National Water Model that continually forecasts flow throughout the river and stream network of the United States. Water has become like weather, forecast everywhere, at local scale, all the time. In Texas, flow forecasting is provided on about 190,000 miles of streams and rivers divided into about 100,000 forecast reaches. However, the streamflow measurement data available to correct and validate the National Water Model are sparse. At present, the National Water Model uses data from about 550 US Geological Survey stream gaging sites in Texas. There are 27,000 Texas bridges located on stream reaches forecast by the National Water Model. This project establishes a transect of radar streamflow measurement sites on Interstate Highway 10 (I-10) bridges as a pilot implementation to examine the feasibility of a broader streamflow measurement program on bridges maintained by the Texas Department of Transportation (TxDOT).

Each of the 20 sites is instrumented with an RQ-30 indirect measurement system, which uses radar to measure both the water elevation and velocity without the instruments touching the water. Water velocity data are useful in tidal zones, such as those in the Beaumont District, where all the gage sites on I-10 are in the coastal zone. Each gage site is powered by a battery recharged from a solar panel. Water level and velocity data are communicated every 15 minutes through a cell phone connection. Each bridge and radar site is documented using 360° photography and a virtual staff gage is superimposed on the bridge at the gage site to allow better visualization of the water height. The stream cross-section is measured by using lidar data and GPS surveying, supplemented for sites with permanent water in the coastal zone using Acoustic Doppler Current Profiler measurements.

The data are received and processed in a cloud data system maintained by the Kisters firm, in which water level and velocity are converted to streamflow discharge. The Kisters Big Data system also ingests the National Water Model flow forecasts for all of Texas and converts these to an estimate of water level in each stream reach. The water levels measured at the TxDOT radar gages and the USGS gages are compared with the levels estimated from the National Water Model. A detailed 2D hydrodynamic model was created for the West Navidad River at I-10, which has two bridges, one on the main channel and another in the floodplain. This model illustrated the flow patterns in the floodplain and through the highway bridges. Lidar land surface terrain data with 1m cells proved admirable to support the modeling study and to characterize the road elevation profile and stream cross-section at all the gaging sites.

A statistical methodology for using the errors between observed and forecast water levels and flows has been developed and applied to a test case in the Navidad river basin. This methodology shows promise for improving the flow forecasts for about 15 miles upstream and 30 miles downstream of the I-10 gage transect. A geostatistical variogram showed that peak flows during Tropical Storm Imelda were correlated up to a distance of 50 miles along I-10. The I-10 transect gage spacing is about 20 miles west of Houston and 10 miles east of Houston, so the coverage of flows along I-10 is adequate using this gage spacing. A plan for installing gages on additional highway transects north of I-10 is presented. On September 17–20, 2019, Tropical Storm Imelda occurred in Southeast Texas, and the report concludes with a preliminary assessment of the lessons learned during this large flood event. An appendix summarizes the experience accumulated during this project for installing radar gages on I-10.

Chapter 1. Introduction

1.1. Motivation for the Project

The National Weather Service has developed a National Water Model that continually forecasts flow in the river and stream network of the United States (https://water.noaa.gov/about/nwm). The National Water Model operates as part of the nation's weather forecasting system, so water flow has become like weather, continually forecast everywhere, at local scale, all the time. In Texas, water flow forecasts are provided on about 190,000 miles of streams and rivers divided into 102,000 individual stream reaches. As shown in Figure 1-1, there are 27,000 Texas bridges located on 15,700 of these stream reaches, so the National Water Model provides for the first time a statewide method of assessing in real time the flow conditions at the Texas bridge system.

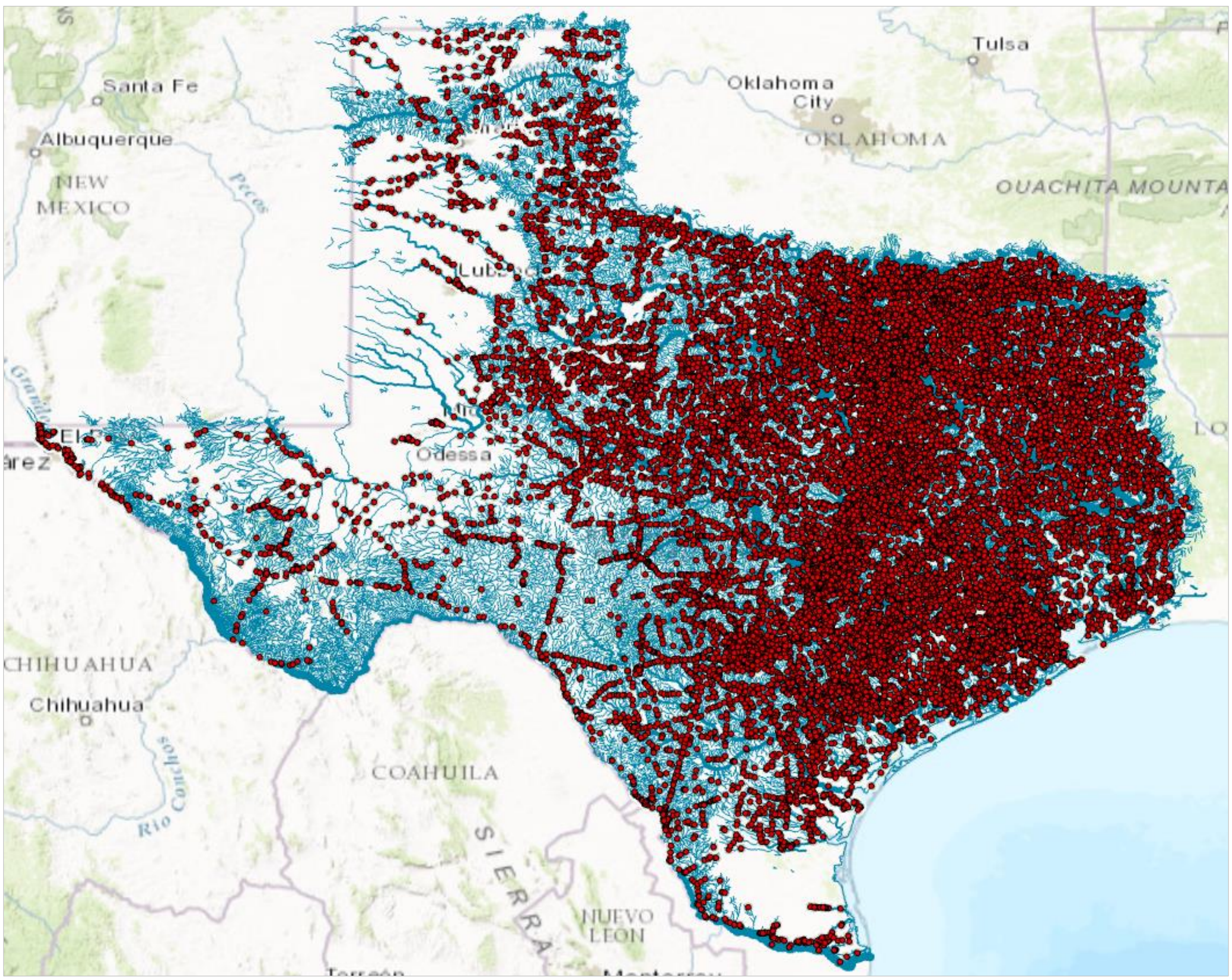


Figure 1-1 Locations of approximately 27,000 Texas bridges overlying National Water Model stream reaches

The Center for Water and the Environment of the University of Texas at Austin led the engagement of the US academic community in working with the National Weather Service to develop the National Water Model. The prototype national model was created at the Texas Advanced Computer Center in Austin in 2014–2015, with the help of the National Center for Atmospheric Research. This prototype was subsequently moved to the Weather and Climate Operational Supercomputer System of the National Weather Service in Maryland, where it presently operates. Several upgrades to the National Water Model have subsequently been produced, most recently Version 2.0, which became operational in June 2019. This work is coordinated at a National Water Center operated by the National Oceanic and Atmospheric Administration (NOAA) on the Tuscaloosa campus of the University of Alabama. This Center achieved an initial operating capacity as a national center for flood forecasting on 1 October 2019.

Forecasts from the National Water Model in Texas are checked against observations from about 550 US Geological Survey stream gaging stations, as shown in Figure 1-2. Since forecasts are being made at more than 100,000 stream reaches, it follows that only one reach in about 200 is actually being observed and measured. It is clear by comparing Figures 1.1 and 1.2 that if the Texas bridge network could be more fully utilized for stream measurement the National Water Model forecasting would be more securely anchored to measured data, and thus more accurately depict and forecast flow conditions on the bridge and transportation network.

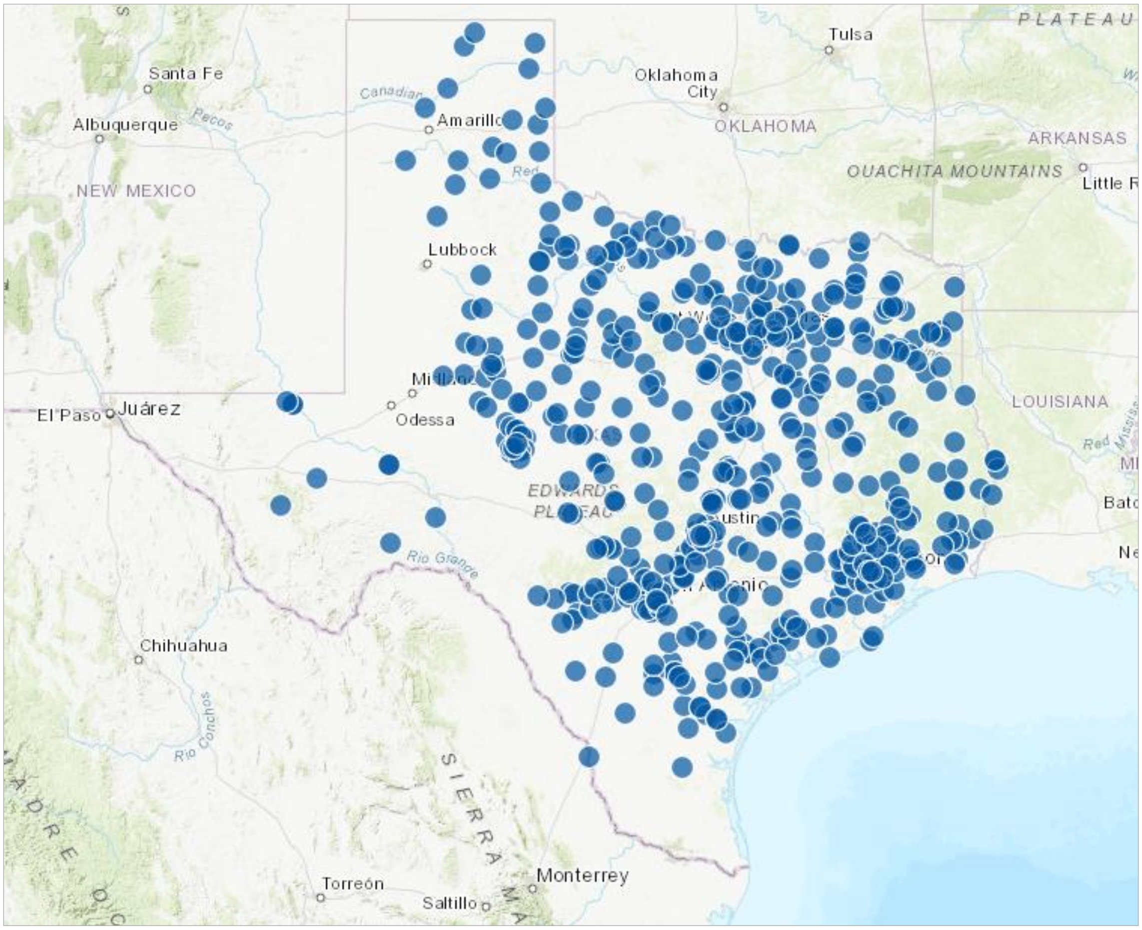


Figure 1-2 Locations of 550 USGS Stream gaging stations in Texas

1.2. Transect of Gages on I-10

In this project, a transect of 20 radar streamflow gages has been installed on Interstate Highway 10 (I-10) distributed from west of San Antonio across south Texas to the Louisiana border, as shown in Figure 1-3. I-10 was chosen because it is a critical transportation conduit for Texas and because it is regularly subjected to flooding. From 2014 to 2018, about 330 road closures have been recorded on I-10, half of which occurred during Hurricane Harvey, and I-10 was closed again in September 2019 during Tropical Storm Imelda. TxDOT state-wide road closure data show that about three-quarters of road closures result from flooding. Figure 1-3 shows that gages were not installed on I-10 in the Houston area—this occurred because this area is already very densely gaged by the local authorities, in particular, the Harris County Flood Control District. Nine of the 20 transect gages were installed in the Beaumont District, east of Houston, where I-10 has a high flood risk.

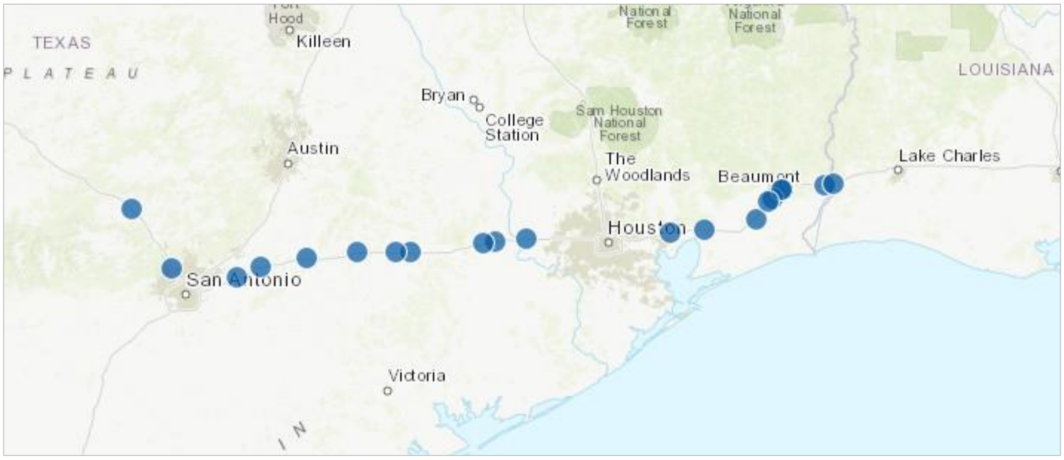


Figure 1-3 Locations of 20 radar streamflow sites installed on I-10

Using the Interstate Highway system as a base for streamflow measurement is novel. Usually gages are placed at strategic locations on rivers and streams near the outlets of watersheds, and the density of gages increases in the large cities, as can be seen in Figure 1-2. Few USGS gages are placed on the Interstate Highway system because access to the gages is difficult there. When viewed from a national perspective, the interstate highway system runs West to East and North to South to provide a national transportation network. However, this network could also be thought of as a national transect system for streamflow measurement if it were more fully instrumented.

Normally at stream gaging sites the instruments measure only water level, but TxDOT chose in this project to utilize a more comprehensive radar stream gaging instrument called the RQ-30 developed by Sommer Messtechnik in Koblach, Austria, and marketed in the United States by Hydrological Services America. The RQ-30 measures water level by using a radar sensor pointing straight down at the water. It has in addition a velocity sensor that points out at an angle to the water surface, where it measures the velocity using a Doppler radar effect from the movement of ripples on the water surface. These are both considered indirect measurements since none of the instrumentation is touching the water. The gage is mounted by being bolted to the side of the bridge, is powered using a battery recharged by a solar panel, and communicates through the cell phone network. Thus the whole gage package is a standalone system that does not require an external power source or a gage house on the bank of the river.

1.3. Kisters Water Data System

Access to the TxDOT bridge sensor data and also to the USGS flow data is provided through a TxDOT Water Data Viewer developed by the Kisters water data management firm, as shown in Figure 1-4. Kisters is the largest water data management firm in the world, whose data system is used for the whole national hydrological network in the United Kingdom and several European countries. The Kisters data system is also used by the City of Austin, Lower Colorado River Authority, City of Houston, and the Harris County Flood Control District, to record, archive and display the data from their gaging networks. In this project, the Kisters data system not only records and displays the TxDOT bridge sensor data, it also stores and displays the corresponding forecasts from the National Water Model for all 102,000 stream reaches in Texas. Besides using the web viewer, water level, velocity and flow data can be accessed programmatically using water data services for inclusion in other applications. The bridge sensors are alarmed so that if the water rises to critical levels, messaging is sent out to the TxDOT emergency response system.

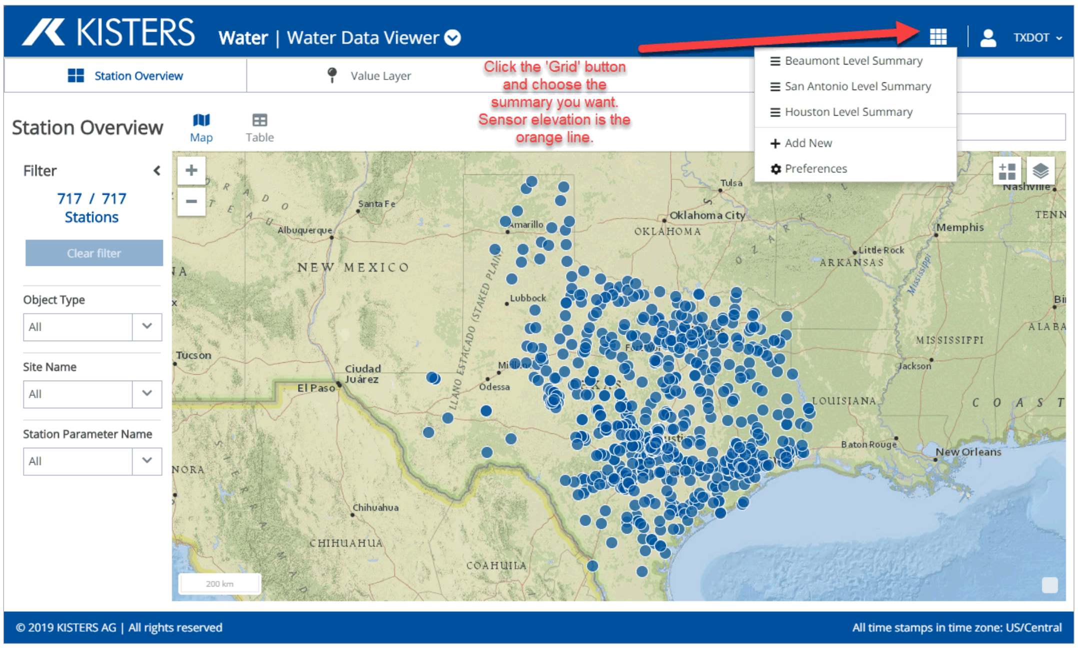


Figure 1-4 Kisters Water Data Viewer

1.4. Outline of the Report

Chapters 2-3 of this report describe how the sites were selected and the equipment installed, and how the sites were characterized using surveying, lidar data and 360° photography. Chapters 4–5 describe how the data are processed, archived, and accessed in the Kisters data system, and how web access is provided to the data for each site, and for Texas as a whole. Chapter 5 describes how a statistical method was developed to adjust the National Water Model forecasts to account for measured gage data. Chapters 6 and 7 were not part of the project scope but were added to provide additional detail—Chapter 6 describes a detailed hydraulic model of one of the bridge sites, and Chapter 7 provides a brief review of Tropical Storm Imelda, which impacted southeast Texas on 17–20 September 2019. Chapter 8 provides concluding comments. An appendix summarizes the experience accumulated during this project for installing radar gages on I-10.

Chapter 2. Streamflow Gaging Sites

2.1. Selection of Sites

Given the focus on I-10, the next step was to determine the locations of individual gaging sites. The 20 sites were initially envisaged as being reasonably uniformly located along the highway on the larger river stream systems. Because of concerns about traffic interruption during gage installation and maintenance there was a desire to avoid siting gages on the main lanes of I-10 but in some instances that was unavoidable, and in such cases, gages were only installed on the main lanes if there was a significant shoulder width available. Many gages are installed on the frontage roads of I-10, which have the advantage of much lower traffic volume. A few gages are installed on roads nearby I-10 so as to measure rivers that impact I-10 without having to install equipment on I-10 itself. There was some consideration given to collocating TxDOT radar sensors with USGS gaging sites, and that was done at Site 120 on the Guadalupe River.

After initial site visits, we decided that bridge sites should be located where the gage can be installed and accessed for maintenance without lane closure. In every case, we avoided lane closures but at some sites TxDOT provided a crash attenuator truck on the shoulder for an added margin of safety.

The process to select a site includes these steps:

- Desktop survey via Google Earth to identify possible bridge sites within large watersheds.
- Confer with the local TxDOT District to identify bridges within their district where they have experienced flooding or bridges where they would want gages installed.
- Compare the possible sites with TxDOT's bridge replacement list and eliminate those bridges scheduled for maintenance.
- Conduct an onsite reconnaissance of each site to ensure the conditions are favorable for gage installation and to determine if there are other gages (such as USGS or water control district) on or near the bridge.
- Make final selection of gage sites.
- Prepare engineering plans of the gage installation for each bridge and submit to TxDOT for permit and permission to install.
- Once permit has been approved, proceed with installation.

2.2. Gage Installation

The process to install a radar gage includes the following steps.

Prior to Installation:

- Request traffic control for installation date at least seven days out.
- Make detailed measurements on the size and style of the bridge rail.
- Determine the type of mount necessary for the gage and prefabricate all fittings.
- Program the data logger and radar using the designated standard settings files.
- Test each logger and sim card to confirm it is properly reporting to the Kisters Cloud prior to installation.

During Installation:

- Confirm traffic control measures are in place.
- Assemble and wire gage off the bridge and away from the roadway.
- On the bridge, drill four holes and install bolts for mounting brackets.
- Take accurate measurements of the four bolts and adjust gage mounts to fit.
- Install and secure gage on the bolts; make sure no part of the gage extends over the bridge rail and that the solar panel is angled to the South, if possible.
- Make sure radar is pointed parallel to the direction of flow.
- Install battery and activate system.
- Exit the bridge and wait for the first successful report of data (no longer than 10 min) before locking the shelter and removing traffic safety.
- The installation team of two persons usually takes 1.5 to 2.5 hours to install the gage.

Figure 2-1 shows installed equipment at two sites. There are three parts of the equipment: the solar panel on top, the gage box beneath, and the radar sensor at the bottom. These are connected by each being bolted to a 2” galvanized pipe, and the pipe in turn is bolted onto the bridge berm or railings, as shown in Figure 2-2. This installation method proved to be secure and kept the equipment in place even at three sites that were overtopped by flooding during Tropical Storm Imelda.

a) Site 105 Hillebrandt Bayou

b) Site 114 West Navidad River

Figure 2-1 Examples of installed gage equipment

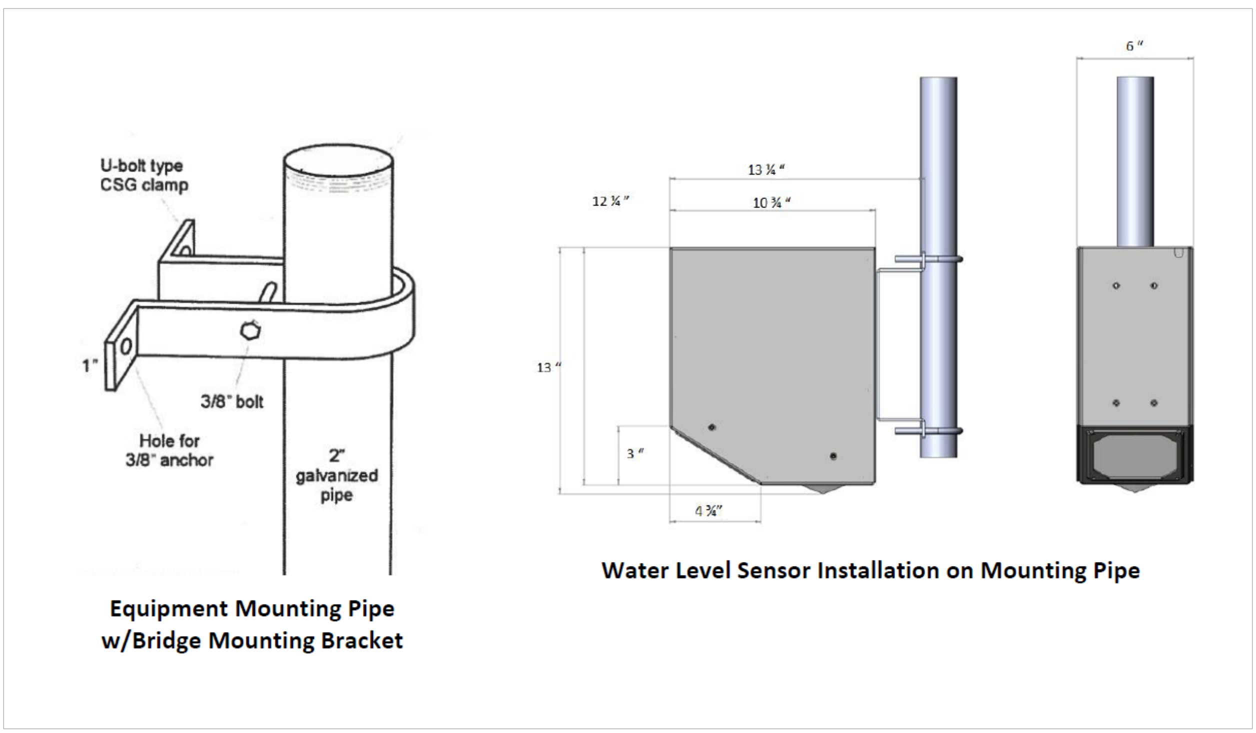


Figure 2-2 The mounting pipe and its attachment to the bridge and to the equipment

Figure 2-3 shows the interior of the gage electronics box, which contains the battery, data logger for recording sensor measurements, and cell phone communications equipment to transmit the data to the Kisters Big Data system.

Figure 2-3 Interior of the gage electronics box

TxDOT considers the integrity of a bridge to be threatened if flood waters reach the low chord elevation, as shown in Figure 2-4.

Figure 2-4 Low chord elevation (LCE)

At the time of equipment installation a series of vertical measurements are made using a tape measure or a weighted tape from the bridge down to the water surface and streambed, as shown in

Figure 2-5. These measurements are very important for later checking of the interconnection of GPS surveying, lidar, and stream bathymetry at the gage site.

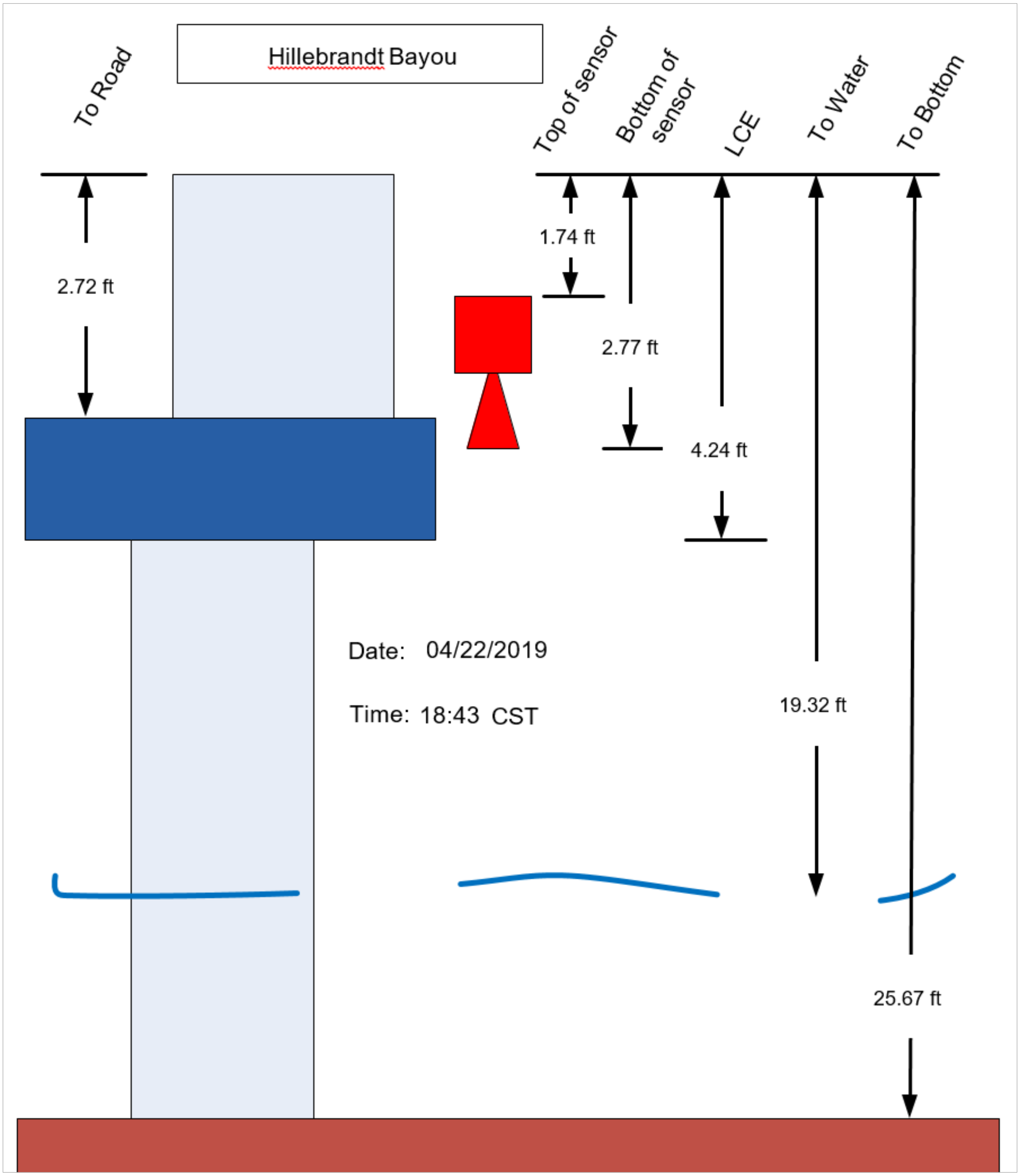


Figure 2-5 Elevation measurements for Site 105, Hillebrandt Bayou

Gaging equipment is installed at 20 site locations, as illustrated in Figure 2-6 where the TxDOT District regions are colored so it can be seen in which districts the sites are located. The listing of sites by road and river name is given in Table 2-1. The site with yellow dot in Figure 2.6 is where the gage has been moved to Church Creek, a tributary of the San Bernard River, because the bridge on the San Bernard river where the gage was originally installed is scheduled for replacement.

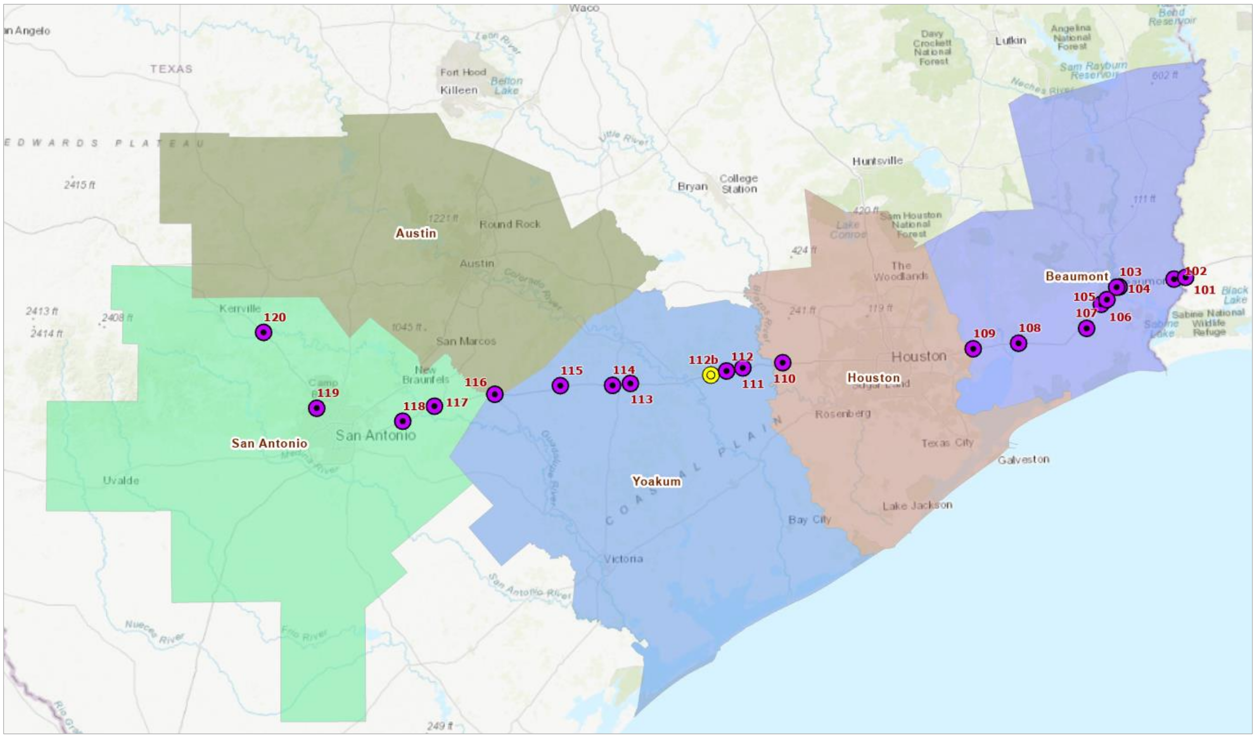


Figure 2-6 Locations of streamflow sensors

Table 2-1 Locations of TxDOT bridge streamflow sensors.

Site	Location	Site	Location
101	Sabine River at I-10	111	East Bernard Creek at I-10
102	Adams Bayou at I-10	112	San Bernard at I-10 (moved to Church Creek at I-10)
103	Bairds Bayou at I-10	113	East Bernard River at US-90
104	Neches River at I-10	114	West Navidad River at I-10
105	Hillebrandt Bayou at TX-124	115	Peach Creek at I-10
106	Willow Marsh Bayou at I-10	116	Plum Creek at I-10
107	North Fork Taylor Bayou at I-10	117	Geronimo Creek at I-10
108	Turtle Bayou at I-10	118	Santa Clara Creek at I-10
109	Cedar Bayou at I-10	119	Leon Creek at I-10
110	Bessies Creek at I-10	120	Guadalupe River at US-87

Sites 101 through 109 are east of Houston and have streambed below sea level. Sites 110 through 120 are west of Houston and have streambed well above sea level.

At Site 120, Guadalupe River at US-87, the TxDOT RQ-30 sensor is located next to a USGS stream-gage sensor as shown in Figure 2-7. This is USGS gage 08167000, which has been in its current location since 2010, so it is a well-gaged and rated site. The data measured at the TxDOT and USGS sites can be visually compared in Figure 2-8 and there is little visual difference between them. It should be noted that the TxDOT transect is installed specifically for flood warning and assessment and is not intended as an all-purpose water resources gage suitable for all ranges of flows. In particular, it is not intended for accurate measurement of low flows, which would require repeated field measurements of flow at various water levels not undertaken in this project.

Figure 2-7 Guadalupe River at US-87 near Comfort, Texas

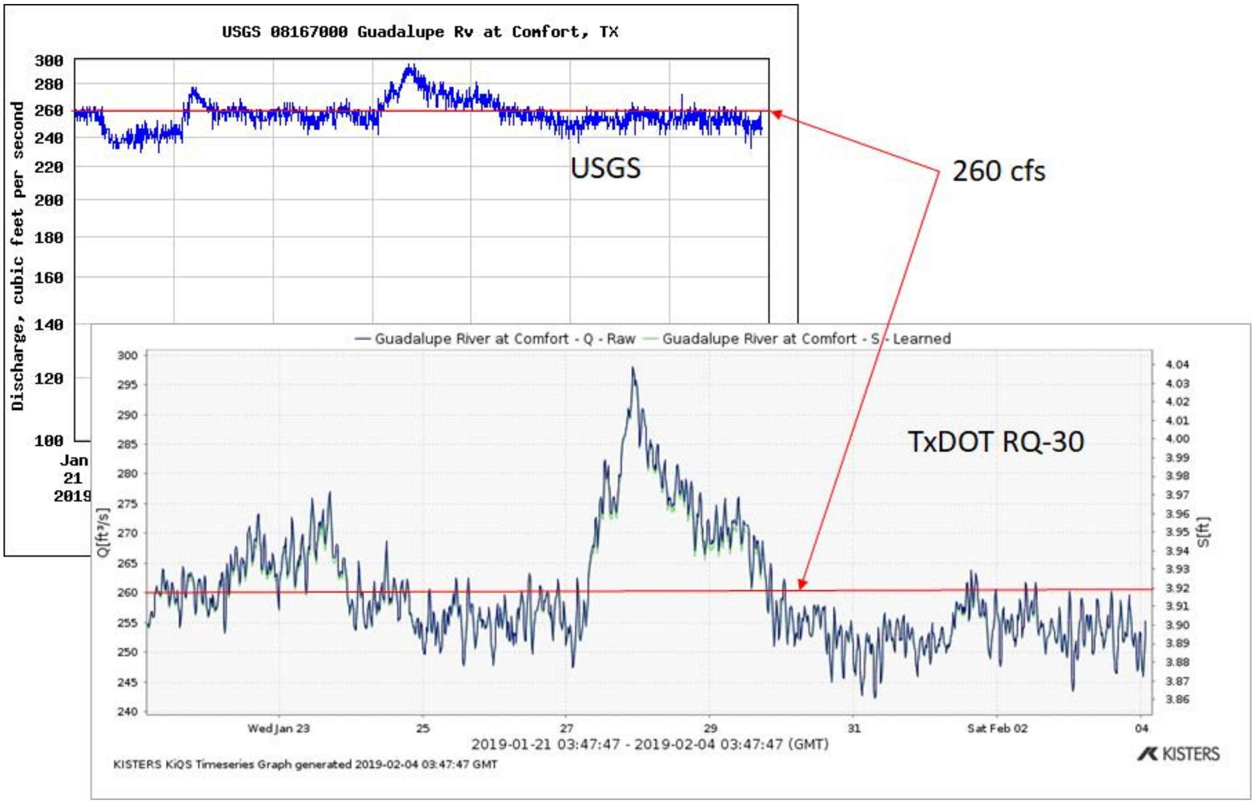


Figure 2-8 Comparison of flow measurements from USGS and TxDOT sensors

Chapter 3. Site Characterization

3.1. Requirements for Computation of Discharge

The RQ-30 sensor simultaneously measures water surface elevation, *h*, and the local velocity, V_l, at a point on the stream water surface located obliquely in front of the sensor, as shown in Figure 3-1.

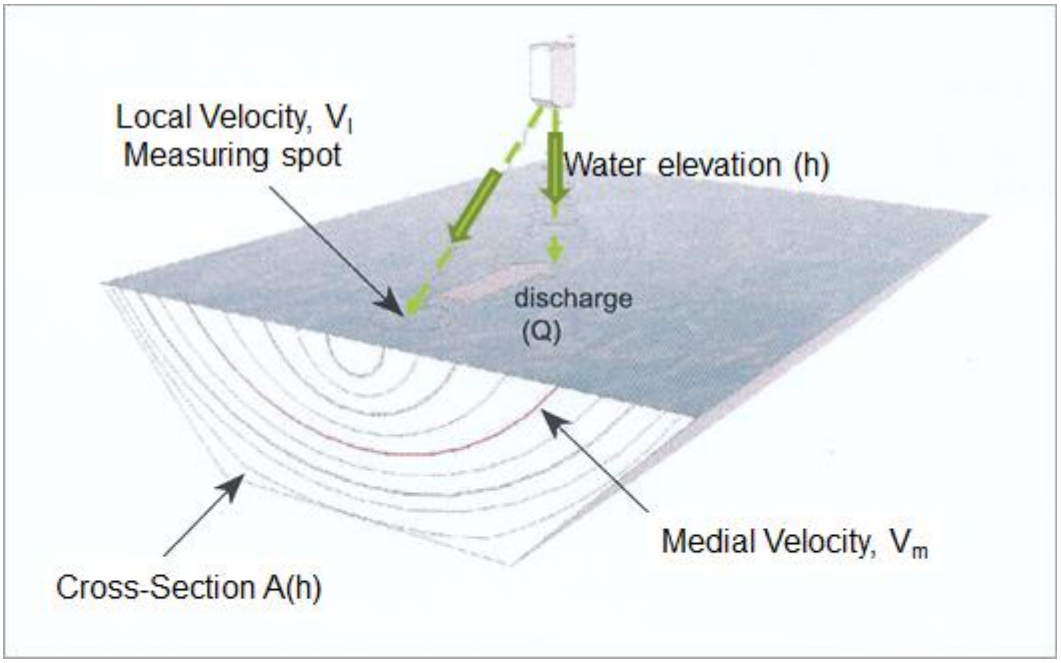


Figure 3-1 The RQ-30 sensor simultaneously measures water surface elevation and surface velocity

A line across the channel perpendicular to the sensor was surveyed at each site and used to compute the cross-sectional area of the stream channel, *A(h)*, for a given water surface elevation. An adjustment factor, *k*, generally on the order of $k \sim 0.6$, is used to compute the mean velocity, V_m, from the surface velocity, V_l. This value was verified using Acoustic Doppler Current Profiler (ADCP) measurements along the surveyed line, as described later in this chapter. The discharge, *Q*, is computed as the product of the mean velocity and the cross-sectional area, as shown in Figure 3-2. In the TxDOT application, the quantities shown in green in Figure 3-2 occur at the sensor location. The resulting water level and surface velocity data are stored with the sensor in an on-site data logger and transmitted each 15 minutes via the cell phone network to the Kisters cloud data system. The quantities shown in purple in Figure 3-2, the cross-section profile and the k-factor velocity calibration, require a one-time specification for the site and the data are then stored in the Kisters cloud system. The quantities shown in blue in Figure 3-2 are the computations that occur continuously in the Kisters cloud system to produce the cross-sectional area for a given stream depth, the mean velocity determined from the surface velocity, and then the discharge is computed as the product of the cross-sectional area and the mean velocity.

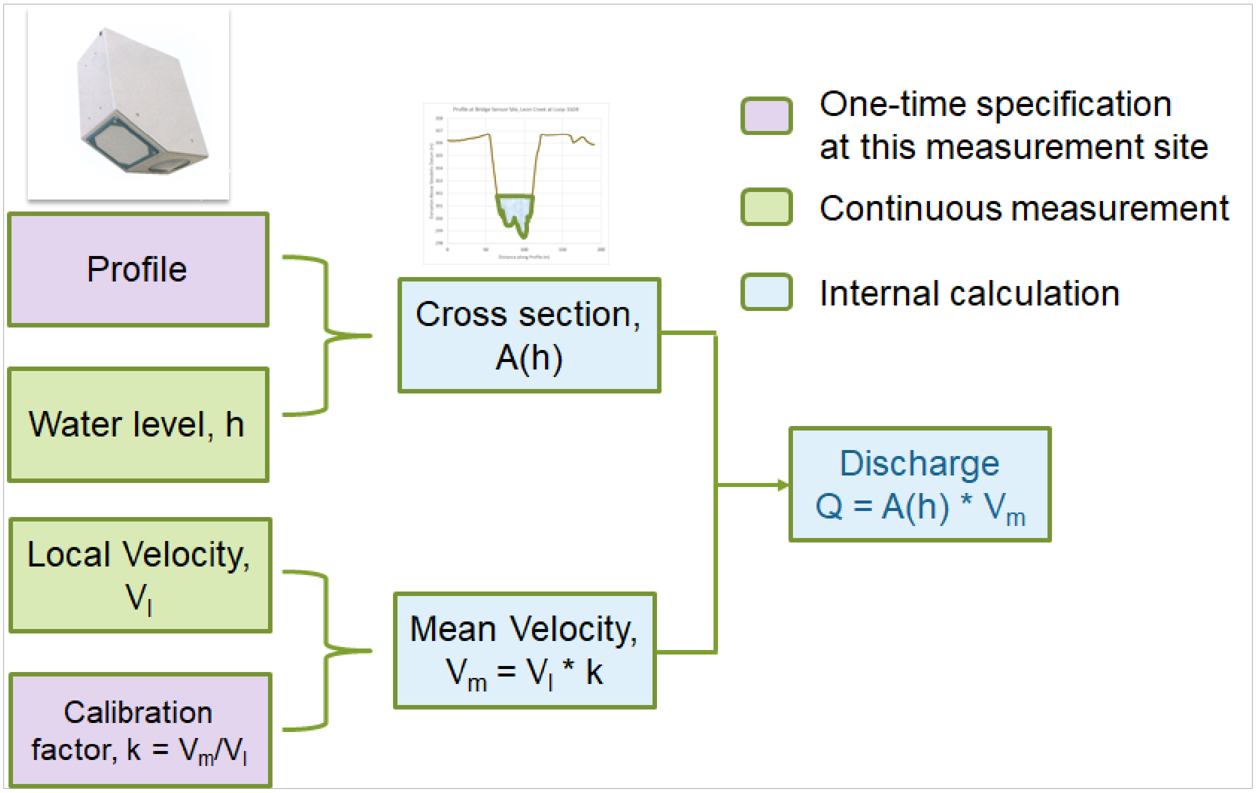


Figure 3-2 Procedure for computing the discharge

A complication for the sites east of Houston is that many of those river channels are impacted by tidal fluctuations. This is apparent in the sinusoidal shape of the flow and water surface elevation at certain sites (see Figure 3-3, for example), and confirmed with the surveying which showed bottom of the channel is below mean sea level. The velocity sensor helps to distinguish between river flow and tidal surge at each site, and to improve water surface elevation forecasting. It should be noted that the USGS does not install stream gages in the coastal zone because of the difficulty in estimating flow strictly from water surface elevation.

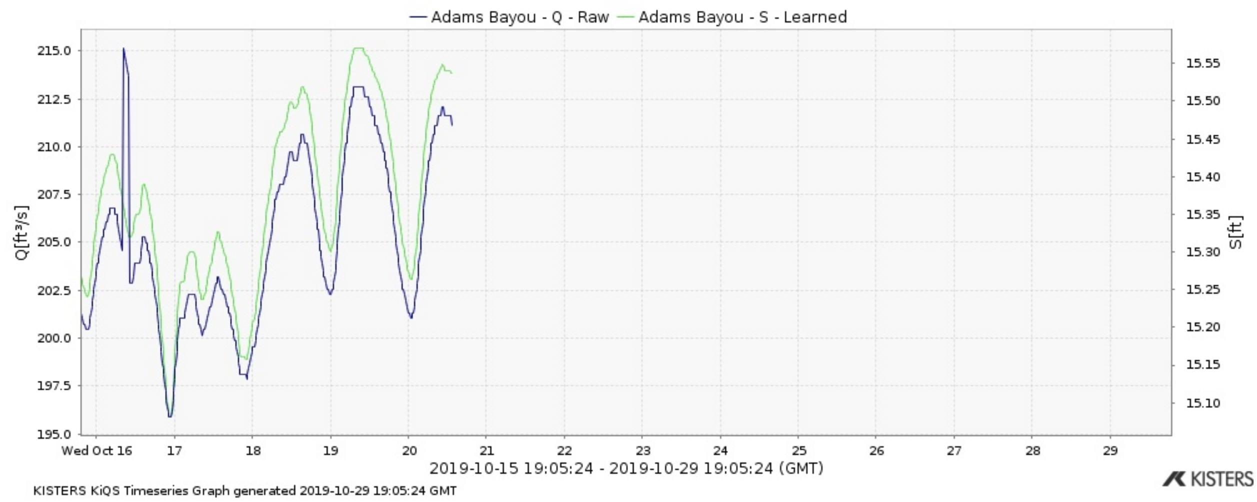


Figure 3-3 River flow under the influence of tide at Site 102: Adams Bayou

A schematic of the sensor unit and the direction of its radar beam measuring surface water velocity is shown in Figure 3-4. The angle of deflection from the horizontal of the radar beam is 58°, and tan 58° = 1.60. Hence, if the sensor is 16m above the water, the point of velocity sensing is 10m in front of the gage, and if the sensor is 8m above the water, the point of velocity sensing is 5m in front of the gage. There is some spreading of the radar beam as it travels from the sensor to the water surface. On a very high bridge, where the sensor is more than 50 feet above the normal water level, a special radar sensor is needed to avoid too wide a spreading of the radar beam before it hits the water. This high bridge sensor is used at Sites 101 on the Sabine River and 105 on the Neches River in this project.

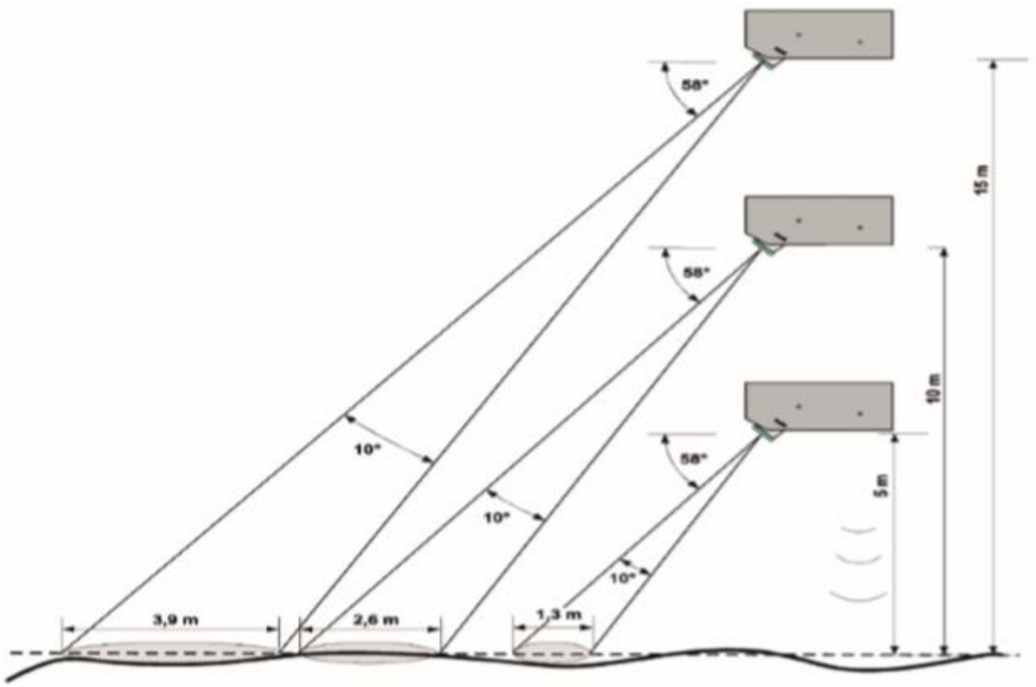


Figure 3-4 Geometry of the measurement beams

3.2. Describing the Stream Cross-Section

The computation of discharge at a gage site requires the specification of the stream cross-section. The reference height used for the cross-section can be measured from a locally established gage datum, as is normal at USGS gaging sites. However, the rationale for establishing a local gage datum differs from one organization to another. In some instances, mean sea level or geodetic datum is used. In other cases, a level five feet below the current streambed is chosen as the datum to allow for possible erosion of the streambed later. To avoid all these local variations and to construct a system with consistent specifications at all sites, heights above the NAVD geodetic datum were used at all sites, so that the stream cross-section appears as shown in Figure 3-5, except that in this project all distances are measured in feet not meters. The distance along the cross-section is measured from the left abutment of the bridge where left is interpreted as looking at the bridge in the direction of flow from upstream to downstream.

It is critical that the location of the RQ-30 sensor in (x,y,z) is measured accurately with a survey quality GPS unit.

In this project a Trimble R-10 GPS survey unit was used at all sites. The rental agency, Allterra in Austin, Texas, has in place an extensive network of differential GPS reference sites, which enabled the survey accuracy needed with minimal effort on our part. This proved to be remarkably accurate, and in all locations where the survey instrument was well exposed to the sky, the location measurement converged to a stable value in just a few seconds.

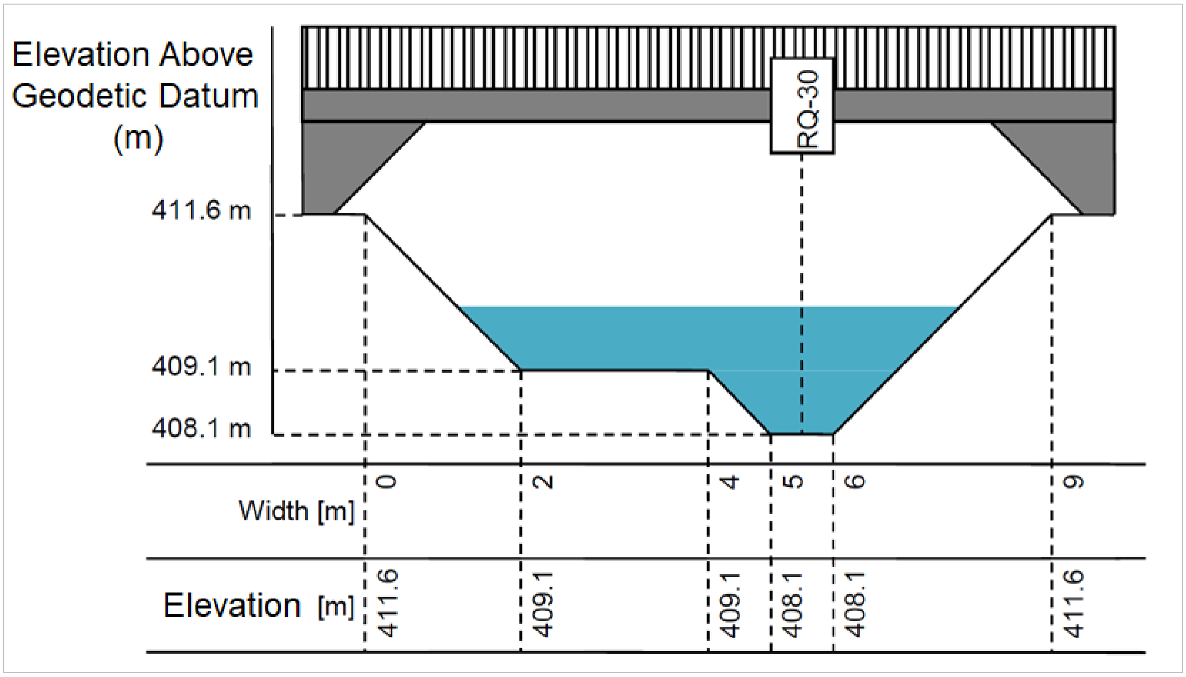


Figure 3-5 River cross-section at the RQ-30 measurement site (Sommer Messtechnik, 2018, p.20)

3.3. Surveying the Road and Stream Cross-Section

One of the most interesting insights that emerged from this project resulted from the conjunction of using lidar data and GPS surveying to measure stream cross-sections, as illustrated for Site 114 on the West Navidad river at I-10 in Figure 3-6. Texas now has statewide airborne lidar measurement of land surface terrain and most of these data have been processed and are accessible from the Texas Natural Resource Information System (https://tnris.org/stratmap/elevation-lidar/). Lidar (a term created from the phrase LIght Detection And Ranging) is a remote sensing technique in which pulses of laser light are emitted from a sensor, reflected from the land surface, and the elevation of the surface determined from the height of the aircraft and the time taken for the emitted pulse to be reflected back to the aircraft sensor.

Lidar data consist of point clouds, or the original points of laser reflection collected by the lidar instrument, and a bare earth Digital Elevation Model (DEM), which is an interpolation onto a regular grid mesh of the elevations of points representing the land surface itself below vegetation. The point clouds are also classified by type of surface reflection (e.g., land, water, vegetation, roadways, etc.), and points representing significant bridges are separately identified and removed from the data before the bare earth DEM is calculated.

In this project, a profile line was drawn along the road edge at the bridge berm. Its elevation was determined using the lidar point cloud data, and also by using GPS surveying at intervals along the road edge, usually 20 points except in a few high traffic density sites where 10 points were measured. The corresponding streambed profile was determined from the bare earth lidar DEM, and by using a weighted tape to measure the vertical height difference between a reference line along the bridge berm and the bottom of the streambed. Where water and flow were present at the site during surveying activities, distance to water surface elevation was measured. Some height adjustments are needed to allow for the difference in height between the height of the road surface used for the GPS surveying and the height of the reference line along the bridge berm used for the weighted tape measurements.

There was a remarkable cohesion between these two forms of measurement, lidar and GPS surveying, as shown in Figure 3-6. In this figure, the black line is the lidar profile of the road and the grey dots are the GPS elevations of individual points along the road edge. The brown line is the lidar profile of the streambed, and the orange dots the bed elevation as determined by a weighted tape. The gray line below the road profile is the profile of the low chord of the bridge, measured at one location on the bridge and then extended along the bridge in parallel with the road profile. The red square shows the location of the radar sensor, determined using GPS surveying, with the elevation being that of the bottom of the sensor box, which is offset by 1 ft from the top of the sensor box where the base of the survey rod rests.

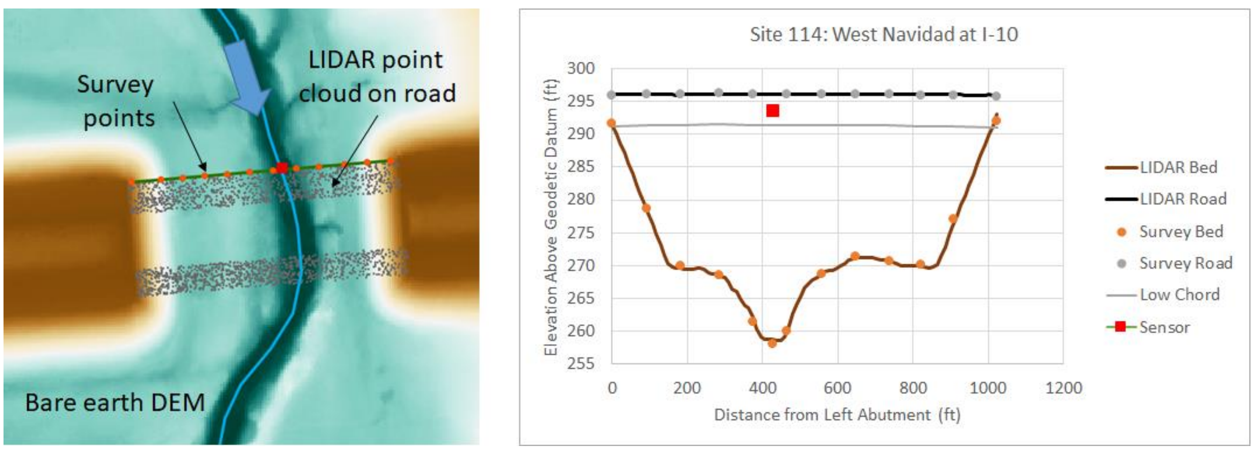


Figure 3-6 Lidar and survey data for Site 114: West Navidad River at I-10

The final stream cross-section (Figure 3-7) is determined from the lidar cross-section adjusted where necessary by the weighted tape measurements.

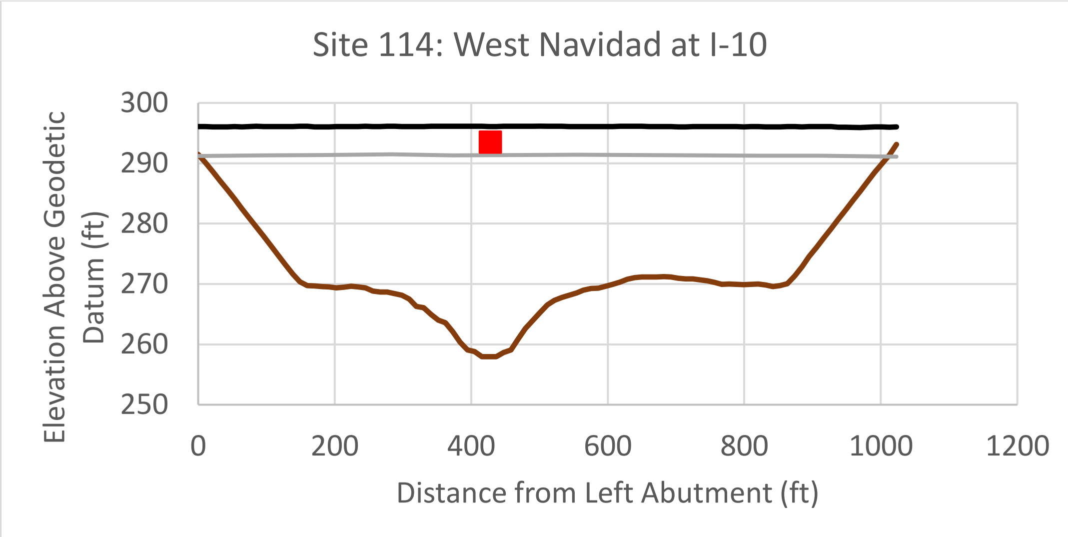


Figure 3-7 Final profiles for West Navidad site

3.4. Bathymetry in Sites with Permanent Water

The procedure just described for the West Navidad River, was applied to all gage sites west of Houston, which were found to be mostly dry when the surveying was done during July 2019. For two sites that had flowing water (Site 120 Guadalupe River and Site 118 Plum Creek), the depth of water was only a foot or so and the depth to the bottom of the stream could still be measured with a weighted tape. Normal lidar measurements do not penetrate water, so where there is permanent water depth, lidar data just show a “shelf” at the water surface.

All nine sites east of Houston on I-10 are in the coastal zone, meaning that they have standing water in them all the time at approximately zero geodetic datum elevation, and varying slightly as tides change in the larger rivers such as the Neches and Sabine. Bathymetry measurements using GPS and ADCP were done at all these nine sites by wading or by canoe where necessary, to measure the true bottom profile, and to the extent possible to measure the distribution of water velocity across the cross-section. This work was done by Barney Austin, Annabeth McCall, and Tim Osting of Aqua Strategies as a subcontract to EarthViews.

After installation of the sensors, the team went to each site to survey the channel cross-section and take flow and velocity measurements. For most channels, the team was able to use an Acoustic Doppler Current Profile (ADCP). We used the Sontek River M9, mounted on a boogie board and with Trimble R-10 survey-grade GNSS (GPS). The ADCP was either dragged across using ropes between a person on each shore, or towed by boat. The team brought both a kayak and a small johnboat to each site. The team followed the procedures recommended by the USGS for flow estimation, consisting of at least three passes. The ADCP measures both the depth of water under the unit, geo-referenced using both the Trimble unit and bottom-tracking, as well as the velocity profile. Surface velocity measurements are used to help calibrate the radar sensor, and velocity measurements integrated across the channel provide a flow estimate. Figure 3-8 shows the operation of the ADCP unit. A GPS receiver is mounted on the kayak directly above the ADCP.

Figure 3-8 The M9 ADCP attached to a kayak to collect flow and bathymetry

Where the channel was too small, or the water too shallow to deploy the ADCP, a hand-held Sontek River Surveyor was used, which measures velocity using acoustics at a point 15cm in front of the sensor, as shown in Figure 3-9. Cross-section profiles were measured from bank to bank. The RTK-GPS Elevation Points (red) indicate elevation measurements taken with a Trimble R10 GNSS. Figure 3-10 displays depth along the profile track from bank to bank with a full contour plot of the water velocity profile (ft/s) and bottom bathymetry. Individual cell velocity is indicated by color.

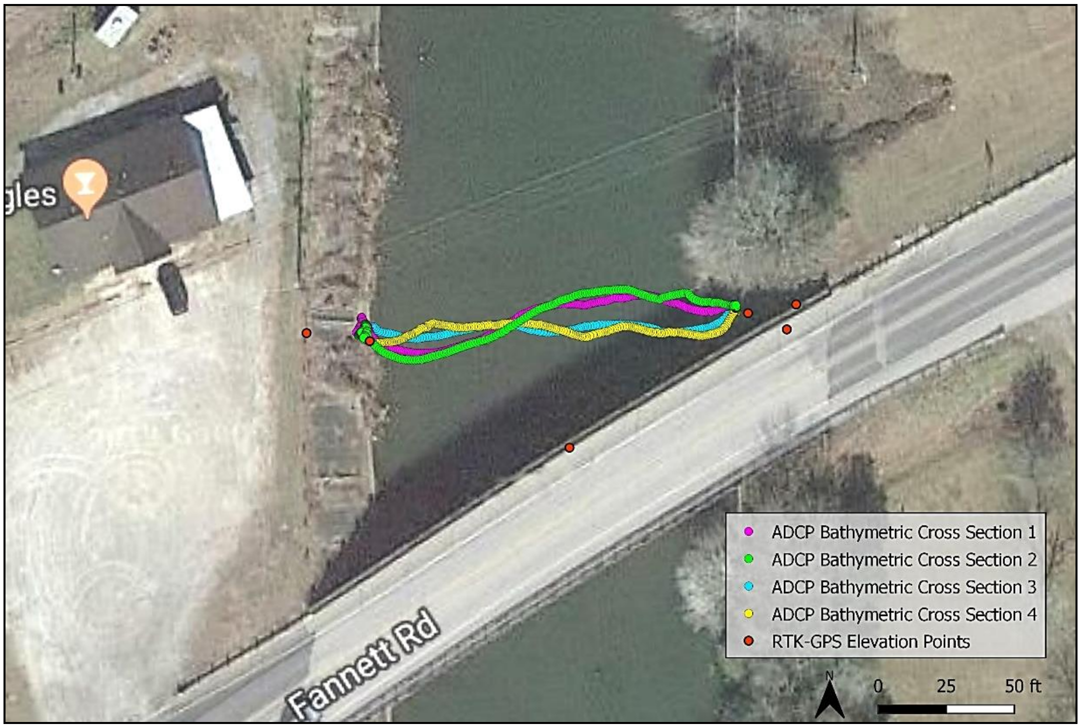


Figure 3-9 Measurement of bathymetry at Site 105, Hillebrandt Bayou

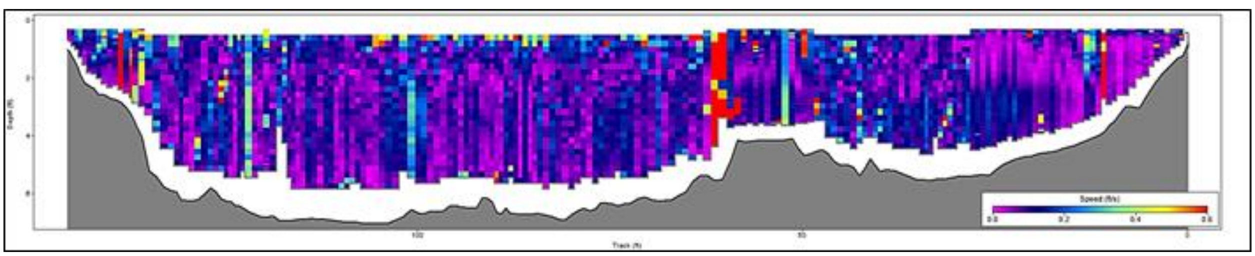
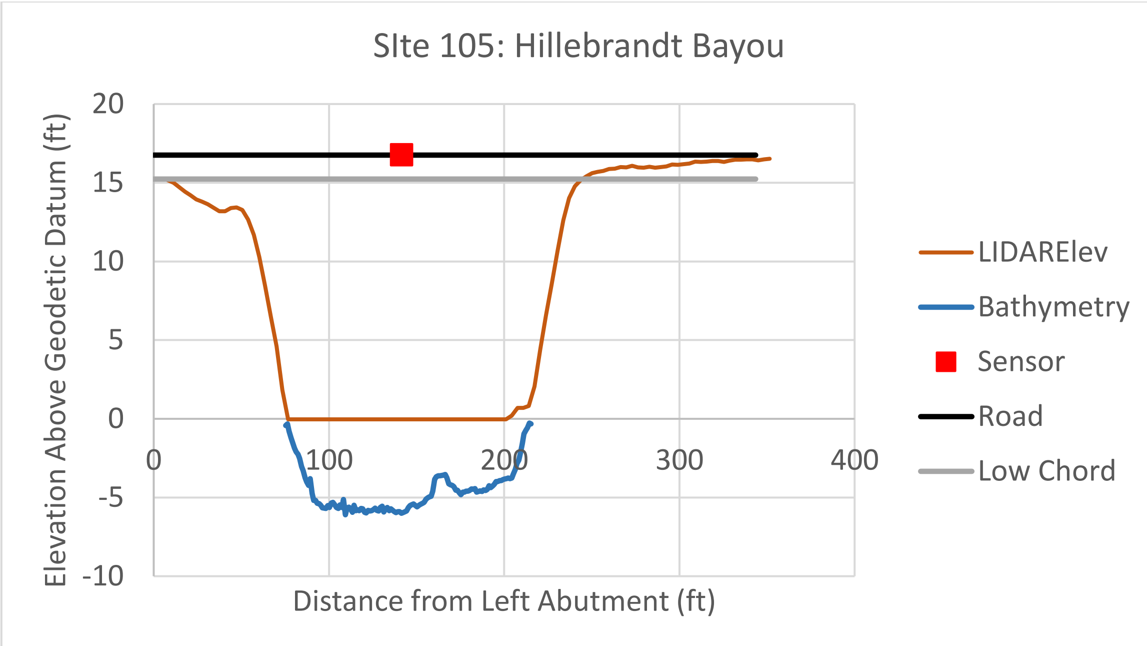


Figure 3-10 Site 105, Hillebrandt Bayou, ADCP cross-section profile from SonTek RiverSurveyor software

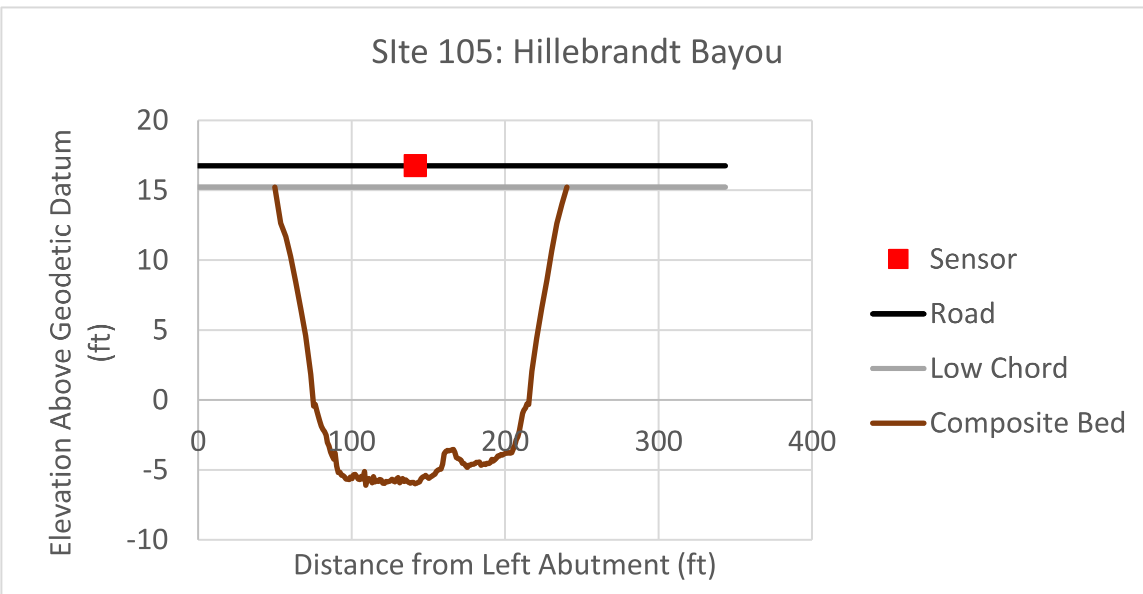
As shown in Figure 3-11 a surface water velocity measurement at a point in the middle of the radar beam helped to provide assurance that the bridge-mounted equipment was working properly. The team anticipated having to estimate flow using a series of velocity and depth measurements across the channel, but they did not encounter the physical conditions that would make this practical or worthwhile. While out on site, a set of survey points were collected with the Trimble unit, such as road elevation, bridge abutment elevation, water's edge, location of the instrument, etc. This information helped georeference other data collected on site, as well as provide elevation information for the EarthViews imagery

Figure 3-11 Spot velocity measurement taken in the field within the radar beam of the project stream gage

Bathymetry data from multiple ADCP or the Sontek River Survey transects at each site were averaged to form a representative transect for the site and georeferenced to a profile line drawn between end points on the left and right banks of the river. Where necessary, this profile line was extended laterally out across the floodplain to the bridge abutments using lidar data, and the lidar and bathymetry profile transects were combined to form a single cross-section profile. This involved some adjustment and data editing at the end points. Also the bathymetry profile was transposed to the edge of the bridge to conform to the lidar measurements on the bridge and the floodplain. The results are shown in Figure 3-12 for Site 105, Hillebrandt Bayou, where part (a) shows the separate lidar and bathymetry profiles, and part (b) the result once they were edited and combined.



(a) Lidar and ADCP bathymetry for Hillebrandt Bayou



(b) Final profile for Hillebrandt Bayou

Figure 3-12 Cross-section profiles for Site 105, Hillebrandt Bayou

3.5. 360° Photography of Bridges

In order to provide a visualization of each site, a 360° photographic survey was conducted using a camera that, when triggered, takes photographs continuously. These data are processed and mounted into an ArcGIS web platform by EarthViews so a viewer can visually travel through the site and under the bridge, as shown for the Hillebrandt Bayou site in Figure 3-13. A "virtual staff gage" is constructed to enable a viewer to translate real-time water level measurements against a background of the actual bridge for a virtual picture of expected conditions. An example of this 3D view of the bridge at Hillebrandt Bayou is shown at https://arcgis.earthviews.com/public/105-hillerbrandt-bayou#22.

(a) Photography approaching bridge

(b) Photography beneath the bridge

(c) Virtual staff gage on Hillebrandt Bayou

Figure 3-13 EarthViews photography of Site 105, Hillebrandt Bayou

Figure 3-14 shows a chart of the water level profile recorded on Hillebrandt Bayou during TS Imelda and a comparison with the virtual staff gage at this site. In this instance, the peak water level was located just beneath the low chord elevation of the bridge. This is very useful for public safety officials to be able to visualize the risk to the bridge of current flood conditions.

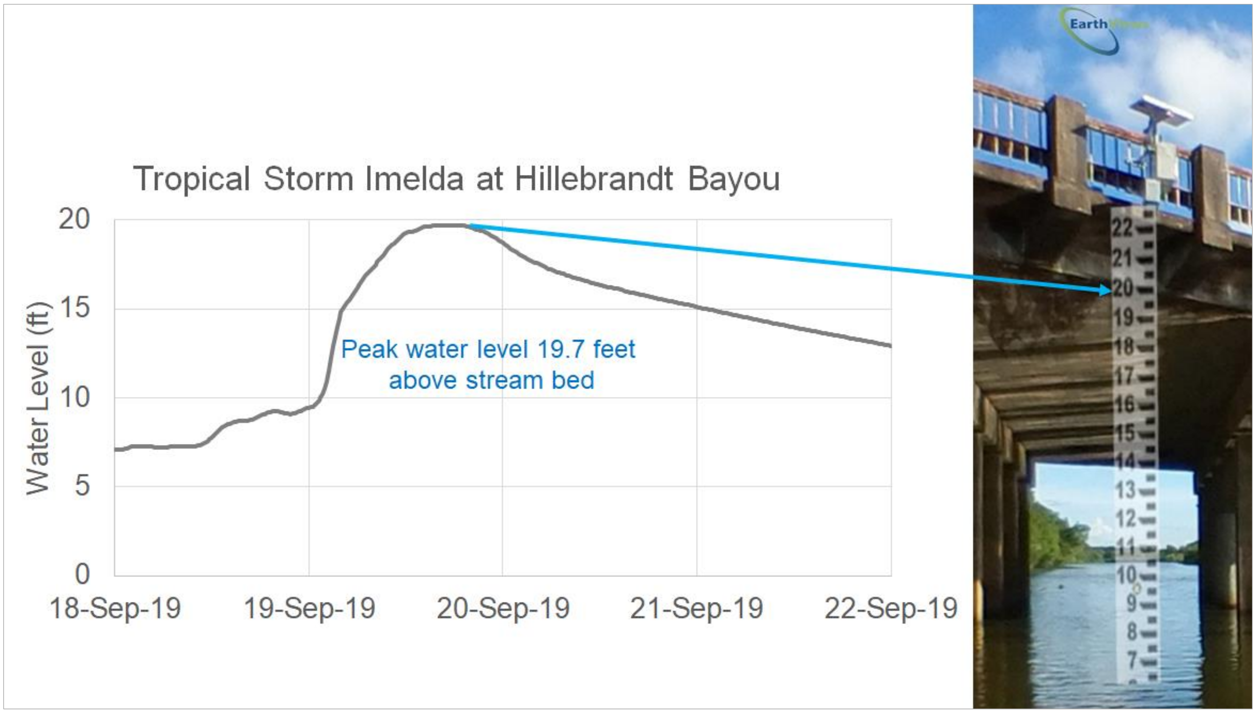


Figure 3-14 Water level profile and the virtual staff gage

3.6. Story Map Displaying the Site Characterization Data

The development of the data describing each site is a lengthy process that involves many data sources. All these data were compiled into a single website and published as an ArcGIS StoryMap at as shown in Figure 3-15. This proved to be a very effective way of retrieving this information later when it was required for further steps in the site characterization. These data include:

- Google Earth Map link
- EarthViews virtual staff gage and tour
- Gage charts for the last two weeks (water level, discharge, velocity; battery level)
- Site survey details
- Lidar point cloud and DEM
- TxDOT bridge plans
- Nearby Geodetic benchmark, where available
- GPS coordinates of sensor
- Elevation measurements made during gage installation
- Sensor calibration certificate

- Stream Cross-Section Elevation profiles
- Site Photos

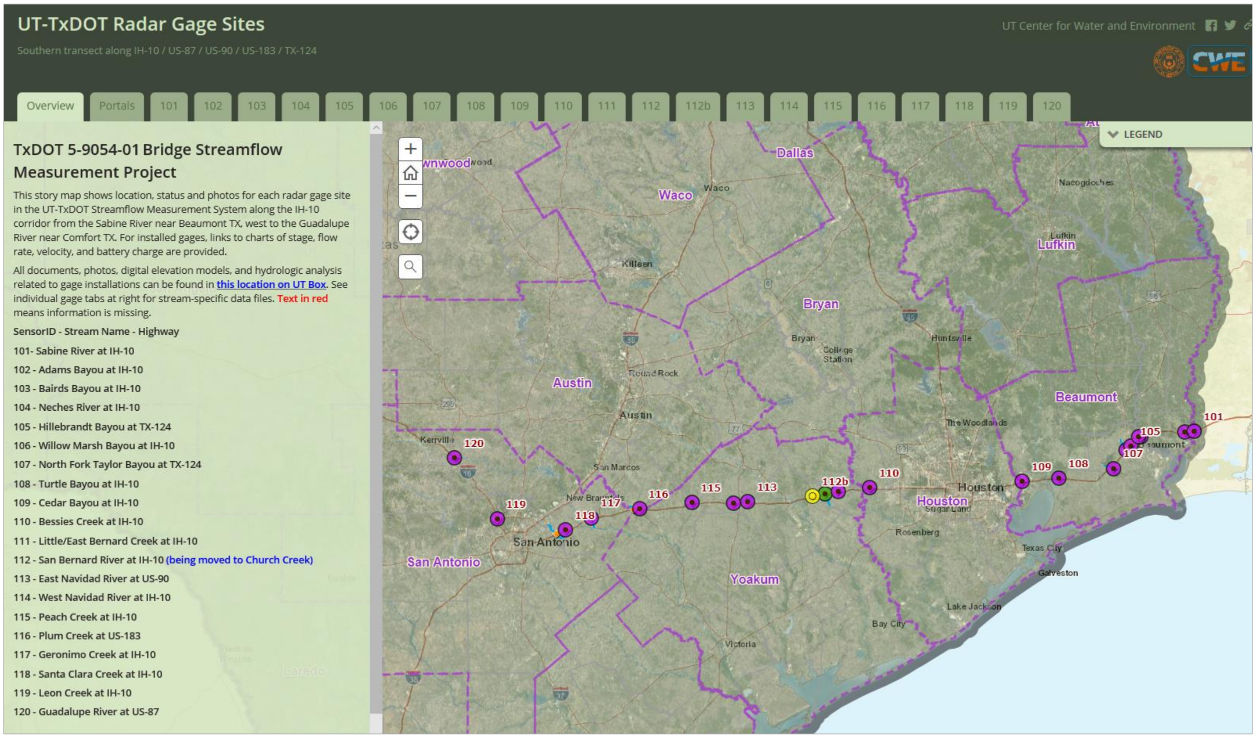


Figure 3-15 ArcGIS story map of the site characterization information [*https://arcg.is/0WqTS0*](https://arcg.is/0WqTS0)

Chapter 4. Data Processing and Access

4.1. Kisters Big Data System

The Kisters firm operates a cloud-based data system called the Kisters Big Data (KiBiD) system in Aachen, Germany, the firm's headquarters. Kisters North America, of which Matt Ables is President, was the subcontractor to UT Austin for this study, and they in turn worked with the KiBiD team in Germany to store the data and mount the web interfaces and services produced during this project. The functioning of the KiBiD system is illustrated in Figure 4-1. It consists of three basic layers. First comes a Data Ingestion Layer that takes in data in various forms, both observations and forecasts. Next comes a Data Processing Layer that stores and performs validation checks on the data and transforms it into useful products. Finally, there is a Data Distribution Layer that publishes the information through web dashboards and services. The KiBiD system is used globally for many purposes, dealing with water, weather, and energy data. For example, precipitation data from many European countries is ingested into KiBiD and transmitted daily to the European Centre for Medium Range Weather Forecasting (ECMWF).

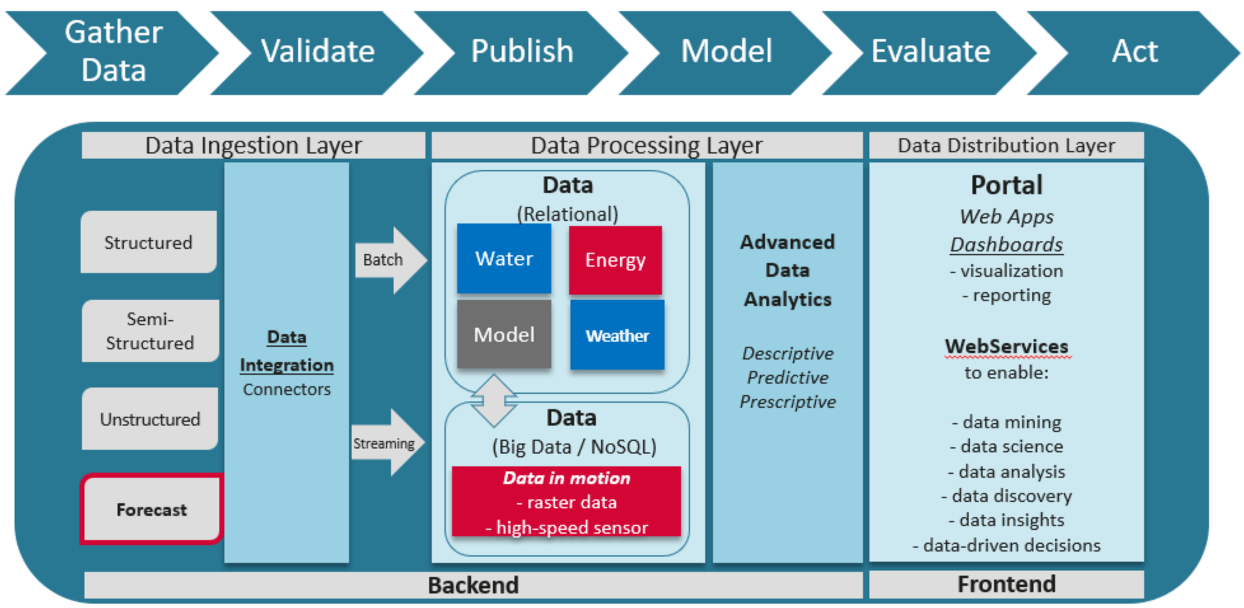


Figure 4-1 Functions of the Kisters Big Data system

In this project, stream gage data for Texas from the USGS, Lower Colorado River Authority, City of Austin, Harris County Flood Control District, and others are ingested continuously into KiBid. The National Water Model forecasts are produced by the National Weather Service in the form of NetCDF files with one file per variable per forecast time step covering the continental US.

The Kisters Big Data System gathers the National Water Model's short-range and medium-range forecasts as they are published from NOAA. A defined study area which encompasses 102,000 stream segments in Texas is extracted from each forecast. The forecast discharge is then processed using discharge to water level ratings created using the Height Above Nearest Drainage (HAND) method. The final product is both water level and discharge forecasts for 102,000 stream reaches in Texas. The data are compared with actual measured data collected by the stream gages. The results are prepared and served through Kisters Web Services and REST APIs to front-end applications like the Kisters portal and ArcGIS Online for further analysis and validation.

4.2. Data Adjustments and Error Checking

At each measurement site, whether for TxDOT data or those coming from USGS and other organizations, it is useful to make sure that the base water elevation for low flows is consistent between the observations and the water depths being computed from the National Water Model using rating curves. This ensures that as flows and water levels rise during flood events, the observations and forecasts are starting from a common base level. A simple offset is computed by comparing the monthly minimums of the three-day moving averages on both the forecast and radar level time series. The adjustment will adapt if gage construction or other actions cause a change in either datum. This is illustrated in Figure 4-2 for Site 116, where an adjustment is made on 1 July 2019. The red lines in this figure refer to water depths computed from the National Water Model and the blue lines to water depths measured by the TxDOT gage. The near horizontal lines at the bottom of the figure are the monthly minimum values of those quantities.

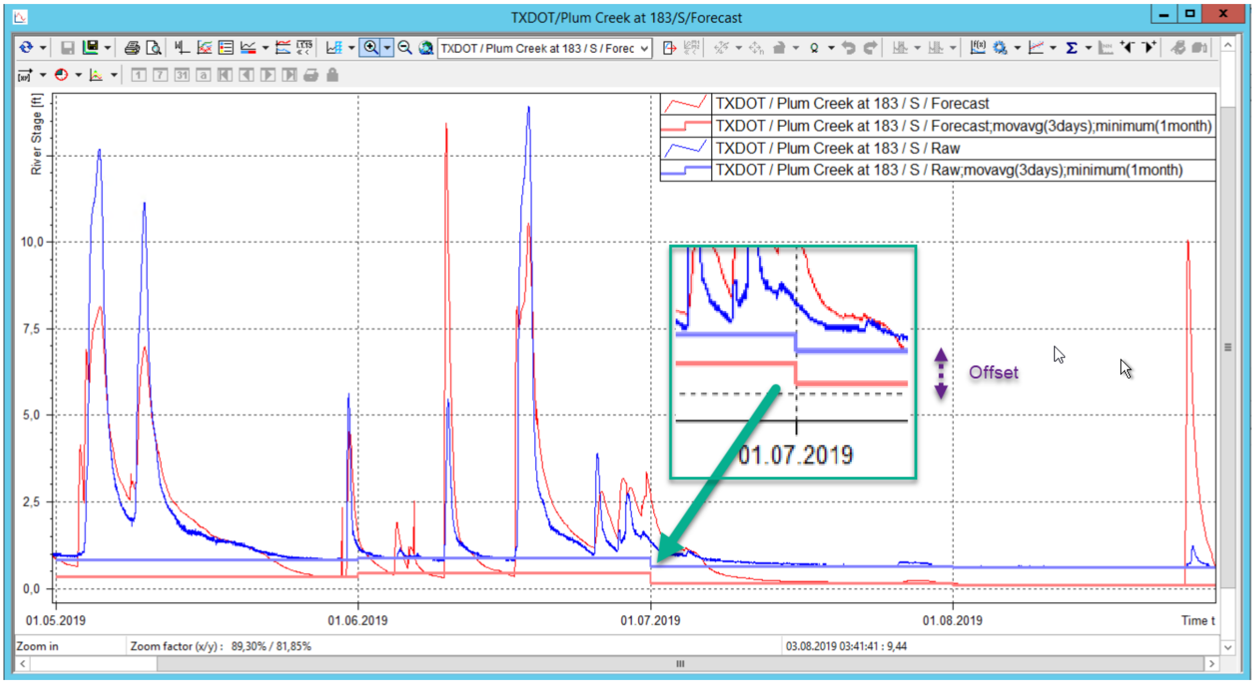


Figure 4-2 Base water level adjustment at Site 116, Plum Creek

Another form of validity checking is to compare the observed water level at any time at a gage and the corresponding level inferred from the National Water Model. Figure 4-3 shows a heat map of these water level errors which identifies larger error concentrations in the big cities because there are many USGS gages there.

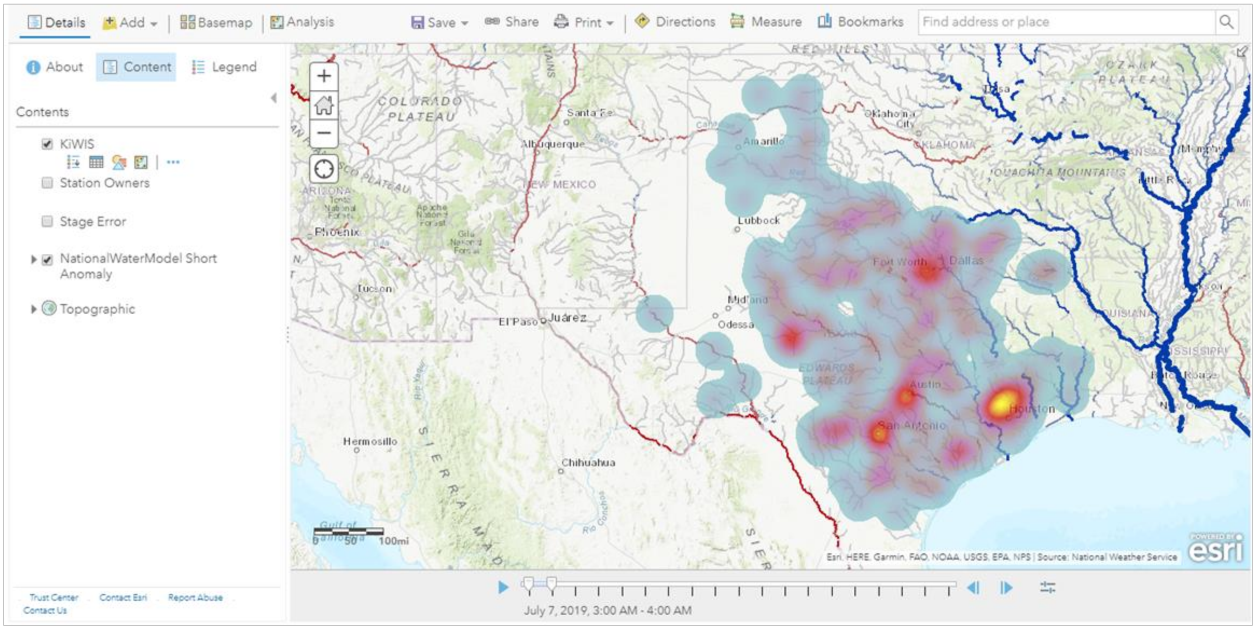


Figure 4-3 Error heat map for forecast and observed water levels

4.3. TxDOT Water Data Viewer

A special dashboard for accessing TxDOT radar gage data and other observational datasets has been configured by Kisters for this project, as shown in Figure 4-4. This dashboard (https://nwm.kisters.de/wdv/) requires a login and password. Users can choose a particular gage or set of gages and define precomputed charts of the data measured there. In Figure 4-5 is shown a chart for Hillebrandt Bayou in which the observed water level at the TxDOT gage (blue) is compared to the modeled water level (green) derived from the time zero value of the National Water Model short term discharge forecast using a rating curve to transform discharge into water level. It can be seen that the National Water Model (green line) had this gage being inundated because the forecast water level exceeds the sensor elevation (orange line). Fortunately, that did not happen as the blue line shows the observed water depth rose to about two feet below the sensor but did not reach it.

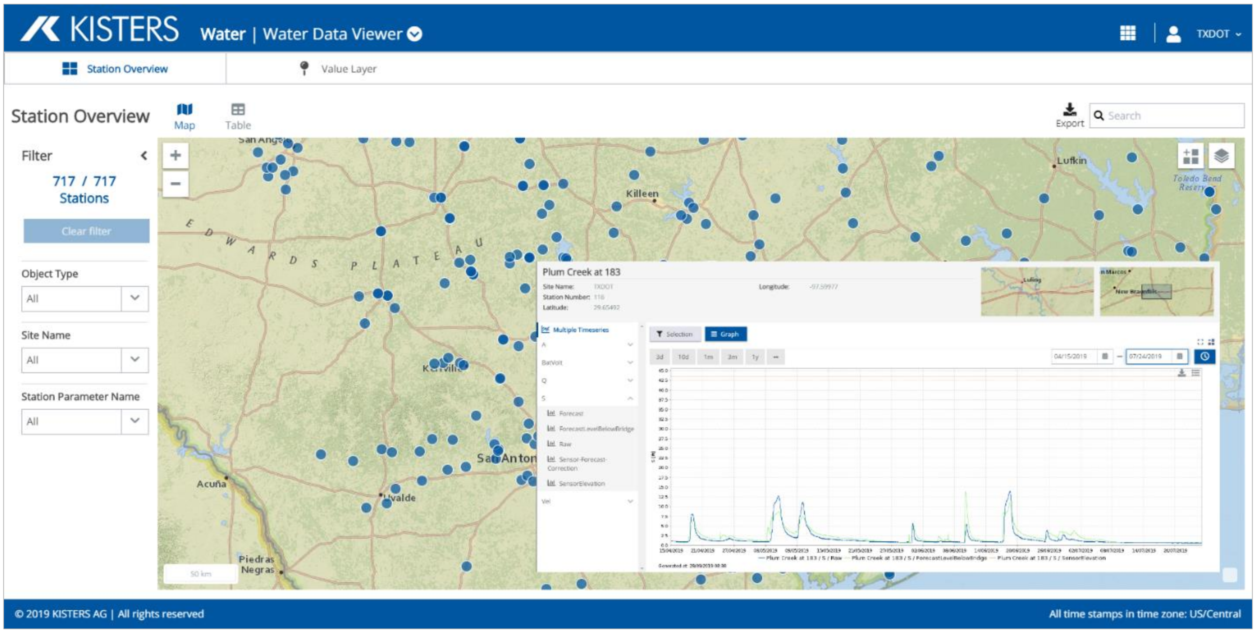


Figure 4-4 Kisters Water Data Viewer

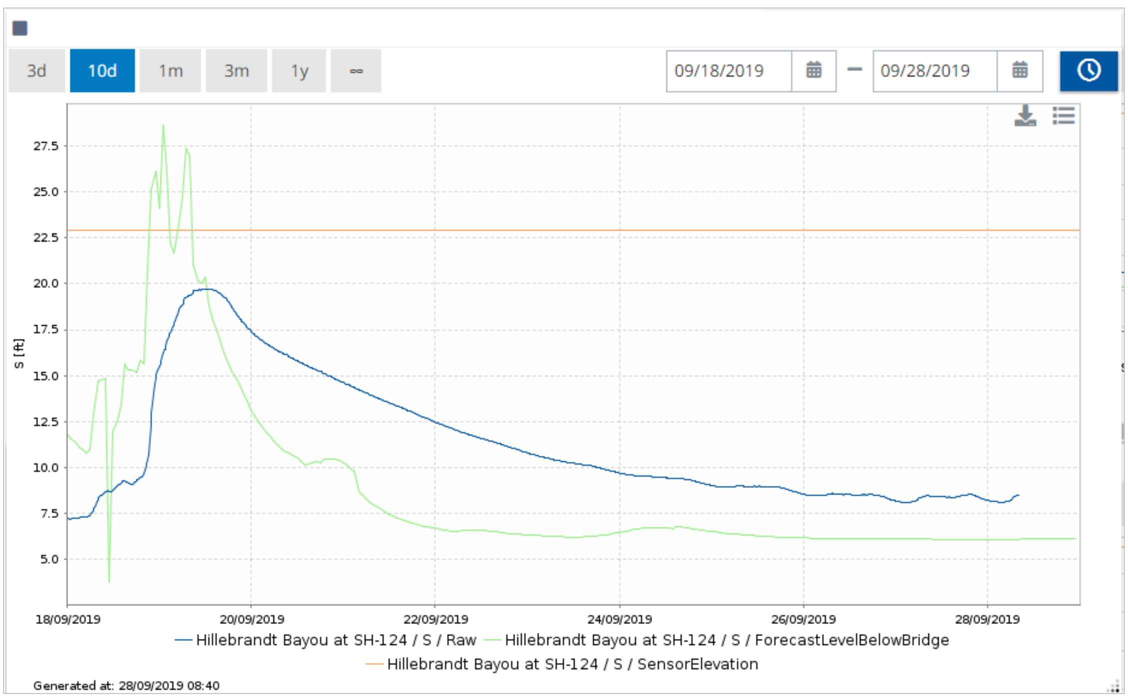


Figure 4-5 Chart in the Water Data Viewer for Hillebrandt Bayou during TS Imelda

4.4. TxDOT Bridge Portal

A second web interface to access streamflow data and forecasting for Texas is provided by the TxDOT Bridge Portal (https://txdot.kisters.de/), as shown in Figure 4-6. (This requires a login and password.) The Portal covers all the 102,000 reaches at which National Water Model forecasting is provided in Texas, and produces the Short-Range (18 hours ahead) and Medium-Range (10 days ahead) National Water Model forecasts for discharge and water level. Where there are observations to which the forecasts of these quantities can be compared, they are shown as well, as in Figure 4-7, which shows observed and forecast water levels for the Neches River at I-10 during the period of falling water following Tropical Storm Imelda. It is notable that the impact of tidal variation in the Neches river is apparent in the TxDOT data though not in the National Water Model forecasts which are not yet connected to a coastal water model, although that work is in progress.

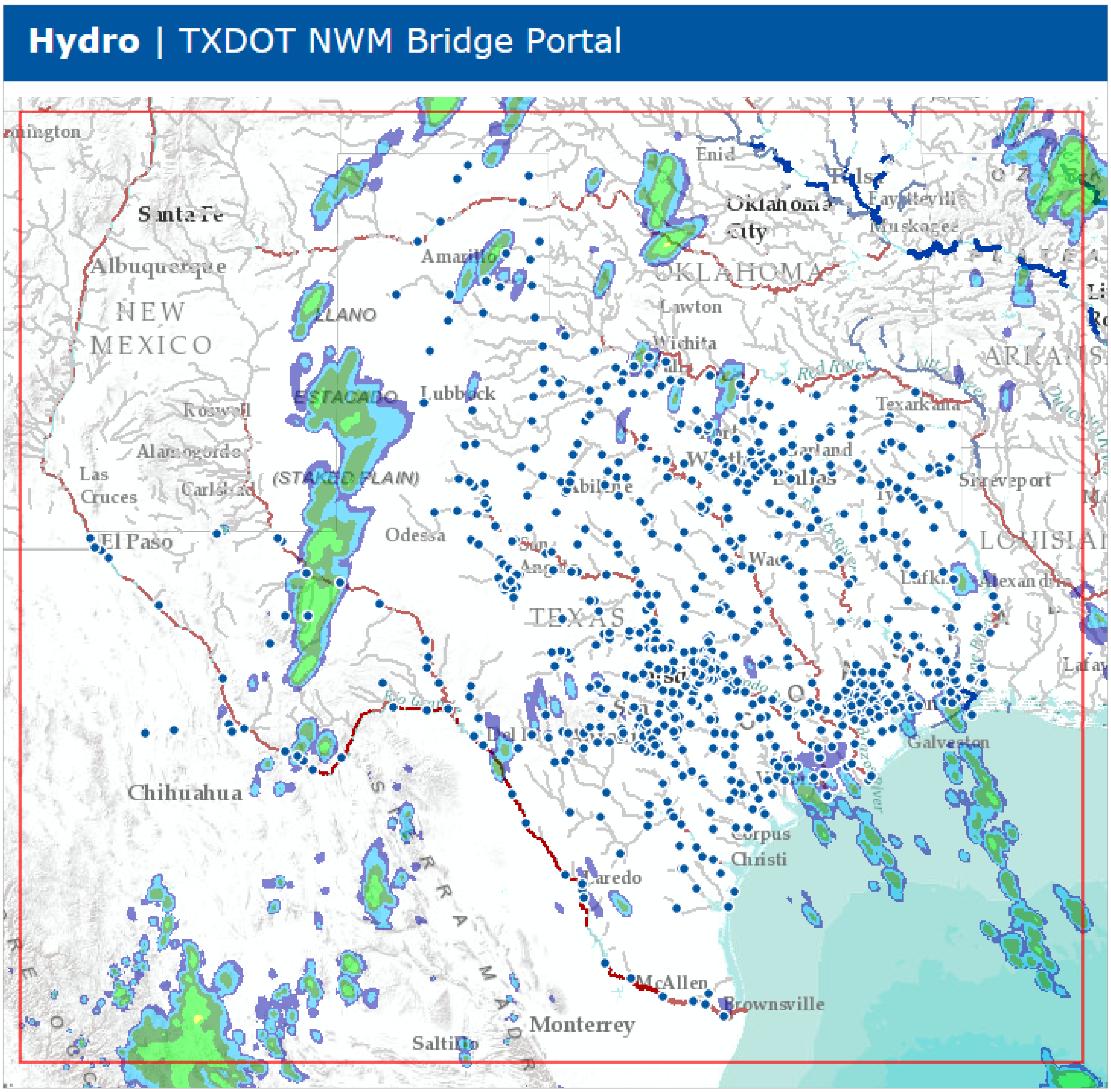


Figure 4-6 TxDOT Bridge Portal

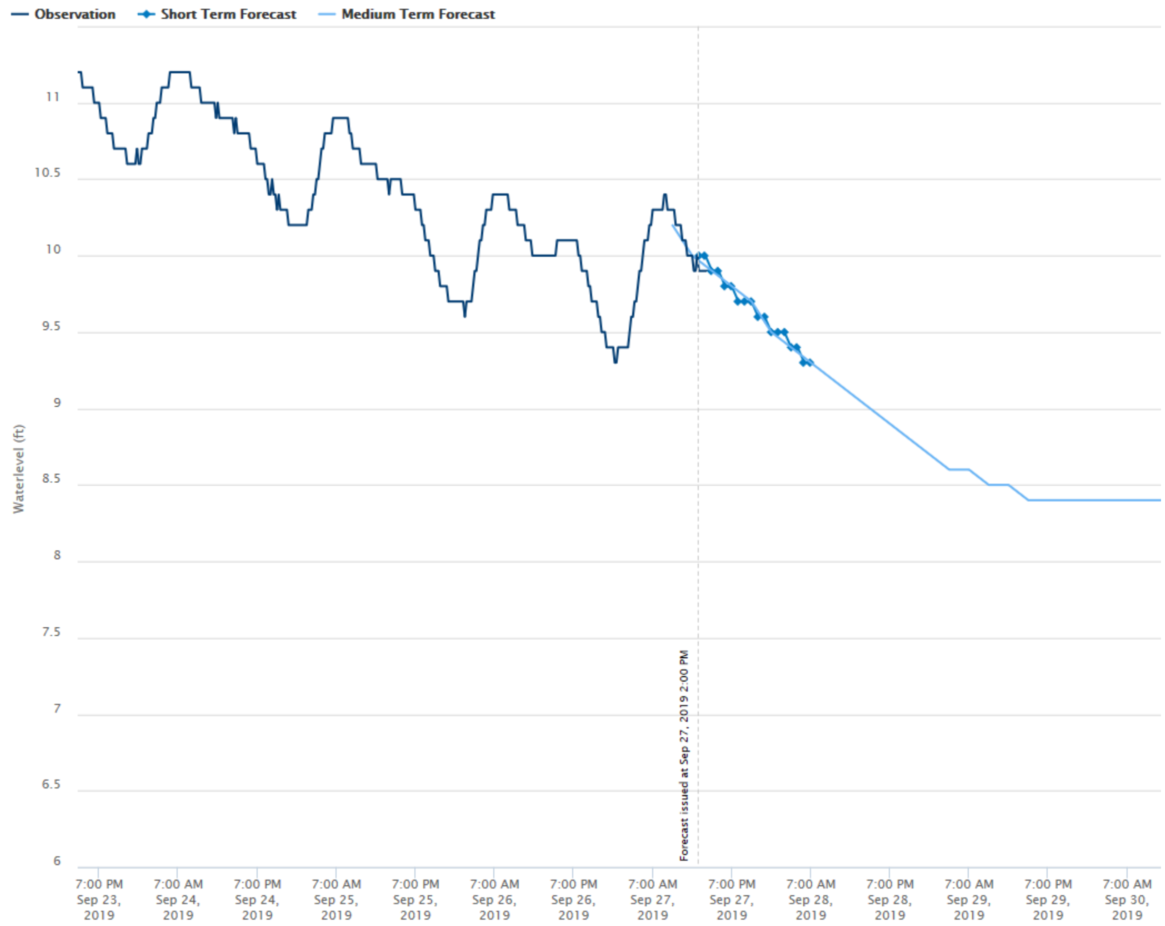


Figure 4-7 Chart in the TxDOT Bridge Portal showing the TxDOT radar observations and the National Water Model forecasts, for Neches River at I-10 after TS Imelda

4.5. Water Data Services

Another way to access observed and forecast data in the Kisters Big Data system is to use data services. These are REST calls that produce output in html and other formats, including Excel, csv, and plotted charts. The first step is to obtain a listing of TxDOT sites at which data is available. This is executed using this web services request:

https://nwm.kisters.de/KiWIS/KiWIS?service=kisters&type=queryServices&datasource=0&request=getStationList&format=html&site_id=30284&addlinks=true

This request produces the listing of accessible time series for each site as shown in Table 4-1.

Table 4-1 Listing of Time Series data accessible at TxDOT radar gaging sites.

station_name	station_no	station_id	station_latitude	station_longitude	timeseries_href
Adams Bayou	102	30498	30.12180734	-93.76684348	Timeseries List
Bairds Bayou	103	30499	30.0955379	-94.07677142	Timeseries List
Bessies Creek Old I-10 Westbound Bridge	110	30505	29.78240565	-95.98070323	Timeseries List
Cedar Bayou at I-10	109	30503	29.82151422	-94.90970525	Timeseries List
East Navidad River at US-90	113	30508	29.69758263	-96.83794853	Timeseries List
Geronimo Creek at Westbound I-10	117	30511	29.59961211	-97.93917087	Timeseries List
Guadalupe River at Comfort	120	30285	29.965285	-98.897213	Timeseries List
Hillebrandt Bayou at SH-124	105	30500	30.03612141	-94.14860619	Timeseries List
Leon Creek at 1604	119	30302	29.590676	-98.604403	Timeseries List
Little-East Bernard at Westbound I-10 Access Roab	111	30506	29.76167567	-96.20532652	Timeseries List
Neches at I-10	104	30504	30.0944264	-94.090941	Timeseries List
North Fork Taylor Bayou	107	30501	29.90014164	-94.26914465	Timeseries List
Peach Creek at Westbound I-10	115	30510	29.69264649	-97.23149516	Timeseries List
Plum Creek at 183	116	30308	29.654922	-97.599771	Timeseries List
Sabine at I-10 Eastbound	101	30497	30.12730094	-93.70141505	Timeseries List
San Bernard River at Westbound I-10 Access Road	112	30507	29.74867864	-96.29685578	Timeseries List
Santa Clara Creek Westbound I-10	118	30512	29.52738549	-98.11777167	Timeseries List
Turtle Bayou at I-10	108	30502	29.84058145	-94.65422483	Timeseries List
West Navidad at Westbound I-10	114	30509	29.6899574	-96.93826241	Timeseries List
Willow Marsh Bayou at I-10	106	30513	30.01472869	-94.18120659	Timeseries List

KISTERS

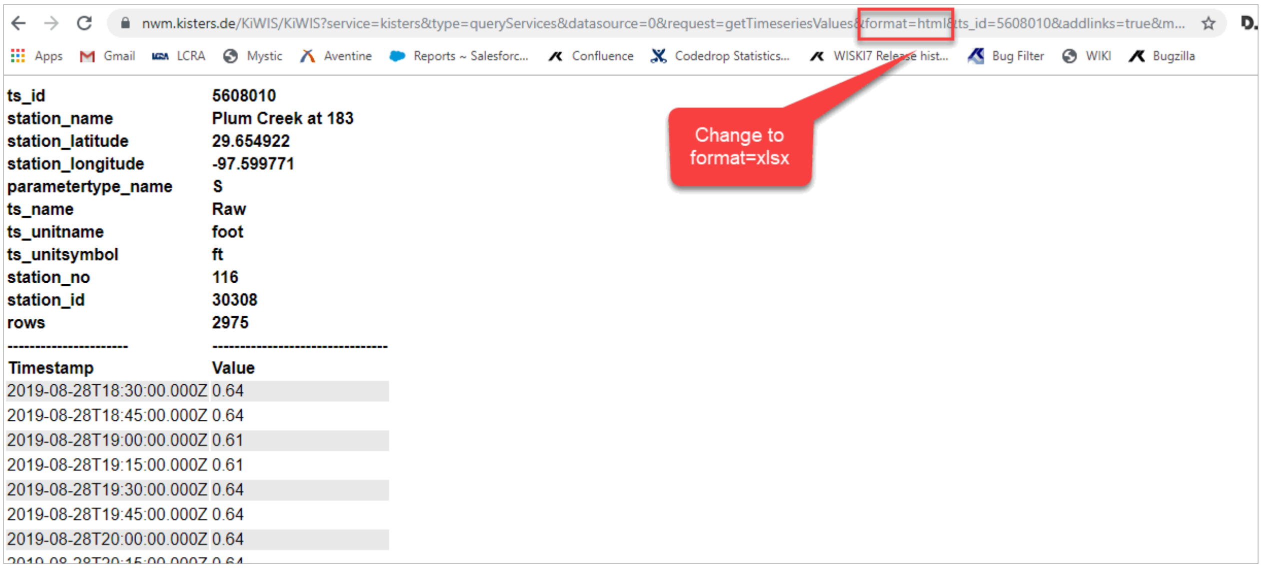
If one of these lists is selected, such as that for Plum Creek as shown in Table 4-1, the variables accessible there are obtained as in Table 4-2, where S stands for water level, Q for discharge and V for velocity. The services can supply Last Value (LV), most recent 1 Day (V1D), 1 Month (V1M) or 1 Year (V1Y).

Table 4-2 Variables whose data are accessible at this site.

ts_id	station_no	station_name	stationparameter_name	ts_name	from	to	values_last_href	values_p1d_href	values_p1m_href	values_p1y_
5924010	116	Plum Creek at 183	S	ManualObs			LV	V1D	V1M	V1Y
6026010	116	Plum Creek at 183	S	ForecastLevelBelowBridge	2019-04-16T14:00:00.000Z	2019-09-29T09:00:00.000Z	LV	V1D	V1M	V1Y
5724010	116	Plum Creek at 183	BatVolt	Day.Max	2018-11-15T06:00:00.000Z	2019-09-29T06:00:00.000Z	LV	V1D	V1M	V1Y
5831010	116	Plum Creek at 183	A	01.Original	2019-02-08T15:30:00.000Z	2019-09-28T18:00:00.000Z	LV	V1D	V1M	V1Y
5828010	116	Plum Creek at 183	S	Forecast	2019-04-16T14:00:00.000Z	2019-09-29T09:00:00.000Z	LV	V1D	V1M	V1Y
6025010	116	Plum Creek at 183	S	SensorElevation	2018-11-15T13:45:00.000Z	2020-01-01T06:00:00.000Z	LV	V1D	V1M	V1Y
5609010	116	Plum Creek at 183	BatVolt	Raw	2018-11-15T14:00:00.000Z	2019-09-28T18:00:00.000Z	LV	V1D	V1M OR	V1Y
5611010	116	Plum Creek at 183	Q	Raw	2018-11-15T13:45:00.000Z	2019-09-28T18:00:00.000Z	LV	V1D	V1M	V1Y
6027010	116	Plum Creek at 183	S	Sensor-Forecast-Correction	2019-02-01T06:00:00.000Z	2019-10-01T06:00:00.000Z	LV	V1D	V1M	V1Y
5827010	116	Plum Creek at 183	Q	Forecast	2019-04-16T14:00:00.000Z	2019-09-29T09:00:00.000Z	LV	V1D	V1M	V1Y
5608010	116	Plum Creek at 183	S	Raw	2019-02-08T15:30:00.000Z	2019-09-28T18:00:00.000Z	LV	V1D	V1M	V1Y
5882010	116	Plum Creek at 183	Vel	test	2018-11-15T13:00:00.000Z	2019-09-28T18:00:00.000Z	LV	V1D	V1M	V1Y
5610010	116	Plum Creek at 183	Vel	Raw	2018-11-15T13:45:00.000Z	2019-09-28T18:00:00.000Z	LV	V1D	V1M	V1Y

Finally, if a link is clicked in one of the boxes in Table 4-2, the result appears in html format as in Table 4-3. If the “format = html” is changed to csv or xlsx, the result appears in comma-separated-variable (csv) or in Excel format.

Table 4-3 Time series of water levels at Plum Creek.



ts_id	5608010
station_name	Plum Creek at 183
station_latitude	29.654922
station_longitude	-97.599771
parametertype_name	S
ts_name	Raw
ts_unitname	foot
ts_unitsymbol	ft
station_no	116
station_id	30308
rows	2975

Timestamp	Value
2019-08-28T18:30:00.000Z	0.64
2019-08-28T18:45:00.000Z	0.64
2019-08-28T19:00:00.000Z	0.61
2019-08-28T19:15:00.000Z	0.61
2019-08-28T19:30:00.000Z	0.64
2019-08-28T19:45:00.000Z	0.64
2019-08-28T20:00:00.000Z	0.64

Figure 4-8 shows the water level, velocity and discharge, at Site 105 Hillebrandt Bayou during Tropical Storm Imelda in September 2019. The water level reached nearly 20 feet above the streambed, and the velocity reached about 6 ft/second during the flood peak. The time series of discharge for Hillebrandt Bayou during TS Imelda, which reached a peak of about 5530 cfs on 19 September. It should be noted that the computation of discharge relies on the accuracy of the k-factor in the RQ-30 gage which converts the surface velocity shown in Figure 4-8 to the mean velocity across the stream cross-section. The validity of this k-factor has not been independently verified using field stream gaging at this site. These charts were produced in Excel using the water data services access method just described with xlsx substituted for html in the appropriate web services call to the Kisters Big Data system.

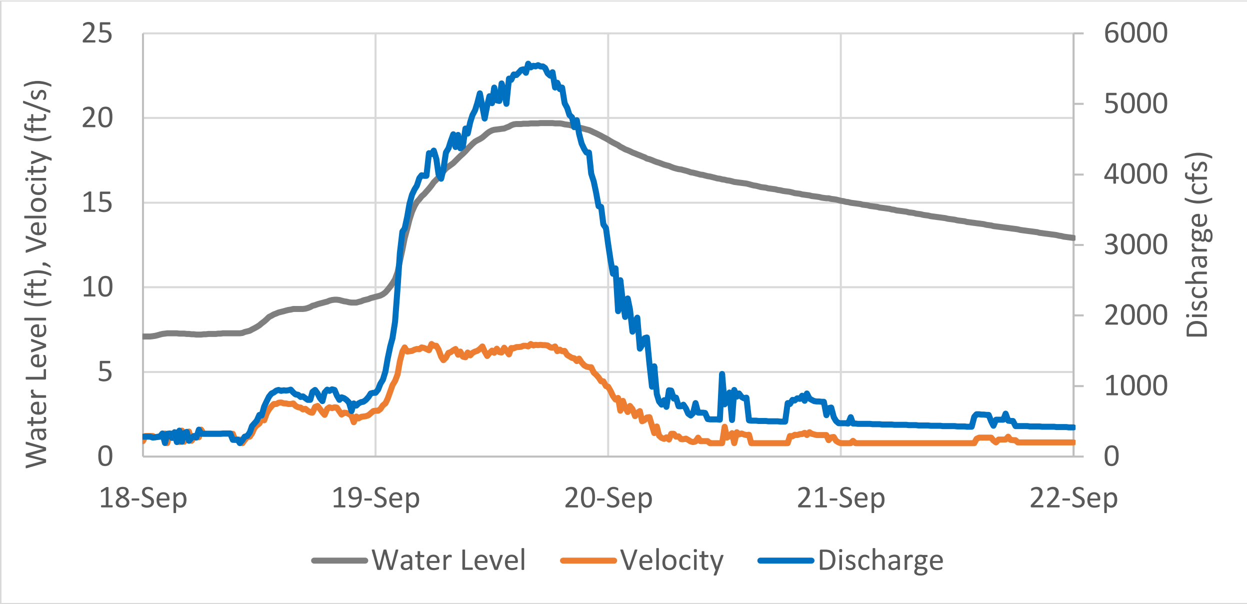


Figure 4-8 Time series of observed water level and velocity at Hillebrandt Bayou during TS Imelda, September 2019

Chapter 5. Statistical Analysis

5.1. Data Assimilation and Flow Routing

Besides the TxDOT radar gages providing observed information on water level, velocity, and discharge, it is desirable that these data be used conjunctively in real time with the National Water Model forecasting system to produce an adjusted forecast at the observation site. It would be even better if this forecast error could be redistributed across the neighboring stream reaches to produce a corrected forecast across a zone upstream and downstream of I-10. This research was undertaken in a task directed by Dr. Paola Passalacqua and carried out by a graduate student, Leah Huling. The research was done collaboratively with Dr. Dirk Schwanenberg, the Director of Business Unit Water at Kisters in Aachen, Germany. Ms. Huling went to Germany and worked at the Kisters office in Aachen for two months during June–July 2019. This is the first year of her MS degree and it is anticipated that this research will be continued during the second year of her degree, to be completed in May 2020. Once finalized, the resulting procedure could be implemented as part of the Kisters Big Data system.

The task of improving the National Water Model discharge data with the streamflow recorded at TxDOT radar gages was undertaken by using data assimilation. Simply put, data assimilation is a mathematical method that combines theory (in this case, a flow routing model) with observations. The type of data assimilation used in this study was four-dimensional variational data assimilation (4D-Var DA). In broad strokes, 4D-Var DA alters the upstream discharge to match sensor data observed downstream. This concept is illustrated in Figure 5-1.

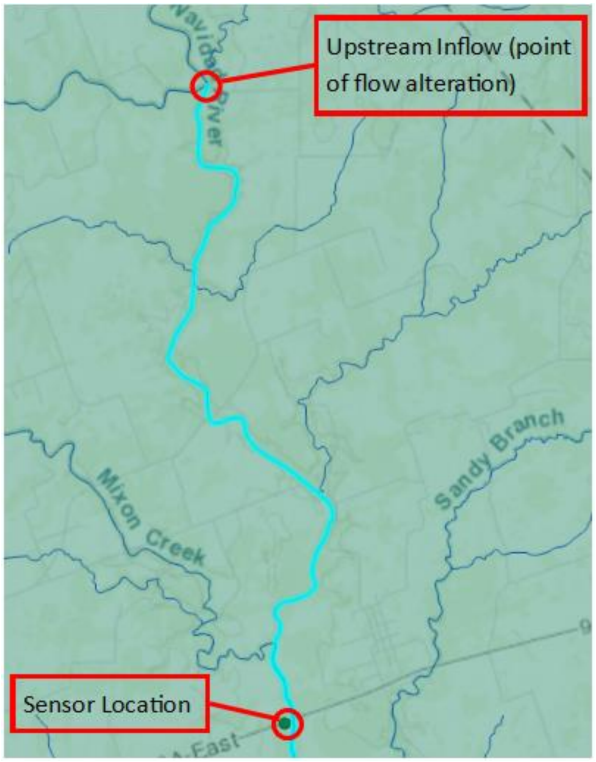


Figure 5-1 4D-Var data assimilation layout

The streamflow is routed downstream using a Muskingum-Cunge hydrological routing scheme, similar to the routing scheme used by the National Water Model.

The theory behind using the 4D-Var data assimilation approach to improve streamflow profiles has been under development since 2012 by Dr. Dirk Schwanenberg and his associates. The method aims to minimize an objective function containing a trade-off between two factors: (1) the amount of upstream flow alteration introduced into the model, and (2) the difference between simulated and observed streamflow at the sensor location (Reichle, 2008). This approach is different from the assimilation methodology currently in use by the National Water Model, which employs nudging data assimilation at the gage location alone so that streamflow is only altered downstream from points of observation. The new variational approach instead forces alteration of streamflow in upstream branches in order to close the gap between the downstream simulated and observed flow at the sensor location. Therefore, the variational data assimilation of this study creates a larger area of improved streamflow forecast than existing methods.

5.2. Proof of Concept Test Basin

The two National Water Model forecast configurations that are the focus of this study are the Analysis and Assimilation (AnA) and the Short-Range forecasts. The AnA configuration is a real-time analysis of a wide array of current conditions, from observed streamflow to meteorological data. As a result, the AnA product serves as a snapshot of current conditions in every stream reach in the United States such as streamflow, velocity, etc. The Short-Range forecast cycles hourly and produces hourly forecasts of streamflow and hydrologic states out to 18 hours. The Short-Range forecast is initialized with a restart file from the AnA forecast. This essentially means the forecasts have no memory of previously released forecasts.

When assimilating observations into a 4D-Var model, it is necessary to determine a look-back period. Generally, the look back period is the window of past observations being used to inform the model. In this instance, the look-back period is the portion of the short-range forecast contributing to data assimilation. This concept is illustrated in Figure 5-2. For example, say at 8-27-17 10:00, the goal is to run a data assimilation with nine hours dedicated to assimilation and nine hours for the forecast. Doing this, requires retrieval of the short-range forecast published at 8-27-17 1:00. By comparing this with the last nine hours of observed discharge from the gage, the resulting data assimilation then improves the remainder of the forecast.

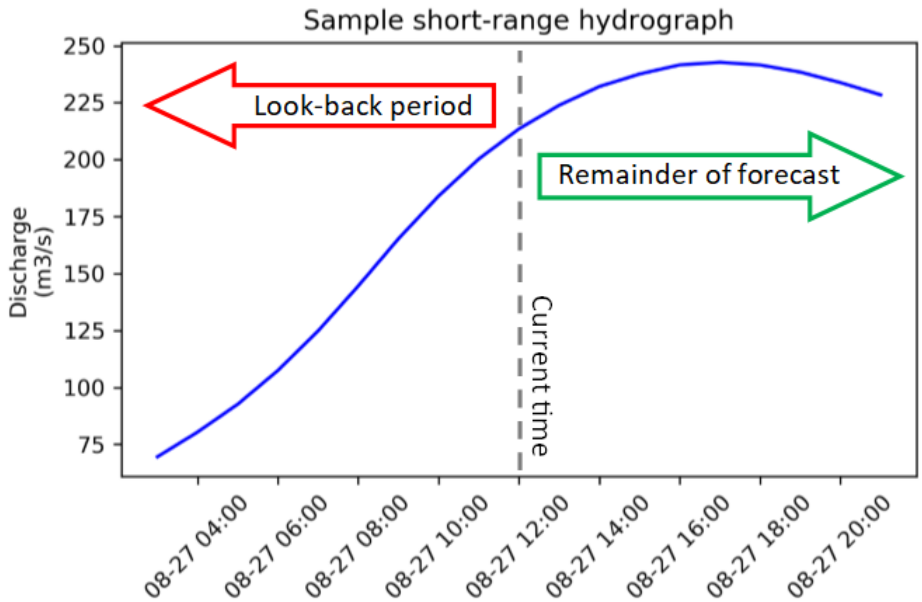


Figure 5-2 Demonstration of a look-back period

For the test case, we used two USGS gage sites in the Navidad HUC8 basin. USGS flow data for gages downstream of I-10 were employed for the concept application because the TxDOT radar gages had just been installed in this basin (the red dots in Figure 5-3) and did not yet have a long enough flow record for testing purposes. The two USGS gage sites used in this study are the upstream gage, site number 08164300, and the downstream gage, site number, 08164390, on the Navidad River. These gages are shown in Figure 5-3 and will be referenced as Gage 1 and Gage 2, respectively.

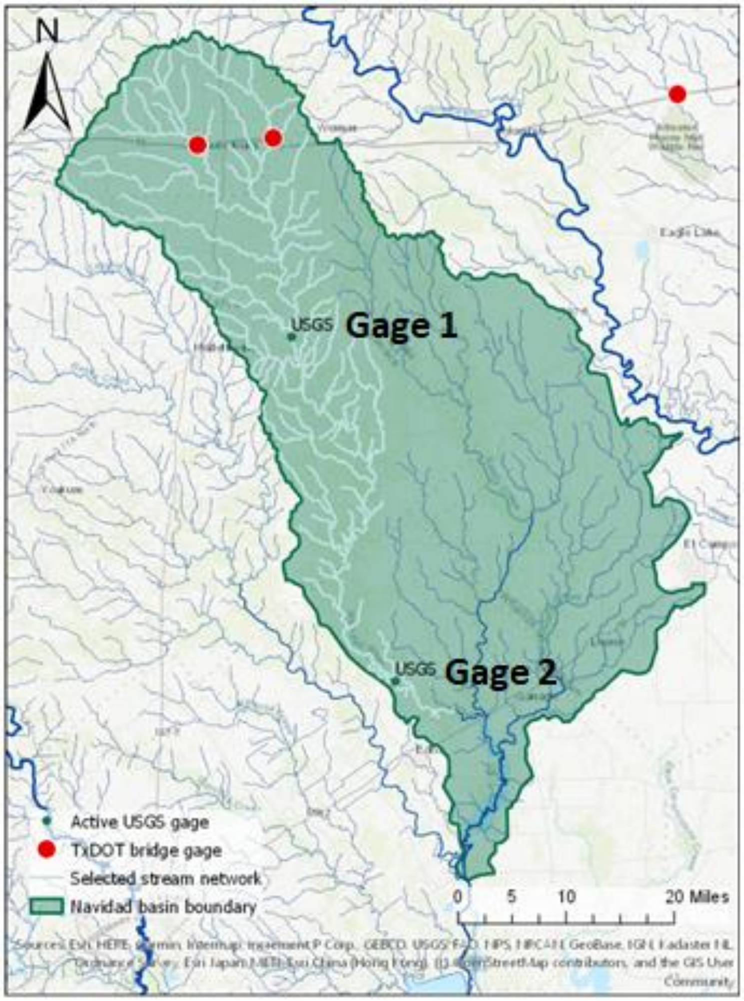


Figure 5-3 USGS gages and study area for test case

The storm used as a test case was Hurricane Harvey. The National Water Model outputs produced from August 18 to September 10, 2017 were archived by the Renaissance Computing Institute (RENCI) at the University of North Carolina at Chapel Hill.

5.3. Results from Data Assimilation

The National Water Model inflows upstream of Gage 1 were adjusted to correct the flow at Gage 1 to match the observed data. The flow was then routed down to Gage 2 using the Muskingum-Cunge scheme. Figure 5-4 illustrates the results using a look-back window of 6 hours (upper graphs) and 12 hours (lower graphs), with the upstream flows on the left and the observed and simulated flows at Gage 1 on the right. The gray lines indicate the expected values from the National Water Model (no assimilation).

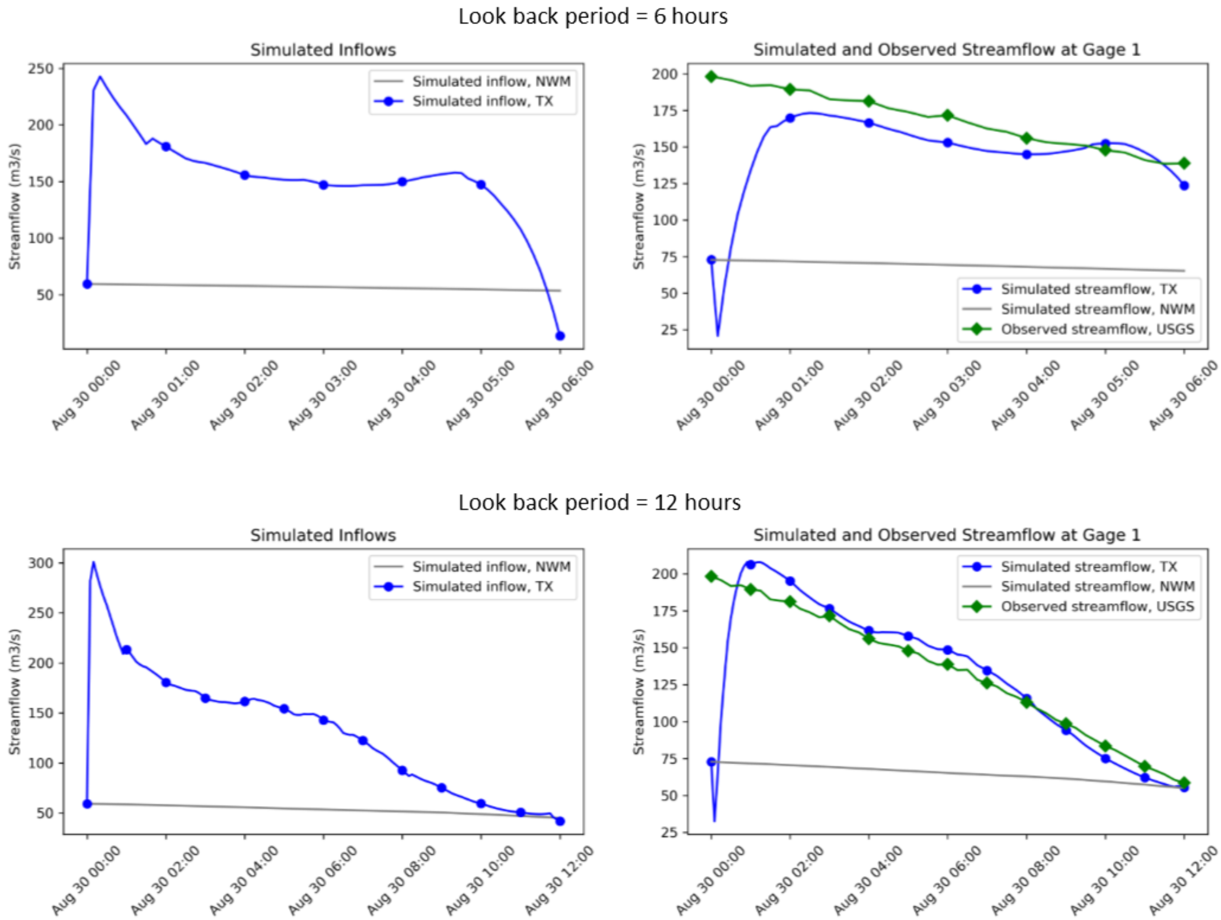


Figure 5-4 Successful data assimilation at Gage 1

The altered flow of the six-hour look-back window was then propagated downstream by Muskingum-Cunge flow routing. Figure 5-5 follows the altered flow as it travels downstream, moving from the upper left graph to the lower right window (Gage 2). The dashed vertical line indicates the current time and the solid line represents a five-hour window into the future. The last chart in the lower right of Figure 5-5 is a comparison of the computed flow at Gage 2 (blue), compared with the observed flow measured by the USGS (green). It can be seen that there is a substantial discrepancy between these two lines, which results from the fact that the flows from all the tributaries to the West Navidad river between the two gages have not been included in this computation.

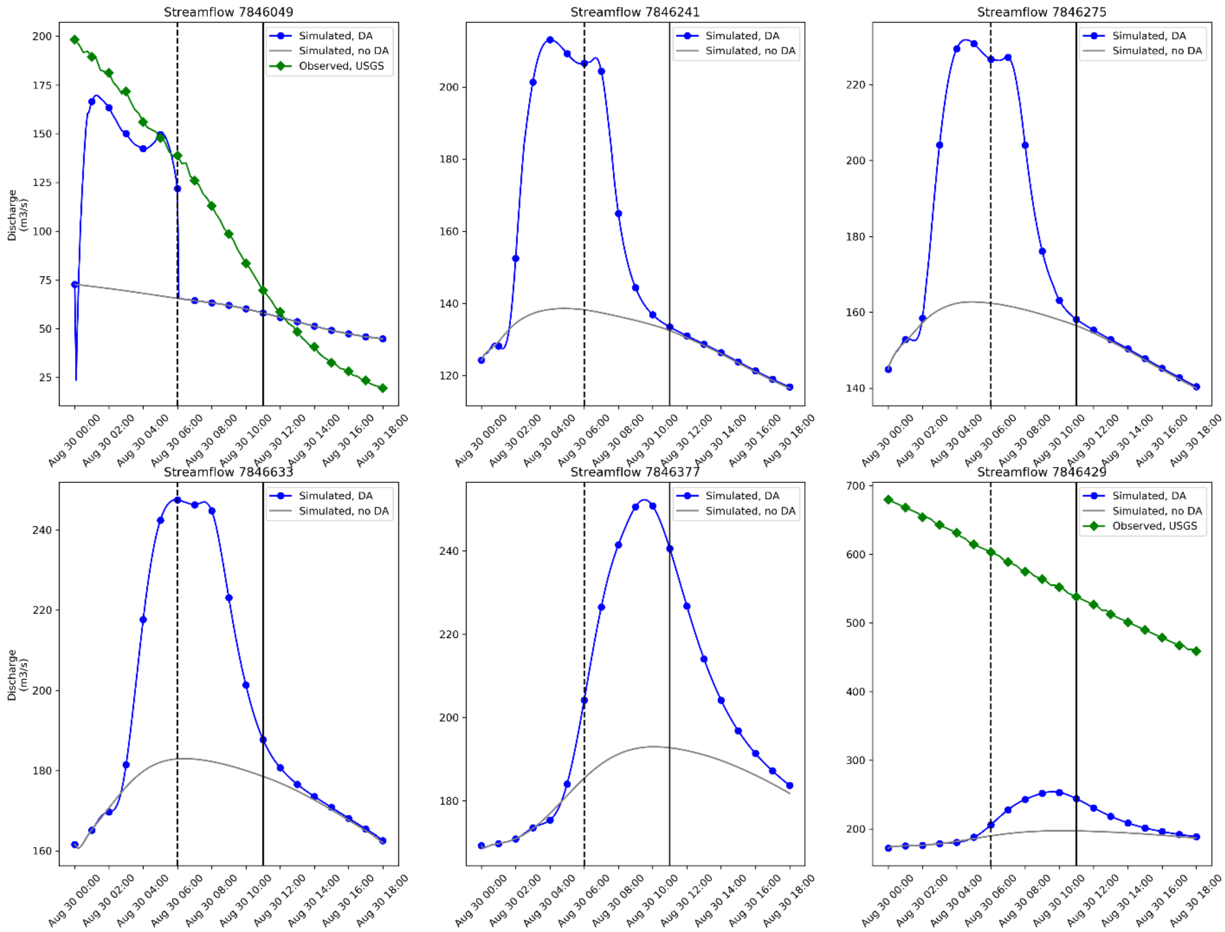


Figure 5-5 Propagation of altered flow downstream the Navidad River

The lumped flow travels through the network and is still visible 30 miles down the channel at the next USGS gage. It is considered that the “reach” of this method is up to 15 miles upstream, and downstream as far as 30 miles. This is visualized in Figure 5-6.

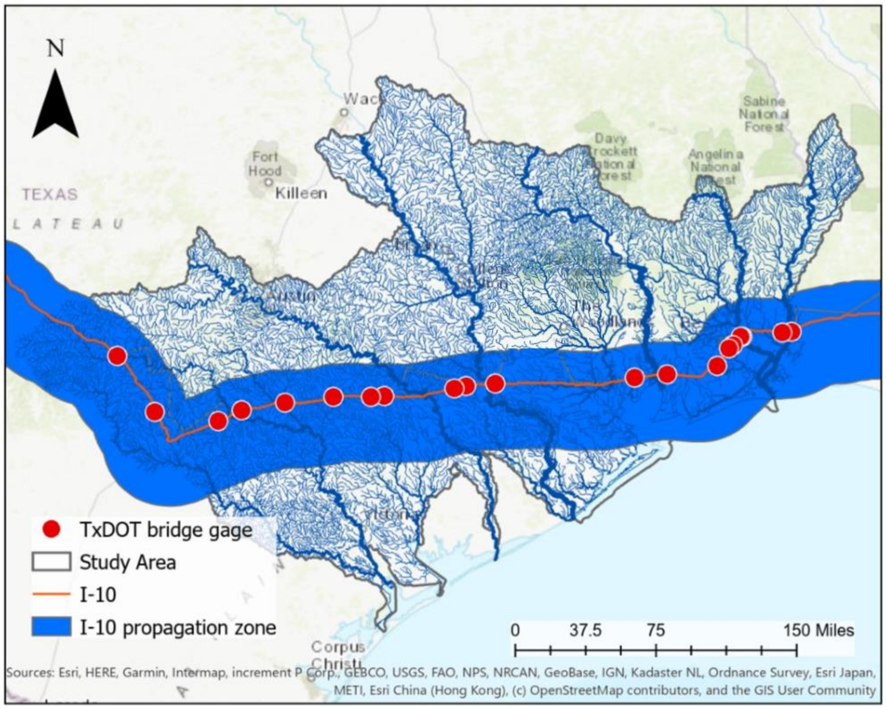


Figure 5-6 Upstream-downstream propagation extent from test case

Although this work is just a proof of concept, the approach looks promising. The 4D-Var data assimilation is valuable because it improves the streamflow upstream of the sensor location. However, the improvement upstream and at the sensor location only exists in the lookback period, which is then propagated downstream and into the future. Figure 5-7 illustrates this concept.

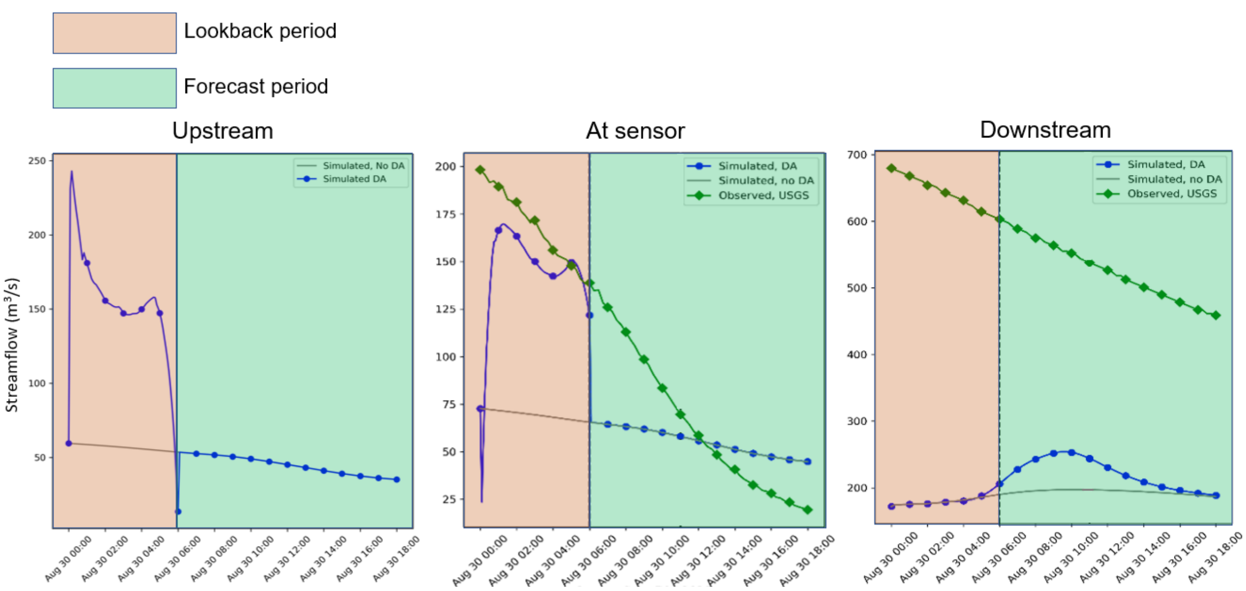


Figure 5-7 Timeframes of improved flow upstream, at the sensor, and downstream

Since we are operating outside of the National Water Model forecast system, there is currently no way to change the forecast at the point of observation (Figure 5-6). Until the TxDOT radar sensors are directly assimilated into the NWM, we recommend installing sensors upstream of critical bridges for corrected forecasts at those points. Alternatively, the Kisters Big Data System could be used as a post-processing system to reconcile the National Water Model forecasts and local observations, and thus arrive at improved real-time forecasts at the TxDOT bridges.

A limitation of the current methodology is that the data assimilation can only consider the main channel directly upstream of the lower gage, and not the tributaries that come into it. An extension is develop a model that considers complex branching stream networks. The Muskingum-Cunge flow routing has been adapted to handle the multiple inputs, and further study would involve including this in the data assimilation model. This would create a much more robust model. The comparison is illustrated in Figure 5-8.

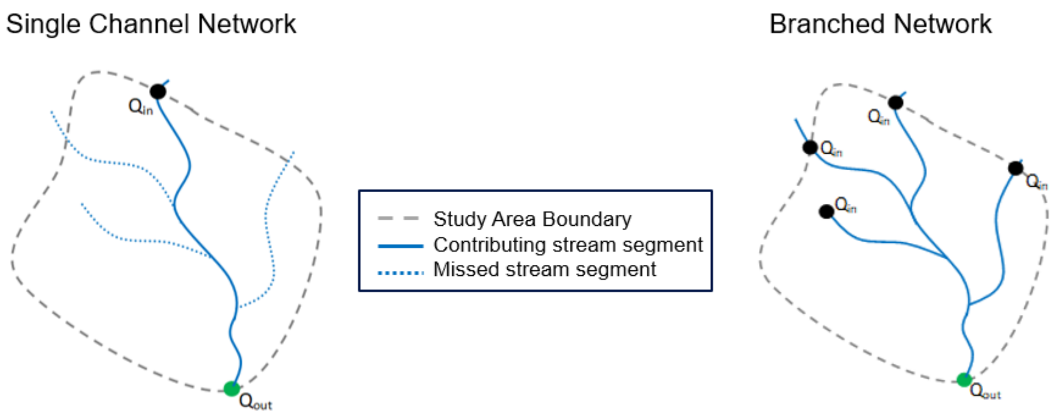


Figure 5-8 Comparison of model inputs and outputs for single channel and branched networks

5.4. Correlation along the I-10 Transect

Another objective of this analysis was to inform the placement of future TxDOT radar sensors to create a statewide network. In order to investigate possible lateral spatial correlation, we analyzed the analysis and assimilation streamflow for Tropical Storm Imelda in September 2019 from the National Water Model for stream reaches directly intersecting I-10 between San Antonio and Houston (Figure 5-9). This dataset was comprised of 147 stream segments.

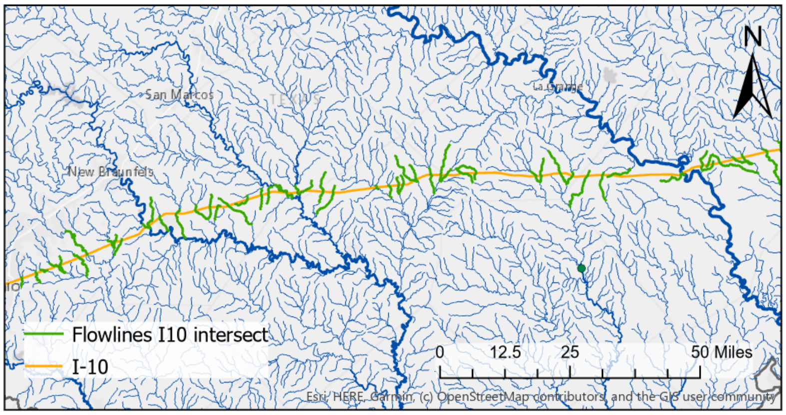


Figure 5-9 Partial extent of the selection of NHD stream segments for lateral correlation analysis

To test for spatial correlation, variograms were constructed, which plot variability of measurement against separation distance between the two points of measure (Figure 5-10).

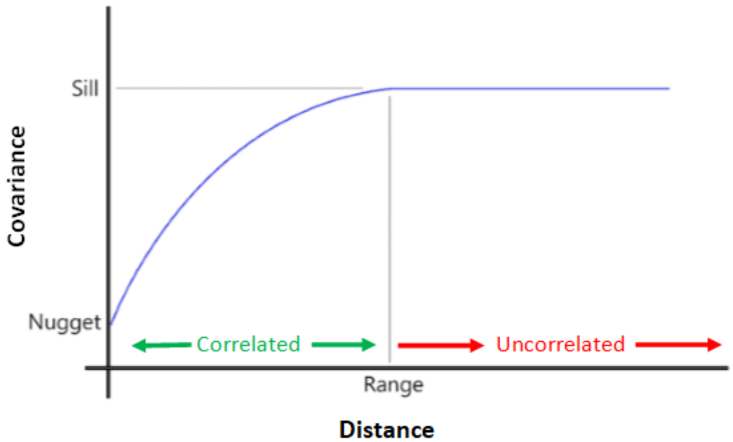


Figure 5-10 Ideal variogram

Variograms typically show a region of positive correlation for small separation distance followed by a flat line at large separation distances, which is the variance of the dataset and indicates no correlation between the stream reaches. The line in Figure 5-10 is a fitted model of the covariance measured between all possible combinations of paired data.

In this study, the measurements were taken as the instantaneous streamflow from the National Water Model weighted by their mean annual flow, as registered in the National Hydrography Dataset. The separation distance in this study was computed as the geodesic distance between the coordinates associated with the intersection of I-10 with each stream reach. The instantaneous streamflow was measured during peak flows of tropical storm Imelda. Figure 5-11 illustrates the results of the analysis. The analysis indicates a correlation zone of about 50 miles (where the black line coincides with the red dashed line in Figure 5-11).

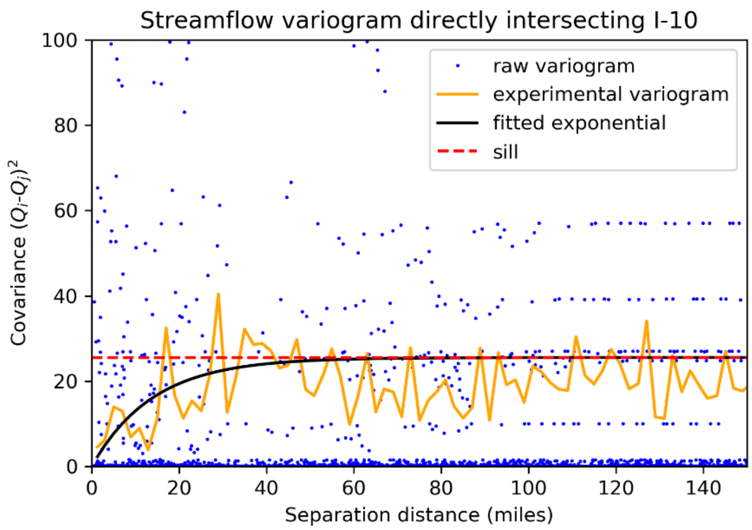


Figure 5-11 Variogram of streamflow in streams directly intersecting the I-10 transect

By combining the statistical analysis from the data assimilation and the spatial correlation analysis, we can extrapolate windows of correlation/propagation around each TxDOT radar gage (Figure 5-12). This indicates that during TS Imelda there was lateral flow correlation along I-10 from one stream reach to the next out to a distance of about 50 miles. The earlier data assimilation study indicates that each gage can influence assessment of flow for about 15 miles upstream of a gage and 30 miles downstream. The gaps between the TxDOT radar gages are about 20 miles west of Houston and about 10 miles east of Houston. This spacing, and the statistical correlation revealed by these studies diminish the possibility of "gaps" in a sensor network where local storms can slip through the network undetected. Further analysis of the data from the TxDOT gages should be conducted to confirm this preliminary analysis.

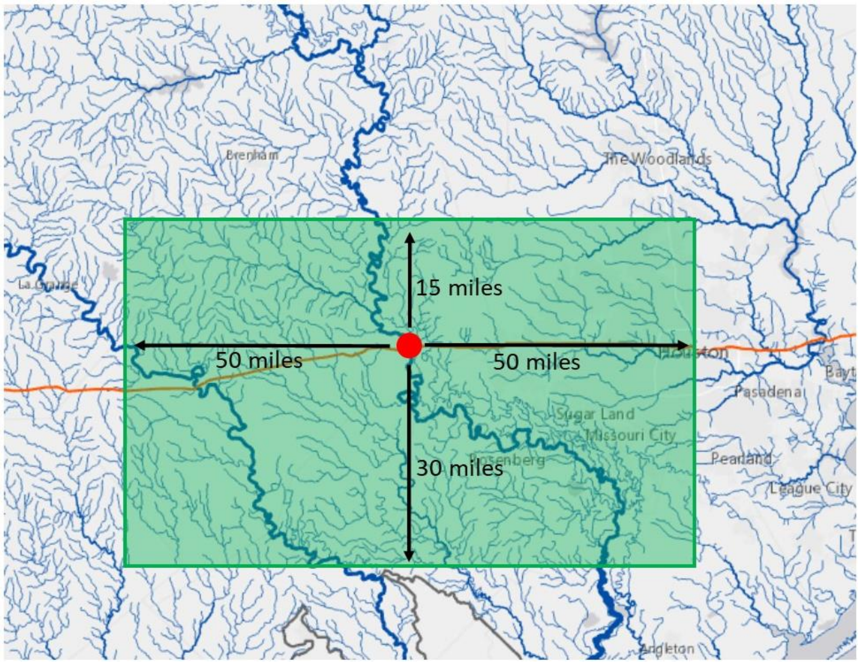


Figure 5-12 Window of correlation laterally and upstream/downstream for streamflow sensors

5.5. Local Observation Networks

Besides the observations of the US Geological Survey and the TxDOT transect, other observation networks are operated by local authorities, such as that of the Jefferson County Drainage District No. 6, as shown in Figure 5-13. This network measures both rainfall and water level comprehensively in Jefferson County around Beaumont and in portions of neighboring counties, such as Chambers County. Just as it has already been demonstrated that data from the TxDOT and USGS networks can be ingested into the Kisters Big Data system, the data from this system could also be ingested and assimilated into KiBiD. Sufficient discussion has taken place to assure the technical feasibility of this step. If that were to be achieved a more comprehensive application of the data assimilation forecast error methodology for the Beaumont region could be achieved.

The Kisters data system is used by the City of Austin, Lower Colorado River Authority, Harris County Flood Control District, and the City of Houston. Data from these regions is already being ingested into the Kisters Big Data system and could also be used for data assimilation and forecast adjustment in those regions of Texas.

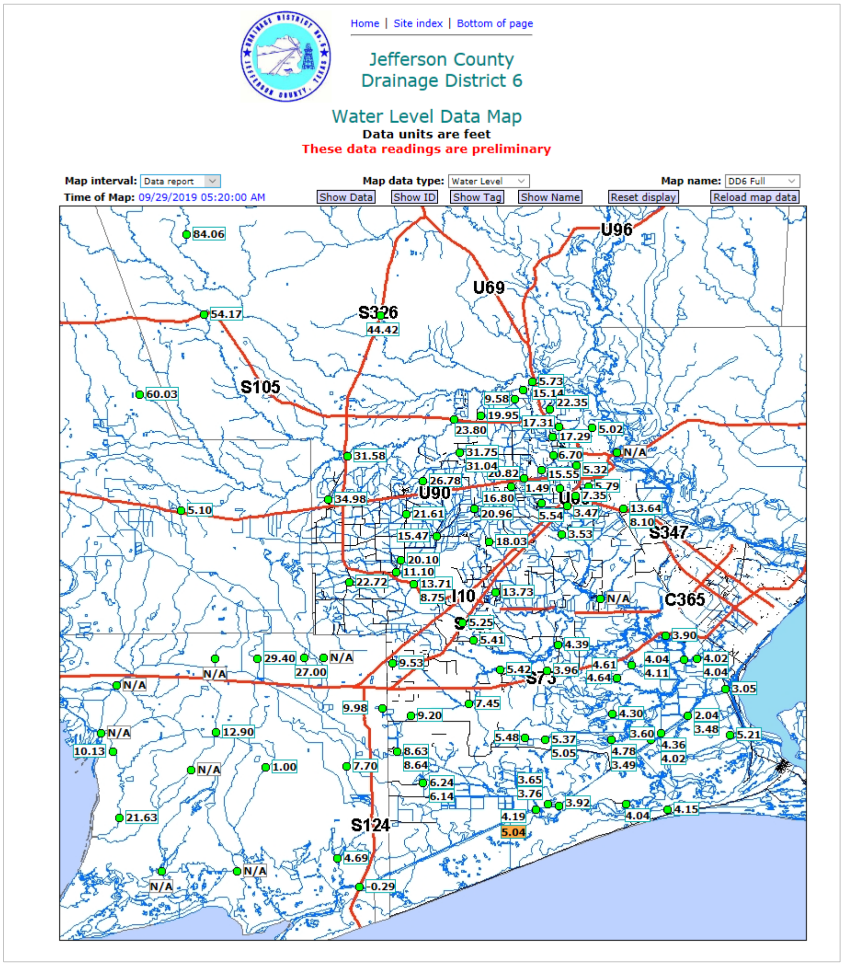


Figure 5-13 Water level data map from Jefferson County Drainage District No. 6 [*http://rainfall.dd6.org/maps.html*](http://rainfall.dd6.org/maps.html)

5.6. Correlation Zones and Additional Transects

In March 2019, a request was made to the research team by TxDOT to consider installing 30 more stream gage sites during the summer of 2019. Ultimately, this did not prove to be feasible, but in considering where those sites might be located, a concept arose to establish additional highway transects roughly parallel to that on I-10, as shown in Figure 5-14. Moving north, this would include transects on US 190/290, on US 67/84, and on I-20. As has been demonstrated in the concept study of data assimilation already completed, it is feasible to use downstream measurements to perform flow corrections upstream of a gage site. Hence, the areas between the gage transects can be considered “correlation zones” whose flows could be informed by the measurements made on transects bounding each zone.

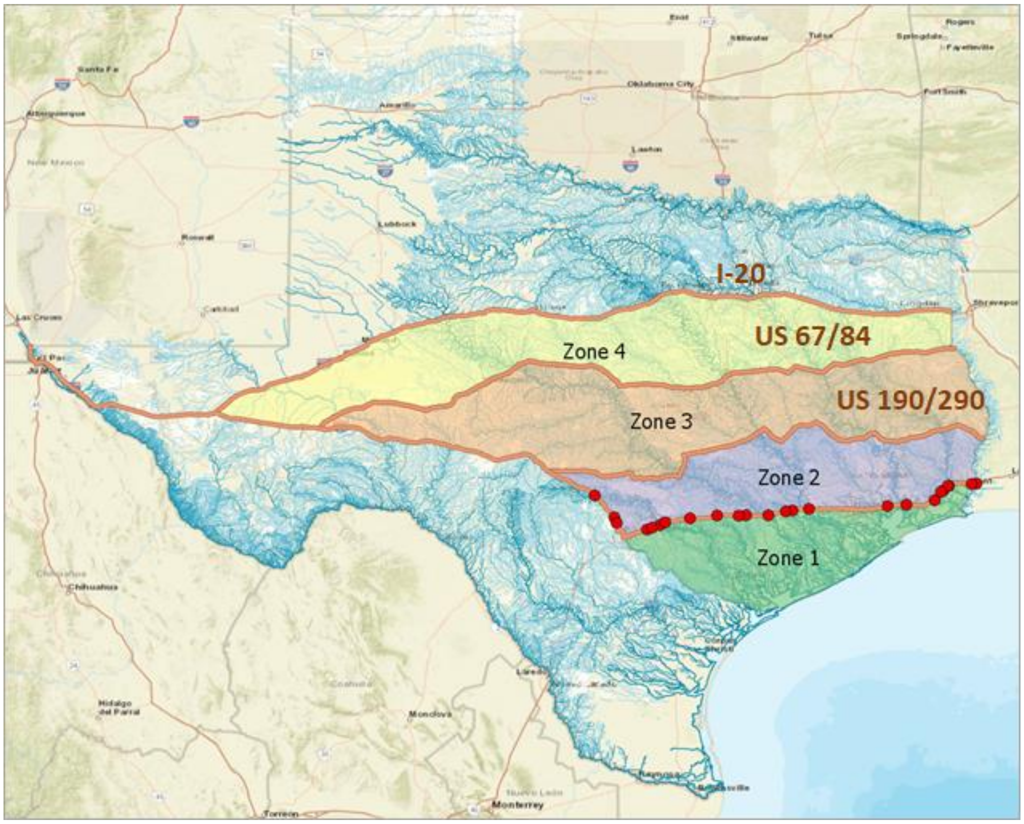


Figure 5-14 Additional transects and correlation zones between them

Chapter 6. Flow Modeling at Bridge Sites

6.1. West Navidad River at I-10

In almost all cases, each bridge where the TxDOT radar sensors are installed is the sole conduit through which all the drainage from the upstream drainage area is conveyed downstream. It turned out, however, that in the case of the West Navidad River at I-10, there is a second bridge located in the floodplain to the west of the main river that acts as a relief channel when the flow covers the floodplain. In order to get an estimate of total discharge in the West Navidad river, it is useful to construct a model of the flow hydraulics in the West Navidad river.

The watershed draining to the sensor on the West Navidad River at I-10 is shown in Figure 6-1. This is a USGS Hydrologic Unit Code 12 region, one of 6339 such HUC12 subwatersheds in Texas. Its drainage area is 61 square miles.

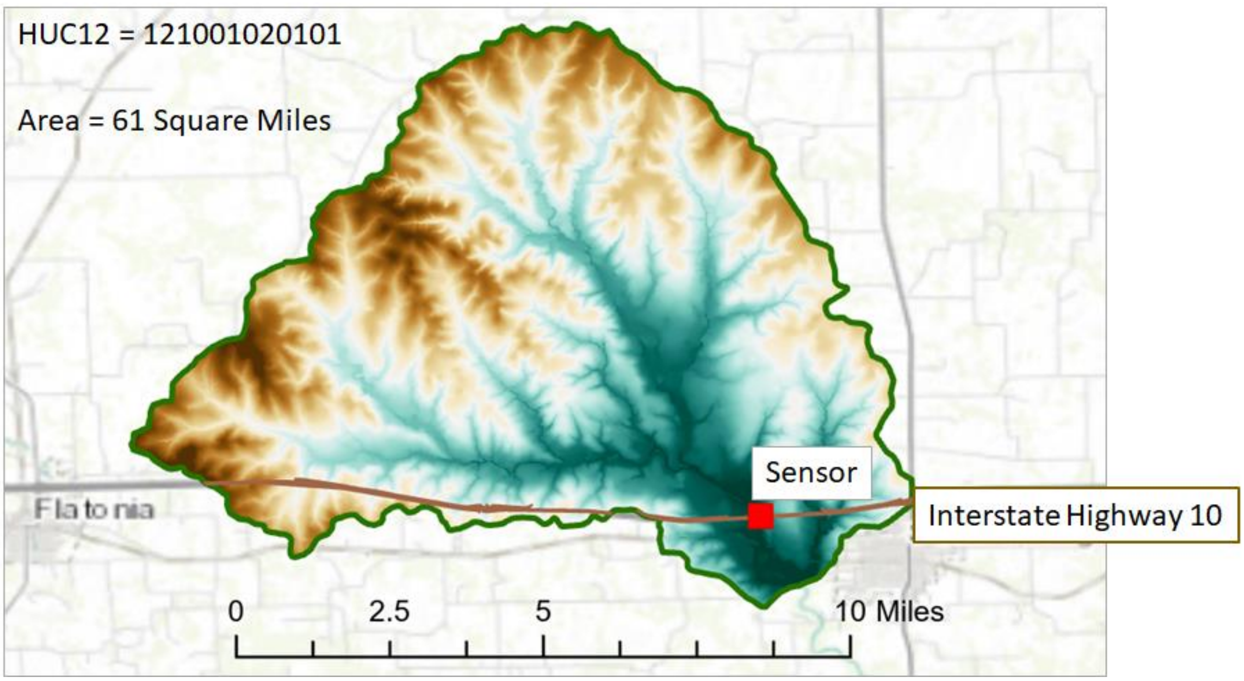


Figure 6-1 Watershed of the bridge sensor on West Navidad River at I-10

For purposes of representation of this watershed in the National Water Model, the drainage area is divided into 23 “reach catchments” where each reach catchment encompasses a single stream reach from confluence to confluence, as shown in Figure 6-2. The reach catchment containing the TxDOT bridge sensor is catchment 7845263, one of the 2.7 million similarly constructed catchments describing the drainage of the continental United States. The GIS dataset used as the basis of these catchments is the Medium Resolution NHDPlus, developed by the USGS and EPA. This is the stream reach and catchment dataset used in the National Water Model.

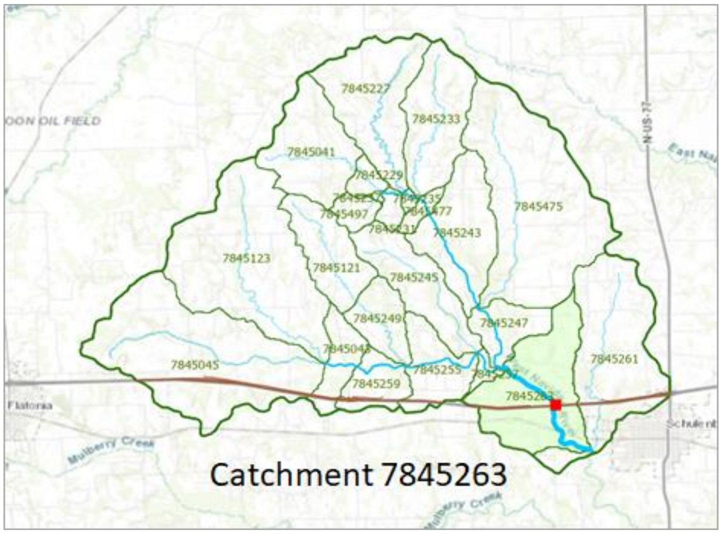


Figure 6-2 Representation of the West Navidad watershed in the National Water Model

6.2. Flood Inundation using Height Above Nearest Drainage

Flood inundation mapping from the National Water Model is done at the National Water Center using the Height Above Nearest Drainage (HAND) method, as illustrated in Figure 6-3 for Catchment 7845263. The National Elevation Dataset (using 10m grid cells) produced by the USGS is analyzed to create a relative elevation model of height of each point on land surface above the location on the streambed where its drainage enters the stream. The I-10 highway has an elevation of approximately 11 meters above the streambed at the point where the West Navidad river crosses I-10. Hence if I-10 is flooded, the extent of the resulting inundation area is found as the zone where the HAND value is 11 meters or less, and a grid of depth of flooding in that zone is found by subtracting the HAND value for each grid cell from 11 meters.

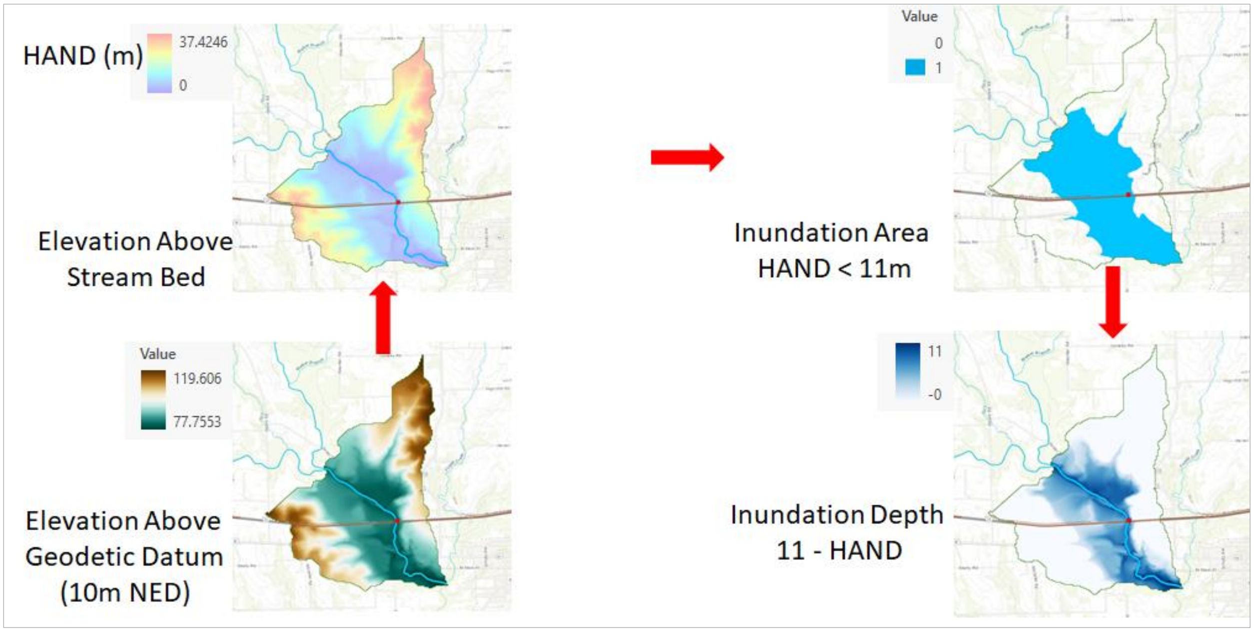


Figure 6-3 Flood inundation mapping using the HAND method

6.3. Elevation Data Describing I-10

Two sources of gridded land surface topography in the region of I-10 are available. The first is the National Elevation Dataset (NED), which has 10m grid cells, and is produced by the USGS nationally on the basis of elevation contours in its 1:24,000 scale topographic maps and additional land surface elevation data subsequently gathered by lidar and other means. The second is 1m lidar data collected in Texas with the coordination of the Texas Natural Resource Information System (TNRIS). For this region of I-10, the applicable data collection is the “Central Texas Lidar 2017” by StratMap, the State’s strategic mapping program (https://data.tnris.org/). Elevation maps produced from the 10m NED and the 1m lidar DEM are shown in Figure 6-4, and it is clear how the additional detail available in the lidar more clearly identifies where I-10 is located, and reveals the presence of the second bridge and the relief channel in the floodplain. Indeed, the presence of I-10 is not recognizable in the 10m NED data.

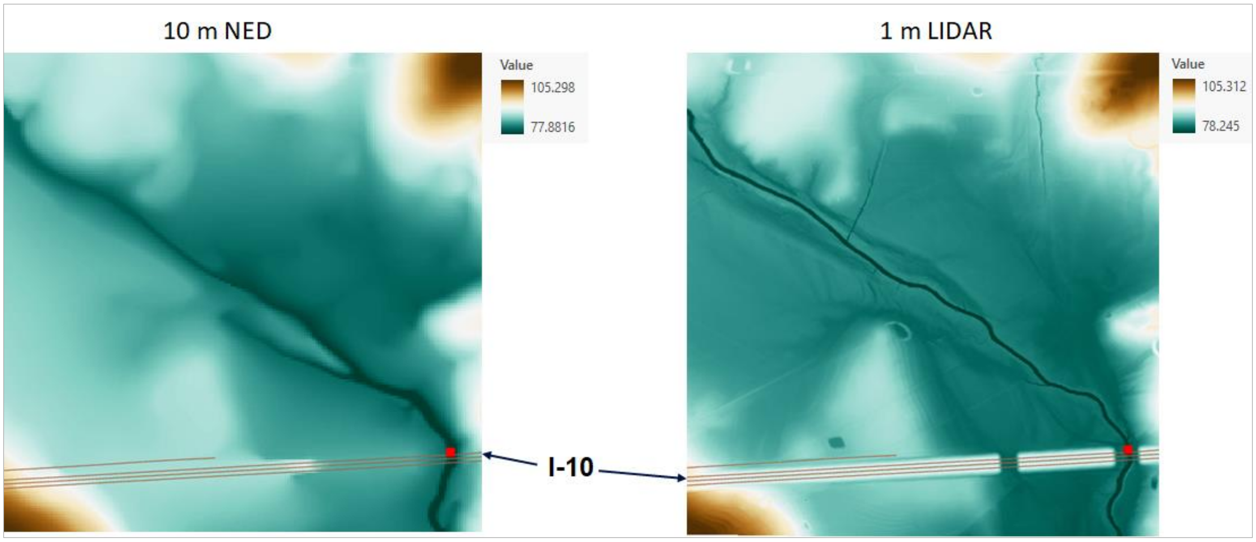


Figure 6-4 Elevation data describing I-10

This point is further reinforced when looking at an elevation profile along the West Bound lane of I-10, as shown in Figure 6-5. The purple line from the National Elevation Dataset follows the general land surface contour and correctly identifies the bed of the West Navidad river. However, the lidar data show that I-10 has a horizontal profile all along through the area of the West Navidad River and its floodplain. It is clear how the highway embankment in the floodplain impedes the flow of water and forces the flow towards the two bridge openings.

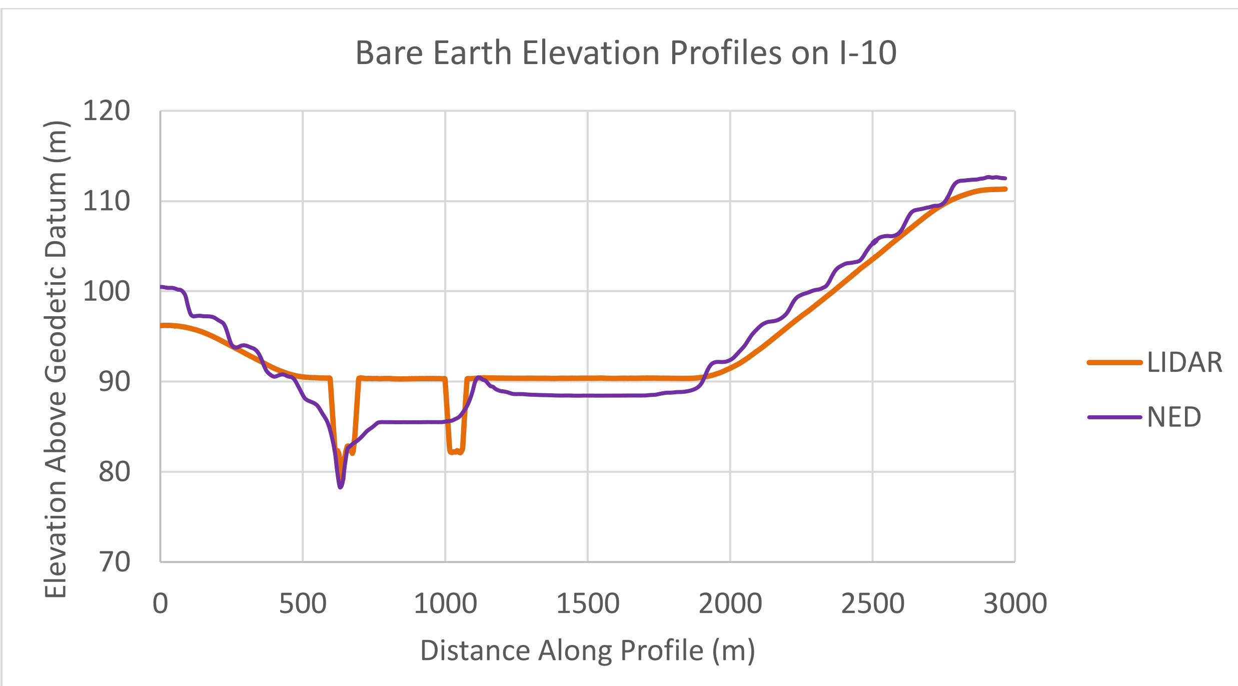


Figure 6-5 Elevation profiles along I-10

6.4. HEC-RAS 2D Model[1]

HEC-RAS 2D is a river hydraulic model developed by the US Army Corps of Engineers Hydrologic Engineering Center in Davis, California. This model is built as an extension of the traditional 1D version of HEC-RAS and provides an option to look at the spatial pattern of flow in the river floodplain, as is needed in this instance for modeling the two bridges in the floodplain of the West Navidad River. The scope of the HEC-RAS 2D model is shown in Figure 6-6, defined mainly by the boundary of catchment 7845263, including an additional area downstream of I-10 to encompass a tributary that joins the West Navidad at the catchment outlet. The 1m lidar bare earth DEM was used as the terrain base for the HEC-RAS 2D model.

The initial mesh was developed using 100ft cells, and then was densified along the river and along I-10 with smaller cells, especially in the zone of convergent flow in and through the bridge where the cells are nominally 25 ft in size. HEC-RAS 2D is a volume balancing model where the flow between adjacent cell centers is computed taking into account the full detail of the underlying terrain which is sampled as a cross-section profile along the cell boundary lines to define the geometry of flow between each pair of cells. Profile lines are drawn along the main path of the West Navidad River and across the two bridge openings to permit assessment of the flow, velocity, and water depths along these lines. The model was solved initially with the Diffusion Wave option and then with the more comprehensive full Dynamic Wave option.

The model was run for a steady flow input at the top end of the river reach and no rainfall on the land surface. Flow depth and velocity maps for one flow simulation are shown in Figure 6-7, and the detail of the flow field through the two bridges is shown in Figure 6-8. The main bridge opening carries about two-thirds of the flow and the relief channel about one-third of the flow.

[1] The HEC-RAS 2D model development was not part of the original TxDOT project scope, and was carried out with volunteer assistance. The initial draft of the model was developed by Cameron Ackerman of the US Army Corps of Engineers Hydrologic Engineering Center in Davis, CA, and this draft model was further developed and applied by Andy Carter of LandDev in Austin, TX.

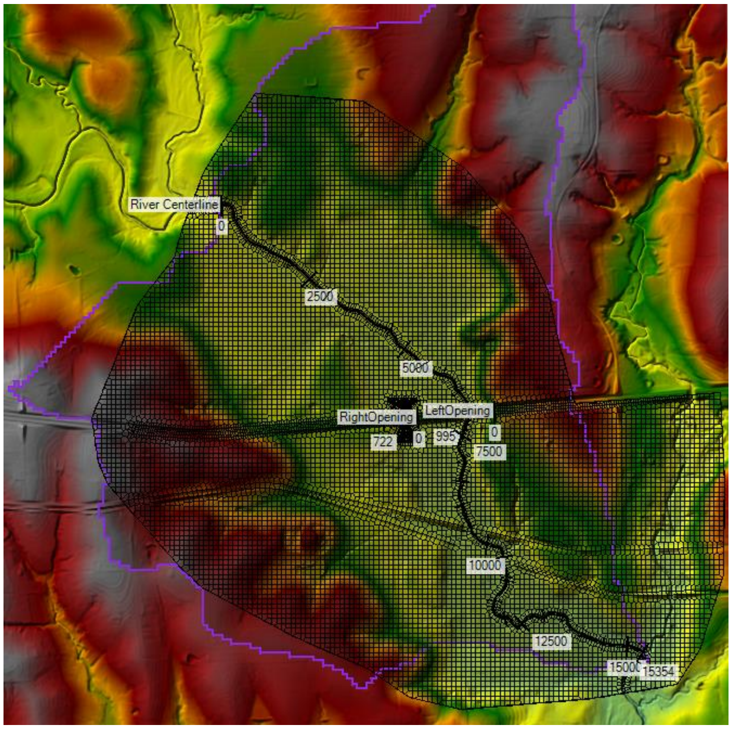


Figure 6-6 HEC-RAS 2D model of the West Navidad river at I-10

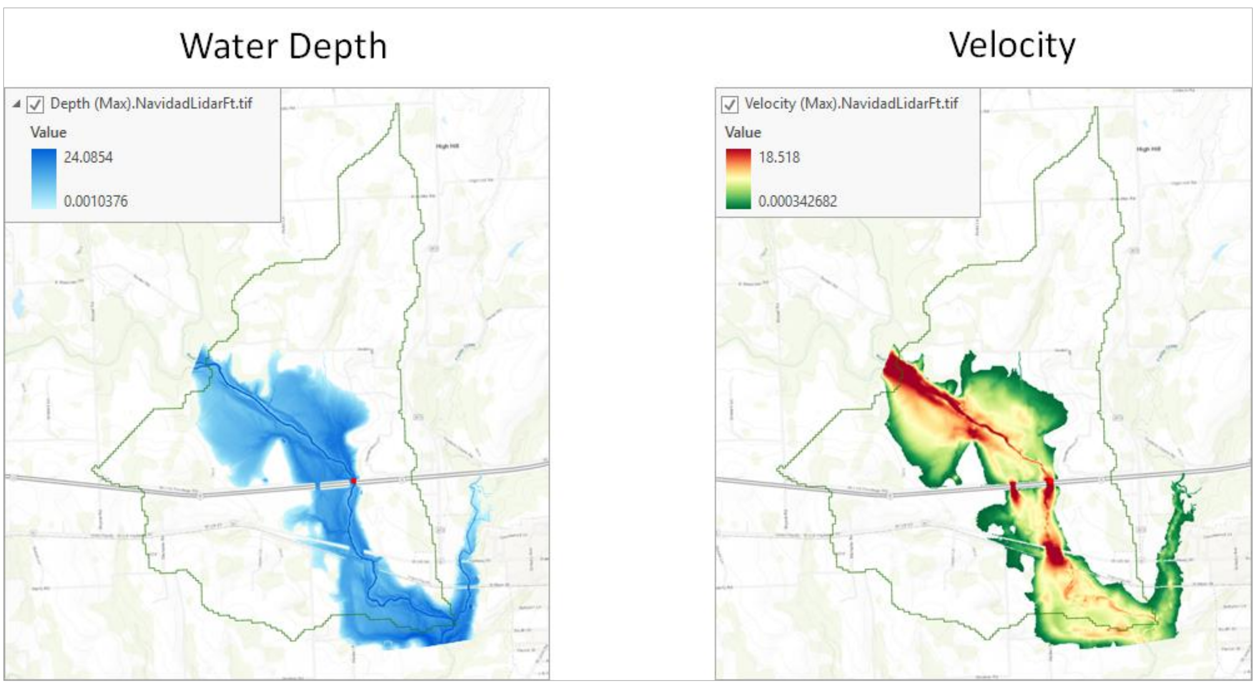


Figure 6-7 Water depth and velocity maps from the HEC-RAS 2D solution

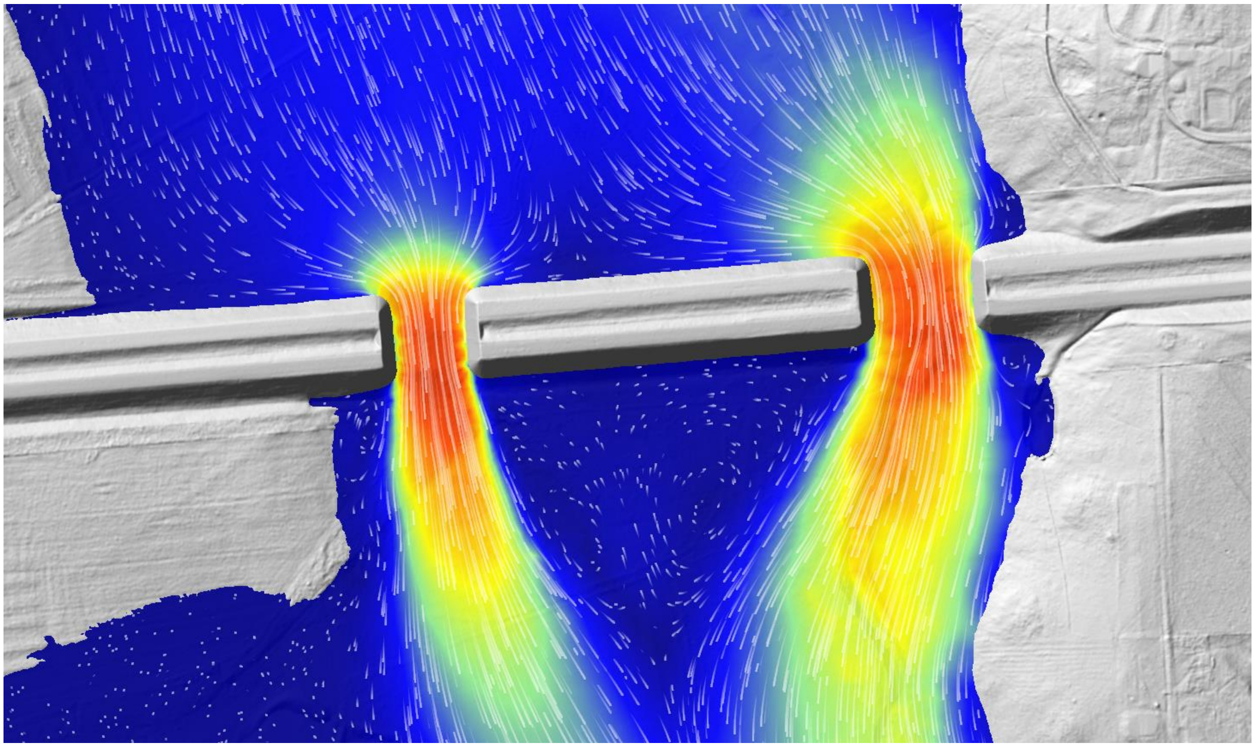


Figure 6-8 Details of flow through the two bridge openings

6.5. Flood Discharge Estimates

As each version of the National Water Model is produced, a retrospective analysis of historical data is simulated to create a reanalysis of the hydrology of the continental US. For version 2.0 released in June 2019, this reanalysis covers the 25-year period from 1993 to 2018, and provides an hourly time step simulation of the flows in the 2.7 million stream reaches in the continental stream network. A flood frequency analysis of these data was performed using the Bulletin 17B procedure[2], considering each reach as an individual time series. The purpose of doing this is to get reasonable estimates of what extreme flood discharges might look like over the stream network. The results for the West Navidad watershed are shown in Figure 6-9. The map shows the 10-year flood frequency estimate in cfs for each stream reach in the blue figures and the popup shows the frequency distribution of the flows in reach 7845263. In this instance, the 10-year return period flow is for reach 7845363 is estimated to be 8520 cfs, and values for other return periods are shown in the popup display in Figure 6-9. This range of flows was used as input for the HEC-RAS 2D model just to provide a set of flows over a reasonable range. More study needs to be carried out of the National Water Model reanalysis flows to assess their cohesion and confidence interval limits with extreme flows measured at USGS gaging sites, and with the USGS regression equations to estimate frequency-based flood discharges.

[2] The flood frequency study of the National Water Model reanalysis data was carried out by Xing Zheng of the UT Center for Water and the Environment.

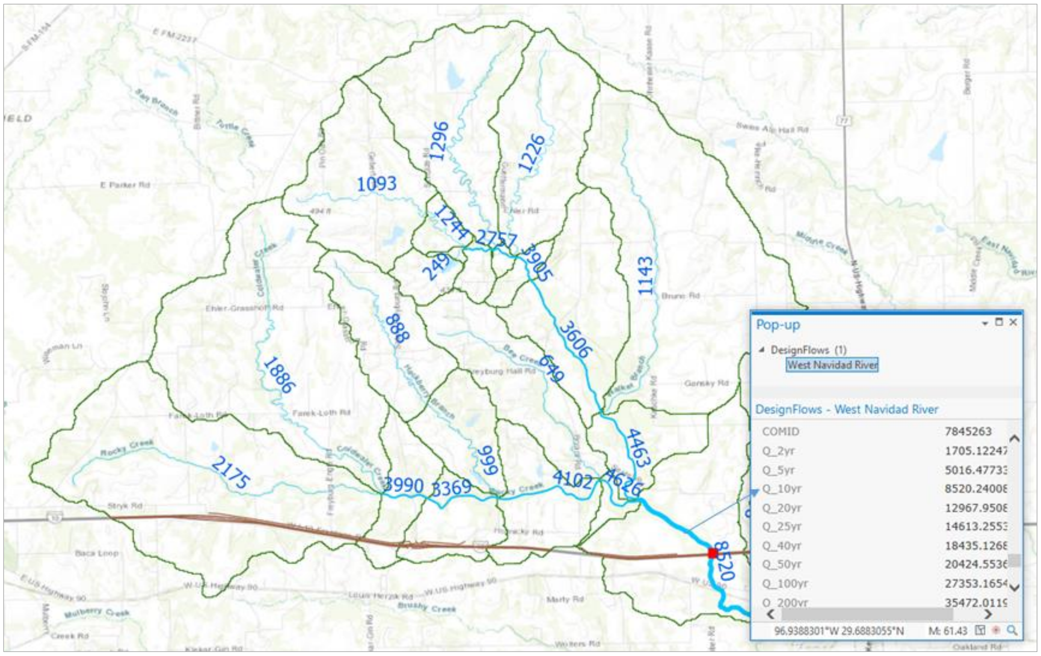


Figure 6-9 Flood discharge estimates derived from the National Water Model reanalysis

6.6. Rating Curves for Bridge and Stream

The central purpose for creating the HEC-RAS 2D model was to get a reasonable estimate of the discharge through both bridges on I-10 given that the water level and velocity are being measured only on the main flow path. This result is shown in Figure 6-10, in the form of a rating curve, which estimates the total discharge through the bridge as a function of the water depth above the streambed at the left or main bridge only, where the sensor is located. For comparison, the virtual stream gage for this bridge is shown adjacent to the rating curve. This calculation indicates that for flows up to about 100,000 cfs, the I-10 bridges would not be inundated, and the road itself would also be clear, showing that this is a safe hydrologic situation with a low risk of highway flooding. Undoubtedly, the presence of the relief bridge in the floodplain is a significant contributor to this safety.

The longitudinal profiles of stream depth above the bed elevation for a range of discharges are shown in Figure 6-11. As the discharge increase, the backwater effect at the I-10 bridge becomes more pronounced, as expected. Indeed it appears likely that there is a critical flow transitioning from subcritical flow upstream to supercritical flow downstream in the terminology of open channel hydraulics. The average stream depth is also shown on these profiles.

If the average stream depth is plotted against discharge, another rating curve is produced as shown in Figure 6-12. The significance of this result is that the average depth rating curve can be utilized to create a set of flood inundation maps. Each inundation map would relate to a computed average depth and an flow. With these maps, an inundation map library can be created, based on HEC-RAS 2D modeling, equivalent to the one normally created using HAND-based inundation mapping with the National Water Model. The HEC-RAS 2D approach uses a better assumption than uniform flow throughout the reach with stream depth equal to a fixed single value, as is normally done with HAND-based mapping.

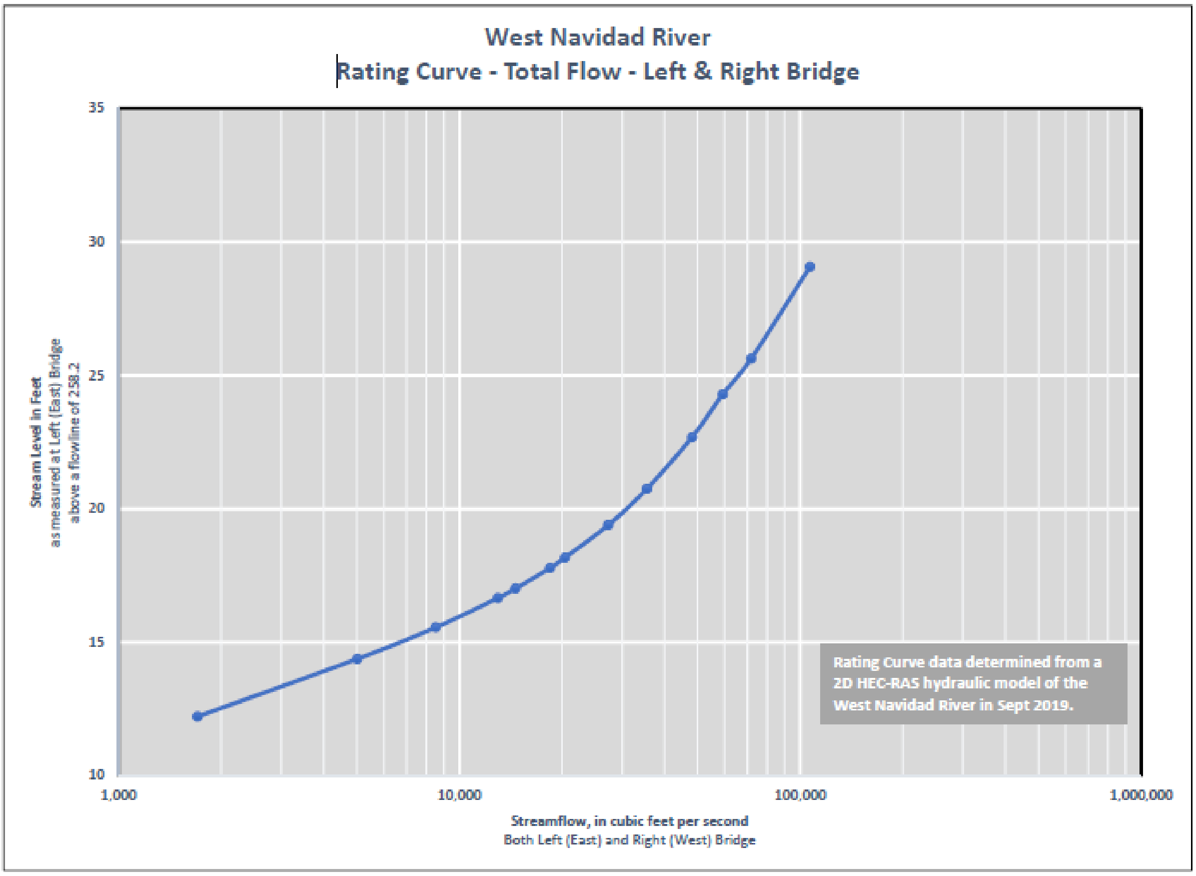


Figure 6-10 Rating curve for total flow of both bridges as a function of water depth above the streambed at the main (left) bridge

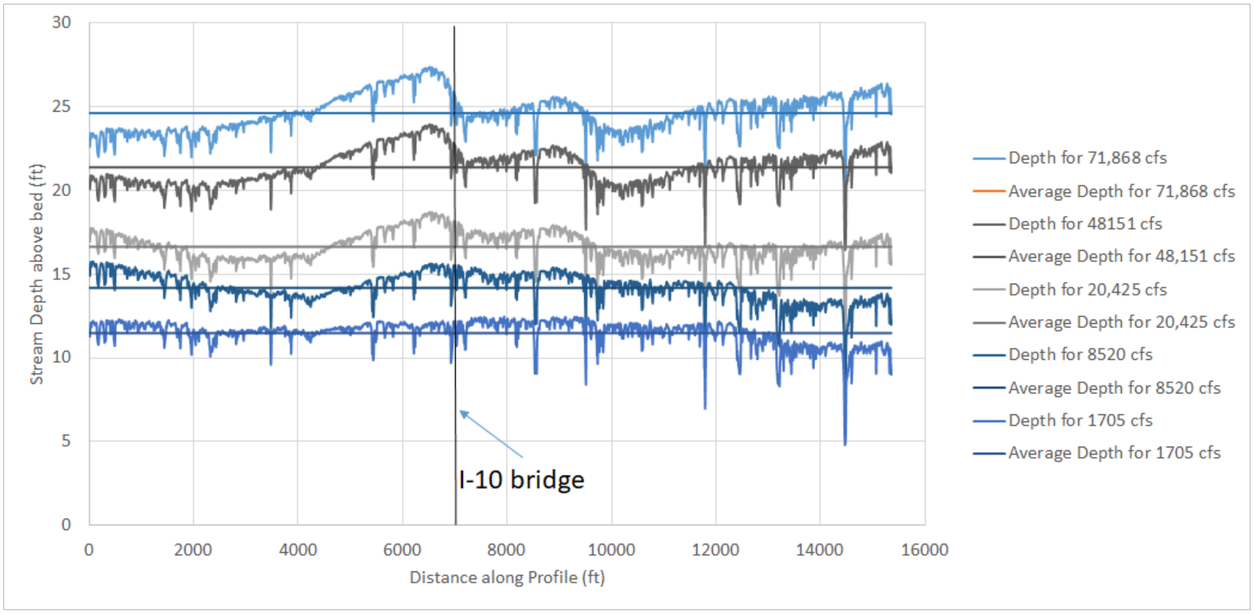


Figure 6-11 Water depth profiles along West Navidad river

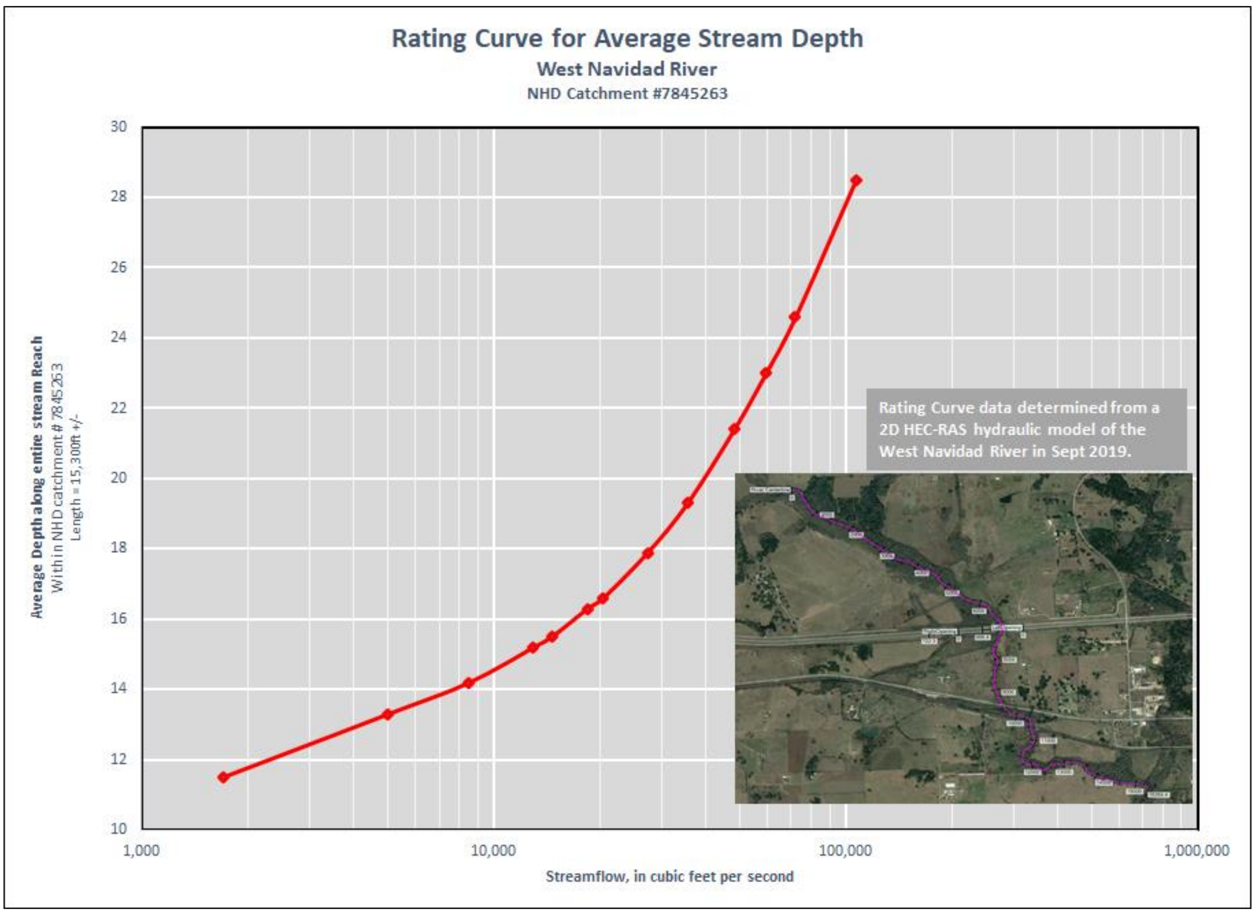


Figure 6-12 Rating curve for West Navidad river as a function of average stream depth along the reach profile

Chapter 7. Tropical Storm Imelda

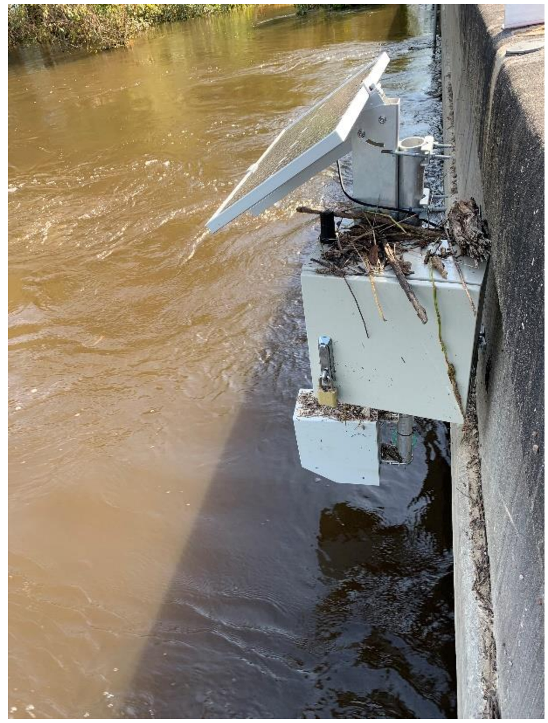
Tropical Storm Imelda hit southeast Texas during the period 17–20 September with peak flows along I-10 occurring on September 19. Given that this event occurred during the time this report was being compiled, there has not been time to do a full assessment of the flows measured in the TxDOT radar network. By inspection of the gage data, the following can be concluded:

- All the radar gages survived the flood.
- Cell phone communication of gage data continued uninterrupted throughout the event.
- Of the nine gages in the Beaumont District, six gages functioned throughout the flood, and three gages were overtopped as I-10 flooded.
- Site 106 Willow Marsh Bayou, Site 107 North Fork of Taylor Bayou, and Site 109 Cedar Bayou have stopped sending water level and velocity data. Field inspection showed water in the equipment box at all three sites—this box was submerged during the flood and its electronics have been at least partially disabled.
- All gage equipment is still in place on the bridges. The radar unit at Site 106 was snapped off, and the gage box was twisted to the side on its mounting pipe. The radar unit at this gage was mounted below the low chord elevation of the bridge and most likely a log or some debris being carried with the flood flow at this site hit the radar sensor. Sites 106 and 109 are continuing to report battery voltage levels, although Site 106 has a declining battery level, indicating that the solar panel is working. Site 109 is communicating battery level, which is functioning normally, which means that the solar panel is still working. Site 107 is not communicating battery level at all.

Photographs of the two sites, Willow Marsh Bayou and North Fork Taylors Bayou, are shown in Figure 7-1.

This event and the resulting gage immersions raise a question as to whether the gages should be remounted at a higher elevation above the bridge berm so as to avoid being flooded during a road overtopping, or whether the loss of some gages during flood events is accepted as a part of the cost of operating such a system and they are replaced after a flood passes. If the gages are remounted higher, they become more visible and could be more likely subject to theft or vandalizing. Elevated gages may also be a distraction to traffic using the bridges.

Willow Marsh Bayou after Imelda



North Fork Taylors Bayou after Imelda

Figure 7-1 Damaged gage sites following Tropical Storm Imelda. Photos by Andrea Johnson, TxDOT Beaumont District Office.

Chapter 8. Conclusions

8.1. What Was Achieved

A transect of 20 bridges on or near I-10 were instrumented with RQ-30 radar streamflow sensors that measure both water level and surface water velocity. This transect stretches from west of San Antonio to the Louisiana border, with 9 of the 20 gaging sites being located in the Beaumont District, the most flood prone section of I-10. A transect of RQ-30 radar gages mounted on a highway is a first for the United States. A repeatable process was defined for gage site selection and installation for use in establishing further highway gage transects. The infrastructure of entirely self-contained, solar powered, non-contact gages and sensors did not have any equipment maintenance or communication issues outside of vandalism and being submerged by flood. This has a significant positive effect on the ongoing cost in any future build-out of this system.

A cloud-based data architecture, the Kisters Big Data system, was used to store, process, and present the data from the 20-gage TxDOT transect, the National Water Model forecasts for 102,000 stream reaches of Texas, observations data from 550 US Geological Survey gaging stations, and data from other local observation networks. The data are made accessible through a TxDOT Water Data Viewer focused on the gage transect, and a TxDOT Bridge Portal that provides access to forecast and gage information throughout Texas. REST-based water data services are provided to allow for direct access to the data for graphing or analysis in Excel or other applications. The data system ran continuously throughout the project period and no data were lost or missed due to outage or system unavailability.

The site location of each stream gage was GPS-surveyed and the stream cross-section across the floodplain determined using lidar terrain data, confirmed by using GPS surveying and weighted tape measurements at many sites. Where gage sites have permanent water, the bathymetry of the cross-section was measured by sonar sounding techniques. The I-10 road profile across stream cross-sections was determined using newly collected Texas lidar data. A 360° dynamic photography survey was made of each gaged bridge to visually record its surroundings and the pilings and substructure beneath the bridge. A virtual staff gage was created at each bridge so the water level can be visualized. A StoryMap was created to archive all the characterization information for each site in a central, readily accessible repository.

A detailed 2D hydrodynamic model was created for the West Navidad River at I-10, which has two bridges, one on the main channel and another in the floodplain. This model illustrated the flow patterns in the floodplain and through the highway bridges. It provides an accurate mechanism for determining rating curves for connecting stream depth with flood discharge at the bridges and for the stream reach upstream and downstream of the bridges.

The project was a resourceful effort to bring clearer picture of the art of the possible for flood modeling, infrastructure protection, and citizen safety on a major interstate highway. The project took significant steps forward to create a communicable and usable tool for use across multiple departments that benefit from predicting, reacting to, and analyzing water flows versus bridge infrastructure. Imagery in and around the bridge structures adds context and the potential to interpret flood conditions from a desktop.

8.2. What Was Learned

The I-10 transect consists of two parts. The first region, west of Houston (11 gages), comprises mostly dry channels, and is easier to operate in. The second region, east of Houston (9 gages), lies in the Beaumont District, where all the gage sites are near enough to the coast that the channel bed is below sea level, the sites have permanent water, the larger rivers are tidally affected, and these sites are more difficult to characterize. This region also has higher highway flood risk.

The transect was tested in a major storm, Tropical Storm Imelda in September 2019, and functioned continuously throughout the storm. All data are communicated through the cell phone system and this communication system did not fail during Imelda. All the equipment remained in place on the bridges after the storm. Three gages in the Beaumont District were inundated and damaged when floodwaters overflowed I-10. The remaining six gages in this area functioned effectively during TS Imelda and contributed a unique dataset of flood water level, velocity, and discharge measurements for the tidal zone near the coast where other gage data is not available.

The decision to choose radar sensor instruments that measure both water level and velocity rather than velocity alone was made by TxDOT management early on the project development process. This was a remarkably prescient decision and resulted in a robust measurement transect that is capable of producing useful information on the most flood-vulnerable region of I-10. An advantage of radar-based devices for estimating flow is that the surface velocity measurements improve the flow estimates, especially at the high flow end of the rating curve where measurements used for calibration may not exist. Another advantage of radar-based flow-measuring devices is that they can be deployed in channels where a simple device that measures water surface elevation only (like the typical USGS stream gage) is not recommended, such as in coastal zones. The addition of a surface velocity measurement helps provide confidence in the flow estimate and many stream gaging sites in Texas may be conducive to these types of devices.

The use of lidar terrain data for stream cross-section and road profile determination was much more effective than was assumed at the beginning of the project. Field checking with GPS surveying along the roadbed near the bridge berm, coupled with weight tape measurements down the streambed and floodplain, yielded spot elevation data so similar to the lidar data values at those locations that the lidar profiles were used at all sites for cross-section characterization. For sites with a significant depth of permanent water, stream bathymetry was measured using sonar techniques. Here again, field checking of the sonar bathymetry data with corresponding points determined GPS surveying at the road and weighted tape measurements to the streambed showed very good agreement.

It is important to get survey-quality GPS coordinates for the location and elevation of each gage. Inexpensive handheld GPS receivers can have significant errors. The Trimble R-10 GIS survey instrument used in this project performed quickly and accurately for measurements made on the bridge. Its accuracy and timeliness of measurement diminished significantly when used near the streambed with overhanging trees and the bridge obscuring access to GPS satellite signals. The best survey approach for streambed cross-sections is to use the GPS survey instrument on the road at the bridge berm then a weighted tape to measure to the streambed

The Kisters Big Data system coped with absorbing, processing, and presenting an enormous volume of data in a seemingly effortless manner. The system was reliable and continuously accessible. A variety of web interface and data services access methods mean that the data can be readily extracted and digested. Storing site characterization data on a web-hosted StoryMap and data files on Box.com is very effective but requires thoughtful organization, and regular updates during the gage installation and survey phases.

A significant effort was expended in statistical analysis to find a way to combine the gage observations with the National Water Model forecasts, to provide an adjusted forecast in tune with the local gage data. A 4D data assimilation method was used which adjusts the flows upstream of a gage so that when they are routed down to gage where the measurements are made, the results agree reasonably with the observed values. These adjusted flows are then routed downstream in the forecast river. It was concluded that this approach can lead to improved forecast information for about 15 miles upstream and 30 miles downstream of a measured gage site. Additional effort is needed to build a comprehensive and transect-wide data assimilation and forecast adjustment method. The National Water Model itself uses just USGS flow data to check the forecasts and a blunt adjustment method of simply forcing each forecast to start with the measured flow at a gage site, regardless of the upstream flow to that site. Forecast adjustments beyond this simple method need more work. Geostatistical variograms were computed for National Water Model flows on rivers crossing I-10 between San Antonio and Houston for peak flows during Tropical Storm Imelda. These computations indicated a spatial correlation out to about 50 miles between stream reaches for this event. The gage spacing used in the TxDOT transect on I-10 is on average about 20 miles between gages west of Houston, and 10 miles east of Houston. These spacings are well within the limits where one gage reading is correlated with its neighbors on either side along the transect.

The gages were set to send out an alarm when the water level reached the low chord elevation of the bridge. It turned out during Tropical Storm Imelda that the alarms were not triggered because the water level sensor stops functioning when the water rises to within 1.5 ft of the sensor. The alarm triggers need to be set with this constraint in mind. Probably, just setting the gages to alarm when water rises within 2 ft of the sensor would be an appropriate approach.

8.3. Challenges to be Faced

A complete set of gage equipment on Taylor Bayou was lost, soon after installation, either through theft, or because somebody attempted to detach the equipment from the bridge and it fell into the bayou. The solar panel on the Sabine River site was also stolen shortly after installation. No further theft or vandalism has occurred up to the time of writing this report. These items of equipment were replaced and both the Taylor Bayou and Sabine River sites functioned effectively during Tropical Storm Imelda. The equipment needs to be attached to the bridges in such a way as to prevent vandalism and theft. That involves a combination of locking mechanisms (e.g., threadlock on the bolts) and minimizing visual contact with drivers. In areas where flooding of I-10 occurs frequently, the gage equipment could be elevated above the bridge level and possibly enclosed in a secure box or cage. A prominent notice could identify the gage as a flood monitor operated by TxDOT.

Discussing the site selection criteria and navigating the TxDOT permitting process delayed the project by several months. Three gages were installed early in the project period. After a long hiatus, a package of 17 site permits was approved by TxDOT for all the rest of the sites. After these installations were complete, TxDOT notified the project team that the San Bernard gage should be moved to an alternative site because the bridge was going to be replaced next year (2020). A check had been made by the project team with the district office and the Austin office regarding bridge replacements prior to making the final site selection. The San Bernard gage has been removed and has been re-installed on the westbound frontage of the Church Creek bridge at I-10. A more structured process for site selection and closer coordination with the TxDOT District offices is needed.

The flow conditions in the coastal zone for I-10 east of Houston are complicated and probably require 2D or 3D flow hydrodynamic modeling to properly make use of the velocity measurement capability of the RQ-30 instrument, which measures the velocity of one point on the water surface and uses that to infer the average velocity across the cross-section. This will likely require sonar measurement of the river bathymetry from the coast inland to the bridge and for some miles upstream of the bridge.

8.4. Recommendation for the Future

This project concerns installation of radar gage sites on TxDOT bridges on I-10 but it really provides a foundation to address the broader question of the flood security of I-10 as an interstate highway. The use of lidar for 3D characterization of both the I-10 road profile and the terrain in the streambed and floodplain means that comprehensive hydraulic modeling can be carried out of flood conditions upstream, through and downstream of the highway. When coupled with the National Water Model forecasts in real time and the reanalysis of historical data, an improved basis is created for both highway flood risk assessment and for real-time emergency response operations. This has potential for application across Texas, but the experience in this project suggests that it would be worthwhile to focus further effort on a case study of use of the current TxDOT gage data in the Beaumont District. This should include realistic flood simulation and table-top exercises as are normally used in the emergency response community. This would give TxDOT staff experience in how flood data systems work before they are used during flood events. In particular, a focused case study would provide the District staff the opportunity to direct the effort to best support field operations and flood planning based on their experience during past flood events.

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Appendix: Guide for Radar Gage Installation on TxDOT Bridges

The purpose of this guide is to supplement the manual provided by the equipment manufacturers https://www.hydrologicalusa.com/fileadmin/user_upload/Manual_RQ-30_V2.29_EN.pdf and summarize the experience in installing RQ-30 gages during this project.

Assumptions

(1) That the gage to be installed is a Sommer RQ-30.

(2) That the installation site is on a bridge in Texas.

(3) That the beginning point is the reconnaissance to select a bridge site

(4) That the ending point is with the gage installed on a bridge, the power turned on, and confirmation that data signals are being received via cell phone communications from the site.

1. Bridge Site Reconnaissance

There are four kinds of site locations: (1) those on the main interstate highway lanes, (2) those on interstate highway frontage roads, (3) those on other highways, and (4) those sites recommended by the local TxDOT District or local public safety.

Things to avoid: bridges with lots of overhanging vegetation and metal superstructures, such as metal trusses supporting the bridge deck on older bridges. These can interfere with site surveying, gage communications, and solar cell recharging. It is best to have bridges “open to the sky” as much as possible.

Things to consider:

(i) Safety from traffic during installation

(ii) Ease of installation

(iii) Ease of access for recurring maintenance

(iv) Location of the gage is proximal to the area of concern for TxDOT and/or public safety

(v) A gage location that is obvious to the general public may be more susceptible to vandalism.

Issues for Consideration: What are the pluses and minuses of these three types of highway site locations? Use the above considerations to evaluate each site and conduct a risk benefit analysis to determine which site best meets the need of TxDOT. How far apart should the gages be along a highway? This will depend on factors such as budget, the availability of bridges suitable for mounting, whether only the main rivers are monitored, or main rivers and their tributaries, the reason/purpose for installing the sensors and the desired outcome and ways the data collected will be used to name a few.

Should the gages be sited facing upstream or downstream? The radar sensor can be mounted either facing upstream or downstream. Facing the sensor upstream has essential advantages and is recommended if possible, e.g. the influence of pillars on flow conditions is avoided and the influences of rain and snowfall can be eliminated by a direction separation of the velocity measurement. The radar sensor can differ if water movements occur in direction of the radar sensor or away from the sensor. As rainfall usually moves downwards and therefore away from the radar sensor, some parts of the velocities can be blanked out.

Is it better to install the gages facing downstream so they are less impacted if the bridge overtops or is the equipment robust enough to remain in place anyway? Whether the system survives bridge overtops or not will depend on the strength and method of the mounting. Even if the radar sensor and equipment cabinet (gage controller box) are not washed away, the system may stop working if submerged by water. It is always recommended to install the sensor above the max expected water level although this is not always possible.

Is it useful to site the gages with the solar panel facing south for best recharging, or does the orientation of the solar panel not really matter? Yes, solar panels should be oriented South so as to collect the maximum amount of solar radiation throughout the sun's daily path.

2. Assembly of the Equipment

There are four main components of the gage equipment: (1) Solar panel, (2) Gage controller box, (3) Radar sensor, (4) the pipe and backing plate to which the components are shackled.

Issues for Consideration: How far apart should the solar panel and radar sensor be from the controller box? Is there electrical field interference with the gage performance if the sensor is too close to the controller box? The solar panel does not introduce any interference to the radar sensor. Therefore there is no limitation on distance between the sensor and the solar panel. It is important that the solar panel is not positioned where it can interfere with the radar sensor beams (level and velocity). This is highly unlikely and is avoided by mounting the solar panel either in line with or above the radar sensor. What is the minimum spacing between the units along the pipe? There is no minimum or maximum distance. The position of the components is solely dependent on access for maintenance and ensuring that the solar panel is not obstructed.

Battery installation: Battery installation is done after the gage is mounted. This is to avoid the battery moving inside the controller box and causing damage during installation. Once the gage system has been mounted and is ready to be put in operation, the battery can be installed. The battery is placed inside the box ensuring the battery is not resting on any internal cables. First connect the positive (red) battery cable, then connect the negative (black) cable. Connecting the positive cable first avoids arcing during this process. Once both connections are made turn on the gage with the toggle switch marked "On & Off."

3. Installation on the Bridge

A template is used to locate the bolt holes on the bridge structure. Holes are drilled, and bolt-holders inserted. The complete gage assembly is lifted onto the bridge and screwed onto the support bolts. Epoxy glue is spread around on the bolts and screws.

Issues for Consideration: Should the equipment be installed with the radar sensor above the bridge low chord for protection during high water flow? It is best to have the radar unit mounted above the low chord elevation of the bridge so that it does not get snapped off if hit by floating debris reaching the bridge during a high flood. At Church Creek, the radar sensor was installed approximately 5 inches higher than the low chord elevation. If the sensor is too high the bottom chord could interfere with the signal. Should the equipment be elevated above the bridge to avoid being inundated if the bridge overflows? Should the bolts and threads be covered with an epoxy glue to impede the equipment from being stolen? It is useful to put epoxy on the bolts to deter theft/vandalism. However, there are a number of ways the gage systems could be made more secure, including but not limited to: using locking nuts on the anchor bolts, spot welding the anchor bolt and nut assembly, building an enclosure or cage around the system and placing written warnings or notices on the system. Should the radar unit be turned so that it faces the flow if the stream and bridge do not intersect at right angles? Are there special issues with particular kinds of bridge supports such as installation on concrete columns on the bridge berm versus being bolted to the bridge rails?

4. Surveying the Sensor Location

The exact location of the radar sensor in (x,y,z) in geodetic coordinates is needed. This can quickly be obtained by GPS survey to a very high accuracy if the bridge is "open to the sky." In fact the surveying error is smaller than the size of the sensor box itself. Right now we are surveying any point on the top of the senor box and then adding 1 foot to allow for the difference in elevation between the top and bottom of the sensor.

5. Surveying the Cross-Section

There are several variants here:

1. Surveying a sequence of 10–20 points on the bridge road bed next to the bridge berm, then measuring with a weighted tape the distance between the bridge berm and the stream bed, and finally measuring with a tape measure the height of the bridge berm above the road bed. Use a tape measure to get the height difference between the road berm and the low chord of the bridge. This is a fairly tedious procedure that requires a significant amount of data reduction to produce a cross-section of the stream bed at the sensor location on the bridge.
2. Using GIS analysis of lidar terrain data to determine the stream cross-section and lidar point cloud data to define the road elevation on the bridge. This is much more time-efficient and has proven as accurate as Method (1) in the 11 bridges we installed west of

Houston in largely dry creeks. Tape measurement to get the height difference between the road elevation and the low cord elevation is also needed.

3. Where there is a significant depth of permanent water (say, beyond 1–2 feet of flow), use sonar measurement with an Acoustic Doppler Current Profiler to measure the stream bottom elevation across the stream. Supplement this with lidar data interpretation of the cross-section in the floodplain and on the bridge road bed itself. It takes some effort to overlay the lidar and sonar data so they are consistent with one another. Tape measurement to get the height difference between the road elevation and the low cord elevation is also needed.

The stream cross-section narrows in significantly as flow approaches the bridge so to achieve consistent results for the stream cross-section it is necessary that it be surveyed along the line of the bridge berm where the sensor is located. This results in a complete “bridge envelope” of the stream cross-section below and the road and low chord elevations above that completely contains all of the flow provided the bridge is not overtopped. If the ADCP measurements for bathymetry cross-section are made further out in the stream from the bridge, they have to be moved back to the bridge to become part of the “bridge envelope.” This means that the adjustment factor, k, relating the radar sensor velocity to the mean velocity has to account for the distance between the radar impact points for water velocity and elevation. The adjustment factor, *k*, also needs to take into account the effect of the oblique angle of flow if the stream and bridge are not at right angles to one another. The lidar data provide good guidance as to what this oblique angle between the stream direction and the road direction where the road crosses the stream.