Streamgaging in Texas

by

Shannon McCarty, M.S., Heather Rose, M.S., Sam Marie Hermitte, M.P.Aff., Mark Wentzel, Ph.D, Morgan White, M.A.

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LCRA	Lower Colorado River Authority
TxDOT	Texas Department of Transportation
TWDB	Texas Water Development Board
USGS	U.S. Geological Survey

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EXECUTIVE SUMMARY

Streamgaging has been in practice for over a century as a means of understanding stream networks to help protect lives, property, and water supplies. In Texas, there are over 1,500 known streamgages with data publicly available. Many different entities operate these streamgages, including large governmental agencies such as the U.S. Geological Survey and the International Boundary and Water Commission; river authorities such as the Lower Colorado River Authority and the San Jacinto River Authority; and a wealth of cities, counties, drainage districts, and flood control districts. Many smaller entities who have created their own streamgaging networks use the Automated Local Elevation in Real Time (ALERT) system, developed by the National Weather Service for establishing such networks.

There are multiple hardware options for streamgages, including bubble gages, pressure transducers, radar, and ultrasonic sensors, all of which are used to measure stream stage, or water surface elevation. These technologies are comparable in cost and performance, with the exception of ultrasonic sensors which are less expensive and generally have lower performance standards. Hardware such as mechanical, electromagnetic, and acoustic current meters, as well as non-contact velocity sensors are used at streamgaging locations to measure stream discharge, or the quantity of water moving through a stream at a given time. Each streamgage is connected to some type of network system where the data can be transmitted, used, and shared. Data transmission options range from satellite, to radio, to cellular networks. Both satellite and radio networks operate over specific, government-owned frequencies used to transmit hydrological data. Cellular networks are set up through cellular provider companies and involve data plans.

The cost to maintain a streamgage varies drastically depending on what type of sensor is located at a gaging location. The U.S. Geological Survey performs frequent maintenance on their streamgages, develops and updates rating curves to predict discharge, and hosts all streamgaging data on their website, all of which lead to higher costs. ALERT users have slightly lower costs to maintain their networks, as many do not perform discharge measurements and data transmission is a one-time cost during installation of the network. Thus, no additional fees occur when adding gages to the existing network. Entities such as the Iowa Flood Center, the U.S. Department of Homeland Security, and the Texas Department of Transportation are working on developing streamgaging sensors and

networks that are cheaper to install and maintain, ultimately trying to make streamgaging more affordable.

INTRODUCTION

Understanding the characteristics and patterns of Texas' rivers and streams is important for protecting lives, property, and water supplies. Streamgaging informs this understanding by measuring stream stage and discharge at regular time intervals at a cross-section of a water body (Olson and Norris, 2007). Streamgage data is used for a variety of applications including flood warning and management, weather forecasting, engineering designs, water allocation, ecological studies, and recreational safety(Kaur, 2013).

Streamgages maintained by the U.S. Geological Survey (USGS) have been in operation in Texas since 1889 (USGS, 2016). Over the 20th and 21st centuries, streamgaging efforts have expanded both in terms of the number of gages and the entities involved. Today, streamgaging is used for weather forecasting, flood modeling, public communication, and other critical activities in Texas. Major agencies performing streamgaging include the U.S. Geological Survey (USGS), the Lower Colorado River Authority (LCRA), and the International Boundary and Water Commission, all of which have established networks with publicly available data.

The National Weather Service uses these data, among other sources, to make weather forecasts and flood predictions that are published online for public viewing[(1)]. These data are also shared via the Texas Water Development Board's flood information viewer[(2)]. Other local agencies in Texas, including cities, counties, river authorities, and flood control districts, have utilized Automated Local Elevation in Real Time (ALERT) systems to create their own streamgaging networks for local flood monitoring purposes.

The objective of this report is to provide information on current streamgaging technologies, how they work, their approximate costs, existing networks, and their usage across Texas. This information can inform stakeholders of the devices available to them for monitoring flows in their communities.

(1) https://water.weather.gov/ahps/
(2) https://map.texasflood.org/#/

BACKGROUND

The USGS installed its first streamgage in the United States on the Rio Grande in New Mexico in 1889 (Olson and Norris, 2007). The first USGS streamgage in Texas was installed on the Rio Grande at El Paso that same year (Follansbee, 1939). In 1915, the USGS Texas district office opened in Austin when there was a total of 18 streamgages in operation statewide. Today, the USGS owns and operates over 750 streamgages across the state (USGS, 2022a). The Lower Colorado River Authority (LCRA) began monitoring real-time streamflow in the early 1980s (David Murdoch, LCRA, oral commun., 2022). Today, LCRA's Hydromet network includes more than 380 gages (LCRA, 2022). Similarly, the Harris County Flood Control District (HCFCD) first installed streamgages in 1982, initially including 13 gage stations. Today, the Harris County Flood Control District monitors 188 gage stations in their flood warning system network (HCFCD, 2022).

Typically, streamgages can measure stream stage, or the water level above a reference elevation, and discharge, the volume of water moving through the stream at a given time. The streamgage measures stream stage through a variety of different possible technologies. An example of a streamgage setup can be seen in Figure 1 where a bubble-gage is used to measure stage. Stage information is an easily visualized and understood measure of public risk (Mason and Weiger, 1995). The discharge of a stream may be calculated by multiplying the cross-sectional area of a stream by the average velocity of the water in the cross section:

$$Discharge = Area \times Velocity$$

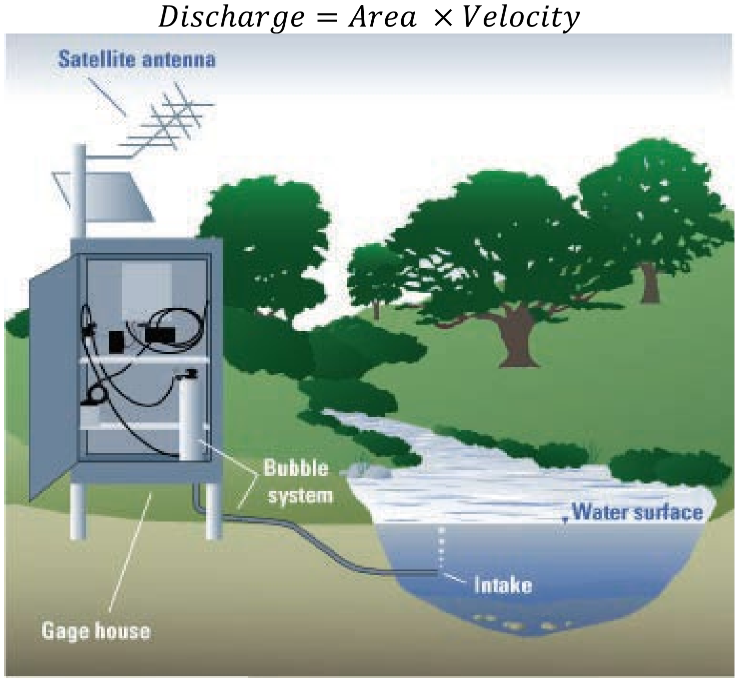

Figure 1: Diagram of typical USGS streamgage system (Lurry D. L., 2011)

Discharge information is beneficial for developing and calibrating complex mathematical flood models because it indicates how specific streams are likely to respond to rainfall or snowmelt (Mason and Weiger, 1995). Performing discharge measurements is often labor intensive and costly; thus, many streamgages across the state only measure stage (Olson and Norris, 2007).

The USGS operates and maintains all of its streamgages but often receives financial assistance from other local, state, federal, or private entities. The expense associated with USGS streamgages can prohibit collaboration with smaller entities and hinders the expansion of the USGS streamgaging network across the state. In response to these limitations, certain entities in Texas have invested in less costly alternatives to create flood monitoring networks, such as the Automated Local Elevation in Real Time (ALERT) system developed by The National Weather Service in the 1970's (ALERT User Groups 2022). ALERT uses similar gaging technology to the USGS but different data transmission and maintenance methods. Maintenance of ALERT streamgages is left to the discretion of each agency, making this system more affordable. Other systems explored in this report, such as those used in Iowa and Kentucky, are focused on reducing the cost of hardware to create stream stage sensors that are more affordable. These alternative streamgaging systems allow more agencies to create their own flood warning systems and report flood conditions back to operations centers, first responders, and citizens (Department of Homeland Security Science and Technology Directorate, 2018).

STREAMGAGING TECHNOLOGIES

Streamgaging technologies fall into two major categories: technologies that measure stage and technologies that measure discharge. The primary stream stage measurement technologies discussed in this report are bubble gages, pressure transducers, radar sensors, and ultrasonic sensors. Agencies choose specific stage measurement technologies based on factors such as cost, maintenance capabilities, and site characteristics. There are a variety of technologies used to provide estimates of stream discharge. One set of technologies relies on measurements of stream stage, which are used to estimate discharge based on a rating curve that relates stage to discharge. Rating curves are developed by obtaining numerous simultaneous stage and discharge measurements at the location of the gage. A second set of technologies relies on measurements of stream velocity, which are used to estimate discharge based on estimates of flow area multiplied by measured velocity. The primary methods of measuring velocity for discharge calculation are mechanical, electromagnetic, and acoustic current meters, as well as non-contact velocity sensors.

Stage Measurements

There are several different types of stage measurement technologies. This section explores the technologies of bubbles gages, pressure transducers, radar sensors, and ultrasonic sensors. Each technology varies in its advantages and disadvantages in terms of measurement accuracy, upfront costs, and maintenance costs.

BUBBLE GAGES

In the past, bubble gages, or bubblers, were the most common equipment used to measure stream stage (Sauer and Turnipseed, 2010). This instrumentation is configured to measure the water level based on pressure differentials (Sauer and Turnipseed, 2010). A gas is forced through an orifice into the stream at a continuous rate and a fixed elevation for reference. The water pressure at the orifice is transmitted through a glass tube to a pressure sensor and then ultimately converted to a stream stage measurement. Every bubble-gage system requires a pressure sensor, a gas purge system, and a bubble-gage orifice, as shown in Figure 2. The pressure sensors, often non-submersible pressure transducers, are used to measure the pressure differentials caused by forcing the gas through the fixed orifice. They are internally programmed to convert the gas pressure to units of water head, or the feet of water above the sensor, before transmitting the data to the recording equipment, called an electronic data logger (Sauer and Turnipseed, 2010).

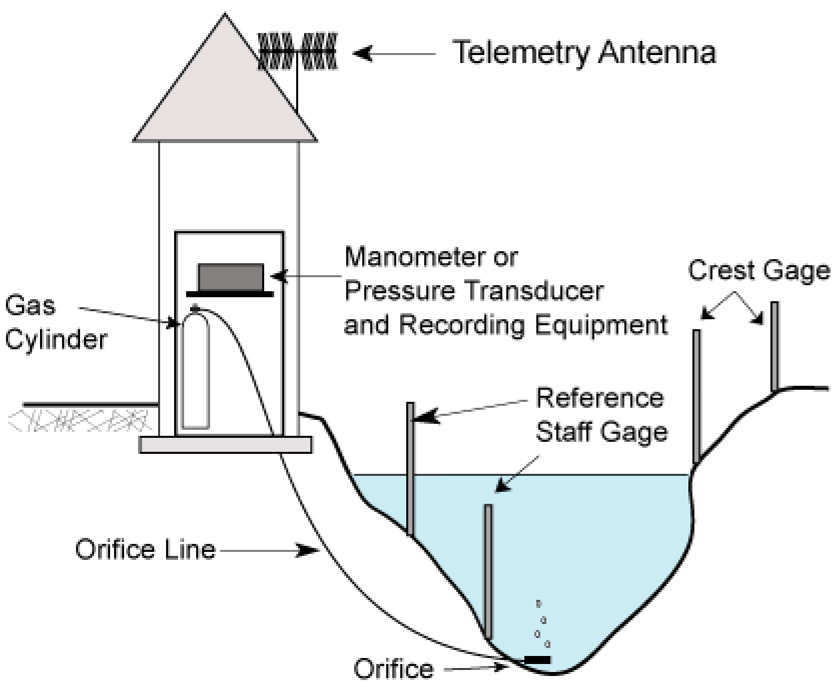

Figure 2: Bubble gage or gas-purge gaging station components (Finney, 2019)

Pressure Transducers

Pressure transducers are often used in conjunction with bubble gages, but they can also be used independently to measure stream stage. Pressure transducers are submersible and are mounted at a set elevation in the stream. The transducer can then convert the water pressure to a measurement of water head (Sauer and Turnipseed, 2010).

Radar Sensors

Radar sensors are a more recent development in stage measurement instrumentation that can measure water surfaces without direct contact. These devices first came on line during the early 2000s (Intergovernmental Oceanographic Commission, 2016). Older technologies such as bubble gages and pressure transducers have traditionally provided data at the level of accuracy required by the USGS; however, installation is difficult and these devices are prone to malfunctioning and getting damaged (Fulford, 2016). Despite some initial concerns regarding radar sensor accuracy, recent tests by the USGS Hydrologic Instrumentation Facility have shown them to meet USGS standards (Fulford, 2016). Radar sensors can be easily mounted to a bridge, handrail, or other stable structure where the radar can face downward towards the water (Sutron, 2015).

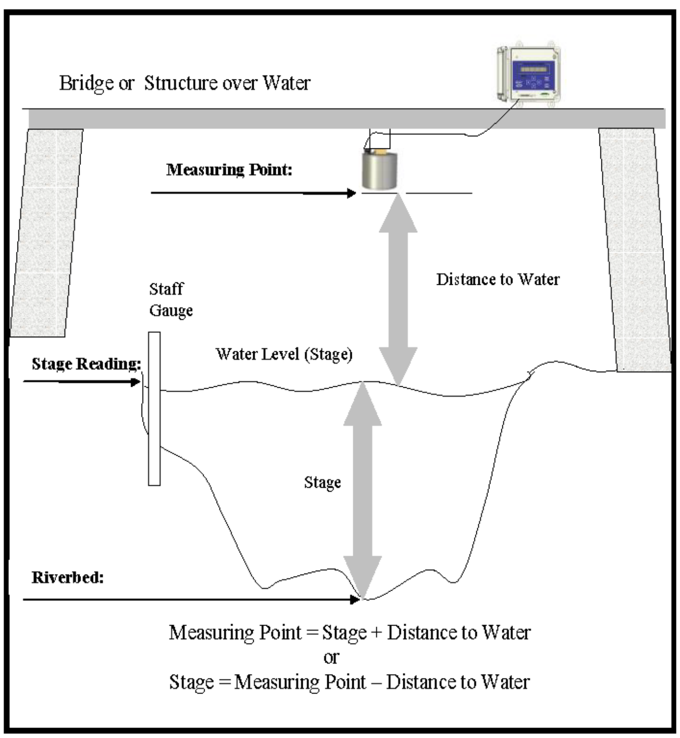

Figure 3: Schematic of radar sensor water level measurement (Sutron, 2015)

The sensor emits a radio wave directed at the water. The wave then reflects off the surface and is directed back at the sensor. The time it takes for the radio wave to return to the sensor is converted into a measure of distance and used to determine the stage of the stream (Figure 3). Radar sensors can be easily programmed to capture continuous measurements of a water level at set time intervals (Sutron, 2015). Due to the sensor's large beam angle, the sensor footprint will be relatively wide across the water surface. To confirm accurate measurements, operators should conduct periodic checks, particularly after large storms to ensure there are no obstructions such as large debris (Sauer and Turnipseed, 2010).

ULTRASONIC SENSORS

Ultrasonic sensors, like radar sensors, are a method of measuring stream stage without direct contact. These sensors operate in the same manner as radar sensors but use ultrasonic waves as opposed to radio waves (Senix, 2022). Ultrasonic sensors are being used widely in Iowa for their Flood Warning System and are used in select USGS gaging locations that are tidally influenced. Commercial ultrasonic sensors are currently not capable of capturing stage measurements to USGS accuracy standards; therefore, applications of the data collected are limited (Weber et. al., 2016). Using a more expensive and elaborate calibration process (the index velocity method), the USGS does use surface velocity measurements made with ultrasonic sensors to monitor flow at tidally influenced and other hard to gage sites (USGS, 2019). The US Department of Homeland Security in collaboration with Charlotte-Mecklenburg Storm Water Services in North Carolina developed ultrasonic sensors for stage measurements that are both affordable and accurate (Charlotte-Mecklenburg Storm Water Services, 2020).

Table 1 includes key aspects of each stream stage measurement technology. The precision, cost, accuracy, and applications of these technologies, along with site characteristics and data needs, determine which is most appropriate for use at a specific location.

Table 1. Product comparison of different stage measurement technologies

	Bubble gages	**Pressure transducers**	**Radar sensors**	**Ultrasonic sensors**
Example of technology				
	OTT CBS	KPSI Model	OTT RLS	ToughSonic 30
Range	0 – 100 ft [1] (0 – 30 m)	0 – 30 PSI[1] (0 - 207 kPa) (69.2 ft H_2O)	0 – 115 ft[1] (0 – 35 m)	0 - 50 ft[3] (0 – 15 m)
Precision	± 0.01 – 0.015 ft[1] (± 0.003 - 0.005 m)	± 0.017 – 0.035 ft[2] (± 0.005 - 0.01 m) 0.1 – 1 percent	± 0.01 – 0.03 ft[1] (± 0.003 - 0.009 m)	0.2 percent of range[1]
Cost (USD)	$3,000 - $5,000[5]	$3,000 - $5,000[5]	$1,000 - $4,000[4]	$450-$1,000[4,6]
Submersible	✓[1]	✓[2]		
Meets USGS accuracy standards[5]	✓	✓	✓	
Application	Surface water, groundwater[1]	Surface water, groundwater[2]	Surface water[1]	Surface water[4]

(1) OTT Website 2022
(2) TE Connectivity Website 2022
(3) ToughSonic Website 2022
(4) Iowa Flood Control 2022
(5) USGS Timothy Rains, written commun., 2018
(6) Whitman Controls 2022

Bubble gages, pressure transducers, and radar sensors are all comparable in purchase cost and accuracy, with radar sensors typically being somewhat less expensive. Ultrasonic sensors are lower in cost but produce data that are less accurate. Ultrasonic and radar sensors are most often used for site locations that include a high bridge to which the sensors can be mounted. These sensors have lower installation and maintenance costs because they are non-contact and are less vulnerable to damages from water or floating debris.

Discharge Measurements

Discharge is sometimes referred to as streamflow and is usually expressed in cubic feet per second (cfs) in the U.S. It is calculated by multiplying measured values of stream channel area by stream velocity. There are various methods and types of equipment used to measure velocity for computing stream discharge, including mechanical current meters, electromagnetic current meters, acoustic current meters, and non-contact velocity sensors.

Mechanical Current Meters

Mechanical current meters, the simplest of all the technologies, measure velocity of streamflow using a wheel of metal cups, or impeller blades, that revolve around a vertical or horizontal axis. The device counts and times the wheel's or impeller's revolutions to determine the water velocity. The Price AA current meter is the most common current meter used by the USGS and has six revolving cups (Turnipseed and Sauer, 2010). Mechanical current meter measurements taken by wading are preferred if conditions permit (Turnipseed and Sauer, 2010). When wading is infeasible, measurements are taken from the top of a bridge or on stationary boats. To measure stream channel area, subsection width is measured using steel tape or a cable and subsection depth is measured using wading rods or sounding weights.

Electromagnetic Current Meters

Electromagnetic current meters measure velocity at specific points by producing a magnetic field and then measuring the electric current produced by water flowing through the field (Jones, 1980). Tests have shown that electromagnetic meters are less accurate than the Price AA mechanical current meters, but one advantage of using these devices is that they have no moving parts (Turnipseed and Sauer, 2010). Performance of electromagnetic current meters depends on the probe shape, location of the electrodes on the probe, and the construction of the meter electronics (Fulford et al., 1994). Velocity measurements are taken by wading, from bridges, or stationary boats. Area measurements are taken using similar methods to those described in conjunction with mechanical current meters.

Acoustic Current Meters

Acoustic current meters use the Doppler Effect to measure velocity and area, sending a sound pulse into the water and measuring the change in frequency of that sound pulse when reflected back to the device. Acoustic Doppler Current Profilers, Acoustic Doppler Velocimeters, and Acoustic Digital Current Meters are all examples of acoustic current meters. The different types of equipment are either mounted onto a moving boat and guided across the water surface to obtain measurements of velocity and area across the channel, or they are mounted to wading rods to take measurements at specific points in the channel. Acoustic meters are typically more expensive than mechanical and electromagnetic meters because the technology is more complex. However, they are easier to use in unsafe stream conditions, take discharge measurements faster, have no moving parts, and produce more accurate results (Turnipseed and Sauer, 2010). Using acoustic meters also enables discharge measurements to be made in some flooding conditions that would not be possible with mechanical or electromagnetic meters.

NON-CONTACT VELOCITY SENSORS

Non-contact velocity sensors are an additional method of measuring stream velocity that can be used to collect streamgage data remotely. These sensors are often radar sensors set to target the surface of the water at an angle, and the frequency reported by the sensor determines the velocity of the water at the surface of the stream (HyQuest Solutions America, 2022). Initial measurements of the stream cross section and average stream velocity are made using an acoustic dopplercurrent profiler. Using both the acoustic doppler current profiler and the velocity sensors, a relationship is developed between the surface water velocity and the average stream velocity; as the sensor measures surface velocity, an average stream velocity is predicted (David Maidment, UT Austin, oral commun., 2018). Once the stream velocity is determined, it can be multiplied by the known measured cross-sectional area to determine discharge (David Maidment, UT Austin, oral commun., 2018).

Velocity sensors are low maintenance, as there are no moving parts, and the non-contact equipment mounted above expected flood levels is less likely to encounter damages. Additionally, they can take measurements at regular time intervals without the presence of field technicians to run the equipment, ultimately reducing the cost of operations and maintenance (Matt Ables, KISTERS, oral commun., 2018).

Velocity sensors are accurate in their measurements of surface water velocity, but their predictions of average stream velocity can be less accurate than those of current meter technologies if the equipment is not calibrated regularly (Matt Ables, KISTERS, oral commun., 2018). Unlike current meters, a rating curve is not typically developed when using a velocity sensor since the senor can take continuous measurements. Though not as accurate as the USGS methodology of developing rating curves in connection with current meters, using velocity sensors is still beneficial for certain applications such as flood warning (Matt Ables, KISTERS, oral commun., 2018).

Table 2 provides examples of commercially available discharge measurement technologies.

Table 2: Examples of different discharge measurement technologies

	Mechanical current meter	Electronic current meter	Acoustic current meter	Acoustic current meter	Non-contact radar sensor
Example technology	Price AA Current Meter[1] 	Marsh-McBirney Model 2000 electromagnetic meter [1] 	SonTek/YSI FlowTracker ADV[1] 	Teledyne RD instruments rio grande ADCPs[2] 	RG 30 non-contact radar[2] 

(1)Turnipseed and Sauer, 2010
(2)Teledyne Marine RD Instruments, 2022

Stage-Discharge Relationship (Rating Curves)

A rating curve represents concurrent measurements of stage and discharge, as shown in Figure 4. It is produced by making frequent discharge measurements at various stage heights for a given streamgaging location. Rating curves are unique to each location and often change over time because each curve depends on the changing hydraulic characteristics of the river (Olson and Norris, 2007).

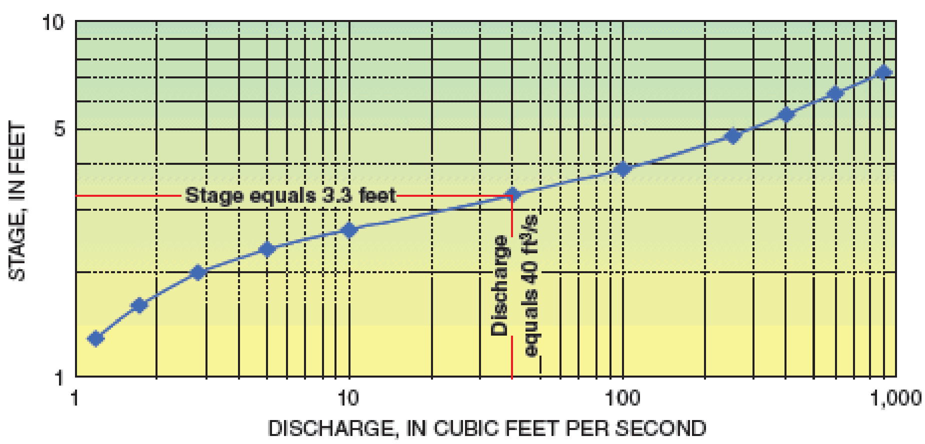

Figure 4: Typical stage-discharge relationship (Olson and Norris, 2007)

The USGS is the primary entity that develops rating curves at streamgaging locations in Texas, though some other entities also develop curves, including the Lower Colorado River Authority and the Harris County Flood Control District. To develop a rating curve, physical measurements of the stream velocity at different stream stages must be taken at a gage site.

Once the rating curve is developed, a discharge measurement can be predicted for every stage measurement. The USGS performs stream discharge measurements to update rating curves every six to eight weeks for most streamgages (USGS, 2018), ensuring that the range of stage and flows at the streamgage are measured regularly (Olson and Norris, 2007). Special efforts are made to measure extremely high and extremely low stage measurements as they occur less regularly (Timothy Raines, USGS, written commun., 2018).

DATA TRANSMITTING SYSTEMS

Multiple methods exist to transmit data from streamgages. Methods used for data transmission, which include radio, satellite, and cellular, vary from entity to entity. Larger agencies that have networks covering larger areas typically use satellite transmissions, while more local streamgaging networks typically stick to radio. At least one agency, the City of Austin, operates different gages with both radio and cellular services, where one system is used for flood early warning and another for water quality research, respectively. Cellular networks are a newer form of hydrological data transmission and are currently used for transmitting streamgaging data by a few agencies in Texas, including the Texas Department of Transportation.

RADIO NETWORKS

Many systems, including those of ALERT and ALERT 2™ users and the Lower Colorado River Authority, transmit data through radio networks. ALERT 2™ differs from ALERT in that it is a more recently upgraded system and is faster and more accurate than the previous version. ALERT 2™ is also a trademark of the National Hydrologic Warning Council (National Hydrologic Warning Council, 2022). Radio networks are beneficial because they can transmit data without a direct connection. The U.S. government owns a range of frequencies that are protected specifically for the transmission of hydrologic data (Markus Ritsch, Water & Earth Technologies, oral commun., 2018). Agencies may access these frequencies and transmit data collected from streamgages back to their base stations. All radio networks are line-of-sight networks, meaning that they apply to a limited distance, typically around 40 miles (64 km) (Markus Ritsch, Water & Earth Technologies, oral commun., 2018). Radio transmission requires a clear path between antennas, so connections at longer distances are more difficult to make due to greater disruptions. Short range radio transmitters can be used to send data from a stage sensor, such as a bubble gage, to a data logger (Sauer and Turnipseed, 2010). Figure 5 provides a schematic of an example radio data transmission system.

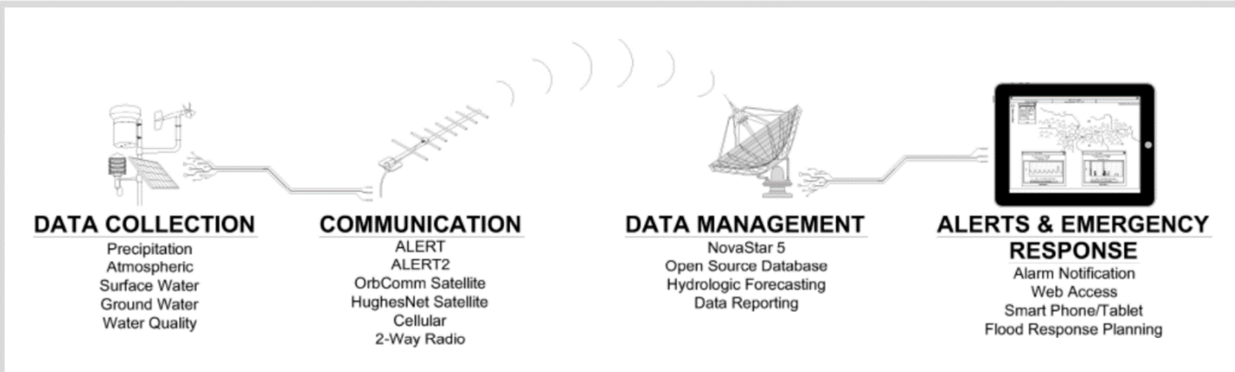

Figure 5: Data transmission of ALERT 2TM networks (Trilynx, 2022)

Agencies often operate radio networks across one or several specific frequencies. ALERT 2™ systems use the time division multiple access (TDMA) protocol in which each transmitter is assigned specific times to transfer information so that data is not lost when transmitters operate on the same frequencies (OneRain, 2018).

Satellite Networks

Similar to radio networks, the U.S. government owns satellite frequencies that are protected for the specific purpose of transmitting hydrologic data (Markus Ritsch, Water & Earth Technologies, oral commun., 2018). The USGS and the International Boundary and Water Commission use the Geostationary Operational Environmental Satellite transmission system to broadcast stream stage data, allowing them to provide regular stage and discharge data to the public. With satellite networks, information is typically not collected and transmitted in real time. Rather, information is collected and stored before being transmitted in as little as 15-minute intervals and as long as hourly intervals.

Satellite networks use higher frequencies that are more powerful than other radio waves and allow them to concentrate all available power into a narrow beam. (Northwestern University 2022). A schematic of a satellite-based data transmission system is displayed in Figure 6.

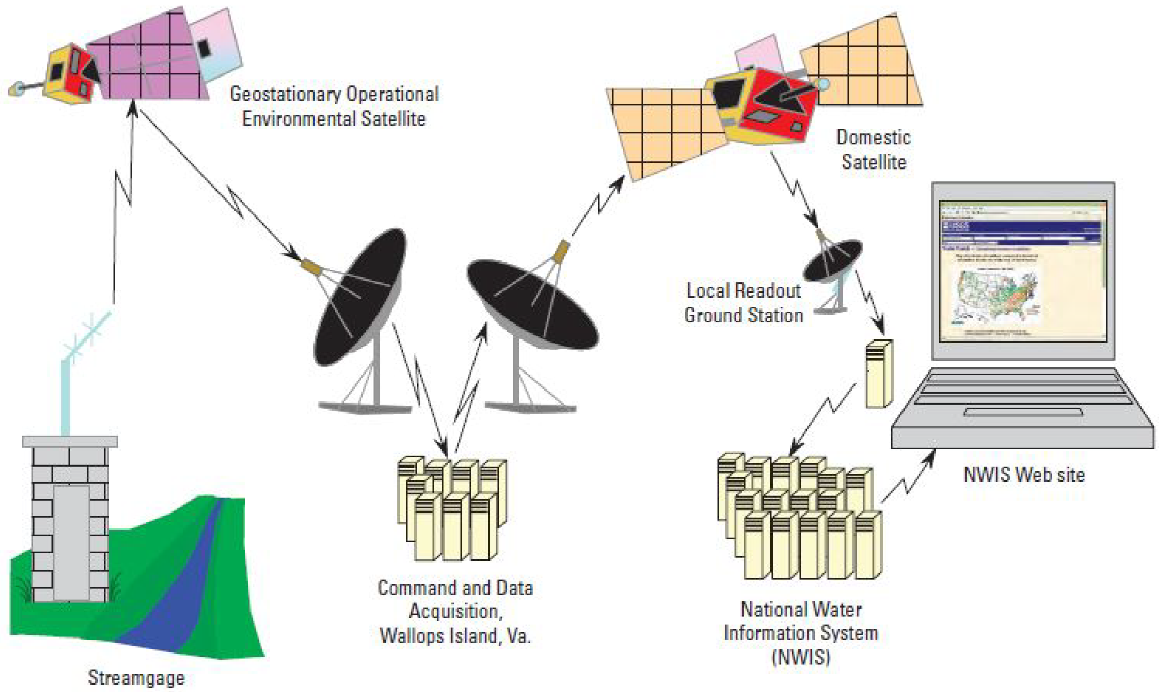

Figure 6: Schematic of the USGS hydrological data flow (Sauer and Turnipseed, 2010)

Cellular Networks

Alternatively, agencies can use cellular networks to transmit hydrological data. Connecting streamgages to cellular networks is a relatively simple and inexpensive process, and no license is required to access the network. Instead, cellular network transmission requires data plans and monthly fees paid to cellular companies (David Maidment, UT, oral commun., 2018). For example, the Iowa Flood Center uses cellular plans for each sensor to transmit data by connecting a cellular modem to each streamgage. The system utilizes 2G networks where each sensor is on a 5MB per month cellular plan (Weber et al., oral common., 2018).

Although these systems are unable to transmit data when cellular networks fail, they have become more resilient and dependable over time.

STREAMGAGING NETWORKS IN TEXAS

Texas has several large agencies that have established streamgaging networks. The USGS, LCRA, City of Austin and International Boundary and Water Commission are agencies that have reliable and accurate stage and discharge data available for public viewing. ALERT and ALERT2™ networks are also well established in Texas with seven known agencies who have set up networks which they each individually fund and maintain. ALERT/ALERT2™ networks are more affordable for smaller agencies to participate in as opposed to partnering with the USGS. These networks use technology capable of collecting data to meet USGS accuracy standards.

U.S. Geological Survey Water Data Network

The USGS streamgage network contains over 750 gages at locations across Texas that collect stage and often flow data for rivers and streams. Over 150 additional gages are located on lakes and reservoirs that monitor water levels in larger bodies of water. The USGS utilizes rating curves to measure stream flow and visits each field site every six to eight weeks to ensure accurate rating curve calibration and flow estimates. They use a variety of different technologies to measure stage, including bubble gages, pressure transducers, and radar sensors as well as current meters or acoustic doppler current profilers to measure stream velocity for flow estimates.

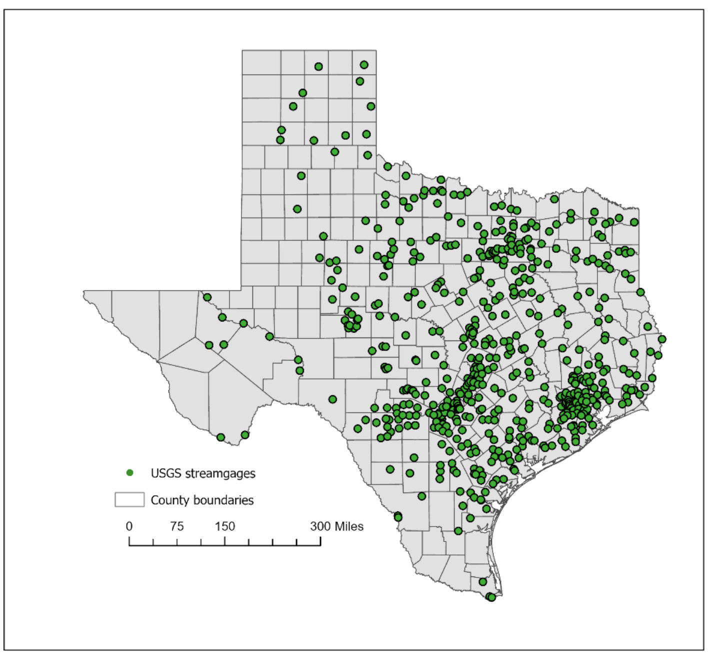

Figure 7: Map of all USGS streamgaging locations in Texas (2022)

The USGS collects, stores, and provides data in accordance with the agency's internal standards (Sauer 2002, Sauer and Turnipseed 2010) and international standards set by the World Meteorological Organization (World Meteorological Organization 2010a, World Meteorological Organization 2010b). All data are required to be accurate to the nearest 0.01 foot or 0.2 percent of stage height, whichever is greater or a more conservative number. Each measurement is taken at 15-minute intervals and automatically updated through their online, publicly accessible platform. Because the USGS network contains a centralized repository of data from each streamgage, this information can easily be made available to the public. These data are currently available on the USGS website as well as on TexasFlood.org at map.texasflood.org (USGS 2022b, USGS 2022c, Texas Natural Resources Information System, 2022).

Many of the sites operated and maintained by the USGS are done so in partnership with other entities. Some entities fund streamgaging locations entirely, while others only contribute a small amount (Timothy Raines, USGS, written commun., 2018). Partners include the Texas Water Development Board (TWDB), the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, various river authorities, and cities across the state. Other entities that cannot help with funding gages are able to utilize USGS data for local flood monitoring purposes. Additionally, the National Weather Service uses USGS streamgaging data to help forecast statewide weather conditions.

USGS streamgages can be an expensive gage option due to the upfront costs for calibration and installation of a site, as well as the annual maintenance fee required to calibrate and estimate flow. In Texas it costs approximately $55,000 to purchase and install a single flood-hardened gage and an additional $17,000 annually to keep up with maintenance and calibration (TWDB, 2022).

Lower Colorado River Authority Hydromet

The Lower Colorado River Authority (LCRA) hosts a public-facing streamgaging network called Hydromet that shares data from over 200 streamgaging locations across the state of Texas. The LCRA owns 105 of the streamgage stations, and the remaining sites are owned by the City of Austin, as shown in Figure 8. The USGS operates and maintains roughly 30 of the LCRA-owned gages, while the remainder are operated and maintained by the LCRA (David Murdoch, LCRA, written commun., 2018).

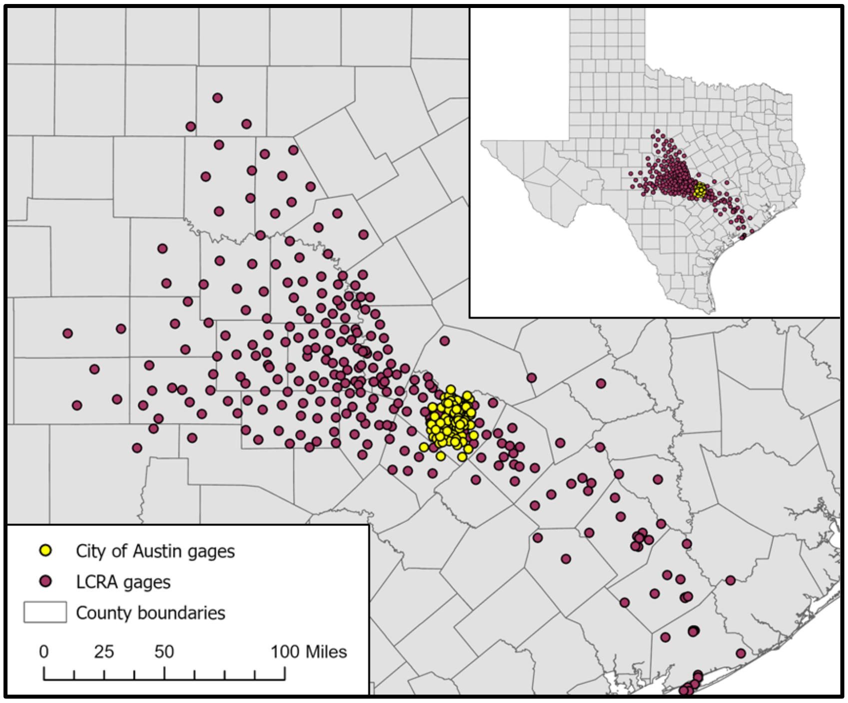

Figure 8: Map of LCRA and City of Austin streamgaging locations (2022)

The LCRA predominantly takes stage measurements at each of their streamgages but also collects precipitation and flow measurements at some locations. All data obtained are to USGS accuracy standards (David Murdoch, LCRA, written commun., 2018), and the LCRA develops their own rating curves for gage locations where they collect flow measurements. While the USGS aims to take discharge measurements at gaging locations every six weeks (USGS 2022c), the LCRA performs these measurements roughly three times per year. If precipitation is unusually high in a given year, the LCRA will take additional measurements to improve their rating curves.

Stage measurements are taken using pressure transducers, while discharge is measured with current meters using acoustic doppler current profilers or acoustic doppler velocimeters.

(David Murdoch, LCRA, written commun., 2018). LCRA streamgages are comparable to the cost of USGS gages at approximately $50,000 for installation of a single gage and $15,000 for annual maintenance (David Murdoch, LCRA, written commun., 2018).

Once the data are collected, the information is transmitted through the LCRA's Open Sky radio network, a line-of-sight radio system used to transmit data. The City of Austin owns and operates eight of its own streamgages. While they perform their own maintenance, repairs, and management of all of their field hardware, they utilize the LCRA Hydromet to retrieve their streamgage data and display it on their public facing webpage (hydromet.lcra.org/coa) (David Murdoch, LCRA, written commun., 2018).

International Boundary and Water Commission Network

The International Boundary and Water Commission's jurisdiction extends along the United States-Mexico border where the two countries have international projects. The commission is responsible for settling differences that may arise in the application of boundary and water treaties (International Boundary and Water Commission, 2022). The 1944 Water Treaty requires the commission to keep record of all Rio Grande waters belonging to each country. Through this treaty, the agency is tasked with regulating and conserving the waters of the Rio Grande and operating and maintaining the international reservoirs on the Rio Grande (Water Treaty, 1944).

As of September 2022, the commission operates 58 gaging stations that measure both stage and discharge. The International Boundary and Water Commission, like the USGS, uses Geostationary Operational Environmental Satellite telemetry for data transmission. The commission provides provisional data through their publicly accessible website (ibwc.gov/Water_Data/rdata.htm). These data are also used by the National Weather Service to aid in weather forecasting and flood modeling.

ALERT Users Group Network

ALERT was created by the National Weather Service in the 1970's for the purposes of flood warning and environmental monitoring (Van Wie, 2011). This system has since been upgraded by the National Hydrologic Warning Council to the current ALERT 2™ system (Van Wie, 2011). ALERT systems typically measure stage and precipitation, and can be programed to only transmit data when water levels reach a specific depth, when water levels change drastically within a particular interval, or when precipitation occurs at a certain intensity. ALERT 1 is a one-way broadcast transmission protocol that does not include error detection or correction. ALERT 1 data packets are susceptible to corruption and/or data packet loss due to very high frequency (VHF) bandwidth saturation, meaning large amounts of data are being sent across the same frequency simultaneously. This makes it difficult for the data receiver to collect all data at once and results in some data being lost. The ALERT 2™ protocol was developed to overcome the problems inherent in ALERT 1. ALERT 2™ uses time division multiple access to coordinate data transmissions from remote stations and includes error detection (Van Wie, 2011). With ALERT 2™ systems there is no data loss due to simultaneous data signals being received at the same time.

Both ALERT 1 and ALERT 2™ systems are licensed to use very high frequency radio. When an agency sets up an ALERT system, it can access and transmit data using specific frequencies. ALERT ensures systems that are in close proximity to each other operate at different frequencies to avoid data obstruction (Markus Ritsch, Water & Earth Technologies Inc., written commun., 2018). ALERT 1 and ALERT 2™ systems report data in real-time; in other words, as a streamgage takes a measurement, the gaging station will initiate data reporting (Markus Ritsch, Water & Earth Technologies Inc., written commun., 2018).

Participating state and local agencies must own the rights to operate specific radio frequencies to transmit data, and they must purchase streamgage hardware and software infrastructure to be part of an ALERT system. The hardware used at streamgaging stations may include bubble gages, pressure transducers, and radar sensors if a bridge is present. ALERT systems can also include precipitation gages, weather stations, and water quality stations. All gaging equipment used produces results that achieve USGS accuracy standards. Additionally, all equipment is open source, so any type of software can operate in conjunction with any type of hardware (Markus Ritsch, Water & Earth Technologies Inc., written commun., 2018).

Many agencies choose to use ALERT systems because they involve a one-time set up fee for the installation of the software and allow an agency to install and connect up to 1,000 gages to their networks at no additional cost. The initial set up fee is roughly $60,000, and the installation of a single gage ranges from $10,000 for precipitation gages to $20,000 for streamgages. Gage installation costs generally include identifying necessary hardware, engineering the set-up for site-specific conditions, purchasing the equipment, and installing the gaging station (Markus Ritsch, Water & Earth Technologies Inc., written commun., 2018). Agencies in Texas using ALERT systems include the City of Dallas, the City of Fort Worth, Fort Bend County, Hays County, the City of Grand Prairie, the San Jacinto River Authority, Jefferson County Drainage District 6, and the Harris County Flood Control District. The Harris County Flood Control District maintains an interactive flood warning system map which displays data from local ALERT 2™ gages (harriscountyfws.org). A map of some ALERT 2™ streamgaging locations across Texas is shown in Figure 9.

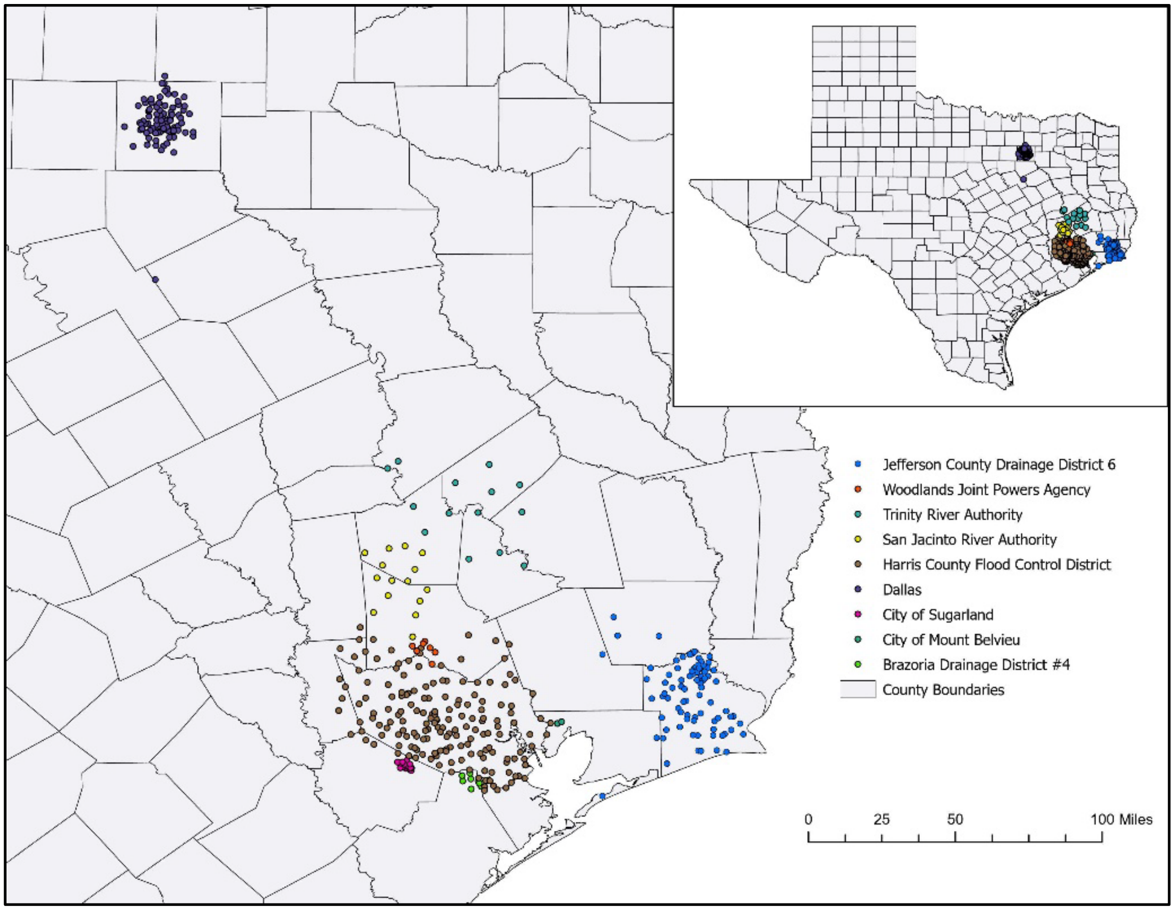

Figure 9: ALERT 2™ User Group streamgaging locations in Texas (2022)

ALERT systems are often a more affordable option than contracting with the USGS for streamgage installation and maintenance. Individual agencies retain ownership of the infrastructure and can reduce associated service costs. Operation and maintenance of the system is left at the discretion of each agency. As such, some partners may perform infrequent maintenance on gaging stations to reduce costs, which may decrease the reliability of data produced from these systems (Markus Ritsch, Water & Earth Technologies Inc., written commun., 2018). With no centralized structure in place to regulate gage maintenance, it is difficult to determine the quality of data resulting from ALERT networks.

ALTERNATIVE GAGING OPTIONS

Various agencies both in Texas and across the country have developed alternative options for streamgaging and flood monitoring. Rice University and the Texas Medical Center created a flood warning system that focuses streamgaging and flood modeling efforts at a local level. The Texas Department of Transportation (TxDOT), in collaboration with the University of Texas at Austin, completed a pilot project in 2019 that created a low-cost streamgaging network that incorporates radar sensors that are anticipated to reduce annual maintenance costs. The Iowa Flood Center has a well-established network of ultrasonic sensors across the state used to measure stream stage. These sensors are low in cost, allowing for coverage of more locations. Since 2016, the US Department of Homeland Security has been working with business partners on developing an inexpensive wireless stage measurement sensor that will reduce hardware installation and maintenance costs but will also perform to USGS standards (Department of Homeland Security Science and Technology Directorate, 2018).

Rice University and Texas Medical Center Network

Rice University and the Texas Medical Center have created a flood warning system in Houston's Texas Medical Center and surrounding areas to protect infrastructure, the public, and hospital residents from potential floods. The system contains web-based maps that allow users to see how predicted floods will impact neighborhoods, streets, and buildings in the Brays Bayou watershed (Bedient, 2018). Three different iterations of the web-based flood alert system have been developed with the goal of making real-time flood warnings accessible and easily understandable by the public. The models utilize land use and soil classification data to characterize the watershed while incorporating stage, flow, and precipitation data to determine the likelihood and severity of floods (Bedient, 2018).

This system is highly accurate (80 – 90 percent) in predicting peak water flows and timing. It has also successfully predicted flood levels for more than 40 storms. Each prediction generally provides two to three hours of lead-time prior to maximum flood conditions, allowing emergency and hospital personnel to mitigate losses (Bedient, 2018).

Texas Department of Transportation Network

The Texas Department of Transportation (TxDOT) has led several projects that help with flood warning, including road monitoring, USGS gaging partnerships, and a pilot gaging project with the University of Texas at Austin (UT Austin). TxDOT maintains a public-facing website, DriveTexas.org, that is used as a communication tool for all highway conditions. Conditions include construction, road damage, and flooded roads, all of which are updated in real-time. TxDOT has an inter-agency agreement with the USGS on roughly 60 gages throughout west Texas, all of which are operated and maintained by the USGS (David Maidment, UT Austin, oral commun., 2022). Figure 11 shows a screenshot of the Drive Texas website illustrating flooding in Edinburg TX.

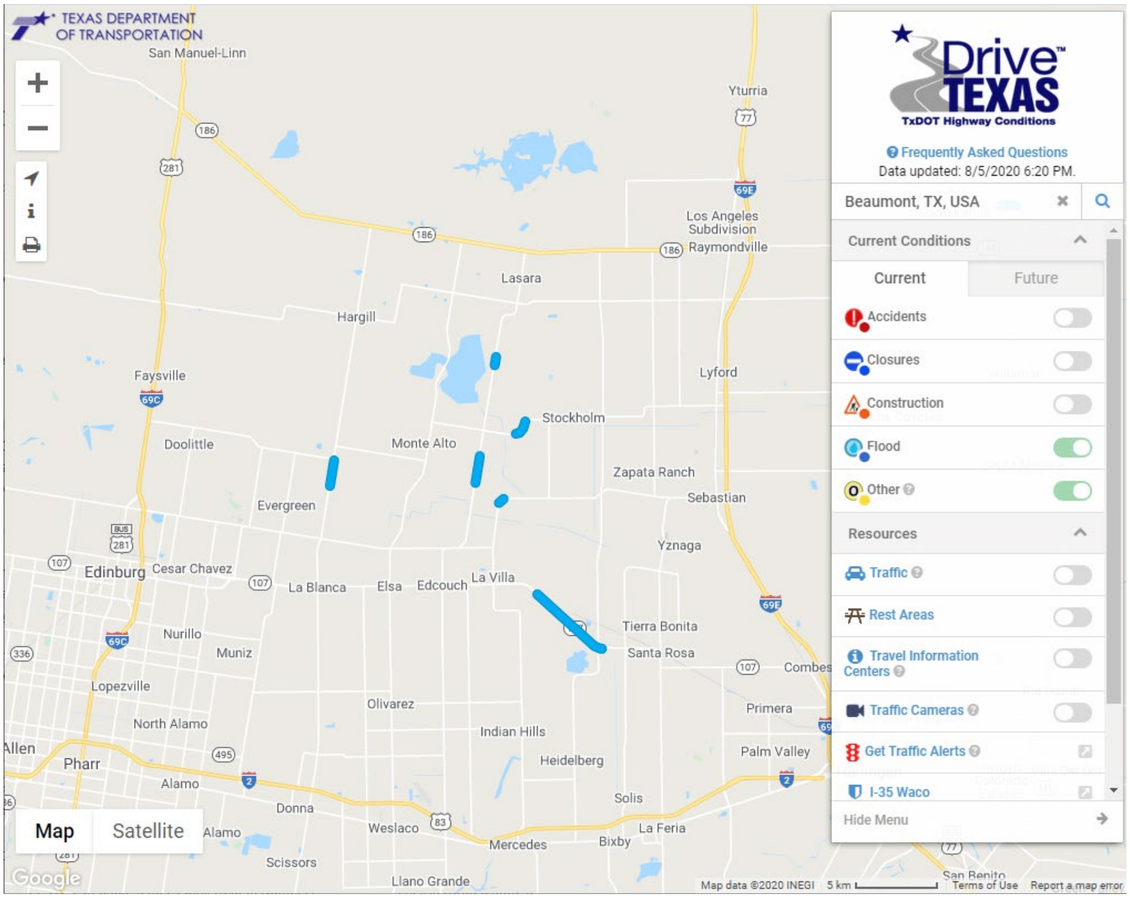

Figure 10: Drive Texas map. The blue lines represent flooded roads. (TxDOT 2021)

From 2017 to 2019 TxDOT partnered with UT Austin on a pilot project that involved the installation of 20 streamgages along Interstate Highway 10 from San Antonio to Beaumont, Texas. From 2020 to 2023, a second streamflow measurement project is being undertaken which extends the coverage to 80 gages with all the gages being installed and operated by the USGS. Figure 12 shows a map of the streamgage locations, which are roughly evenly distributed across TWDB riverine and coastal drainage basins. All gages are non-contact sensors, specifically RQ 30 models from HyQuest Solutions America (David Maidment, UT Austin, oral commun., 2022). These sensors have the ability to measure both stage and velocity and provide the information necessary to calculate discharge. Gages from this pilot project are connected via a cellular network and are able to provide real-time data updates. The gages produce water elevation data accurate to two millimeters (David Maidment, UT Austin, oral commun., 2022).

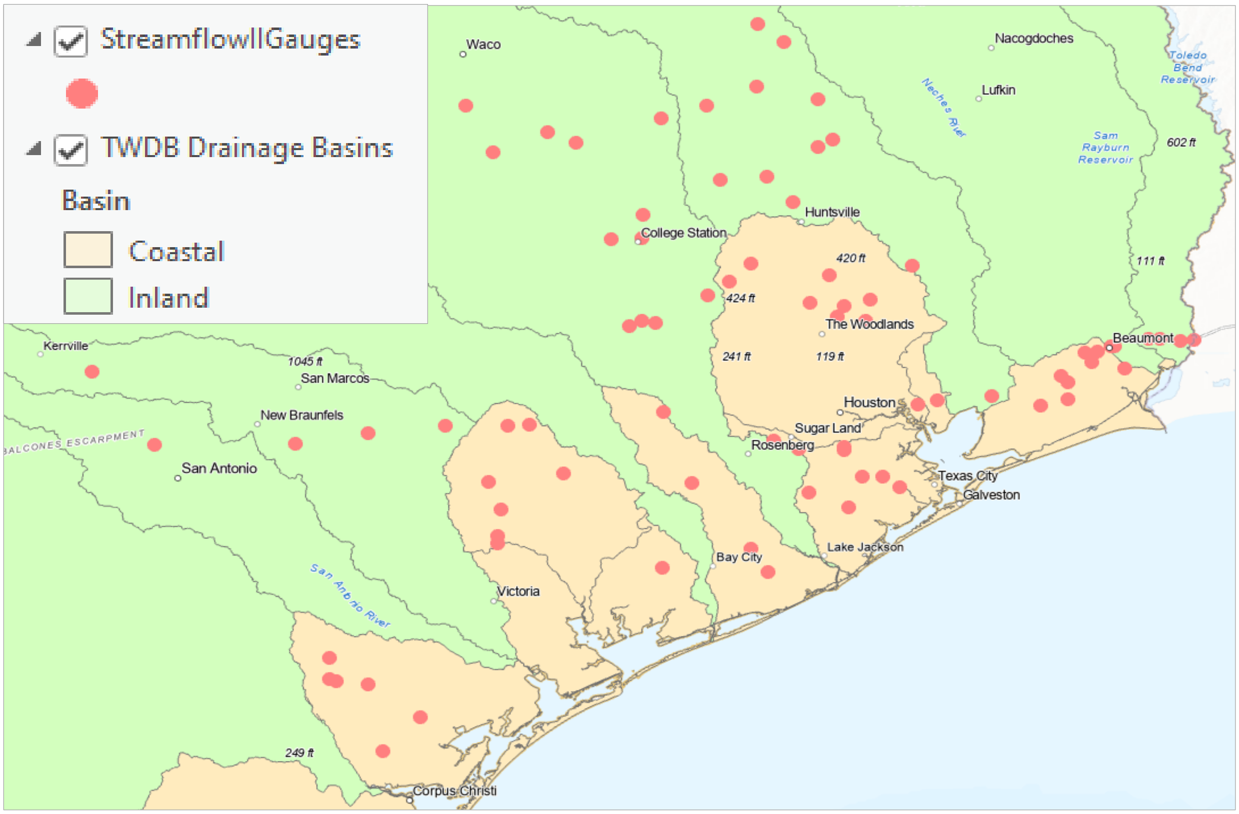

Figure 11: Location of TxDOT radar streamflow gages and TWDB drainage basins

(Maidment, 2022)

The purpose of this pilot is to create a streamgaging network that could serve as a model for flood warning and response for other Texas roadways. The goal of this project is to test if using less expensive radar gages and lidar data to create stream cross sections could provide comparable results to USGS streamgages. Data from the project are intended to supplement measurements from other gages in the state to better inform the flood predictions of the National Weather Service, and also have the potential to be useful for National Weather Service River Forecast Centers. TxDOT found the radar gages coupled with lidar data for stream cross sections to be useful indicators for predicting road inundation.

Iowa Flood Center

In 2010, the Iowa Flood Center began designing and building what is now a network of 250 streamgage stations across the state of Iowa. Through internal research efforts, the Iowa Flood Center created its own stage monitoring system using in-house expertise (L. Weber and others, Iowa Flood Center, oral commun., 2018).

Iowa Flood Center streamgages incorporate the use of ultrasonic sensors, 6-watt solar panels, reusable desiccant, lead-acid batteries, cellular modems, GPS sensors, LED lights, and data loggers. Each station is durable and located on a bridge to allow the sensor to accurately gauge the water level. These sensors are relatively easy to install and require minimal maintenance. The sonar signal is used to measure the distance from the water surface to the sensor and data is transmitted via a cellular modem every 15 minutes (L. Weber and others, Iowa Flood Center, oral commun., 2018). The data is then displayed on the Iowa Flood Information System's public website which utilizes an interactive Google Maps-based tool (ifis.iowafloodcenter.org).

Although variables such as water level, distance, and temperature can impact the accuracy of these instruments, the Iowa Flood Center uses ultrasonic sensors rather than radar sensors because they are cheaper, require less power, and ultimately reduce overall costs to the system (L. Weber and others, Iowa Flood Center, oral commun., 2018). The Iowa Flood Center does not measure discharge. They instead collect stage information only, as this information is cheaper to obtain and still provides valuable data for community flood predictions and modeling efforts. These models can predict how a flood wave will travel through local landscapes and illustrate the extent of flooding under different conditions (Iowa Flood Center, 2022). Community members can access Iowa Flood Center models and maps online to see how flooding events are likely to affect their communities, homes, and businesses (Iowa Flood Center, 2022).

Department of Homeland Security's Science and Technology Directorate Low-Cost Flood Sensors

From 2018 to 2020, the Department of Homeland Security's Science and Technology Directorate worked with small business partners to develop and test a network of inexpensive, easily deployable flood inundation sensors. The sensors are part of a wireless mesh network that can rapidly measure rising water levels. They are intended to provide a less expensive alternative to existing streamgaging technologies that will provide reliable data. Business partners included Evigia Systems Inc., Physical Optics Corporation, and Progeny System Corporation (Department of Homeland Security Science and Technology Directorate, 2018). These partners developed ruggedized, submersible, and deployable prototype flood sensors able to function in different environments.

During the summer of 2019, the Department of Homeland Security installed 93 sensors across Mecklenburg County, North Carolina, to monitor flooding. These sensors were designed to measure the stage and velocity of the water in stream systems, and, in part, to better understand when failures such as overtopping and erosion could occur. Each sensor is estimated to cost less than $1,000, providing drastically lower equipment costs for streamgaging stations. The sensors proved to be accurate within expected tolerance ranges, providing acceptable accuracy levels for general flood monitoring and flood warnings. The researchers did, however, experience issues with low battery voltage, site-specific damage (such as in-stream debris, fallen trees, etc.), and vandalism. For these reasons, the researchers recommend regular site checks to ensure the sensors are working properly (Charlotte-Mecklenburg Storm Water Services, 2020).

COST ANALYSIS

The majority of streamgaging networks utilize similar streamgaging technologies, making the costs of hardware comparable between agencies. The difference in costs of networks depends on the logistics of obtaining data, maintenance requirements, and additional fees for contracting out specific responsibilities. A cost comparison of different streamgaging networks can be viewed in Table 3.

Table 3: Cost estimations of streamgaging networks (2018 dollars)

Network	Hardware and installation	Network connection and data transmission per gage	Monthly web and radio hosting service fees	Annual maintenance
ALERT 2™ Users Group(7)	$20,000	$30,000-$60,000 one-time payment for up to 1,000 gages	Varies depending on agency	$200-300
USGS Water Data(8)	$55,000	NA	(owned)	$17,000
Iowa Flood Center(9)	$3,500	$84	(owned)	NA
City of Austin FEWS(10)	$6,800	$120	$9,700	$900
LCRA Hydromet(11)	$50,000	$2,000	(owned)	$15,000

(7) Markus Ritsch, Water & Earth Technologies, written commun., 2018
(8) Timothy Raines, USGS, written commun., 2018
(9) L. Weber and others., oral commun., 2018
(10) Scott Prinsen, City of Austin, written commun., 2018
(11) David Murdoch, LCRA, written commun., 2018

Variation in cost depends largely on whether discharge measurements are being performed at a given site in order to develop rating curves. This type of data collection requires significantly more maintenance, calibration, and attention per site, ultimately increasing the total cost of the gaging station. Both the USGS and the LCRA develop rating curves at most of their streamgaging locations to obtain discharge estimates, and this is the primary cause for increased hardware installation and annual maintenance costs for these systems.

Additional costs are associated with creating an independent network or contracting with other entities to gather streamgage data. For example, the City of Austin owns and operates all of its streamgages but pays the LCRA $9,700 per month to connect their gages to the LCRA's radio network to transmit and host their data. This relationship is similar to that of entities that pay for a USGS gaging station, as the USGS' annual maintenance costs include fees associated with transmitting and hosting streamgaging data.

The ALERT 2™ users' group can create their own networks for a one-time fee. After the initial set up, they may connect additional gages to their network at no cost. However, ALERT 2™ users must identify their own type of web platform to display data to the public, and these platforms vary in cost. ALERT 2™ also has a low annual maintenance cost in comparison to the LCRA or the USGS networks because the majority of ALERT 2™ gages only measure stage. Those that also measure discharge would require significantly higher maintenance costs. It is also important to note that annual maintenance costs are at the discretion of the partner agency. Some agencies may contribute ample funds and time to ensure their gages are well-maintained and calibrated properly, and other's may not. This causes variation in data reliability, and there is no method to determine the accuracy levels of various ALERT 2™ gages.

By comparison with the USGS, the LCRA's, and Iowa Flood Center's streamgaging networks are significantly lower in cost. This difference results from the use of less expensive technologies that requires relatively lower maintenance.

CONCLUSION

There are many different entities in Texas performing streamgaging for the purposes of flood warning and environmental monitoring. The USGS, the LCRA, and the International Boundary and Water Commission not only use state-of-the-art technology but also perform frequent maintenance checks on their equipment and work to develop accurate, well-calibrated rating curves to estimate discharge. ALERT 2™ user groups utilize the ALERT 2™ protocol to create personalized streamgaging networks with varying levels of data accuracy based on the extent of maintenance performed. Other systems, such as those developed by TxDOT, Rice University and the Texas Medical Center, and the out-of-state Iowa Flood Center, use alternative streamgaging approaches with different types of technologies and methods for developing flood models.

Various technologies are utilized across the state to measure stream stage. Bubble gages, pressure transducers, and radar sensors are all accurate stage measurement technologies with fairly comparable costs. Ultrasonic sensors are less expensive, though often not as accurate. Various methods and types of equipment are also used to measure velocity for computing stream discharge, including mechanical current meters, electromagnetic current meters, acoustic current meters, and non-contact velocity sensors. Discharge measurements developed through rating curves are extremely accurate but labor and cost intensive. New approaches advanced by TxDOT and the Iowa Flood Center use radar sensors to measure stream velocity have the potential to predict discharge accurately, remotely, and with minimal maintenance requirements.

The various methods of data transmission available – satellite, radio, and cellular – do not appear to differ drastically in price or effectiveness, though they have different implications for network accessibility. Tapping into satellite telemetry or radio frequencies must be done via government agencies, but cellular networks can be accessed by purchasing a data plan through a telecommunications company.

Most streamgaging networks across the state present their monitoring information online through publicly accessible websites. Though there is currently no single common platform for information from all streamgaging networks across Texas to be viewed simultaneously, various efforts are underway across the state to improve the accessibility of Texas water data and make visualizing information on river conditions easier. While compiling and visualizing streamgaging data from all entities in Texas that gather it in a single location is a technically complex task, doing so has the potential to improve public consumption of weather forecasts and flood warnings.

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