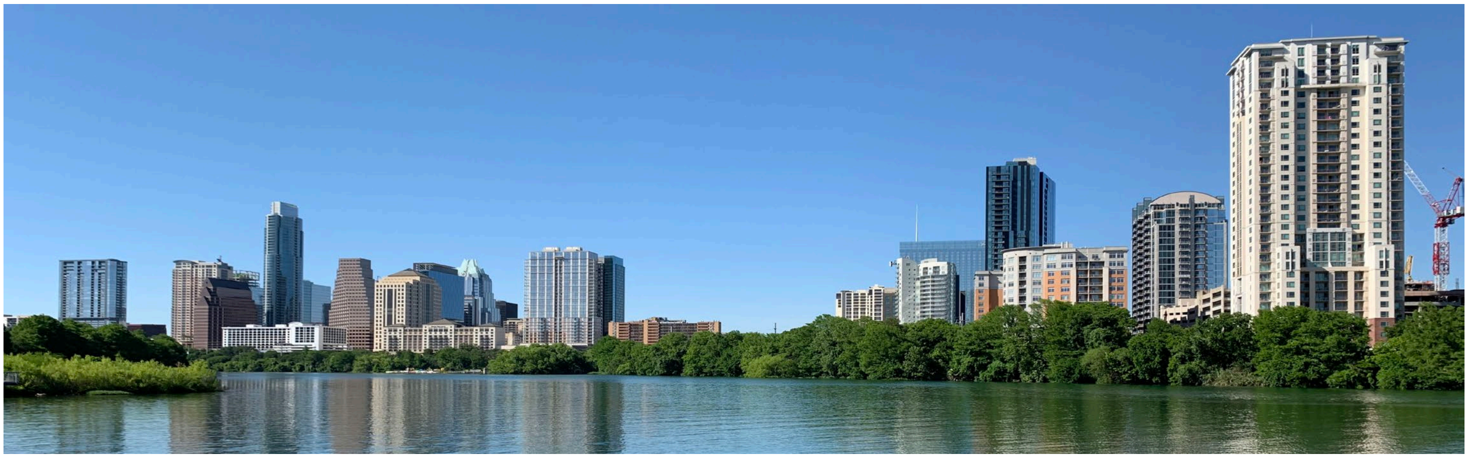

Flood Early Warning Systems (FEWS) Guidance Document

for Texas

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List of Acronyms

ALERT	Automated Local Evaluation in Real Time
CPI	Consumer Price Index
FEMA	Federal Emergency Management Agency
FEWS	Flood Early Warning Systems
FIF	Flood Infrastructure Fund
GLO	(Texas) General Land Office
InFRM	Interagency Flood Risk Management (team)
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
O&M	Operations and Maintenance
QPF	Quantitative Precipitation Forecast
TDEM	Texas Department of Emergency Management
TWDB	Texas Water Development Board
TxDOT	Texas Department of Transportation
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WMO	World Meteorological Organization

Executive Summary

Effective Flood Early Warning Systems (FEWS) are essential to reduce the flood impacts on Texas communities. Many flood events, including recent billion-dollar flood events[1], have not only highlighted vulnerability across the state but also increased interest in FEWS as a non-structural mitigation tool for Texas communities. This is in part due to their life-saving functions, such as rainfall and river level monitoring, real-time flood forecasting, and/or inundation mapping, while remaining relatively low-cost compared to other structure-related mitigation solutions. The vital functions of FEWS can enhance the ability of emergency personnel to save lives through informed decisions, and help residents, visitors, and business owners evacuate or secure properties, valuables, and essential items before floodwaters cause damage.

While many communities in Texas have years of experience in developing and operating FEWS, most are relatively new to the concept. To provide helpful guidance for communities considering or planning to invest in FEWS, the Texas Water Development Board (TWDB) has tasked the University of Texas at Arlington (UTA) (Contract No. 2101792481) to develop a guidance document with essential information on FEWS along with best management practices for communities in Texas. This guidance document aims to provide supplemental information for flood mitigation grant applications and serve as a development reference for community leaders, floodplain managers, other public officials, and supporting consultants or vendors interested in FEWS.

This guidance document was created with tailored information for Texas communities based on a thorough technical literature review and a systematic survey and interview process with existing FEWS communities across Texas and the nation. This document provides basic information on FEWS, the essential guidance for development (e.g., planning strategies, cost estimates, project tasks and timeline, best management practices, etc.), and general recommendations for Texas communities. Funding information from federal and state agencies is also included in this guidance document as additional resources for communities considering FEWS. Communities interested in creating FEWS are encouraged to utilize this document to gain the necessary knowledge and recommendations to establish them effectively.

This document provides an overview of the flood threats to Texas communities, and a roadmap to develop FEWS through the steps of planning, financing, deploying, and managing that are organized in the following chapters:

Chapter 1 provides an overview of the potential types of flooding faced by Texas communities and current public awareness of flood risk. This chapter includes the survey and interview process used to gather information from Texas communities with FEWS. The critical components of FEWS and general project development workflow are also presented

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1 Hurricane Nicholas and South Texas Heavy Rain in 2021; Hurricanes Delta, Laura, and Hanna in 2020; Tropical Storm Imelda and plains flooding in 2019; Hurricane Harvey in August 2017; Houston flooding and Sabine River flooding events in 2016; and Memorial Day flooding in 2015

in this chapter.

Chapter 2 covers the typical goals and objectives of FEWS and provides a detailed list of equipment, data, analysis, models, and existing resources. Communities are encouraged to catalog and utilize all existing resources to inform decision-makers. In particular, the National Weather Service (NWS) offices are a valuable resource and collaboration partner. The selection of appropriate vendors and contractors, which can significantly impact the success of the development of FEWS, is also introduced briefly.

Chapter 3 contains details regarding FEWS costs. Several tables are presented as examples or resource lists, including FEWS tasks with associated costs and cost estimates for instrument types and services. An overview of potential grant sources is provided as well. Because costs are often prohibitive to FEWS development, particularly for small communities, the communities planning for FEWS projects are strongly encouraged to collaborate with federal, state, and local agencies as well as public utilities and other partners to leverage existing resources.

Chapter 4 covers the process of deploying FEWS. This chapter discusses typical tasks involved in deploying FEWS, such as gauge placement, installation, and calibration, and their associated timelines.

Chapter 5 provides details for FEWS management. The organization and typical roles of a FEWS team, including internal and contracted personnel, are introduced. Advice to achieve sustainable performance of the systems is provided concerning equipment and workforce management, operations and maintenance, and system standardization. Suggested practices for event responses and public education on flood risk awareness are also covered in this chapter.

Chapter 6 contains a summary of recommendations for FEWS as presented in **Chapters 2, 3, 4, and 5** (planning, financing, deploying, and managing FEWS, respectively). The recommendations were gathered from the communities through the survey and interview process. Examples of existing FEWS and websites of emergency notification systems are provided. Tables of relevant FEWS-related documents, manuals, and additional resources are also presented.

Two appendices cover the technical perspectives of FEWS. **Appendix A** includes FEWS types and equipment, precipitation and streamflow measurements, warning infrastructure, flood information management, and models. **Appendix B** presents considerations of gauge placement, including information gathered from Texas communities

The guidance document enables communities interested in implementing FEWS to learn from peer communities who have successfully done so and make experience-informed decisions by providing a combination of technical and administrative knowledge and resources.

Acknowledgments

Principal Investigator Dr. Nick Z. Fang at the University of Texas at Arlington and his team of primary authors, including Dr. Philip B. Bedient, Dr. Samuel Brody, and Professor Michael Zaretsky, are grateful to the Texas Water Development Board (TWDB) for providing the opportunity to fulfill Contract No. 2101792481. Dr. Daniel D. Li, Dr. Wenzhao Li, and graduate students Kelli Greenwood and True Furrh were primary team members for assisting in the community survey and interview process and document preparation. The project team is thankful to many FEWS communities which participated in the study and their administrative and technical or engineering staff for their valuable time and meaningful responses to surveys and interviews. Additionally, they want to thank the external stakeholders and partners interviewed for providing insights and resources at the local, state, and federal levels. Lastly, the project team extends its appreciation to all who participated in creating this guidance document that will support the development of consistent and effective flood early warning programs for communities in Texas.

1 Introduction

1.1 Texas Floods and Awareness

Flooding is a pervasive issue across Texas due to the state's variation in topography, climatic features, proximity to the Gulf of Mexico, and other factors. Since the year 2015, when almost every major city in the State was impacted by a major flood (May 2015 – North Texas Floods, Memorial Day Floods 2015 – Houston, and Wimberley 2015 in Austin-San Antonio area), Texas has experienced a total of twelve (12) federally declared significant disasters related to flooding, resulting in billions of dollars in damages and losses of lives (TWDB, 2019; FEMA, 2022). In 2017, Hurricane Harvey devastated the Texas Gulf Coast, displacing over 30,000 people and killing 89, with an estimated $141.3B (CPI-Adjusted) in damages (NCEI, 2022). While flooding can occur anywhere in the State, cities such as Beaumont have been subject to severe repetitive flooding in recent years (e.g., 2017 Hurricane Harvey, 2019 Tropical Storm Imelda, and 2021 Hurricane Nicholas). Further adding to these challenges, Texas is subject to four major flood types: riverine, stormwater, coastal, and structural failure.

Riverine flooding, also known as fluvial flooding, occurs when rivers, streams, or bayous overflow and spill into the floodplain. Eleven percent (11%) of the State's population is exposed to moderate-to-high riverine flood risk as defined by FEMA's flood insurance risk maps (TWDB, 2019). Riverine flooding levels are often quantified in terms of recurrence interval, a classification of the severity of the flood based on historical flow data. For example, a 100-year flood is defined as an event that has a 1% probability of occurring in any given year, which equates to 26% of those properties within the 100-year floodplain being flooded during a typical 30-year mortgage. Riverine flooding occurs as flash flooding (when heavy rainfall rapidly generates runoff in a short period) and slow-rise flooding (when floodwaters arrive days later from precipitation upstream). Riverine flooding resulted in more loss of life than any other weather-related hazard in Texas between 1996 and 2006 (TDEM, 2018).

Stormwater flooding is similar to flash flooding but occurs when rainfall exceeds an engineered drainage system's capacity rather than the soil infiltration capacity. This type of flooding is expected in cities and other developed areas with large swaths of impervious surfaces and is sometimes referred to as pluvial or urban flooding. One major impact of stormwater/urban flooding is roadway inundation, which can damage parked or moving vehicles, threaten drivers, and inhibit emergency management responses.

Coastal flooding is associated with tropical weather systems or tidal events that temporarily elevate coastal sea levels. Coastal flooding is a severe economic threat to Texas. In 2018, the Texas Department of Emergency Management (TDEM) calculated the historical impact of weather-related hazards, showing hurricanes and coastal flooding were found to be the first and second most costly hazards, causing 36% and 21% of the weather-related property damages from 1996 to 2006, respectively (TDEM, 2018). Tropical weather systems can create a storm surge when wind fields push water toward land with the potential to exceed 25+ feet above normal tide levels.

Structural failure flooding is not common in Texas, but the failure of dams and levees can result in a massive release of floodwater, demonstrated by the failures of the Oroville Dam in California in 2017 and the Edenville Dam in Michigan in 2020. Texas has 7,372 total dams, with 1,547 designated as a high hazard (NCEI, 2022), meaning dam failure would probably result in massive loss of life and major damage to properties (USACE, 2004). Refer to the State Flood Assessment (TWDB, 2019) and the State of Texas Hazard Mitigation Plan (TDEM, 2018) for additional information regarding the flood types and risks in Texas with additional statistics.

To mitigate all types of potential flooding, both structural and non-structural practices have been applied. Structural efforts typically include drainage and stormwater infrastructure, levees and flood walls, and reservoirs; non-structural measures include education and outreach, emergency action plans, and early warning systems (Texas Flood Information Clearinghouse, 2020). Flood Early Warning Systems (FEWS), as non-structural flood mitigation tools, have increased in popularity among flood-prone communities due to their life-saving functions like rainfall and river level monitoring, real-time flood forecasting, and estimating potential damages to different communities while remaining relatively low cost compared to other structure-related mitigation solutions.

Figure 1. Road sign for *Turn Around Don't Drown*. Source: TWDB.

As non-structural practices, FEWS require integration with public education efforts to be as effective as possible. Flood awareness programs, which focus on situational awareness and preparation for flood events through the dissemination of hydrologic knowledge and emergency response strategies, have been initiated nationally to raise the attention of stakeholders and educate the public. For example, Texas Flood Awareness Week is one event that brings attention to the citizens of Texas of the dangers that flooding can present. In 2004, the National Oceanic and Atmospheric Administration (NOAA) trademarked the National Weather Service's (NWS) public education campaign, "*Turn Around, Don't Drown*". NWS initially launched this campaign in 2003 after the San Angelo forecast office observed that incidences of driving through low-water crossings made up 80% of all flood fatalities in South Texas (FEMA, 2021). The campaign aims to persuade people to avoid driving or wading into floodwaters – noting that roadway damage, water depth, and flow rate cannot always be easily observed through murky water. This message is displayed on road signs (**Figure 1**) by the Texas Department of Transportation (TxDOT) and used as public outreach by the Texas Floodplain Management Association (TFMA). Additional resources for public education are compiled in the Community Official Flood Resource Guide (TWDB, 2022), Community Resources, and TexasFlood.org. The shared goal of these efforts is to raise flood awareness among Texans, which is particularly important for flood mitigation measures as they are only effective when proper attention is given. Communities should consider the types of flooding and their flood awareness requirements before initiating any potential mitigation efforts. Because the political subdivision responsible for FEWS may vary, the general term "Communities" is used throughout this document to refer to any political subdivision responsible for a flood early warning system.

1.2 Flood Early Warning Systems (FEWS)

FEWS are an effective tool for mitigating flood risk and can be implemented in specific flood-prone localities and potentially upscaled to provide a regional coverage. Compared with the high costs and physical limitations of structural flood mitigation projects, FEWS can be a flexible, cost-effective mitigation solution. The function of FEWS is to "collect, handle, analyze, and disseminate hydrologic information, ideally in real-time, for the purpose of providing accurate advance warnings of an impending flood event." (UNISDR, 2017). Modern FEWS can accomplish this while meeting the needs of specific locations or regions. Systems can range from basic river gauge monitoring networks to complex forecasting systems that employ radar-rainfall data and advanced computer modeling techniques to forecast floods, with lead times ranging from minutes to days.

FEWS can be categorized as either manual or automatic based on the data retrieval process. Most FEWS established today are automatic due to advances in information technologies. Automatic gauges typically have greater initial costs and maintenance requirements but operate autonomously. This frees up labor associated with taking measurements while mitigating risks to emergency management staff during flood events. There are two main types of automatic FEWS in terms of their forecasting capability: 1) *flood monitoring systems* and 2) *flood forecasting systems*. Funding is typically the primary consideration when choosing between flood monitoring or flood forecasting systems, though the complexity of local hydrology is also a consideration. The choice between monitoring or forecasting may depend on the goals and objectives of the FEWS, which must be carefully considered and clearly established beforehand. While long-term economic impacts should be considered for all systems, many systems are first established as monitoring systems, and forecasting capabilities are added later.

1.2.1 Flood Monitoring Systems

Flood monitoring systems are designed to monitor critical hydrologic conditions (e.g., volumetric flow, water surface elevation, precipitation, etc.). When a known threshold is reached (e.g., dangerously high flow in a stream after rainfall, water stage overtopping a road, etc.), warnings may be sent out to internal personnel, residents, and first responders. Alerts sent to public utility departments or first responders can be used to deploy road barriers or turn on flashing lights at low water crossings prior to flooding.

Similarly, warnings to residents may provide notice to evacuate, avoid travel on certain roadways, or move valuables to higher ground. Many FEWS rely on a network of gauges for monitoring purposes only. Such monitoring can be a cost-effective solution, particularly for communities lacking the support staff, field personnel, equipment, or funding necessary to operate a flood forecasting system. While flood monitoring systems do not include predictive or forecasting capabilities, knowledge of current conditions, particularly at upstream locations, can provide valuable knowledge to communities.

1.2.2 Flood Forecasting Systems

In general, flood forecasting systems are built on the foundation of flood monitoring systems but include one or more predictive components. Forecasting systems have an internal predictive module that takes in data (e.g., gauge measurements, predicted conditions via the NWS, etc.) and outputs future hydrologic conditions. This is often done with a hydrologic and hydraulic analysis or a simplified empirical rainfall-runoff algorithm. Forecasting systems may also utilize radar-rainfall coverage to supplement the gauge network. A variety of models exist for forecasting purposes and are covered in greater detail in **Appendix A**. Flood forecasting systems provide additional functionality at the expense of complexity, increased staffing/personnel requirements, and financial cost.

1.2.3 Components of FEWS

FEWS have three key components: data collection, data analysis and visualization, and information dissemination and communication (**Figure 2**). These components are seamlessly integrated, and each component is essential to FEWS performance.

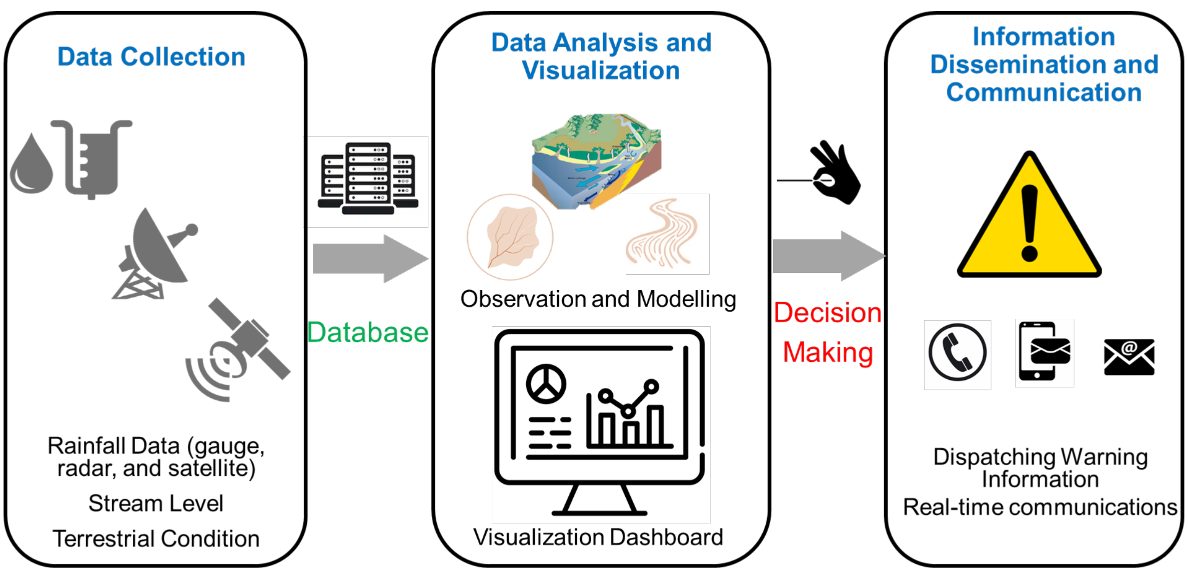

Figure 2. FEWS components

1. Data Collection**:** The first component collects rainfall data from multiple sources (e.g., gauge, radar, and satellite), stream gauge data, terrestrial conditions (e.g., soil and vegetation type), and atmospheric conditions. This includes data collected from existing resources, data collected from federal, state, regional, or local partners, and data gathered from equipment *unique* to FEWS.
2. Data Analysis and Visualization: The second component uses the data from the previous step for analysis. The analysis of a flood monitoring system is often performed by comparing the current condition data with previous datasets or known/established thresholds to determine flooding status. For a flood forecasting system, the data are often used as input to a hydrologic and/or hydraulic model to determine the expected severity of flooding. After the data is collected and processed by the hydrologic and hydraulic analysis (including models—if part of a flood forecasting system), the information and the calculated or simulated results can be visualized for a better decision-making support process. A visualization platform often includes a computer program (typically only for internal use) and an online dashboard. While some FEWS may use a single online dashboard only, others may have different dashboards for internal users and the public. With a visual platform, decision-makers and emergency management personnel can be equipped with appropriate levels of critical information during a time-sensitive flood event.
3. Information Dissemination and Communication: After an internal decision is made by the FEWS operators based on the data analysis and visualization, the flood information can then be dispatched to the public and local emergency personnel through the FEWS communication component. Potential warning delivery methods range from automated messages, public alerts, and alarms to an online dashboard or display. Communities are encouraged to have an easily accessible online dashboard for regular communication with the public that displays a simplified portion of the FEWS information. Communities should work with their internal users (especially emergency management personnel) to determine the appropriate type of information and communication for each user and the public. In addition, local FEWS data can be connected and shared dynamically with regional (e.g., Lower Colorado River Authority viewer), state (e.g., TWDB TexMesonet and Texas Flood Information Viewer), or federal (e.g., National Weather Service (NWS) Advanced Hydrologic Prediction Service) partners.

1.2.4 Benefits of FEWS

Of the four phases of emergency management (mitigation, preparedness, response, and recovery), FEWS are critical components in both flood preparedness and flood response (FEMA, 1998). Depending on the features present in the FEWS, benefits range from allowing staff to monitor multiple sites to increased lead time for watches and warnings at flood-prone locations. As an effective and efficient non-structural measure, FEWS will improve flood readiness and resilience that can prevent severe monetary and human losses.

FEWS without predictive capabilities, referred to as flood monitoring systems, benefit the community by helping it allocate staff more efficiently before, during, and after flooding events. With limited staff, communities that may have previously only been able to monitor one location using on-site personnel may be able to monitor multiple sites using stream gauges and camera feeds. Since flood monitoring systems often focus on the transportation network, FEWS allow communities to remotely determine if a road is flooded (or near flooding levels), utilize cameras to see if the situation is worsening, and decide when and where to activate flashers, place barriers, or close gates. Some flood monitoring systems can even provide lead times for riverine flooding when gauges are placed upstream of the communities. In addition, flood monitoring systems provide valuable historical data for better model construction and are often the predecessor of forecasting systems.

Flood forecasting systems are more complex than flood monitoring systems and require additional information and expertise. These systems utilize a predicted component (e.g., rainfall) to determine the future impact at specific locations under certain conditions. Flood forecasting systems provide the additional benefit of lead time, representing how far in advance flooding conditions can be reasonably predicted. The lead time provided can range from minutes to several hours (or even days for flooding along with larger riverine systems) depending on data inputs and internal monitoring or prediction methods. Flood forecasting systems rely on developed models with accurate input information, which may take time and be difficult to obtain or build, particularly for small watersheds. Forecasting systems also rely on experienced personnel with the capability to calibrate models based on input data and interpret results from the models. The information from a forecasting model can be used to predict whether a flood is about to occur, when it will arrive, and how severe it will be. Personnel can use the interpreted results from these systems for internal operations and in some cases give organizations and individuals advanced notice of flooding to take proper measures to protect themselves and their property from potential floods. The National Weather Service (NWS) is a common source of forecasted information, so communities should work with NWS to determine reliability.

The choice between a flood monitoring and flood forecasting system will be specific to the community. Because of the additional complexity, uncertainty, and experience required, a flood forecasting system may not be appropriate for certain communities. Nevertheless, flood monitoring systems can be expanded or developed into flood forecasting systems later. In cases where there is not a clear need for forecasting capability at the time, a flood monitoring system is recommended.

1.3 Texas FEWS Communities

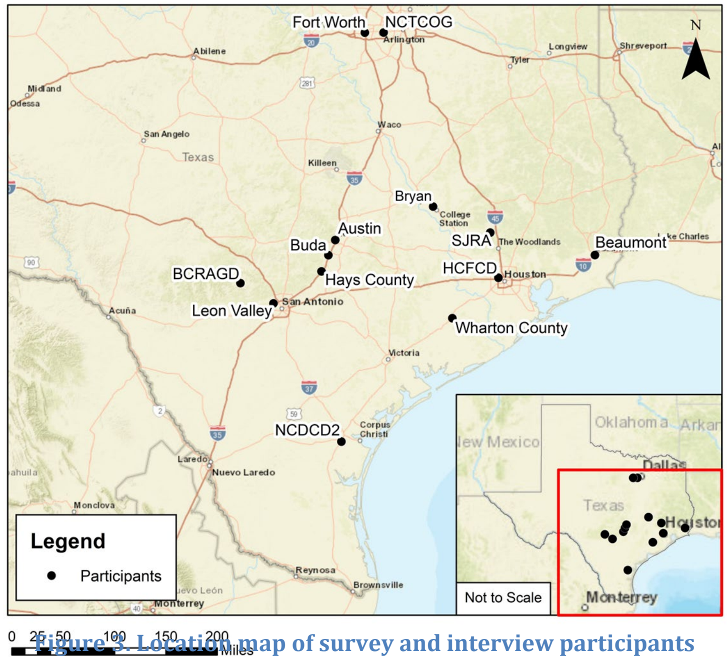

Figure 3. Location map of survey and interview participants

The foundation of this guidance document is the information collected from a systematic survey and interview process conducted with participating Texas communities that have invested in FEWS. These communities received funding from TWDB's financial assistance programs in fiscal years 2016, 2018, or 2020, with some communities obtaining funding repeatedly. Their experiences and recommendations offer helpful insight to communities that are new to FEWS. The thirteen (13) communities around the state that participated in the survey and interview process are shown in **Figure 3**. The participating communities are as follows: City of Austin, Bandera County River Authority and Groundwater District (BCRAGD), City of Beaumont, City of Bryan, City of Buda, City of Fort Worth, Harris County Flood Control District (HCFCD), Hays County, City of Leon Valley, North Central Texas Council of Governments (NCTCOG), Nueces County Drainage & Conservation District No. 2 (NCDCD2), San Jacinto River Authority (SJRA), and Wharton County.

The participating communities in this survey represent broad geographic regions of Texas, from the coastal plains to the hill country and North Texas. The survey and interview process included various community types, sizes, and available resources, which allowed for a complete picture of the status of FEWS in Texas. One participating system was the Harris County Flood Control District's Flood Warning System (**Figure 4**), which is based on nearly 200 gauge locations throughout the bayous and tributaries in Harris County. The system also contains over 100 additional gauges maintained and operated by partner agencies. The stations are strategically placed to transmit sensor data (e.g., rainfall, stream stage, and other parameters) during storm events. Additional examples of FEWS dashboards or online information are shown in **Table 11**, located in **Chapter 6**.

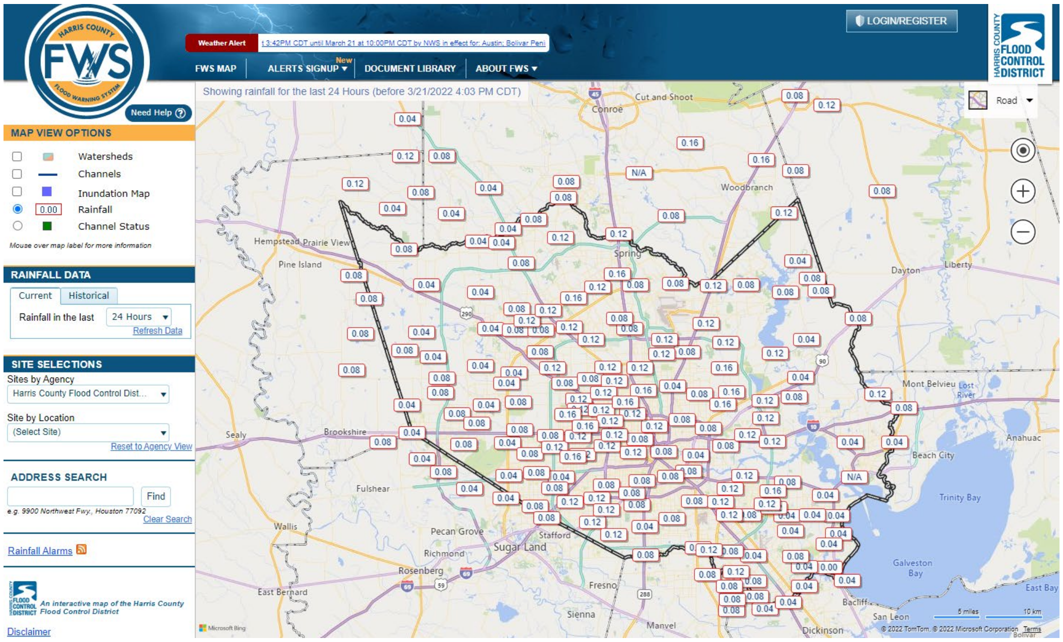

Figure 4. Harris County Flood Control District's Flood Warning System online public dashboard

1.4 Workflow of FEWS Development

While communities have diverse ways to develop FEWS, the procedure always follows a general workflow, as presented in **Figure 5,** with four stages: planning, financing, deploying, and managing. The details of each element are included in the following chapters, with a brief overview provided here.

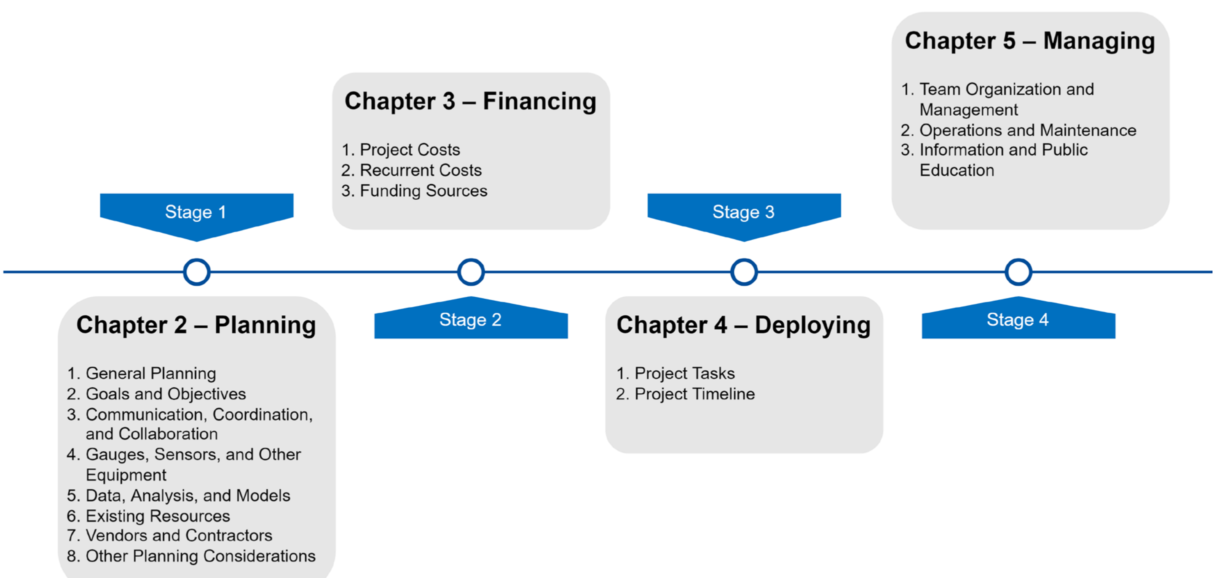

Figure 5. FEWS development workflow

In the *Planning* stage (**Chapter 2**), communities are encouraged to set clear goals and objectives for the system that will guide the selection of system complexity, equipment, and analysis or models in the following stages. While existing resources for the planning stage vary significantly by location, some federal and non-federal resources available throughout Texas for use in FEWS are presented in **Table 3** and **Table 4,** respectively. Communities are encouraged to plan for and embrace communication, coordination, and collaboration with federal, state, regional, and local partners. For example, perhaps a neighboring community, river authority, or federal partner already has FEWS elements (including equipment and data) that can be shared or consolidated, which can significantly reduce the cost of creating a system and lead to better communication of risk across political jurisdictions. Regional partnerships can be mutually beneficial and can provide benefits exceeding those provided by a local system. Lastly, the identification and selection of appropriate vendors and contractors, if needed, is an important consideration that needs to be discussed during the planning stage. The *Financing* stage (**Chapter 3**) is an extension of the planning stage, focusing on the costs, budget, and funding of the system. The costs to be considered for developing FEWS include initial costs or project costs and recurrent costs, including operations and maintenance (O&M) of the system. Grants, loans, and other potential funding sources may be appropriate for use when establishing FEWS in Texas, but a budget for longer-term O&M must be established beyond the initial funding source. The *Deploying* stage (**Chapter 4**) covers typical tasks to be completed during an implementation project and the time required for those tasks. The *Managing* stage (**Chapter 5**) covers the management of internal and contracted personnel, management of the system, and management of the information obtained from the FEWS and delivered to the public or specific users.

2 Planning Flood Early Warning Systems

The planning stage is critical to communities for establishing a successful FEWS. Goals and objectives should first be set to clarify what the FEWS should provide for the community, which guides the selection of appropriate equipment and analysis methods, and the appropriate agency to operate and manage the system. Communities should also consider opportunities to work with federal, state, and local partners to create FEWS. After establishing initial goals and objectives and considering the necessary equipment and analysis methods, communities are encouraged to review existing resources. Existing resources, which may be from federal, state, regional, or local sources, can help communities gather preliminary information and data that may better inform the selection of equipment and analysis methods which may include hydrologic and hydraulic models. The size, location, climate, and hydrologic conditions of a community can affect the decision on the type of FEWS to be established, but the community is encouraged to consider available existing resources first. Furthermore, the community may discover through existing resources that a nearby district, county, or regional entity has already established a FEWS, thus significantly reducing the cost for the community to benefit from a system. Cost, an additional planning consideration, is provided in **Chapter 3** due to its importance.

When planning for FEWS, communities are encouraged to consider:

- **Goals and Objectives (Section 2.1):** FEWS, and the communities that use them, vary in size and function. Having clear goals and objectives as part of the planning process helps ground the project and ensures that the system functions properly and is used as intended. Communities can use the defined goals and objectives to plan for initial construction and incremental expansion in the future. Additionally, communities are encouraged to identify and anticipate potential challenges.
- **Communication, Coordination, and Collaboration (Section 2.2):** Communities are encouraged to communicate, coordinate, and collaborate with federal partners such as the United States Geological Survey (USGS), United States Army Corps of Engineers (USACE), Federal Emergency Management Agency (FEMA), and National Weather Service (NWS); regional partners such as river authorities, Regional Flood Planning Groups, and counties; and local partners such as other nearby communities, drainage districts, and internal departments (police, fire, public works, emergency management, etc.).
- **Gauges, Sensors, and Other Equipment (Section 2.3):** Selection of gauges, sensors, or other equipment, such as cameras, as well as install location, is often considered the most complex part of FEWS implementation. Various types of equipment and their features are discussed. Technical details on various gauges, sensors, and other equipment are provided in **Appendix A**, while detailed information to assist with site selection for gauges is provided in **Appendix B.**
- **Data, Analysis, and Models (Section 2.4):** The data used in FEWS is comprised of those from existing resources, such as USGS gauges, combined with data gathered from gauges, sensors, and other equipment deployed during the establishment of

the FEWS. The data is then analyzed. The type of analysis will depend on whether a flood monitoring system or flood forecasting system is to be established. While not all FEWS incorporate models within their analysis, FEWS with more complex goals may make use of hydrologic and hydraulic models to meet their objectives. Model selection details are provided in **Appendix A**.

- **Existing Resources (Section 2.5):** Existing resources can include information from personnel (institutional or anecdotal knowledge) or information from federal (e.g., NWS, FEMA, USACE), state (e.g., TWDB), regional, and local agencies. Information from these sources can inform and guide further planning efforts.
- **Vendors and Contractors (Section 2.6):** Early in the planning stage, communities are encouraged to consider how vendors and contractors may be used for various aspects of deploying and managing FEWS. Communities can optimize their staff and resources by selecting appropriate and competent vendors and contractors. General planning considerations and a brief overview of procurement for vendors and contractors is presented in **Section 2.6**, while details on the how the procurement of vendors and contractors fits into the process of deploying FEWS is found in **Section 4.1**.
- **Other Planning Considerations** (**Section 2.7**):
    - Costs, Funding, and Budget (**Chapter 3**)
    - Operations and Maintenance (**Section 5.2**)

2.1 Goals and Objectives

One of the first steps in FEWS planning is to identify specific, feasible goals for the system. While the primary goal of FEWS is to enhance the safety of residents, visitors, and personnel working in communities from flooding, communities will have diverse ways of achieving this broad goal. Goals and objectives for the system must be set before a plan can be developed. In this way, strategic planning aims to be proactive, not reactive. Systems vary depending on the community and local flood issues, and their goals and objectives should reflect this. Communities are encouraged to focus on needs rather than wants and identify potential challenges and solutions as part of the project scope during the planning process. Communities should also keep in mind that the goals and objectives may change or expand over time, and FEWS can be expanded and updated in response.

The potential challenges can come from different angles in the planning phase, where public interest and risk awareness require raising. They can also come from general contingency planning instead of a community-specific and tailored one, compliance with landowners, permitting from state and federal governmental levels, the agreement between and support from local authorities, and inter-agency planning and coordination, particularly among transboundary river basins. The lack of political commitment, financial and technical resource constraints, and participation of communities in the decision-making process can hinder the planning phase. These challenges are discussed throughout this guidance document with the purpose of helping communities address them accordingly.

The first step in planning is to establish tailored, common, and clear goals. To better understand local needs for flood warning and mitigation, communities are encouraged to utilize a questionnaire to quantify their goals and objectives, including questions such as:

- What are the common types of floods and dominating factors leading to floods locally?
- Where have human lives been lost?
- How many residents, visitors, or personnel will be at risk during a flooding event?
- What impact will social vulnerability have on flood risk for the local community?
- Where have economic losses occurred?
- What infrastructure and/or vulnerable locations are at risk of flooding?
- What is the total asset value associated with the identified flood risk? (Note: While asset value is an important consideration, communities are strongly encouraged to consider issues of social equity before basing decisions purely on asset values, as this may not address other inequities within the community.)
- What specific locations are alerts to be provided for?
- How much is lead time needed to prepare for flood impacts? In other words, what amount of time is considered adequate for alerts and responses?
- If temporary or permanent relocation of vulnerable assets is feasible, what impacts would that have on the system?
- Are Flood Hazard Maps (with their corresponding recurrence interval) available and recent?

Some of these questions can be easily answered from the previous knowledge from internal personnel, referred to as institutional knowledge. The intent of these questions is to gather information from the past and better prepare for future floods. Other information can be gathered from existing resources, as discussed in **Section 2.5**. Information from these questions should provide a basis for the goals and objectives, and the facts may assist with harnessing local support.

Interest and support from local authorities and the public for FEWS development and implementation often increases following a major flood event. For example, the flood damages resulting from Memorial Day flooding (2015), Hurricane Harvey (2017), and Tropical Storm Imelda (2019) spurred public attention and financial support from local, state, and federal sources in the areas affected by these disasters. While flooding events can help garner local support, communities should ensure that the system is functioning properly at all times. Communities should also exercise caution to ensure that the FEWS reflects local and regional needs and is not used for purposes that exceed their scope. A simple system (e.g., a few rain gauges and streamflow sensors) should not typically be expected to forecast flooding and effectively determine where to deploy emergency assets. Flood mitigation efforts also rely on human expertise and judgment to accompany FEWS. Because of this, communities are encouraged to understand and utilize tools appropriately. Communities are encouraged to define the goal of their system and use the system as

intended. Additionally, the community is encouraged to review local policies and programs and incorporate proactive FEWS planning into their Local Hazard Mitigation Plan (LHMP). Communities can check if there is an existing LHMP by visiting the FEMA LHMP Map. Additional information and funding for creating an LHMP if one does not already exist, are provided by FEMA's Create a Hazard Mitigation Plan and the Texas General Land Office
(GLO)'s Local Hazard Mitigation Plans program.

While the goals of FEWS may be broad and apply to many systems, objectives for a specific system are dependent on the community and how the community intends to use the system. Goals are long-term visions for the system, while objectives define how the goal will be achieved. For example, a common goal of FEWS is to reduce loss of life. This goal is often achieved through the establishment of a clear objective to provide timely flood information for a specific location that has been identified as an established or potential flooding location. However, this objective could also help nearby residents protect their property from damage by allowing them time to move or protect their assets. Communities should work to identify the flooding issues experienced by the community and the potential risk of future flood events and use these to tailor the goals and objectives for the system. The common goals and objectives of FEWS are given in **Table 1**.

Table 1. Common goals and objectives of FEWS

Goals	
• Reduce loss of life	• Warn critical infrastructure
• Inform vulnerable locations	• Guide transportation
• Mitigate damage and economic loss of housing, agriculture, etc.	• Inform emergency response
Objectives	
• Provide timely, detailed, and accurate flood information for current conditions (observations) at specific monitored locations	• Provide timely, detailed, and accurate flood information for future conditions (forecasts) for specific locations
• Enhance understanding of local flooding issues for FEWS operators	• Enhance understanding of local flooding issues for real estate, lending, and insurance professionals
• Increase public awareness of flooding and flood risk (through public education)	• Increase interaction among internal departments and outside partners before, during, and after floods

The objectives are based on the capabilities of the system and often simultaneously address more than one goal of the system. For example, FEWS can reduce loss of life by providing timely, detailed, and accurate flood information for current conditions. At the same time, knowledge of the current conditions can also lead to flood damage mitigation. Some objectives of the system are results of the information that FEWS can provide. For example, the added knowledge and understanding that monitoring can provide real estate, lending, and insurance professionals with the knowledge to better inform their clients of current or future risks. While the goals and objectives of the system should be carefully considered as a community begins planning a system, they should be modified based on additional knowledge or data as the project progresses. The information gained through planning of the system will solidify the goals and objectives of the system and confirm the planned scope and intended use of the system. While every community could utilize the basic goals and objectives established in this section, the final goals and objectives should be specific to the community and provide a foundation for future use of the system.

2.2 Communication, Coordination, and Collaboration

Communities are encouraged to communicate, coordinate, and collaborate with federal, state, regional, and local agencies, and internally. Communities are encouraged to consider what information can be produced and presented from their FEWS internally, to collaborative partners, and to the public. FEWS operators are encouraged to emphasize and use local and internal communication, coordination, and collaboration efforts. Specifically, other departments within the communities, such as fire and police departments, can significantly benefit from FEWS information.

The FEWS planners are encouraged to partner with state, federal, and local agencies, as well as public utilities and commercial businesses, to share the costs of data collection. Government agencies responsible for highway safety and maintenance, pollution control, homeland security, and water management may be willing to participate. Public utilities and commercial enterprises with properties, personnel, and operations in flood-prone areas are also likely to participate.

Communities are encouraged to collaborate with the NWS on the establishment of FEWS regardless of the potential complexity of the system. Communities planning FEWS implementation are strongly encouraged to contact the Warning Coordination Meteorologists or Service Hydrologists from their local NWS office to establish a clear line of communication. NWS staff can assist with the development of FEWS, especially in selecting sites and assuring that NWS will receive data that it can ingest into NWS's internal system. NWS can provide guidance and technical support as well as outreach and education to involved parties and community leadership. The NWS River Forecast Centers operate an existing regional FEWS system and may be able to provide river forecasting services at no cost to local communities. Forecasts from this system are published on the NWS site
(water.weather.gov) for public access. Communities can discuss their needs with their local Weather Forecast Office, or they may contact the River Forecast Center directly. Communities may require additional resources if they are focused on flooding in a smaller scale than the NWS. Still, it is important to partner with the NWS for data access and resource-sharing when possible as a first step.

Among the thirteen National Weather Service River Forecast Centers (RFC) in the U.S., three are relevant to Texas: the West Gulf River Forecast Center, the Arkansas-Red Basin River Forecast Center, and the Lower Mississippi River Forecast Center (**Figure 6**). The West Gulf River Forecast Center has its area of responsibility stretching from the Rio Grande in southern Colorado, New Mexico, and South Texas eastward to the Sabine River along the Texas-Louisiana border. The Arkansas-Red Basin River Forecast Center covers the drainage area of the Arkansas River above Pine Bluff, Arkansas, and the drainage area of the Red River above Fulton, Arkansas, including the panhandle region and some north-central regions in Texas. The Lower Mississippi River Forecast Center covers some portions of eastern Texas along the drainage basins for Cypress Creek and Sulphur River.

Another consideration is discussing flood mitigation strategies with other communities. Communities are encouraged to consider creating or joining a regional FEWS.

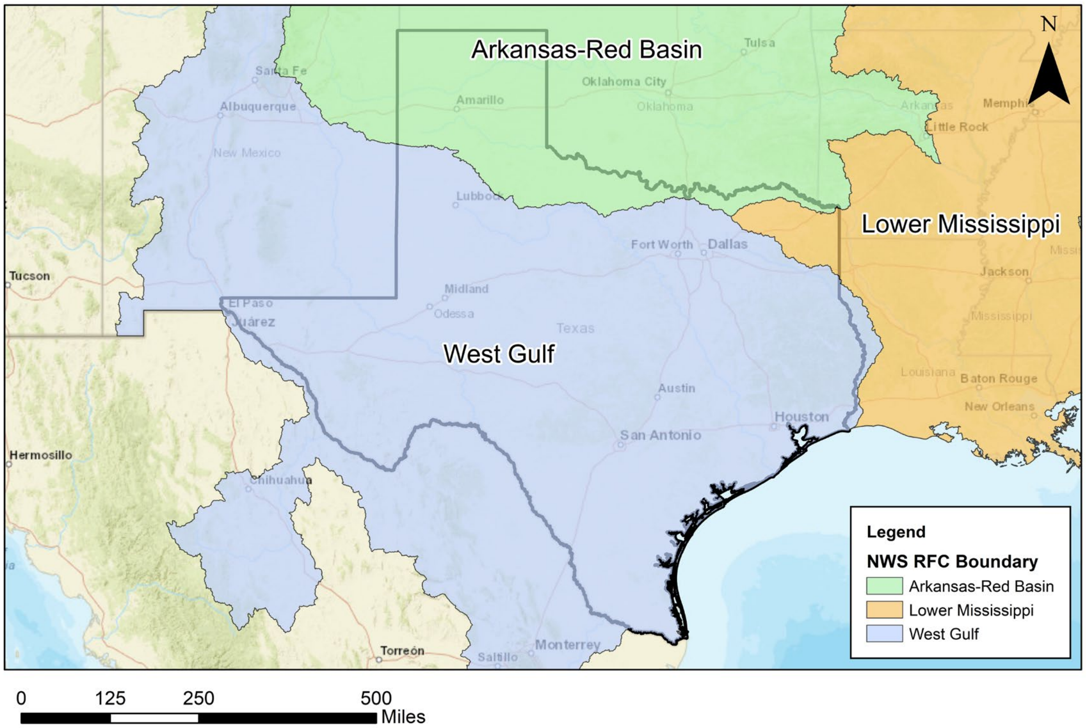

Figure 6. National Weather Service (NWS) River Forecast Center (RFC) boundaries around Texas

Comprehensive regional FEWS can be a sustainable way to develop FEWS, as the data and information can be shared among communities to maximize usability. Regional FEWS can create user focus groups (e.g., public, emergency management, technical) that continue along with growth. Even if a regional FEWS is not intended, the collaboration between entities with and without existing information in the same area can be integral to the success of FEWS. This collaboration can help jumpstart the newer system and improve the overall performance of the existing system. Furthermore, upstream communities can provide advanced warnings of flood waters. Quarterly or bi-annual meetings among federal (e.g., NWS, USGS, USACE, etc.), state (e.g., TWDB, TxDOT, etc.), regional, and local agencies, as well as any other relevant parties and stakeholders to promote communication, collaboration, and information exchange are encouraged. Examples of successful regional FEWS programs in Texas include, but are not limited to, Harris County Flood Control District's Flood Warning System, ATXfloods, and Flood Data North Texas. Additional examples of FEWS dashboards or online information are shown in **Table 11**, located in **Chapter 6**.

2.3 Gauges, Sensors, and Other Equipment

FEWS typically consist of various gauges, sensors, and other equipment that are utilized to mitigate flood risk. Typical gauges, sensors, and other equipment utilized in FEWS are:

- Rain Gauges – Gauges provide the measurement of rainfall and other atmospheric conditions. For more information, please see the *Precipitation Measurement Section* of **Appendix A**.
- Stream Gauges – Gauges measure stream stage (elevation/depth) and sometimes velocity, which along with a gauge-specific rating curve, can provide discharge (flow) information. For more information, please see the *Streamflow Measurement Section* of **Appendix A**.
- Other Stage or Water Level Gauges – Gauges for waterbodies other than streams, such as lakes, reservoirs, and oceans, also exist and typically provide information on the water level or stage. For oceans, these gauges are typically tidal gauges. In many cases, these water level gauges function similarly to stream gauges but provide information for other waterbodies.
- Other Equipment – Other equipment included in FEWS are often utilized in addition to gauges to provide additional functionality to the system. For more information, please see the *Other FEWS Equipment Section* of **Appendix A**. Examples include:
    - Cameras – A camera provides a video feed or still images.
    - Signing and Striping – Warning signs and pavement markings can provide critical visual signals for flood-prone areas, especially roadways.
    - Sirens – Sirens provide an audible alarm to alert for dangerous conditions.
    - Flashing Lights – Flashing lights can provide a visual alarm, often accompanied by a road sign, to alert for dangerous conditions.
    - Float Switches – Float switches provide notification when water in a waterbody, river, or stream reaches a certain threshold.
    - Road Barriers or Gates – A road barrier or gate can block access to flooded roadways. In addition to being permanently located or able to be moved, road barriers can be manually, remotely, or automatically operated.

Rain and stream gauges are the foundation of most FEWS and provide observed precipitation and stream stage elevation/flow. Some FEWS may rely solely on specific gauges, while others leverage broader gauge networks to calibrate and improve radar-rainfall data. While increasing the number and density of gauges generally improves the network's ability to detect flood-producing rainfall and streamflow, gauge installation and maintenance are significant financial commitments that may be prohibitive for some communities. The selection of appropriate gauge sites is often fueled by local knowledge of areas that have experienced repeated flooding but can be enhanced by the implementation of technical analysis and long-term planning strategies. Further details and resources regarding gauge site placement can be found in **Appendix B**. Other stage or water level gauges can also be utilized in the system to provide water level information for lakes, reservoirs, and oceans. The importance of including these other water level gauges in the system will depend largely on the community, and communities are encouraged to review the nearby lakes, reservoirs, and oceans that could impact their system and to locate gauges at these as appropriate.

Communities are encouraged to consider cameras as part of their FEWS. Camera feeds/data can be necessary for verifying predictions in real-time, for verifying gauge data, or for checking the site without having to deploy personnel. However, communities should consider privacy issues such as restricting public access to cameras. For cameras with pan or zoom capabilities, communities are encouraged to set priority when multiple entities or departments would have access to view, pan, and zoom cameras simultaneously. Despite privacy and access concerns, cameras can assist communities in allocating staff effectively. To fully leverage the benefits of using cameras, FEWS should be designed with enough cache and data storage space to handle data from multiple sources (gauge, camera, and model etc.) so the data from different sources can be presented consistently. Equipment necessary for the download, transfer, and transmission of the data from each piece of equipment is an additional consideration that is further discussed in **Appendix A** and **Appendix B**.

Communities are also encouraged to use appropriate signing and striping techniques to alert drivers to potential flood risks. Most driving-related transportation features will be signs, such as those indicating low water crossings. Physical or sensory techniques such as rumble strips or raised pavement markers can be used in addition to signs to indicate areas where drivers need to pay special attention, such as low water crossings or roads known to flood during flood events (e.g., "ROAD MAY FLOOD"). For further guidance on signage, review the Signing Strategies for Low-Water and Flood-Prone Highway Crossings from the Texas Transportation Institute (2011).

Other equipment, such as sirens, flashing lights, float switches, and road barriers or gates, may already exist in the community emergency response. The pros and cons of these types of equipment are shown in **Table 2** and discussed below. Sirens, or audible alarms, can be used to convey flood alert information but may not be able to express a clear message or reach the intended audience. Flashing lights often accompany road signs, which allows them to bring a more concise message to drivers. Flashing lights can also accompany float switches to activate automatic flashing when a road is near flooding conditions. While flashing lights provide warning and can be automatic, they do not block the roadway. Road barriers, barricades, or gates are often used to close roads due to flooding. Physical barriers can be automated or deployed by staff during floods. Deployed manual barriers can have a low material cost but a high labor cost. Personnel will need to move barriers in a timely manner to ensure that the drivers do not ignore or move barriers after or between flood events. If personnel are slow to move barriers, a flood that has multiple peaks may result in drivers moving barriers when it appears that the water has receded, rendering the barrier ineffective for the later peaks. Automated gates, on the other hand, have a high material cost but a low labor cost. Automated gates may be hit by vehicles and require more frequent repairs than others. Additionally, automated gates must be confirmed to be functioning properly. Generally, manual barriers are ideal for locations close to field staff operations, while automatic systems are suggested when locations are more remote. Communities should consider personnel requirements when considering other equipment for FEWS and may choose to implement a combination of other equipment to meet their goals. Communities are encouraged to consider utilizing existing equipment, if possible, but additional equipment may be required.

Table 2. Pros and cons of other FEWS equipment

Equipment	Pros	Cons
Siren	• Easily triggered • Effective in a large area • Automatic operation	• Unclear message • May not be heard • Do not block the roadway
Flashing Light	• Concise message • Automatic operation	• Do not block the roadway
Road barrier (manual)	• Low material cost	• High labor cost • Manual operation
Road gate (manual)	• Moderate labor cost • Moderate material cost	• Manual operation • May be hit by vehicles • High maintenance cost
Road gate (automatic)	• Automatic operation	• May be hit by vehicles • High maintenance cost • High material cost

Before selecting equipment, consider existing resources (**Section 2.5**) and partnership opportunities (**Section 2.2**) to avoid unnecessary or unintentionally redundant installations. Cost is a significant factor in the process of planning and implementing FEWS that will impact equipment selection. More information on the cost for equipment can be found in **Chapter 3**, particularly **Table 6**. Maintenance, another consideration for equipment selection, is discussed in **Section 5.2**. Please refer to **Appendix A** for more technical information on gauges, sensors, and other equipment.

Regardless of the equipment chosen for inclusion in their FEWS, communities are encouraged to consider standardization to ensure that staff, vendors, and contractors are familiar with all equipment present in the system. For example, procuring identical rain gauges can reduce the number of O&M protocols that staff must be trained in. However, some locations may necessitate a different type of gauge, such as a lake or dam instead of a stream. Even within streams, the selection of an appropriate sensor may vary. For example, in a sediment-rich stream, a pressure transducer may fail and provide faulty readings. Conversely, a bubbler may not be appropriate for ephemeral streams. Communications should also be standardized when possible, using the Automated Local Evaluation in Real Time (ALERT) or ALERT2™ protocol, depending on what is being transmitted currently and in the future, explored later in **Appendix A.**

2.4 Data, Analysis, and Models

The data and models utilized in the FEWS will be highly dependent on the FEWS equipment implemented. Most FEWS will include data obtained from rain and stream gauges. In addition to rainfall and stream level data, FEWS gauges can also be used to collect other types of data with relatively small incremental costs. The rainfall, streamflow, and other types of data can also be shared for flood-related research. While some data can be obtained directly, others can be created by combining data obtained from FEWS equipment. For example, historical road closure information can be a dataset derived from float switches, rain/stream gauges, camera footage, or a combination of these. This manually- or automatically- updating data can help to predict future situations for whether a given road is likely to be closed or open. For example, over time, FEWS operators may note that 2" of rainfall within 12 hours in a specific watershed typically creates flooding conditions for a particular roadway.

As discussed in the previous section, communities are encouraged to communicate, coordinate, and collaborate with NWS and other communities. Communities should obtain useful data that they can share with the NWS and other communities. They may communicate with the NWS on the best method and requirements (precision, output type, etc.) for data sharing, as well as any other information (e.g., the definition of Real-time in terms of FEWS reporting) that would help the NWS make use of any FEWS-created data. Collaboration with NWS could optimize the resources and enhance the capabilities in flood response and emergency management.

Analysis methodology for FEWS will depend on the type of system established. Flood monitoring systems will often utilize the obtained data along with established thresholds (based on historical records or hydrologic and hydraulic simulations) to determine if flooding is occurring or will be occurring if the trend continues. This methodology is similar to the NWS river forecasts that establish site-specific stages for the magnitude of flooding, including "No Flooding", "Near Flood Stage", "Minor Flooding", "Moderate Flooding", and "Major Flooding". This type of hydrologic analysis can use rain and stream gauge data along with any observations or previous events. Because flood monitoring systems do not rely on forecasting or predictive methodology, flood alert information is released to the public for flooding that is observed as *immediately occurring*. However, communities can still utilize information from rain gauges and stream gauges, especially from upstream locations, to anticipate that flood conditions are *near occurring* or *will be occurring* and decide to monitor areas more closely and deploy personnel or equipment. Flood forecasting systems, on the other hand, will make use of models or modeling software for hydrologic and hydraulic analysis. While communities that utilize more intensive models or modeling software often employ contractors (typically from engineering consulting firms) to assist with this task, opportunities for models and modeling are present for all communities, even those with fewer resources and less technical expertise.

The primary consideration for analysis and modeling during the planning stage is to consider: (1) what analysis and/or model(s) would help meet the goals and objectives of the system, and (2) what data will be needed to perform the intended analysis or to run the intended model(s). Any model selected for use in a FEWS should be appropriate for the data provided by system equipment (i.e., rainfall, stream stage, and stream discharge) as well as data available in the coverage area (i.e., soils, land use, and topography). In this way, model selection can be finalized and combined with the selection of appropriate equipment and locations to provide the necessary data. Technical details on data for hydrologic and hydraulic analysis, as well as their model selection approaches, are covered in **Appendix A**.

2.5 Existing Resources

Before deciding to implement FEWS, communities are encouraged to gather preliminary information on their community related to flooding by utilizing existing resources. While some of this information may come from personal experience or anecdotes from personnel who have dealt with community flooding issues ("institutional knowledge"), other information is available from federal, state, regional, or local agencies. In the planning process, community personnel should utilize existing resources to gather flooding information about their community. Communities are encouraged to keep in mind that most successful FEWS are designed to meet current needs while allowing for the addition of lower-priority items over time as budget allows. Communities are encouraged to use federal, state, regional, and local resources to plan for developing FEWS. The existing resources presented in this section are intended to function as valuable sources of information and data that can be easily viewed and/or downloaded, though more complex data is available. An emphasis on maps is placed in the tables in **Section 2.5** (**Table 3** and **Table 4**), while the tables presented in **Chapter 6** (**Table 11**, **Table 12**, and **Table 13**) focus on examples of FEWS websites, additional documents related to FEWS, and additional websites or links with more expansive information, respectively. Communities should also contact agencies that operate FEWS to learn as much as possible about operating and maintaining a system.

2.5.1 Federal Resources

The U.S. Geological Survey (USGS) and the National Weather Service (NWS) — part of the National Oceanic and Atmospheric Administration (NOAA) — work together to maintain and operate a riverine flood warning system and monitor coastal flood hazards across the country. The USGS is responsible for most surface and groundwater data at the federal level, operating most of the existing stream gauging stations in the U.S., including gauging of the local river networks, regional water districts, river authorities, and ground water districts. NWS uses the data from USGS and other sources to issue river forecasts and flood alerts for rivers and streams on a regional basis. Through NWS, communities can obtain relevant river forecasts through the Advanced Hydrologic Prediction Service (AHPS). At the forecasted locations, observed stage, rainfall, and hydrologic simulation are used to determine the current and forecasted stages. The NWS RFC provides hydrologic forecasts at selected locations with defined flood categories (in feet) as Action Stage, Flood Stage, Moderate Flood Stage and Major Flood Stage. In addition, weather alerts (warnings, watches, advisories, etc.) are sent out through the NOAA Weather Radio All Hazards network and received by the public through radios, media outlets, and social media platforms. Additionally, NWS sends Wireless Emergency Alerts to cell phones in affected areas. Information and data from the USGS and the NWS are often utilized in FEWS due to the amount of data available and the relevance to FEWS.

Further, for Texas and surrounding states, both USGS and the NWS, along with USACE and the FEMA, participate in the Interagency Flood Risk Management (InFRM) team, which brings together multiple federal agencies to address flooding-related issues for the States of Texas, Oklahoma, New Mexico, Louisiana, and Arkansas. By applying their shared knowledge, InFRM can directly help communities in their land use and floodplain management practices. Local communities also can partner with the InFRM team to incorporate warning systems. InFRM, along with support from TWDB and other regional/local partners, hosts the Flood Decision Support Toolbox, which includes streamflow information, simulated river stage scenarios, and building damage estimates. **Figure 7** illustrates an example of the Flood Decision Support Toolbox, showing the flood-inundation map and affected buildings when the river stage reaches 38 feet (a scenario option) at the USGS station on the Medina River at Bandera, Texas. In addition to flood-inundation maps for each river stage option, a report on the affected buildings and associated damage estimates is available. For this scenario option, multiple buildings are estimated as having greater than 5 feet of water, causing significant estimated damages. The detailed summary of the estimated damages available in the report includes all buildings in the flood map limits and is separated by building type (agricultural, commercial, industrial, public, residential, and vacant or unknown) and by the estimated depth of water.

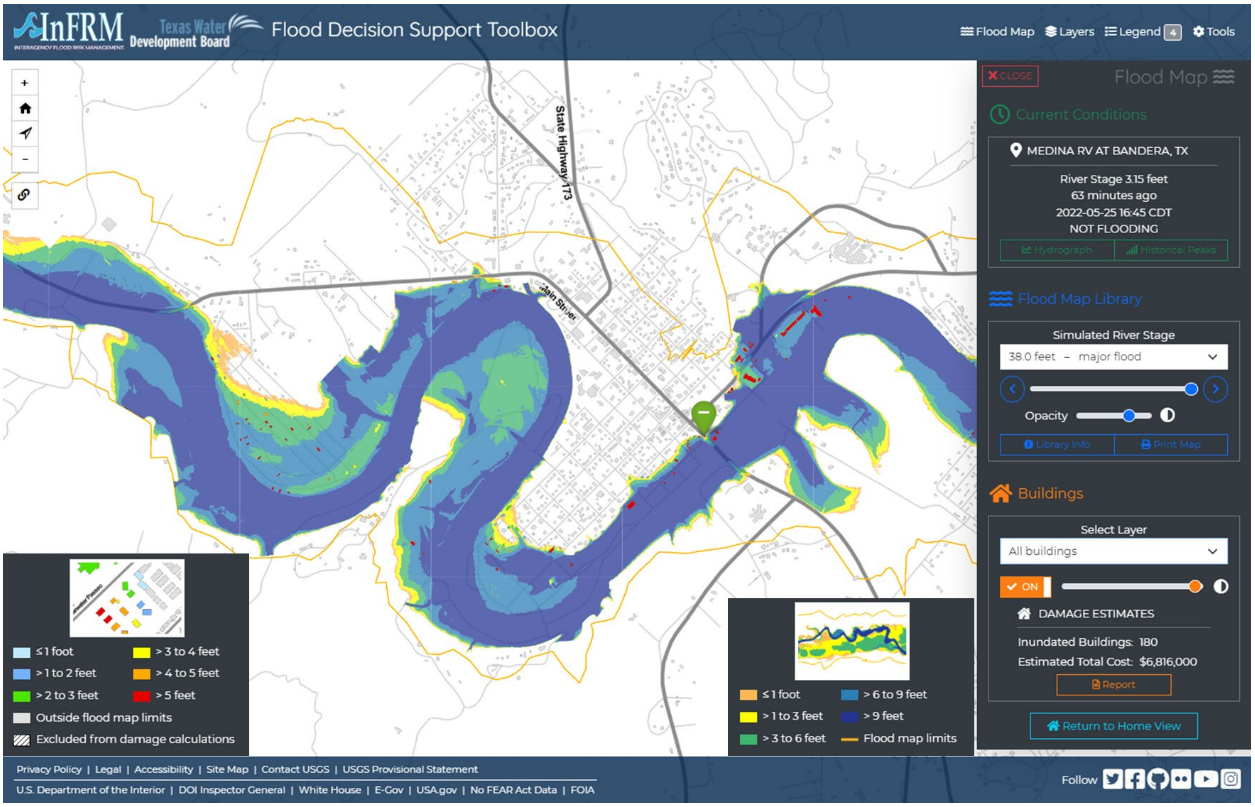

Figure 7. Flood-inundation map at Medina River at Bandera, Texas.
Source: InFRM Flood Decision Support Toolbox

Many federal agencies have programs, data, and models that can assist regional and local communities in promoting sound flood risk management and reducing flood damages. The Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) is not related to the government, but it is a national resource that partners with the NWS that provides Daily Precipitation information. In addition to various public outreach campaigns that can help inform community members, FEMA Flood Map Service Center has flood hazard information in official flood maps as part of the National Flood Insurance Program viewable from the Flood Map Service. NOAA provides information on Tides and Currents for coastal areas. The Natural Resources Conservation Service (NRCS) allows users to view soil maps and data in their Web Soil Survey. The USACE's National Inventory of Dams and National Levee Database allow users to find information on dams and levees, respectively, throughout the nation, including those not operated by USACE. The U.S. Bureau of Reclamation allows users to view information and retrieve data on Texas Lakes and Reservoirs owned/operated by the U.S. Bureau of Reclamation (USBR). The USGS operates the Texas Water Dashboard, which can be used to view information and retrieve data on streams, lakes, wells, water quality, rain, and station cams in Texas. The USGS allows users to sign up for email and/or text message alerts from the dashboard or through the direct WaterAlert website. The USGS also operates the WaterWatch website, allowing access to current streamflow information as well as drought, flood, and past flow/runoff information. The

USGS Streamer traces upstream or downstream information on a user-specified location on a map to show upstream and downstream areas along with weather radar and near real-time streamflow. **Table 3** includes a variety of federal resources listed first by issuing authority or region, then by name, along with a suggested usage. Note that where possible, the Texas-specific information is linked, though many federal resources are available nationwide. Additional resources from federal or national entities that provide more detailed information are provided in **Table 13** in **Chapter 6**.

Table 3. Federal resources for FEWS planning

Name	Issuing Authority or Region	Link(s)	Suggested Usage
Daily Precipitation (Texas)	CoCoRaHS*	cocorahs.org/state.aspx?state=tx	View information and retrieve data on precipitation (including rain, hail, and snow) from a community-based network
Flood Map Service Center & National Flood Hazard Layer	FEMA	msc.fema.gov/portal/home fema.gov/flood-maps/national-flood-hazard-layer	View information and retrieve data on flood hazard maps created under the National Flood Insurance Program; available data includes the National Flood Hazard layer, consisting of the current effective flood hazard data (includes maps)
Flood Decision Support Toolbox	InFRM	webapps.usgs.gov/infrm/fdst/?region=tx	View information on whether stream gauge sites are flooding, not flooding, or flood stage has not been established and whether stage is increasing, decreasing, or constant; for individual sites, view simulated river stage based on flooding scenarios (map)
Tides and Currents (Texas)	NOAA	tidesandcurrents.noaa.gov/map/index.html?region=Texas	View information and retrieve data on water level, meteorological conditions, and currents for coastal areas
Web Soil Survey	NRCS	websoilsurvey.sc.egov.usda.gov/App/HomePage.htm	View information and retrieve data on soil (map)
River Forecasts (Texas)	NWS	water.weather.gov/ahps/region_forecast.php?state=tx	View information and retrieve data on river forecasts in Texas (map)

Name	Issuing Authority or Region	Link(s)	Suggested Usage
River Observations (Texas)	NWS	water.weather.gov/ahps/region.php?state=tx	View information and retrieve data on river observations in Texas (map)
National Inventory of Dams	USACE	nid.usace.army.mil/#/	View information (including owner) on dams (includes maps)
National Levee Database	USACE	levees.sec.usace.army.mil/#/	View information (including owner) on levees (includes maps)
Texas Lakes and Reservoirs	USBR	usbr.gov/gp/lakes_reservoirs/texas_lakes.html	View information and retrieve data on lakes and reservoirs in Texas owned/operated by the United States Bureau of Reclamation
Current Water Data for Texas	USGS	waterdata.usgs.gov/tx/nwis/rt	View information and retrieve data on stream gauge sites including current or past conditions
Streamer	USGS	txpub.usgs.gov/DSS/streamer/web/	View information on traced upstream and downstream locations along rivers and streams along with weather radar and near real-time streamflow conditions (map); download trace reports
Texas Water Dashboard	USGS	txpub.usgs.gov/txwaterdashboard/	View information and retrieve data on streams, lakes, wells, water quality, rain, and station cams in Texas (map)

Name	Issuing Authority or Region	Link(s)	Suggested Usage
WaterAlert	USGS	maps.waterdata.usgs.gov/mapper/wateralert/	View information on stream gauge sites with the ability to subscribe to email and/or text message alerts when a user-defined threshold condition is met (includes maps)
Waterwatch	USGS	waterwatch.usgs.gov/	View information and retrieve data on real-time, recent, and past streamflow, drought, and flood conditions (includes maps)
Estimated Base Flood Elevation (estBFE)	USGS, FEMA	webapps.usgs.gov/infrm/estBFE/	View information and retrieve data on estimated base flood elevations (map)

*While CoCoRaHS is not a federal governmental entity, it is a national entity that has federal partners and thus is included in the table.

Federal and national resources are not the only source of existing resources that can assist with planning FEWS. Communities are also encouraged to reference non-federal resources during the planning process of FEWS, as many state and regional entities have useful information that can often be more relevant to Texas communities.

2.5.2 Non-Federal Resources

Non-federal sources of information and data include but are not limited to the Texas Water Development Board (TWDB), the Texas Department of Transportation (TxDOT), regional councils (i.e., the regional council of governments), counties, river authorities, cities, and various districts (e.g., water, drainage). While available resources vary significantly based on a community's location, some resources are available from state or regional agencies for most communities to use when planning FEWS.

Some non-federal resources are presented in order of issuing authority or region, along with the suggested usage in **Table 4**. TWDB hosts the TexMesonet (**Figure 8a**), which provides real-time maps based on information from weather sensors (including rainfall, soil moisture, and wind conditions). TWDB also hosts Texas Flood Information Viewer (**Figure 8b**) about river flooding conditions and Water Data for Texas concerning reservoir and groundwater information. The Texas Parks and Wildlife Department (TPWD) hosts the Texas Watershed Viewer, which is an online map to view information on watersheds, sub-watersheds, river basins, and river sub-basins for any location in Texas. TxDOT hosts Drive

Texas, which allows users to view current travel conditions on Texas roadways. Communities can verify relevant Texas Regional Councils, which may have warning materials, and Texas River Authorities, which may also have relevant FEWS or data, using information from the Texas Association of Regional Councils and TPWD, respectively. TexasFlood.org provides flood information with links to other flood resources in an accessible format for the Texas communities. Coastal communities can also leverage the resources from the Texas Integrated Flooding Framework for model development, visualization, and risk planning.

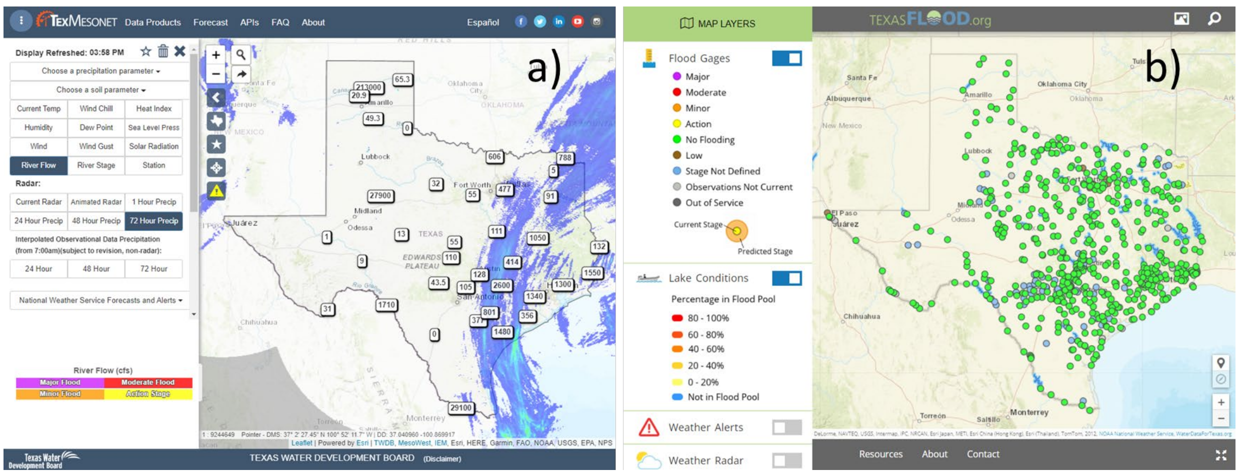

Figure 8. a) TexMesoNet, and b) Texas Flood Information Viewer

Additional resources include the TWDB Flood Planning Regions, which were established in 2020 and whose associated Regional Flood Planning Groups will develop regional flood plans while considering a variety of local and regional interests. The presence of FEWS is included in the planning process for the calculation of the "area vulnerability rating", where a region with a "*Flood warning system in place for all possible sources of flooding*" is designated as a "low-risk area", "*Flood warning system in place for some of the possible sources of flooding*" as a "medium risk area", and "*No flood warning system*" as a "high-risk area", respectively. As part of the flood planning effort, TWDB has compiled relevant data into a Flood Planning Data Hub. For additional information regarding regional flood planning, please refer to the 2021 Technical Guidelines for Regional Flood Planning (TWDB, 2021). The intention of **Table 3** and **Table 4** is to provide quick references with tangible information about existing resources with a heavy emphasis on maps. Additional resources from federal, state, and local governmental agencies and non-governmental organizations are provided in **Table 13** in **Chapter 6**.

Table 4. Regional and local resources for FEWS planning

Name	Issuing Authority or Region	Link(s)	Suggested Usage
Texas Regional Councils	Texas Association of Regional Councils	txregionalcouncil.org/regional-councils/	View information on Texas regional councils with individual links (map)
Texas River Authorities	TPWD	tpwd.texas.gov/landwater/water/habitats/rivers/authorities.phtml	View information on Texas river authorities with individual links (list).
Texas Watershed Viewer	TPWD	tpwd.texas.gov/education/water-education/Watershed%20Viewer	View information on watersheds, sub watersheds, river basins, and river sub basins for any location in Texas (map)
Texas Flood Information Viewer	TWDB	map.texasflood.org/	View flood gauge, lake conditions, weather alerts, and weather radar for Texas from various data sources (map)
Texas Flood Planning Data Hub	TWDB	twdb-flood-planning-resources-twdb.hub.arcgis.com/	View information and retrieve data on critical infrastructure, flood infrastructure, flood risk, hydrology, jurisdiction boundaries, parks, population, property, terrain, and transportation
Texas Flood Planning Regions	TWDB	twdb.texas.gov/flood/planning/index.asp	View information on Texas flood planning regions
TexMesonet	TWDB	texmesonet.org/	View information and retrieve data on precipitation, soil parameters, and radar from various data sources (map)

Name	Issuing Authority or Region	Link(s)	Suggested Usage
Water Data for Texas	TWDB	waterdatafortexas.org/	View information and retrieve data on reservoirs, drought, groundwater, coastal, and lake evaporation/rainfall (maps); links to TexMesonet
TexasFlood.org	TWDB, TDEM, GLO	texasflood.org/	View flood information for public education and links for other flood resources
Texas Integrated Flooding Framework	TWDB, USACE, USGS, GLO	webapps.usgs.gov/tiff/	View information about the risk of flooding in counties affected by Hurricane Harvey
Drive Texas	TxDOT	drivetexas.org/	Used to view current travel conditions for Texas roadways (map)

2.6 Vendor and Contractor Selection

FEWS design, installation, and maintenance are typically less expensive when conducted internally, but not all communities have the resources, experience, or workforce. Communities often utilize vendors and contractors to install gauges and other FEWS equipment and sometimes include their services for maintenance. Communities are encouraged to identify qualified vendors and contractors in an early stage of planning to be used for FEWS deployment. The selection of vendors and contractors can significantly impact system success. Before selecting appropriate vendors or contractors, communities are encouraged to ask extensive questions about their prior works with FEWS, including system performance and growth. References from past clients should also be provided. Communities are encouraged to do their due diligence when looking into vendors and seeking long-term solutions. Vendors or contractors should emphasize FEWS as safety tools and conduct business accordingly. In other words, vendors and contractors should continuously focus on providing services to meet the overall needs of the system rather than focusing on quick deployment. Qualified vendors and/or contractors should be able to provide references of their FEWS-related experience to ensure competency in both system installation and continued service. For example, some contractors have provided training for internal staff on maintenance procedures. By using the same contractor for both installation and maintenance and/or occasional service, knowledge of the system and its components can be retained.

Communities will need to follow the relevant local and state procurement regulations, and if a FEWS project is supported with federal funding, perhaps certain federal regulations as well. Generally, procurement responsibilities include advertisement, delegation, competitive bidding, ethics & oversight, and posting for public view. For state agency-funded procurement, regulations to be followed depending on the contract category and value. The Texas Procurement and Contract Management Guide provides detailed information regarding procurement for further reference. An example of the *Procurement Value Threshold Chart* is provided in its Appendix 8 as a useful reference. Details on the procurement process and how vendors and contractors fit into the process of deploying FEWS are provided in **Section 4.1.4**.

2.7 Other Planning Considerations

Other considerations that have significant impacts on the planning stage of FEWS are discussed in the following chapters. Costs, funding, and budget information (**Chapter 3**) can impact the system significantly, including what equipment, data, models, vendors, and contractors can be used. Operations and maintenance, especially in terms of staff, personnel, vendors, or contractor responsibilities (**Chapter 4**), are also part of the considerations during the planning stage.

3 Financing Flood Early Warning Systems

FEWS development requires functional data collection equipment, data storage & processing infrastructure (e.g., telemetry, servers), and a platform for information dissemination, contributing to the overall project cost. Generally, the cost can be estimated in terms of two aspects: 1) project cost, including design and procurement (**Section 3.1**), and 2) recurrent costs (**Section 3.2**), particularly operations and maintenance. While cost is identified as a challenge by many communities, multiple grants or loans are available from federal, state, and local agencies, some of which are described in **Section 3.3**. Additional information on potential funding opportunities can be found at the Texas Flood Information Clearinghouse. Communities are encouraged to seek grants and other funding opportunities to establish FEWS.

While grant funds are available for FEWS, steady funding streams are required to ensure the longevity and long-term reliability of the FEWS. The budget should not decrease during drought periods or dry years to maintain the system's optimal performance. Communities are encouraged to maintain and operate the FEWS continuously, plan for and incorporate long-term costs and benefits into the budget and consider the useful life of equipment and replacement costs along with the progression of technology when considering the costs and benefits of FEWS.

Early in the process, FEWS planners must decide how much of the design, implementation, and operation phases should be performed by existing or additional internal personnel versus contractors. This decision is community-specific and will depend on available resources. Contractors can perform tasks ranging from design and IT support to system operation. Similar jobs may also be carried out by internal staff, other agencies, and even volunteers at lower costs, but typically with a much higher level of coordination required. FEWS planners are encouraged to consider using contractors where appropriate.

Conventionally, most communities to date have not performed traditional cost-benefit analyses (or benefit-cost analyses) for the establishment of FEWS due to the challenging task of quantifying losses of life in a financial sense. Additionally, some benefits of FEWS are not easily quantified, such as additional local flood knowledge. Instead, communities tend to address a known issue (e.g., low water crossing vehicle accidents) with an often-implemented solution (e.g., a flood warning system with a gauge at that location). While cost-benefit analysis is not typically required for FEWS, communities concerned about proper sizing or sustainability of the system can utilize tools (e.g., FEMA benefit-cost-analysis) and studies (e.g., Guidelines for Estimating Life Loss for Dam Safety Risk Analysis) to assist in performing a cost-benefit analysis if desired.

The estimated cost of initiating and maintaining FEWS will depend highly on the purpose of the system and the size of the intended coverage area. The overall project cost of FEWS is highly variable. Projects funded using TWDB grants in the Fiscal Years 2016 and 2018 had total costs ranging from $23,000 to $1.5 million, with project scopes ranging from adding certain equipment, such as sirens, to assembling an entire FEWS. Costs can be split into project costs, explained in **Section 3.1**, and recurrent costs explained in **Section 3.2**.

3.1 Project Costs

Project costs are the initial costs of designing and implementing FEWS. **Table 5** shows an example of a budget based on the tasks needed for a FEWS project, including typical tasks and estimated cost ranges. Please note that the cost range can vary significantly due to the size of the FEWS, local watershed features, and the equipment and services used. The cost of each task is generally higher if using contractors. The data contained in **Table 5** is based on Flood Infrastructure Fund (FIF) Category 4 Projects funded by TWDB in the Fiscal Year 2020. The costs of individual tasks vary greatly as a percentage of the overall project cost, but implementation (where procurement, installation, calibration, testing, and training occur) is the largest percentage of the project cost for all projects in the sample. Permitting, project management, and documentation are typically small portions of the initial project budget. The Data Collection & System Design task has the most variable costs and sometimes makes up a significant portion of the budget. An additional consideration for each task is the time it needs, which is discussed in **Section 4.2**. While the cost of permitting is generally a relatively low percentage compared to the total project cost, it is usually time consuming and could result in project delays.

Table 5. FEWS project cost ranges by task

Task	Description	Range of Task Costs	Percentage of Total Project Cost*
Data Collection & System Design	Data Collection and Evaluation, Gauge Placement, Identification of Standards and Communication Protocols, Plan, etc.	$ 4,000 - $ 200,000	**2% - 30%**
Permitting	Federal Communications Commission Licenses; Land Use, etc.	$ 1,500 - $ 15,000	**1% - 3%**
Implementation	Procurement, Installation, Calibration, Testing, Training, etc.	$ 185,000 - $ 450,000	**70% - 90%**
Management	Project and Grant Management, Financial Advice, Fiscal/Legal, Outreaching, etc.	$ 4,500 - $ 45,000	**3% - 10%**
Documentation	Project Executive Summary Report, User Manual, etc.	$ 5,000 - $ 10,000	**3% - 5%**

*For each Fiscal Year 2020 project, the percentage of each task out of the total budget was calculated. The ranges were then established using the lowest and highest percentages out of all Fiscal Year 2020 projects. It is noted that the percentages themselves do not directly correlate with the ranges of task costs provided.

For some grant applications (e.g., TWDB FIF program), the project budget should also be submitted based on the expenses, including items such as 1) Salaries and Wages; 2) Fringe; 3) Travel; 4) Subcontract Services; 5) Equipment; 6) Overhead, and 7) Other Expenses. It is noted that operations and maintenance costs are not part of the initial project cost and thus not included in the FEWS task budget table (**Table 5**). Recurrent costs, such as operations and maintenance, are discussed in the following section.

Data collection and system design are usually required at the beginning of a FEWS project, which involves gauge placement to find the proper locations to meet the operational requirements and budget limitations. Detailed information on site selection for gauges (also referred to as “siting”) can be found in **Appendix B**. Other data collection and system design tasks include surveys to understand drainage basin delineations during various conditions, as well as reviewing the standards and protocols of the FEWS equipment. While not all communities will conduct professional surveys, communities will need to gather information on the potential sites. The tasks of FEWS implementation, including procurement, installation, calibration, and testing, almost always occupy the largest share of the overall project cost. The project needs to be carried out by effective management for timely deliverables, but it also needs personnel in support of grants, finances, and legal advice. Permitting costs should also be included in the project costs. Communities may need permits, licenses, and permission to use land when placing gauges or other equipment. For example, approval and permits may be required from TxDOT for placement on a TxDOT bridge. Local permit requirements will still apply to equipment placed in the right-of-way of roads. Certain licenses, such as communications (e.g., Federal Communications Commission License), may also be required. Communities should follow all state and federal requirements. Costs should also include documentation, such as a project report and user manual. Communities are encouraged to establish a clear protocol for future operations. Project costs also include the costs for equipment, referred to as “instruments” in **Table 6**, which provides estimated costs for various instruments and services that are part of FEWS projects. The data contained in **Table 6** is based on FIF Category 4 Projects funded by TWDB in the Fiscal Year 2020 and is provided as an example. It is noted that the line items mentioned in this table are just examples of specific items utilized in the FIF projects and are not necessarily representative or required for all FEWS. Unless otherwise noted, the instrument costs do not include installation costs.

Table 6. FEWS project cost by instrument or service

Instrument or Service	Approximate License or Unit Price*
Base Station	
ALERT2™ Software	$10,000
Integrator Assistance	$8,000
Radio Frequency Hardware	$10,000
Radio Frequency Installation	$5,000
Receiver Equipment	$5,000
Cellular telemetry subscription	$2,000
Cloud backup database annual subscription	$12,000
Gauge Sites	
Data logger control box and board relays	$1,300
Data logger/flasher beacon cabinets	$1,000
Enclosure and Hardware	$2,500
Flasher beacon including box	$1,000
Galvanized conduit	$300
Integrator Installation Fees	$3,000
Precipitation Sensor	$1,000
Solar Panel, Battery, and Antenna	$500
Stream sensor (pressure transducer, ultrasonic, contact based)	$500
Transmitter	$2,000
Water Level Sensor	$1,000
Sirens	
Siren (1.5 Mile Range, 148 dB Peak Output, Omni-Directional) and Installation	$31,000
Cameras	
Camera, Pole, Antenna, and Cell Modem	$7,500
Consulting and In-House Services	
Construction Observation and Inspections	$25,000
Technical Services (Siting)	$15,000
Survey Benchmarks	$5,000

* The listed prices are from 2019 and may not be reflective of the current prices. Information from FIF FY20 projects.

3.2 Recurrent Costs

Long-term operations and maintenance (O&M) and replacement costs must be emphasized in projected or annual budgets, meaning that communities should consider the life cycle of various equipment and the best time to repair or replace components or equipment. Communities are also encouraged to emphasize proper asset management, including records of equipment, software, and maintenance. Systems without adequate budgetary support for O&M and replacement eventually experience a decrease in performance due to unreliable measurements or reporting. When this happens, users lose confidence in the information, and the investment in the FEWS effort is wasted. Without adequate O&M, the equipment can also become obsolete or unusable. Details on the management of O&M are discussed in **Section 5.2**.

A system that has not been properly maintained cannot provide the necessary information for running the system. Consistently, proper maintenance can avoid unnecessary repairs or, in some cases, system failure. To ensure the systems' operational longevity and reliability, communities are encouraged to prioritize long-term investment in FEWS. Cost planning for a sustainable O&M program must cover all elements of the FEWS: gauges, communications media, software and computer, outreach, preparedness, response, and, most importantly, sound administrative management of the O&M budget. For example, the FEWS O&M budget in one major Texas city includes a variety of expenses like 1) contractual obligations to vendors (gauge-adjusted radar rainfall, predictive modeling, communications for gauge data, cameras at low water crossings, maintenance of the FEWS website, etc.); 2) repair of rain/stage gauge equipment, flashing lights and float switches at low water crossings, cameras, etc.; and 3) salaries for dedicated FEWS staff and IT staff. Accessibility and travel time are additional O&M items that may have a significant impact on the budget and thus should be considered during the planning stage.

Although FEWS equipment is built for durability and typically has long-life spans, all environmental sensors are subject to potential damage. Even simple things like insects, pollen, bird droppings, and fallen leaves may impact gauge performance, and regular maintenance must include gauge cleaning. Vandalism of easily accessible equipment is an additional concern that can be better addressed with some forethought in equipment location and housing and proper O&M.

Communities are encouraged to establish and follow preventive maintenance schedules for each type of hardware component. Along with equipment maintenance, communities are encouraged to continuously train FEWS users and keep their roles and responsibilities updated. The FEWS owner must also prepare for equipment replacement. While life spans for gauge and communication equipment typically range from 10 to 15 years, tipping buckets, batteries, solar panels, and antennas require replacements more frequently. If equipment and software become outdated or no longer supported by the manufacturer, the life span may also be shortened. O&M should be budgeted at roughly 10-15% of the initial costs per year (NWS 2012). Replacement costs are a separate consideration that will depend significantly on what components or equipment need to be replaced and when.

Replacement costs for the equipment itself could be as much as new equipment or as little as the replacement of one sensor. However, many initial costs associated with the planning stage are not repeated, such as site selection and initial permitting. Replacements can also be done on an offset schedule, in which you avoid too much equipment reaching the end of its useful life simultaneously by replacing or upgrading a portion of the equipment before it begins malfunctioning.

3.3 Funding Sources

Funding for FEWS is available through federal financial assistance grants to implement flood risk mapping and flood mitigation, planning, and protection activities, regional or state funding, or local funding. Funding can vary depending on the timing of the application (e.g., Presidential Disaster Declarations), FEWS components, and the community locations. This section intends to describe various grant and loan funding opportunities available for communities to establish FEWS.

Funding opportunities available through the federal government can be accessed from their main grant website (www.grants.gov). Communities may also be able to identify additional funding from private foundations and state agencies. A summary of existing programs with the associated funding is available as part of the 2019 Texas Flood Assessment, particularly *Appendix A- "Estimating financial need for mitigation"*. The Texas Flood Information Clearinghouse Committee is made up of members from the Texas Division of Emergency Management (TDEM), the Texas General Land Office (GLO), the Texas Water Development Board (TWDB), the Texas State Soil and Water Conservation Board, the Texas Department of Agriculture, and the Texas Commission on Environmental Quality. Communities can submit a "Request for Information Form" to receive advice from the committee on potential funding sources. For further information and to submit the form, visit the Texas Flood Information Clearinghouse. Some grants and loans that may be appropriate for use with the establishment of FEWS are presented in **Table 7** (Texas Flood Information Clearinghouse 2020).

Table 7. Grants and loans for FEWS projects

Name	Administering Entity	Disaster-dependent	Grant/Loan	Grant Percentage
Hazard Mitigation Grant Program	TDEM	Yes	Grant	Varies; up to 90%
Flood Infrastructure Fund	TWDB	No	Both	Varies; up to 90%
Texas Water Development Fund	TWDB	No	Loan	N/A
Community Development Block Grants – Mitigation	Texas GLO	Yes	Grant	100% (No local match requirements) *
Development Block Grants – Disaster Recovery	Texas GLO	Yes	Grant	100% (No local match requirements) *

*Community Development Block Grant funds may be used to pay a local/non-federal matching requirement for some other grants if the grant provider recognizes the block grants as local funds and the activity follows all block grant program guidelines.

The FEMA Hazard Mitigation Grant Program (HMGP), administered by the Texas Division of Emergency Management (TDEM), provides disaster response and recovery assistance to prevent or reduce future losses of lives and property through the identification and funding of cost-effective mitigation measures, and to minimize the costs of forthcoming disaster response and recovery. A Presidential Disaster Declaration must be available to be eligible for these funds. HMGP can fund up to 75% of eligible hazard mitigation projects, including FEWS, for affected communities. FEWS and other non-structural flood mitigation initiatives fall under the HMGP's "5 percent initiative", a funding stream for activities that are difficult to evaluate with traditional BCA methodologies. Under the initiative, up to 5% of total HMGP funds may be set aside by the primary recipient (TDEM) to pay for these activities. More information, such as program requirements, is available at TDEM's Hazard Mitigation Section.

In Texas, the TWDB Flood Infrastructure Fund (FIF) program is a state-funded source of financial assistance for flood mitigation projects. It supports the establishment of flood early warning systems for projects deemed to be Category 4: "projects that can be implemented quickly and are understood to be immediately effective in protecting life and property." Various aspects of FEWS are available for Category 4, including entire warning systems, roadblocks, gauges, and public education and outreach. According to FIF requirements, the application of the FEWS project should include the flood-hardening level of the FEWS system (i.e., FEWS equipment able to withstand 2% or 1% annual chance of storm events, etc.). Development of a benefit-cost ratio (BCR) is not required for a FEWS project.

FEWS equipment should be flood-hardened to maintain full system functionality during extreme events (i.e., 100-year, 500-year floods). Additionally, FEWS equipment should follow standards equivalent to the National Flood Insurance Program minimum requirements (FIF, 2020). Prior to any equipment procurement, communities should complete an Engineering Feasibility Report (EFR) and start an Environmental Review to produce a Determination of No Effect forms. Depending on the environmental finding and coordination with other agencies, this can take several months to a year to complete. The EFR must be sealed by a professional engineer and contain the following information: a description and purpose of the project, the entities to be served and current and future population, the cost of the project, a description of alternatives considered, and reasons for the selection of the project proposed, sufficient information to evaluate the engineering feasibility of the project, maps and drawing as necessary to locate and describe the project area. Lastly, a final report must be submitted to TWDB. More information about FIF project requirements may be found in the FIF program guidance manual, and additional information, such as application documents and pre-application webinars, are available on TWDB's FIF program page.

The Texas Water Development Fund (DFund) is a streamlined state loan program available to all political subdivisions of the state. The DFund provides financing for various types of infrastructure projects and enables funding of multiple eligible components into one loan for the borrowers, e.g., an application for funding of water and wastewater components can be processed in a single loan. FEWS are eligible to receive financial assistance from the DFund as flood control projects. The DFund does not receive federal subsidies and is not subject to federal requirements. Loans are available through this program for FEWS as a flood control measure. Eligible applicants for the DFund include all political subdivisions of the state (at tax-exempt rates) and nonprofit water supply corporations (at taxable rates). Political subdivisions include cities, counties, districts, and river authorities. Other special requirements, such as a water conservation and drought contingency plan, or U.S. Iron and Steel Manufactured Goods requirements, may also need to be met. More information, such as the loan process and other requirements, is available on TWDB's DFund program page.

The Texas General Land Office (GLO) administers the 1) Community Development Block Grants – Mitigation (CDBG-MIT), which will be used to build and implement structural and non-structural projects, programs, and partnerships throughout the state of Texas that reduce the risks and impacts of future natural disasters; and 2) Community Development Block Grants – Disaster Recovery (CDBG-DR), which provides flexible grant-based assistance to help cities, counties, and states recover from certain disasters declared by the President of the United States, subject to congressional funds appropriation. Communities within the Combined River Basin Flood Studies area (49 counties impacted by Hurricane Harvey and 4 Lower Rio Grande Valley counties impacted by severe flooding in 2015) should review documents from the GLO-funded effort. More information is available on CDBG-MIT and CDBG-DR program pages.

Regional and local sources of funding vary significantly across the state. Some examples of local funding include stormwater utility fees; capital improvement plans or programs (CIP); bond programs; cost sharing with other departments such as transportation, utility, or emergency management departments; and general funds. Local funding may also include cost-sharing or in-kind service agreements with adjacent communities, utility, drainage, special purpose districts, or local businesses that may benefit from having nearby gauges. For example, the Bandera County River Authority and Groundwater District partnered with several local entities for the project, received TWDB grant funding, and entered a joint funding agreement with the USGS for gauge installation. One of the flood inundation maps of the project is shown in **Figure 7**. Local funding varies from community to community, dependent on population and other factors. Regional funding, on the other hand, may be provided through relevant regional/state agencies, such as river authorities or the Texas Water Development Board (TWDB). Communities can utilize the Request for Information Form found on the Texas Flood Information Clearinghouse to get additional feedback on relevant federal and state funding sources. FEWS are often funded from a variety of sources.

4 Deploying Flood Early Warning Systems

4.1 Project Tasks

Deployment of a FEWS involves some general project tasks that can be broken up into several project phases, including outreach, data collection and site selection, design, procurement and installation, and testing and closeout. Before the deployment phase, communities are encouraged to establish lines of communication with appropriate stakeholders, potential collaborators (including NWS), and the public. Additionally, communities are encouraged to gather information and data from existing resources in the planning phase. The deployment phase formalizes and finalizes the efforts from the planning stage while incorporating financial information from the financing stage.

4.1.1 Task 1: Coordination

At the project kick-off, the scope, schedule, and responsibilities should be formally established and agreed upon by all parties. FEWS planners should coordinate and engage with stakeholders and the public to ensure that the final product is usable by the entire target audience. Coordination should include the NWS, other local/regional FEWS, and authorities with relevant gauges, among others. Components of the FEWS may be incorporated into the National Flood Insurance Program's Community Rating System (CRS) under the flood mitigation plan, if applicable. CRS is a voluntary program that provides discounted flood insurance rates to all citizens in a community based on their community's level of involvement in CRS through improved floodplain management standards and practices. The coordination allows for engagement with local flood mitigation public committees and public hearings. Detailed information on communication, coordination, and collaboration among FEWS stakeholders in the planning stage can be found in **Section 2.2**.

4.1.2 Task 2: Data Collection and Site Selection

Data collection should include identifying data quality standards and communication protocols. This will help ensure FEWS assets align with existing state and national data collection efforts and allow for consistency and compatibility between existing FEWS across the state. Additionally, all existing resources (e.g., gauges, sensors, or other equipment) owned by the planning authority or interlocal partners should be cataloged. Geospatial data (e.g., LiDAR topography) and relevant environmental data should also be collected because of their relevance to the flood and water quality modeling performance. The data may be available through existing resources or collaborators, but field surveys may be necessary. Field surveys for high-risk crossings may include location, channel centerline, bank elevations, ground distance to the nearest channel, drainage features (e.g., number, types of culverts, inverts), and bridge deck railroad deck, height and width, any obstructions or ineffective flow areas, including structures, piers, and abutments. Data on available funding through the community itself (e.g., through stormwater fees) and through appropriate loan or grant programs should be obtained and explored to ensure the system can be built as desired. Upon completion, the Texas Disaster Information System (TDIS) could also serve as a central hub for collecting and storing disaster-related data.

FEWS planners should also collect and review all previous flood-related studies in the area, including the following: previous drainage studies, drainage complaint reports, flood damage reports, traffic accident data, and existing storm response plans. Survey data from previous studies and public engagement information can provide a foundation for the FEWS project. Infrastructure data such as roadway master plans, existing roads, property line boundaries, natural barriers, and ongoing/planned maintenance projects can help provide context for site selection, a topic explored in further detail in **Appendix B**. Communities could also leverage the resources from the appropriate Regional Flood Planning Group, which may help identify vulnerable and high risks locations during site selection.

4.1.3 Task 3: Design

The design phase involves developing installation plans, specifications, and cost estimates for FEWS instrumentation and other equipment. Installation plans should include the type of the FEWS (monitoring or forecasting), selected gauge locations, equipment, and connectivity (e.g., radio frequency, fiber optics, power system, radio transmitters, etc.), information and communication techniques needed for data transmission, storage and analysis, development of decision support system, and other items required for the system to function. Permission should be acquired for gauge installation or upgrades in TxDOT or other jurisdictional rights-of-ways.

Permits should be obtained as needed (i.e., depending on the amount of new construction required). Relevant permitting entities may include but are not limited to TWDB (Determination of No Effect forms), Texas Historical Commission, Texas Parks, and Wildlife Department, FEMA (Floodplain Development Permit if sites are in current effective 100-year floodplains), etc.

As with any installation, care should be taken to determine whether temporary construction easements, right-of-entry, or other easements are required to perform the work. Also, the design phase should assess whether other utilities may be nearby or in conflict with the proposed gauge site(s).

4.1.4 Task 4: Procurement and Installation

Procurement involves bidding (if applicable), evaluating, and awarding contracts to purchase and install FEWS equipment and software. The exact procurement process and rules depend on the method selected, briefly overviewed in the following sentences. Common procurement methods include Invitation for Bids (IFB), Request for Proposals (RFP), and Request for Qualifications (RFQ). An IFB is a simple solicitation of bids that are evaluated based on best value and adherence to requested specifications. In an IFB, products and services are standardized or uniform, which can lead to difficulty when defining the specifications. Bids will be reviewed by FEWS planning authorities, are subject to a competitive process, and are checked for quality assurance and quality control. For

IFB, bids for the project should be advertised following rules in state and local statutes as briefly mentioned in **Section 2.7**. One major disadvantage of an IFB is that a solicitor cannot negotiate if more than one bidder responds. Additionally, IFBs do not encourage innovation. Conversely, an RFP solicits sealed proposals and can be negotiated after submission. RFP allows for more considerations than price alone and more complex proposals but generally takes significantly more time. RFPs can also result in more innovative solutions. An RFQ evaluates bidders solely on qualifications, and the price is negotiated after the qualifications-based selection. RFQs emphasize experience and competency but can be time-consuming as it is a two-step process. Commonly, an RFQ for professional services includes the purchase and installation of equipment, circumventing an additional solicitation. For further guidance, please refer to the Texas Procurement and Contract Management Guide.

Installation of the system includes both hardware and software required for any FEWS. The hardware parts will often involve the placement of many gauge (rain and/or stream) sites, some of which may be remote. The details of gauge and principle of site selection are discussed in **Appendix A** and **Appendix B**. At each site, data loggers, electrical wiring, and the gauges themselves will have to be installed. For sites located near roadways, coordination with traffic control may be necessary during installation. Installation requires coordination among personnel, including internal personnel, vendors, and contractors. Information technology staff may be required to ensure proper communication between gauges and the personnel using the information at the office. Depending on the hardware required, there may be additional requirements for office space or equipment. Hardware configuration may consist of the following items, with adjustments and additions depending on the exact project: data logger configuration, electrical layout, wiring, microcontroller programming, range testing, power management, housing unit layout planning, weather-proofing, and initial gauge/sensor calibration. In the installation process of the software, the software development ranges from database management to measurement transmission, involving structured query language (SQL) programming, backend database design, Application Programming Interface (API) development for frontend websites, two-way communication testing, and alert notification testing (e.g., email, Short Message Service, radio, etc.).

4.1.5 Task 5: Testing and Closeout

The final task in FEWS development is testing and closeout to ensure the system is operational before launch. All equipment should be tested (measurement and communication) to ensure full functionality. Any biases, errors, or other issues should be corrected. Preventative maintenance schedules for the various assets should be defined. Stakeholders (particularly operations and emergency response teams) should be trained in using the FEWS through multi-day workshops and simulations of storm events. Additionally, a user manual and training module should be produced to maintain institutional knowledge. In addition to technical documentation, FEWS management should consider documents such as FEWS preparedness plans that integrate gauge data collection with elements of education, public information, response and recovery, and other documents as essential requirements for a successful FEWS. Team organization and management, operations and maintenance, and public information and outreach are covered in detail in **Chapter 5** on FEWS management. As necessary, reports to TWDB or other funding sources should be drafted during this and following phases of the project. The elements of the final report may include the following:

1. Executive summary (overview) of the project
2. Communities and entities involved and dates of contact
3. Public comments
4. Selected sites (e.g., gauge, siren, road gate, etc.)
5. Installed equipment and connectivity (plans, specifications, and costs)
6. Proposed maintenance schedules
7. Proposed monitoring steps
8. Funding plan to cover future costs of maintenance, monitoring, and replacement of equipment
9. Technical descriptions of engineering analyses, methodologies, assumptions, and modeling notes
10. Other pertinent information (e.g., diagrams, graphics, or tables that explain procedures and results)

4.2 Project Timeline

FEWS task completion timelines will vary depending on available existing resources, the scale of the project, and the exact types of gauges, sensors, and other equipment installed. All components should be tested rigorously and calibrated before operating. Internal models should also be tested by using the information from historical events (with initial conditions) and comparing the simulated results with observations as records allow. Note that some tasks may overlap in time, and some may have dependencies (e.g., sites must be selected before equipment can be installed).

The overall project may take roughly 1-2 years to build a FEWS, though existing resources can help expedite the process. For instance, installation time is less if adding a new sensor to the existing gauge than building a new gauge from scratch. Furthermore, the colocation of equipment may allow for easier installation. The most time-intensive tasks are typically design, procurement, and installation. Some tasks may be optional, depending on the scope of the project. Examples of deployment task timelines are provided in **Table 8**. Note that some tasks may be completed concurrently, and additional tasks may be necessary. The data contained in the table is based on FIF Category 4 Projects funded by the TWDB during Fiscal Year 2020. Some tasks (e.g., quality assurance, quality control, and manual drafting) may require more time to finish than the presented timeline. Tasks such as calibration and training are recurrent after the completion of FEWS deployment.

Table 8. FEWS deployment timeline by task category

Category	Instrument or Service	Expected Timeline
Coordination **(Task 1)**	Engage with stakeholders, potential partners, stakeholders, and end-users	1–4 months
Data Collection & Site Selection **(Task 2)**	Survey and catalogue all existing FEWS assets	2 months
	Collect site location data	1 month
	Identify, evaluate, and select final gauge sites	1–3 months
Design **(Task 3)**	Draft necessary plans and specifications	6 months
	Obtain relevant permitting	6 months
Procurement & Installation **(Task 4)**	Communications tower (transmits all nearby gauge data to FEWS server)	6 months
	Gauges (streamflow & rainfall measurement instrumentation)	3–6 months
	Centralized/base station equipment	3–6 months
	Siren (entire housing unit and software to trigger alarm)	2.5 months
Testing and Closeout **(Task 5)**	Measurement calibration (streamflow and rainfall measurement equipment)	1 month
	Quality assurance/Quality control (assess data inputs and identify corrections if needed)	2 weeks
	User Manual and Training	2 weeks
Total	**Initial Deployment (Excludes O&M)**	**12–24 Months**

5 Managing Flood Early Warning Systems

5.1 Team Organization and Management

Communities are encouraged to assemble a qualified FEWS team, including personnel with knowledge of local flooding issues and previous flood mitigation efforts. FEWS managers should have a thorough understanding of the FEWS tasks to be assigned and completed recurrently. FEWS teams should be scalable and flexible.

Typical roles of a FEWS team are shown in **Table 9**. The Director is a person employed internally who manages flood-related projects for the community. The Director's actual title will depend on the type of community. For example, for a city, the Director may be the Public Works Director. The FEWS Project Management team may include one or more people overseeing and managing the system itself, including all related personnel. The FEWS Project Management may be composed of internal or contracted personnel, or a mix of both. The Grant Specialist or Legal Counsel assists with administering the project and helps the project adhere to the grant program or other legal requirements and may be internal or contracted. The System Design Personnel can be internal or contracted personnel who design the system, including the hardware, software, and database. The FEWS personnel are internal or contracted personnel who perform installation, testing, operation, and maintenance for the system. Finally, public outreach personnel assists with the creation or attainment of public education materials. These personnel also perform outreach activities to inform the public of the system. For more complex systems, other personnel might also be involved. For simpler systems, personnel may be filling more than one of these roles.

Table 9. Roles within a FEWS team

Role	Type	Job Description
Director	Internal	Manage flood-related projects for the community
FEWS Project Manager(s)	Internal or Contracted	Manage the system itself
Grant Specialist & Legal Counsel	Internal or Contracted	Assist with administering the project and helps the project adhere to grant program
System Design Personnel	Internal or Contracted	Design the system, including hardware, software, and database
FEWS Personnel	Internal or Contracted	Perform installation, testing, operation, and maintenance for the system
Public Outreach Personnel	Internal or Contracted	Assist with creation of public education materials and that perform outreach activities to inform the public of the system

In practice, the management styles and staff composition may vary significantly depending on the scale of the authority in charge of the FEWS. Small systems may be managed by a few staff members holding multiple roles or having primary responsibilities outside of the FEWS (e.g., emergency management, city/county government, etc.), whereas large systems may have a large, dedicated workforce and perform all aspects of gauge installations and other services using internal personnel. Communities with limited staff are encouraged to have a plan to expand the FEWS workforce in the event of a flood, working with temporary personnel from other or partnering authorities for key tasks (e.g., setting up road signs and network monitoring). Communities are strongly encouraged to establish a documented procedure for all tasks to limit the loss of institutional knowledge due to staff or contractor turnover. Similarly, communities are encouraged to develop a regular training protocol so that senior personnel may pass down anecdotal expertise and best practices. Whether internal or contracted, personnel must be familiar with FEWS equipment, hardware, and software. Communities are encouraged to establish and maintain standardization within the system.

5.2 FEWS Operations and Maintenance

Communities are encouraged to develop and adhere to Operations & Maintenance (O&M) programs. A robust O&M program with regular maintenance scheduling can determine and prevent issues from arising when the FEWS is needed the most during flooding. Communities are encouraged to inspect, clean, test, and calibrate gauges or sensors regularly. This includes all parts of the equipment, including the housing unit, power system, and any other components. Communities are encouraged to routinely test other flood infrastructures, such as flashing lights and roadblocks. Without regular testing, the status of FEWS equipment, like sensors deployed in dry streambeds, may not be known until they malfunction during a storm. Communities are encouraged to test batteries from solar-powered units regularly to ensure battery storage is not an issue in the event of extended time without sunlight due to cloudy weather or obstructions. Measurements can be unreliable and erroneous if a gauge or sensor is filled with sediment, covered with dust or droppings, or compromised.

Communities are encouraged to document and distribute O&M plans to all team members and contract parties. If a system is not well-maintained, it may fail when needed during a storm, reducing the credibility of the FEWS. Designating internal personnel for O&M may allow for more flexibility and affordability, though it may not always be feasible due to staffing concerns. For all systems, regardless of whether internal or contracted personnel performs the O&M, standardization of equipment and software simplifies maintenance. A lack of software and hardware standardization throughout the FEWS established by different vendors can cause use and maintenance issues. Communities will need to select a balance between standardization and specialization in some cases. Older systems may use outdated technology and protocols that are not compatible with new equipment. Communities are encouraged to select equipment that will minimize expensive and constant upgrades or updates by thoroughly reviewing available and upcoming technologies. A consistent maintenance program can ensure equipment remains functional for its useful life. Furthermore, an offset replacement program, in which a certain percentage of equipment is replaced on a schedule before it reaches the end of its useful life, can eliminate the need to replace too much equipment at once.

5.3 FEWS Information Dissemination

During flood events, flood warning information should be sent to FEWS operators in a timely manner. FEWS operators are encouraged to communicate with internal personnel, other departments, and relevant federal, state, regional, and local partners on the flooding situation continuously to ensure timely mitigation actions. To accomplish this, consistent templates for communicating and displaying FEWS data and model results for different users should be established to provide the correct information, such as flood hydrographs for users with technical expertise. Communities are also encouraged to create one or more FEWS dashboards for information visualization that is designed to display information relevant to each target user. An example of one such dashboard intended for a public audience is the LCRA Hydromet dashboard, shown in **Figure 9**.

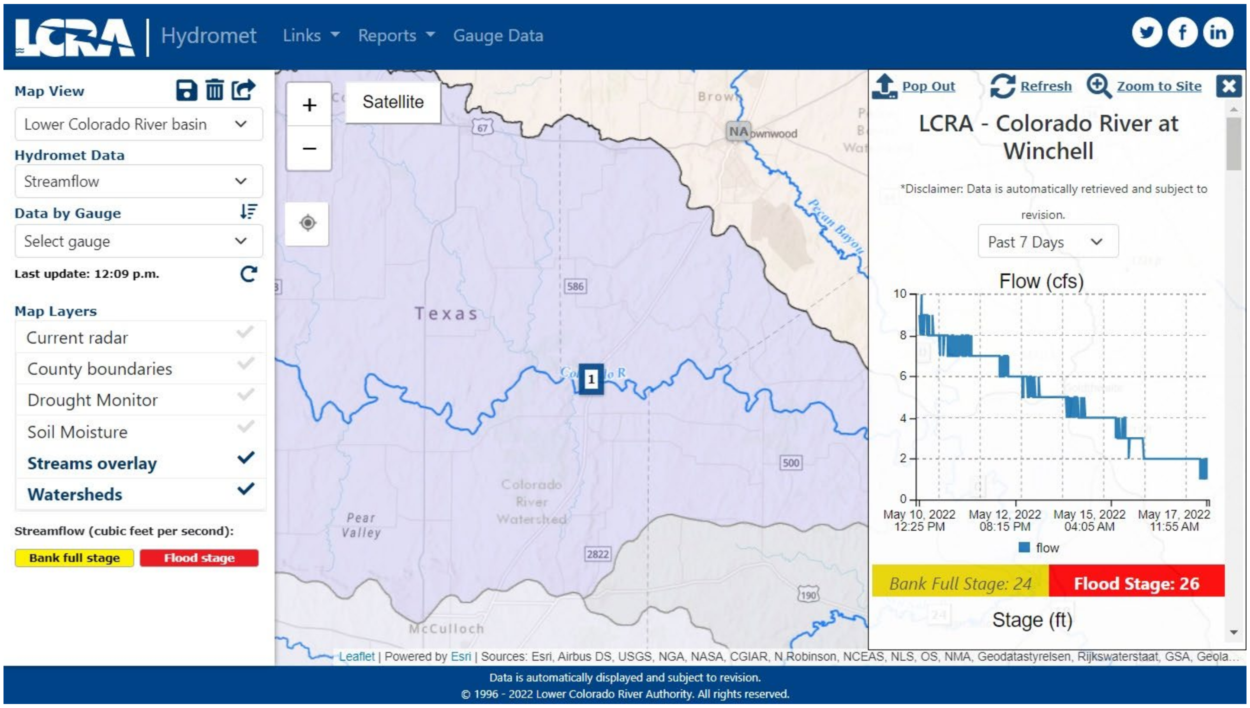

Figure 9. LCRA Hydromet dashboard

While engineers may need different information than emergency managers or first responders, communities are encouraged to provide links from a central landing page to reduce confusion. For example, engineers may need hydrographs to anticipate flooding, but emergency managers and first responders may require information regarding flood locations, timing, and inundation maps to make decisions. While the information should be tailored to different users, a common dashboard, which shows an identical display of relevant (operational) information, can keep everyone on the same page by bringing all the data together on one platform.

Meanwhile, communities are encouraged to consider the accuracy and appropriateness of the information and its potential impacts (e.g., losing public trust) when disseminating information and alerts to the public. Too many messages, especially if they conflict with previous or other messages, can make it difficult for people to understand what to do. Excessive information distracts FEWS users, making them unable to find useful information to take actions. When possible, communities are encouraged to notify the public of impending threats before floodwaters arrive. Clear and consistent road signage (flashing lights, sirens, gates, etc.) is essential for sending a cohesive message to drivers, and communities are encouraged to avoid ambiguous signage. When signage is not clear, drivers can become confused and frustrated, leading to traffic accidents or equipment tampering.

In general, most FEWS information is appropriate for only emergency managers and first responders rather than the public. Communities are encouraged to tailor or simplify the public message and information accordingly. Communities are encouraged to provide a clear message with directions to the public while allowing more advanced personnel to make use of all available data. To further prevent confused or frustrated drivers, communities are encouraged to emphasize outreach and education before flooding events. Additional details of flood information management are included in **Appendix A**.

5.4 Public Outreach and Education on Flood Risk

Communities are encouraged to include general flood education in their public outreach and education efforts and partner with agencies on these efforts when possible. Communities are encouraged to conduct long-term educational campaigns, including efforts to increase situational awareness, interpret flood risk data to better understand actual inundation potential from floodwaters, promote safe practices, and reduce the need for emergency response. The outreach aims to educate the public and help them better understand and interpret the flood warning information from FEWS. For example, communities utilizing FEWS with forecasting capabilities based on their flood inundation maps should make a point to emphasize the difference between the flood inundation maps from FEWS and those from FEMA or other sources (e.g., Flood Decision Support Toolbox shown in **Figure 7**, presented in **Chapter 2**). For FEMA flood maps, education must target the fact that the high-risk zone shown on a flood insurance rate map relates to the requirement to purchase flood insurance. It does not identify whether one is safe or not safe from a flood event. Flood maps produced by FEWS may communicate potential risks differently than FEMA flood maps, which may lead to confusion during flood events.

Public outreach and education covering flood risk are also encouraged through the development of user-friendly websites and documentation based on observed data from memorable local events and general floodplain management concepts. Outreach and collaboration with local schools or universities can provide additional opportunities for flood risk awareness and flood education campaigns. For example, TWDB provides education resources for community officials in the Community Official Flood Resource Guide (TWDB, 2022) and Community Resources. FEMA offers many available flood educational resources on their Tools for Practitioners webpage. TexasFlood.org (homepage shown in **Figure 10**) was developed in collaboration with TWDB, TDEM, and GLO to provide accessible flood information for all Texans. For quick reference information with an emphasis on maps, refer to **Table 3** and **Table 4** in **Chapter 2**. Additional documents related to FEWS are located in **Table 12**, and additional online resources are provided in **Table 13**, both located in **Chapter 6**.

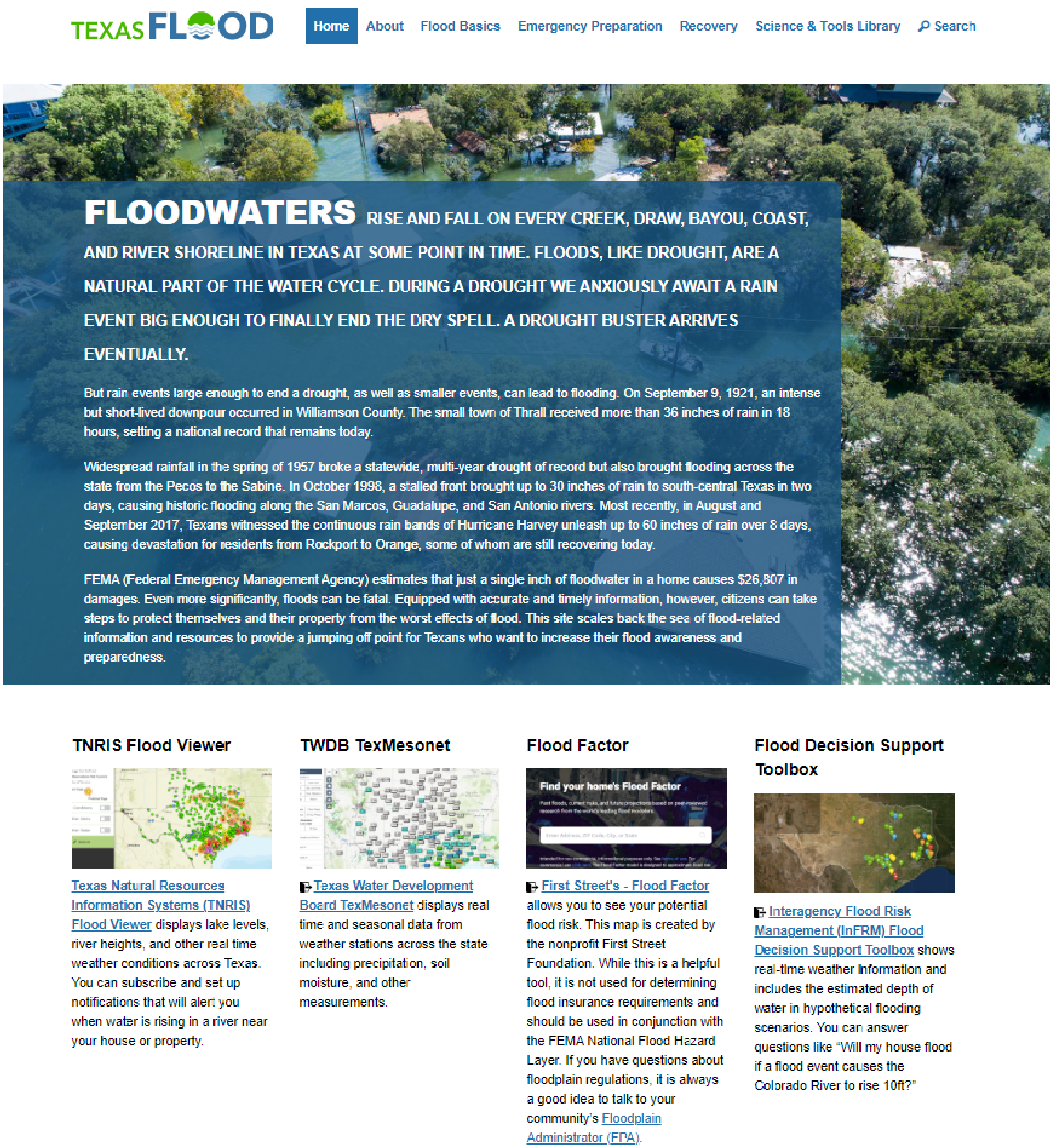

Figure 10. Texas Flood (TexasFlood.org) homepage

6 Recommendations and Resources for FEWS

6.1 Recommendations

While technical information is essential for establishing FEWS, information from other communities that have already established FEWS can be invaluable to understanding how to create an effective, sustainable system. Information in this section was obtained from surveys and interviews with communities. For more details on the communities included in the survey and interview process, please see **Section 1.3**. The responses from communities were gathered, analyzed, and aggregated into recommendations as illustrated in **Table 10**. The suggestions and other thoughts from the communities surveyed have been carefully considered in creating this document. The general recommendations for current and future FEWS developers are summarized in **Table 10** below. Please note that while the information contained in this section was collected directly from communities, some of the lessons and practices may not apply to all FEWS.

Table 10. Recommendations for Flood Early Warning Systems

FEWS Planning	FEWS Financing	FEWS Deployment	FEWS Management
Set clear goals and objectives. Customize the system to the local flooding issues. Focus on needs rather than wants.	Seek steady funding sources.	Maintain all equipment properly. Avoid fixing the symptom rather than the problem.	Send a clear, concise, and consistent message to the public using a template. Use clear and consistent road signage. Maintain an online dashboard with different levels of access to different target users.
Coordinate and collaborate with local, regional, state, and federal entities when planning. Communicate with local NWS offices via the Warning Coordination Meteorologists. Consider combing data and systems to create a regional system.	Apply for applicable grants.	Maximize standardization of the equipment installed for the system.	Prioritize internal communication in communities with small staff who hold multiple roles.
Customize the system to the community and local flooding issues. Define the system scope. Utilize the FEWS in accordance with the defined scope.	Maintain the budget to ensure that the system does not become obsolete or dysfunctional, as this could lead to increased costs later.	Fully investigate vendors and contractors before selection. Consider contracts carefully.	Communicate and collaborate with nearby local, regional, state, and federal entities on a regular schedule and share data.
Identify appropriate vendors and contractors in an early stage with determined goals and project scope.	Consider the long-term costs and benefits of the system.	Verify flood data by using cameras and personnel.	Utilize and maintain FEWS properly to simplify existing tasks and better utilize staff.
Evaluate potential sites using an engineering approach and investigate them for potential issues of access, utilities, erosion, debris, and vandalism. Utilize local flooding information to prioritize site selection, but also consider protection in less risky areas.	Finalize a reasonable scope with a proper budget.	Understand fully and effectively communicate what the data (and model results, if applicable) do and do not show.	Ensure there is documentation to secure the institutional knowledge of the FEWS. Train and develop staff to ensure that knowledge is maintained and documented. Avoid staff turnover resulting in the loss of important FEWS-related information.
Enhance FEWS data by utilizing all available data sources	Allocate 10-15% of the overall budget for O&M.	Calibrate models prior to a flood event (if models are used in FEWS).	Perform education and outreach for all target users. Flood maps should be utilized where helpful but require adequate education for public understanding.

6.2 FEWS and Emergency Notification System Examples

When establishing FEWS or deciding on an effective emergency notification system, it can be helpful to view existing FEWS examples. **Table 11** includes a list of FEWS and emergency notification system examples that can be used as references when considering the implementation of FEWS, listed in alphabetical order by owner or operator of the system. In many cases, the links refer to websites accessible to the public. Keep in mind that many of these systems may also have internal programs or websites with additional information that may not be publicly accessible.

Table 11. FEWS and emergency notification system examples

Name	Owner/Operator	Link	Description
ATXfloods	Austin, City of	www.atxfloods.com/	FEWS Example
Flood Early Warning System	Bandera County River Authority & Groundwater District	www.bcragd.org/early-flood-warning-system/	FEWS Example
Bexar Flood	Bexar County	www.bexarflood.org/	FEWS Example
WarnCentralTexas	Capital Area Council of Governments	warncentraltexas.org/	Emergency notification system example
Fort Worth Flood Warning System	Fort Worth, City of	cs-029.onerain.com/	FEWS Example
Harris County Warning System	Harris County	www.harriscountyfws.org/	FEWS Example
Hays County WETMap	Hays County	novastar-main.co.hays.tx.us/WETMapV3/HaysCounty/public/ WETMap.html	FEWS Example
Iowa Flood Information System	Iowa Flood Center	ifis.iowafloodcenter.org/ifis/	FEWS Example
Leon Valley Flood Warning System	Leon Valley, City of	www.leonvalleytexas.gov/departments/fire_and_ems/ flood_warning.php	FEWS Example
Hydromet	Lower Colorado River Authority	hydromet.lcra.org/	FEWS Example
Roadway Flooding Status	McKinney, City of	mckinneytexas.onerain.com/	FEWS Example
Montgomery County Live	Montgomery County	gis.mctx.org/	FEWS Example

Name	Owner/Operator	Link	Description
Texas SHARE Regional Flood Warning Software Program	NCTCOG	northtexasshare.org/SHARE_partners/onerain-flood-management/	Emergency notification system example
Flood Data – North Texas	North Central Texas Council of Governments	nctcog.onerain.com/ or flooddatantx.com/	FEWS Example
Flood Alert System 5	Rice University and Texas Medical Center	fas5.org/home.html	FEWS Example
TRWD Contrail	Tarrant Regional Water District	trwd.onerain.com/	FEWS Example

6.3 Additional Documents

Additional documents are available in **Table 12** that may provide additional information, instruction, and context for FEWS projects. Documents include other recommendations, technical manuals, and guidelines that are often more focused than the material presented in this guidance document. For example, the National Weather Service Flood Warning Systems Manual provides national guidance for FEWS working with NWS, including more detailed contracts, procedures, and technical information (NWS 2012).

Table 12. FEWS-related documents

Name	Link
A Guide to Public Alerts and Warnings for Dam and Levee Emergencies	www.hsdl.org/?abstract&did=810121
ALERT2 Public Interest Documents	www.hydrologicwarning.org/content.aspx?page_id=86&club_id=617218&item_id=11986
Automated Flood Warning Systems	water.weather.gov/afws/pdf/AFWS_End_User_Guide.pdf
Flood Early Warning Systems: A Review of Benefits, Challenges and Prospects	https://inweh.unu.edu/flood-early-warning-systems-a-review-of-benefits-challenges-and-prospects/
Flood Warning Systems: A Guide to Understanding, Implementing, and Operating Flood Warning Systems	www.nexsens.com/pdf/Guide_Flood_Monitoring.pdf
General Guidelines for Setting-Up a Community-Based Flood Forecasting and Warning System	typhooncommittee.org/docs/publications/WMO_TD1472_2008.pdf
Manual on Flood Forecasting and Warning	library.wmo.int/doc_num.php?explnum_id=4090
National Flood Insurance Program Community Rating System	www.fema.gov/sites/default/files/documents/fema_community-rating-system_local-guide-flood-insurance-2018.pdf
National Weather Service Flood Warning Systems Manual	www.hsdl.org/?abstract&did=818329
Recommendations for New Stream and Rain Gauges in Texas	www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012027_aquaStrategies.pdf
Techniques of Water-Resources Investigations Reports	pubs.usgs.gov/twri/index090905.html
TWDB 2019 State Flood Assessment	texasfloodassessment.org/doc/State-Flood-Assessment-report-86th-Legislation.pdf

6.4 Additional Resources

The additional resources provided in **Table 13** extend the existing resources provided in **Table 3** and **Table 4**. These resources include flood education materials, additional data and information, and specific information for certain locations. Resources included range from those specifically for personnel in charge of FEWS to resources that can be provided to residents.

Table 13. Additional resources

Name	Issuing Authority or Region	Link
ALERT Users Group	ALERT Users Group	alertsystems.org/
Association of State Flood Plain Managers	ASFM	floods.org/
Flood Smart	FEMA	floodsmart.gov/
Flood Factor	First Street Foundation	riskfactor.com/?utm_source=floodfactor
Federal Alliance for Safe Homes Flood Resources	FLASH	flash.org/peril_flood.php
National Hydrologic Warning Council	NHWC	hydrologicwarning.org/
National Water Model	NOAA	water.noaa.gov/about/nwm
Advanced Hydrologic Prediction System	NWS	water.weather.gov/ahps/
Arkansas-Red Basin River Forecast Center	NWS	weather.gov/abrfc/
Lower Mississippi River Forecast Center	NWS	weather.gov/lmrfc/
National Snow Analyses	NWS	nohrsc.noaa.gov/nsa/
Storm Prediction Center	NWS	spc.noaa.gov/products/wwa/
West Gulf River Forecast Center	NWS	weather.gov/wgrfc/
Texas Floodplain Management Association	TFMA	tfma.org/

Name	Issuing Authority or Region	Link
Flood Planning Useful Links and Resources	TWDB	www.twdb.texas.gov/flood/planning/resources/index.asp
Flood Community Resources	TWDB	twdb.texas.gov/flood/resources/index.asp
Flood Risk Management Program	USACE	iwr.usace.army.mil/Missions/Flood-Risk-Management/Flood-Risk-Management-Program/
How Streamflow is Measured	USGS	usgs.gov/special-topics/water-science-school/science/how-streamflow-measured#overview

7 Appendix A: FEWS Technical Information

7.1 FEWS Types

Most FEWS around the state, especially flood monitoring systems, utilize extensive gauge networks to monitor flooding at a local level. This requires equipment that can take measurements (e.g., streamflow, precipitation) and a telemetry system that can transmit the measurements to a receiver. A flood forecasting system is built on this framework by adding a predictive component, a model that ingests predictions (e.g., NWS Quantitative Precipitation Forecast (QPF)) and produces future flood conditions.

7.1.1 Monitoring

Gauging networks have comprised the backbone of most FEWS despite recent advances in weather forecast systems due to affordability and dependability. Typically, systems are commonly composed of an extensive network of stream and rain gauges which can automatically send alert messages when measurements exceed local thresholds (Li et al., 2021). In the U.S., one of the principal gauge-based FEWS is the USGS's National Water Information System (NWIS) (waterdata.usgs.gov/nwis/rt) (**Figure A1**).

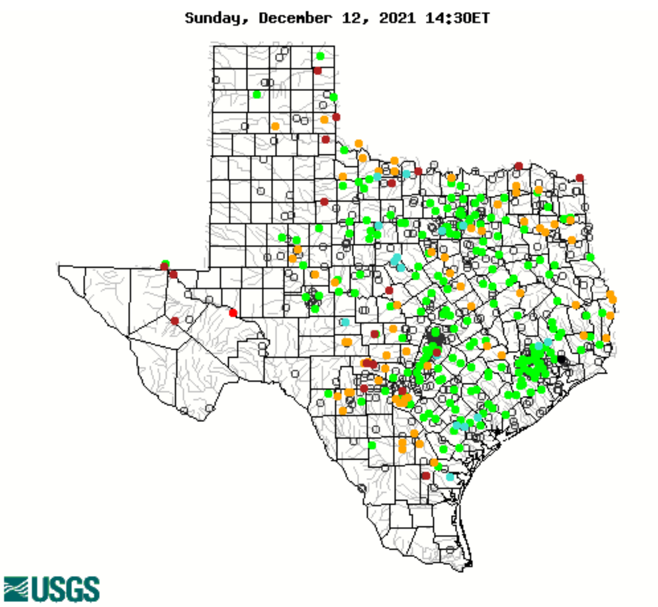

Figure A1. USGS National Water Information System in Texas

Local flood warning systems allow for close communication between local agencies and their residents in a way that national systems cannot provide. Since flooding occurs very quickly following heavy rains, local gauge monitoring is more valuable than that of the national level. Local efforts have also been credited with preventing unnecessary evacuations and other overreactions in cases where flood events were forecasted at the national level but did not occur locally (NWS, 2012). During Hurricane Harvey, the prediction from the National Water Model was evaluated by the local field RFC offices. They cited the presence of high flows at some points, combined with significant run-to-run variability, as reasons for decreased confidence in the NWM output during the event. Hence, consistent warning messages were maintained by adhering to the local RFCs (NWS, 2018). In particularly flood-prone urban areas, existing USGS infrastructure is often augmented with additional gauges in a localized flood warning system. Furthermore, prioritized vulnerable locations on a local scale may be quite different from regional or national priorities, such as when a community is located along smaller streams or tributaries that are too small to harness regional or national attention.

7.1.1.1 ALERT Protocol

For communities planning to develop a flood monitoring system, a system based on gauges that use NWS Automated Local Evaluation in Real Time (ALERT) protocol is presented as an example here. The ALERT protocol was first developed in the 1970s and is now the primary FEWS protocol used nationally. One benefit of ALERT systems is the standardization of communication via terrestrial radio telemetry. The standardization of ALERT hardware and software products means that even equipment developed by different manufacturers is usually cross-compatible. The remainder of this appendix focuses on ALERT protocol implementation.

ALERT gauges utilize sensors to detect changes in an environmental parameter, like precipitation or water level, and then communicate that information to the FEWS via radio telemetry, as previously mentioned. Advanced gauges may also be equipped with other sensors, such as temperature and wind speed sensors. Some ALERT gauges can also provide additional information such as system health, timestamps, and other site-specific information. While the ALERT protocol is still widely used, ALERT2™, the successor to the ALERT protocol, was introduced in 2010 by the National Hydrologic Warning Council (NHWC). ALERT2™ gauges operate similarly to ALERT gauges but transmit information much more efficiently by using different timeslots for each gauge's transmission (e.g., half a second). ALERT2™ protocol also allows for built-in error correction, an increased number of sensors and site IDs, and the ability to transmit readings as floating-point values. The ALERT2™ transmission protocol, as the next generation real-time hydrologic monitoring standard, includes the uses of the Very High Frequency (VHF) radio with other options like cell or satellite transmission. More details on different telemetry options for FEWS are discussed in **Appendix B**

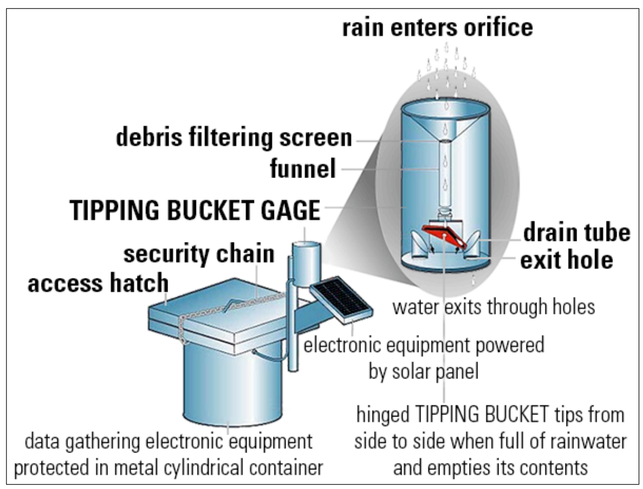

Figure A2. Tipping bucket rain gauge. Source: USGS

7.1.1.2 Precipitation Measurement

Tipping bucket gauges (**Figure A2**) have been used most frequently among all types of precipitation gauges available. Sensing within the tipping bucket gauges involves detecting a particular "event", which is the smallest unit of the measurement, such as 1 millimeter of rainwater entering the gauge's orifice (NWS 2012). When the bucket tips, it spills any water within, tripping a switch that transmits ALERT data and resetting the bucket, readying it to measure the next millimeter of rain. The ALERT gauges will report a "no rain" event on days without rain to show the device's health. Gauges are usually powered by solar panels, and ALERT2™ gauges can achieve lower power consumption through more efficient communication.

Other sensors can also activate the ALERT data transmitter after sensing a specific event such as wind speed, temperature, relative humidity, etc. The system should allow for multiple sensors at a particular site and report through a single communication platform to maximize the flexibility of the system, which requires a unique identifier for each sensor type (e.g., precipitation, stream level, temperature, etc.) for communication. The collected data can be stored at a data logger, which may also be designed to control sampling rates and transmit data to a central location in real-time.

7.1.1.3 Streamflow Measurement

Streamflow, or stream discharge, is the quantity (or volume) of water flowing through a stream over a specified period. Because streamflow is difficult and costly to measure directly, river discharge is typically determined from the ongoing record of the stage by establishing a relationship between stage and discharge. The process of calculating streamflow is known as streamgaging, and generally involves three steps: stage measurement, discharge measurement, and the derivation of the stage-discharge relationship (Turnipseed and Sauer, 2010). The stream stage, also known as gauge height, is the water surface elevation at a specified location in the stream or river being measured. To ensure that the measurements are valid over time, the stage must be measured relative to a datum. It may be necessary to re-survey the datum over time to account for erosion, subsidence, or other processes that impact elevation.

The stage may be measured using several techniques. A vented pressure transducer can be placed along the stream bank in a pipe. Vented pressure transducers are generally the cheapest option for measuring stages and are helpful in sites with limited space. Many agencies (e.g., the USGS) utilize "bubblers" pressure transducers, which force air through a tube and measure resistance to determine the water level. If a location has a tall structure like a bridge over the stream, radar or ultrasonic water level sensors may be used to measure the stage. Some radar sensors can also measure velocity in addition to depth, allowing for more sensitive estimates of discharge. Please note that many FEWS will often only deploy stage gauges or sensors due to costs and the relative ease of measurement compared to flowrate sensors.

Discharge (flowrate) is the volume of water flowing past a specified location in the stream or river at a given time. It is often expressed in units of cubic feet per second (CFS) or gallons per day (GPD). Traditionally, discharge is measured manually and is labor-intensive. One simple way to conceptualize discharge is by multiplying the vertical cross-section's water area in a channel by the average water velocity (**Figure A3**). The USGS commonly uses the current meter and Acoustic Doppler Current Profiler techniques

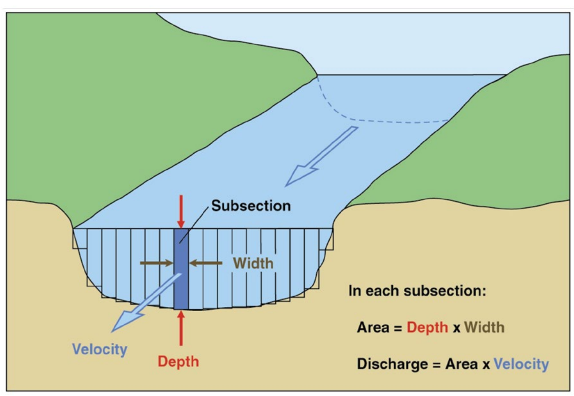

Figure A3. USGS stage-discharge measurement. Source: USGS

to measure discharge. The current meter method uses a wheel with many cups that rotate in the water. Each revolution is electronically monitored and used to calculate water velocity (USGS, 2010). To generate a total discharge value for the stream, the cross-section must be cut into several rectangular shapes. Each shape's depth and width must be recorded, and the area is multiplied by the current meter's measured velocity. The sum of all shapes' discharge is the total discharge. A more expensive and much faster technique uses an Acoustic Doppler Current Profiler (ADCP) attached to small watercraft. The ADCP generates a pulse of sound and measures slight changes in the pulse's frequency upon return. This technique is faster than the current meter method because the instrument measures velocity and depth simultaneously while the width is measured as the watercraft navigates the channel. Similar devices can be used while wading in the case of shallow streams. The ADCP is also used by other Texas agencies, such as the Harris County Flood Control District and Lower Colorado River Authority.

The stage-discharge relationship is referred to as a rating curve and can be produced with continuous and concurrent measurements of both stages and discharge at a specific location (**Figure A4**). However, the relationship is only accurate if the discharge is measured throughout a wide range of stage heights. A reliable rating curve may take years to develop due to the need to measure a wide range of flows and events. Additionally, changes in channel shape, vegetation cover, and other factors must be accounted for. A well-defined rating curve can provide helpful information about a stream and allows for converting the measured stage into an estimated discharge. This is typically done by the USGS at surveyed locations. There are instances where the same stage may not produce the same discharge at the same point in a stream which may be caused by high tailwater effects (more flooding downstream) or other factors. This complexity is often referred to as a "looped rating curve," and the risk of significant loop impacts on measurement and flow estimates should be considered when placing and operating each gauge.

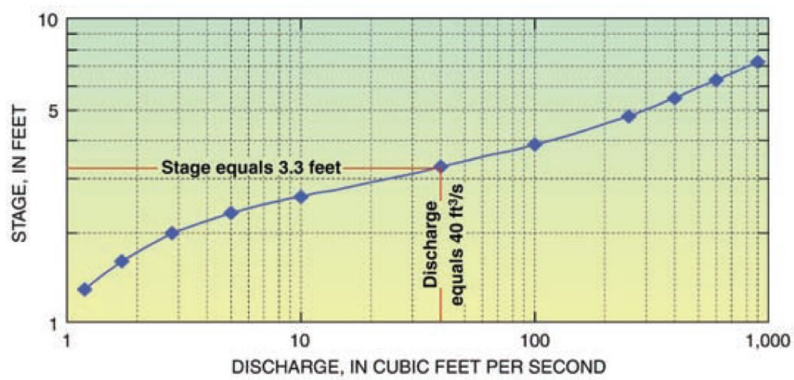

Figure A4. Stage-discharge relationship. Source: USGS

7.1.2 Forecasting

As previously mentioned, forecasting systems are built from the monitoring system by adding a predictive module that uses gauge-based, radar-based, and projected rainfall data sources. In these systems, radar-rainfall data is often utilized to provide higher spatial resolution and coverage than gauge-based data. Radar inaccuracies must be calibrated (conveniently, with the existing precipitation gauge network), though uncertainties still exist as a trade off for the coverage. Projected rainfall data, like the NWS's Quantitative Precipitation Forecast (QPF) can be ingested as an alternative input to predict flooding. QPFs are predictions of the amount of rainfall over a future time period produced by NWS forecasting tools. One community that was interviewed noted that QPFs are useful for stormwater flood prediction in urban environments. The uncertainty associated with forecasting, though always present, can be increased by trying to accurately predict further into the future. The time between the occurrences of predicted and observed flood peaks (discharge or stage) is referred to as lead time in the system. As lead time increases, so does the uncertainty in the forecast conditions. Prediction accuracy must be balanced with the desired lead time to allow for informed decision-making.

A forecasting system should provide a sufficient lead time for flood emergency management with the capability of updating forecasts using a very refined computation interval for the intended spatial coverage. There are a wide variety of models used to predict flooding based on predicted precipitation, from advanced physics-based 2D models to empirical algorithms, which are discussed further in the "Hydrologic and Hydraulic Modeling Tools" **Section 7.4** of **Appendix A.**

7.2 Warning Infrastructure

Many FEWS seek to achieve flood fatality reduction using timely roadway inundation notices. While this can be done with an online dashboard, physical infrastructure is often used to warn drivers at the time of flooding. Manual roadblocks (e.g., barricades, barriers, or gates) may be set up by FEWS staff, though traffic control and other precautions must be taken to ensure worker safety. Pre-installed gates may be manually, remotely, or automatically opened and closed prior to, during, and after flood events.

Automated and remote gates remove the need for manual deployment (and most personnel risks) but may need to be verified to ensure the arms close or open when intended. False closures due to malfunctioning automated gates may erode the credibility of the message and lead to vandalism and tampering from frustrated drivers. Conversely, if manual roadblocks are not removed in a timely manner after the flood recedes, frustrated drivers may vandalize, tamper, and/or move those as well.

Flashing lights, sirens, and cameras can add additional functionality to FEWS. Flashing lights do not themselves obstruct the road but can warn drivers and are often installed at low water crossings. Flashing lights can be automatically triggered by pressure transducers or float switches. Most flasher systems in Texas use a pressure transducer to determine roadway overtopping that occurs when the depth of water is or is close to being above the roadway. These often report data to the central FEWS database like stream gauges. Float switches are another affordable alternative that can be used to trigger lights. Sirens can be utilized for outdoor alert broadcasts. However, the public must be educated on what the siren is messaging to avoid confusion. Depending on community locations, FEWS sirens may conflict with existing outdoor warning systems such as tornadoes or other hazards. Cameras offer an affordable way to verify hydrologic measurements (e.g., stream stage, wind direction, roadway inundation). Videos or still frames are typically transmitted through cellular telemetry. Securing access to sensitive data can be a concern with all FEWS data, especially with camera feeds. Managing the flood information and data received from FEWS is a significant task.

7.3 Flood Information Management

A major part of flood monitoring projects is collecting and accessing the data. Measurements must be recorded and sent at regular time intervals to allow for real-time monitoring. One of the most critical components of flood information dissemination is to ensure that flood information is sent to the right users. In practice, common target users for FEWS are the Emergency Management Department or first responders, as well as government employees. Certain information should be kept internal to avoid unnecessary public panic or mistrust, particularly for hydrologic analysis involving the interpretation of models. The primary function of FEWS is to enhance the safety of the community, so some access to information should be provided to the public via an online dashboard. However, the online dashboard that is available to the public should contain a simplified amount of data or information to provide a clear, concise message. For example, an online public dashboard could provide only road flooding information (flooded, not flooded, unknown status), while internal personnel have access to stream gauge data, precipitation data, and cameras. FEWS planners are encouraged to consider the information available and tailor the information for internal personnel and the public accordingly.

FEWS information dissemination platforms should consider the different access levels and provide consistent templates with relevant information to each user type. For example, a search and rescue team does not need to see the rating curve for a stream location, but a map of which streams have velocities too high to navigate safely may be invaluable. Discussions with the end users should include available data, and communities should factor this into the development of information dissemination templates.

7.4 Hydrologic and Hydraulic Modeling Tools

The hydrologic and hydraulic analysis is typically performed with the use of modeling software packages. Using precipitation data from various sources, along with evaporation and infiltration processes incorporated, hydrologic models can simulate the amount of runoff associated with a certain rainfall event, and that can be used as an input for a hydraulic model that produces key outputs like water depth to create inundation maps (Li et al., 2021). While hydrology deals with determining how much water is present in rivers and streams based on rainfall amounts, hydraulics focuses on how the water moves through the system. Natural processes like infiltration and evaporation govern how much rainfall is converted to runoff and can enter streams, which determines the flow from specific rainfall events. River and channel hydraulics determine water depth, inundation extent, and velocity.

7.4.1 Hydrologic Models

Hydrologic modeling is mathematically representing the response of a watershed (runoff) to precipitation events during the period under consideration. Hydrologic models can be subcategorized as either lumped or distributed. Lumped models convert rainfall over predefined areas of similar hydrologic characteristics (hence, lumps) into runoff and then route the flow downstream (e.g., Sacramento Soil Moisture Accounting Model [SAC-SMA], USACE's hydrologic modeling system [HEC-HMS]). Distributed models use more complex equations to convert rainfall into runoff over a grid of cells using a numeric scheme (e.g., Weather Research and Forecasting Model Hydrological modeling system [WRF-Hydro]). Hydrologic models can use weather forecast data (e.g., QPF), rainfall data from the NWS, temperature data, evapotranspiration data, catchment topography, and land use characteristics to effectively generate runoff forecasts. Lumped models are generally less computationally demanding but may not capture as much detail as distributed models. Distributed models require accurate spatial data (i.e., soils, land cover, and topography) that may not be available in high resolution over all areas. Conversely, lumped models only require general knowledge of each lump's characteristics and may be more appropriate in areas with limited spatial data. Model selection is discussed in greater detail in **Section 7.4.3**.

7.4.2 Hydraulic Models

Hydraulic models simulate river and channel hydraulics using a numerical scheme that applies a mass or momentum conservation relationship with a 1D or 2D solver. A 1D solver requires cross-sectional data at regular intervals along streams, whereas a 2D solver requires topographic and bathymetric data for the entire coverage area. Hydraulic models can enhance FEWS by capturing more complex fluid mechanics in riverine and stormwater/pluvial flooding. Examples of hydraulic models include River Analysis System (HEC-RAS) and Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) (U.S. Army Corps of Engineers), MIKE FLOOD (Danish Hydraulic Institute), BreZo (Sanders & Begnudelli), or LISFLOOD-FP (University of Bristol). 1D models generally only capture riverine flooding and are less computationally demanding, while 2D models may also capture stormwater/pluvial flooding at a greater computational cost. Communities located along a major stream that are primarily concerned about riverine flooding may only require a 1D model for forecasting. However, communities concerned with street flooding from intense rainfall may opt for a 2D model. For detailed model selection criteria, please see **Section 7.4.3**.

7.4.3 Other Models

Other types of flood models that may be used in certain cases, which include storm surge models, urban flooding models, and reservoir flood control models. Empirical algorithms can also be used as an alternative to physics-based models. These algorithms predict streamflow, inundation extent, or other flood impacts based on the statistical association of previous rainfall events in the area. Since empirical algorithms rely on a lengthy record of high-quality data, they may not be appropriate for all areas with limited records. A major advantage of empirical algorithms is the reduced computational cost compared to physics-based models. More information on flood modeling is available in the World Meteorological Organization's Manual on Flood Forecasting and Warning (2011).

7.4.4 Flood Model Selection

When choosing a model, it is important to bear in mind that increased model complexity does not always correlate with an increase in the accuracy of results. The uncertainty in a hydrologic model can come from a wide range of sources (e.g., rainfall data, hydrological loss rate, routing methods and parameter, etc.), but the highest uncertainty is from rainfall estimation. Some models only work well within a limited range of calibration events. The model selection is mainly related to data availability and should also meet the goals and objectives, fit within the project and ongoing budget, and be operational. The following criteria should be considered when selecting the most suitable model for flood forecasting (United Nations Economic and Social Commission for Asia and the Pacific, 2016):

- Proven to be reliable in terms of flood forecasting
- Operational to satisfy end-user requirements
- Able to couple meteorological forecasts
- Easy to use and implement
- Not too demanding in terms of input data
- Fast to run and produce the forecast so that adequate lead time will be available
- Economical to acquire and upgrade
- Able to generate real-time hazard maps
- Able to update the output and correct any errors that occur
- Able to generate user-friendly warning information automatically

Furthermore, it is noted that communities should utilize expertise and experience in both hydrologic and hydraulic modeling and forecasting to build and operate model-based flood modeling systems. When hydrologic models are used for predictive hydrology, relevant initial conditions should first be identified and then used. Model uncertainties and biases should be known and accounted for in decision-making (e.g., when to close road gates, flash alert lights, etc.). Hydrometeorological forecasting information and products (e.g., QPFs) can extend the lead time for flood impact predictions and reduce uncertainties when used appropriately.

8 Appendix B: FEWS Gauge Placement

As a critical component of FEWS, gauge placement is a key task in the planning and deployment phases of any FEWS. FEW planners are encouraged to collaborate with local emergency management officials (e.g., fire department, road, and transportation groups), National Weather Service (NWS) local offices, and USGS local offices to identify high-risk areas and how all parties can be best served by installing new gauge sites. Existing gauges from local (nearby FEWS or monitoring systems) and federal (NWS, USGS, USACE, etc.) partners should be examined to ensure that existing resources can be leveraged and new gauges are not installed too close since that could provide redundant measurements. This appendix emphasizes how to place gauges based on site criteria, site identification and gauge network analysis, and previous gauge placement experience from Texas FEWS communities:

- Site Criteria (**Section 8.1**)
- Site Identification and Gauge Network Analysis (**Section 8.2**)
- Existing Methods of Gauge Placement in Texas Communities (**Section 8.3**)

8.1 Site Criteria

Site criteria include the necessary site characteristics for the equipment to take accurate measurements or transmit the data. The exact site requirements will depend on the specific gauges or sensors with their corresponding telemetry devices to send measurements to the FEWS servers. In general, gauge sites must be clear of obstructions that can interfere with rainfall or streamflow, allow for the transmission of measurements to the servers, and protect against natural and human risks. The relative importance of each criterion depends on the needs of each community.

8.1.1 Precipitation Gauges

Precipitation gauge locations should be selected to minimize environmental disturbance, such as the effects of wind on rainfall measurements. The effects of wind may be reduced by clipping dense vegetation around the gauge orifice to the same height, using fencing to recreate the same effect, and placing windshields around the gauge, in order of descending efficacy (WMO, 2018). Flat surfaces like concrete should be avoided around the gauge orifice to reduce the effect of splashing (WMO, 2018). While this is not often feasible in practice, gauges should be exposed consistently in all directions (e.g., a clearing in a grove of trees) (NWS, 2012). If a gauge must be placed near an obstruction, the distance apart should be greater than twice the height of the obstruction (WMO, 2018). Please refer to the World Meteorological Organization's Guide to Instruments and Methods of Observation (2018) for further details.

8.1.2 Stream Gauges

Specific stream gauge sites should be selected with the following criteria in mind (Sauer and Turnipseed, 2010), including whether stage or discharge measurements are most impacted by the criteria:

1. Orifice intakes should be located in pools or protected areas with little turbulence (stage).
2. Sites should allow for manual backup measurements if the gauge malfunctions (stage).
3. Gauge housing units should be above the 200-year flood level when possible.
4. Generally straight stream course between the upstream and downstream sides (discharge).
5. Stable streambed without obstructions or brush (discharge).
6. Velocities greater than 0.5 ft/s and depths greater than 0.5 ft (discharge).

Few sites can meet all criteria in practice, so one must choose from some undesired locations. Large obstructions (e.g., undersized bridges) may lead to backwater effects, in which flow is impeded and pooled upstream, increasing the stage elevation to higher than would usually be expected. Gauges for FEWS may be deployed at the upstream or downstream side of the bridge, depending on the nature and goals of the FEWS. For example, if the potential flooding impact is on the upstream side of the bridge, the gauge should be deployed at the upstream side. For alert purposes, stream gauges should be placed far enough upstream of key areas to provide warning time (NWS, 2012). In addition, gauges may also be sensitive to sediment in the water (e.g., pressure transducers malfunction if sediment builds up in the sensor). Housing units may be placed directly on a concrete slab or other suitable surfaces, such as dams, bridges, or other structures (Sauer and Turnipseed, 2010).

8.1.3 Telemetry

As mentioned in **Appendix A**, measurements can be transmitted to a receiver via radio, cellular, and satellite telemetry. Radio telemetry is the most common method and requires a clear path from the gauge transmitter to the destination receiver (NWS, 2012). Typical radio telemetry systems used in FEWS are ALERT, including ALERT2™, and Hybrid ALERT systems that consist of an ALERT system integrated with additional sensors and communications peripherals. ALERT and ALERT2™ networks typically use reserved radio frequencies specifically for flood warnings and have little chance of interference. More information on ALERT and ALERT2™ is available at National Hydrologic Warning Council (NHWC) (ALERT2 Frequently Asked Questions). Cellular telemetry is an affordable option, but it can be limited by cellular coverage in the area. Cellular networks can experience interference during high-load events, but some carriers offer services that prioritize emergency communications. Lack of coverage may pose a problem, particularly for rural communities. Satellite telemetry is often cost-prohibitive but may be used if radio and cellular telemetry options are not available or feasible for a site of importance.

8.1.4 Other Requirements

The actual structure that the gauges or sensors are attached to must be able to withstand the elements in both extreme weather events (e.g., high winds, lightning) and typical conditions (e.g., heat, cold, humidity). Gauge equipment should be protected from lightning to reduce severe damage and ensure that data collection and transmission are not interrupted. Multiple lightning-proofing methods should be combined, including the following: internal circuitry protection, supplemental surge-protection devices, and low-resistance grounding, often in the form of a buried rod that is connected to the housing unit (Sauer and Turnipseed, 2010).

Surveyed communities noted that the structure should be located reasonably above observed or potential high water marks during flood events. If water overtops the gauge, the electronic telemetry components may short-circuit and fail. Additionally, vulnerable parts like cables should have limited exposure to reduce the risk of vandalism or animal interference. Worker safety must also be considered when choosing new sites. Locations along major highways pose threats from nearby traffic to workers during installation and routine maintenance. There should be a clear line of sight for both workers and drivers to reduce the chance of a collision, and blind corners should be avoided.

8.2 Site Identification and Gauge Network Analysis

Site identification includes ways to design the system to reduce costs and maintenance. For practical purposes, streamflow gauges are typically co-located with precipitation gauges to reduce the cost of installation and maintenance at multiple sites. Sites are preferentially placed in flooding hotspots or areas subject to repeated flooding as identified by local authorities (e.g., a stream gauge may be placed on a road that is known to flood often). Sites should be easily accessible by vehicles to reduce logistic issues during installation and routine maintenance while avoiding the roadway hazards described in the previous subsection. Gauge sites should be considered as a network and can be strategically selected to help calibrate hydrologic and hydraulic models and validate flood inundation maps in the future.

FEWS gauges should be viewed and designed accordingly as a network of measurement devices that provide spatially representative data inputs for timely warnings. A balance between network redundancy and efficiency must be struck to allow for a resilient but not excessively expensive FEWS. The gauge network should be redundant enough to allow for some gauges/sensors to fail or malfunction during a catastrophic event and still function well overall. However, redundancy should not exceed budget constraints. Because sites are constantly changing due to environmental conditions, alternative sites should be considered for each chosen location until installation can occur.

Gauge density also plays a key role in determining network accuracy. Gauges are often used to ground truth radar estimates of rainfall and should be strategically placed in gaps between radar coverage if used for this purpose. Local weather patterns and storm characteristics influence the need for gauge density. Areas with greater variation in topography (e.g., West and Central Texas) typically need a higher gauge density than flat areas (e.g., Texas Coastal Plains). According to the World Meteorological Organization's (WMO) Guide to Hydrological Practice (2008), areas with frequent convective storms require a higher gauge density to adequately capture the intense, small spatial extent typical of convective storms, whereas areas with more frequent frontal rainfall (typically larger spatial extents) may not need as dense of a network.

Technical analyses of gauge networks are typically performed by contracted consulting firms and involve the use of various statistical and/or modeling tools to systematically determine biases and gaps in coverage based on historical records or other methods. A technical analysis typically involves one of the following tasks: 1) analysis of spatially representative data for timely and reliable warning, 2) analysis of the best management practices with limited gauge numbers to account for redundancy and efficiency, 3) analysis of existing gauges to identify poorly performing equipment and recommend replacement, relocation, or removal of existing infrastructure, and 4) analysis of potential sites for the expansion of the gauge network. When a portion of the coverage area is oversaturated with gauges, some may be relocated or removed. While relocation is usually less costly than the installation of a new unit, it is still an expensive process that can be avoided by proper initial site selection and foresight. Gauge removal reduces the overall system cost. Technical analysis also identifies the best gauge types for specific locations, which can reduce the chance of premature failure and ultimately reduce costs. Smaller systems (i.e., 3-4 gauges deployed at key low water crossings) often do not warrant a gauge network analysis, but communities who plan to deploy many gauges (i.e., 12 across a watershed) that have a variety of viable sites are strongly encouraged to perform (or advise the contractor to perform) one, especially at the early stage of the technical planning (prior to finalizing locations) if the budget allows.

As an example, the Guadalupe-Blanco River Authority (2019) expanded its rain gauge network into Hays County, considering the following factors when selecting sites: a) maintain a spacing of 5- 6 miles between gauges for adequate density to capture the compact nature of Central Texas storm systems, b) ensure a clear radio path to the site, c) provide ease of obtaining right-of-way for installation, and d) provide ease of access for maintenance. A review of relevant literature in the same report found that a distance of 7-8 miles between gauges was the general recommendation. For more information, please refer to the full report: Early Warning System Report—Hays County Rainfall Gauges by the Guadalupe Blanco River Authority. As part of a FEWS feasibility study, Cameron County Drainage District 5 (2019) identified all existing rain and stream gauges in-network as well as regional trends in gauge equipment to inform recommendations to make future improvements to the network. Major recommendations for the gauge network included the replacement of tipping bucket gauges with weighing rain gauges to capture high-intensity rainfall and the installation of 15-minute interval cameras at gauges to better validate observations. For more information, please refer to the full report: Flood Protection Planning Study Final Report by the Cameron County Drainage District 5.

In addition, a gauge network analysis can be performed to evaluate the existing gauge placement in the gauge network. For example, in 2005, the Edwards Aquifer Authority conducted a rain gauge analysis that analyzed 63 tipping bucket gauge station data from

January 1, 2003, to May 31, 2005. Gauge measurements were compared against the NWS automated surface observing system data interpolated over the coverage area with a distance-weighted technique. A double-mass analysis was performed for each tipping bucket gauge by plotting the cumulative rainfall vs. the standard NWS values. Tipping bucket gauges were then categorized into good, suspect, and poor groups. The report then recommended that many of the poor gauges (over 35% different than NWS recorded values) be relocated or removed from the system. The recommended reconfiguration density was increased to one gauge per 66 mi^2 compared to the existing density of one per 87 mi^2. The study also found that an improved maintenance routine, including field calibration tests, could reduce measurement errors by up to 35%. For more information, please refer to the full report: Edwards Aquifer Authority Rain Gauge Analysis Study Report.

Further details regarding both individual gauge site selection and network design may be found in the WMO's Guide to Hydrological Practices, Volume I: Hydrology from Measurement to Hydrological Information (2008).

8.3 Existing Methods of Gauge Placement in Texas Communities

A comprehensive community survey, as described in **Section 1.3**, was conducted to gather information on the current practices among the Texas FEWS communities. Based on the community survey conducted for this guidance document, information about the methodologies used to select gauge sites was gathered as follows: 1) impact (e.g., flooding hotspots), 2) co-location with existing facilities or gauges or sensors, 3) distance between gauges or sensors, 4) the use of a long-term plan, and 5) engineering analysis, as shown in **Figure B1a**.

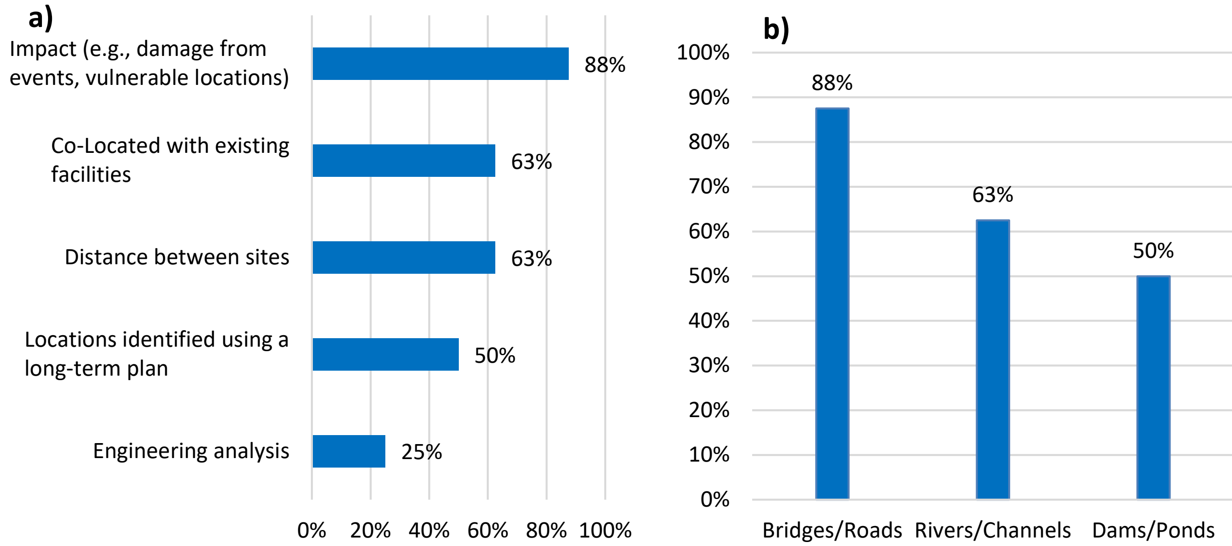

Figure B1. Percent of communities using a) specified gauge placement methodologies, and b) gauges at specified location types

Note: For a) Survey responses presented as the percentage of communities that utilize the above methods when choosing gauge sites. Many FEWS operators use multiple methods in combination; For b) Survey responses presented as the percentage of communities that deploy gauges at the above locations. The survey considered all gauge types due to frequent co-location of stream and rain gauges.

Most communities considered impact (88%) as the top factor when selecting gauge locations, meaning locations that have previously experienced flooding are particularly vulnerable. Most communities also considered co-locating FEWS assets with existing facilities (63%), which reduces installation costs and is convenient for future operation and maintenance. Similarly, many communities scrutinized the distance between gauge sites(63%) to ensure adequate coverage across the service area. 50% of communities utilized a long-term plan to select gauge sites—only 25% performed a gauge network analysis to optimize gauge sites. While gauge network analysis was determined to be the least practiced method among the interviewed communities in Texas, conducting a gauge network analysis by local or regional experts is highly recommended since it will optimize the FEWS gauge network and aid in establishing a long-term plan for anticipated expansion, if applicable.

The survey indicates that gauges were placed at 1) bridges/roads, 2) rivers/channels, and 3) dams/ponds, as shown in **Figure B1b**. Gauges at these locations often measure both stage/streamflow and rainfall to reduce installation and O&M costs. Again, the percentages are a representation of popularity among responses. The most common gauge locations are at bridges and roads (88%), which offer easy access for installation and maintenance. Next, water features are often selected as gauge locations: rivers/channels (63%) and dams/ponds (50%) for direct streamflow measurements and co-located rainfall gauges. Please note that most communities indicated more than one of the methodologies applied, so the percentages reflect the popularity of the selected locations for gauges. In other words, the percentages indicate what percentage of the interviewed communities included that methodology in the survey.

Gauge network analyses are typically performed by engineering consulting firms, which can be cost-prohibitive for communities with fewer staff, staff shortages, or limited funding. Regardless of available resources locally, communities are strongly encouraged to consult with their local NWS offices for assistance with gauge placement, as NWS can provide valuable input on site selection. For more information, please refer to **Section 2.2** and view National Weather Service Flood Warning Systems Manual (NWS 2012).

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