Aquifer Storage and Recovery Report: Longevity Assessment for the City of Bandera Water Wells

Azzah AlKurdi, Shirley C. Wade, Ph.D., P.G., James Golab, Ph.D., P.G., Andrea Croskrey, P.G.

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by
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February 2023

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The contents of this report (including figures, tables, and plates) document the work of the following licensed Texas geoscientists:

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Cover photo courtesy of Andrea Croskrey "Live oaks on rural ranch in Bandera County, TX"

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1. Executive summary

Aquifer storage and recovery (ASR) utilizes injection wells for the local storage and subsequent recovery of water within an aquifer for beneficial use, and aquifer recharge (AR) is the intentional recharge of an aquifer by injection well or other means of infiltration. Interest in both ASR and AR projects has been increasing across the nation and Texas primarily to address the need to store excess water supplies. Implementation of ASR and AR in Texas, however, has been somewhat limited. Presently, there are only two municipal-scale ASR systems and one municipal-scale hybrid (ASR-AR) system in Texas.

In 2019, the 86th Texas Legislature passed House Bill 721, which tasked the Texas Water Development Board (TWDB) with two legislative mandates: 1) to complete a statewide suitability survey of ASR and AR and 2) to conduct ASR or AR studies (Texas Water Code § 11.155). The TWDB was charged with implementing these mandates for the purpose of providing support for water planners, engineers, and government officials that may be investigating the development of ASR and AR projects within Texas. The statewide study created a methodology for surveying the suitability of areas for ASR or AR projects across Texas; the methodology was based on mapping the hydrogeological characteristics of the major and minor aquifers, sources of excess water, and water supply needs, as outlined in the house bill. The resulting survey was published as a GIS geodatabase and an interactive web map viewer and serves as an effective tool for initial consideration of ASR and AR as potential water management strategies at statewide scale.

The second mandate was for the TWDB to work with appropriate interested entities to conduct studies of ASR and AR projects in the state water plan or identified by others and report the results of these studies to the regional water planning groups and interested persons. A list of ASR or AR projects from the 2017 State Water Plan was developed and the details of each project were researched from the draft 2021 regional water plans, news articles, professional presentations, and correspondence with the project sponsors. The information gathered was scored based on several criteria: sponsor interest, staff skillset, source water, data availability, planning status, and online decade. Based on this research and scores, TWDB staff conducted a longevity assessment of the existing City of Bandera lower Trinity aquifer public water supply wells to support the associated ASR project in the 2017, as well as 2022, state water plans. The City of Bandera plans to inject treated surface water from the Medina River into the lower Trinity aquifer to be recovered when water supply demand is high and straining the capacity of the existing wells. This study was selected due to its high sponsor interest, match between the project need and staff skillsets, the source water type being treated surface water, the availability of data, and the online decade of the ASR project being moved from 2040 to 2030 in the latest state water plan.

The City of Bandera and the Bandera County River Authority and Groundwater District (BCRAGD) are concerned with increased water demand associated with the rapid growth in the Texas Hill County. The City of Bandera is considering alternative water supplies, including ASR, to increase the reliability of its current water resource infrastructure and prepare for future development. A key component of the city's future water supply planning involves the need to better understand how increased pumping could affect the life span of its lower Trinity aquifer wells. This information will assist the City in evaluating the viability of the recommended ASR project and will aid in determining a timeline for project implementation. Currently, the City of Bandera produces all its municipal supply water from three wells in the lower Trinity aquifer (93 percent of total production) and one well in the middle Trinity aquifer (seven percent of total production). The water level in the lower Trinity aquifer wells has fallen about 350 feet since the 1950s. This longevity assessment focused on the lower Trinity aquifer due to it being the primary water production source for the City of Bandera and the target for the ASR project. The most recent data available for the lower Trinity aquifer was used to predict the longevity of the wells under different pumping scenarios.

An analytical solution for the Mulberry Street well, the City of Bandera's most productive lower Trinity aquifer well, was first used to model the behavior of the well-aquifer system under different pumping rates. Under present pumping conditions, the Mulberry Street well has a drawdown of 46 feet after 3.6 hours of pumping, which is nearly equivalent to the current pump depth. The maximum stress scenario for the City of Bandera would be to utilize all existing groundwater supply listed in the 2022 State Water Plan; this is the amount of groundwater the City's infrastructure could obtain, treat, and deliver it to the municipal user group, which would be equivalent to increasing total current production by 91 percent. In this scenario, the Mulberry Street well would need to produce almost twice the current production amount with the same pumping rate and would need to operate for 6.9 hours, resulting in a total drawdown of 91 feet, which would be below the current pump depth. This showed the Mulberry Street well cannot supply this amount without the pump being lowered to least 45 feet below current pump level (545 feet below ground surface). The results of this analysis also show that the minimum static water level required for the Mulberry Street well to maintain the existing supply is 621 feet above mean sea level (maximum of 639 feet below ground surface).

While the simple analytical solution could provide estimates of pumping levels level at a fine scale with current parameters, which is valuable information for the operation of the well, it could not be used to forecast future aquifer conditions. Such a forecast was considered critical because future planning and management decisions require modeling long-term regional groundwater levels. To address this need, TWDB staff constructed a numerical model, the Bandera well longevity model, using the framework of the 2012 updated TWDB Hill Country Trinity Groundwater Availability Model (GAM). The GAM has four layers: the Edwards Group, the upper Trinity aquifer, the middle Trinity aquifer, and the lower Trinity aquifer. Stratigraphic tops and bottoms of these layers were updated with data from the TWDB report, *Brackish Groundwater in the Hill Country Trinity Aquifer and Trinity Group Formations, Texas*. Additionally, the grid cell size was refined from one-mile to 0.25-mile in Bandera County, a new low hydraulic conductivity zone was added in the City of Bandera area of the lower Trinity aquifer, historical pumping data was updated with 20 additional years, and several other modifications were made to characterize the lower Trinity aquifer more accurately in Bandera County.

After calibrating the Bandera well longevity model using more than 2,400 water level observations from 464 wells, the model closely matched historical water level data. This match is based on statistical analysis of available measured data, which may be sparse in locations throughout the model.

The Bandera well longevity model was then used to forecast future aquifer conditions up to 2079. Three future scenarios were tested on the wells with this numerical model:

1. Pumping will remain static with no increases to meet future water supply demands.
2. Pumping will increase to match the projected demands in the 2022 State Water Plan.
3. Pumping will increase even more to produce the volumes of groundwater listed as existing supply to the City of Bandera in the 2022 State Water Plan.

If current pumping remains static and never increased to meet increasing water demands, the model shows that the Mulberry Street well will be able to provide sufficient water through the entire period modeled to 2079. The model also indicates water level decline of 65 feet in the lower Trinity aquifer over almost 60 years period, and, after 16 years, the pump may need to be lowered to remain functional. If pumping is increased to match the projected demands in the 2022 State Water Plan, the predicted lower Trinity aquifer water levels would fall to the pump depth after two years of increased pumping, which would require the pump to be lowered for the well to remain functional. Under this second scenario, a gradual water level decline would continue for 29 years, at which point the water level would reach the bottom of the well casing making the Mulberry Street well no longer useable. If pumping were to increase to produce all available groundwater supplies allocated to the City of Bandera in the 2022 State Water Plan, the wells would no longer be usable after five years.

The Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects identified the Trinity Aquifer as the most suitable aquifer for an ASR project within the model study area. This supports the City of Bandera's current project plan of injecting into the lower Trinity aquifer. Additionally, there is an existing ASR facility located in the City of Kerrville that uses the lower Trinity aquifer for storage. This project could be used as a comparison to inform project planning; however, the lower Trinity aquifer contains cleaner sand and is closer to the surface in Kerr County, making a direct comparison challenging.

Evaluation of an aquifer-well system is essential for successful management and planning for future use. The analytical solution presented in this study provides a focused evaluation on the operation of the Mulberry Street well. The Bandera well longevity model forecasts long-term, regional groundwater levels based on expected hydrogeologic behaviors, modeled aquifer properties, historical water levels, and planned water supply demands. The results of both methods support the need for the City of Bandera to implement alternative water strategies to meet growing demands. The City of Bandera can use these results to develop a timeline for implementing alternative projects, such as ASR, as well as adjusting current operational procedures. These forecasts are based upon limited publicly available data on aquifer properties, pumping, and observed water levels. New data would improve the accuracy of the model and may change the results. Further, site-specific data will need to be considered should the City of Bandera consider further evaluating the information on the feasibility and impacts of an ASR project.

2. Background

Aquifer storage and recovery (ASR) utilizes injection wells for the local storage and subsequent recovery of water within an aquifer for beneficial use (Texas Water Code § 27.151). Aquifer recharge (AR) is the intentional recharge of an aquifer by injection well or other means of infiltration (Texas Water Code § 27.201). Interest in both ASR and AR projects has been increasing across the United States due to decreasing water levels, increased reliance on vulnerable surface water supplies, and increased need for seasonal or emergency water storage (Pyne, 2005). Aquifer recharge from the surface is feasible in places where sediment near the surface is permeable and surface water can easily reach the water table. In less permeable sediment or for deeper aquifers, an injection well must be used (Pyne, 2005). Most ASR projects typically inject and recover water from the same location as this provides significant engineering and cost advantages to having separate injection and recovery wells. Both ASR and AR can use a variety of treated sources of injected water (Pyne, 2005).

2.1 Aquifer storage and recovery in Texas

In Texas, ASR and AR have been used to store surface water, groundwater, and reclaimed water (Webb, 2015). Presently, there are two municipal-scale ASR systems and one municipal-scale hybrid (ASR-AR) system in Texas. The City of Kerrville Plant became operational in 1998 and has two ASR wells and a recovery capacity of about 2.6 million gallons per day. The ASR facility at San Antonio Water System's H2Oaks Center located approximately 30 miles south of San Antonio became operational in 2004 and has 29 ASR wells and a recovery capacity of about 60 million gallons per day. The Fred Hervey Water Reclamation Plant in El Paso became operational in 1985 and has a spreading basin, recharge well field with one shallow vadose well active, and a down gradient Hueco Bolson Aquifer production well field.

The TWDB ASR program is housed under the Innovative Water Technologies Department. It was created in 2009 with the TWDB funding a study, *An Assessment of Aquifer Storage and Recovery in Texas*, to determine why ASR was not being more widely implemented in Texas (Malcolm Pirnie, 2011). As part of the study, 10 entities were surveyed and indicated that the concerns preventing them from implementing an ASR project were related to the recovery and quality of stored water, as well as implementation costs.

Four years later, the TWDB published Technical Note 15-04, *Aquifer Storage and Recovery in Texas: 2015*, which summarized ASR activities in Texas (Webb, 2015). Also, in 2015, the 84th Texas Legislature passed House Bill (HB) 655 amending the Texas Water Code to make statute more conducive to implementing ASR projects. The 84th Texas Legislature also passed HB 1, Rider 25, which appropriated $1 million from the General Revenue Fund to the TWDB to fund groundwater conservation districts for demonstration projects or feasibility studies that will prove up aquifer storage and recovery or other innovative storage projects. As a result, the TWDB provided funding to the Corpus Christi Aquifer Storage and Recovery Conservation District, the Edwards Aquifer Authority, and the Victoria County Groundwater Conservation District to acquire site-specific hydrogeological conditions for possible ASR projects by either drilling test wells or converting an existing groundwater production well to an ASR test well.

2.2 Legislative mandate

In 2019, the 86th Texas Legislature passed HB 721, which tasked the TWDB with two ASR related legislative mandates (Texas Water Code § 11.155). The first mandate was to conduct a statewide survey to determine the relative suitability of using Texas aquifers for ASR and AR projects based on consideration of: 1) hydrogeological characteristics with a focus on storage potential, transmissivity, infiltration characteristics, storativity, recoverability, and water quality; 2) the frequency, volume, and distance to excess water available for potential storage; and 3) the current and future water supply needs identified in the state water plan. To implement the first mandate, the TWDB funded the *Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects* study that was completed in 2020 (Shaw and others, 2020). The TWDB submitted an overview of the statewide survey to the governor, lieutenant governor, and house speaker by December 15, 2020 (TWDB, 2020). The results of this statewide survey in the study area will be discussed later in the report.

The second mandate was for the TWDB to work with appropriate interested persons to conduct studies of ASR and AR projects in the state water plan or identified by others and report the results of these studies to the regional water planning groups and interested persons. To implement the second mandate, a newly formed ASR team with staff and funding appropriated from the Texas Legislature evaluated all ASR and AR recommended water management strategy projects in the 2017 and 2021 regional water plans.

2.3 Study selection process

To determine the first studies to initiate and fulfill the second mandate from HB 721, the TWDB researched ASR and AR projects recommended in the 2017 State Water Plan. The evaluation of each of the 21 projects included gathering information from the 2017 State Water Plan and draft 2021 regional water plans, calling project sponsors to obtain status of project and interest, and then classifying different components of projects (Figure 2-1). The information gathered for each project was scored according to the following criteria:

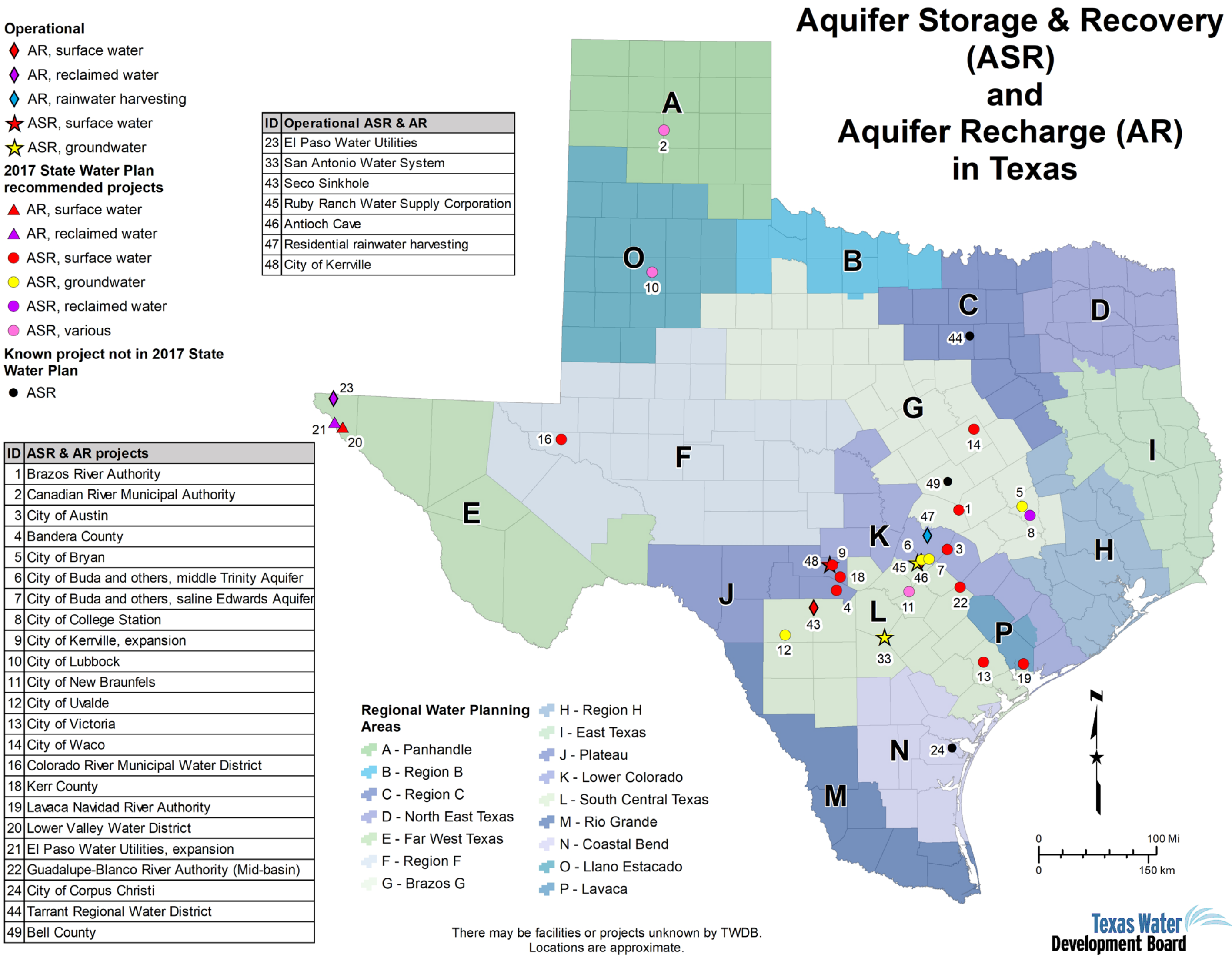
1. Sponsor interest: The level of interest a sponsor expressed in having TWDB staff complete a study; a higher score was given to interested sponsors that identified a need for a study by the TWDB. Interest from the project sponsor was the most important criterion since we would not be able to successfully complete a beneficial study that moved a project forward without sponsor support.
2. Matching study type with staff skills and availability: The type of study needed to advance the project had to match the skillset of TWDB staff and the timing of staff being available to complete the study.
3. Source type: The type of water identified for the ASR project's source water (in order of decreasing score)—groundwater, surface water, a mix, reuse, or brackish groundwater. In general, higher quality source water is more suitable for an ASR project.
4. Data availability: The relevant data available for the ASR proposed study. Existing data would allow the team to quickly start and complete the first ASR or AR study per the requirements of HB 721, so a higher score was given to proposed studies that had high quality data readily available to complete them.
5. Planning status: The status of any work or studies related to the ASR project ranged from no studies to a complete facility. A higher score was given to projects with less work completed, because a TWDB study would provide more benefit.

6. Online decade: The decade listed in the regional water plan or state water plan for the water management strategy project. An earlier online decade was given a higher score.

In addition to the listed criteria, each sponsor was contacted to verify and collect the most recent information on the status of their recommended ASR or AR project. The ASR team provided the project sponsor with background on the legislative mandate, the type of studies that could be completed by the team, and the rough timeline in which we were looking to complete the study. The first study selected to be completed was an aquifer characterization for the ASR component of the Guadalupe-Blanco River Authority Mid-Basin Water Supply Project (Croskrey and others, 2022).

The second study is a longevity assessment of the public supply wells for the City of Bandera to evaluate the viability of existing wells and the need for an ASR project to meet the growing demand of the city and new subdivisions in Bandera County. The City of Bandera has an ASR recommended water management strategy and project in the 2022 State Water Plan that includes retrofitting the City's existing lower Trinity wells for ASR. The strategy also includes construction of a surface water treatment plant, distribution system, diversion structures, and wellfield. The online decade is 2040 in the 2017 State Water Plan and 2030 in the 2022 State Water Plan. The proposed ASR project is at a conceptual level and only had a broad-scale ASR feasibility in Bandera County completed in 2009 (Ashworth and others, 2009). Additionally, the City of Bandera and the Bandera County River Authority and Groundwater District (BCRAGD) expressed interest in a study to assess the longevity of the public supply wells due to water level declines in the lower Trinity Aquifer.

The TWDB ASR team selected this study because the team had recent experience with the Trinity Aquifer and an opportunity to apply recently completed mapping and modeling studies. Since the 2009 ASR feasibility study, the TWDB has recently completed high-quality regional stratigraphic mapping (Robinson and others, 2022) and groundwater modeling (Jones and others, 2011), which would provide the foundational framework for this subregional well longevity assessment. The proposed groundwater model would evaluate the lower Trinity aquifer's historic water levels in Bandera County and predict future water levels under different production scenarios.



ID	Operational ASR & AR
23	El Paso Water Utilities
33	San Antonio Water System
43	Seco Sinkhole
45	Ruby Ranch Water Supply Corporation
46	Antioch Cave
47	Residential rainwater harvesting
48	City of Kerrville

ID	ASR & AR projects
1	Brazos River Authority
2	Canadian River Municipal Authority
3	City of Austin
4	Bandera County
5	City of Bryan
6	City of Buda and others, middle Trinity Aquifer
7	City of Buda and others, saline Edwards Aquifer
8	City of College Station
9	City of Kerrville, expansion
10	City of Lubbock
11	City of New Braunfels
12	City of Uvalde
13	City of Victoria
14	City of Waco
16	Colorado River Municipal Water District
18	Kerr County
19	Lavaca Navidad River Authority
20	Lower Valley Water District
21	El Paso Water Utilities, expansion
22	Guadalupe-Blanco River Authority (Mid-basin)
24	City of Corpus Christi
44	Tarrant Regional Water District
49	Bell County

Figure 2-1. Aquifer storage and recovery and aquifer recharge projects in Texas and their status from the 2017 State Water Plan.

2.4 City of Bandera – Surface water acquisition, treatment, and ASR project

The proposed ASR project for the City of Bandera in the 2022 State Water Plan involves the construction of a new surface water treatment facility and associated conveyance pipelines to provide 1,000 acre-feet of treated water per year through the 2040 decade, and this volume is projected to increase to 1,500 acre-feet per year by 2060. The planned source water is surface water diverted from the Medina River based on a water supply agreement between Bandera County and Bandera-Medina-Atascosa Water Control and Improvement District (WCID) #1 for a diversion of up to 5,000 acre-feet per year. The construction of a new diversions and control structure will be needed upstream of the Medina River. Run 3 of the Guadalupe-San Antonio Basin Water Availability Model (WAM) estimated an average supply of 4,761 acre-feet per year available for diversion (TCEQ, 2022). The 2019 Plateau Region Water Plan indicates that 3,100 acre-feet per year of this total volume is readily available for planning purposes. When the direct demands are fully met, the excess will be injected into the lower Trinity aquifer through the ASR system. The stored water will be recovered and used in conjunction with treated surface water during peak demand. The size of the facility and number of wells required is not specified in the regional water plan. The estimated cost of the ASR project is $34.2 million.

The TWDB previously funded an ASR feasibility study in Bandera County that developed an ASR model to assess different ASR scenarios, including water levels in the aquifer, injection volumes, operation cycles, and possible locations for a new ASR well (Ashworth and others, 2009). This study considered both surface water from the Medina River and wastewater as potential sources of injected water but showed that the average discharge of wastewater within the City of Bandera was insufficient to meet demands. The study suggested a surface water treatment plant with a capacity of at least 6.7 million gallons per day (7,505 acre-feet per year) with the excess water being injected into the lower Trinity aquifer. The study also concludes that the most appropriate rate of injection would be 0.5 million gallons per day (560 acre-feet per year) within the City of Bandera or lower. Additional injection could be accomplished further from the city if additional storage capacity was needed.

3. Study area

There are many reasons a water provider may consider adding ASR to its water portfolio. Most pertinent to the City of Bandera is adding reliability to its current water resources and infrastructure. The lower Trinity aquifer has been the primary water supply source for the City of Bandera since the 1950s and there have been concerns about the declining water levels. In addition, water demand for the City of Bandera and the new subdivisions in the surrounding area, some of which also have lower Trinity aquifer wells, is projected to increase in the coming decades due to population growth (TWDB, 2022). Therefore, the goal of this study was to evaluate the life span of the City of Bandera's public water supply wells based on water levels in the lower Trinity aquifer and well configuration. The middle Trinity aquifer was excluded from this analysis for the following reasons: (1) the City of Bandera's reliance on the lower Trinity aquifer surpasses that of the lower Trinity aquifer, (2) the lower Trinity aquifer is the target for the ASR project as listed in the 2022 State Water Plan, and (3) the City of Bandera is considering a possible retrofit of an existing lower Trinity aquifer well for the development of the potential ASR project.

Groundwater modeling was used for the following objectives:

1. Evaluate historic water level trends in the lower Trinity aquifer.
2. Predict future water levels under three different well production scenarios:
    a. The no change scenario (S1), which assumes the City of Bandera continues to produce from the lower Trinity aquifer at the current rate.
    b. The projected use scenario (S2), which assumes the City of Bandera will produce enough groundwater from its lower Trinity aquifer wells to satisfy the projected future demand volumes listed in the 2022 State Water Plan.
    c. The maximum supply use scenario (S3), which assumes the City of Bandera will utilize all existing lower Trinity aquifer groundwater supply reported to be annually available for the City in the 2022 State Water Plan.

3.1 Study location

The Bandera well longevity model created in this study covered a sub-regional area within the lower Trinity aquifer with a model extent fully or partially within eight counties: Bandera, Bexar, Blanco, Comal, Hays, Kendall, Kerr, and Travis (Figure 3-1). The model extent was based on the overlap between the Hill Country Trinity Groundwater Availability Model (GAM) (Jones and others, 2011) and the hydrostratigraphic surfaces generated as part of the recent brackish groundwater mapping by Robinson and others (2022). The model extent was much greater than the study area, which focused on the lower Trinity aquifer in Bandera County, an area of 1,181 square miles (Figure 3-1). The active limit of the lower Trinity Aquifer layer in the Hill Country Trinity GAM was bounded to the west by the assumed limit of groundwater flow paths, and therefore, the western portion of Bandera County was not included in the Bandera well longevity model or focus study area (Jones and others, 2011). The vertical extent of the Bandera well longevity model contains the Edwards aquifer group, the upper Trinity aquifer, the middle Trinity aquifer, and the lower Trinity aquifer. A detailed description of the development of the Bandera well longevity model is in Appendix B.

The study area is in the Plateau (Region J) Regional Water Planning Area and Groundwater Management Area 9. In addition to the previously mentioned BCRAGD, the study area also contains portions of the Cow Creek Groundwater Conservation District, the Headwaters Underground Water Conservation District, the Medina County Groundwater Conservation District, the Trinity Glen Rose Groundwater Conservation District, and the Uvalde County Underground Water Conservation District. The Edwards Aquifer Authority is also located within a portion of the study area; however, its jurisdiction is limited to the Edwards Aquifer. This area also overlaps with parts of the Hill Country Priority Groundwater Management Area, which is one of the areas identified by the Texas Commission of Environmental Quality (TCEQ) facing current or projected water challenges (Figure 3-2).

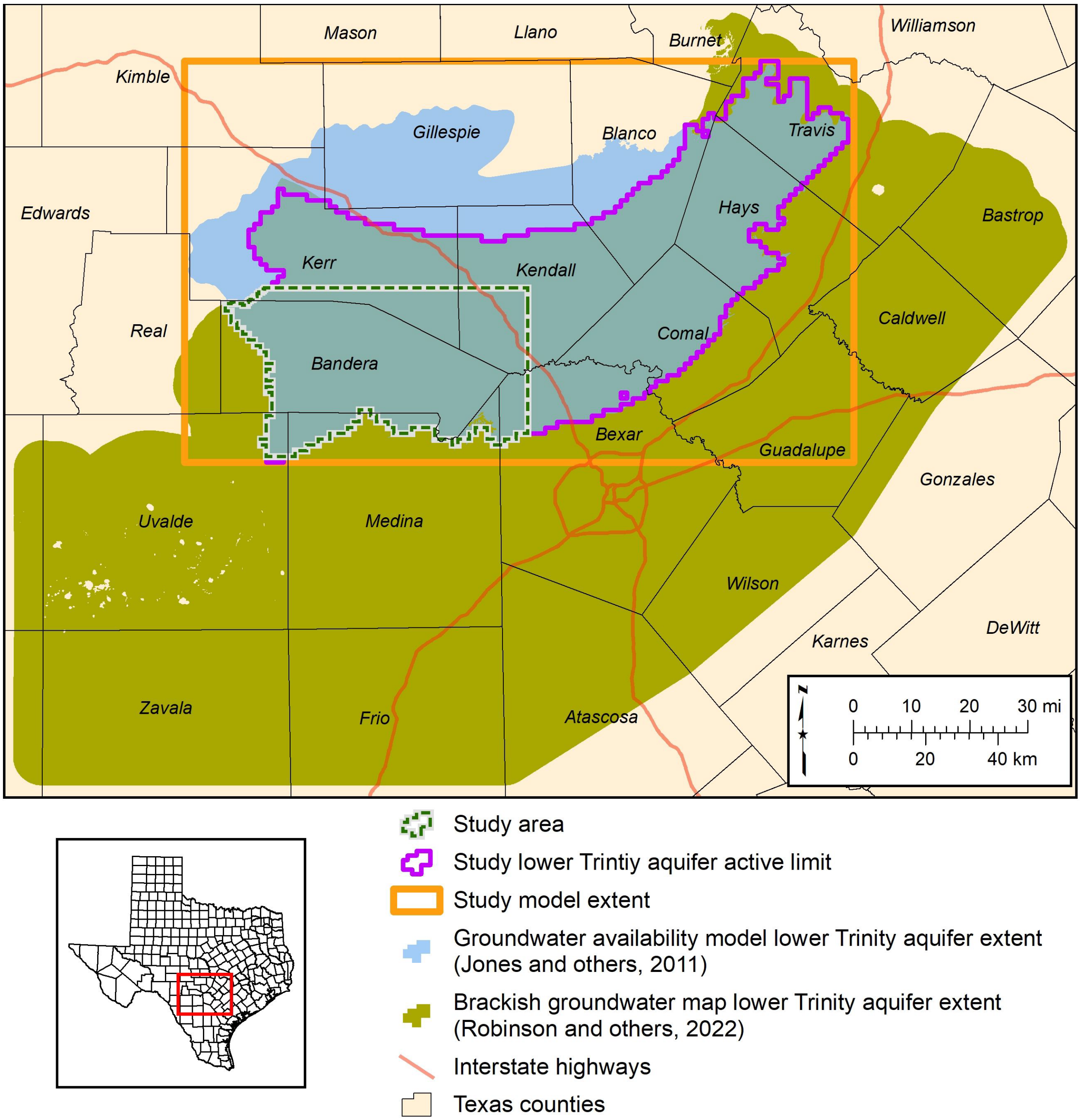


Figure 3-1. Map of the study area and extents of the lower Trinity aquifer in referenced models and studies.

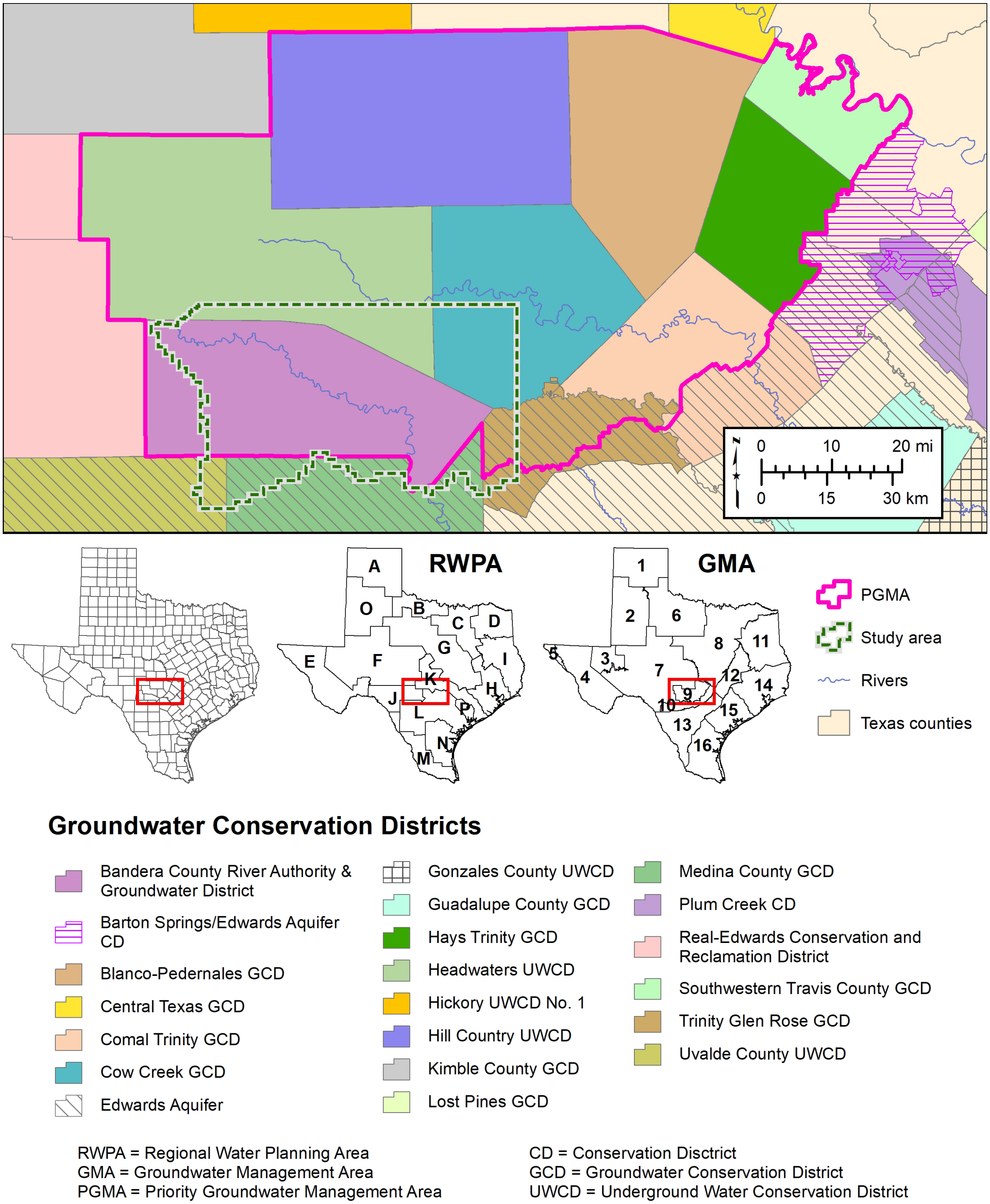


Figure 3-2. Map of administrative boundaries within and bordering the study area.

3.2 Hydrogeological setting

The Trinity Aquifer is the primary source of groundwater for Bandera County. It is found across the entire extent of the county, but a groundwater flow divide excludes modeling the western most portion of the county in this study. It is a highly permeable aquifer that can produce large volumes of water regionally (Reeves and Lee, 1962). However, the Trinity Aquifer only produces exceptionally large volumes of water in limited locations within Bandera County. The county also contains a small amount of the even more permeable karstic Edwards Aquifer, which overlies the Trinity Aquifer but is only present in portions of the county and is relatively thin and discontinuous (Broad, 2011). Both the Trinity and Edwards groups are heavily faulted throughout the county by the near-vertical faults of the Balcones Fault Zone, which has a significant impact on their hydrologic properties (Horvorka and others, 1994; Collins 1995). Alluvial deposits along major rivers and smaller streams may also contain groundwater and shallow wells capable of producing moderate amounts of groundwater (Broad, 2011).

3.2.1 *Trinity Aquifer*

The Trinity Aquifer is contained within the Trinity Group, which is located across most of south-central Texas (Imlay, 1945). The Trinity Group unconformably overlies Paleozoic–Jurassic strata, commonly grouped together as the "pre-Comanche" or "pre-Cretaceous" series (Imlay, 1945; Reeves and Lee, 1962). This contact has considerable paleorelief, which affects the thickness of the overlying Trinity Group throughout its extent; in general however, the Trinity Group is thinnest over the Llano Uplift and thickens to the south and southeast (Imlay, 1945; Ashworth, 1983; Ashworth and others, 2001).

The Trinity Group is a succession of three second-order, transgressive–regressive sequences composed of a siliciclastic lowstand unit and an overlying carbonate highstand unit (Figure 3-3; George, 1952; Stricklin and others, 1971; Bebout and others, 1977). These three sequences from oldest to youngest are: 1) the Hosston and Sligo formations; 2) the Hammett Shale and Cow Creek Limestone; and 3) the Hensel Sand and the Glen Rose Limestone (Stricklin and others, 1971). Within the study area, the Trinity Group is up to approximately 1,500 feet thick in southern Bandera County and thins northward.

The Trinity Group is further subdivided into hydrostratigraphic units based on the porosity and permeability characteristics. Hydrostratigraphic units have distinct hydrologic characteristics based on the physical properties of the rock unit including lithology, sedimentary structures, bioturbation, and structural features (Maxey, 1964; Choquette and Pray, 1970; Clark and Morris, 2015; Golab and others 2017a and b). The middle and upper Trinity aquifers have been subdivided into 13 hydrostratigraphic units that are classified as being confining, semi-confining, or transmissive based on their overall physical characteristics (Clark, 2003, 2004; Clark and others, 2009, 2014, 2016a and b, 2020; Blome and Clark, 2014; Pantea and others, 2014; Clark and Morris, 2015; Golab and others, 2017a and b). The lower Trinity aquifer has not been divided into hydrostratigraphic units due to limited outcrop throughout most of south-central Texas and little information available from cores (Clark, 2003; Golab and others 2017b).

The Trinity Aquifer is recharged by subsurface inflow of groundwater from the Edwards Plateau or infiltration on exposed outcrop (Barker and Ardis, 1996; Clark and others, 2016). The carbonate units of the Trinity aquifer system are highly transmissive through secondary porosity such as faults, fractures, and biogenic pores (Clark and others, 2016; Golab and others 2017a and b).

<table>
<tr><th>Epoch</th><th>Age</th><th>Group</th><th>Formation</th><th>Member</th><th>Hydrostratigraphic unit</th><th>Aquifer</th></tr>
<tr><td rowspan="18">Lower Cretaceous</td><td rowspan="7">Albian</td><td>Edwards</td><td>Fort Terrett</td><td>Basal Nodular</td><td>VIII
Transmissive</td><td>Edwards</td></tr>
<tr><td rowspan="17">Trinity</td><td rowspan="11">Glen Rose Limestone</td><td rowspan="5">Upper Glen Rose Limestone</td><td>Cavernous
Transmissive</td><td rowspan="5">Upper Trinity</td></tr>
<tr><td>Camp Bullis
Semi-confining</td></tr>
<tr><td>Upper Evaporite
Transmissive</td></tr>
<tr><td>Fossiliferous
Semi-confining</td></tr>
<tr><td>Lower Evaporite
Transmissive</td></tr>
<tr><td rowspan="6">Lower Glen Rose Limestone</td><td>Bulverde
Semi-confining</td><td rowspan="8">Middle Trinity</td></tr>
<tr><td rowspan="9">Aptian</td><td>Little Blanco
Transmissive</td></tr>
<tr><td>Twin Sisters
Confining</td></tr>
<tr><td>Doeppenschmidt
Transmissive</td></tr>
<tr><td>Rust
Confining</td></tr>
<tr><td>Honey Creek
Transmissive</td></tr>
<tr><td rowspan="3">Pearsall</td><td>Hensell Sand</td><td>Hensell
Confining</td></tr>
<tr><td>Cow Creek Limestone</td><td>Cow Creek
Transmissive</td></tr>
<tr><td>Hammett Shale</td><td>Hammett
Confining</td><td>Confining unit</td></tr>
<tr><td>Sligo</td><td rowspan="3"></td><td rowspan="3">Lower Trinity
Transmissive</td><td rowspan="3">Lower Trinity</td></tr>
<tr><td>Barremian</td><td rowspan="2">Hosston</td></tr>
<tr><td>Hauterivian</td></tr>
</table>

Figure 3-3. Stratigraphy and hydrostratigraphy of Bandera County.

Lower Trinity aquifer

The lower Trinity aquifer has historically been less utilized than the middle and upper Trinity aquifers in Bandera County; however, increased demand from municipal users, such as the City of Bandera and growing residential development, has created interest in the lower Trinity aquifer and made drilling to this deeper reservoir more economical. The lower Trinity aquifer is contained within the Hosston and Sligo formations of the Trinity Group. The thickness of the lower Trinity aquifer varies due to the significant paleorelief of the pre-Cretaceous strata below it but in general ranges from approximately 360 feet along the southern boundary of Bandera County to approximately 150 feet along the northern county boundary (Ashworth and others, 2001).

The Hosston Formation is the lowermost unit of the aquifer and dominated by heterogeneous alluvial conglomerates and course-grained sandstones (Reeves and Lee, 1962; Wierman and others, 2010). The Hosston Formation also grades laterally into dolomitic strata south of the Llano Uplift and some dolomitic units can be seen in the southern portions of Bandera County (Reeves and Lee, 1962; Wierman and others, 2010; Clark and others, 2020). The Hosston Formation is approximately 280 feet thick in the southernmost portions of Bandera County and thins northward, eventually pinching out in northwestern Kerr County (Ashworth and others, 2001). The Hosston Formation is the most abundant water producer in the lower Trinity aquifer; however, alluvial deposits such as the Hosston Formation have highly variable hydraulic properties caused by variations in grain size and interbedded fine-grained units. The Hosston Formation is primarily clean sand and conglomerate near Kerr County and grades into interbedded shale and sand in Bandera County.

The Hosston Formation grades upsection into the Sligo Formation, which consists primarily of argillaceous limestone and sandy dolomite (Reeves and Lee, 1962). The base of the Sligo Formation is often difficult to pick on logs or in cuttings but is commonly siltstone and shale and grades upsection into fossiliferous limestone and dolomite (Wierman and others, 2010). The Sligo Formation is generally thinner than the underlying Hosston Formation with a maximum thickness of 80 feet in southern Bandera County. The Sligo Formation thins northward becoming undifferentiated from the Hosston Formation in northern Bandera County and pinching out in northwestern Kerr County (Ashworth and others, 2001).

Both the Hosston and Sligo formations have limited outcrop and the aquifer is not directly recharged by precipitation. The aquifer also receives very minor recharge from infiltration through overlying formations due to the confining overlying Hammett Shale (Ashworth and others, 2001). Most recharge of the aquifer likely occurs to the north and west, outside of Bandera County, where the Hammett Shale is not present and the units are thinner (Ashworth and others, 2001).

The lower Trinity aquifer has been the focus of a few feasibility studies for ASR in Central Texas. The Hosston Formation has several characteristics that make it a good candidate for ASR storage and recovery. Generally, siliciclastic rocks that contain high porosity and permeability—and therefore hydraulic conductivity—are considered ideal targets for ASR due to their ability to store water and their predictable flow (Shaw and others, 2020). The lower Trinity aquifer is also well confined by the overlaying Hammett Shale, which allows any stored water to be controlled and recovered efficiently (Pyne, 2004; Shaw and others, 2020)

Hammett Shale

The lower Trinity aquifer is overlain by the Pearsall Formation, which is characterized by its abundant shale content (Imlay, 1945). The lowest member of the Pearsall Formation is the Hammett Shale, a relatively thin calcareous shale unit that ranges from 60 feet thick in southern Bandera County to less than 30 feet thick along the northern boundary of the county (Ashworth and others, 2001; Clark and others, 2016). The basal contact of the Hammett Shale is sharp and easily identifiable in logs by a sharp gamma-ray spike (Lozo and Stricklin, 1994). The Hammett Shale generally forms a hydrogeologic barrier between the lower and middle Trinity aquifers and, historically, it was assumed that there was no communication between these two aquifers (Ashworth and others, 2001; Wierman and others, 2010; Clark and others, 2014). However, some communication likely occurs between these aquifers, possibly along faults or through well bores.

Middle Trinity aquifer

Water-bearing strata of the middle Trinity aquifer consists of the Cow Creek Limestone and Hensel Sand members of the Pearsall Formation and the Lower Glen Rose Limestone. The contact between the Cow Creek Limestone and the Hammett Shale is somewhat gradational but can be identified easily in logs because of the Cow Creek Limestone's increased resistivity (Lozo and Stricklin, 1994).

The Cow Creek Limestone was divided into three informal members by Lozo and Stricklin (1994) and subsequently referred to as the lower, middle, and upper members. The lower member is highly permeable and characterized by alternating beds of massive, fossiliferous packstone and thinner calcareous shale beds (Stricklin and Smith, 1973). The middle member is the least permeable member of the unit and is characterized by thinly bedded, fine-grained calcarenite with some silt and fine-grained sand (Stricklin and Smith, 1973). The upper member is the most permeable and consists primarily of coarse-grained packstone with large crossbeds (Stricklin and Smith, 1973). The uppermost beds of the Cow Creek Limestone grade into siliciclastic sands and gravels that become coarser to the north of the study area along the Llano uplift.

The Cow Creek Limestone grades upsection into the overlying Hensell Sand which is a siliciclastic unit consisting of primarily sand and shale (Reeves and Lee, 1962). Within northern Bandera County, the Hensell Sand is characterized by conglomerates and coarse-grained sandstone and grades into sandstone and sandy dolomite toward the southern portions of the county (Reeves and Lee, 1962). The Hensell Sand grades into the Bexar Shale south of Bandera County (Barker and Ardis, 1996).

The uppermost unit in the middle Trinity aquifer is the Lower Glen Rose Limestone, which consists primarily of argillaceous limestone with interbedded calcareous shales and some evaporites. Limestones are commonly comprised of alternating beds that grade from fossiliferous wackestone to packstone upsection and contain numerous large-scale interconnected burrows that may be conduits for fluid flow (Cunningham and Sukop, 2012; Clark and others, 2016;

Golab and others, 2017a and b). The Lower Glen Rose Limestone was subdivided into eight distinct hydrostratigraphic units by Blome and Clark (2014) and Clark and others (2014) that can be subdivided into transmissive, semi-confining, and confining units (Golab and others, 2017a and b).

The middle Trinity aquifer has been considered for use in ASR projects but is generally considered to be less ideal than the Hosston Formation. Karstic carbonate units, like the middle Trinity aquifer pose several challenges for the development of an ASR project. The large secondary porosity created by faults and fractures may lead to highly permeable zones within the aquifer, but these are difficult to accurately map in the subsurface and injected water will preferentially flow along these paths, preventing the injected water to be recovered (Cunningham and others, 2009; Golab and others 2017b). Additionally, many carbonates may contain pyrite, which may be oxidized by the addition of treated water and release arsenic (Arthur and others, 2002)

Upper Trinity aquifer

The upper Trinity aquifer consists of the Upper Glen Rose Limestone, which is primarily argillaceous limestone with interbedded calcareous shales and significant deposits of evaporites and some gypsum beds (Golab and others, 2017a). The limestone beds are generally coarser grained than those in the lower unit and are therefore commonly more permeable. The Upper Glen Rose Limestone is more transmissive than the lower unit, in part due to the high permeability of the evaporite units (Clark and others, 2016). The Upper Glen Rose Limestone was subdivided into five informal hydrostratigraphic units by Clark (2003) and Clark and others (2009) that are subdivided into transmissive, semi-confining, and confining units. The Upper Glen Rose Limestone is the most abundant outcrop at the surface in Bandera County and recharge by precipitation to the middle and upper Trinity aquifers occurs locally (Ashworth and others 2001).

The upper Trinity aquifer is not considered a feasible location for an ASR project within the study area. Similar to the middle Trinity aquifer, it is a karstic carbonate unit and shares many of the same issues with the underlying units. Additionally, the upper Trinity aquifer is unconfined across the study area, which makes predicting the hydraulics and potential drifting of the stored water challenging (Shaw and others, 2020). Additionally, being at the surface makes the unit susceptible to surface contamination (Shaw and others, 2020).

3.2.2 *Edwards Aquifer*

The Edwards Aquifer is located above the Trinity Aquifer and consists of the Georgetown Formation of the Washita Group and the Person and Kainer and Fort Terrett formations of the Edwards Group. The Edwards Aquifer was subdivided informally into hydrostratigraphic units numbered I–VIII by Maclay and Small (1976). Most of the Edwards Group within the study area has been eroded away, leaving only the lowest member of the Fort Terret Formation, commonly referred to as the basal nodular unit, which is characterized by nodular, heavily bioturbated mudstone to grainstone successions (Clark and others, 2016; Golab and others 2017a). Within Bandera County, the Edwards Group is only present in the northwestern portion of the county (Mace and others, 2000). Outcroppings of the Fort Terrett Formation can commonly be found on hilltops in Bandera County, but these discontinuous units do not play a major role in the subsurface hydrogeology.

3.2.3 ***Alluvial deposits***

Bandera County's only other groundwater source consists of minor alluvial deposits along rivers and streams such as the Medina River (Reeves and Lee, 1962). These deposits may have a high permeability but are generally less than 50 feet thick and cover a small area within some floodplains (Figure 3-4, Ashworth and others, 2001). These deposits are also unconfined, and their potential output may vary seasonally.

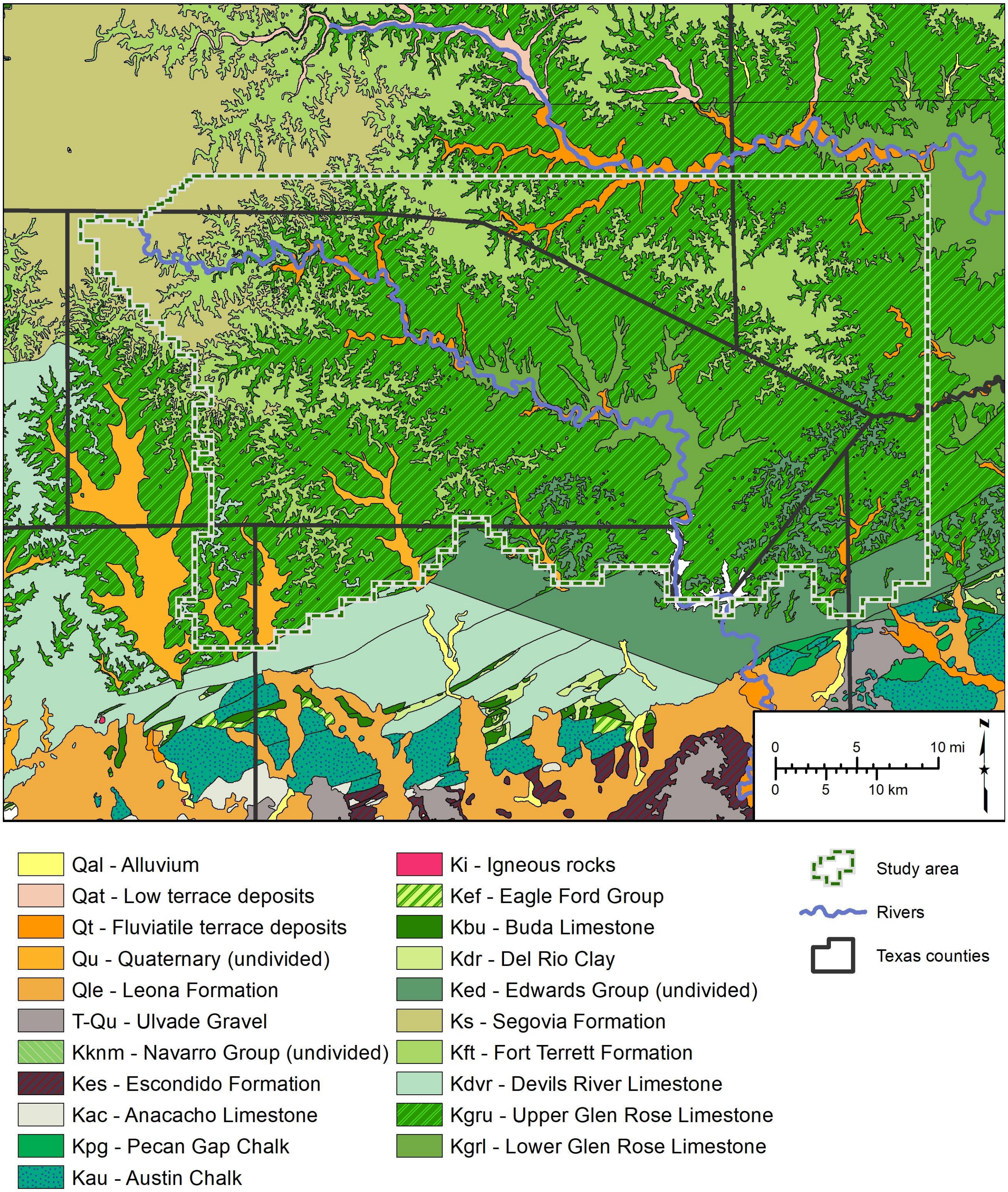


Figure 3-4. Surface geologic map for the study area (TWDB, 2007b).

3.2.4 *Balcones Fault Zone*

The hydrogeology within the study area is also controlled by faults, fractures, and geologic structure. All of the units contained within the Edwards and Trinity groups were faulted during the Miocene, creating the Balcones Fault Zone; a northeast–southwest trending zone of near-vertical normal faults that extend from central to north Texas (Collins, 1995). These faults and fractures provide the primary means of water flow through most of the carbonate units of the Trinity and Edwards aquifers. This faulting allows for rapid infiltration of water and has resulted in solution-enhanced fractures, bedding planes, and caves (Clark and others, 2016).

Recent studies have shown that there are more faults within the region than previously mapped, and these faults may be offset by more than 100 feet. Clark and others (2020) show that Medina County, which borders Bandera County to the south, contains numerous previously unmapped faults. Some of these faults have enough apparent throw to completely displace the Hammett Shale in the subsurface, allowing for communication between the middle and lower Trinity aquifers. The lower Trinity aquifer also has higher hydraulic head than the middle Trinity, which may lead to equilibration of hydraulic heads along these faults (Kelley and others, 2020).

4. City of Bandera production wells

Understanding the characteristics and operation of an aquifer-well system is necessary to evaluate historic and current state of the system and plan for future conditions. The City of Bandera has three public supply wells in the lower Trinity aquifer: the Mulberry Street well (#4) located on the northern side of the city, the Dallas Street well (#5) located northwest of the city, and the Indian Waters well (#6) located far north and outside of city limits (Figure 4-1). The most recently drilled well, the Dallas Street well (#5a) is completed in the middle Trinity aquifer. Table 4-1 lists the details for these wells including names and identifier aliases, formation and well completion, operation details, and available water level observations.

Overall, the City of Bandera total groundwater production is 248,760 gallons per day (273.6 acre-feet per year). The three lower Trinity aquifer wells produce 93 percent of this output (231,480 gallon per day or 259.3 acre-feet per year) and the single middle Trinity aquifer well produces seven percent of the output (17,280 gallons per day or 19.3 acre-feet per year). Of the three lower Trinity aquifer wells, the Mulberry Street well alone produces 42 percent of the city's total output (103,680 gallons per day or 116.1 acre-feet per year). The Mulberry Street well is not only the most productive well, but it also has the most available associated data, therefore it was the focus for much of this project's analysis.

Based on the current operation and configuration of the City of Bandera's four wells, pumping water levels are reaching close to the current pump depth (Roy, 2021, personal communications). Therefore, any increase in production volume would require lowering the pumps within the well to sustain municipal supply. Additionally, three of the four wells are completed as open hole (Indian Waters #6 is screened). Pumps in open hole completed wells cannot be lowered into the open hole because sediment may be drawn into the pump and motor, which would damage the system (Walker, 1978). Therefore, if water levels drop below the casing into the open hole, the well would no longer be usable. Although the City of Bandera added a middle Trinity aquifer well and no longer rely solely on the lower Trinity aquifer, the daily water demands could stress the system if any of the city's four public water supply wells were offline for an extended time.

The Mulberry Street well is the oldest of the four operating production wells and was drilled in 1953. It was completed with 90 feet of open hole that spans the entire thickness of the lower Trinity aquifer (TWDB, 2021a; BCRAGD, 2021). The pumping rate of the Mulberry Street well is 480 gallons per minute. The City of Bandera reported that the daily average run time for the Mulberry Street well is 3.6 hours, at which point the pumping water level reaches near the pump depth at 490 feet below ground surface (Roy, 2021, personal communications). This results in 46 feet of drawdown from the static water level at 444 feet below ground surface, measured during winter conditions (Figure 4-2). For consistency, mean sea level is used for reporting because the ground surface in the Hill County area is highly irregular. The Mulberry Street well current static water level is at 816 feet above sea level and the current pumping water level is at 760 feet above mean sea level (Figure 4-3). The top of the Hosston Formation, which is at the bottom of the Mulberry Street well casing, is at 520 feet above mean sea level. When the Mulberry Street well was drilled, the pump was placed 400 feet below the ground surface (871 feet above mean sea level). In the late 1980s to the late1990s, the pump was lowered to 500 feet below ground surface (771 feet above mean sea level, as documented in the well schedule (TWDB 2021a; BCRAGD, 2021).

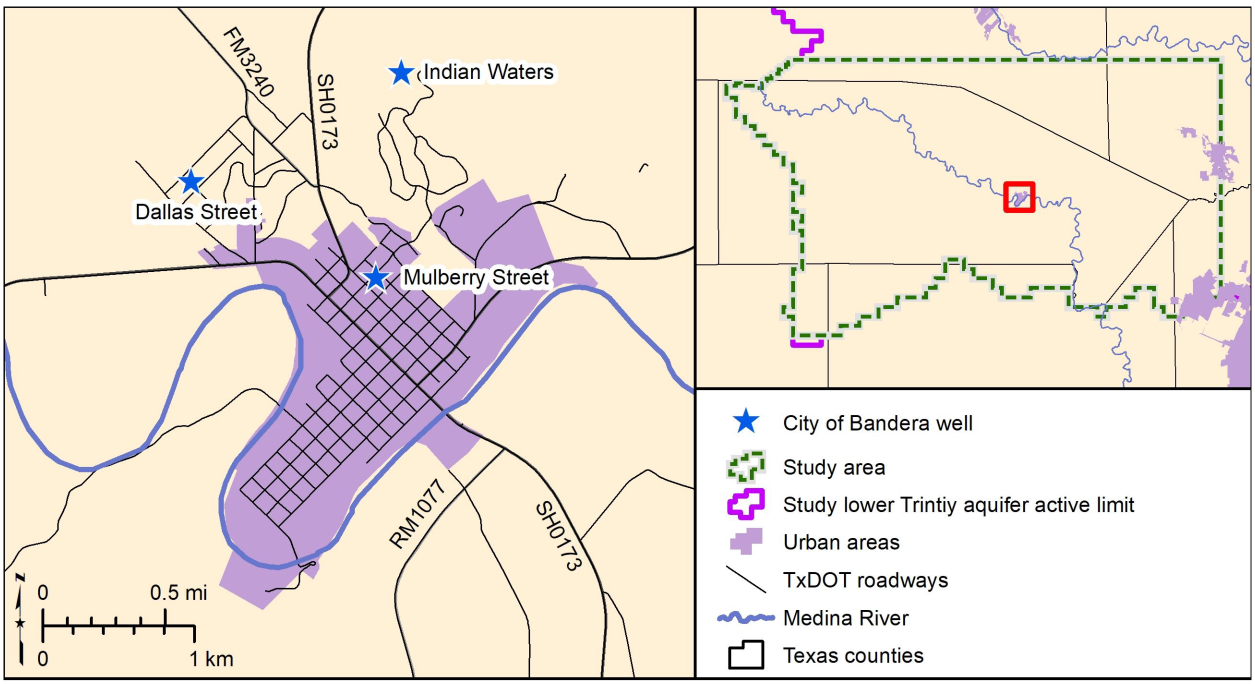


Figure 4-1. **City of Bandera lower Trinity wells.**

Table 4-1. City of Bandera water supply wells.

Well name	Dallas Street (#5a)	Dallas Street (#5)	Mulberry Street (#4)	Indian Waters (#6)
BRACS ID	88033	88432	52986	58742
State well number	6924116	6924102	6924202	6924221
PWS source number	1000012	G0100012C	G0100012B	G0100012D
Drill year	2017	1967	1953	1998
Well depth (feet)	480	805	842	770
Screen intervals (feet)	221-480	533-805	740-842	610-710
Well completion	Open hole	Open hole	Open hole	Screened
Operation rate (gallons per minute)	120	500	480	300
Daily average run time (hour)	2.4	2.4	3.6	3.1
Average production per day (gallon)	17,280	72,000	103,680	55,800
Percentage of total production	7	29	42	22
Static water depth (feet)	257	468	444	444
Pumping water depth (feet)	268	581	490	494
Drawdown (feet)	11	113	46	50
Aquifer code	Middle Trinity	217HSTN-Hosston formation	217HSTN – Hosston formation	217HSTN-Hosston formation
Available water level information – measurements	-	19	20	3
Available water level information – publishable winter values	-	6	5	1

Notes: PWS = public water supply and BRACS = Brackish Resources Aquifer Characterization System.

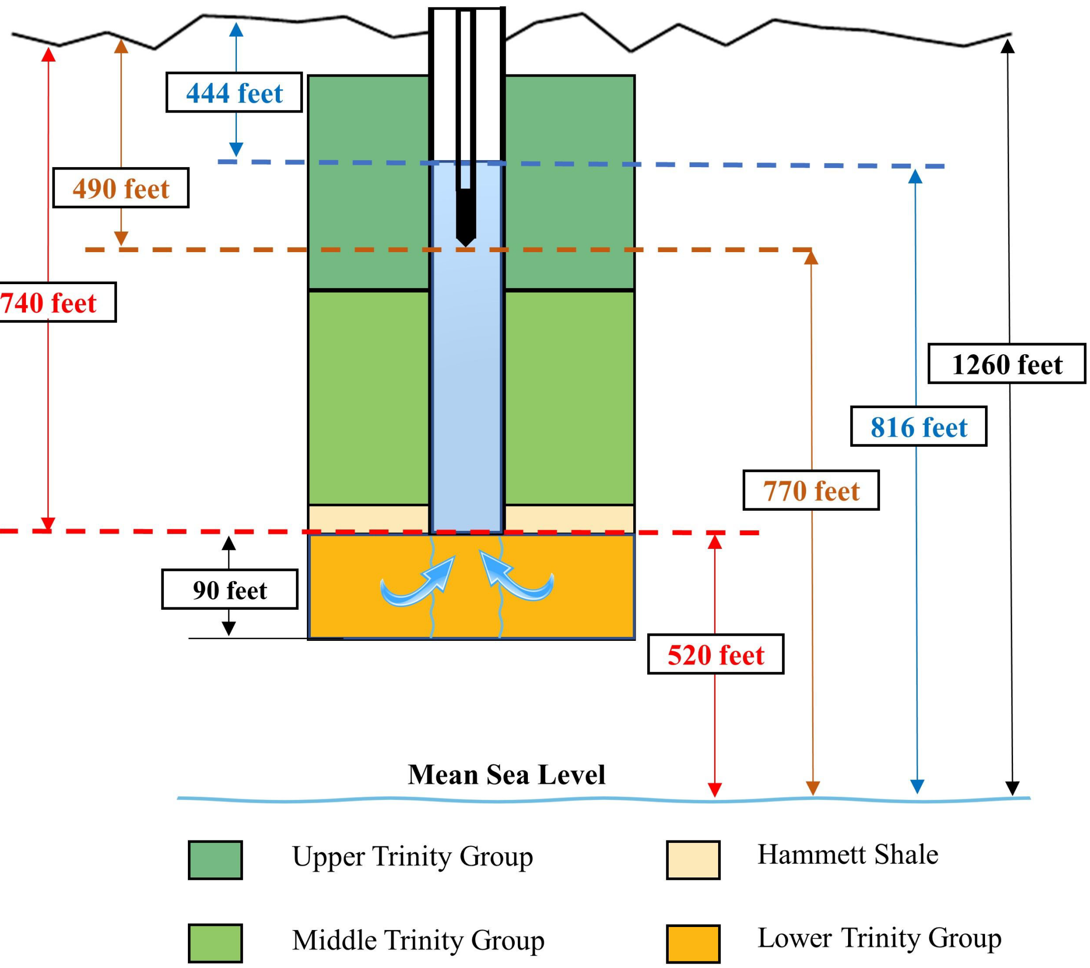


Figure 4-2. Mulberry Street well (#4) water levels elevations and depth below ground surface.

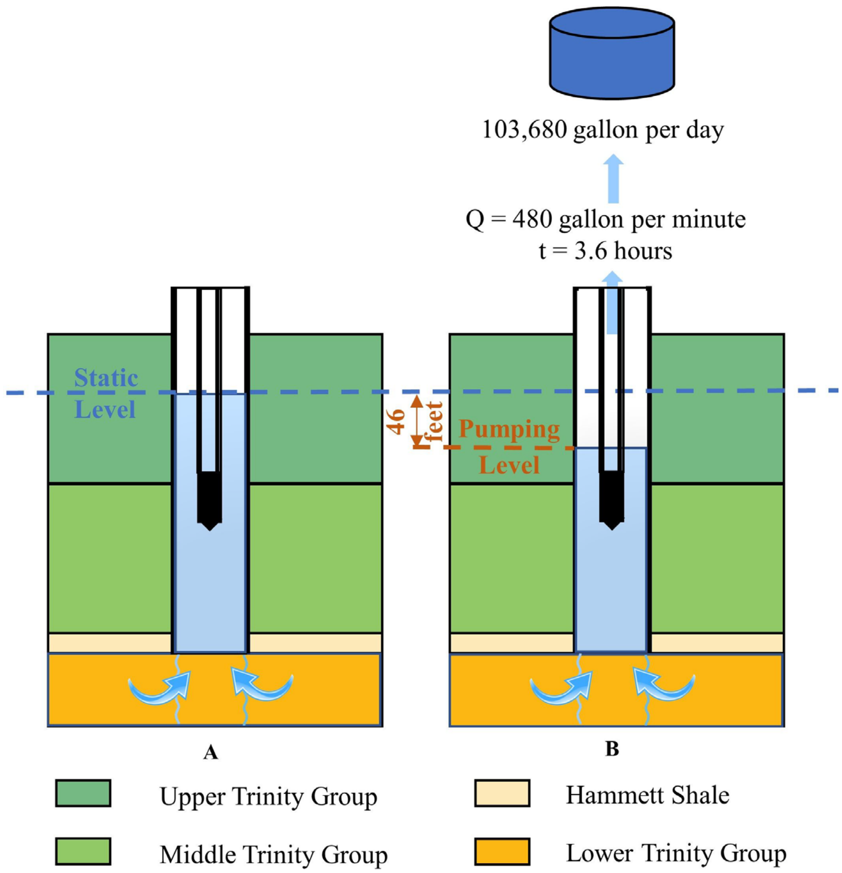


Figure 4-3. Mulberry Street well (#4) water level in static condition (A) and pumping condition (B).

The goal of this study is to understand the potential longevity of the City of Bandera's wells and how they will be affected by both future production and water level changes. This is a key component for the City of Bandera's future water supply planning to assist the city in evaluating the need for alternate water supply strategies such as the proposed ASR project.

Historical data can be used to gain a better understanding of the aquifer-well system and be used to interpret how it may change in the future. Available historic water level measurements (observations) for the three lower Trinity aquifer wells are shown in Figure 4-4. Initial water levels were 1,214, 1,147, and 747 feet above mean sea level for the Mulberry Street well (in 1953), the Dallas Street well (in 1963), and the Indian Waters well (in 1998), respectively. The general trend of the observed static water level shows three historic periods. The first period is between 1950 and 1996. This period is characterized by a continuous decline in water levels of up to 400 feet in the Mulberry Street well and 477 feet in the Dallas Street well. The drought conditions of 1996 may have significantly influenced this decline. The second trend period is in 1997 with a significant increase in water levels of almost 105 feet in the Mulberry Street well and 136 feet in the Dallas Street well. Lastly, the third historic water level trend period is between 1998 to 2004, characterized by water level fluctuations between 800 feet and 900 feet above mean see level for both wells. After this historic period, the City of Bandera reported the available water level observations for the 2021 static conditions. As for the Indian Waters well, there are only two water level observations that are publishable and historic and show an increase in water levels of almost 140 feet between 1998 and 2003.

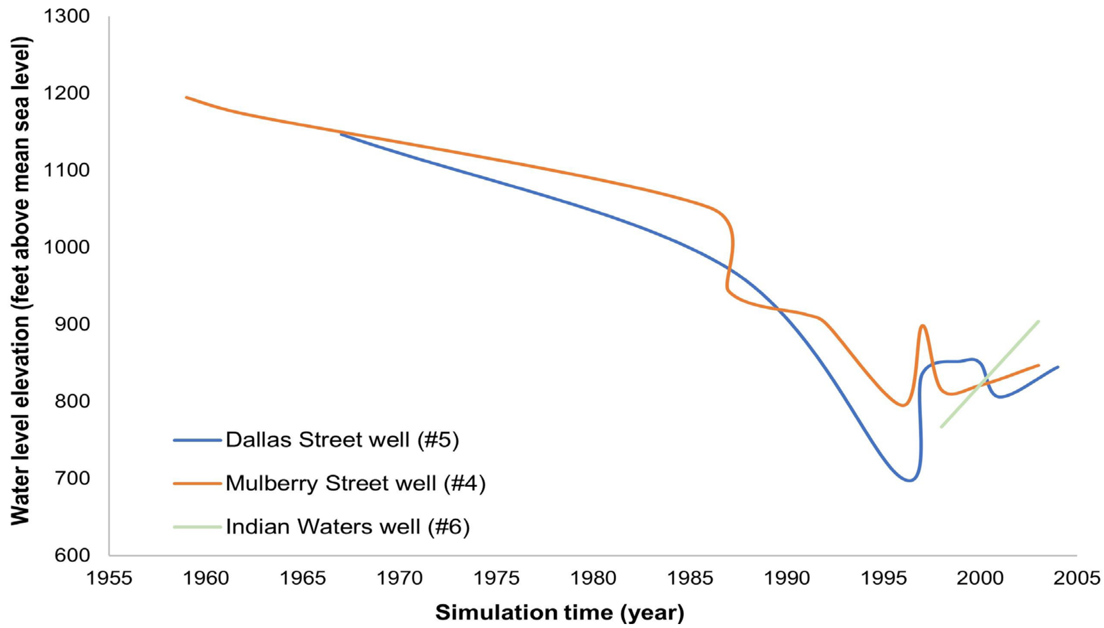


Figure 4-4. Historic water level elevations of the City of Bandera lower Trinity aquifer public supply wells.

The City of Bandera is interested in understanding how long the city's wells can reliably supply the city with water under both current and future conditions. The City of Bandera is facing several water-supply challenges, including

- increase in water demand due to population,
- reliance on a single water supply source (groundwater from the Trinity aquifer),
- capacity/limitations of wells have reached maximum drawdown under the current pump configurations, and
- the wells lack redundancy to compensate for one of the wells failing.

The historical data on these wells shows that there is a complex relationship between the water levels and well operations and provides a solid foundation for understanding how the system reacts to changing conditions. This information can be used to test different future scenarios and inform the water planning process.

5. Theis analytical solution for well operations

Now that we understand the City of Bandera production wells, conducting a quick evaluation of operation scenarios for an individual well will help us predict the ability of this well and interpretations from this evaluation can guide future numerical models. Predicting the longevity of a well based on the well-aquifer system (water levels and well configuration) can be achieved by using an analytical solution that studies the groundwater flow to that well. The Theis (1935) analytical solution is a basic groundwater flow equation to investigate simple well-aquifer systems and determine water levels in response to the pumping well. It provides high resolution values for a specific point within the well's zone of influence and the timeframe of pumping and water level recovery. The values solved for include water levels, production rates, volumes, and pumping time, all of which are useful for managing individual well operations. While the simplicity of the equation allows for quick computation, the main limitations of the Theis analytical solution are it assumes a simple well-aquifer system with ideal characteristics and a single pumping event.

The Theis analytical solution was applied to the Mulberry Street well because it has the most available data of the city's lower Trinity aquifer wells and currently produces 42 percent of the city's water supply (TWDB, 2021a; BCRAGD, 2021). The results were used as a quick evaluation of future operation scenarios and to predict the ability of this individual well to meet increasing demands starting at the current static water level. A detailed description of the method and its application to the Mulberry Street well is in Appendix A.

Lower Trinity well-aquifer system values at the Mulberry Street well were estimated for three pumping scenarios: (1) current operations, (2) existing supply, and (3) end-of-life. Current operations of the well are described in Section 4. Existing supply scenario for the Mulberry Street well would be to produce 42 percent of all existing groundwater supply for the City of Bandera listed in the 2022 State Water Plan. The state water plan existing supply is the reliable volume of water the City of Bandera has the infrastructure to obtain, treat, and deliver to the municipal water user group during a repeat of the 1950s drought of record (TWDB, 2022, and WSP and Carollo Engineers, Inc., 2021). End-of-life scenario for the Mulberry Street well would be producing water at a rate that would render the well inoperable regardless of lowering the pump.

Figure 5-1 shows the current and projected future operational conditions for the Mulberry Street well assuming the same current static water level. Subpanel A shows the current static water level of 444 feet below the ground surface, which is equivalent to 816 feet above mean sea level. During current operations, shown in subpanel B, the pumping water level reaches approximately 10 feet above the pump in 3.6 hours with a total drawdown of 46 feet and recovers to the static water level daily after pumping ceases (Roy, 2021, personal communications).

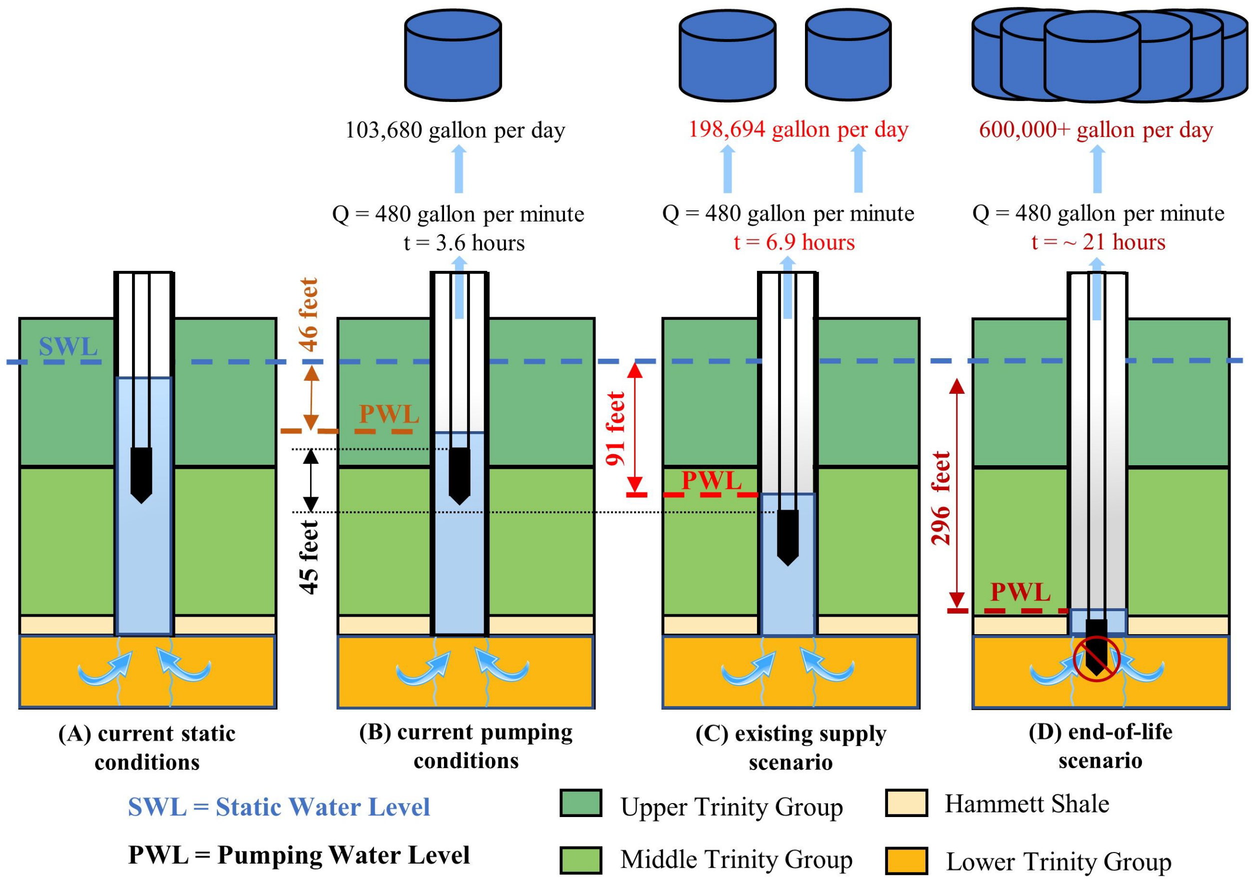


Figure 5-1. The analytical solution results for the Mulberry Street well (#4).

The existing supply scenario is shown in Figure 5-1 subpanel C. The City of Bandera existing groundwater supply listed in the 2022 State Water Plan is 534 acre-feet per year or 467,726 gallons per day (TWDB, 2022). In comparison with the current total groundwater production of 279 acre-feet per year or 248,760 gallons per day, producing the entire existing groundwater supply would be equivalent to increasing total production by 91 percent; slightly less than twice what the city is currently delivering. Assuming the same ratio of current production between the city's wells, the Mulberry Street well would need to increase production to 223 acre-feet per year or 198,694 gallons per day. At the current pumping rate of 480 gallons per minute, the well would need to operate for almost twice the current run time, or 6.9 hours, and would create a total drawdown of 91 feet. At this duration the pumping water level would drop below the current pump level. To continue use of the Mulberry Street well in the existing supply scenario, the pump would need to be lowered to at least 545 feet below ground surface (45 feet below the current pump level) within the casing to avoid negative suction. In other words, in this very simplistic evaluation we predict that the Mulberry Street well cannot provide the existing supply listed in the 2022 State Water Plan without the pump being lowered.

Subpanel D of Figure 5-1 shows the Mulberry Street well end-of-life operation limits based on the current static water level and well configuration. The Theis analytical solution for this hypothetical scenario indicates that the pumping water level drops 296 feet from the current static water level to an elevation of 520 feet above mean sea level. This would place the pumping water level below the maximum possible depth of the pump, which would be in the open hole portion of the well. This represents the end-of-life for the well since a pump lowered into the open hole portion of a well would produce mud (Walker, 1978). Assuming the same current pumping rate of 480 gallon per minute, it would take almost 21 hours of pumping to drop the water to an inoperable level in the open hole. This much pumping would produce more than 600,000 gallons per day, approximately three times the rate the Mulberry Street well would have to produce to match the existing supply listed in the 2022 State Water Plan. Adding to the inoperability of the well in this scenario, pumping would occur 21 hours of a 24-hour day, so the well would not have enough time to return to the current static water level between pumping cycles and achieve full recovery.

The results of the simple Theis analytical solution were reviewed to estimate an approximate minimum static water level needed to maintain the capacity of the Mulberry Street well to produce the existing supply during a repeat of the drought of record. Developed on the previous estimate of the drawdown in this scenario (91 feet) and the following assumptions: (1) the city would lower the pump to approximately the bottom of the well casing with an appropriate interval above the open hole suitable for the pump type, (2) the current 10 feet gap of water would be maintained above the pump to ensure successful pump operation, and (3) the well is able to achieve full recovery between the 6.9-hour daily pumping sessions. The results of these assumptions and the solution indicate that a static water level greater than 621 feet above mean sea level should be maintained to sustain the capacity of the Mulberry Street well to produce water at the existing supply scenario rate. This is a maximum of 195 feet below the current static water level of 444 feet below ground surface. Figure 5-2 depicts the above assumptions and results. This quickly estimated minimum static water level does not account for the additional wells in the Mulberry Street well's zone of influence or surrounding changes in the lower Trinity aquifer.

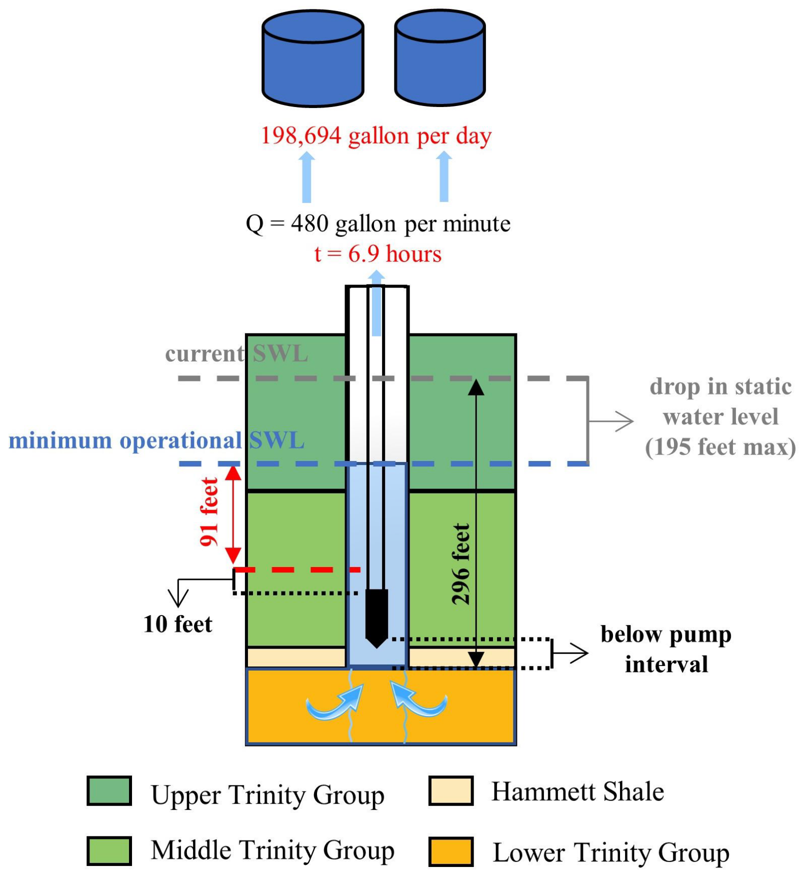


Figure 5-2. Minimum required operational static water level (SWL).

The lower Trinity well-aquifer system in Bandera County is much more complex than can be represented by an analytical solution alone. Both the existing supply and end-of-life scenarios for the Mulberry Street well are extremes, and there will likely be changes in the lower Trinity well-aquifer system over time. The City of Bandera has three wells that share a zone of influence and the results in the above analysis are based on the pumping effects of only one well. Attempting to estimate the overall effect of all three wells over decades requires higher computational capabilities to solve a complex mathematical equation. While the Theis analytical solution provided a quick overview of the operations of the Mulberry Street well, a numerical model can take into account a complex aquifer system, historical conditions, and projected regional demand increases, which are needed for the decadal planning required to implement new water supply strategies such as ASR.

6. Numerical model for water planning

A numerical groundwater model is a computer-based representation of the structure, hydrology, and hydrological processes of an aquifer system that takes into account both internal and external influences. Groundwater models enable the investigation of a system's response to stressors by applying complex mathematical equations, along with field measured parameters, to calculate water levels over time. While analytical methods can capture temporal extremes at a fine spatial resolution, which is particularly important when evaluating water level changes at supply wells, numerical models' results provide long-term regional changes in water levels which is a major element in regional water management and multi-year planning (MacMillan and Schumacher, 2014). Numerical models may be guided by or complemented with interpretation from analytical solutions. The Bandera well longevity model created for this study is a numerical groundwater model used to simulate the lower Trinity aquifer system and the City of Bandera's wells and was created because the analytical solution alone could not capture the full complexity of the system. This model was constructed using the framework of the Hill Country Trinity GAM that simulates the period from 1980 to 1997 (Jones and others, 2011). The model has four layers: layer one is the Edwards Group of the Edwards-Trinity (Plateau) Aquifer, layer two is the upper Trinity aquifer, layer three is middle Trinity aquifer, and layer four is the lower Trinity aquifer.

While the Hill County Trinity GAM represents the regional transient groundwater flow in the Hill Country portion of the Trinity Aquifer, this study required a model focused on a subregional level in Bandera County. To accomplish that, several modifications were made to the Hill Country Trinity GAM grid. The top and bottom of each of the four layers were updated with the most recently created surfaces of the Hill Country portion of the Trinity Aquifer study by Robinson and others (2022) and the grid cell size was refined from one-mile to 0.25-mile in Bandera County to produce a finer water level resolution.

The lower Trinity aquifer is the focus of this study, being the primary water supply source for the City of Bandera (93 percent of the city's total production). Its properties were updated by adding a new low hydraulic conductivity zone in the City of Bandera area to better reflect actual conditions in the area. The other three model layers, which are not under consideration for ASR, were excluded from the hydraulic property analysis and no further modifications beyond the structural and grid changes required for the soundness of the model were applied to these layers. A detailed description of the modification applied to each layer is in appendix B.

The pumping data for this study was updated with 20 additional years (1998–2018) compared to the Hill County Trinity GAM. As a result, the model simulated a total of 39 years from 1980 to 2018. Water use data (primarily municipal and irrigation use in the lower Trinity aquifer) and well locations were collected from the following sources:

- TWDB Groundwater Database (TWDB, 2021a)
- TWDB Brackish Resources Aquifer Characterization System (BRACS) Database (TWDB, 2021b)
- TWDB Historic Groundwater Pumpage (TWDB, 2021c)
- Texas Department of Licensing and Regulation State Driller Reports Database (TWDB, 2021d)
- TCEQ Database (TCEQ, 2021)
- Bandera County River Authority and Groundwater District Database (BCRAGD, 2021)

After the modifications mentioned above were incorporated in the Bandera well longevity model, it was calibrated using over 40,000 water level measurements (observations) from more than 600 wells. The calibrated model was then used as a predictive tool to forecast future conditions under three different scenarios. A more detailed description of the Bandera well longevity model and the predictive model construction is in Appendix B.

6.1 Historic modeling (calibration) results

There are several measures that can be used to evaluate the effectiveness of the Bandera well longevity model in reproducing observed historic field data. These measures include both statistical and graphical comparisons between modeled and observed water levels.

The first measure used to evaluate the model is a statistical comparison between the modeled and corresponding observed water levels. Generally, the results should closely match the observations within an acceptable level of deviation. In practice, an acceptable deviation is generally within 10 percent of the observation's range (Rumbaugh and Rumbaugh, 2020). This difference can be attributed to the discrepancy in scale between the observed and modeled water levels. Observed water levels are point measurements, whereas modeled water levels represent average water level over the model's grid cell size. Figure 6-1 shows a comparison between the results and observations for the middle Trinity aquifer (layer 3) and the lower Trinity aquifer (layer 4) in the Bandera well longevity model. Although the middle Trinity aquifer is not the focus of the study, as previously discussed, it had the most available water level observations and was therefore the best layer for comparing the model's calibrated results to the observed historical measurements. The lower Trinity aquifer results were also compared to the middle Trinity aquifer calibration results to determine if there were any large discrepancies between the layers.

Most of the Bandera well longevity model results fall close to the 1:1 (perfect fit) line on the graph, with some outliers (Figure 6-1). These outliers are observations that the model either overestimated (i.e., falling further above the line), or underestimated (i.e., falling further below the line). Overall, the model showed good performance in matching the lower Trinity aquifer observations with a residual (observed-modeled) mean of 2.52 feet and scaled standard deviation (the ratio of the residuals standard deviation to the range of the observations) of 9.6 percent. Additionally, the correlation between the modeled and the observed water levels, represented by the best fit line in Figure 6-1, has a coefficient of determination (R^2) equal to 0.82, this is a correlation coefficient (R) of 0.91. The slope of the correlation line is 1.009, nearly the same as the 1:1 (perfect fit) line, which indicates the Bandera well longevity model's simulated water levels follow the same general trend as the observed water levels. The correlation line also falls barely below the 1:1 line, i.e., 37 feet of difference, indicating a general bias to slightly underestimate water levels, but this is within the acceptable practical limits.

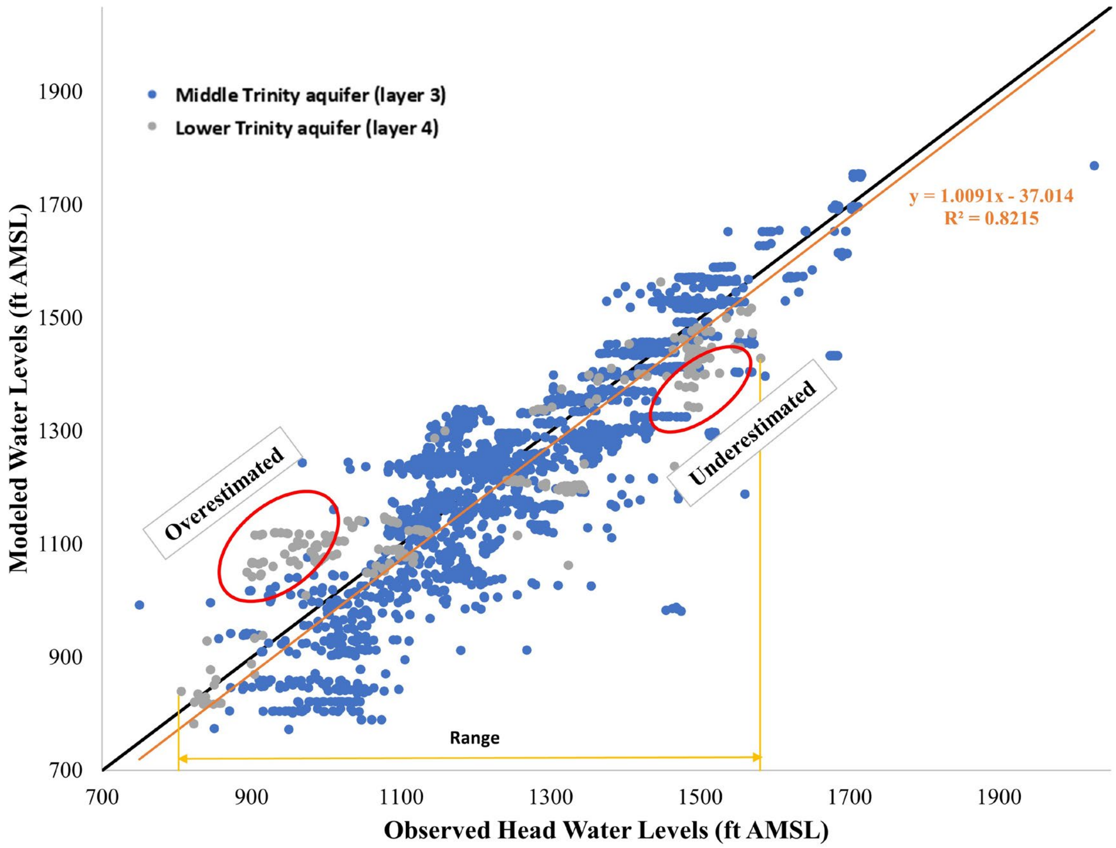


Figure 6-1. Comparison between modeled and observed water levels for the middle Trinity aquifer (blue) and the lower Trinity aquifer (gray) layers. The black line is the 1:1 perfect fit line and the orange line is the correlation or best fit line.

The second measure used to evaluate the results of the Bandera well longevity model was the match between modeled and observed water levels in individual well hydrographs. The degree of fit between the modeled water level variations to the corresponding observations trend were analyzed for the City of Bandera wells and the BCRAGD monitoring wells. The Bandera well longevity model showed good performance reproducing year-to-year water level variations in the majority of the lower Trinity aquifer observation wells. The hydrographs presented below show modeled water levels throughout the simulation (1980–2018), as well as the available quality (publishable) water level observations collected for each well. Both the modeled and observed water levels represent average winter conditions per year. Most of the wells had incomplete records of observed water levels over the simulation period.

Water level observations were available for the period between 1987 to 2004 for the Dallas Street well, and between 1991 to 2003 for the Mulberry Street well. The Indian Waters well had only one good-quality observation in 1998. The modeled water levels show a good match with the available observations' general trend over time with a small variation of about 50 feet in the Dallas Street (Figure 6-2) and Mulberry Street wells (Figure 6-3). This is generally an acceptable variation when gaging the overall performance of the model. However, these slightly coarse results can be integrated with the focused fine results of the analytical solution presented in

Section 5 for a comprehensive understanding of these supply wells and maximum utility in short term as well as long-term planning.

The hydrographs show an overall trend of declining water levels, with the sharpest decline from 1994 to 1996. After 2001, water level increased until 2007, followed by a significant decline that continued until 2014. The last four simulated years are characterized by fluctuating water levels between 20 to 25 feet. The total decline in water levels from 1998 to 2018, i.e., the 21 additional years of the Bandera well longevity model compared to the Hill Country Trinity GAM model, was about 7 feet in the Mulberry Street well and 9 feet in the Dallas Street well. The City of Bandera production from the lower Trinity aquifer varied between 311 and 224 acre-feet per year during this 21-year period, with an average of 257 acre-feet per year. The fluctuations of the water levels seen in the hydrographs are most likely directly related to changes in pumping as opposed to other factors, such as recharge in the lower Trinity aquifer. The overall lower Trinity municipal pumping in Bandera County increased from 372 acre-feet per year in 1998 to 443 acre-foot per year in 2018. This highlights the regional effect of groundwater production on local water levels. Regional recharge of the lower Trinity aquifer occurs at the outcrop, very distant from the City of Bandera area. It has a relatively slow velocity, thus, minor effect on water levels variations. More details on the lower Trinity pumping applied in the Bandera well longevity model are in Appendix B.

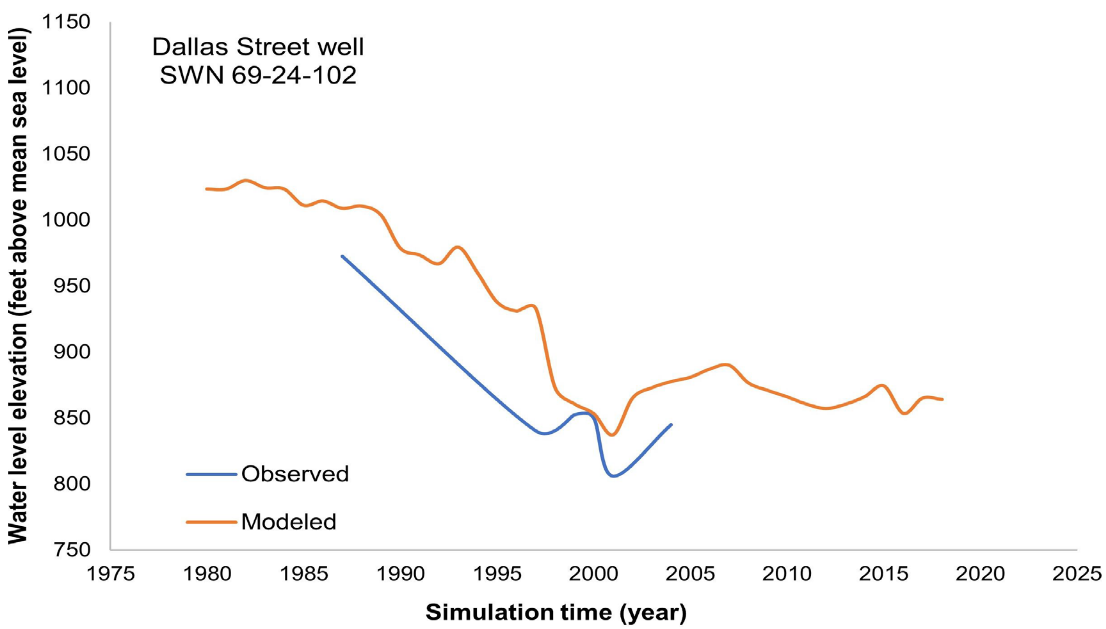


Figure 6-2. **The Dallas Street well hydrograph showing a comparison between modeled and simulated water heads. SWN = State Well Number.**

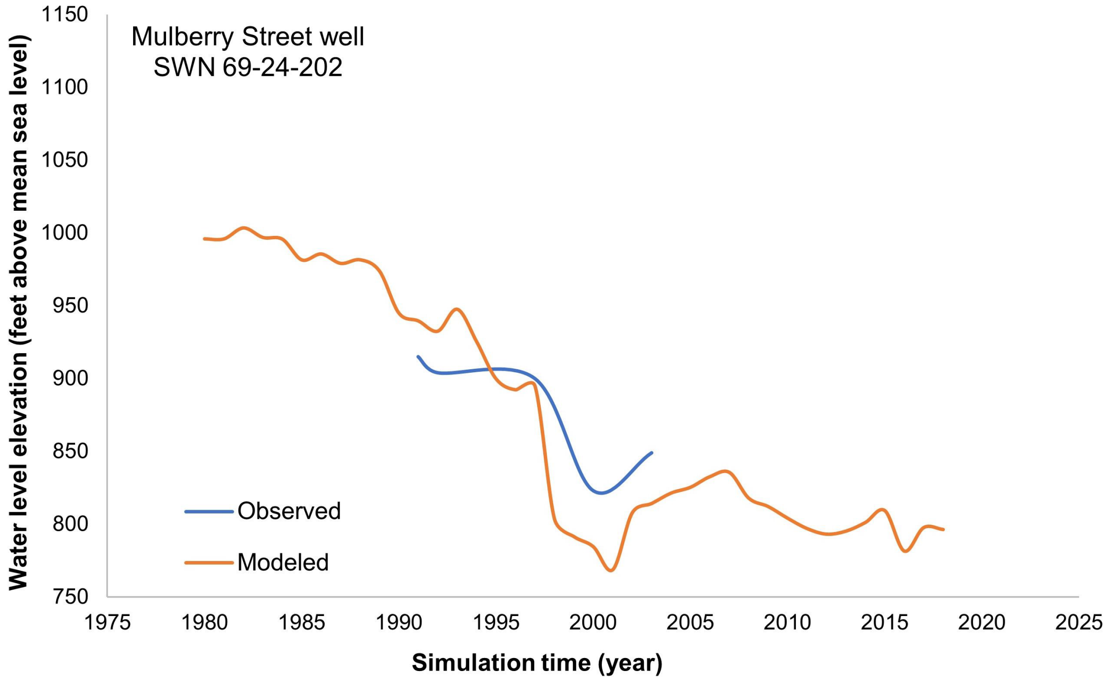


Figure 6-3. The Mulberry Street well hydrograph showing a comparison between modeled and simulated water heads. SWN = State Well Number.

The locations of the seven BCRAGD monitoring wells are shown in Figure 6-4. The Latigo Ranch well is the farthest from the City of Bandera public supply wells. Both the modeled and observed water levels are nearly at the same elevation in the hydrograph (Figure 6-5). The TWDB recorder well is the closest observation well to the City of Bandera wells, and its hydrograph shows underestimated heads with a maximum difference of 50 feet (Figure 6-6). This is the only monitoring well located within the new low hydraulic conductivity zone that was added to the model.

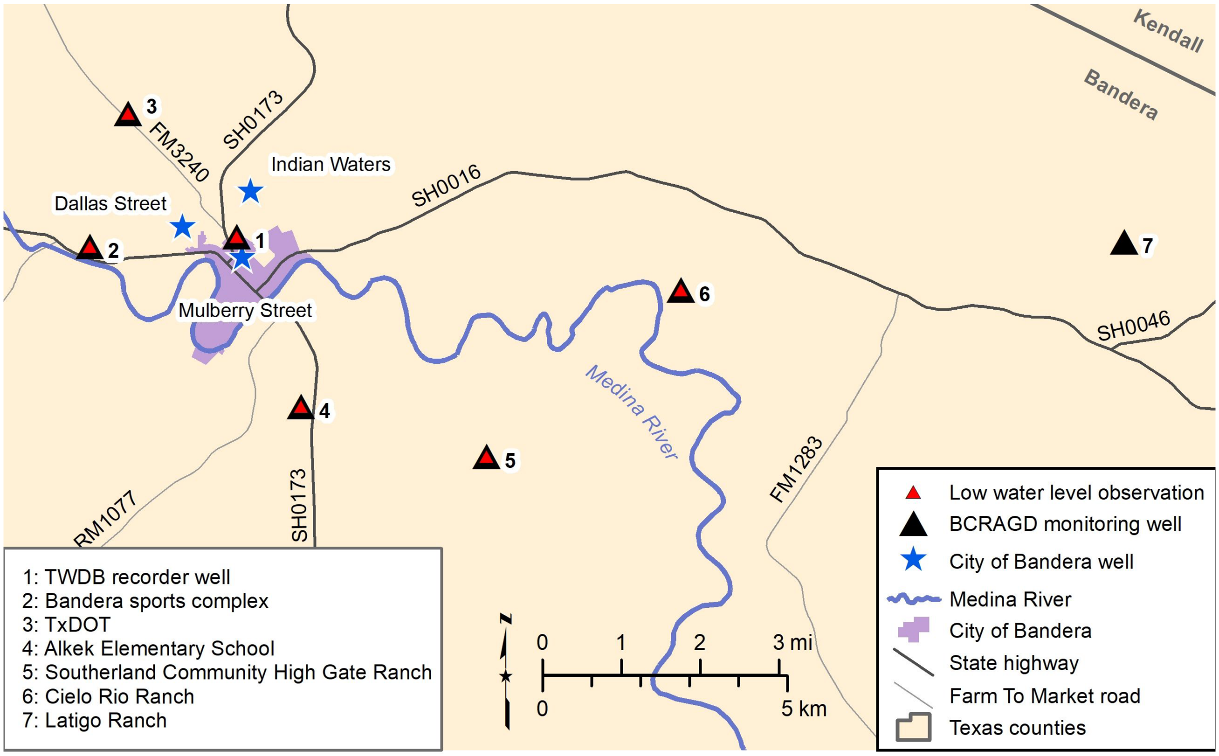


Figure 6-4. **Map showing the locations of the Bandera County River Authority and Groundwater District monitoring wells.**

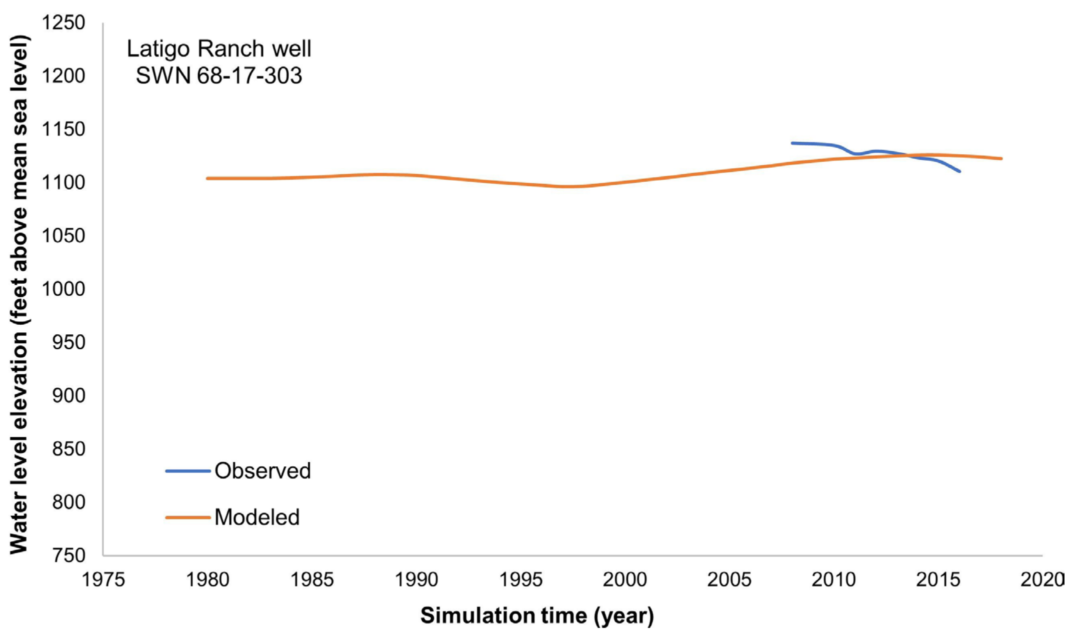


Figure 6-5. **The Latigo Ranch well hydrograph (matching hydrograph example). SWN= State Well number.**

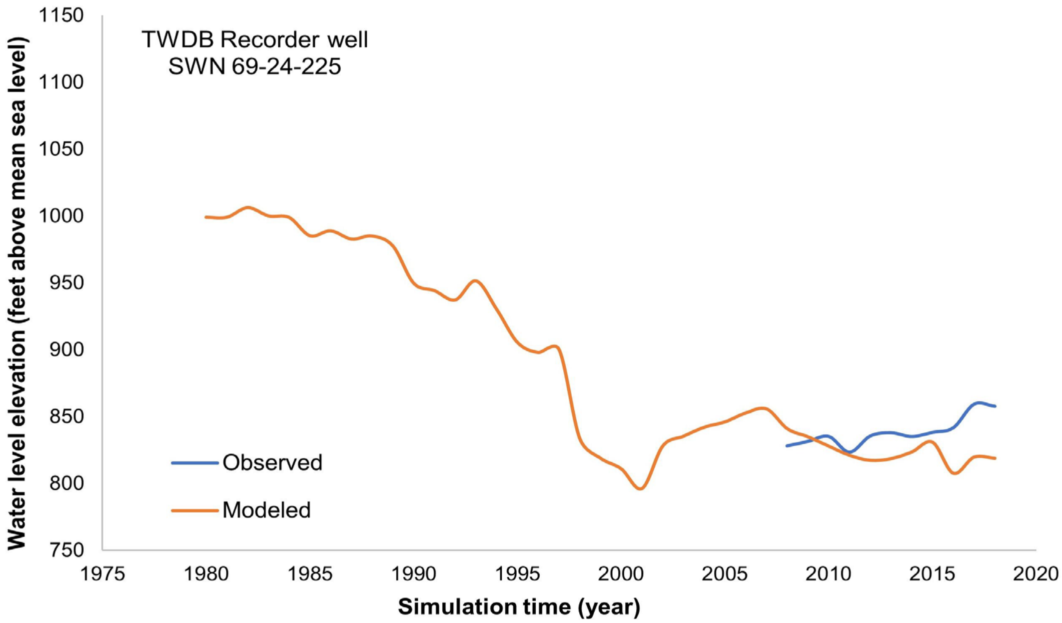


Figure 6-6. **The TWDB recorder well hydrograph. SWN = State Well Number.**

The hydrographs of the Alkek Elementary School well (Figure 6-7), Cielo Rio Ranch LTD well (Figure 6-8), TxDOT well (Figure 6-9), Bandera Sports Complex Lower Trinity well (Figure 6-10), and the Southerland Community High Gate Ranch LTD well (Figure 6-11) display the same general matching trend between the modeled and observed water levels. However, the model overestimates the water levels in most of these BCRAGD monitoring wells close to the City of Bandera's wells. The modeled water level hydrographs of these monitoring wells show a general decline with less fluctuation compared to the City of Bandera wells. The observed levels, however, show some fluctuation over the same 2014 to 2018 timeframe as the City of Bandera wells. The maximum difference between modeled and observed water levels in the monitoring wells is about 150 feet. Further discussion on this low hydraulic conductivity zone and the overestimated monitoring wells results is in Section 6.3.

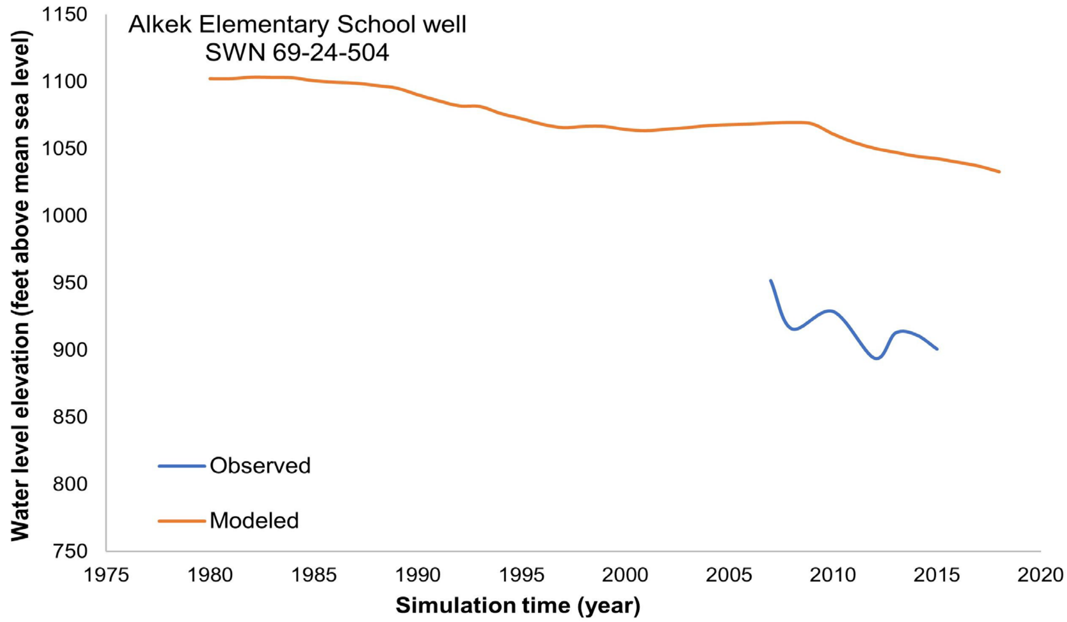


Figure 6-7. **The Alkek Elementary School monitoring well hydrograph with overestimated water levels. SWN= State Well number.**

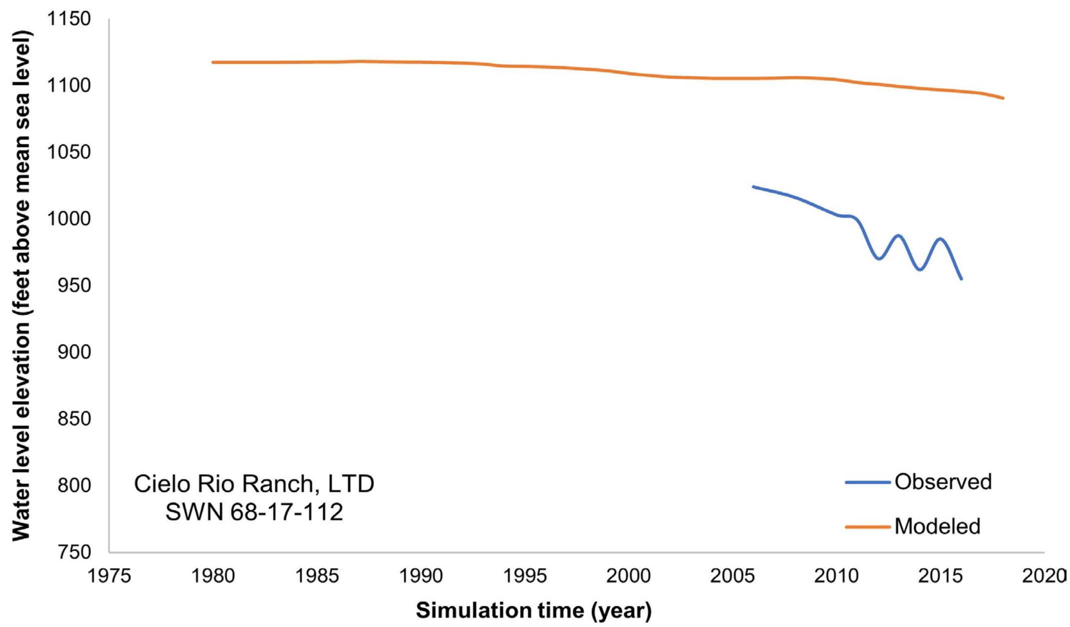


Figure 6-8. **The Cielo Rio Ranch monitoring well hydrograph with overestimated water levels. SWN = State Well Number.**

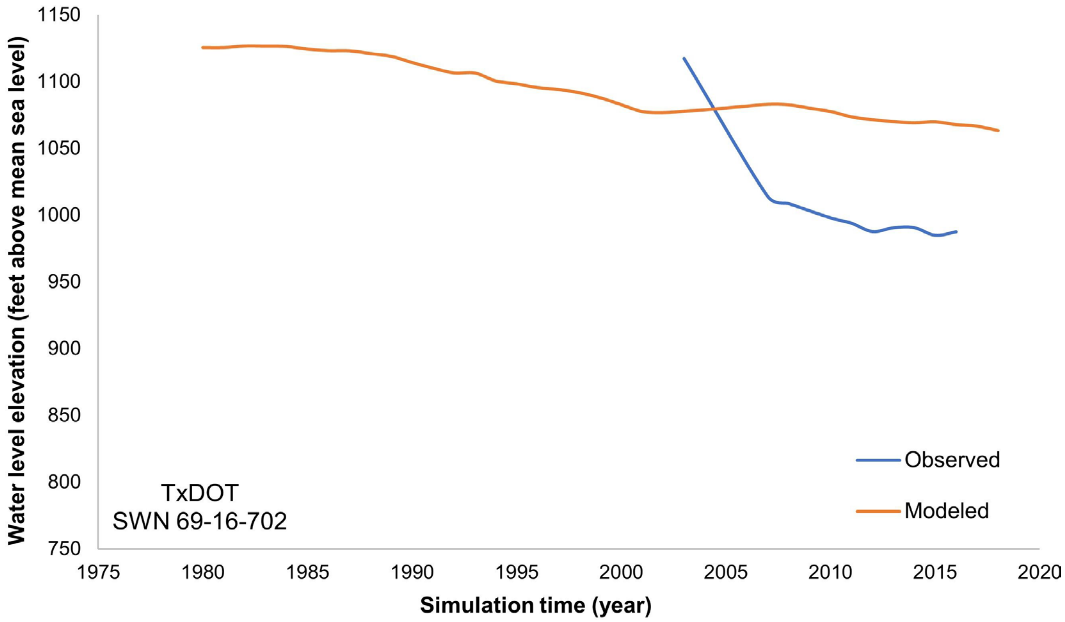


Figure 6-9. **The TxDOT monitoring well hydrograph with overestimated water levels. SWN = State Well Number.**

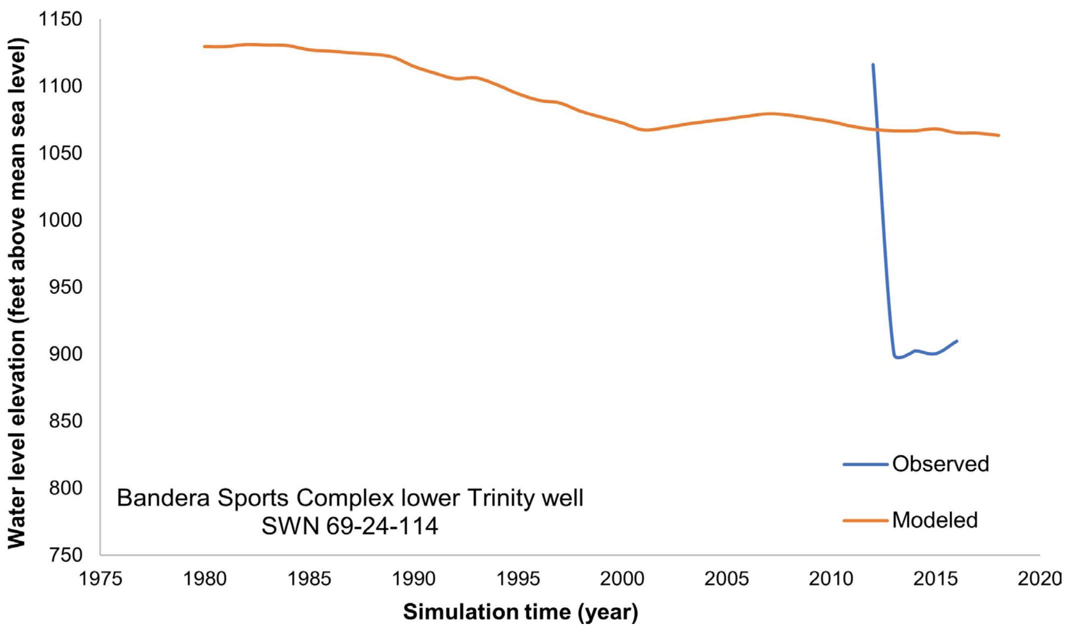


Figure 6-10. **The Bandera Sports Complex lower Trinity monitoring well hydrograph with overestimated water levels. SWN = State Well Number.**

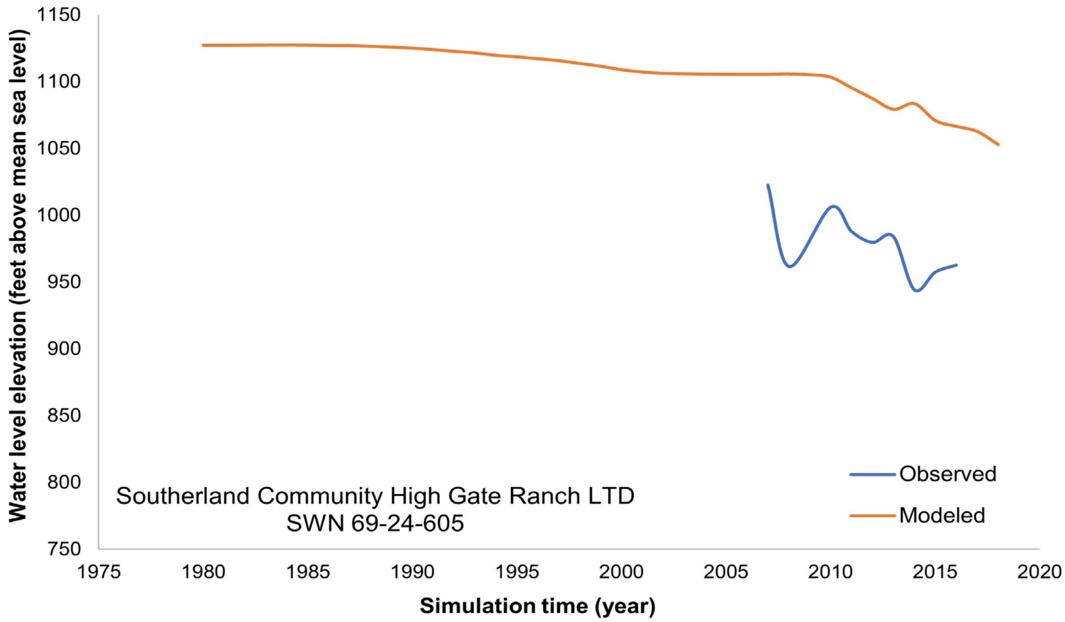


Figure 6-11. **The Southerland Community High Gate Ranch LTD monitoring well hydrograph with overestimated water levels. SWN = State Well Number.**

6.2 Predictive model results

The calibrated Bandera well longevity model was used to forecast future conditions from 2020 to 2079 under three different scenarios. Scenario one (S1, no change) assumed the City of Bandera will continue pumping current (2018) production volumes until the year 2079. Scenario two (S2, projected demands) assumed the City will gradually increase production to meet water demand projections in the 2022 State Water Plan. Scenario three (S3, maximum planned supply) assumed the City will increase production immediately to produce the annual existing groundwater supply in the 2022 State Water Plan. The model presents results as annual average water levels over the respective grid cell size.

The following predictive model results focused on the Mulberry Street well for two reasons. The first reason is the open hole interval of the Mulberry Street well matches the depth and entire thickness of the lower Trinity aquifer. This detail is important because the predictive model results will be the highest quality for wells that have production intervals that completely match the modeled layer. The Dallas Street and Indian Waters wells have production intervals that are only a portion of the lower Trinity aquifer. Secondly, of the three wells, the Mulberry Street well has the most available and highest quality data to show the historical water levels compared to the modeled and predictive water levels. The Mulberry Street Well accounts for 42 percent of the city's total production as discussed in Section 4. More details on the predictive model and considered scenarios are in Appendix B.

Figure 6-12 shows the results of the three predictive scenarios for the Mulberry Street well (S1, S2, and S3). These resulting hydrographs display 100 years of water levels (historic observed, historic modeled, and predicted) from 1980 to 2079. The modeled water level elevation at the Mulberry Street well in 2018, the last year of the historic period, is approximately 795 feet above mean sea level. This 2018 average water level is 35 feet above the elevation of the pump (760 feet above mean sea level). The elevation of the bottom of the Mulberry Street well casing, which is the top of the lower Trinity aquifer, is 520 feet above mean sea level and the bottom of the aquifer is 430 feet above mean sea level. The figure also shows the minimum operational static water level for the Mulberry Street well to produce 42 percent of the City of Bandera's existing water supply listed in the 2022 State Water Plan as per the analytical solution results (Section 5).

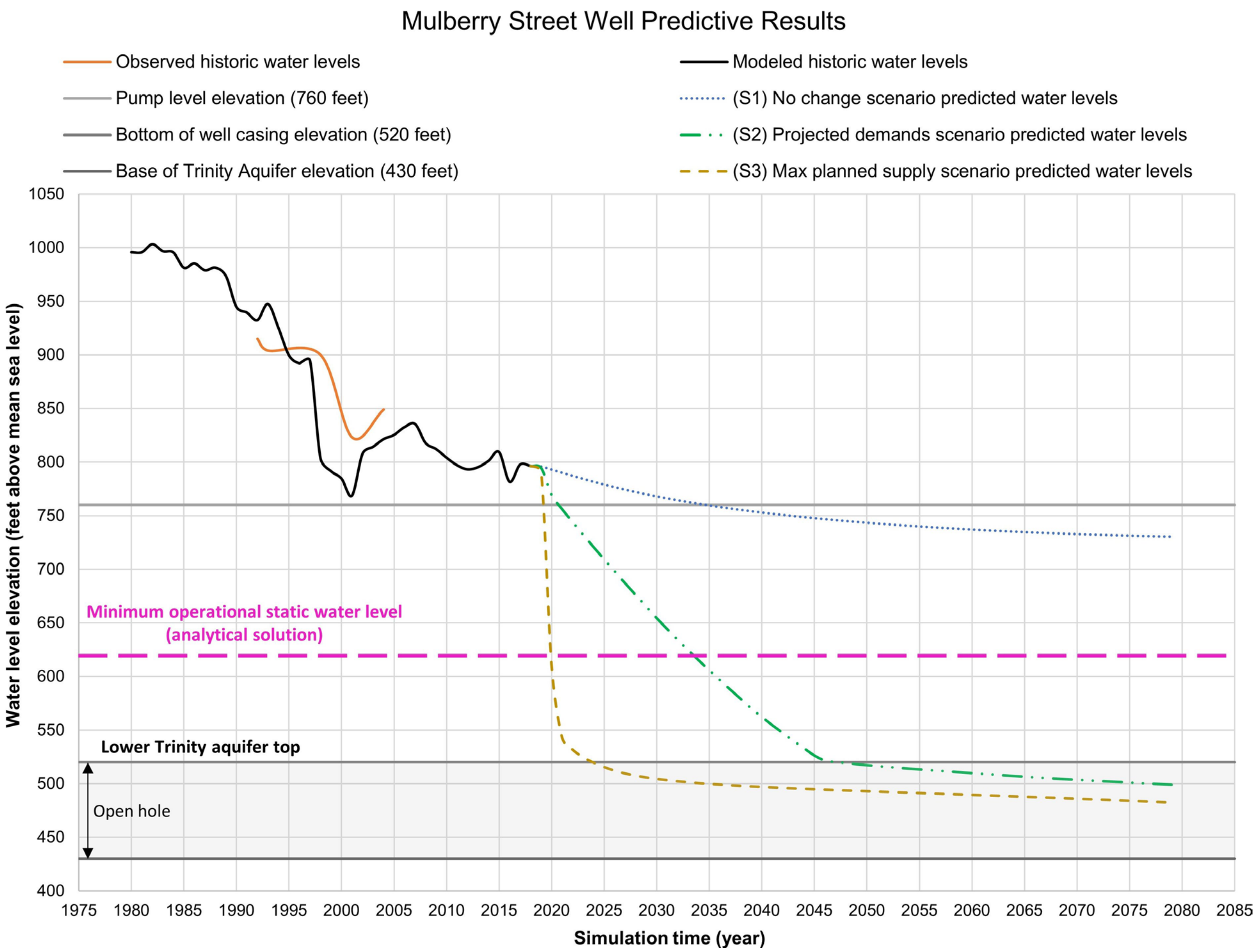


Figure 6-12. Bandera well longevity model predictive water level results for the Mulberry Street well.

The "no change" scenario (S1) maintained the regional pumping rates of the model historical period final year (2018) through the entire five-decade predictive period (2020–2079). The 2018 reported annual water use for the City of Bandera is 231 acre-feet. This is the most optimistic scenario for maintaining average water levels in the lower Trinity aquifer.

The results predict that the average water level in the Mulberry Street well would fall below the current pump level after approximately 16 years. This would result in 36 feet of cumulative decline in water level from the end of the historic model period year 2018. After this 16-year period, average water levels may continue to decline and require the pump to be lowered within the casing of the well to remain operational. Predicted average water levels for this scenario remain above the bottom of the casing (i.e., projected sustainable production) throughout the entire modeled period with a maximum cumulative decline in water levels of 65 feet from year 2018. Figure 6-13 is a map of the predicted drawdown contours for this scenario after 16 years (upper map) and after 62 years (lower map). The maximum water level decline after 16 years (46 feet) and after 62 years (79 feet) occurs east of the city of Bandera, where cones of depression of multiple active wells in the area overlap. This predicted water level decline would require careful management in developing further groundwater production in the area in order to maintain operational conditions for the City of Bandera's wells.

The "projected demands" scenario (S2) assumes that groundwater pumping will gradually increase to meet the city's growing water demands as projected in the 2022 State Water Plan. This is the most likely scenario since it reflects what is currently planned. Detailed description of the simulated pumping amounts in this scenario is provided in Appendix B.

The results of this scenario predict average water levels in the Mulberry Street well would reach below the elevation of the pump after two years (from the beginning of 2020 to the end of 2021) of pumping increased to meet projected 2020-decade demands. This would result in 49 more feet of decline from the end of historic model period year 2018. Mulberry Street well operation could continue by lowering the pump greater than 49 feet within the well casing. Additionally, the model predicted a gradual average water level decline that would continue for 29 years (year 2048), creating a total cumulative decline in water levels of approximately 277 feet to an elevation of 519 feet above mean sea level at the Mulberry Street well. At this time, the average water level would reach below the bottom of the well casing, into the open hole, making the well unusable. This would also mean loss of artesian pressure since the casing of the Mulberry Street well goes down to the top of the lower Trinity aquifer (520 feet above mean sea level). These results indicate that water management strategies aiming to diversify water sources for the City of Bandera would need to be implemented before the 29-year-margin of pumping at the projected demands rates.

Figure 6-14 shows the predicted drawdown contour maps for this scenario (S2). The upper map shows the maximum decline after two years of increased pumping to planning decade 2020 projected demands is 124 feet. The lower map shows the maximum water levels decline after 29 years of increased pumping is 306 feet (year 2048). In both maps, maximum decline occurs east of the city of Bandera, the overlap point of the cones of depression of multiple active wells. Large water level decline is also shown around the city of San Geronimo in the lower map.

The "maximum planned supply" scenario (S3) increases pumping to annually produce all of what is called "existing groundwater supplies" in the 2022 State Water Plan for the City of Bandera. This is a 91 percent increase compared to the city's production in 2018. Appendix B provides more details on the conditions of this scenario.

The results of this scenario, as shown in Figure 6-12, predicted Mulberry Street well average water levels would drop in elevation from almost 796 feet to 609 feet above sea level within one year; this is 651 feet below ground surface or 12 feet below the minimum operational static water level determined by the analytical solution for this scenario's conditions. At this point the Mulberry Street well would not be able to supply the existing water supply rate. The well would become unusable in five years when water levels would reach the bottom of the casing.

The results of this scenario indicate that it would be challenging for the current City of Bandera lower Trinity wells to accommodate rapid twofold increase in demands. In addition, the City of Bandera would need to implement new water management strategies prior to considering producing the existing groundwater supplies with their current lower Trinity wells capacity.

Figure 6-15 contour maps show predicted decline in water levels for one year and five years into scenario S3. The upper map shows the maximum decline is 187 feet after one year of pumping the maximum planned supply volume of groundwater, and it occurs at the Mulberry Street well. The lower map shows that the decline would increase at the Mulberry Street well to 277 feet in five years, with maximum decline of 308 feet located to the west of the Mulberry Street well, in particular at the Dallas Street well location.

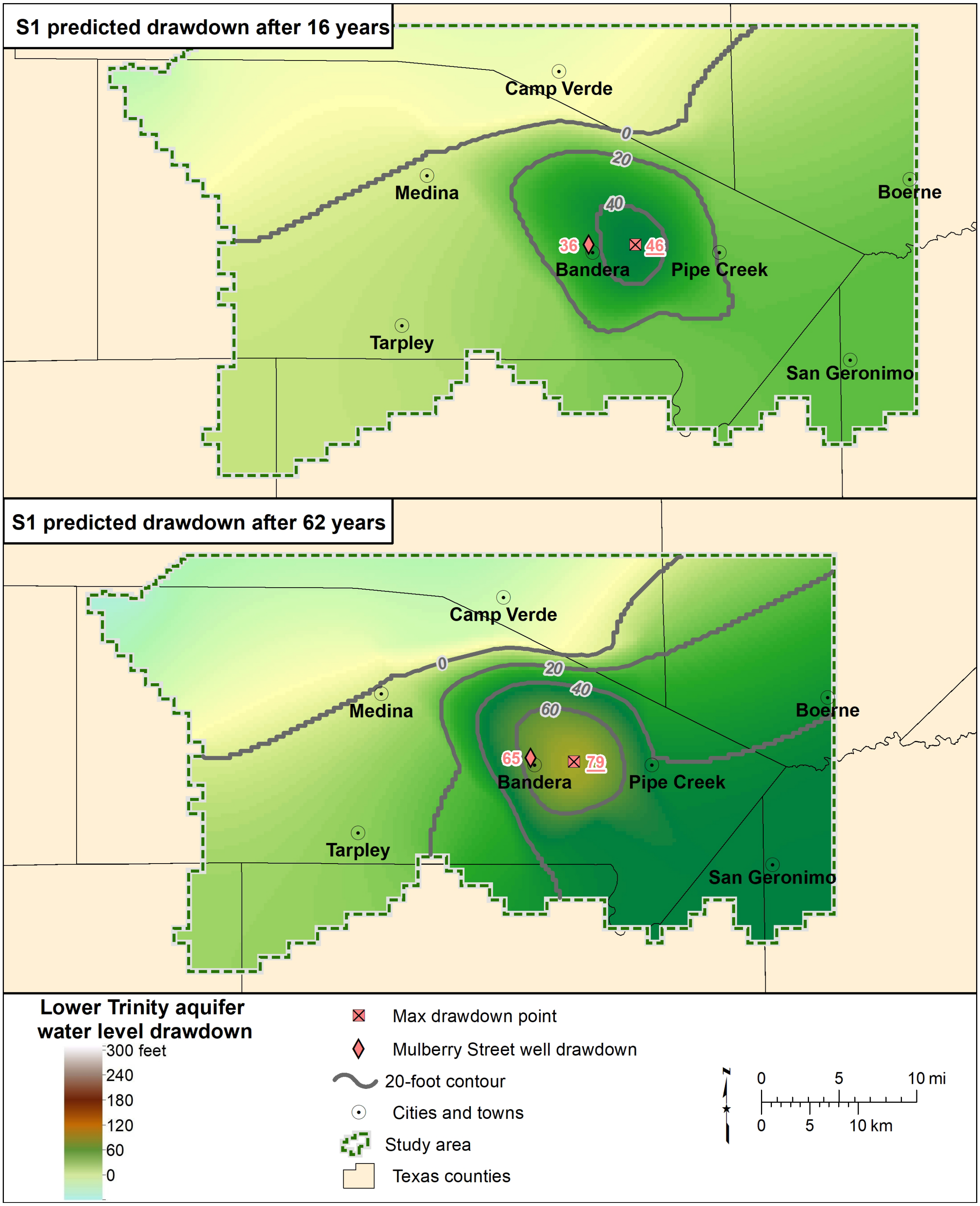


Figure 6-13. **Bandera well longevity model "no change" scenario (S1) predicted drawdown after 16 years (2035), when water levels reach below the pump level in the Mulberry Street well, and after 62 years, at the end of the predictive modeling period (2079).**

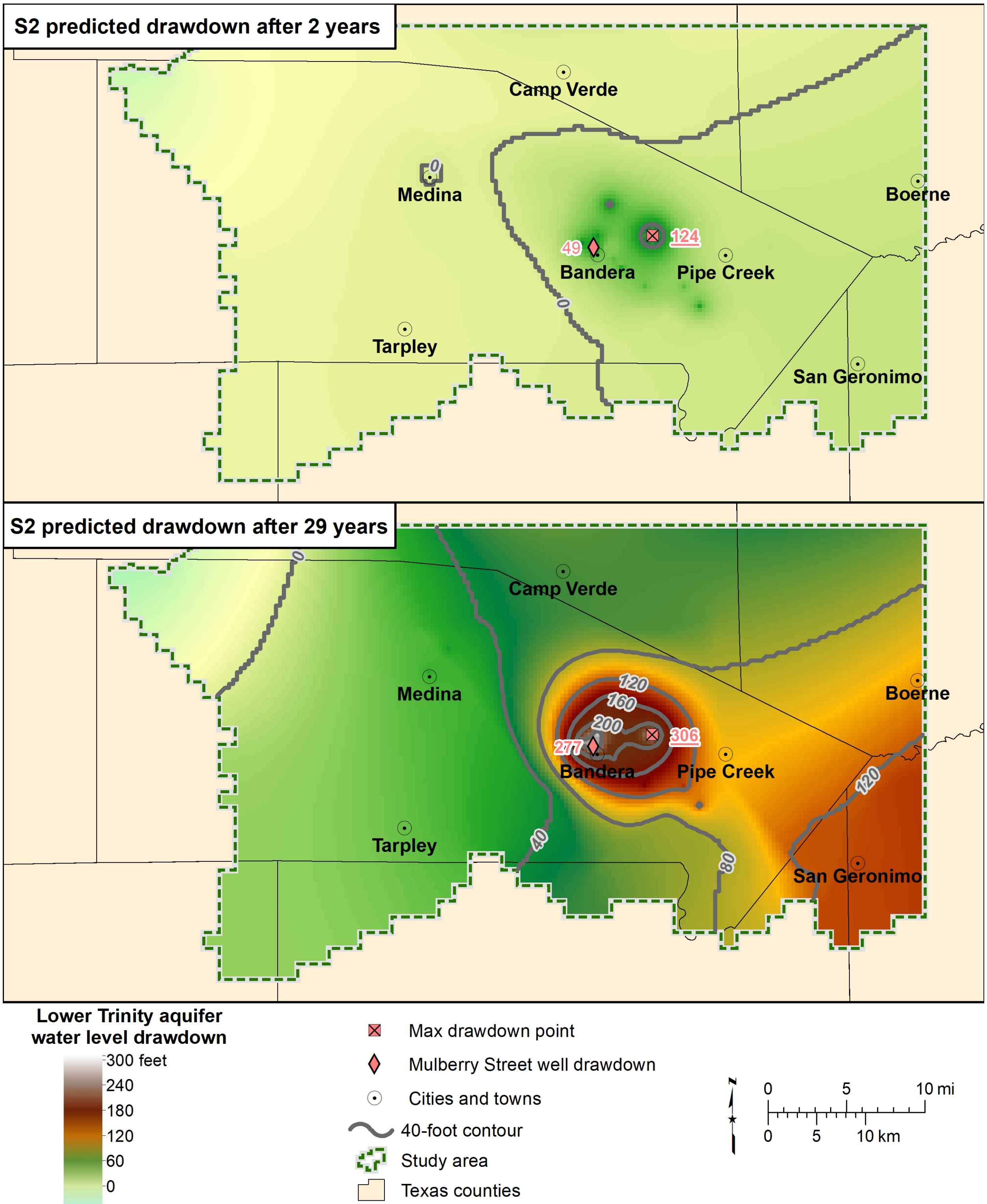


Figure 6-14. **Bandera well longevity model "projected demands" scenario (S2) predicted drawdown after 2 years (2021), when water levels reach below the current pump level in the Mulberry Street well, and after 29 years (2048), when water level reach below of the Mulberry Street well casing.**

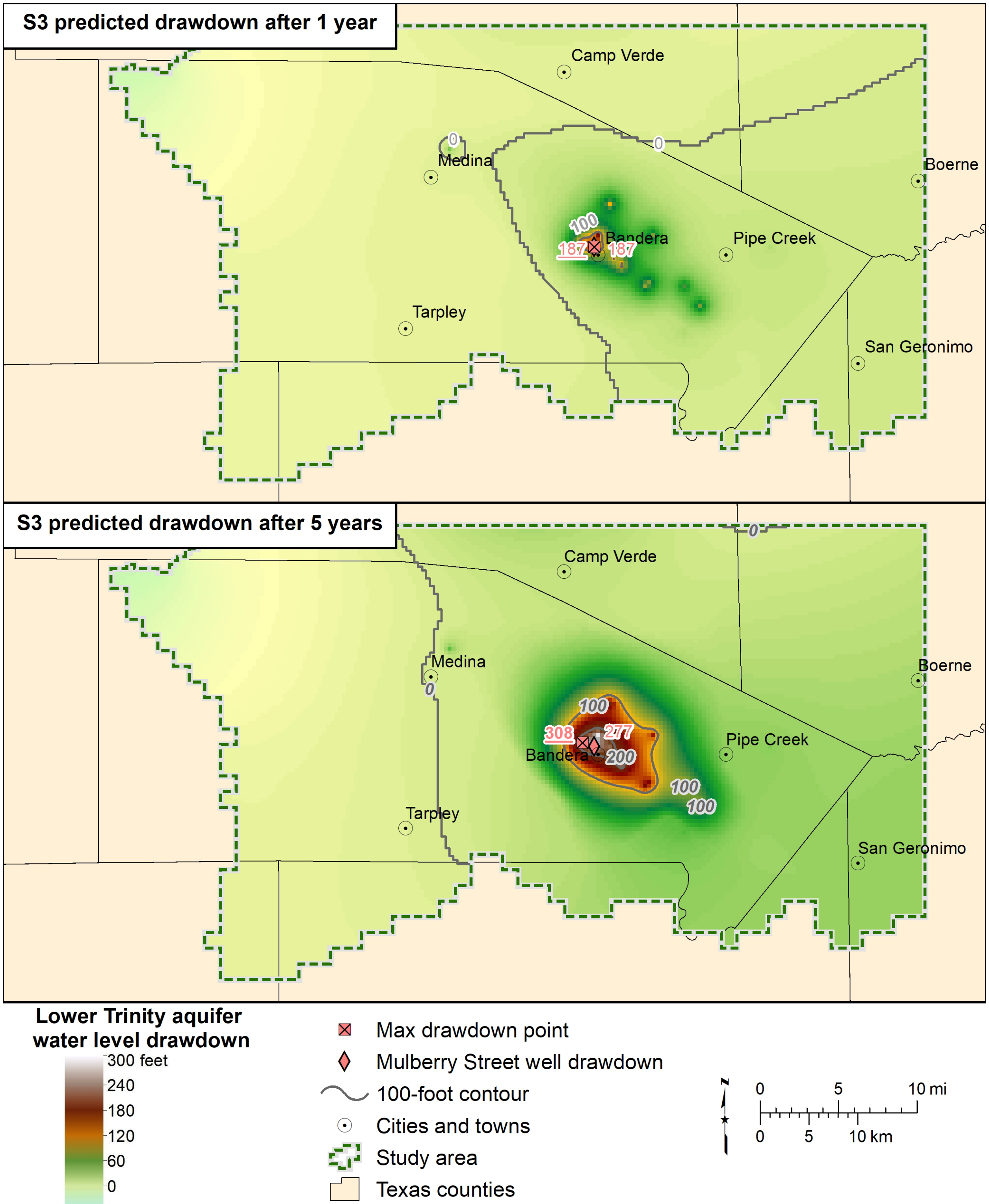


Figure 6-15. **Bandera well longevity model "maximum planned supply" scenario (S3) predicted drawdown after 1 year (2020), when water level reaches below the pump in the Mulberry Street well, and 5 years (2024), when water levels reach below the casing of the Mulberry Street well.**

6.3 Model results discussion

Models are approximations to investigate complex natural systems and the quality of the model is data dependent. Assumptions made about model parameters or boundary conditions due to data scarcity affect how closely the model matches the observations and increases the uncertainty of the model's forecasts. The objective of the calibration process is to minimize the difference between modeled and observed water levels, which is achieved by adjusting all or a subset of the parameters used in the model. This is due to the higher confidence in the water level observations compared to the model parameters. The parameters used for calibrating the Bandera well longevity model were the flow and storage characteristics of the lower Trinity aquifer (layer 4). These parameters control the water movement into and out of the modeled area. Appendix B further explains the process of selecting and adjusting these parameters.

The Bandera well longevity model has 21 more stress periods than the Hill Country Trinity GAM and this increase resulted in more available observations for comparison to modeled water levels. A region of consistently overestimated modeled water levels was observed in the lower Trinity aquifer layer. This region included the City of Bandera's wells and most of the BCRAGD observation well and these outliers resulted in poor calibration of the model. This anomalous area in the model is possibly due to local conditions, such as high rates of pumping, site-specific geology, or aquifer characteristics that are not captured in detail by the model. Extensive data mining was completed but finding good quality data on the hydraulic properties of the lower Trinity aquifer was challenging, especially around the City of Bandera. Figure 6-16 shows the distribution of available aquifer test data in the Hill Country Trinity study area from Robinson and others (2022).

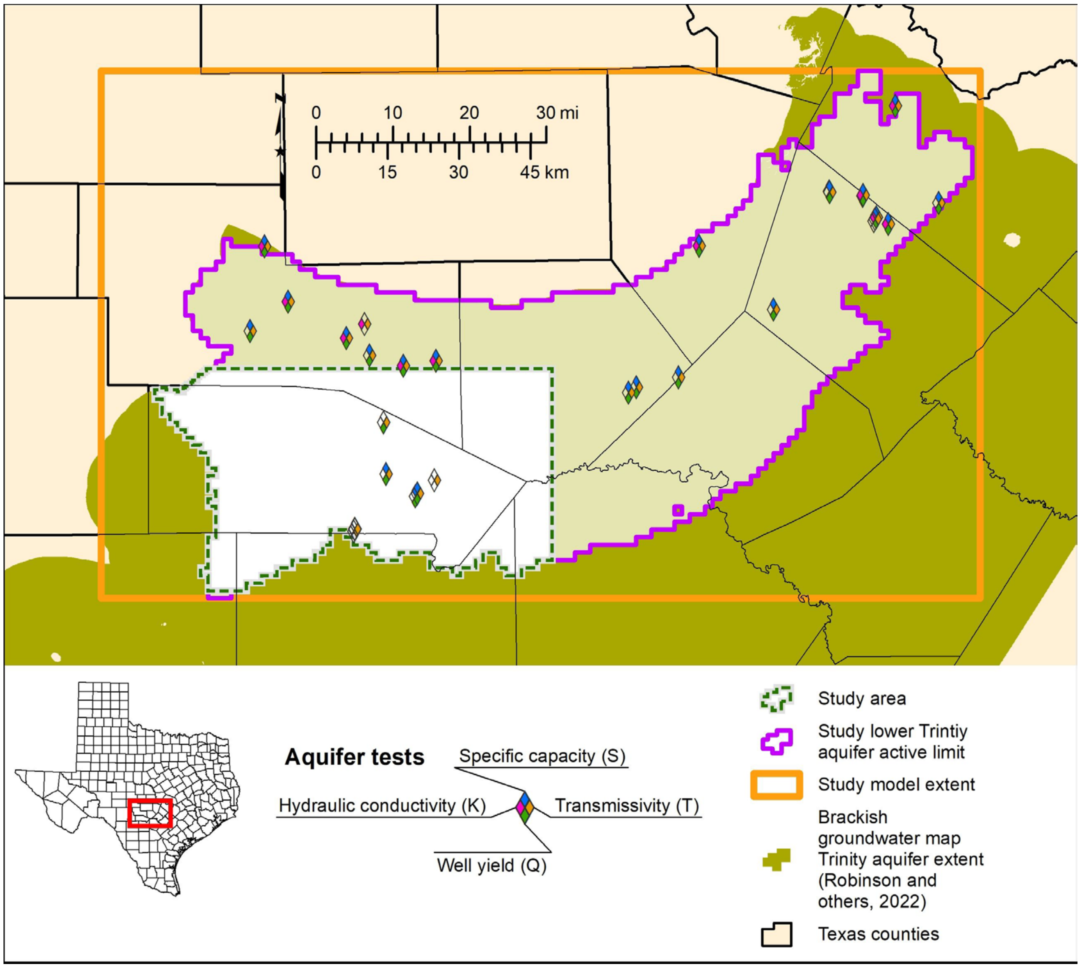


Figure 6-16. Available aquifer properties in the lower Trinity aquifer area from the brackish water resources study by Robinson and others (2022).

The Hill Country Trinity GAM has two zones of aquifer properties in the lower Trinity aquifer layer. One of these zones represents the Balcones Fault Zone in the southeast section of the layer and the other zone covers the remainder of the model layer. Due in part to the zone of overestimated water levels, it was determined that a single uniform hydraulic conductivity for most of the active area of the layer was likely not representative of the heterogeneity present in the Lower Trinity Group. As a result of this determination, a new zone of aquifer properties was created to cover the region of overestimated water levels (Figure 6-17).

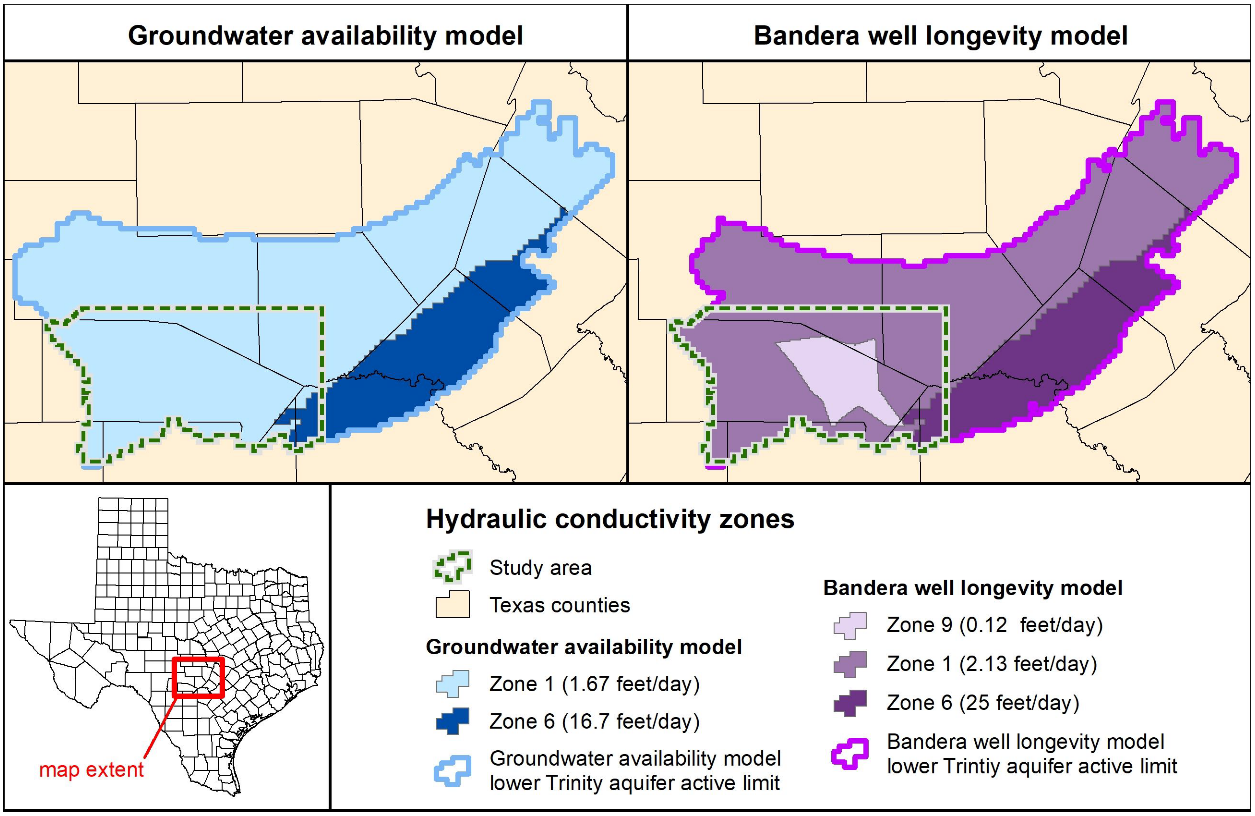


Figure 6-17. Hydraulic conductivity zones and calibrated values in Hill Country Trinity Groundwater Availability Model (left) and Bandera well longevity model (right).

Due to the lack of detailed hydrologic data, this new hydraulic conductivity zone was ultimately delineated using the Thiessen polygon method, which depends on the spatial distribution of wells (Figure 6-18). This new hydraulic conductivity zone was assigned a starting hydraulic conductivity value of 0.1 feet per day because this value is reported in the Ashworth (2009) for the calibrated hydraulic conductivity around the City of Bandera. The same value is also reported by Toll and others (2018) as the 25th percentile of all the available hydraulic conductivity values both collected and computed for the entire extent in layer 4 of the Hill Country Trinity GAM. The same storage coefficient of the original zone (i.e., 1.0×10^{-7} per foot) was used (Toll and others, 2018). The hydraulic conductivity value for the new zone changed slightly after calibration to 0.12 feet per day. The hydraulic conductivity value for the original zones increased from 1.6 to 2.13 feet per day.

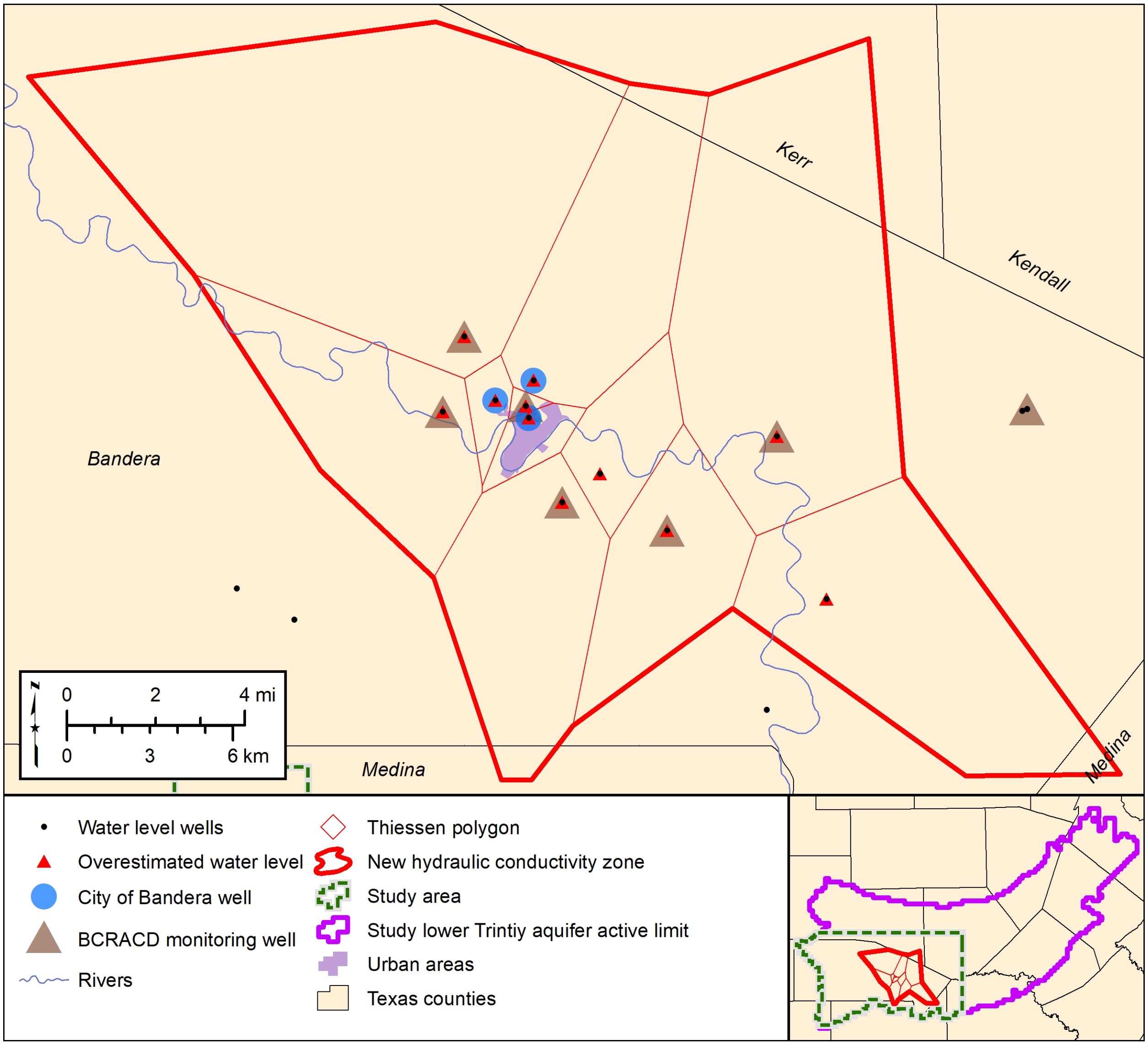


Figure 6-18. **Map of the new lower Trinity aquifer (layer 4) low hydraulic conductivity zone in the Bandera well longevity model created using the spatial distribution of wells with overestimated modeled water levels.**

The new low hydraulic conductivity zone resulted in a better match with historic observations for the City of Bandera wells with a relatively small difference of 50 feet compared to more than 200 feet difference before adding this zone. However, this resulted in underestimating the modeled water levels of the BCRAGD observation well that is the closest to the City of Bandera production wells (i.e., the TWDB recorder well). The most recent available water level observations of this well (between 2008 and 2018) show a slight increase of about 30 feet compared to the decline seen in the older observations from the City of Bandera wells (Figure 6-19). This may indicate that local conditions in the area have changed over the simulation period. Further investigation of this zone is required to better understand the properties of the region and determine whether there is any structural reason in the area causing these anomalies rather than over-pumping. The 1953 aquifer test analysis report of the Mulberry Street well also suggested a presence of a geological structure causing water levels taken during the pump test to deviate from a typical confined aquifer curve (TWDB, 2022b; BCRAGD, 2021).

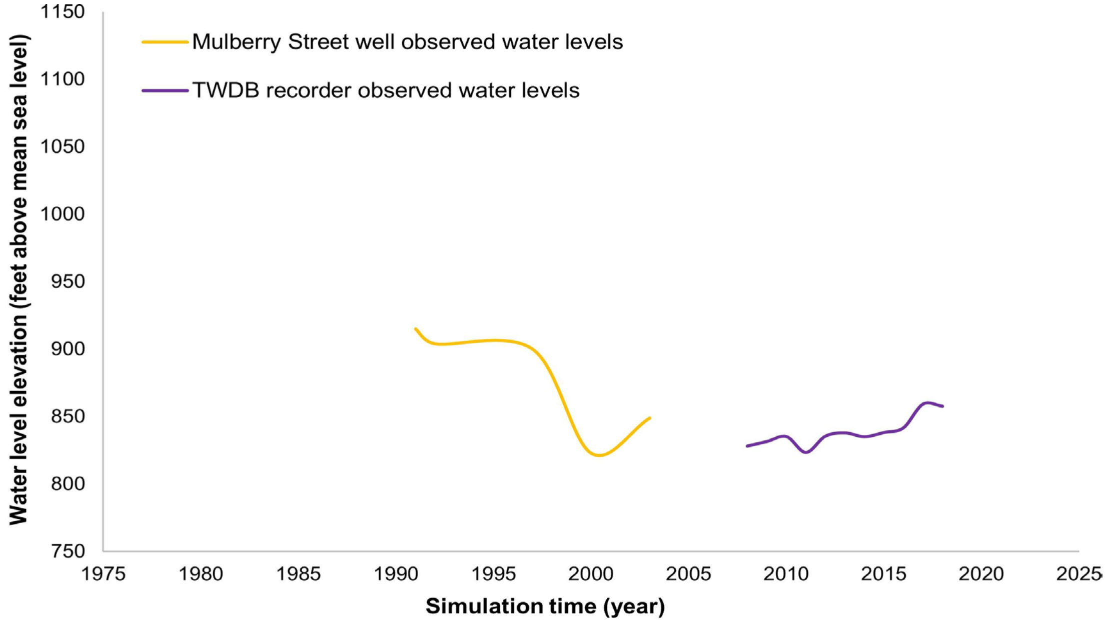


Figure 6-19. Historic water level observations in the Mulberry Street well (#4) and the TWDB recorder well.

The Bandera well longevity model also could not fully replicate the large drawdowns observed in the rest of the BCRAGD observation wells even after incorporating the new zone. The difference between modeled and observed water levels reaches up to 150 feet in some of these wells. This could indicate that the low hydraulic conductivity zone is even more widespread than currently estimated. After testing, it was determined that these outliers cannot be modeled by adjusting spatial parameters (i.e., the hydraulic conductivity and storage coefficients) due to lack of available data on aquifer properties. These differences between modeled and observed water levels may also suggest that not all pumping was accounted for in the model.

Although an extensive review process was conducted, it is likely that there is more pumping from the lower Trinity aquifer in Bandera County than can be accounted for on this model. Not all residential or agricultural wells may have publicly available data and may be drawing greater volumes than is currently modeled. Additionally, the faults throughout the county are extensive and communication between the lower and middle Trinity aquifers is poorly understood in this area. Groundwater flow between the lower and middle Trinity aquifers may also account for some of the discrepancies seen in the Bandera well longevity model. If this information becomes available from future studies, it could be used to further refine the model. Although this is a known limitation, the Bandera well longevity model results are within the defined range for a well fit model.

Uncertainty of parameters and uncertainty in predictive model results are part of any model. Models, by definition, are simplifications of complex environments where properties and process are not sufficiently known. To reduce uncertainty, models are built based on the best understanding of the system's elements and supported by field data. However, the final calibrated model is not considered an absolute representation of the groundwater system. It is understood that the model has uncertainties related to assumptions made during development as well as errors in observation measurements (Anderson and others, 2015). It should be noted that overfitting or over calibrating models may also result in uncertainty of how representative the model is of physical conditions. Minimizing the uncertainty requires finding a middle point with minimum total errors of the extreme cases. The goal is to build a reasonable model without oversimplification. Uncertainty associated with modeling cannot be eliminated; however, it can be quantified.

Estimation of a model's uncertainly is complex, time consuming, and beyond the scope of this work; however, it could be considered for future work. Additionally, the provided forecasts represent the potential of the results to occur based on the considered scenarios or influences, rather than giving absolute predictions of the future. Further, the results of the numerical models are averages over gird cell size and model time unit (stress period), which is not representative of local conditions required for managing operations of supply wells. Therefore, integrating numerical models with finer scale analytical solutions that captures the temporal changes at supply well provides comprehensive analysis of supply wells as part of regional systems (MacMillan and Schumacher, 2014). The analytical solution for the Mulberry Street well specified potential operational limitations of the well that are not attainable through the Bandera well longevity model results alone. In practice, models are used for risk-assessment analyses and planning given that they produce an unbiased forecast of what is expected to occur.

6.4 Future water planning

Water planning decisions are made by assessing current conditions and using available data to forecast future conditions. The assessment of the current conditions in the city of Bandera illustrates the challenges the City is facing with its water supply. The city is highly dependent on the lower Trinity aquifer for most of its groundwater production. The Bandera well longevity model provides useful information for the City of Bandera and can help mitigate risk and determine the likelihood of undesired conditions occurring. The predictive model results indicate that the city may need to implement mitigation plans in the future to be able to supply water to its increasing population. The City of Bandera is considering enhancing and managing current resources along with developing other water supply sources besides groundwater, such as surface water from the Medina River as part of the surface water acquisition, treatment, and ASR project. The purpose of this strategy is to help maintain reliably recoverable water levels, increase the longevity of the City's wells, and supply reserves in case of drought.

The Bandera well longevity model can be a useful tool to run further predictive scenarios to determine candidate locations for an ASR well and the adequate water volumes to be injected to meet the objective of the project. The model could be used to estimate how far the bubble would extend and test the cyclic operation of the ASR well (pumping and injection), in order to maintain a buffer zone. This will require applying further modifications to the model, such as reducing the length of the model's unit time (stress period). However, the model can support these changes and provide answers for such questions. For future consideration of this option, as previously noted, the performance of the model would also greatly improve if more detailed and accurate aquifer properties as well as pumping volumes are incorporated.

The City of Bandera is also considering an alternative groundwater development strategy that suggests drilling a new lower Trinity well outside of the city's current cone of depression in 2030. The proposed location for this new well is 4 miles north of the city. However, careful consideration should be given in determining the location of any new well because an increase in pumping could overlap with the current cone of depression and widen it. The Bandera well longevity model shows water level elevations less than 1,000 feet above sea level extended to 1.6 miles upgradient (northwest) and to 2.4 miles downgradient (southeast) from the Mulberry Street well by the end of the historic simulation period (2018) (Figure 6-20). Water level elevations less than 1,000 feet above mean sea level are less than the average water level for the lower Trinity aquifer observations collected for the calibration of the Bandera well longevity model. In this analysis, these water levels were considered low observations and the Bandera well longevity model tended to overestimate them. Therefore, the 1,000-foot elevation was used as a threshold to investigate the predicted cone of depression around the City of Bandera.

Figure 6-21 shows the predicted cone of depression for the "projected demands" scenario (S2) in 2030, the online year for the proposed new lower Trinity well (upper map), as well as 2048, the year in which the Mulberry Street well is forecasted to be unusable under this scenario (lower map). In 2030, after 11 years of gradually increasing pumping to the 2022 State Water Plan listed demands, the cone of depression is predicted to extend 2.4 miles upgradient (northwest) and about 4.3 miles downgradient (southeast) from the Mulberry Street well. In 2048, after 29 years of gradually increasing pumping, the cone of depression is predicted to extend about 3.5 miles upgradient (northwest) and about 7.2 miles downgradient (southeast) in this scenario.

The Bandera well longevity model can be used to assess the effect a new well would have on the existing production wells at different locations. The radius of influence of the new well can be estimated based on the projected rates and duration of pumping as well as the aquifer properties used in the model. The results can be compared to the currently existing/forecasted cone of depression to check for overlap and/or to adjust the location of the new well.

As mentioned in previously, more investigation on the lower Trinity aquifer around the City of Bandera is needed for accurate characterization of its properties. As more data becomes available, the parameters of the predictive model can be updated or adjusted. Acquiring more data will allow for more certainty in model results and higher confidence in planning decisions.

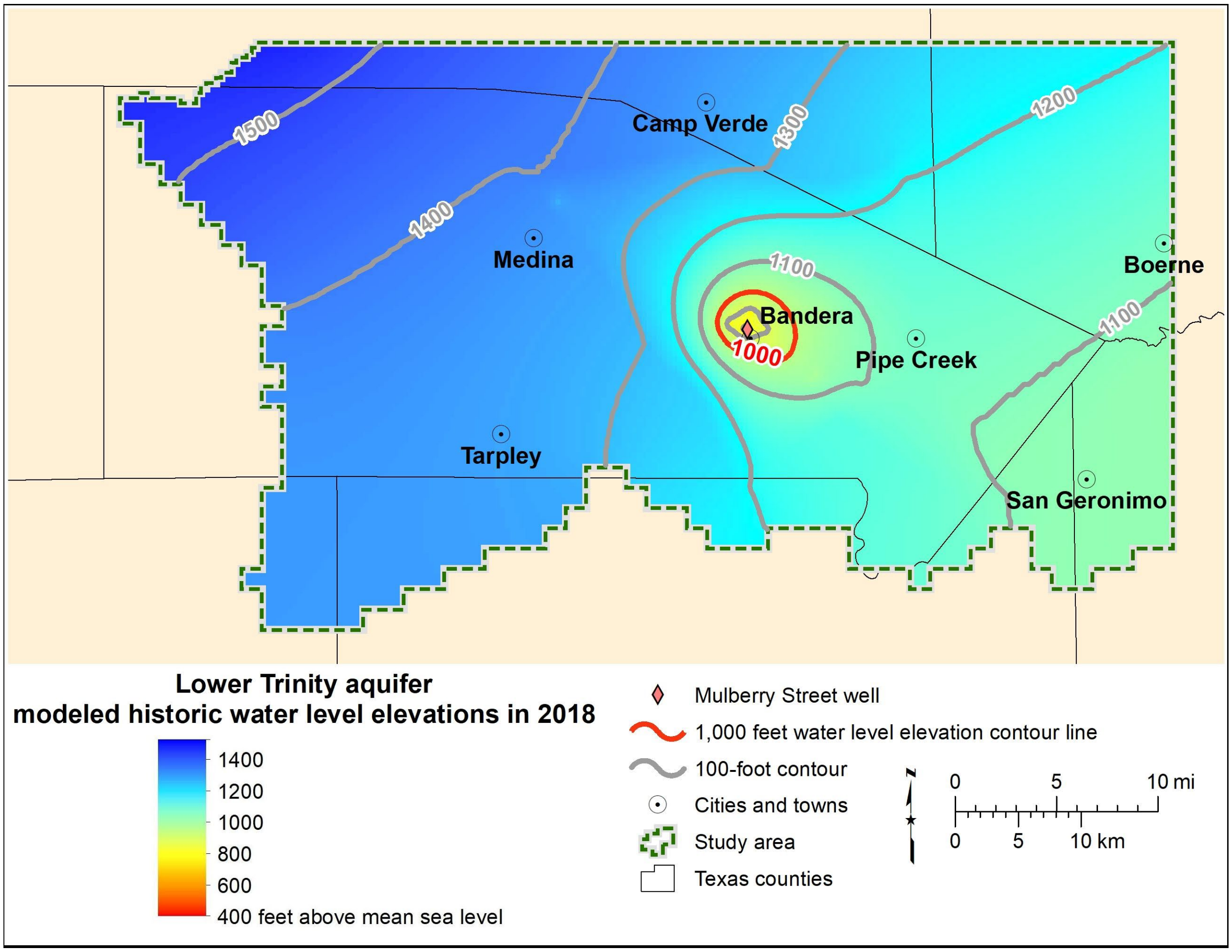


Figure 6-20. Bandera well longevity model simulated water levels for the historic period (1980-2018).

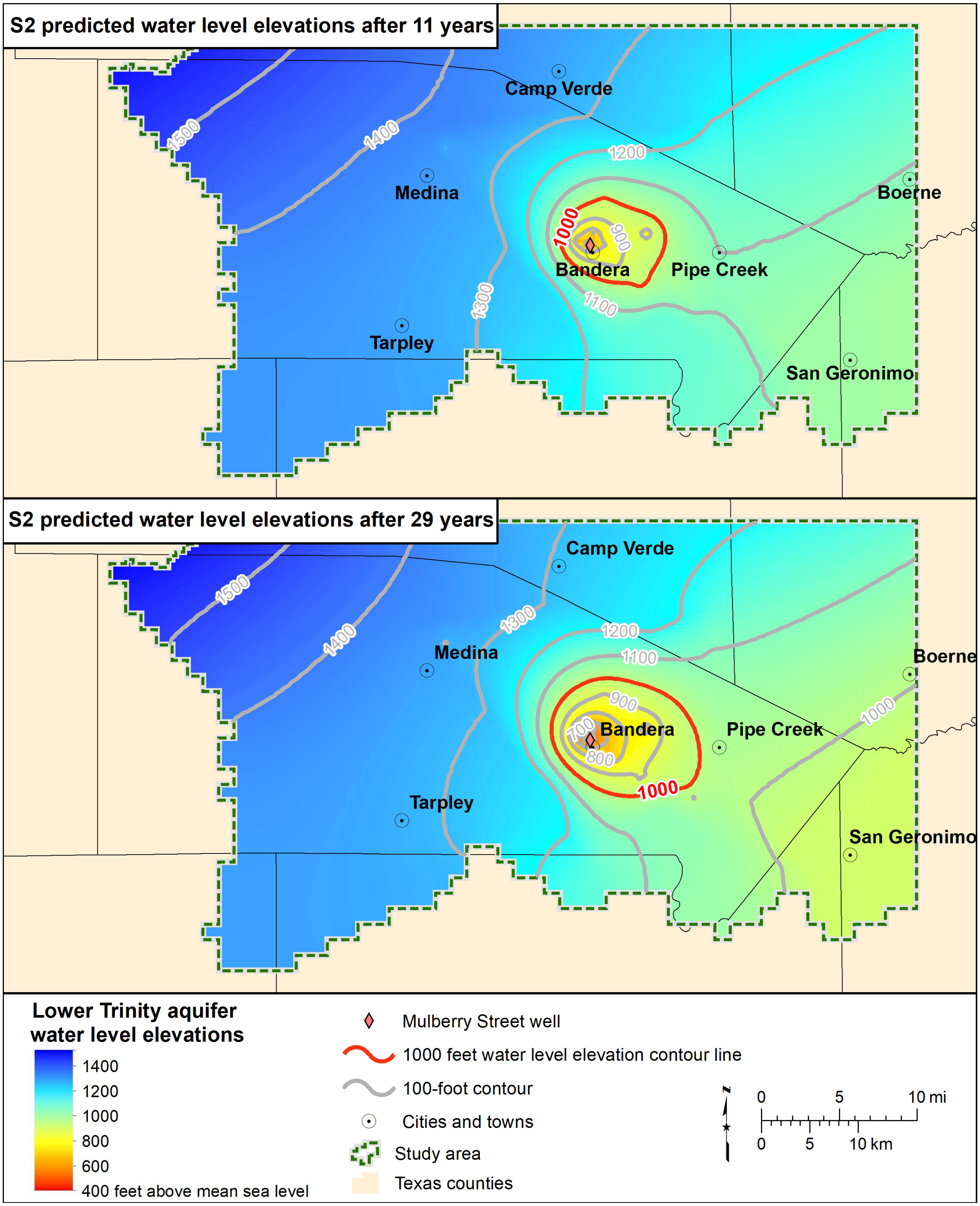


Figure 6-21. **Bandera well longevity model predicted water levels from 2020 to 2030 in the top map, and to 2048 in the bottom map based on the "projects demand" scenario (S2).**

7. Discussion

Understanding the characteristics of an aquifer is an integral part of water planning and project development. ASR projects have been developed in numerous aquifers with highly variable physical and geochemical characteristics, and although most conditions can be accounted for during the planning and engineering process, these factors may affect the choice of site location and potential success of the project (Smith and others, 2017). Success of an ASR project is also dependent on other variables including, but not limited to

- proximity to existing water supply, water demand, and infrastructure;
- compatibility with existing water supply, water demand, and infrastructure; and
- the water quality of the injected and recovered water.

Infrastructure projects, such as ASR or AR, are complex and require examining all projects variables in order to plan a viable project. It can often be beneficial to compare other local and regional projects to gain an understanding of challenges that may be encountered during project development.

7.1 Statewide suitability survey for ASR and AR results

The Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects (referred to as the Statewide ASR Suitability Survey in this report) mapped Texas with 50,000- by 50,000-foot grid cells and screened each grid cell for three primary criteria used to determine suitability for ASR or AR as identified in HB 721 (Shaw and others, 2020):

1. Hydrogeological characteristics (such as storage potential, transmissivity, infiltration, storativity, recoverability, and water quality)
2. Frequency, volume, and distance to excess water that may be available for storage
3. Current and projected future water supply needs identified in the state water plan

Each of these three criteria were screened independently and screening scores were normalized to a score of 0–1. In grid cells where two or more aquifers were present, such as the Sparta Aquifer stacked on top of the Queen City Aquifer, the aquifer with the highest scoring hydrogeological characteristics was used for the screening. Due to the complex nature of many ASR and AR projects, values for excess water and water needs screening scores were considered for a distance of up to two grid cells from any given aquifer score, and a weight was applied to give stronger consideration to closer grid cells. Because all three criteria are considered critical for the successful completion of an ASR or AR project, only grid cells that contained scores for all three screenings were given a final ASR or AR rating. This final suitability rating placed regions into one of three general categories of relative suitability: less, moderately, or most suitable. Additional details on the methodology used for rating ASR or AR suitability across the state is found in Shaw and others (2020).

7.1.1 *Hydrogeological rating*

For the hydrogeological characteristics screening, the majority of the study area received a medium score (0.5–0.7) for ASR suitability (Figure 7-1). The screening indicates that the highest scoring aquifer in most of the study area is the Trinity Aquifer (TRNT). The normalized hydrogeological screening scores for the Trinity Aquifer range from 0.52 to 0.82 (moderately to most suitable). The Trinity Aquifer is a complex system but is primarily carbonate within interbedded sandstone and shale. The permeability of the Trinity Aquifer is highly controlled by the Balcones Fault Zone, which is primarily east of Bandera County. Generally, permeability in the Trinity aquifer decreases with distance from the fault zone. The Trinity Aquifer in this area generally scores high for recharge and storage potential, but scores lower for recoverability. This may be attributed to poor confinement of most units in the middle and upper Trinity aquifers. Several hydrogeological parameters and their screening values for the Trinity Aquifer such storage potential, transmissivity, infiltration characteristics, storativity, recoverability, and water quality are summarized in Table 7-1.

The Edwards-Trinity Plateau aquifer system (ETPT) is present in some areas in the study area, primarily in the north and west. The Edwards Aquifer is highly permeable and scores high for ASR suitability where present. However, many of the outcrops of the Edwards Group in Bandera County are laterally discontinuous and would not make ideal ASR targets.

The Statewide ASR Suitability Survey supported the use of the Trinity Aquifer as an ASR target within the study area. However, closer look at the Trinity aquifer's scoring also showed that the scores related to ASR were decreasing from west to east across the county as the Trinity Aquifer graded into the Edwards-Trinity Plateau System (Figure 7-1). This is likely because of increased distance from the Balcones Fault Zone and increased depth.

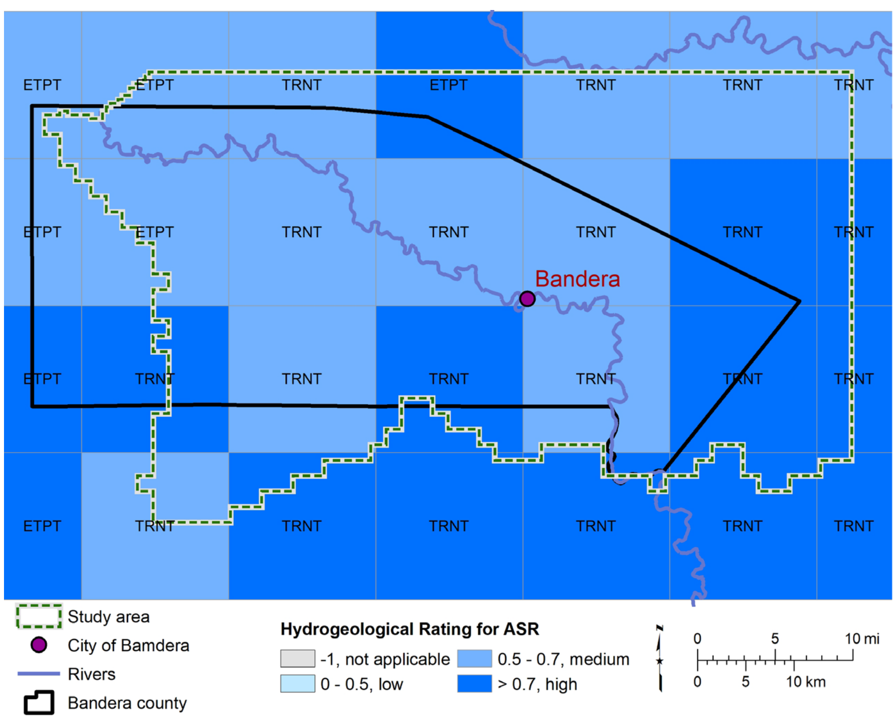


Figure 7-1. **Hydrogeological parameter screening results for ASR from the statewide survey for the study area. Grid cells are labeled with the highest scoring aquifer in that location. Aquifers include the Trinity Aquifer (TRNT) and Edwards-Trinity Plateau System (ETPT).**

Table 7-1. Hydrogeological screening parameter values for the Trinity Aquifer from the Statewide Suitability Survey within the study area. Units are given for each value.

Parameter	Value	Normalized score
Storage zone depth	11 - 3439 feet	0.1 - 1.0
Horizontal hydraulic conductivity	1.4 - 7.0 feet/day	0.3 - 0.5
Drawup available	44 - 459 feet	0.1 - 1.0
Dominant lithology	Sand	1.0
Aquifer thickness	11 - 445.3 feet	0.1 - 1.0
Aquifer storativity	9.75 E0-5 - 0.0001 S	0.4 – 0.6
Sediment age	116.4 million years	0.87
Confinement	confined in subsurface unconfined in outcrop	1.0 where confined 0.0 where unconfined
Groundwater quality	372.1 - 2098.1 mg/L	0.6 - 0.9
Drift velocity	3.69 - 67.7 feet/year	0.75 - 1.0
Drawdown available	-11.2 - 3156.9 feet	0.1 - 1.0

Notes: Normalized scores range from 0 to 1 based on individual parameters. Additional information on the methodologies used to determine values and normalized scores is found in Shaw and others (2020).

7.1.2 *Excess water rating*

The statewide survey did not identify potential excess water over a large portion of the study area (Figure 7-2). The cells with identified sources received a moderate ASR suitability score (0.34–0.67). Most of these scored cells contain a moderate amount of excess surface water. Most of this water is unappropriated river flows, which were calculated using the Hill Country Trinity Water Availability Model. No surplus appropriated water or reservoirs are present in the county. In general, available excess water increases east of Bandera County. Very little excess water is observed west of Bandera County, which becomes increasingly arid. The survey also indicates the presence of excess groundwater south and east of the study area, approaching the City of San Antonio.

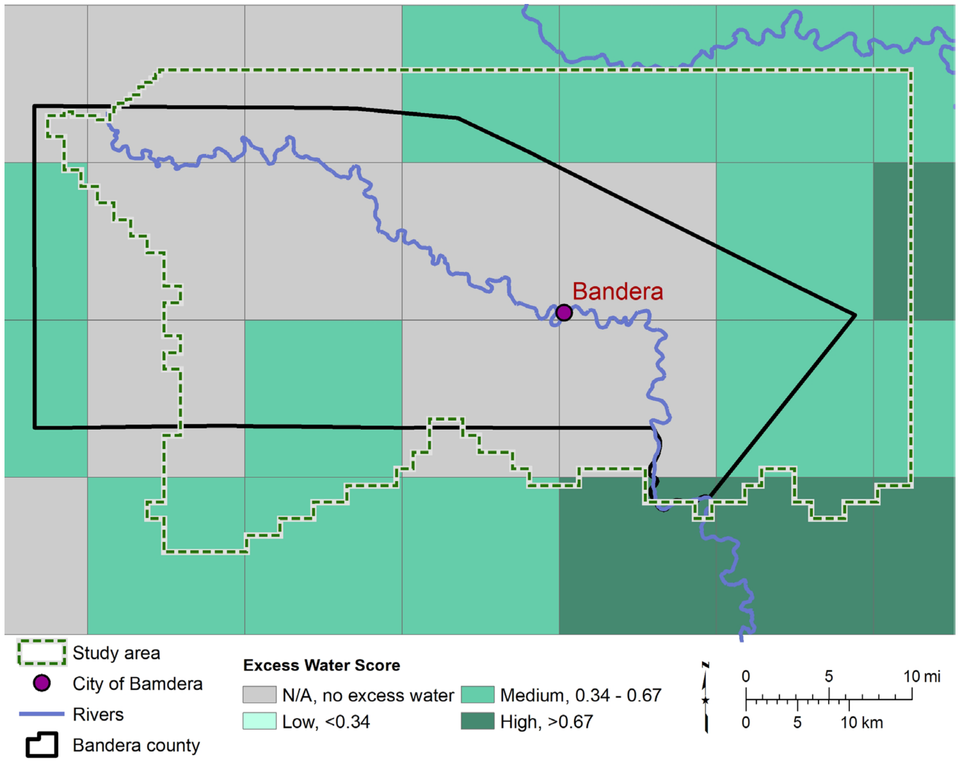


Figure 7-2. **Excess water ratings from the statewide ASR and AR survey for the study area (Shaw and others, 2020).**

7.1.3 *Water supply needs rating*

The majority of the study area did not receive a water supply needs score (Figure 7-3). Western Bandera County contains no *water user group*. The City of Bandera is a water user group, but its needs volume was too low to be scored on the large-scale statewide survey. Needs scores increase to the east approaching the highly populated San Antonio metropolitan area, and some of these municipal needs can be seen in scored grid cells in eastern Bandera County. Although no needs are shown for most of the county, the Statewide ASR Suitability Survey is a relative tool and does not necessarily indicate that a local, smaller-scale need may be present.

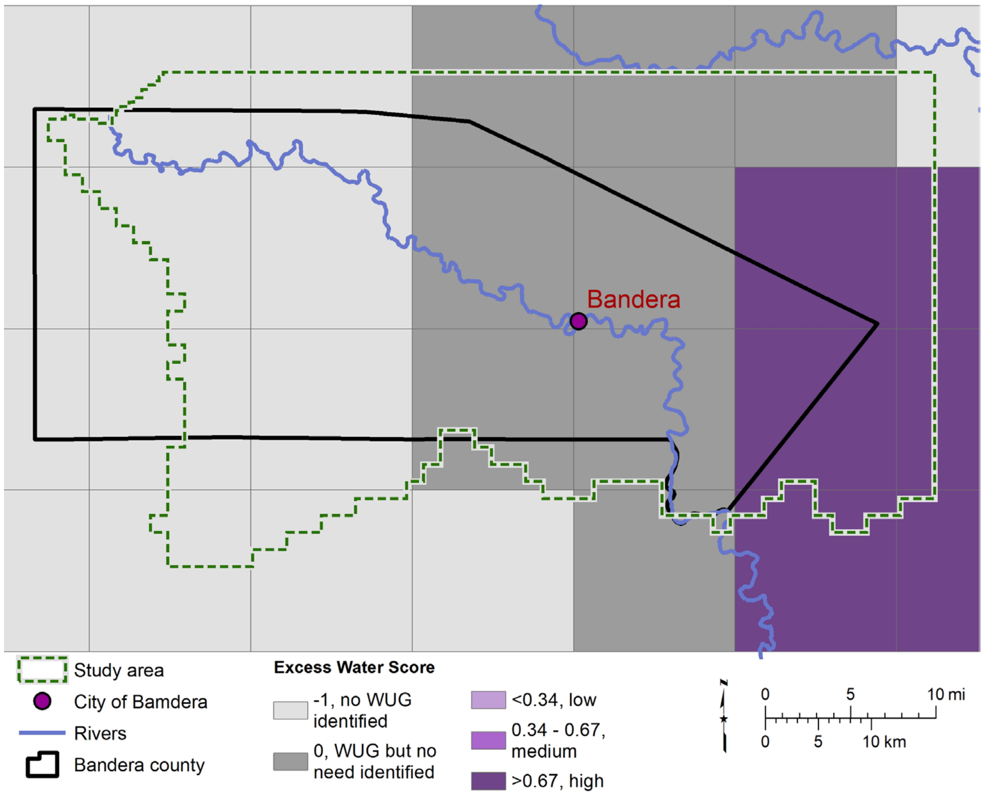


Figure 7-3. **Water supply need ratings from the statewide ASR and AR survey for the study area (Shaw and others, 2020). A score of 0 indicates that a Water User Group is present, but need was not scored in that location.**

7.1.4 *Final ASR rating*

Only grid cells that received a score from all three previous screening received a final suitability score. The cells scored in eastern Bandera County range from less to most suitable and increase in score eastward, towards the San Antonio area (Figure 7-4). This trend is primarily controlled by the increase in available water to the east, as well as the increased demand from the more developed metropolitan area to the southeast. Although the majority of the cells in Bandera County scored low for ASR suitability, it does not indicate that an ASR project in the area is not feasible.

The Statewide ASR Suitability Survey is a large-scale study designed to give a preliminary assessment of an area's suitability for an ASR project. Site- and system-specific needs may not be directly reflected in this type of report and additional smaller-scale investigations are needed in order to develop a project (Shaw and others, 2020). For example, the City of Bandera is concerned with increasing water demand associated with rapid development in the area and lack of alternative water supplies, which may not be fully represented in such a large-scale study. Additionally, some county-scale needs, such as irrigation are also not represented in the Statewide ASR Suitability Survey, but these growing needs may affect site-specific evaluations (Shaw and others, 2020).

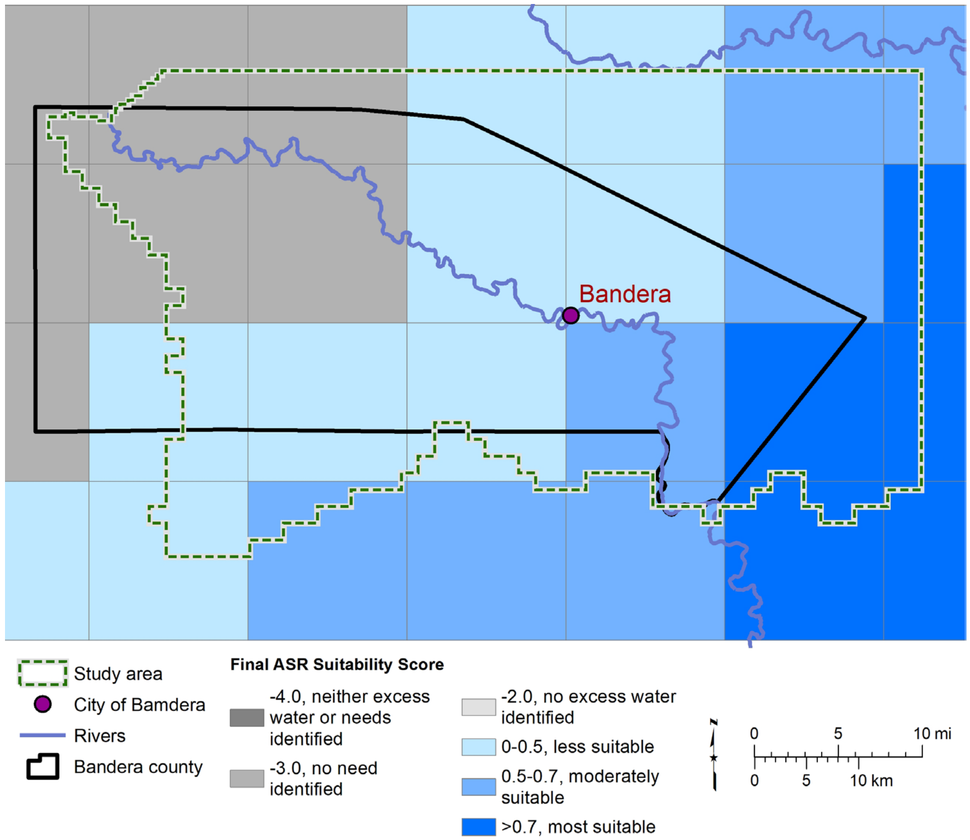


Figure 7-4. Final suitability ratings for aquifer storage and recovery from the statewide survey for the study area (Shaw and others, 2020).

7.2 City of Kerrville ASR

Learning from the experiences of existing operational ASR facilities is important and should be considered in the development of a new ASR project. The City of Bandera ASR project proposes to store treated surface water from the Medina River in the lower Trinity aquifer using retrofitted existing public water supply wells (WSP and Carollo Engineers, Inc., 2021). An existing ASR facility is located nearby in the City of Kerrville, Texas, only 25 miles north of the City of Bandera.

According to the 2020 census, the City of Kerrville has a population around 20,000 people while the City of Bandera only has approximately 900 people (census.gov). In state water planning, water demands are projected for utility-based water user groups that may include customers outside of city limits. The 2022 State Water Plan lists the Kerrville public works water user group population at 25,658 people with a water demand of 5,082 acre-feet per year in the 2020s. This demand is expected to increase to 5,364 acre-feet per year by the 2070s.The 2022 State Water Plan lists Bandera utilities with a water use group population of 1,875 people and a water demand of 342 acre-feet per year in the 2020s. The water demand for the City of Bandera is expected to increase to 423 acre-feet per year by the 2070s. Both cities have projected population growth and therefore growing water demands. The expected water demands are at different scales with the projected volume increase for Kerrville to be more than 300 acre-feet per year but less than 100 acre-feet per year for Bandera. However, the percent-of-use increase for Bandera is 24 percent, whereas it is only a 6 percent increase for Kerrville.

Kerrville has been successfully storing and recovering treated surface water from the Guadalupe River in the lower Trinity aquifer since the 1990s. Both Bandera and Kerr counties are in the Plateau (Region J) Regional Water Planning Group, Groundwater Management Area 9, and the Hill Country Priority Groundwater Management Area. We will examine the existing ASR operations in Kerrville to see how the recommended Bandera ASR project compares to it and look for lessons learned and differences of note.

7.2.1 *Purpose for implementing ASR*

The City of Kerrville had historically relied on groundwater production since the 1940s until the water table levels fell 100 to 290 feet in the city's lower Trinity aquifer wells (Amans, 1988); in 1980 it switched to surface water for the primary public water supply source (Terry, 2022, personal communication). The City of Kerrville was motivated to drill two ASR wells as part of a conjunctive use plan following these declines in the lower Trinity aquifer wells (Webb, 2015). Normal operations of the two ASR wells involves injecting treated surface water from the Guadalupe River in the winter months and then recovering that water in summer months. Presently, the City of Kerrville only uses the lower Trinity aquifer production wells to meet peak demands during the summer months. Water levels in the lower Trinity aquifer wells have stabilized since implementing ASR (Figure 7-5). Kerrville plans to increase both the surface water treatment volume and number of ASR wells to capture more high flows from the Guadalupe River to make the city's water supplies more reliable during drought-of-record conditions (WSP and Carollo Engineers, Inc., 2021). The city is also considering storing and recovering highly treated wastewater to increase the reliability of the source water supply available for ASR.

Similar to Kerrville, the City of Bandera has a historical trend of water level declines in the Trinity Aquifer (Figure 7-6). The water level in the city's public water supply wells has fallen about 350 feet since the 1950s (Ashworth and others, 2009). In response to lowering water levels and growing population projections, the City of Bandera is recommending an ASR project to enhance its water supply reliability (WSP and Carollo Engineers, Inc., 2021).

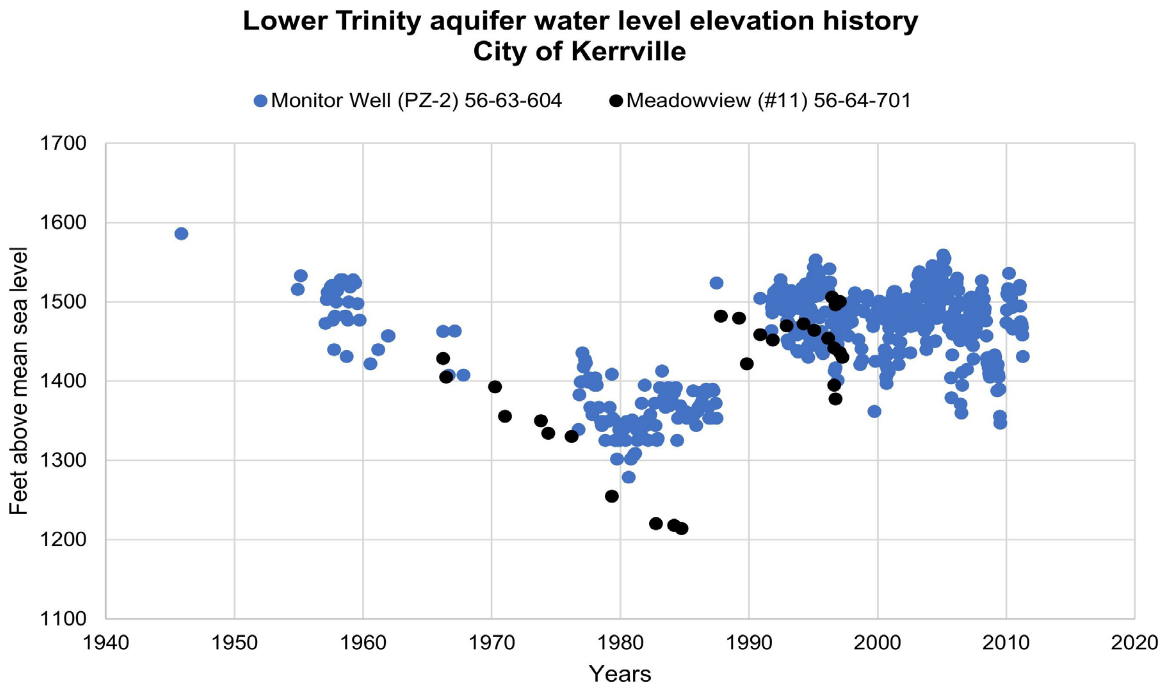


Figure 7-5. Historic water level measurements (observations) in the City of Kerrville.

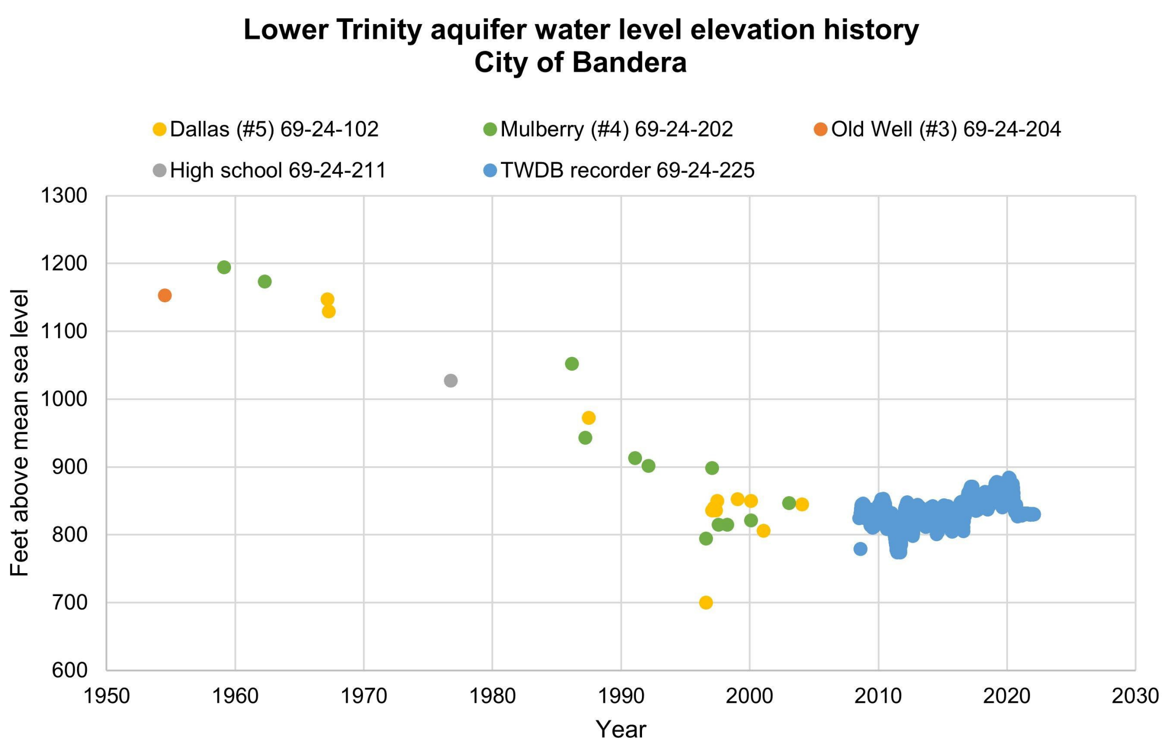


Figure 7-6. Historic water level measurement (observations) in and near the City of Bandera.

7.2.2 *Source water for injection*

Any viable ASR requires a source of excess water to be stored for later recovery and beneficial use (Shaw and others, 2020). This water may be from a variety of sources including surface water, groundwater, or highly treated wastewater (Shaw and others, 2020). Understanding the volume and reliability of this water supply is critical for developing an ASR project plan. The City of Bandera plans to use excess surface water from the Medina River for its ASR project.

The reliability of surface water supplies for the City of Bandera was assessed using the official TCEQ Water Availability Model of the Guadalupe-San Antonio Basin, dated October 2014 (WSP and Carollo Engineers, Inc., 2021). The model identified an average of 4,761 acre-feet per year available for diversion from 1934 to 1989. This modeled available diversion would be enough to cover the maximum 1,500 acre-foot per build of the city's surface water plant planned for the 2060 decade; however, the City of Bandera does not own a right to this water. The current proposal would have the city partner with Bandera County to build the ASR facility. Bandera County currently has an agreement to purchase of up to 5,000 acre-feet per year of Medina River water from the Bexar-Medina-Atascosa Water Control and Improvement District #1 (BMAWCID#1). However, BMAWCID#1's Certificate of Adjudication (CA-19-2130) is for diversion from Medina Lake and Diversion Dam, downstream of the City of Bandera. Therefore, this certificate would need to be amended to include an upstream diversion from the Medina River in the vicinity of the city (WSP and Carollo Engineers, Inc., 2021).

Use of a diversion upstream from Medina Lake as the source water for the City of Bandera ASR project has benefits for both the city and county. The most obvious benefit is that costs such as right of way easements, pipelines, and booster stations can be reduced by placing the diversion near the city's existing water infrastructure. Another benefit would be reducing Medina Lake water losses. Medina Lake is the largest surface water reservoir in the area with a conservation pool capacity of 254,823 acre-feet encompassing a surface area of 6,066 acres at conservation pool elevation of 1,064.2 feet above mean sea level (Sullivan and others, 2003). However, the water is stored above the Edwards aquifer recharge zone and in an area with a median annual net evaporation of 20 inches per year over the last 67 years (TWDB, 2021e). Therefore, some of the hydrologic budget for the lake is lost to the groundwater system and evaporation. The U.S. Geological Survey conducted a hydrologic budget for the lake during the time period of October 1995 to September 1996 (Lambert and others, 2000). For the selected hydrologic budget periods, it was estimated that Medina Lake loss an average volume of water at a rate between -14.0 and 135 acre-feet per day to the groundwater system and between 10.2 and 62.2 acre-feet per day to evaporation (Lambert and others, 2000). The more recent TWDB report "Evaporative Losses from Major Reservoirs in Texas" evaluated the time period of 2001 through 2018 and found an average evaporation loss of 18 acre-feet per day and an average annual net evaporation loss of 5,837 acre-feet per year for Medina Lake (Zhu and others, 2021). In comparison, the 500 acre-feet per year planned to be used for ASR would be protected from these losses as it would be stored in a confined portion of the Trinity Aquifer, away from the surface factors that lead to evaporation and water migration into the Edwards Aquifer recharge zone. Water losses during operation of the ASR facility will depend on the water chemistry compatibility between the source water and the aquifer, storage and recovery cycle lengths, and hydraulic gradient of the lower Trinity aquifer.

Another source water for the city to consider for ASR is highly treated wastewater. Based on the average reported outflows in the U.S. Environmental Protection Agency Enforcement and Compliance History Online database (EPA ECHO), there would be enough average daily flows from the City of Bandera wastewater treatment plant to provide approximately 150 acre-feet per year of water for reuse. This volume is less than the 500 acre-feet per year planned to be used from the Medina River for ASR but could prove to be more reliable because 1) the City of Bandera owns the wastewater discharged from its wastewater treatment plant until it is returned to a state watercourse and 2) municipal discharge volumes mostly result from indoor water usage and therefore are generally unaffected by drought and increase with population growth. The city already has sewer collection infrastructure in place and is exploring options for relocating the current wastewater treatment facility. If the wastewater treatment relocation included an upgrade to the treatment train, this could provide access to a smaller but more reliable source of water for ASR than surface water. Additionally, this would create a closed loop system where water withdrawn from the lower Trinity aquifer would be returned to the aquifer via an injection well installed at the new wastewater treatment plant location instead of discharged into the Medina River (Figure 7-7).

The exception to this loop would be any distributed water that was consumed or wasn't returned to the wastewater treatment plant, such as water used for outdoor irrigation. El Paso Water Utilities successfully recharges the Hueco Bolson aquifer with highly treated wastewater and may be an example for designing the wastewater treatment plant upgrades. Rainwater harvesting is also a potential source water that could be investigated for the proposed ASR facility since it is also listed as a water management strategy in the 2022 State Water Plan.

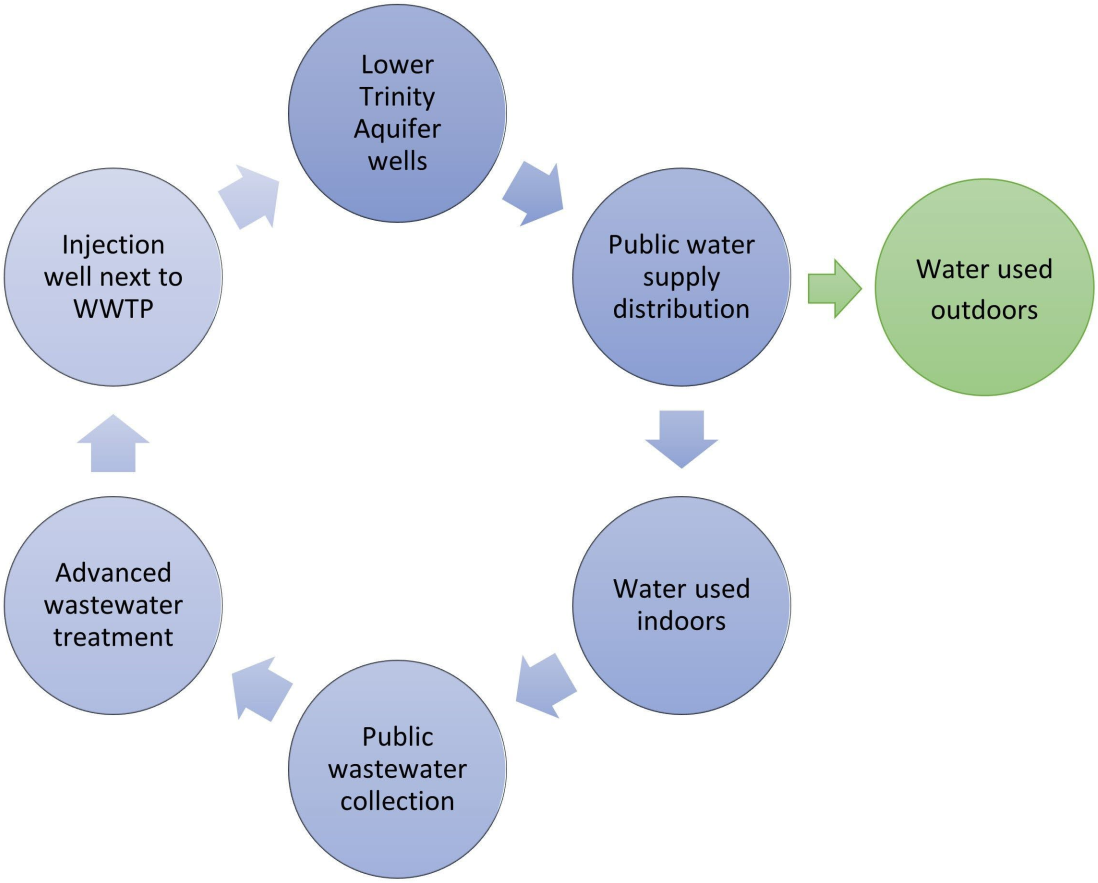


Figure 7-7. Diagram showing how the City of Bandera could theoretically create a "One Water" closed system using the lower Trinity aquifer, indirect potable reuse, and ASR. Water that does not get collected and sent to the advanced water treatment plant, such as outdoor irrigation, escapes the "One Water" closed system.

7.2.3 *Treating source water for injection and distribution*

The source water used for an ASR project usually requires treatment before injecting it underground. The type of treatment is based on local and federal groundwater regulations, the characteristics of the source water, and the compatibility of the source water with the native groundwater with which it will be in contact with. The cost of constructing an ASR system is greatly increased if a new water treatment plant needs to be constructed to implement the new system. The type and size of the treatment plant is dependent on several factors including the necessary capacity, water quality, and water availability (Rogers, 2008).

In 1980, the City of Kerrville started to treat surface water from the Guadalupe River for distribution in its public water supply system. A 5-million-gallon-per-day (5,600-acre-foot-per-year) water treatment plant was constructed to utilize this new surface water diversion. The plant capacity was designed to meet the maximum daily demand, which was 2.2 times the average daily demand (Amans, 1988). As a result, the water treatment plant often operated well below capacity. Early ASR feasibility studies found that ASR wells could store large volumes of treated surface water produced by the plant, which would allow the City to utilize the full capacity of the plant and delay the need to expand the water treatment facility to meet future growing water demands. Additionally, Texas has prioritized more senior surface water right appropriations and the City holds a junior water right that could be restricted in times of low river flows. After three phases of feasibility studies, the City decided to implement ASR to fully utilize the capacity of the new water treatment plant and to meet peak demands and for use in periods of drought.

Currently, after more than 20 years of service, the water treatment plant capacity is the primary limiting factor on ASR storage. As a result, the City of Kerrville plans to expand the surface water treatment facility to support increasing the ASR system from 2 to 4 million gallons per day (2,240 to 4,480 acre-feet per year) (WSP and Carollo Engineers, Inc., 2021). The City of Kerrville surface water treatment plant is a conventional plant that consists of pretreatment, coagulation tanks, upflow clarifiers, gaseous chlorine disinfection, and mixed media filters (TCEQ, 2022; Terry, 2022 personal communication). The plant also contains a membrane system that consists of microfiltration membranes, contact chambers, and gaseous chlorination (TCEQ, 2022; Terry, 2022 personal communication). For the City of Kerrville ASR facility, once the stored water is recovered from the aquifer, the post-treatment consists only of disinfection by adding chlorine, allowing sufficient contact time, and then pumping into the distribution system (Webb, 2015).

The City of Bandera does not have an existing surface water treatment plant. Currently, the City's groundwater public water supply wells only require disinfection and detention prior to distribution. The proposed ASR facility includes the construction of a 0.5-million-gallon-per-day (560-acre-foot-per-day) surface water treatment plant to treat water from the Medina River and should produce enough treated water to meet the initial planned supply of 500 acre-feet per year. (Ashworth and others, 2009). The majority of this treated surface water would go to distribution and reduce the amount of water pumped from the lower Trinity aquifer. When there is surplus capacity, the excess treated surface water would be injected in the lower Trinity aquifer for later recovery, also reducing the strain on the lower Trinity aquifer.

The proposed project to provide surface water to the City of Bandera for distribution and ASR will cost $34.2 million where the majority of the cost is for construction of the surface water treatment plant. The initial planned capacity of the proposed surface water treatment plant is one tenth the size of Kerrville's surface water treatment plant. Treatment costs are affected by a combination of factors including the type of treatment, the source water quality, and the average flow rate of the plant (Plumlee and others, 2014). Although water treatment plants can be scaled to different demand needs, larger plants tend to be more cost-efficient than smaller plants and production costs per gallon of water decrease with increasing production capacity (Table 7-2) (Rogers, 2008).

Table 7-2. Annual cost for conventional water treatment facilities. Costs are estimated from 2001. Modified from Rogers (2008).

Production of facility in million gallons per day	Total production cost in USD per 1,000 gallons
0.25	1.70
0.50	1.25
0.75	1.05
1.00	1.00

Conventional treatment, which includes coagulation, sedimentation, filtration, and disinfection, is common for surface water facilities. These types of facilities are generally lower cost, both in terms of capital investment and operational costs. However, if the City of Bandera chooses to include treated wastewater as part of an ASR project, these facilities are commonly insufficient to treat wastewater effluent to a sufficient level for reuse (Gumerman and others, 1979). In this case, advanced treatment options such as membrane treatment are needed. For systems with a flow rate under 5 million gallons per day (5,600 acre-feet per day), ultrafiltration may be more cost effective than conventional treatment (Figure 7-8). However, with any membrane technology, membrane replacements are a large component of the cost (Weisner and others, 1994). Ultrafiltration is also relatively limited in the amount of dissolved organic compounds it can remove, so other more expensive high-pressure membranes, such as nanofiltration or reverse osmosis may be needed prior to injection underground (Gumerman and others, 1979; Plumlee and others, 2014). These technologies are significantly more expensive to build and operate than either conventional or low-pressure membrane facilities (Plumlee and others, 2014). However, the City already owns the discharge from its wastewater treatment plant and using it as the source water for the ASR project could provide a less challenging legal path than modifying BMAWCID#1's certificate of adjudication to divert water from the Medina River upstream of the lake.

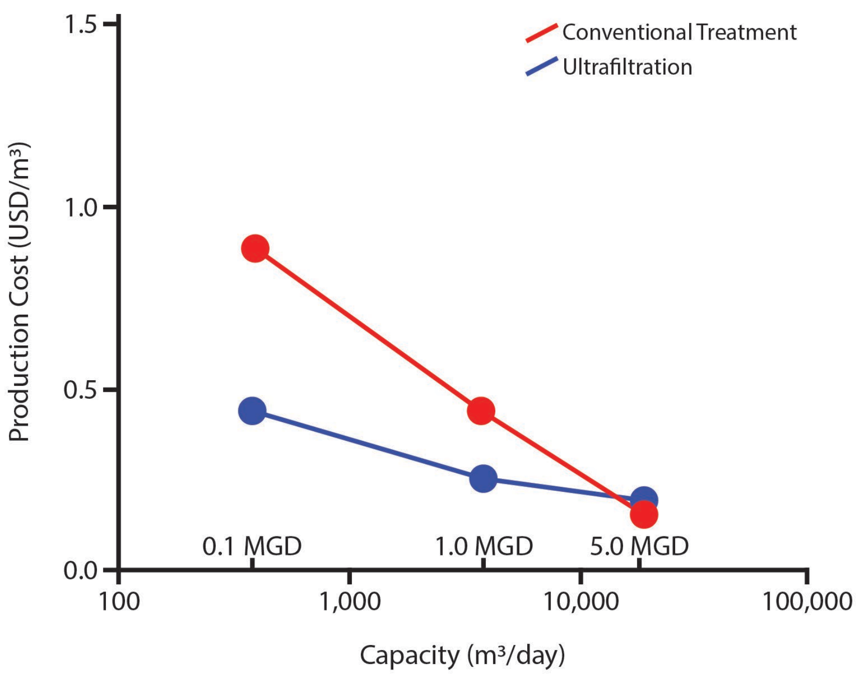


Figure 7-8. Total average production costs for conventional and ultrafiltration systems. Modified from Weisner and others (1994).

7.2.4 *Trinity Aquifer for storage*

The characteristics of the aquifer used to store the injected water is a critical consideration of any ASR project. Site selection for an ASR well must include hydrogeological considerations including well yields, storativity, water quality, and depth to the target aquifer (Pyne, 2005). To maintain control of the injected water and reduce drift, the target aquifer should be vertically confined both above and below the aquifer (Shaw and others, 2020). The stability of the storage bubble is most easily maintained in an aquifer with consistent horizontal conductivity, such as a clean sandstone. Aquifers with high secondary porosity, such as fractured and karstic carbonate environments, are more likely to lose water down these flow paths that cannot be recovered (Shaw and others, 2020).

The lower Trinity aquifer has been considered for ASR storage by several projects within Texas due to its favorable physical properties such as being primarily sandstone and having hydraulic flow that is predictable using traditional fluid flow equations. The middle and upper Trinity aquifers, by contrast, are karstic carbonate aquifers with high permeability from faults, fractures, and biogenic secondary porosity, (Golab and others, 2017a). The lower Trinity aquifer is also well confined throughout Bandera and Kerr counties, being bounded above by the Hammett Shale and below by highly compacted pre-Cretaceous (Pennsylvanian–Permian) rocks (Plummer and Moore, 1921). The Hammett Shale acts as an impermeable confining unit where present but may allow communication with the middle Trinity aquifer along faults, specifically those with large displacements. Generally, Bandera County is west of the Balcones Fault Zone and therefore contains less faulting than seen toward the east, such as in Bexar County, where the confinement may become leakier. Ongoing studies indicate that there may be more faulting in Bandera County than previously mapped (Clark, 2022, personal communication)

As previously discussed in Section 3.2, the Lower Trinity Group changes significantly between the City of Kerrville and the City of Bandera. The Lower Trinity Group is just over 50 feet thick in the Kerrville area and thickens to approximately 300 feet thick in central Bandera County (Figure 7-9). Although the Lower Trinity Group is thicker in Bandera County, the character of the aquifer units is significantly different. The top of the Hosston Formation is 511 feet below the ground surface in Kerrville (Robinson and others, 2022). Geophysical well logs from Kerrville show that the Lower Trinity Group only contains the Hosston Formation, which is very porous and homogeneous. Very little indication of clay is seen in the Hosston Formation from the City of Kerrville's outside of the contact with the above the Hammett Shale. The transmissivity of the aquifer near Kerrville is very high at 15,000–46,000 gallons per foot per day (Ashworth and others, 2001). The specific capacity of the aquifer is also high and ranges from 2.5 to 31.9 gallons per minute per foot.

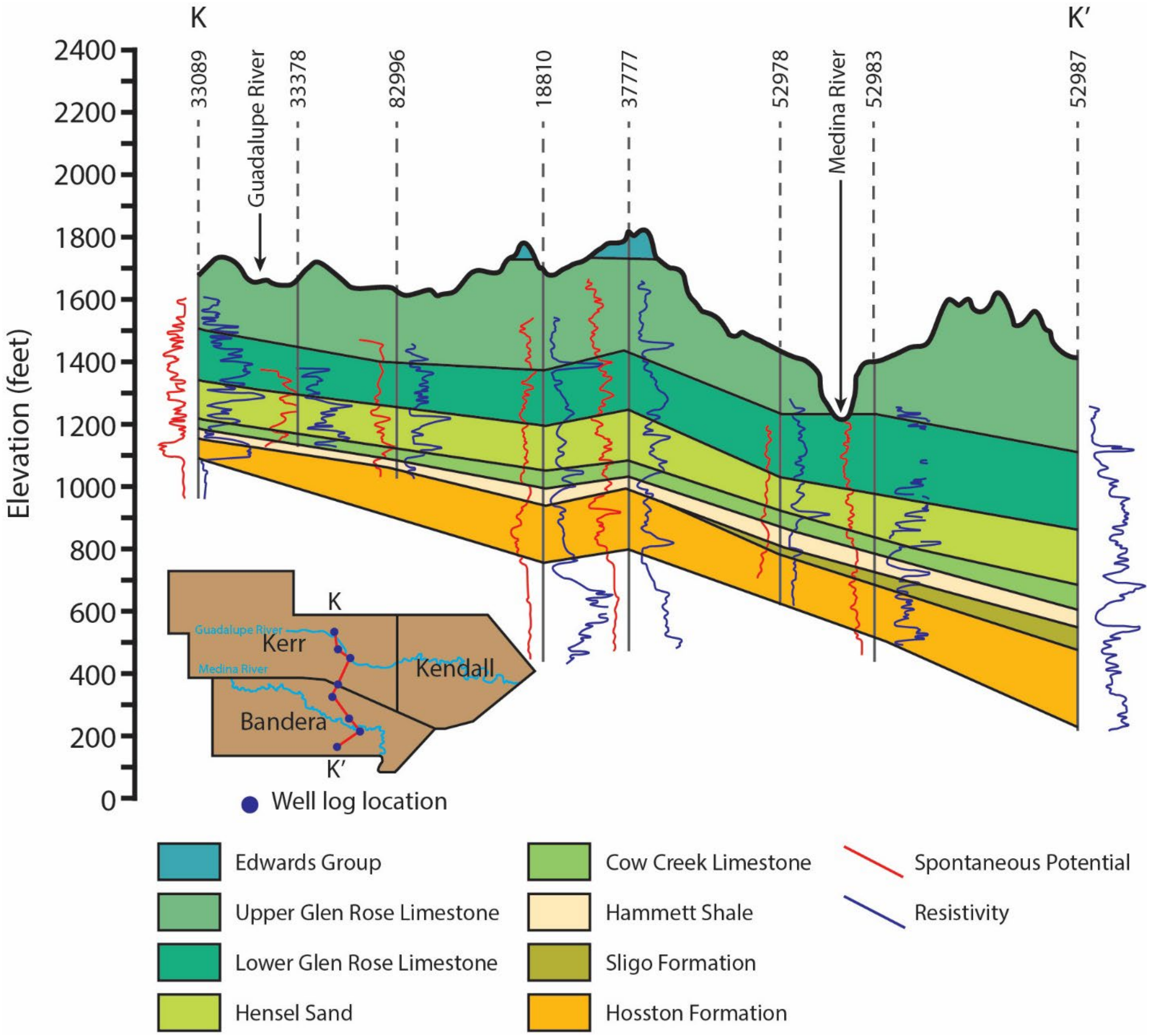


Figure 7-9. **Cross-section that illustrates the change in depth and thickness of the Trinity Group formations from the cities of Kerrville to Bandera. Wells labels indicate the record number in the TWDB BRACS database. Modified from Ashworth and others (2001).**

In the City of Bandera area, the Lower Trinity Group contains both the Sligo and Hosston formations. The Sligo Formation is only present in southern Bandera County and reaches a thickness of approximately 80 feet along the southern border of Bandera County. The Sligo Formation is primarily dolomite and associated calcareous clay (Figure 7-10). The Sligo Formation is only a minor producer of water compared to the Hosston Formation. The Hosston Formation in the area around the city of Bandera is over 220 feet thick. The top of the Hosston Formation is at 651 feet below the ground surface in the city of Bandera (Robinson and others, 2022). Geophysical well logs from central Bandera County show that the Hosston Formation is not a continuous sandstone unit but contains significant amounts of interbedded clay. The uppermost portion of the Hosston Formation in this area is primarily clay with some sand and grades down section into more sand-dominated units. The Hosston Formation in the City of Bandera area contains only a thin bed of clean sandstone at 790 feet below ground surface. This thin bed is less than 30 feet thick and then grades into interbedded clay down section before the lower contact with the pre-Cretaceous strata. The transmissivity of the strata within the City of Bandera area is significantly less than observed in Kerrville at 1,900–6,000 gallons per foot per day (Ashworth and others, 2001). The specific capacity of the aquifer was recorded as 14.6 gallons per minute per foot at the city's Mulberry Street well during the initial pump test in 1962.

The differences in the Lower Trinity Group strata between Kerr and Bandera counties is likely related to changes in depositional environment as discussed in Section 3.2. Generally, the lower Trinity aquifer is not considered a great producer south of Kerr County (Ashworth and others, 2001). This drastic change in aquifer characteristics may be responsible for some of the challenges encountered when calibrating the longevity model to this study area. Other characteristics such as recharge and communication with other aquifer strata also present challenges to understanding the lower Trinity aquifer within the study area but are difficult to quantify due to a lack of subsurface data.

In addition to the physical differences in aquifer strata between Kerr and Bandera counties, there are also differences in the groundwater geochemistry (Table 7-3). Water from the lower Trinity aquifer in Kerr and Bandera counties is generally good. It should be noted, however, that water quality degrades downdip and deeper portions of the aquifer contain moderately to significantly higher concentrations of several constituents (Ashworth and others, 2001). Lower Trinity aquifer groundwater ranges from fresh to slightly saline in Kerr and Bandera counties (Ashworth and others, 2001). The salinity of this water within Kerr County averages around 475–500 mg/L total dissolved solids, whereas downdip in Bandera County the salinity is commonly measured higher than 500 mg/L total dissolved solids (Ashworth and others, 2001). Lower Trinity aquifer water from Bandera County tends to be significantly higher in sodium and moderately higher in potassium (Ashworth and others, 2001). Lower Trinity aquifer water from Kerr County has slightly higher concentrations of calcium (70 mg/L) and magnesium (44mg/L) than in Bandera County.

These groundwater aquifer characteristics will not prevent the development of ASR in the lower Trinity aquifer within Bandera County but need to be considered during project development. Due to the lower transmissivity and specific capacity, an ASR well in Bandera County will have much slower injection and recovery rates than what is observed at the Kerrville ASR facility. Additionally, special care will need to be taken to make sure the treated injectate is compatible with the native groundwater. Although an ASR project in Bandera County faces several challenges, the use of Lower Trinity Group strata for ASR still has several advantages over other water storage and management strategies in the area, such as surface water reservoirs.

Table 7-3. Average water quality averages measurements for the lower Trinity aquifer in Kerr and Bandera counties. Modified from Ashworth and others (2001).

	Kerr County	Bandera County
Total dissolved solids	451 mg/L	492 mg/L
pH	7.5	7.9
Calcium	67 mg/L	43 mg/L
Magnesium	43 mg/L	27 mg/L
Sodium	29 mg/L	97 mg/L
Potassium	7 mg/L	14 mg/L
Bicarbonate	351 mg/L	342 mg/L
Sulfate	56 mg/L	70 mg/L
Chloride	41 mg/L	58 mg/L

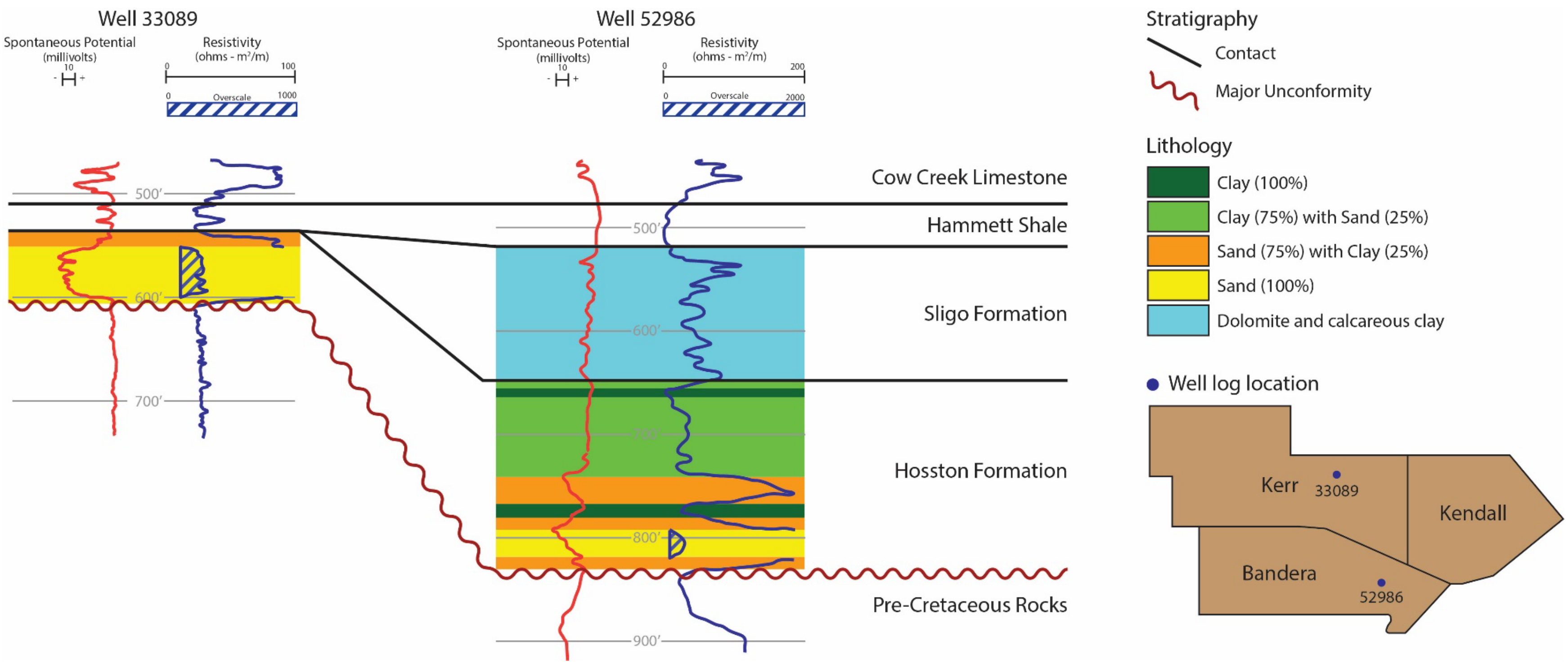


Figure 7-10. **Geophysical well log curves from wells in Kerrville and Bandera to highlight the difference in tool readings for the lower Trinity aquifer in these two locations. Wells labels indicate the record number in the TWDB BRACS Database.**

7.2.5 *Well construction and operation*

The City of Kerrville's water supply comes from the Guadalupe River and nine wells completed in the lower Trinity aquifer, including two ASR wells. These nine wells are 603–831 feet deep and have screen lengths that vary between 59 and 179 feet. The lower Trinity aquifer in Kerrville is between 600 and 800 feet below ground surface and, as discussed above, is primarily clean sandstone and shale. The City of Bandera's water supply is produced from four wells, three of which are in the lower Trinity aquifer and one in the middle Trinity aquifer. The three lower Trinity wells range in depth from 770 to 842 feet below ground surface. However, due to the change in lithology from Kerr County in the lower Trinity aquifer strata, clean sands are not reached until a depth of 790 feet.

Both the depth to ideal strata and smaller population of the city of Bandera poses significant challenges for the development of an ASR project for the City. The capital expenses for starting an ASR project can be significant and the depth to the clean sands increases the potential costs associated with developing an ASR well. Additionally, the increased depth of the Trinity Aquifer is associated with higher salinity, which can have a significant impact on the choice of materials used for an ASR well. Currently, Kerrville can store more than 3 million acre-feet of water in its two ASR wells (Figure 7-11). This project is much larger than what would be needed for a project in the city of Bandera; therefore, any future engineering plans must take a close look at the potential capital costs in order to make it feasible. The smallest permitted ASR system in Texas is run by Ruby Ranch Water Supply Corporation and is permitted to recover up to approximately 12.3 million gallons (37.7 acre-feet per year) (TCEQ authorization 5R2100053, 2020).

The City of Bandera has proposed retrofitting an existing well for ASR. The use of an existing well would save on the capital costs of drilling a new well to the lower Trinity aquifer, however, several studies and previous projects indicate that the use of preexisting production wells for ASR projects can cause issues in development and in operations. Wells for ASR projects must endure stresses different than those found in either production or injection wells due to water flowing both into and out of the aquifer at pressure (Pyne, 2005). If an existing production well is chosen to be used for ASR, its condition must be examined before the project can begin in order to verify the integrity of the casing and other vital components (Pyne, 2005). If an inappropriate well is chosen, the well may fail during testing (Pyne, 2005). It is often advised to use purpose-designed wells for ASR due to this risk (Pyne, 2005; Blumberg and Pyne, 2019).

Although Kerrville converted production wells to ASR wells, these wells were designed with ASR in mind and were much newer than the City of Bandera's existing wells. Other ASR projects within Texas have used retrofitted production wells, and the challenges faced by these projects are well documented. For example, the City of Victoria retrofitted a production well for ASR in 2016 (Blumberg and Pyne, 2019). During the retrofitting and testing process this well overflowed due to clogging and corrosion on both the casing and screen was discovered (Blumberg and Pyne, 2019). Rehabilitation plans for the well, which included wire brushing, had to be modified due to risk of well collapse, and further logging showed that there were still blockages in the screen (Blumberg and Pyne, 2019). Although the retrofit for this well was completed, the additional complications cost the project both time and money.

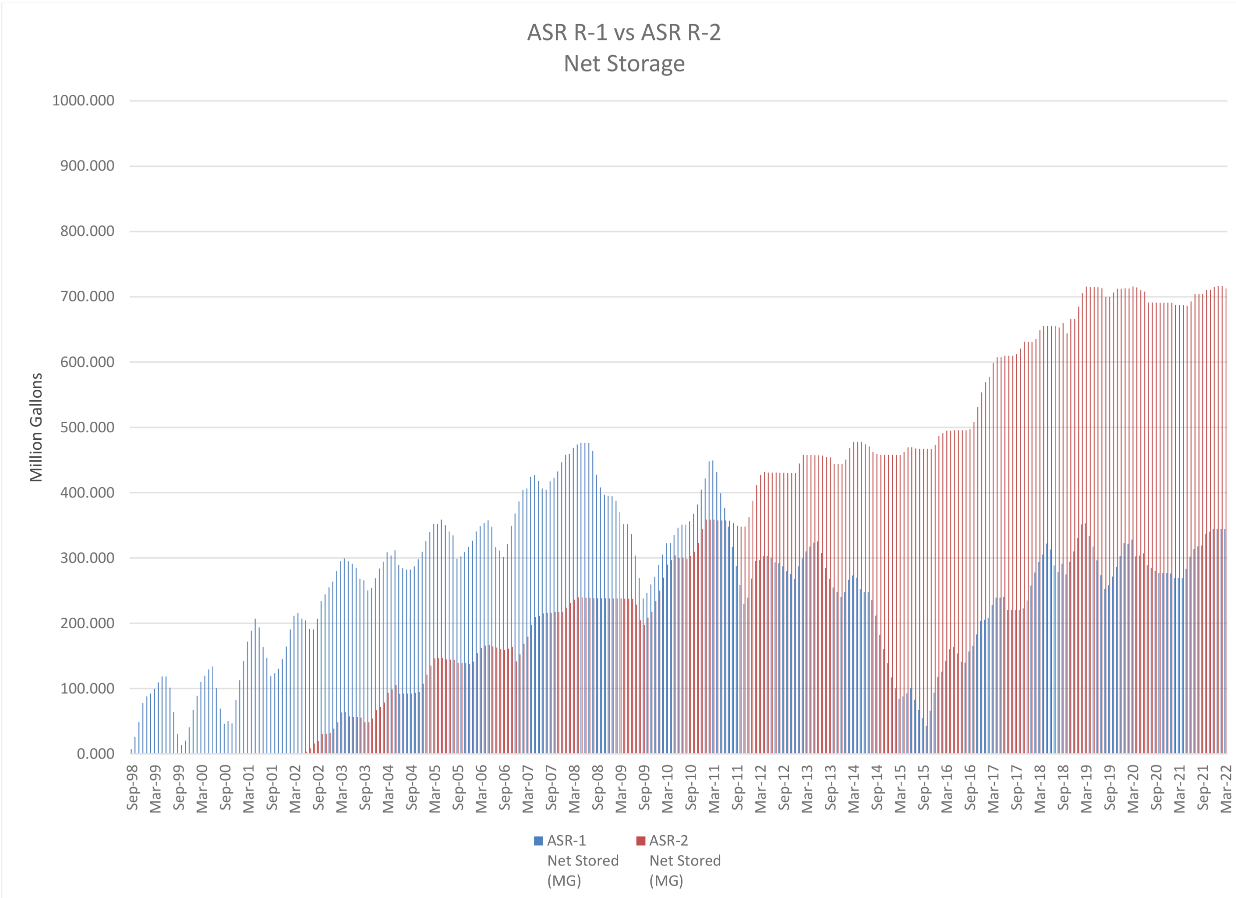


Figure 7-11. Net stored water in Kerrville wells ASR-1 and ASR-2.

7.2.6 *Maintaining ownership of stored water*

Based on a 1904 ruling by the Texas Supreme Court, Texas is a "rule of capture" state when it comes to groundwater law and doctrine (Houston & T.C. Ry. Co. v. East, 1904). Outside of the jurisdiction of a groundwater conservation district, and if a water right is not legally separated from the land, landowners have the right to produce as much of the water under their property as they would like as long as they are not being wasteful, malicious, or cause subsidence (Texas Water Code § 36.002). Therefore, maintaining ownership of stored water is another vital aspect for an aquifer storage and recovery project in Texas. Because all of the City of Kerrville ASR wells are within city limits, the City has been able to restrict access to the injected water using a city ordinance requiring wells completed in the lower Trinity aquifer to meet public water supply standards (Figure 7-12). The high cost of operating such a system deters others from drilling wells to access the water the City has stored. Additionally, the City of Kerrville and the Headwaters Groundwater Conservation District have an agreement where the City reports cumulative net stored water to the district and only water recovered in excess of water injected is applied to the City's existing groundwater production permits (Webb, 2015).

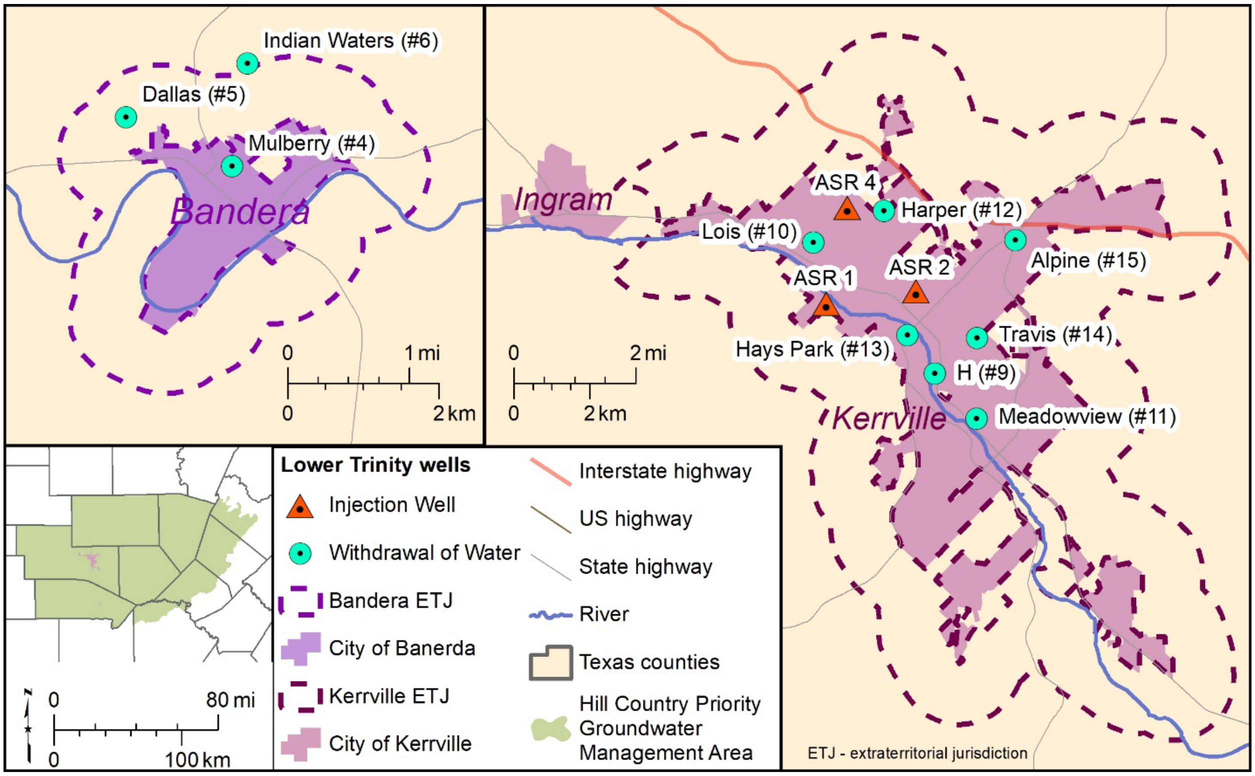


Figure 7-12. Cities of Bandera and Kerrville lower Trinity aquifer public water wells, city limits, and extraterritorial jurisdiction areas.

The City of Bandera's current wells are located both within and outside of the city limits. The Mulberry Street well (#4) is within city limits, the Dallas Street Well (#5) is within the extraterritorial jurisdictional area (ETJ), and the Indian Water well (#6) is just outside of both the city limits and the ETJ. Therefore, if the City is inclined to retrofit these wells, it may not be able to deploy the same tactic used by Kerrville to shield its stored water from other well owners. The 2009 *ASR Feasibility in Bandera County* report does not discuss how the City of Bandera could control ownership of their injected water (Ashworth and others, 2009). The potential City of Bandera ASR project would occur in the jurisdiction of the Bandera County River Authority and Groundwater District (BCRAGD). Under Texas statute, groundwater conservation districts can regulate through permitting the spacing between and production from wells in their jurisdiction (Texas Water Code Chapter 36). In 2015 an exception was made for ASR wells authorized by the TCEQ. So as long as the ASR project injects more water than is determined to be recoverable, BCRAGD cannot require operating permits for production of stored recoverable water for the project (Texas Water Code § 36.454).

While the ASR project may not need a permit from BCRAGD, the utility must apply for a Class V injection well from the TCEQ. Regulatory requirements for Class V injection wells are in the 30 Texas Administrative Code § 331. Subchapter H provides the standards for all Class V wells and Subchapter K has additional requirements for ASR projects. All ASR injection and recovery wells associated with a single ASR project must be located within a continuous perimeter boundary of one parcel of land or within two or more parcels of land under common ownership or lease. Additionally, according to Texas Water Code § 36.453, the ASR well operator will need to: (1) register the wells with the district, (2) submit a monthly report to both the TCEQ and the district, (3) submit an annual report to the TCEQ and the district, and (4) if the ASR project recovers more water than is determined to be recoverable the operator must report that volume to the district. In addition to these forementioned requirements, working closely with the BCRAGD may also be beneficial to the project's success since the district may have options to help the city maintain ownership of its stored water by regulating spacing of and production from new lower Trinity aquifer wells. Additional options for protecting the stored water could include:

- passing an ordinance limiting the drilling of additional lower Trinity aquifer wells within the extraterritorial jurisdictional area and then installing new ASR wells within that boundary but distant from existing lower Trinity aquifer wells, or
- purchasing a large tract of land on which to place the ASR well(s) and isolating the stored water from existing and future wells.

8. Conclusions

The management of water supplies into future decades is a critical challenge faced by many water producers across Texas. The 2022 State Water Plan projects increasing need across the state, particularly in areas with growing populations, and meeting this increasing demand in many cases may require adopting new water management strategies. Bandera County in the Texas Hill Country has seen a rapid increase in population over recent years and this growth is projected to continue. The City of Bandera produces water for municipal use primarily from the lower Trinity aquifer, and water levels in these wells have decreased significantly since the 1950s (Ashworth and others, 2009). In response to these factors, the City of Bandera recommended several water management strategies in the 2022 State Water Plan to enhance the city's water supply reliability. These strategies include drilling two new middle Trinity aquifer wells with a total yield of 161 acre-foot per year. The City also recommended implementing surface water acquisition, additional treatment facilities, and an ASR project.

Like the City's current production wells, the lower Trinity aquifer is the proposed target for this proposed ASR project. The City of Bandera needed to understand how increased pumping, such as in high demand scenarios, could affect the longevity of its major supply wells to aid in future planning and development. This report focuses on modeling the lower Trinity aquifer being the target for the ASR water management strategy and the location of most of the City's current production. This report presents the results of two models: an analytical solution and a numerical groundwater flow model, which both focus on the City of Bandera's most productive well, the Mulberry Street well.

An analytical solution is used to estimate water levels under different pumping scenarios using current lower Trinity aquifer parameters and the configuration of the Mulberry Street well. It shows that under present pumping conditions, there is a drawdown of 46 feet after 3.6 hours of pumping, which is nearly equivalent to the current pump depth. The maximum stress scenario for the City of Bandera would be producing all existing groundwater supply listed in the 2022 State Water Plan, which would be equivalent to increasing total current production by 91 percent. In this scenario, the City of Bandera's wells would need to produce almost twice the current production amount with the same pumping rate and the Mulberry Street well would need to operate for 6.9 hours, resulting in a total drawdown of 91 feet, which is below current pump depth. This would be possible by lowering the pump at least 45 feet below the current level. However, this rate of production would eventually lower water levels below the depth of casing, at which point the well would reach its operational limit. The analytical solution results were further evaluated to approximate the minimum static water level required for the Mulberry Street well to continue operating under maximum stress conditions. The results showed that the static water level should be greater than 621 feet above mean sea level, a maximum of 639 feet below ground surface. Any increase in production that would lower the static water level below this point would be beyond the current resources and infrastructure of the city of Bandera.

While analytical solutions can provide short-term pumping water level changes below static water levels under known conditions and at the well scale, which is a valuable operational information, it cannot be used to forecast future regional water levels important for multi-decadal planning. Because of this limitation, a numerical groundwater flow model was used to show the regional effects of pumping over time. The Bandera well longevity model was built using the framework of the Hill Country Trinity GAM. Several modifications and updates were needed to shift the focus of the model out of the regional domain to the lower Trinity aquifer in Bandera County. These changes included an update of the surface layers and footprint, as well as the boundary conditions and model parameters. The 1-mile grid size of the regional model was reduced to 0.25-miles over Bandera County. The Bandera well longevity model was calibrated using historic conditions between 1980 and 2018 and used to forecast future conditions from 2020 to 2079 under three scenarios.

The results of the Bandera well longevity model's first scenario showed that the Mulberry Street well could sustain the current volumes of pumped water for at least another 16 years before the pump level would need to be lowered and that the available water was sufficient to provide water through the entire modeled period. This first scenario, however, assumes that production would not increase to meet demand in neither the city of Bandera nor the entire modeled region. The second scenario assumed the city would pump enough volume to meet the demands listed in the 2022 State Water Plan. In this scenario, the City would need to lower the pump of the Mulberry Street well after two years of increased pumping and water levels would reach the bottom of the well casing after 29 years. At this point, the Mulberry Street well would no longer be usable. The third scenario assumed the City of Bandera would begin producing the entire existing available groundwater supply listed in the 2022 State Water Plan. Under this high-stress scenario, the Bandera well longevity model forecasts that water level in the Mulberry Street well would reach below the pump level in one year after beginning pumping at this rate. At which point production of the existing water supply rate from the Mulberry Street well would not be possible. The model also forecasts that the water level in the Mulberry Street well would be lowered to the depth of the bottom of the casing in five years and would be no longer usable.

While the two models presented in this study provide a first look at the potential well-aquifer system conditions in the Mulberry Street well and lower Trinity aquifer, they do not replace the need for further site-specific investigations. These models are informed by subsurface data and water level histories for the lower Trinity aquifer, which is limited. The lower Trinity aquifer is a highly heterogenous system and the collection of new data or further development and withdrawal from the aquifer may change observed results. The comparison of the historic modeled levels and the observations highlighted a zone of large drawdowns, or low water levels, compared to the rest of the available observations in the lower Trinity aquifer in the area around the City of Bandera. These anomalous results could be attributed to unaccounted pumping or to local aquifer conditions that need further assessment.

These results indicate that the City of Bandera may need to implement mitigation plans such as diversifying its water resources and improving the management of the lower Trinity aquifer. This could be attained with the treated surface water and ASR project recommended water management strategy listed in the 2022 State Water Plan. This strategy would use treated surface water to inject into the lower Trinity aquifer, which would help maintain reliably recoverable water levels, increase the longevity of the city's wells, and supply reserves in case of drought.

The Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects identified the Trinity Aquifer as the most suitable aquifer for an ASR project in the study area. The survey scored most of the study area as low for ASR suitability, with moderately to most suitable scores occur in the eastern portion of the county towards San Antonio area. This is attributed to the higher municipal demands to the southeast as well as higher excess water availability in the east. The large-scale scope of the survey provides a foundation for consideration of ASR but may not fully capture the water supply challenges at the more local scale for the City of Bandera.

The first ASR project in Texas was implemented by the City of Kerrville in the 1990s in response to rapid population growth and water level declines. The Kerrville ASR project stores treated surface water from the Guadalupe River and stores it in the lower Trinity aquifer for later recovery when needed. The City of Kerrville is only 25 miles north of the City of Bandera and acts as a point of comparison for the development of an ASR project. Although these two cities are relatively close together, there are significant differences in the characteristics of the aquifer that will need to be considered for an ASR project in Bandera County. The city of Kerrville also converted existing production wells to ASR wells, similar to the City of Bandera's current plan. However, the City of Kerrville designed these wells with ASR in mind and these wells were newer than the City of Bandera's existing wells. The challenges faced by the retrofitting of production wells to ASR wells in Texas is well documented and the City of Bandera will need to carefully examine the condition of its existing wells.

If an ASR project is considered for further evaluation, the Bandera well longevity model can be a useful tool for setting project's timeline, determining candidate well locations, testing operation scenarios, and many more purposes. However, the City of Bandera will need to consider data collection, such as aquifer properties and detailed pumping volumes, for further refinement of the model and improvement of its results accuracy. In addition, the city will need assess the economic viability of the project. Discussions with experienced operators of ASR projects, such as the City of Kerrville, may aid in making future decisions. However, every ASR project is unique, and these differences must be considered.

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10. Appendix A – Analytical solution detailed methodology

The analytical solution is based on a groundwater flow equation that determines water levels in an aquifer in response to a pumping well. Equation 10-1 describes the transient radial flow to a pumping well in a confined aquifer. It was published by Charles Theis in 1935. The equation solves for drawdown (d) at any distance (r) from a well pumping at a rate (Q) in an infinite and uniform aquifer with Transmissivity (T), Storativity (S), and constant thickness at any point in time (t) (Figure 10-1). Drawdown and water level (h) relationship is expressed by Equation 10-2, where h_o is the initial water level before pumping started. Equation 10-3 gives T for an aquifer with known hydraulic conductivity (K) and the thickness (b).

$$d(r,t) = \frac{Q}{4\pi T} W\left(\frac{r^2\, S}{4Tt}\right) \qquad \textbf{Equation 10-1}$$

$$d(r,t) = h_o - h(r,t) \qquad \textbf{Equation 10-2}$$

$$T = Kb \qquad \textbf{Equation 10-3}$$

W is the exponential integral function known as the well function.

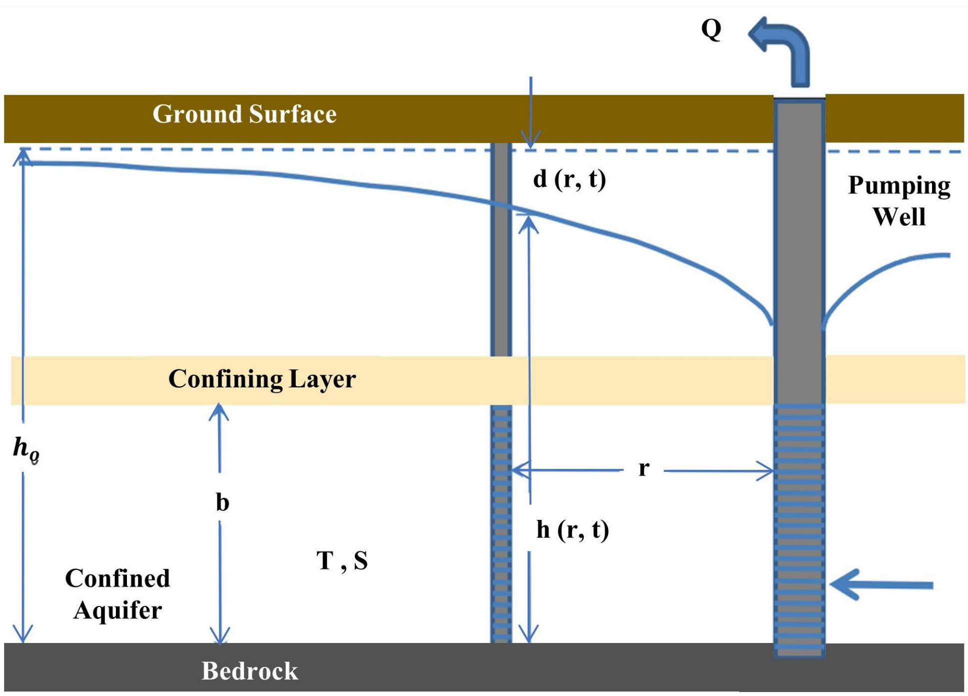

Figure 10-1. Diagram of the well-aquifer system assumed for the analytical solution.

This solution makes several assumptions that include: (1) the aquifer in the system is confined, homogeneous, of a uniform thickness, and has infinite areal extent; (2) the aquifer releases water from storage instantaneously with decline in hydraulic head; (3) the well fully penetrates the aquifer and the well diameter is small compared to the area of the aquifer (i.e., storage in the well is negligible); and (4) the groundwater follow is unsteady (i.e., changing with time) and perpendicular to the wellbore.

Available aquifer test information for the lower Trinity aquifer were collected from Myers (1969) and well schedules and well reports were gathered from the TWDB Groundwater Database (GWDB) (TWDB, 2021a). Additional information was provided by the BCRAGD (BCRAGD, 2021). Some of the well logs had aquifer test data that were not processed to calculate aquifer properties. The Cooper-Jacob (Cooper and Jacob, 1946) method was applied to calculate aquifer transmissivity (T) and operational details provided by the City of Bandera were used to estimate aquifer hydraulic conductivity (K). These data and results are listed in Table 10-1.

Table 10-1. Pump test and aquifer properties.

		Well #5 or Dallas Street	Well #4 or Mulberry Street	Well #6 or Indian Waters
Pump test		2	2	1
Pump test dates		3/15/67 and 04/21/76	4/28/1953 and 05/02/1962	10/21/1998
Pump test analysis	Test date	4/21/1976	05/02/1962	10/21/1998
	Well yield (gallons per minute)	800.00	535.00	280.00
	Transmissivity (square feet per day)	not available	3,074.70	not available
	Hosston thickness (feet)	not available	90	not available
	Hydraulic conductivity (feet per day)	not available	34.16	not available
	Storativity (/)	not available	not available	not available
	Remark	Test data in scanned document	TWDB report 98	Test data in scanned document
Cooper-Jacob Analysis	Test date	4/21/1976	4/28/1953	10/21/1998
	Well yield (gallons per minute)	800.00	1,327.00	280.00
	Well capacity (gallons per minute per foot)	3.10	8.28	4.38
	Transmissivity (square feet per day)	642.23	997.79	837.52
	Hydraulic conductivity (feet per day)	3.85	5.53	4.84
	Storativity (/)	-	-	-
Estimated hydraulic conductivity from well operations (feet per day)		1.00	4.04	1.88

The Theis (1935) solution produces water levels at a specific point in space and time with a high resolution and can be applied to determine water level at the radius of the producing well (r_w). The analytical equation was applied to the Mulberry Street well to predict future water levels in response to current pimping volumes as reported by the City of Bandera, in addition to two pumping scenarios: (1) existing supply and (2) end-of-life. In the first scenario, the City of Bandera would begin producing the total groundwater supply as listed in the 2022 State Water Plan. The second scenario tests the operational limit of the Mulberry Street well. Table 10-2 lists the variable values used in Equation 10-1 for these scenarios.

Table 10-2. Mulberry Street well parameters applied in the analytical solution.

Q (gpm)	t (hours)	r_w (feet)	b (feet)	K (feet/day)	S (/)
480	3.6	0.5	90	4	0.00013

The storativity value was obtained from the Hill County Trinity conceptual model report (Toll and others, 2018) and the aquifer thickness and well radius was collected from the Mulberry Street well well-schedule. Hydraulic conductivity was estimated from production information provided by the City of Bandera.

The Theis (1935) solution for groundwater flow is applicable for a simple well-aquifer system with ideal characteristics. In reality, well-aquifer systems are more complex, which may not match the assumptions used. For each unmet assumption in complex systems, more term(s) are added to the equation, and it becomes harder to solve and requires more computational power to process it. An example of such a complex system would be a confined aquifer with hydrogeological boundaries (e.g., fault zones and surface water bodies), different zones of hydraulic properties, multiple pumping wells, or all the above. In addition, the simple form of the analytical solution is limited to a single well and does not provide contours for regional water levels trends and gradients.

11. Appendix B – Numerical model detailed methodology

The Bandera well longevity model was developed using the framework of the Hill Country Trinity GAM to assess historic and future water levels in the lower Trinity aquifer in Bandera County. Both models are computational representations of the regional groundwater transient flow in the Hill Country portion of the Trinity Aquifer. Turning a conceptual model into a groundwater flow simulation model requires the selection of simulation code, discretization of the aquifer (i.e., design of grid cells and layers), and assignment of groundwater flow parameters. An effective model closely matches the conceptual understanding of the aquifer.

The numerical modeling computer program used for the Hill Country Trinity GAM was upgraded from MODFLOW-96 to the unstructured grid version of MODFLOW (MODFLOW-USG) for the Bandera well longevity model. MODFLOW-USG is a three dimensional, steady-state, and transient groundwater flow simulation program that uses the generalized control volume finite-difference approach (Panday and others, 2013). It does not limit the model grid to the orthogonal structure grid like the earlier versions of MODFLOW (Panday and others, 2013). Grid cells in MODFLOW-USG can be any shape (e.g., triangles or hexagons). MODFLOW-USG also supports nested grids, which enable refining a part of the model domain (e.g., along rivers or around wells) without continuing that refinement to the edge of the course grid. This option is useful for using regional models to study more focused areas of interest without adding computation burden. To solve the groundwater flow equation, MODFLOW-USG uses the Sparce Matrix Solver (SMS). A specified a convergence criterion of 0.0001 feet was used for the Bandera well longevity model. All input and output data are in units of feet for length and days for time. Groundwater Vistas software was used as a third-party graphical interface to facilitate the use of the MODFLOW-USG for the pre- and post-processing work, i.e., building, running, and analyzing numeric flow models as well as for calibration (Rumbaugh and Rumbaugh, 2020).

Discussion on the spatial discretization, framework, and boundary conditions of both the Hill Country Trinity GAM and Bandera well longevity model is in the following sections. For temporal discretization, the Hill Country Trinity GAM transient model simulated the fluctuation in the groundwater flow system during 18 stress periods covering the period from 1980 to the end of 1997. A stress period of a transient model is the time unit during which the stresses (e.g., pumping) are constant. The length of a transient stress period in the Hill Country Trinity GAM is 365 days (one year). The first stress period is steady state and was calibrated to the observed water levels from 1977 to 1985, a period of a fairly stable conditions, and used to represent the conditions in 1980 (Jones and others, 2011). The resulting modeled water levels representing 1980 conditions were used as the initial conditions for the Bandera well longevity model. The construction of the Bandera well longevity model included adding 21 new stress periods covering the period from the beginning of 1998 to the end of 2018. Predictive modeling was used to forecast future water levels until 2079 for three scenarios:

1- The “no change” scenario (S1): applying the 2018 pumping volumes with no increase throughout the entire simulated period
2- The “projected demands” scenario (S2): applying pumping volumes that meets the demands listed in the 2022 state water plan
3- The “maximum planned supply” scenario (S3): applying pumping annually to produce all of the City of Bandera existing groundwater supply listed in the 2022 State Water Plan

11.1 Grid design

Both the Hill Country Trinity GAM and the Bandera well longevity model were designed with four layers: layer 1 is the Edwards Group of the Edwards-Trinity (Plateau) Aquifer, layer 2 is the upper Trinity aquifer, layer 3 is the middle Trinity aquifer, and layer 4 is the lower Trinity aquifer. This section introduces the grid design updates applied to the Hill Country Trinity GAM to develop the Bandera well longevity model.

The Hill Country Trinity GAM has 69 rows and 115 columns in each of the model’s four layers for a total of 31,740 cells with a uniform size of one square mile. While this cell size was appropriate for the regional model, it was not suitable for the objectives of the Bandera well longevity model. Therefore, the nested grid option offered by MODFLOW-USG was utilized. The nested grid size is 116 rows and 220 columns over Bandera County and a two-mile buffer for a total of 25,250 cells with a uniform size of 0.25 mile by 0.25 mile (Figure 11-1). Table 11-1 compares the specifications of both models.

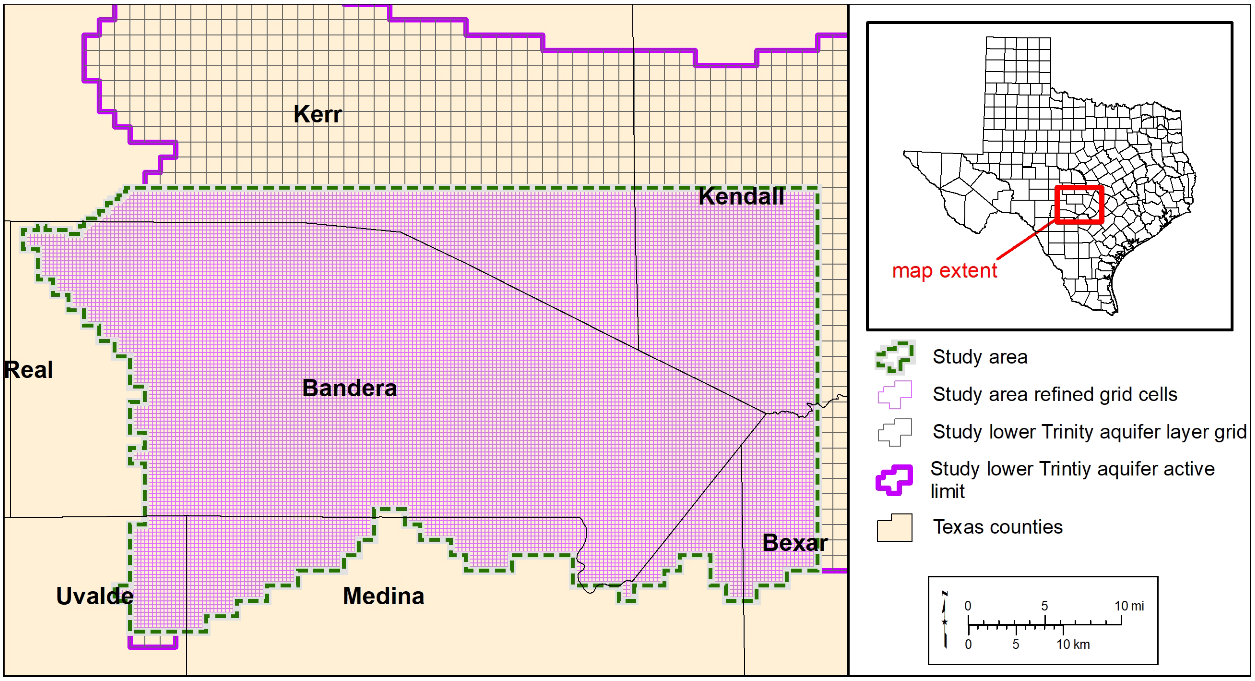

Figure 11-1 The refined grid cells in the study area of the Bandera well longevity model created with MODFLOW-USG nested grid.

Table 11-1. Comparison between Hill Country Trinity Groundwater Availability Model (GAM) and Bandera well longevity model grid design. Area is in square miles.

		Hill Country Trinity GAM	Bandera well longevity model
Total number of cells		31,740	127,440
Total active model cells		12,976	67,050
Active area per layer	1	1,107	869.44
	2	3,562	3,246.75
	3	4,517	4,263.44
	4	3,790	3,365.44

11.2 Framework

The footprint of the Bandera well longevity model is based on the overlap between the active area of the Hill Country Trinity GAM by Jones and others (2011) and the Brackish Water Resources study of the Hill Country portion of the Trinity Aquifer study by Robinson and others (2022). These two studies had different methodologies and objectives; therefore, the study areas do not match in some locations.

Jones and others (2011) is a groundwater flow model. The active footprint for this model is bounded by several hydrogeologic features. The eastern and southern portion of the footprint is bounded by major faults of the Balcones Fault Zone. The northern portion of the footprint is bounded by the outcrops of the Edwards and Trinity aquifer or major rivers (Jones and others, 2011). The western portion of the footprint is bounded by the limits of groundwater flow paths for the Trinity Aquifer. Groundwater flow paths were primarily used to bound the model because MODFLOW uses pumping data to predict groundwater flow and availability. However, these boundaries do not match the exact outline of the aquifers in the Hill County area. Parts of western Bandera and northeastern Uvalde counties were excluded from the model. Some thin portions of the Edwards Group in the eastern third of the footprint were also excluded from the model because many of these units are discontinuous and would be difficult to model on a regional scale due to extensive faulting by the Balcones Fault Zone. The model also contains parts of the Edwards-Trinity Plateau Aquifer System in Bandera, Gillespie, Kendall, and Kerr counties (Jones and others, 2011).

This study's stratigraphic surfaces were based on Robinson and others (2022), as opposed to the above-described GAM. This decision was made in order to accurately model the study area using the most up-to-date stratigraphic surfaces that were available. Robinson and others (2022) is an aquifer characterization study that includes stratigraphic, lithologic, and geochemical analyses. The study area for Robinson and others (2022) is larger than Jones and others (2011) and includes all the TWDB-defined Trinity Aquifer outcrop and subcrop areas in the Texas Hill Country region. Part of the reason this study area is larger was that much more downdip area of the aquifers were included to both minimize edge effects from interpolations and to map deeper, brackish portions of the Trinity Aquifer (Robinson and others, 2022). Additionally, Robinson and others (2022) includes parts of other aquifers that overlie the Trinity Group in the study area including the Carrizo, Edwards, and Edwards-Trinity (Plateau) aquifers. However, due to the purpose of this study, the considered study area does not extend as far on the North and Northwestern boundary as that of the Jones and others (2011) as shown in Figure 11-2. Therefore, some modifications were made to account for the discrepancy in study area extends and is further explained in Section 11.4.1.

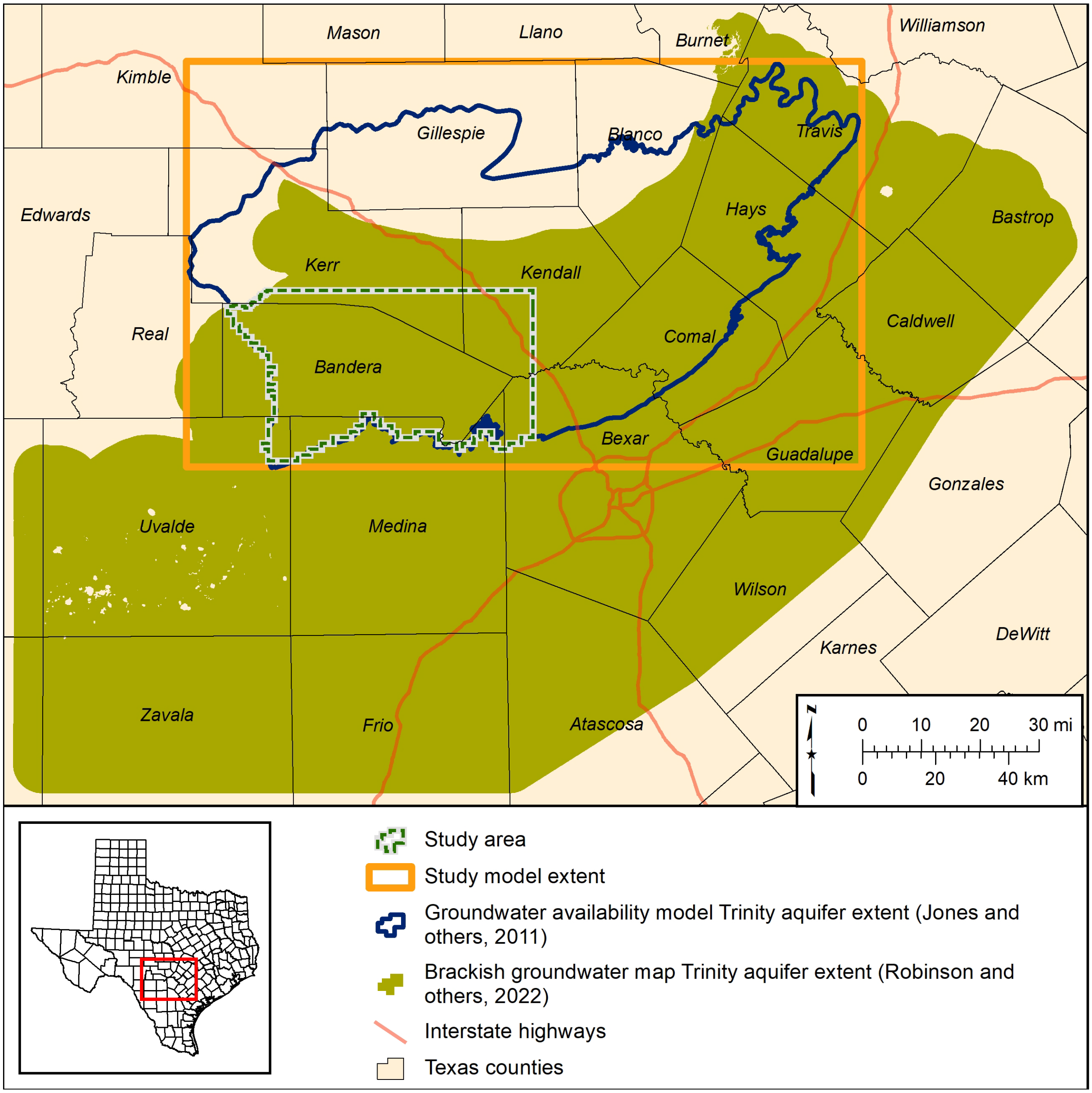

Figure 11-2. **Map of the footprint of the Hill Country Trinity Groundwater Availability Model (GAM) which includes the major aquifers in the study area, and the study area boundary of the Brackish Water Resources of the Hill Country portion of the Trinity Aquifer System study. BRACS = Brackish Resources Aquifer Characterization System.**

11.3 Layers and model parameters

The modeled layers in the Bandera well longevity model are shown in Figure 11-3. Layer 1, the Edwards Group, was simulated as an unconfined aquifer with a free water table below the top of the layer. The saturated thickness of this layer is defined at the elevation of the water table measured from the bottom of the layer. Layers 2 and 3, the upper Trinity aquifer and the middle Trinity aquifer, were simulated as convertible layers in which the water table can be above or below the top of the respective layer. The saturated thickness of these layers is defined by the upstream water table depth. Layer 4, the lower Trinity aquifer, was simulated as a confined aquifer with heads above the layer's top and a constant saturated thickness. The parameters of the model are the layers' top and bottom elevations, horizontal and vertical hydraulic conductivity, and storage parameters (specific storage and specific yield).

Development of the Bandera well longevity model included assigning new approximations for the top and bottom elevations of each layer based on Robinson and others (2022). The top elevation of layer one was assigned as the land surface elevation obtained from the 30-meter digital elevation model. Land surface elevation was assigned to the top of layers 2 and 3 in areas where they have outcrop. Otherwise, the top of layers 2 and 3 were simulated as the base of layers 1 and 2, respectively. The Hammett Shale is the confining unit between middle Trinity (layer 3) and lower Trinity (layer 4) aquifers; and as such, the bottom elevation of the Hammett was used to define the top of layer 4. Lastly, the base of layer 4 was simulated as the top of the pre-Cretaceous units.

<table>
<tr><th>Era</th><th>System</th><th>Group</th><th colspan="2">Stratigraphic unit</th><th colspan="2">Hydrologic unit</th><th>Model layer</th></tr>
<tr><td>Cenozoic</td><td>Quaternary</td><td></td><td colspan="2">Alluvium</td><td colspan="2">Alluvium</td><td></td></tr>
<tr><td rowspan="9">Mesozoic</td><td rowspan="9">Cretaceous</td><td rowspan="2">Edwards</td><td colspan="2">Segovia Formation</td><td colspan="2" rowspan="2">Edwards Group</td><td rowspan="2">Layer 1</td></tr>
<tr><td colspan="2">Fort Terrett Formation</td></tr>
<tr><td rowspan="7">Trinity</td><td rowspan="2">Glen Rose Limestone</td><td>Upper Member</td><td rowspan="7">Trinity Aquifer System</td><td>Upper Trinity</td><td>Layer 2</td></tr>
<tr><td>Lower Member</td><td rowspan="3">Middle Trinity</td><td rowspan="3">Layer 3</td></tr>
<tr><td colspan="2">Hensel Sand/Bexar Shale</td></tr>
<tr><td colspan="2">Cow Creek Limestone</td></tr>
<tr><td colspan="2">Hammett Shale</td><td>Confining unit</td><td></td></tr>
<tr><td colspan="2">Sligo Formation</td><td rowspan="2">Lower Trinity</td><td rowspan="2">Layer 4</td></tr>
<tr><td colspan="2">Sycamore Sand/Hosston Formation</td></tr>
<tr><td colspan="3">Paleozoic</td><td colspan="2">Undifferentiated Pre-Createaceous rock</td><td colspan="2"></td><td></td></tr>
</table>

Figure 11-3. Stratigraphic and hydrostratigraphic column of the Hill Country area. Modified from Jones and others (2011).

MODFLOW requires parameters to be defined at each cell either individually or in zones of uniform values. For the Bandera well longevity model, prior to calibration we started with the calibrated values of the flow and the storage parameters of the Hill Country Trinity GAM. Jones and others (2011) reported their post calibration values of hydraulic conductivity, and these are listed in Table 11-2. During calibration a new hydraulic conductivity zone (zone 9) was added in the layer 4 and it was assigned a horizontal hydraulic conductivity value of 0.1 feet per day (Figure 11-4). This zone was added to address observed water level anomalies in the City of Bandera area. Due to the lack of detailed data, the new hydraulic conductivity zone was delineated using the Thiessen polygon method, which depends on the spatial distribution of wells. The method involves creating a polygon around each well point so that each polygon is bounded at half the distance to the nearest well in all directions. Starting values of vertical hydraulic conductivity for calibration were assigned as one-tenth of the horizontal hydraulic conductivity.

Table 11-2. Hydraulic conductivity values in feet per day used in the Hill Country Trinity GAM and starting values for the Bandera well longevity model prior to calibration.

Layer	Hydraulic conductivity
Edwards Group	11
Upper Trinity aquifer	9 to 150
Middle Trinity aquifer	7.6 to 15
Lower Trinity aquifer	1.67 to 16.7

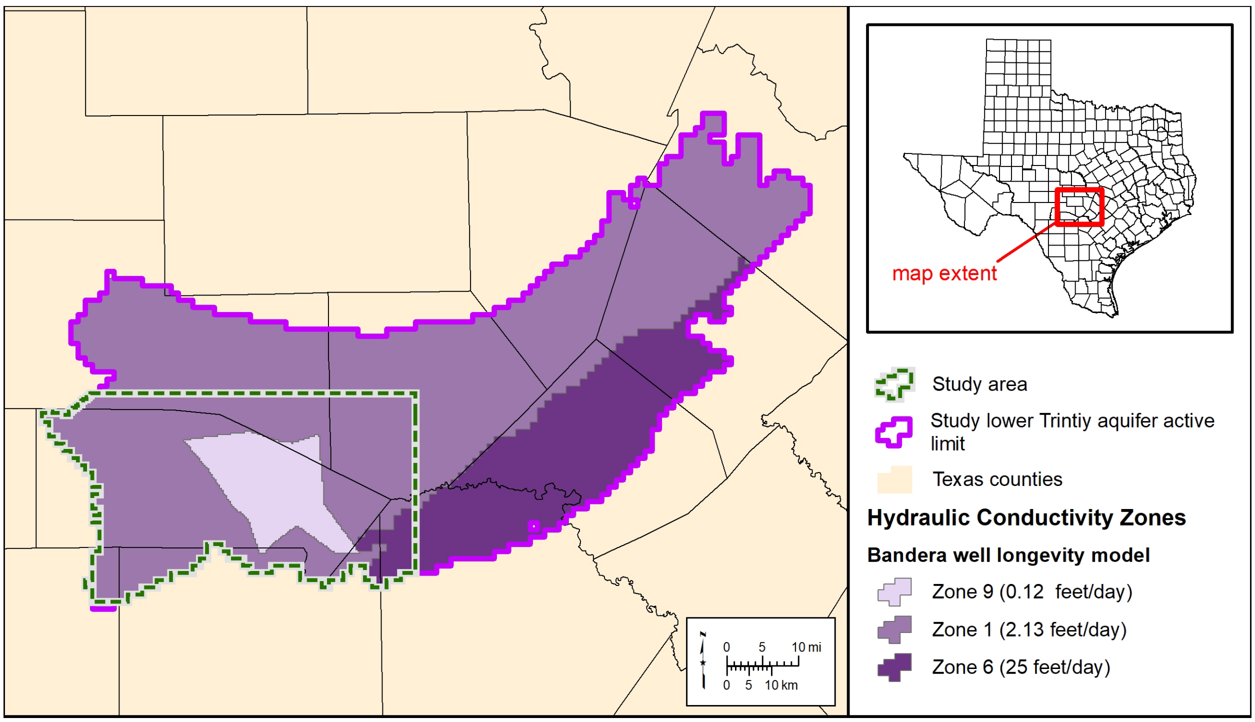

Figure 11-4. Spatial distributions of the calibrated hydraulic conductivity zones in the lower Trinity aquifer (layer 4).

The Hammett Shale was not simulated as a separate confining layer in the Bandera well longevity model. Jones and others (2011) simulated groundwater flow through the Hammett shale with vertical leakance, which simulates vertical flow through confining units when horizonal hydraulic conductivity is assumed to be negligible. For the Bandera well longevity model, we simulated the presence of the Hammett shale unit by controlling the vertical hydraulic conductivities of both the middle Trinity and the lower Trinity aquifers to limit the communication between the units.

For storage parameters, Jones and others (2011) reported uniform values of specific storage (confined aquifers) and specific yield (unconfined aquifers) in each layer. The Bandera well longevity model assigned post-calibration specific-storage values from Jones and others (2011) as pre-calibration values for the parameter. These values were 10^{-5}, 10^{-6}, 10^{-7}, and 10^{-7} per foot in for the Edwards Group, and upper, middle and lower Trinity aquifers, respectively. In addition, calibration was started with post-calibration assigned specific-yield values of 0.008, 0.0005, 0.0008, and 0.0008 (unitless) from Jones and others (2011) for the Edwards Group, and upper, middle, and lower Trinity aquifers, respectively. Finally, transmissivity and storativity were not assigned in the Bandera well longevity model; they were calculated internally by MODFLOW based on the above-mentioned parameters and saturated thicknesses. All the model parameters were imported into Groundwater Vistas (Rumbaugh and Rumbaugh, 2020) for the Bandera well longevity model as shapefiles prepared using ESRI ArcMap 10.7®.

11.4 Boundary conditions

Boundary conditions are values and locations of external factors (physical and hydraulic) in the model domain that define groundwater flow into or out of the aquifer. Jones and others (2011) simulated the following boundary conditions in the Hill Country Trinity GAM: (1) recharge, (2) rivers and streams, (3) reservoirs, (4) outer model boundaries, and (5) pumping. These boundary conditions are consistent with the natural hydrogeologic boundaries of the Hill County portion of the Trinity Aquifer and the Edwards Aquifer, including the Balcones Fault Zone.

We applied several changes to the boundary conditions in the Bandera well longevity model. The boundary condition values assigned throughout the Hill Country Trinity GAM's stress periods were maintained. In addition, we extrapolated the boundary condition values of the Bandera well longevity model's new stress periods from the Hill Country Trinity GAM values for streams, drains, general head boundaries, and pumping boundary conditions in layers one through three. We extended the spatial distribution of the general head boundaries to reflect the new outer boundaries of the Bandera well longevity model active area, this was necessary because the Robinson and others (2022) surfaces did not extend as far as the Hill country Trinity GAM on the north and northwest boundaries. Lastly, we updated the lower Trinity pumping for the period of 1998 to 2018 based on use reported in the TWDB Water Use Survey (TWDB, 2021c), the BCRAGD records (BCRAGD, 2021), and the TCEQ (TCEQ, 2021) database.

11.4.1 *Recharge, rivers, drains, and general head boundaries*

Jones and others (2011) simulated and calibrated three main recharge zones in the Hill Country Trinity GAM. First, the Balcones Fault Zone was assigned a recharge rate of five percent of annual precipitation. In addition, the Recharge along Cibolo Creek was assigned a recharge rate of about 70,300 acre-feet per year, which is equivalent to the streamflow losses. Finally, the rest of the model area was assigned a recharge rate of 3.5 percent of the annual precipitation. The Bandera well longevity model maintains the recharge values used in Jones and others (2011).

Rivers and drains are the MODFLOW packages used to simulate the surface water features in the Hill Country Trinity GAM. The MODFLOW general head boundary package was used to represent the hydraulic boundary conditions of the model's outer boundaries as well as the Balcones Fault Zone. MODFLOW requires a set of input data for each cell of these boundary conditions. These data are head values (water level elevation), location (defined by layer and node number for MODFLOW-USG), starting and ending stress periods (duration of the active boundary condition), and a conductance term. Conductance is a measure of the ability to transmit flow in or out of the boundary, computed as the boundary width times boundary length times hydraulic conductivity of the boundary bed material divided by the boundary bed thickness (Rumbaugh and Rumbaugh, 2020).

The MODFLOW river and the drains packages differ in how they simulate communication between the aquifer and the boundary. The river package allows flow in and out of the aquifer based on the water stage, whereas the drain package allows only flow out of the aquifer even if the drain water levels are higher, in which case the drain condition becomes inactive (Rumbaugh and Rumbaugh, 2020). Jones and others (2011) discussed the design approach of the Hill Country Trinity GAM of simulating lakes in the study area using the river package. These lakes are Medina Lake, Canyon Lake, Lake Travis, and Lake Austin. The assigned river package datasets per cell were: 1 mile (cell size) length, estimated width per lake, and riverbed vertical hydraulic conductivity of 0.1 feet per day and thickness of 1 foot. For hydraulic heads, an average of each lake's level elevations was assigned to the respective river package cells. Level averages were obtained from the Lower Colorado River Authority, the U.S Army Corps of Engineers, and the U.S. geological survey for Lake Travis, Canyon Lake and Medina Lake, respectively (Jones and others, 2011). These boundary conditions were considered active throughout all stress periods.

The drain package was used to simulate rivers and springs in the Hill Country Trinity GAM area because the river package could allow overestimated baseflow into the aquifer which may not reflect actual conditions due to pumping and droughts (Jones and others, 2011). Conductance term, cell size and vertical hydraulic conductivity of the drain package were similar to the river package. Additionally, the drain package was used to simulate springs in the Hill Country Trinity study area. Lakes and rivers are located in the top three layers of the Bandera well longevity model.

The outer boundaries of the model delineate the active area of the model's domain, whether it is defined by a physical feature (e.g., fault zones and surface water bodies) or a hydraulic approximation due to the absence of physical boundaries. The convention in groundwater modeling is to assign no flow boundaries to the cells in contact with units of at least two orders of magnitude lower hydraulic conductivity (Anderson and others, 2015). An example of a no-flow boundary condition is at the bottom of the Hill Country Trinity GAM where the Hosston Formation sandstone is in contact with pre-Cretaceous shale. It is also acceptable to place a no-flow boundary at the perimeter of the model's active area where no physical boundary is present so long as it is far away from the interest area of the model and the hydraulic conditions at the boundary do not affect the head levels within it. Jones and others (2011) used a general head boundary to delimit the Hill Country Trinity GAM study area where the use of a no-flow boundary was not appropriate. A general head boundary allows flow into or out of the aquifer based on a regional hydraulic gradient. For the Bandera well longevity model, a general head boundary was assigned to the new perimeter of the study area resulting from the overlap between the Hill Country Trinity GAM and Robinson and others (2022) study active area discussed in Section 11.2. This is located mainly in the north-western edge of all the layers, as well as the northern boundary of layer 4 (Figure 11-5). We used simulated head values from the Hill Country Trinity GAM for the 1997 stress period for the new general head boundary cells, and we used a conductance of 500 square feet per day, which is 50 percent of the conductance assigned for the general head boundary in the Balcones Fault Zone. This value changed after calibration to

1500 and 25 square feet per day for the 1-mile and the 0.25-mile cells, respectively. We set this boundary condition active throughout new stress periods.

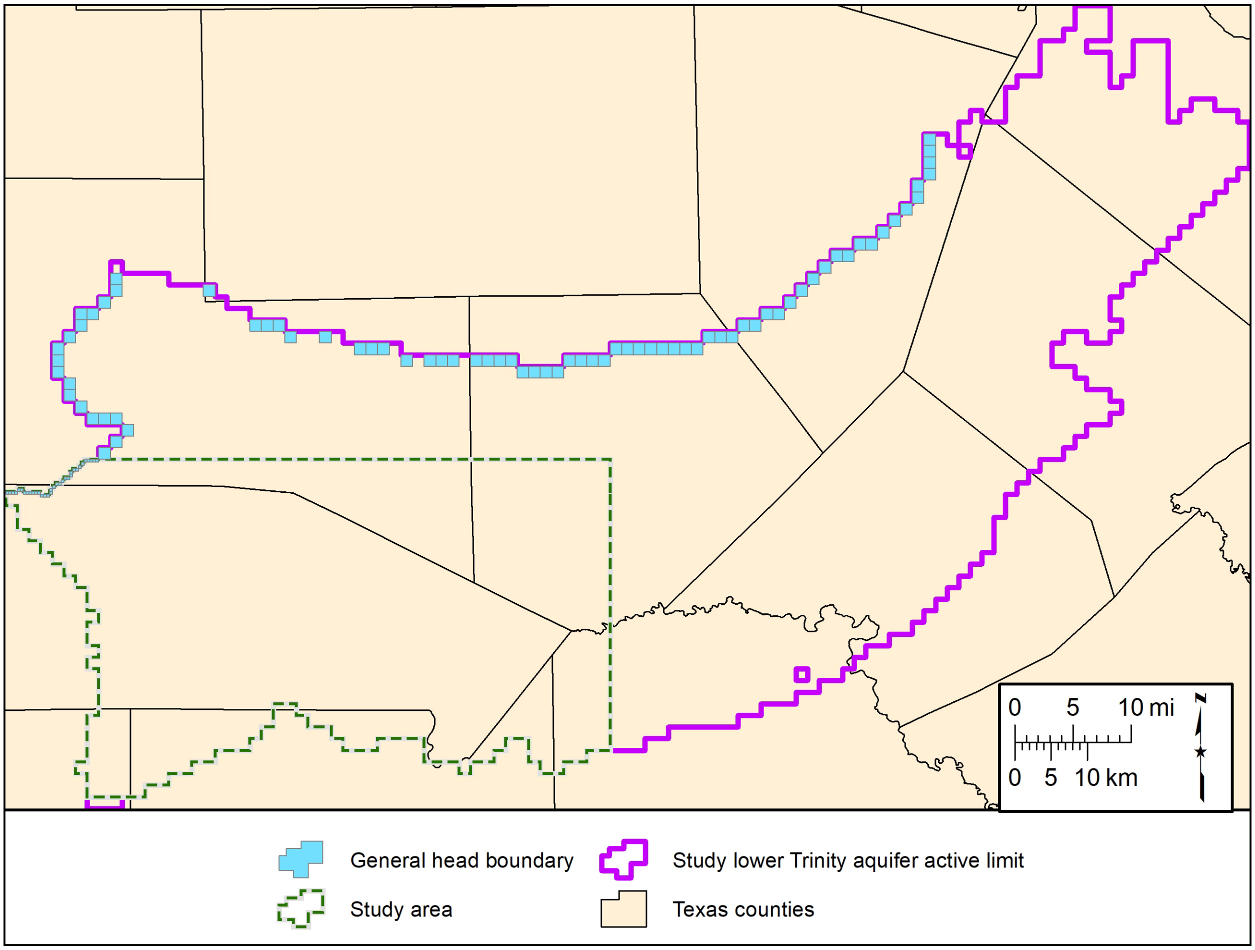

Figure 11-5. The general head boundary in the Bandera well longevity model lower Trinity aquifer layer.

The parameters used for lakes, rivers and drains and the general head boundary in the Hill Country Trinity GAM stress periods were maintained, and head values were linearly extrapolated for the 21 new stress periods. For all the boundary condition cells within the nest grid area, conductance values were adjusted to reflect the new cell size of 0.25 mile.

11.4.2 *Pumping*

The Bandera well longevity model pumping boundary condition was developed specifically in lower Trinity aquifer (layer 4) to meet the study objective of assessing the longevity of the City of Bandera public water supply wells. Jones and others (2011) simulated pumping effects on groundwater levels in the region for the water use categories of municipal, rural domestic, industrial, livestock and irrigation from 1980 to 1997. For the Bandera well longevity model, the Hill Country Trinity GAM pumping over the 21 new stress periods was extrapolated for Edwards Group, upper Trinity aquifer, and middle Trinity aquifer. Table 11-3, Table 11-4, and Table 11-5 summarize pumping from 1998 to 2018 for model layers 1, 2, and 3, respectively, for the counties of the study area.

Table 11-3. Edwards Group total pumping (acre-feet per year) per county.

Year	Counties			
	Bandera	Gillespie	Kendall	Kerr
1998	105	274	132	659
1999	105	282	126	671
2000	107	287	129	684
2001	110	293	132	696
2002	113	298	135	708
2003	116	303	138	720
2004	119	308	141	732
2005	121	313	144	744
2006	124	318	147	756
2007	127	323	150	768
2008	130	328	152	781
2009	132	333	155	793
2010	135	338	158	805
2011	138	343	161	817
2012	141	348	164	829
2013	144	354	167	841
2014	146	359	170	853
2015	149	364	173	865
2016	152	369	176	877
2017	155	374	179	890
2018	157	379	182	902

Table 11-4. Upper Trinity aquifer total pumping (acre-feet per year) per county.

Year	Counties										
	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Medina	Travis	Uvalde
1998	1,079	849	277	445	297	1,157	1,063	1,937	54	121	13
1999	1,105	855	303	461	317	1,090	866	1,936	54	128	13
2000	1,131	869	313	470	321	1,115	883	1,973	55	131	13
2001	1,156	883	323	479	325	1,140	901	2,010	55	133	13
2002	1,182	897	333	488	329	1,166	918	2,047	56	136	13
2003	1,185	911	343	497	333	1,192	935	2,084	57	138	14
2004	1,208	925	353	506	337	1,219	953	2,121	57	141	14
2005	1,234	939	363	516	342	1,245	970	2,159	58	143	14
2006	1,260	953	374	525	346	1,272	988	2,196	59	146	14
2007	1,285	967	384	534	350	1,299	1,005	2,233	59	148	14
2008	1,311	981	394	543	354	1,325	1,022	2,270	60	151	14
2009	1,337	995	404	552	358	1,352	1,040	2,307	60	153	14
2010	1,363	1,009	414	561	362	1,379	1,057	2,344	61	156	14
2011	1,388	1,023	424	570	366	1,406	1,075	2,381	62	158	14
2012	1,414	1,037	434	579	370	1,433	1,092	2,418	62	161	14
2013	1,440	1,051	444	588	375	1,461	1,109	2,455	63	163	14
2014	1,466	1,065	454	597	379	1,488	1,127	2,492	64	166	15
2015	1,492	1,079	464	606	383	1,515	1,144	2,529	64	168	15
2016	1,517	1,093	475	615	387	1,542	1,162	2,566	65	170	15
2017	1,543	1,107	485	624	391	1,570	1,179	2,603	66	173	15
2018	1,569	1,121	495	634	395	1,597	1,196	2,640	66	175	15

Table 11-5. Middle Trinity aquifer total pumping (acre-feet per year) per county.

Year	Counties									
	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Medina	Travis
1998	261	1,248	166	621	1,531	1,494	2,431	617	0	5
1999	275	1,313	171	573	1,450	1,462	2,022	596	0	5
2000	283	1,355	176	586	1,505	1,502	2,090	601	0	5
2001	290	1,397	182	599	1,560	1,543	2,158	606	0	5
2002	298	1,439	188	613	1,615	1,583	2,225	610	0	5
2003	305	1,482	193	628	1,670	1,624	2,293	615	0	6
2004	313	1,524	199	642	1,725	1,664	2,360	620	0	6
2005	320	1,566	205	656	1,779	1,705	2,428	624	0	6
2006	328	1,608	210	670	1,834	1,746	2,496	629	0	6
2007	335	1,650	216	684	1,889	1,788	2,563	634	0	6
2008	343	1,692	222	699	1,944	1,829	2,631	638	0	6
2009	350	1,735	227	713	1,999	1,870	2,698	643	0	6
2010	357	1,777	233	727	2,054	1,911	2,766	648	0	6
2011	365	1,819	239	742	2,108	1,952	2,833	652	0	6
2012	372	1,861	244	756	2,163	1,994	2,901	657	0	6
2013	380	1,903	250	771	2,218	2,035	2,969	662	0	6
2014	387	1,945	256	786	2,273	2,076	3,036	666	0	6
2015	395	1,988	261	800	2,328	2,118	3,104	671	0	7
2016	402	2,030	267	815	2,383	2,159	3,171	676	0	7
2017	410	2,072	273	830	2,437	2,201	3,239	680	0	7
2018	417	2,114	278	845	2,492	2,242	3,307	685	0	7

Lower Trinity aquifer pumping values from 1998 through 2018 were estimated based on annually reported groundwater consumption in the TWDB Water Use Survey (TWDB, 2021c). Municipal and irrigation water use groups were the largest in the study area. These use groups were considered in Bandera County and in five other counties: Bexar, Comal, Hays, Kendall, and Kerr. Municipal use was assigned based on known public water supply well locations after cross referencing key information from different sources with the municipal entities' names on the Water Use Survey. These sources are:

- TWDB Groundwater Database (TWDB, 2021a)
- TWDB Brackish Resources Aquifer Characterization System (BRACS) Database (TWDB, 2021b)
- Texas Department of Licensing and Regulation State Driller Reports Database (TWDB, 2021d)
- TCEQ Database (TCEQ, 2021), and
- Bandera County River Authority and Groundwater District Database (BCRAGD, 2021)

The key information used were entity, owner, well names, well locations, well depth, and drilled dates. Table 11-6 lists the lower Trinity aquifer municipal use per county in the study area from 1998 to 2018.

Table 11-7 and Table 11-8 detail the considered municipal entities in Bandera County and their lower Trinity aquifer use reported during simulation time. The lower Trinity aquifer municipal use per each entity is divided by the number of the lower Trinity wells identified for each entity. For the City of Bandera, the percent contribution of each of the three lower Trinity wells was based on current production volumes, to assign municipal use to the respective cells. Figure 11-6 shows the public water supply wells used to create municipal pumping cells in Bandera County. Table 11-9 lists the public water supply wells matched to entities from the Water Use Survey in Bandera County and synonymous IDs and names for the wells used by TWDB and Texas Department of Licensing and Regulation (TDLR), as available.

Table 11-6. Lower Trinity aquifer municipal water use (acre-feet per year) per county.

Year	Counties					
	Bandera	Bexar	Comal	Hays	Kendall	Kerr
1998	372	490	67	295	202	350
1999	372	490	71	295	202	350
2000	374	515	80	295	242	350
2001	369	550	101	367	245	231
2002	296	571	76	235	245	282
2003	333	589	80	393	251	174
2004	303	571	86	364	233	422
2005	323	654	87	393	301	259
2006	320	684	88	405	284	865
2007	319	334	391	259	256	832
2008	347	623	450	347	234	1,286
2009	359	674	467	453	206	1,031
2010	428	771	438	394	221	756
2011	433	1,039	427	568	214	1,437
2012	469	1,285	480	338	217	1,637
2013	427	1,178	386	370	190	1,230
2014	410	1,059	243	354	205	1,264
2015	424	2,270	298	296	215	1,389
2016	472	3,332	248	344	216	731
2017	432	2,529	324	386	221	859
2018	443	2,391	397	493	217	848

Table 11-7. **Bandera County lower Trinity aquifer municipal water use (acre-feet per year) per entity from 1998 to 2007.**

Entity name	Year									
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Aqua Texas Inc-Blue Medina water	-	-	-	-	-	-	-	-	10	10
Aqua Texas Inc-Blue Medina water	-	-	-	-	-	-	-	-	-	-
Bandera County Justice Center	-	-	-	-	-	-	-	-	-	-
Bandera Falls Water Subdivision	28	28	28	6	5	25	2	2	2	2
Bandera ISD	-	-	2	3	3	4	4	5	6	5
Bandera River Ranch # 1	-	-	-	-	-	-	-	-	-	-
Bridlegate Ranch Subdivision	286	286	286	311	244	244	244	244	237	237
City of Bandera	3	3	3	3	3	3	3	3	3	3
Comanche Cliffs Aqua Source	-	-	-	-	-	-	-	6	6	6
Enchanted River Estates	22	22	22	13	11	12	12	16	18	17
Flying L. PUD	-	-	-	-	-	-	-	-	-	-
Latigo Ranch Subdivision	33	33	33	33	30	45	38	47	48	39
Medina WSC	-	-	-	-	-	-	-	-	-	-

Notes: Inc.= Incorporation. ISD= Independent School district. PUD= Public Utility District. WSC= Water Services Corporation.

Table 11-8. Bandera County lower Trinity aquifer municipal water use (acre-feet per year) per entity from 2008 to 2018.

Entity name	Year										
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Aqua Texas Inc-Blue Medina water	10	10	11	11	9	9	8	10	9	9	9
Bandera County Justice Center	-	-	-	-	-	-	-	-	-	-	-
Bandera Falls Water Subdivision	-	-	-	-	-	-	-	-	-	-	-
Bandera I.S.D	4	4	4	7	3	23	25	31	31	31	31
Bandera River Ranch # 1	7	7	18	18	22	23	23	21	18	20	27
Bridlegate Ranch Subdivision	-	-	-	7	14	20	7	27	27	27	36
City of Bandera	267	267	267	267	267	253	238	224	268	229	231
Comanche Cliffs Aqua Source	3	3	13	13	13	13	13	11	14	13	13
Enchanted River Estates	-	-	37	18	18	18	18	22	18	18	16
Flying L. PUD	19	17	34	34	42	28	34	27	30	34	35
Latigo Ranch Subdivision	-	-	-	-	-	1	-	4	6	6	7
Medina WSC	37	51	44	58	81	39	44	47	51	45	38

Notes: Inc.= Incorporation. ISD= Independent School district. PUD= Public Utility District. WSC= Water Services Corporation.

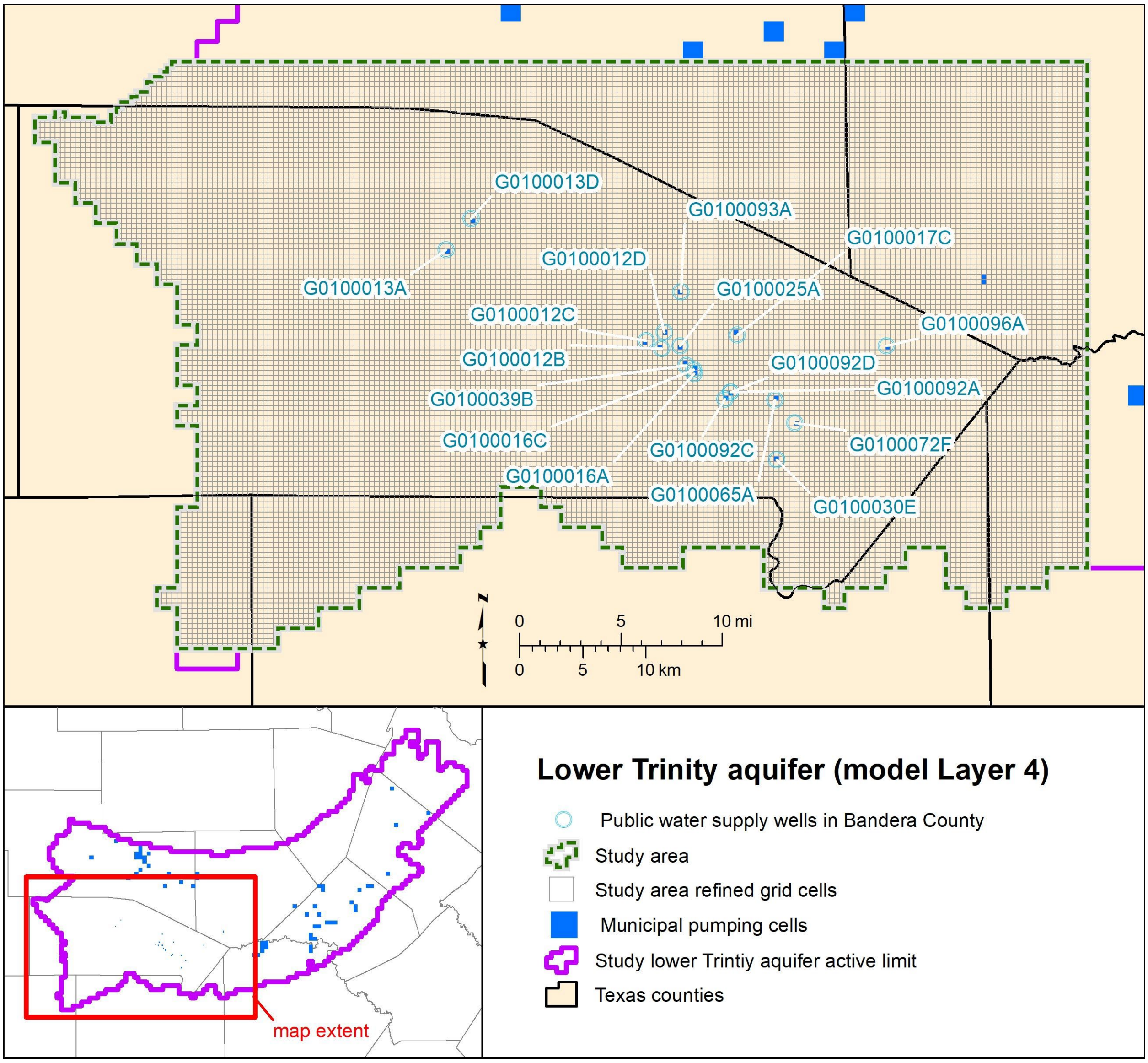

Figure 11-6. Municipal use pumping cell distribution in lower Trinity aquifer layer of the Bandera well longevity model. Public water supply wells used for the model in Bandera County are labeled with TCEQ facility IDs (TCEQ, 2021).

Table 11-9. Bandera County municipal wells used in the Bandera well longevity model.

Entity name	Well number	Well ID	SWN	Tracking	PWS	Permit	Drill date	Well depth (feet)
Aqua Texas, Inc. Blue Medina Water	Well #5 Rio Ranchero Rd.	100857	6817726	181909	G0100030E		8/4/2006	555
Bandera County Jail & Justice Center	Well #1 - HWY 173	101390	6916807	145379	G0100093A	P-1074	6/16/2008	810
Bandera Falls Water Subdivision	Well #6 Red Bud Ln.	101391	0	173775	G0100072F	P-1075	3/4/2009	900
Bandera I.S.D.	Well #1 HWY 16, Enchanted River	94219	6924211	0	G0100025A		9/30/1976	1160
Bandera River Ranch #1	Well #3	94222	6924308	0	G0100017C	P-1072	7/13/2000	1000
Bridlegate Ranch Subdivision	Well #3 Highgate Dr/ Bridle Chase	88036	6924609	104538	G0100092C	P-1049	12/17/2006	940
Bridlegate Ranch Subdivision	Well #1 High Gate Dr.	88393	6924607	138759	G0100092A	P-1058	4/24/2006	990
Bridlegate Ranch Subdivision	Well #4 Highgate Dr./ Palomino Springs	88394	6924610	215208	G0100092D		5/14/2007	580
City of Bandera	Well #4 Mulberry St.	52986	6924202	0	G0100012B	P-1134	8/20/1953	898
City of Bandera	Well #6 Indian Waters	58742	6924221	0	G0100012D	P-1135	9/24/1998	865
City of Bandera	Well #5 Dallas St.	88432	6924102	0	G0100012C	P-1133	4/17/1967	805
Comanche Cliffs Aqua Source	Well #1 Comanche path/ Eagle feather	88039	6817402	0	G0100065A		10/10/1984	704
Enchanted River Estate	Well #2 114 Chapparal Ct.	94221	6924226	66015	G0100039B	P-1032	8/14/2005	800
Flying L. Ranch P.U.D.	Well #1 Driving Range	52982	6924208	0	G0100016A		6/18/1972	790
Flying L. Ranch P.U.D.	Well #3 Runway	100900	6924220	0	G0100016C		3/26/1998	815
Latigo Ranch Subdivision	Post Oak Development	87893	6817304	111566	G0100096A		12/5/2006	1030
Medina WSC Well	Well #4 Stringtown Road	100856	6915404	138774	G0100013D		2/27/2004	940
Medina WSC Well	Well #1 Finch St.	100902	6914601	0	G0100013A		6/1/1967	819

Notes: Well ID is the BRACS well identification number. SWN= State Well Number. Tracking is the TDLR tracking number. PWS is TCEQ Public Water Supply umber. Permit is the BCRAGD permit number

Irrigation use estimates reported in the water use survey per county for the Trinity Aquifer were also considered. Irrigation estimates in the water use survey are based on a comprehensive statewide dataset collection through a collaboration between the TWDB and the U.S. Department of Agriculture's Farm Service Agency and the TCEQ. Groundwater irrigation values are computed as the residual of the county totals not attributed to either surface water or wastewater reuse. The percentage of lower Trinity irrigation use was estimated as a fraction of the overall Trinity aquifer irrigation wells for each county individually. This was based on collected data from the TWDB Groundwater Database, BRACS Database, and the TDLR Submitted Driller's Reports Database. Table 11-10 summarizes the irrigation values used in the Bandera well longevity model from 1998 to 2018 per county. We used the same spatial distribution of irrigation use as the Hill Country Trinity GAM, which was based on land use and land cover 1:250,000-scale maps obtained from the U.S. Geological Survey (Jones and others, 2011). Considered land classifications were orchards, row crops, or small grains (Figure 11-7). Irrigation cells in Hays and Kendall counties were added based on the irrigation wells we found in the above-mentioned databases.

BCRAGD reviewed the data we collected and provided reported use in their records. In addition, we verified municipal use values in Bandera County against the TCEQ reported average consumption. ESRI ArcGIS 10.7® was used for the update and preparation of the values and spatial distribution of all the boundary conditions files.

Table 11-10. Irrigation pumping (acre-feet per year) in Trinity Aquifer (T) and the lower Trinity aquifer (LT).

Year	Counties											
	Bandera		Bexar		Comal		Hays		Kendall		Kerr	
	T	LT	T	LT	T	LT	T	LT	T	LT	T	LT
1998	56	28.76	0	0	11	2.49	0	0	808	122.42	396	103.71
1999	56	28.76	0	0	9	2.03	0	0	808	122.42	396	103.71
2000	325	166.92	600	230.74	13	3.03	6	0.7	286	43.33	107	28.02
2001	263	131.43	663	236.79	14	3.17	9	0.98	726	110	113	29.6
2002	263	131.43	976	325.39	21	4.63	9	1.19	726	110	113	27.62
2003	161	78.51	446	106.3	44	10.66	63	8.25	131	18.19	77	18.82
2004	266	121.06	559	133.17	61	16.12	79	9.58	115	15.97	47	10.77
2005	246	98.79	571	114.21	24	6.32	89	9.46	135	18.75	76	17.42
2006	284	112.92	611	113.23	293	78	153	19.04	138	19.17	120	24.44
2007	365	125.95	233	41.53	100	27.25	776	98.05	113	15.69	133	26.54
2008	374	110.62	434	58.67	169	48.68	454	59.22	12	1.67	73	14.57
2009	888	263.8	1148	139.99	238	54.44	463	58.41	736	102.22	246	51.25
2010	887	247.94	548	61.19	98	21.47	416	53.44	543	75.42	420	87.5
2011	1396	390.23	694	66.21	189	40.21	559	72.22	824	98.1	275	51.76
2012	824	230.33	843	69.18	127	26.06	413	52.07	575	63.89	431	73.01
2013	778	218.67	601	45.31	100	21.23	290	35.7	477	56.12	1011	171.25
2014	797	234.78	459	32.4	71	14.43	393	46.94	211	22.21	1417	240.02
2015	578	168.24	475	30.39	103	19.46	165	19.28	250	28.13	570	96.55
2016	656	191.62	511	32.29	157	28.93	268	30.05	181	20.36	373	63.18
2017	788	229.33	657	40.62	148	29.39	236	28.63	221	23.68	1423	233.26
2018	1626	473.21	599	36.99	176	35.07	263	31.94	228	24.43	983	171.71

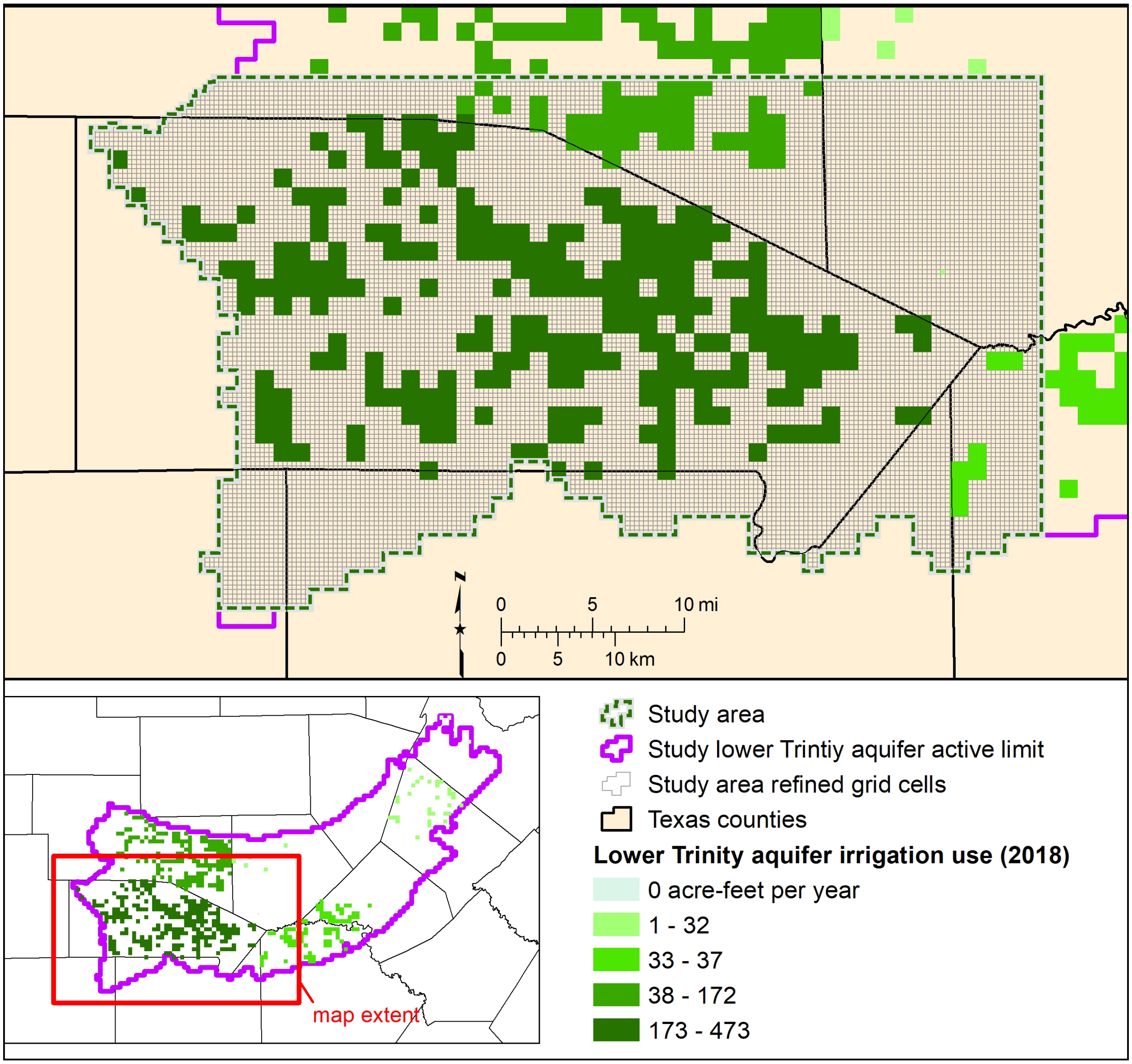

Figure 11-7. 2018 irrigation use (acre-foot per year) applied in the Bandera well longevity model layer 4, the lower Trinity aquifer.

11.5 Initial conditions

Initial conditions are defined as cell's specified water level at the beginning of the simulation. Defining the initial conditions is a requirement of a transient model. In practice, the initial heads of a transient model are usually the generated heads of a steady state model or another transient model. The initial conditions of the 1980 steady state stress period in the Hill Country Trinity GAM were calibrated to the 1977 to 1985 conditions as mentioned previously. For the Bandera well longevity model, a first run of the model using the top of layer one elevation as the initial heads was performed. The resulting head of the first stress period (steady-state period) was then imported as the initial heads for the model.

11.6 Modeling approach

Models are developed to represent the behavior of a system under external and internal influences, to predict the future conditions of the system, or for both purposes. In both cases, the model results should match the historic observations of the system. In most cases, models require calibration to achieve a close match between modeled and observed water levels. A good match produces the smallest average difference between modeled and observed water levels (i.e., close to zero). Practically, field measurements (observations) of water levels hold a higher degree of confidence compared to the estimated model parameters (aquifer properties). Therefore, calibration adjusts the model's parameters within a predetermined acceptable range given the aquifer type and makeup to meet the calibration objective. This section discusses calibration of the Bandera well longevity model, the scenarios we considered for predicting future water levels in the lower Trinity aquifer in Bandera County, and the application limitations of the numerical modeling method.

11.6.1 *Historical modeling*

As previously mentioned, the Bandera well longevity model was constructed following the same framework as the Hill Country Trinity GAM. Therefore, initial parameters were set to the same starting values as the post-calibration results of the Hill Country Trinity GAM. To calibrate the Bandera well longevity model, over 40,000 water level observations for more than 600 wells (targets) were collected. This data was obtained from the TWDB groundwater database (TWDB, 2021a) as well as records from the Bandera County River Authority and Groundwater District (BCRAGD, 2021). These observations were collected for all four layers throughout the simulation period (1980–2018).

All available targets were examined to create a subset suitable for calibration. Screen intervals were used to determine the model's layer each target represented. Only 149 out of the 600 plus wells collected had available screen information. Wells with cross completion, where two or more layers were screened, were disregarded. For wells with missing screen information, well depth was used to assign layers under the assumption that the well is screened or open at the bottom. Due to the uncertainty associated with this assumption, we assigned weights of 0.5 to these targets to decrease their contribution to the calibration residual. Wells with total depths in layer one and those with available screen information were assigned weights of 1.0 to emphasize confidence in assignment and importance to be matched. Further, a calibration weight of 1.0 was assigned to the subset of targets defined as the lower Trinity aquifer wells after manual inspection. This inspection included reviewing available well data in the TWDB groundwater database (TWDB, 2021a) and TCEQ database (TCEQ, 2021). The lower Trinity aquifer targets included the three City of Bandera public supply wells as well as seven BCRAGD monitoring wells listed in Table 11-11. The spatial distribution of the calibration targets used in the model is shown in Figure 11-8 for the Edwards Group, Figure 11-9 for the upper Trinity aquifer, Figure 11-10 for the middle Trinity Aquifer, and Figure 11-11 for the lower Trinity aquifer.

Finally, we considered only the targets with winter observations of water levels. We averaged winter values for each target with multiple observations per year.

Table 11-11. Bandera County River Authority and Groundwater District monitoring wells.

SWN	Owner name	Well type	Drill year	Well depth	Screen information	Number of target points
6817112	Cielo Rio Ranch, LTD	Unused	2005	760	300-440	9
6817303	Latigo Ranch	Unused	NA	1080	NA	8
6916702	TxDOT	Public Supply	1980	798	Screen (565-640) Open hole (650-798)	10
6924114	Bandera Sports Complex Lower Trinity well	Unused	NA	870	NA	5
6924225	Bandera Co. RA&GCD	Unused	Na	800	NA	11
6924504	Alkek Elementary School	Public Supply	1986	930	Open hole (640-930)	7
6924605	Southerland Comm. High Gate Ranch LTD	Unused	NA	940	NA	9

Notes: SWN = State Well Number. Target points are the available good quality water level measurements (observations).

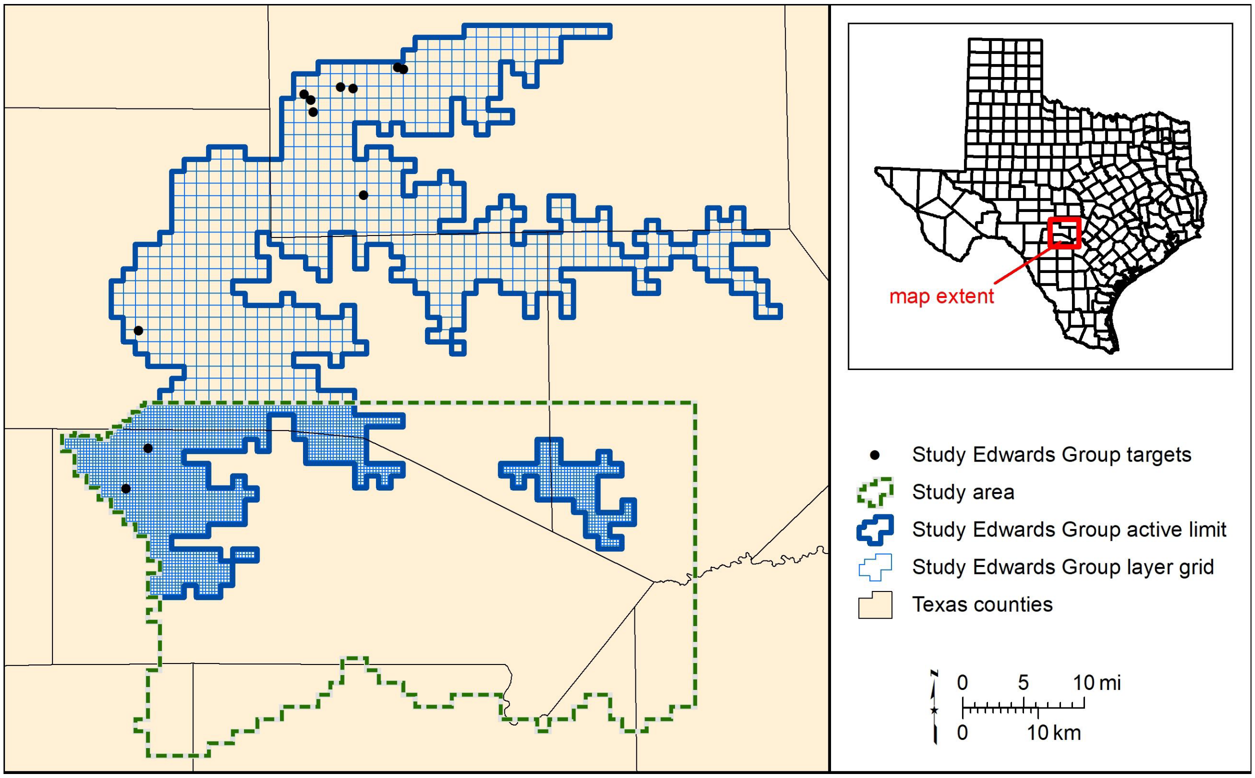

Figure 11-8. **Final set of observation wells in the Edwards Group used for the Bandera well longevity model calibration.**

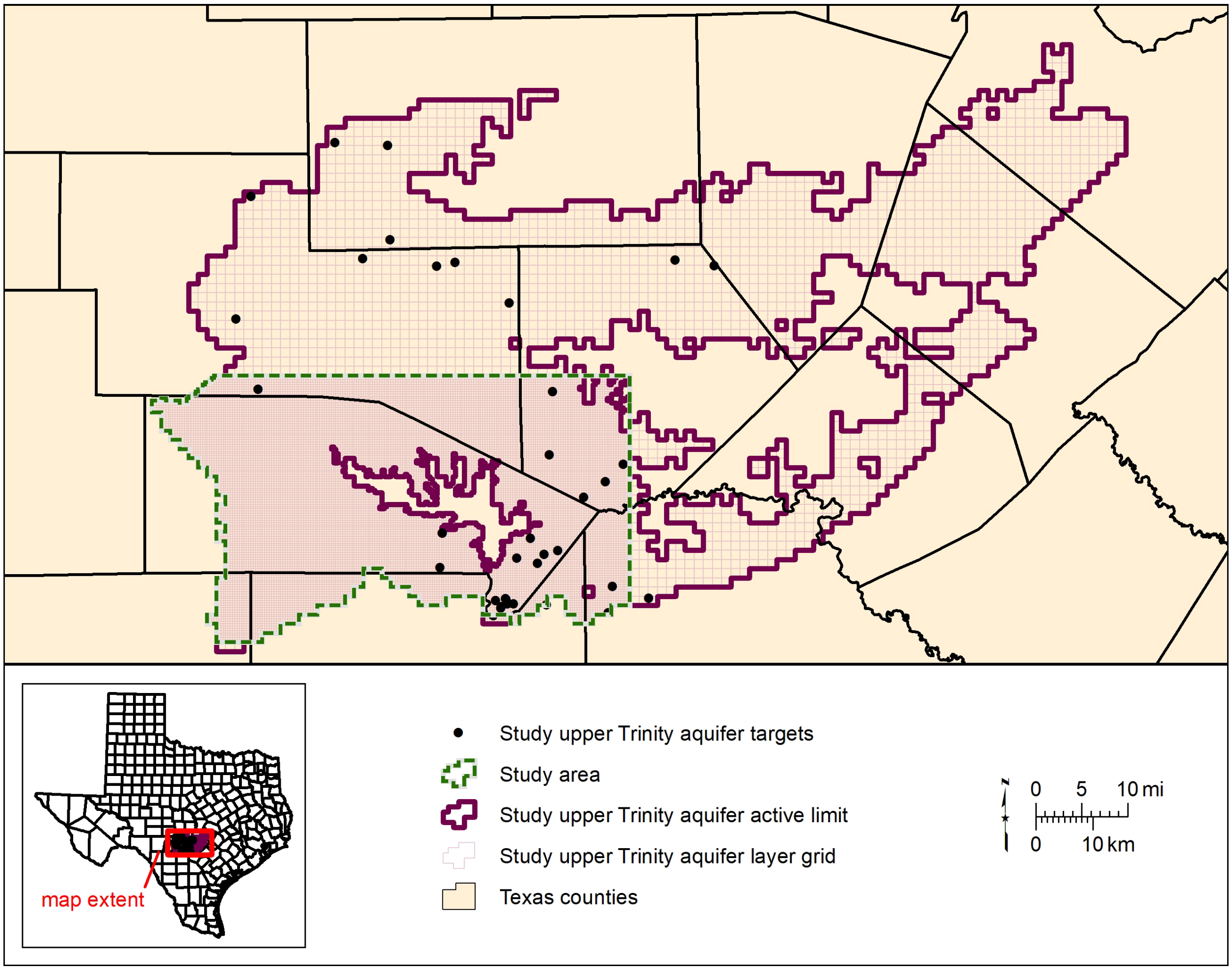

Figure 11-9. Final set of observation wells in the upper Trinity aquifer used for the Bandera well longevity model calibration.

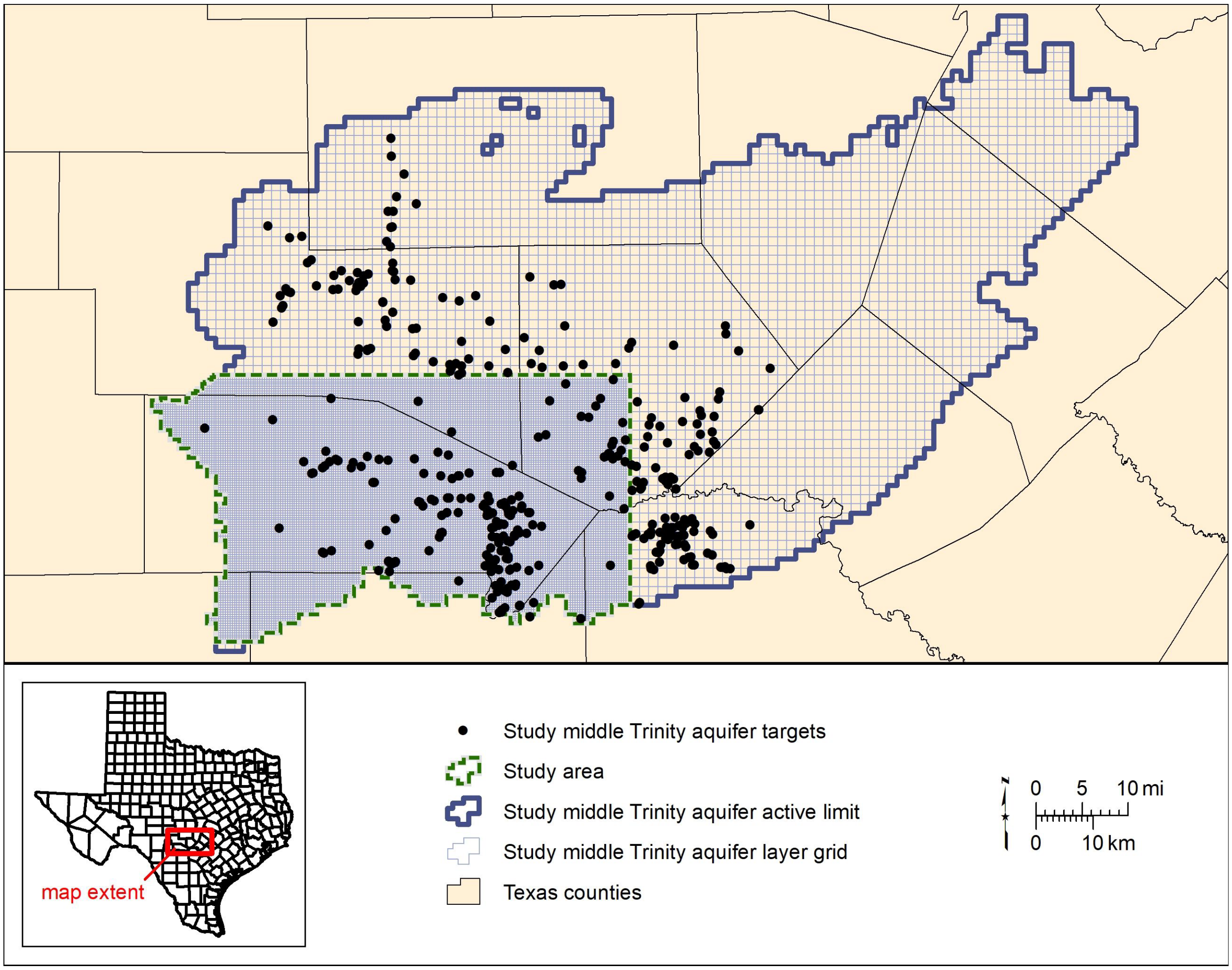

Figure 11-10. Final set of observation wells in the middle Trinity aquifer used for the Bandera well longevity model calibration.

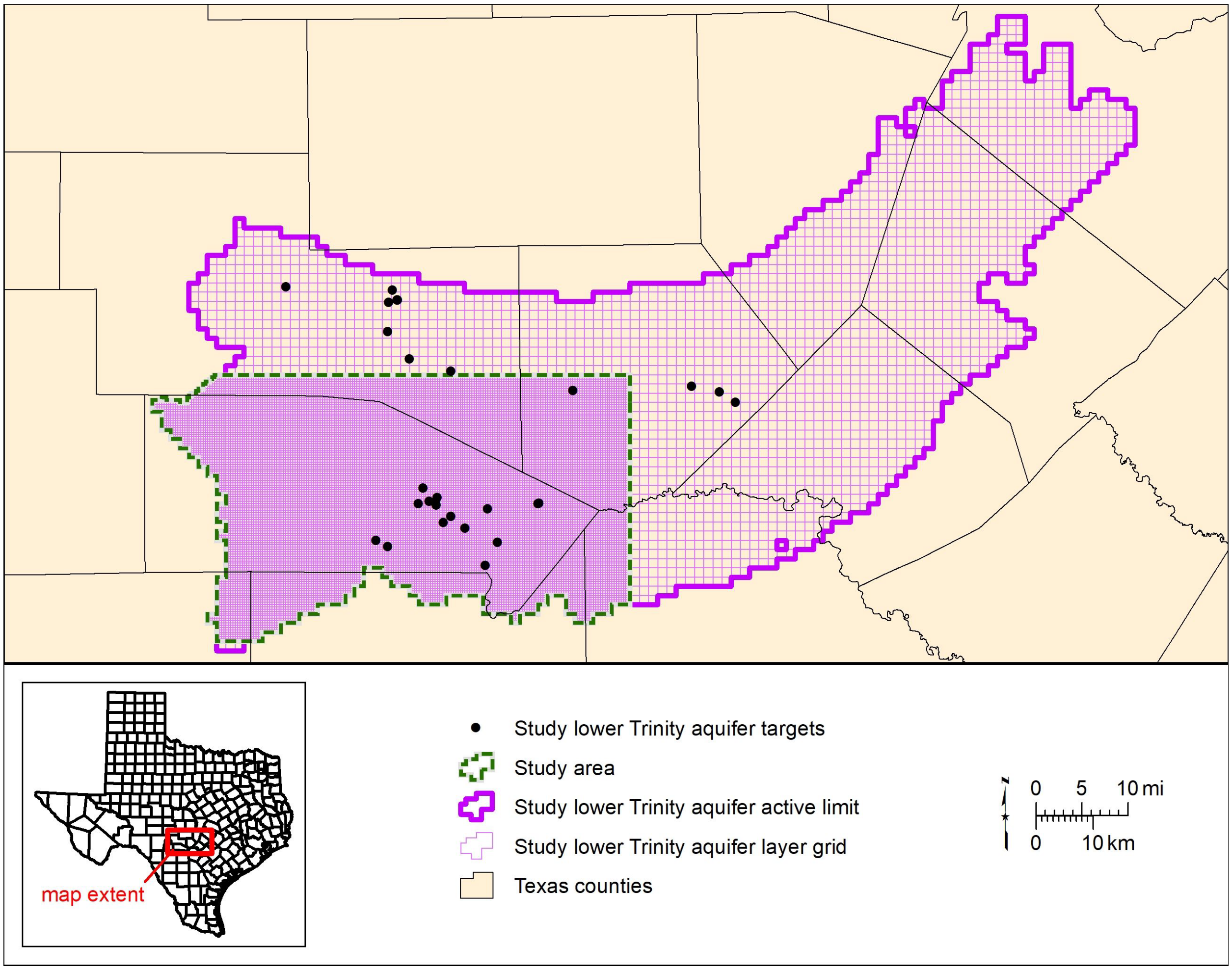

Figure 11-11. Final set of observation wells in the lower Trinity aquifer used for the Bandera well longevity model calibration.

Calibration parameters

Calibration was performed using the Parameter Estimation and Uncertainty Analysis (PEST) software supported by Groundwater Vistas (Doherty, 2010). The parameters identified for calibration adjustment were the hydraulic conductivities (both vertical and horizontal), the storage properties (specific storage and specific yield) in layers 3 and 4, and the conductance term of the general head boundary in layer 4. The vertical hydraulic conductivity controls the inter-flow between the middle and lower Trinity aquifers. Limiting the vertical hydraulic conductivity in layers 3 and 4 simulates the presence of the aquitard (Hammett Shale) in the Bandera well longevity model. As for the conductance term of the general head boundary in layer 4, it was determined that it should be calibrated, since that the boundary is a new structural element that was not part of the calibrated Hill Country Trinity GAM.

Calibration also included the addition of the new hydraulic conductivity zone in layer 4 to address the region of water level anomalies. This region included the City of Bandera's three public supply wells and six of the seven BCRAGD monitoring wells. Due to the lack of detailed data, the new hydraulic conductivity zone was ultimately delineated using the Thiessen polygon method which depends on the spatial distribution of wells. The method involves creating a polygon around each well point so that each polygon is bounded at half the distance to the nearest well in all directions (Figure 11-12). This zone was assigned a low starting hydraulic conductivity value of 0.1 feet per day. This value is reported in Ashworth and others (2009) for the calibrated hydraulic conductivity of the lower Trinity aquifer around the City of Bandera. This value is also reported by Toll and others (2018) as the 25th percentile of all the available hydraulic conductivity values both collected and computed for the entire Hill Country Trinity GAM layer 4 extent. Post calibration parameters values are listed in Table 11-12.

The hydraulic conductivity value for this new low conductivity zone (zone 9) changed slightly after calibration to 0.12 feet per day. The hydraulic conductivity value for the original zones (zones 1 and 6) increased from 1.6 to 2.13 feet per day and from 16 to 25 feet per day, respectively, resulting in a better match for the rest of the wells. The Bandera well longevity model has 21 more stress periods than the Hill Country Trinity GAM and this increase resulted in more available observations for modeled water levels comparison. As for the vertical hydraulic conductivity, the calibrated values are significantly low. However, these values are consistent with reported material properties and reported properties of the Hammett Shale (Toll and others, 2018).

The Bandera well longevity model results showed a higher degree of match with the low observed water levels in this zone after adding the low conductivity zone. The residual mean for the model and the lower Trinity aquifer (layer 4) are 22 and 2.86 feet, respectively. The scaled standard deviation is 7.5 and 9.6 per percent, respectively.

Table 11-12. Parameter values post calibration.

Parameter	Post calibration value
Horizontal hydraulic conductivity (zone 1)	2.14
Horizontal hydraulic conductivity (zone 6)	25
Horizontal hydraulic conductivity (zone 9)	0.103
Vertical hydraulic conductivity (zone 1)	5.00E-08
Vertical hydraulic conductivity (zone 6)	5.00E-08
Vertical hydraulic conductivity (zone 9)	3.99E-09
General head boundary conductance (1-mile cells zone)	1,500
General head boundary conductance (0.25-mile cells zone)	25
Specific storage in layer 3 (middle Trinity aquifer)	1.00E-05
Specific storage in layer 4 (lower Trinity aquifer)	1.88E-06

Notes: Hydraulic conductivity is in feet per day. Conductance is in square feet per day. Specific storage unit is 1/feet.

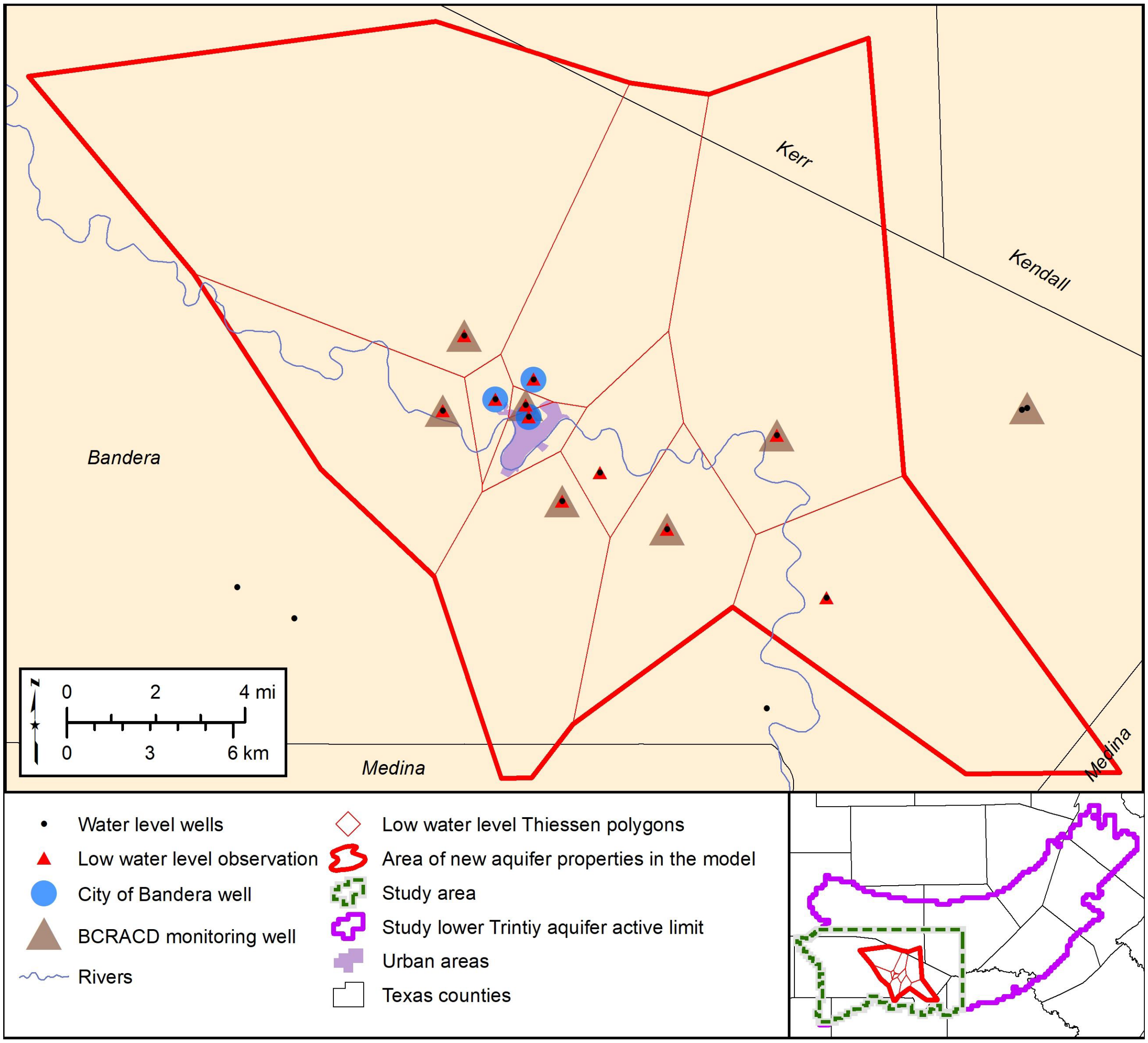

Figure 11-12. The Thessien polygons outlining the low modeled water levels in the the lower Trinity aquifer.

Sensitivity analysis

PEST also provides sensitivity analysis for the parameters used in calibration. Sensitivity analysis measures the effect an incremental variation in a parameter value would cause on the model results (simulated water levels). Variation of insensitive parameters has insignificant effects on model results; therefore, their values can be fixed at the initial values (or a reasonable value) during calibration. A parameter's sensitivity is expressed as the sensitivity coefficient. In practice, sensitive parameters have sensitivity coefficients that are two orders of magnitude greater than insensitive parameters. The sensitivity analysis results for the lower Trinity aquifer parameters considered for calibration are listed in Table 11-13. The results indicate that the lower Trinity aquifer is most sensitive to changes in the horizonal hydraulic conductivity in zone 1. This zone covers most of the layer's area and has most of the observation wells used for calibration. The least sensitive parameter of the lower Trinity aquifer is the conductance parameter of the general head boundary in the 1-mile cells zone.

Table 11-13. Sensitivity analysis results for the lower Trinity aquifer calibrated parameters. Sensitivity coefficient is unitless.

Parameter Name	Sensitivity coefficient
horizontal hydraulic conductivity (zone 1)	1.35
horizontal hydraulic conductivity (zone 6)	3.21E-02
horizontal hydraulic conductivity (zone 9)	0.165
vertical Hydraulic conductivity (zone 1)	0.235
vertical Hydraulic conductivity (zone 6)	0.312
vertical Hydraulic conductivity (zone 9)	3.80E-02
general head boundary conductance (1-mile cells zone)	1.70E-02
general head boundary conductance (0.25-mile cells zone)	6.38E-02
specific storage in layer 3 (middle Trinity aquifer)	0.239
specific storage in layer 4 (lower Trinity aquifer)	0.219

Notes: Sensitivity coefficient is unitless.

Water budget

One output of numerical groundwater models is water budget results which can be summarized for the model as a whole and for individual layers. This summary shows a snapshot in time of annual inflows and outflows. Table 11-14 summarizes the water budget results for the Bandera well longevity model and for the lower Trinity aquifer layer for the last simulated year (2018). The net flow is the difference between the inflow and the outflow. Negative net flow indicates discharge from the aquifer.

Influxes to the model active domain are through recharge from precipitation and the general head boundary. The general head boundary represents the Balcones Fault Zone and the outer boundaries of the active domain in each layer. Outfluxes are primarily the discharge of pumping wells and the interaction with lakes and rivers within in the study area. By using the MODFLOW drain package, the Bandera well longevity model simulates rivers in the study area as gaining; allowing only flow out of the aquifer. The model allows flow in both direction for lakes depending on water level gradients and the resulting net flow shows gaining lakes.

The lower Trinity aquifer (layer 4), on the other hand, has limited communication with the middle Trinity aquifer (layer 3) through the Hammett Shale. The net flow of only 8 acre-feet per year agrees with the properties of aquitard units and shows that the calibrated model parameters properly simulated the Hammett Shale. Local recharge in the lower Trinity aquifer is insignificant, estimated at only 0.14 percent of the overall recharge in the model. Because the lower Trinity aquifer is deep, recharge from precipitation or interaction with surface water does not occur. Recharge in layer 4 of the model occurs in cells that are in the northeast part of the mode, particularly in Travis County which is relatively far from the study area and where model cells in upper layers become dry and inactive during simulation. The main discharge from layer four is through pumping wells. This is compensated for by the inflows through the general head boundary that represents communication with the extended aquifer limit not included in the model’s active domain.

As for budget storage, inflow means water coming out of the aquifer's pore spaces and going into the dynamic flow system. Therefore, positive storage change indicates declining water levels. The net storage change for both the model and the lower Trinity aquifer shows declining water levels. Lastly, the inflow and outflow for the water budget total are equivalent with zero net flow for the model and the lower Trinity aquifer layer. This is a good indication that the model has no numerical discrepancy in closing the water budget. These results indicated high confidence of the effectiveness of the model. Therefore, it was used it to forecast future water levels in the lower Trinity aquifer.

Table 11-14. Water budget summary for the Bandera well longevity model and lower Trinity aquifer.

	Model			Lower Trinity aquifer		
	Inflow	Outflow	Net flow	Inflow	Outflow	Net flow
Top	not applicable	not applicable	not applicable	1	9	-8
Wells	0	28,197	-28,197	0	5,634	-5,634
General head boundary	696,603	174,013	522,591	4,303	171	4,133
Lakes	24,752	57,861	-33,109	0	0	0
Rivers	0	699,141	-699,141	0	0	0
Recharge	219,388	0	219,388	306	0	306
Storage	18,609	141	18,468	1,338	135	1,203
Total	959,352	959,352	0	5,948	5,948	0

Note: Inflow, outflow, and net flow values are in acre-feet per year.

11.6.2 *Predictive model*

After confirming the ability of the Bandera well longevity model to reproduce observed water levels, it was used as a predictive tool to forecast future conditions under three different scenarios. Scenario one, the "no change" scenario (S1) assumed that the City of Bandera will continue pumping current (2018) production volumes starting in the year 2020 until the year 2079. This scenario represents the most conservative interpretation of possible future conditions. Scenario two, the "projected demands" scenario (S2) assumed the City will gradually increase production to meet water demand projections in the 2022 State Water Plan. This simulation is the most probable scenario. Lastly, scenario three, the "maximum planned supply" scenario (S3), assumed the City will increase production immediately (in year 2020) to produce the existing groundwater supply in the 2022 State Water Plan. This is the extreme condition or the worst-case scenario that we also applied using the analytical solution discussed in Section 5. The forecast period for all three scenarios covers the six coming decades used in the 2022 State Water Plan (2020–2079).

The predictive model was constructed by adding 61 transient stress periods to the Bandera well longevity model, covering the period from 2019 to 2079. This resulted in a total of 100 years of simulated stress periods (1980 to 2079). Calibrated values of the Bandera well longevity model were applied for the layer 4 parameters. The types and spatial distribution of the boundary conditions of the Bandera well longevity model were maintained. Constant stages of rivers and lakes were applied for water levels and the same conductance values of the Bandera well longevity model were used. The heads in the general head boundaries of the Bandera well longevity model were extrapolated for the new 61 stress periods.

Two major water use groups in Bandera County were considered for this model: irrigation and municipal. For S1, pumping volumes were maintained at the values used in the last simulated year of the Bandera well longevity model (i.e., 2018) until 2079. For S2 and S3, the "county-other" category was also included to account for potential increases in lower Trinity aquifer domestic use due to growing subdivisions in the area.

The 2021 Plateau Region Water Plan reported projected groundwater demands and existing groundwater available supplies in Bandera County per user group for the Trinity Aquifer system (WSP and Carollo Engineers, Inc., 2021). The regional water plan lists several municipal users in Bandera County. Out of these, four entities were identified as lower Trinity aquifer users: City of Bandera, Bandera County Freshwater District, Bandera River Ranch 1, and West Medina Water Supply Corporation. The county-other use represents mainly the domestic use in the area, and it is reported for the entire Trinity Aquifer system. To estimate the lower Trinity aquifer use, the collected wells database was used to compare the percentage of domestic wells in the lower Trinity aquifer to all wells within Trinity Aquifer in Bandera County. In addition, the top surface of the lower Trinity aquifer was compared with depths from the Texas Department of Licensing Regulation domestic well depths shapefile (TWDB, 2021d). It was determined that between 2.9 and 12 percent of the total domestic wells were completed in the lower Trinity aquifer. The higher end of this range (12 percent) was applied to estimate the lower Trinity projection for domestic use to account for the potential growth of subdivisions. Table 11-15 and Table 11-16 list the projected municipal use (including county-other) based on S2 and S3.

Lower Trinity aquifer irrigation pumping was based on the percentage of irrigation wells in lower Trinity aquifer compared to the overall Trinity Aquifer irrigation wells in Bandera County. Table 11-17 lists the irrigation pumping from the lower Trinity aquifer for S2 and Table 11-18 lists the values for S3. We assigned lower Trinity irrigation pumping to layer 4 grid cells following the same spatial distribution used in both the Hill Country Trinity GAM and the Bandera well longevity model. This spatial distribution is based on land use and land cover 1:250,000-scale maps obtained from the U.S. Geological Survey.

A gradual increase in pumping rates starting in 2018 to meet the demands of each decade by its end was used to simulate S2. For example, the listed demand of the 2020 decade is gradually met by the year 2029. A constant rate of pumping equivalent to the existing supply starting year 2020 was used for S3. Pumping rates were maintained from the reported 2018 rates as this is limited by the well and pump construction.

Table 11-15. Municipal and county-other demands (acre-feet per year) in Bandera County for the Trinity Aquifer (T) and the lower Trinity aquifer (LT).

	Year					
Water user group	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**
Bandera	342	382	404	413	419	423
Bandera County FWSD 1	141	158	167	171	174	177
County Other| Medina WSC	93	104	109	111	112	113
County other	1,881.30	2,094.3	2,202.3	2240	2,272.3	2,290.3
LT/T (based on domestic wells)	0.12	0.12	0.12	0.12	0.12	0.12
LT county other	225.756	251.316	264.276	268.8	272.68	274.836

Notes: WSC = Water Supply Corporation.

Table 11-16. Existing groundwater supplies for municipal and county-other use (acre-feet per year) in Bandera County based on the lower Trinity (LT) aquifer to the Trinity (T) Aquifer domestic wells percentage.

Water user group	Source description	Basin	Year					
			2020	**2030**	**2040**	**2050**	**2060**	**2070**
County Other	Trinity Aquifer	Nueces	399	399	399	399	399	399
Bandera	Trinity Aquifer	San Antonio	534	534	534	534	534	534
County Other| Bandera River Ranch 1	Trinity Aquifer	San Antonio	69	69	69	69	69	69
County Other| Medina WSC	Trinity Aquifer	San Antonio	58	58	58	58	58	58
County Other	Trinity Aquifer	San Antonio	4,356	4,356	4,356	4356	4,356	4,356
County Other total	Trinity Aquifer		4,755	4,755	4,755	4,755	4,755	4,755
LT/T (based on domestic wells)			0.12	0.12	0.12	0.12	0.12	0.12
County other	Lower Trinity aquifer		571	571	571	571	571	571

Notes: WSC = Water Supply Corporation.

Table 11-17. Irrigation demands (acre-feet per year) in Bandera County for the Trinity Aquifer (T) and the lower Trinity aquifer (LT).

	Year					
Water user group	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**
Irrigation total (T)	946	946	946	946	946	946
LT/T (based on irrigation wells)	0.3	0.3	0.3	0.3	0.3	0.3
LT irrigation percentage	283.8	283.8	283.8	283.8	283.8	283.8

Table 11-18. Existing groundwater supplies (acre-feet per year) for irrigation in Bandera County.

			Year					
Water user group	**Source description**	**Basin**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**
Irrigation	Trinity Aquifer	Nueces	279	279	279	279	279	279
Irrigation	Trinity Aquifer	San Antonio	684	684	684	684	684	684
Trinity Aquifer irrigation total			963	963	963	963	963	963
Lower Trinity irrigation pumping			289	289	289	289	289	289

Notes: lower Trinity percentage (based on wells count) is 30 percent applied for all decades from 2020 to 2070.

11.6.3 *Limitations of the model*

Limitations associated with groundwater flow models stem mainly from data scarcity, which makes it difficult to completely characterize complex hydrogeological systems. Jones and others (2011) discussed the limitations of the Hill Country Trinity GAM. These limitations center around the system's structure and the hydrogeological parameters. Lack of good quality data leads to simplifications made to construct the conceptual representation of the system. Simplification includes generalization of the hydrological properties, and representation of the study area in a course resolution layout. These simplifications make regional models less reliable for localized studies. We used the more detailed Robinson and others (2022) Hill Country Trinity Aquifer stratigraphic surfaces in the Bandera well longevity model to control structural simplifications. Additionally, we overcame the grid cell size issue in the Bandera well longevity model by using a refined spatial resolution (0.25-mile) to highlight the focus study area of Bandera County. While the model's resolution is more refined, the model still may not be able to show sufficient detailed variation of water levels at the individual well scale. The finer the resolution the more challenging the model is to process computationally for complex systems and wide coverage areas. Additionally, we added a new hydraulic conductivity zone in the City of Bandera area in the lower Trinity aquifer. However, the update of hydraulic parameters is primarily done through calibration based on available water levels observations. Although calibration resulted in adequate fit simulations, it was based on limited water level observations for the lower Trinity aquifer.

Jones and others (2011) also discussed the assumptions used in the Hill Country Trinity GAM related to boundary conditions: recharge, rivers, and lakes. These boundary conditions are in layers 1 through 3 and we carried these approximations to the Bandera well longevity model with the assumption of little communication with layer 4 (the study focus). The boundary conditions in layer 4 are general head boundary and pumping. We introduced the general head boundary in layer 4 to account for the difference in the footprint between the stratigraphic surfaces of Robinson and other (2022) and the GAM. We assumed linear variation of heads in the general head boundary conditions during the simulation time span.

For pumping, we made some assumptions to address the discrepancy and data gaps between the different sources of data. After discussion with the BCRAGD, we used the District's (2021) records explicitly starting with 2010. In addition, for municipalities or corporations missing annual use data, we applied the average reported use for each entity if it is more than what is listed in the TWDB (2021c) or the TCEQ (2021). The assumptions applied to the lower Trinity layer must be considered and reevaluated when applying the model for other purposes than the one in hand.

The purpose of this model poses a limitation on universally applying it to address other issues. The Bandera well longevity model assumes linear variation of pumping in layers 1, 2, and 3 from 1998 to 2018 for the historic simulation, and up to 2079 for the predictive modeling. This assumption must be carefully assessed before applying the model to localized studies in these aquifers.

12. Appendix C – GIS datasets

All Geographic Information System (GIS) datasets and each of the GIS files prepared for this study are available for download from the TWDB website. These files were created using ArcGIS® 10.2 and the Spatial Analyst® extension software by Environmental Systems Research Institute, Inc. (ESRI).

Point files are in the ArcGIS® shapefile format. Point files of well control used for general purposes are originally projected as a geographic projection North America with the North American Datum 1983 as the horizontal datum. Point files are re-projected to a TWDB GAM projection and the North American Datum 1983 as the horizontal datum.

All surface files are in the ArcGIS® raster integer grid file format with a GAM projection and the North American Datum 1983 as the horizontal datum.

Polygon and polyline files are in the ArcGIS® shapefile format with a GAM projection and the North American Datum 1983 as the horizontal datum.

All well records are managed in the Microsoft® Access® BRACS Database. Well records are queried from the database and imported into ArcGIS® for spatial analysis. When new attributes are obtained for a well using ArcGIS® the information is imported into Microsoft® Access® and the well record is updated. Every well record in each supporting database used for this study contains latitude and longitude coordinates in the format of decimal degrees with a North American Datum of 1983. These well records are imported into ArcGIS® and georeferenced in a geographic coordinate system North America with the North American Datum 1983 as the horizontal datum.

13. Appendix D – Modeling dataset

All associated files for MODFLOW (MODFLOW-USG) and associated geodatabases prepared for this study are available for download from the TWDB website (www.twdb.texas.gov/innovativewater/asr/projects/Bandera/index.asp). These files were prepared using Groundwater Vistas® Version 8 by Environmental Simulations, Inc. (ESI). The model was developed and ran on a Dell Precision 5820 with a 3.70 GHz Intel® Xeon® W-2145 with 64 GB of RAM and an NVIDIA Quadro P4000 GPU with 8 GB GDDRS running at 60 Hz. The computer was operated using Microsoft Windows 10 Enterprise (10.0.18363). All parameters and observations were imported from ESRI ArcGIS® 10.2. All data were imported as point, line, and polygon shapefiles.