# Memorandum

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| **To:** | Scott Storment, EAHCP Program Manager |
| **From:** | Erin Hitchcock and Lucas Bare, ICF |
| **Date:** | September 15, 2023 |
| **Re:** | **Proposed Changes to EAHCP Existing Conditions for the Permit Renewal** |

# 1. Introduction

The Edwards Aquifer Habitat Conservation Plan (EAHCP) Permittees are currently preparing updates and revisions to the EAHCP for the incidental take permit (ITP) renewal. This memo outlines the process used to identify proposed changes to the Existing Conditions chapter of the EAHCP (Chapter 3). It also summarizes the proposed updates to Chapter 3. Although this memo strives to identify as many of the updates as possible within Chapter 3, some updates are contingent upon information that is not yet available and cannot be determined at this time. Therefore, this memo includes information on the current progress made to update the chapter and details the outstanding information needed to finish updating it as part of the complete, amended EAHCP.

Examples of Existing Condition updates that cannot be determined at this time are those pertaining to Covered Species. At a minimum, seven listed species will be covered in the amended HCP. However, additional data regarding the species will be needed to evaluate fully the other species being considered for coverage. Specifically, there are currently eight species for which a recommendation for coverage cannot be made at this time and further evaluation is needed.[1] These species include Bexar County deep aquifer species, the Barton Springs Segment of the Edwards Aquifer salamanders, and riverine mussels. The Covered Species list is expected to be evaluated throughout the planning process and finalized in 2024.

[1] Refer to the Evaluation of Covered Species for the Amended EAHCP Memo (dated April 26, 2023) for more information on species proposed for coverage.

The EAHCP permit renewal process is a multi-year planning process.[2] We anticipate submitting the draft amended EAHCP and ITP amendment application to the U.S. Fish and Wildlife Service (USFWS) in 2025. Given this timeline, some Existing Conditions information will need to be updated as close to submittal of the amended EAHCP as possible to ensure that the document includes the most current information (e.g., hydrology data). This memo identifies information for which updates are recommended to occur during preparation of the complete, amended EAHCP (anticipated during the first half of 2025) to avoid duplicative update efforts.

Consistent with the process for other EAHCP chapter updates, once all Existing Conditions changes and updates have been made, the changes identified will be reviewed and then “signed-off” on by the EAHCP Implementing Committee. After that, the changes will be incorporated into the amended EAHCP and submitted to the governing bodies of the ITP Permittees, and, if approved, then submitted to the USFWS with the ITP amendment application.

This memo describes the general process for identifying changes to the Existing Conditions. It also summarizes the proposed changes, which are categorized by topic (as shown below). The proposed text edits to the Existing Conditions chapter of the EAHCP are provided in ***Attachment 1: Edwards Aquifer Habitat Conservation Plan, Chapter 3, with Proposed Changes***.

# 2. Evaluation of Existing Conditions

The Existing Conditions chapter of the EAHCP (Chapter 3) provides the foundation for assessing how Covered Activities affect ecologic and hydrologic systems, species’ habitats, and the species occurring within the EAHCP Plan Area. The sections that follow describe the evaluation process for updates to the EAHCP’s Existing Conditions discussion for the permit renewal process.

## 2.1 Process for Evaluating Existing Conditions

The process for identifying potential changes to the EAHCP’s Existing Conditions discussion started with a review of the current Existing Conditions chapter. We identified conditions that are either 1) different from those of the original HCP and need updating or 2) may be different, depending on the outcome of outstanding information or decisions. We then identified information that could be updated at this time as well as information that should be as current as possible in the amended HCP; therefore, requiring update during preparation of the complete amended EAHCP, anticipated during the first half of 2025. In addition, the chapter was reviewed for relevancy to the covered species effects analysis, conservation strategy, and the monitoring program. Sections or information determined to be irrelevant or extraneous are removed from the chapter.

### 2.1.1 Proposed Changes

A summary list of the changes proposed for Chapter 3, *Existing Conditions* is provided below. For each change, we indicate whether the change has been made in Attachment 1 or whether we recommend the change be made later to account for the most current data.

[2] A detailed project schedule is available here: - PREAHCP_Detailed Schedule_230410 (eahcprenewal.org)

Proposed Revisions to *Climate* (Section 3.1)

- Update general temperature and precipitation information for region, based on recent data, information, and sources (some changes made, and others proposed for 2025).
- Update rainfall data with most current data and information (changes proposed for 2025).
- Remove climate change discussion (formerly Section 3.1.3) from Chapter 3 and address in the *Temperature and Rainfall Scenarios Report*, which will include downscaled climate scenarios (changes made).
- Update drought discussion, based on current information, and re-evaluate drought of record, based on most current information and conditions (some changes made, and others proposed for 2025).
- Update assessment of rainfall and drought data, including methodology used for determining data distribution (changes proposed for 2025).
- Update all figures and tables (changes proposed for 2025).

Proposed Revisions to *Edwards Aquifer-fed Springs* (Section 3.2)

- Update general spring conditions, based on recent data and information (some changes made and others proposed for 2025).
- Update summary of flows by spring (changes proposed for 2025).
- For pending Covered Species decisions, consider updating discussion of other springs to ensure that this section is relevant to Covered Species and effects analysis (2025).
- Update and/or refresh all figures (changes proposed for 2025).

Proposed Revisions to *Edwards (Balcones Fault Zone) Aquifer* (Section 3.3)

- Minor text clarifications (changes made).
- Edwards Aquifer Authority (EAA) to update all EAA report references and information, based on current studies, reports, and in-house information (changes expected in 2023/2024).
- Update and/or refresh all figures (changes proposed for 2025).

Proposed Revisions to *Description of the Edwards Aquifer, Comal Springs, and San Marcos Springs Ecosystems* (Section 3.4)

- General updates to spring ecosystem descriptions (changes made).
- Update spring ecosystem descriptions, based on current biological monitoring program information (changes proposed for 2025).
- Updates needed for any Covered Species added and relevant to specific ecosystems (changes to be determined for 2025).

- Add discussion of deep aquifer if deep aquifer species (such as blind catfish) are added as Covered Species (changes proposed for 2025).
- Add discussion of downstream conditions if riverine mussel species (such as Guadalupe Orb) are added as Covered Species (changes proposed for 2025).
- Remove Fern Bank Springs discussion as this spring is not relevant to the covered species effects analysis (i.e., the EAHCP does not estimate take at Fern Bank Springs), conservation strategy, or monitoring program (changes proposed for 2025).
- Update and/or refresh all figures (changes proposed for 2024/2025).

Proposed Revisions to *Listed Covered Species* and *Other Covered Species* Sections (Sections 3.5 and 3.6)

- Update list of covered species listed as threatened or endangered that are addressed in HCP once covered species list is finalized (changes proposed for 2025).
- General updates to species accounts, based on recent data and information (changes made).
- Update species accounts as appropriate, based on most recent biological monitoring program data and the final Covered Species list (changes proposed for 2025).
- Remove discussion of San Marcos gambusia because it will be removed from the list of covered species in the amended EAHCP (formerly Section 3.5.8 [changes made]).
- Remove discussion of Comal Springs salamander because it will be removed from the list of covered species in the amended EAHCP (formerly Section 3.6.3 [changes made]).
- Add species accounts for any species added to the covered species list anticipated to be finalized in 2024 (changes proposed for 2025).
- Update and/or refresh all figures (changes proposed for 2025).

References

- Update references, as applicable, and compile updated references list for Chapter 3 and include in the Literature Cited chapter (changes proposed for 2025).

# Attachment 1
# Edwards Aquifer Habitat Conservation Plan
# Chapter 3, with Proposed Changes

# Attachment 1
# Edwards Aquifer Habitat Conservation Plan, Chapter 3, with Proposed Changes

[*Note to reviewer: Gray highlight indicates updated text. Yellow highlight indicates a placeholder for future update.*]

## 3.1 Climate

### 3.1.1 Climate of South-Central Texas

The prevailing climate of the Habitat Conservation Plan (HCP) study area varies from subtropical steppe in the western region to subtropical subhumid in the central and eastern regions (see Figure 3-1) (Bradley and Malstaff 2004). The subtropical steppe is characterized by semi-arid to arid conditions (Stamm et al. 2015). The subtropical subhumid climate is typified by long, hot summers and short, mild winters; the subtropical humid climate exhibits higher humidity and slightly milder summers than the subtropical steppe. Prevailing winds are generally southerly, except during winter when they are frequently from the north. Latitude, elevation, and proximity to the Gulf of Mexico influence the climate of the region.

The average annual temperature in the study area is about 21 degrees Celsius (°C) (70 degrees Fahrenheit [°F]). The average annual high temperature ranges from 27°C to 31°C (80°F to 87°F) (Figure 3-2) (National Oceanic and Atmospheric Administration [NOAA] 2022). Average monthly high temperatures range from 34°C (93°F) to 37°C (99°F) (NOAA 2022). Summertime temperatures commonly exceed 38°C (100°F). Winters are generally mild, with average monthly low temperatures ranging from about 5°C (41°F) to 12°C (54°F). Temperatures fall below freezing about 22 days each year (NOAA 2022).

Average annual precipitation within the region varies from east to west, with the eastern portion receiving more precipitation than the western portion. For example, average annual precipitation is about 22 inches in western Kinney County and about 40 inches in eastern Caldwell County (Figure 3-3); however, in some years, the region may receive as much as 50 inches or as little as 10 inches of precipitation (NOAA 2022). During the period of 1934 to 2021, San Antonio averaged 32.4 inches of precipitation (NOAA 2022). Historically, precipitation is highest during May and September and lowest during the winter. Stalled cool fronts and summer tropical storms may result in above-average precipitation.

The potential for an incidence of high-magnitude flooding is greater for the Balcones Escarpment area of central Texas than for any other region of the United States (Caran and Baker 1986; Saharia et al. 2017). In part, this is due to the climatic provenance of central Texas; the area lies within a convergence zone of high- and low-pressure air masses. In addition, tropical storms and hurricanes that originate in the Gulf of Mexico produce some of the area's heaviest rainfall (Patton and Baker 1976). Once rainfall hits the ground, infiltration rates are a function of landscape physiography and antecedent conditions (i.e., the amount of water stored in the soil profile before the rainfall began). Along the Balcones Escarpment, valleys are narrow and the slopes are sparsely covered by vegetation.

**Figure 3-1. Climate Regions of Texas [refresh figure]**

**Figure 3-2. Annual Average High Temperature, 1971- 2024 [Update figure]**

**Figure 3-3. Average Annual Precipitation in Inches, 1971- 2024 [Update figure]**

The surface is either marked by exposed bedrock or overlain by thin layers of upland soils. This area is known as "flash flood alley." Below the Escarpment, soils of the Blackland Prairies have low absorption rates or infiltration capacities (Caran and Baker 1986; Patton and Baker 1976). Interacting together, these factors severely limit infiltration and greatly increase runoff and drainage discharge.

Regional surface water features and near-surface soil moisture levels are subject to evaporation, especially during hot summer months. Average gross lake-surface evaporation in the region ranges from approximately 2 inches in January to approximately 7 to 11 inches in August (Texas Water Development Board [TWDB] 2022). Evapotranspiration percentages vary throughout the region, with an average of approximately 60 percent of regional precipitation lost through evapotranspiration (TWDB 2022).

### 3.1.2 Floods and Tropical Storms

As stated in Runkle et al. (2022), there were more than 85 tropical storms and hurricanes in Texas between 1900 and 2020; approximately half of these storms were hurricanes. Since 2000, Texas has experienced numerous severe storms and destructive hurricanes, including Hurricane Harvey (Category 4), Hurricane Rita (Category 3), and Hurricane Ike (Category 2) (Runkle et al. 2022). Occasionally, these storms move inland, resulting in severe weather over the region. As moisture-laden air masses move inland from the Gulf of Mexico, they are forced to rise at the Balcones Escarpment, then mix with low-pressure fronts from the north or west. Such systems have resulted in some of the largest storms ever recorded in the United States, with high winds, excessive rainfall, hail, and tornadoes.

Flash flooding is common within the Plan Area due to the susceptibility to extreme rainfall events that are exacerbated by the thin soils, exposed limestone bedrock, and steep slopes that characterize the area and promote runoff (Furl et al. 2018). One notable event occurred in May 2015, during a spring season marked by record setting rainfall across Texas. Within the Plan Area, the Blanco River watershed received an average of 165 mm of precipitation across 15 hours (Furl et al. 2018). A catastrophic floodwave moved through the Blanco River resulting in severe and deadly flooding.

## 3.1.3 Temperature and Precipitation Trends in Texas, Based on the Historical Record from 1895

Temperatures in Texas have risen almost 1.5°F since the beginning of the 20th century (Runkle et al. 2022). According to data compiled by the National Climatic Data Center (2010) over the period of record between 1895 and 2010, the temperature in Texas has increased at a rate of about 0.1°F per decade, or about 1°F over the past century.

Precipitation is widely variable across Texas, both spatially and temporally. Since modern record-keeping, historically significant droughts have been recorded in the late 1910s, the early 1950s, and the early 2010s; the driest calendar years were 1917, 1956, and 2011. The driest consecutive 5 years was the period from 1952 to 1956; the wettest was the period from 2015 to 2019. Droughts often coincide with strong and extended La Niña events.

A multi-year drought in the 1950s continues to be used as the worst-case scenario for water-resources planning in many regions (i.e., the official drought of record), including the EAA management area, although the more recent 2011 drought was the worst single-year drought in recorded history (Nielson-Gammon 2012). Notably, the Lower Colorado River Authority officially recently recognized a new drought of record that includes 2011 for the nearby Colorado River Basin, which is located just north of the Edwards Aquifer Authority's management area (LCRA, 2019). The new drought of record for the Lower Colorado River Basin is October 2007 to April 2015.

## 3.1.4 Droughts

Droughts are generally thought of as extended events, lasting months, years, or even decades, starting with periods of reduced rainfall. However, "flash droughts," brought on in a matter of days because of precipitation deficits accompanied by extreme high temperatures or high winds and a lack of humidity, are a growing phenomenon (Otkin et al. 2018). Texas experienced a flash drought in 2012. Seasonal summer droughts, accompanied by seasonal low flows, are commonplace in Texas. Many small creeks run intermittently during the summer months when precipitation is often less than needed to compensate for a high level of evapotranspiration and minimal surface runoff. Drought may also result in springflow decreases, which can act to reduce the availability of aquatic habitat. Extended periods of reduced or no precipitation are also common in Texas. Those periods of time, combined with high summer temperatures, can lead to severe drought conditions in which even larger creeks, streams, and springs run dry and inflows into mainstem rivers are greatly reduced.

Serious droughts have been recorded in some parts of Texas in every decade since 1900. Droughts result from lower-than-normal precipitation levels; however, years with above-average precipitation totals may still experience low water availability, especially after dry periods when soil moisture may not rebound. Therefore, the *annual average amount of rainfall* does not reflect occurrences of droughts or the impacts that droughts have on Edwards Aquifer (Aquifer) and the living organisms that depend on it. Averaging the rainfall data tends to mask the duration and intensity of droughts.

Droughts vary significantly in duration and intensity. Riggio et al. (1987) conducted a comprehensive analysis of droughts, using monthly rainfall data for sites across Texas from 1931 to 1980. They found that at least five droughts of extended duration and extreme intensity have occurred since 1931 in the Plan Area (Riggio et al. 1987). Between 1931 and 1985, the frequency of occurrence for the three-month drought in the Edwards Plateau region varied from 62 to 70 occurrences, depending on location. During the same period, the frequency of occurrence for the six-month drought varied from 32 to 40 occurrences (Riggio et al. 1987). Fewer than 24 occurrences of the 12-month drought were recorded between 1931 and 1985 (Riggio et al. 1987). Although droughts are cyclic in nature, they are not consistent in frequency.

The 6-year drought that occurred from 1951 through 1956 is considered the drought of record for the Aquifer because it was the most severe drought recorded, according to documented Aquifer records maintained since 1934. This drought resulted in the only known cessation of the artesian flow at Comal Springs, occurring in 1956 and lasting for 144 days (Longley 1995).

To understand the drought of record and how it relates to the long-term climate of the Aquifer, a study using dendrochronology was conducted using existing databases to evaluate historic drought patterns in the Aquifer region (Mauldin 2003). Dendrochronology is the use of tree-ring analysis to evaluate historic climatic conditions. It is an established, critical element of climate research (Blasing and Fritts 1976; Robinson 1976; Stahle et al. 1985; Stahle and Cleaveland 1988; Cook et al. 1999). An extensive database of tree-ring data for the southwest was used in the analysis (Cook 2000). Data collected from existing databases was correlated with the Palmer Drought Severity Index (PDSI) for a 280-year period (1700–1979). The PDSI is a standard measure of soil moisture conditions and used to classify drought frequency, intensity and duration. It has a range of -4.0 to 4.0, with an average year falling between -0.5 and 0.5. Droughts are defined as -1.0 through -4.0. Over the 280-year period studied, 25.7 percent of the years were drought years (Mauldin 2003).

The study showed that droughts are not uncommon to the Aquifer region; however, they are usually short in duration and generally not too intense. During the 280-year period (1700 through 1979), the Aquifer region experienced 40 droughts of various lengths. The duration of the average drought was 1.8 years; droughts that lasted only 1 year were more common. Long-term droughts, defined as those exceeding 3 years in duration, occurred only four times; three of those were in the 1700s. The fourth long-term drought was the drought of record (1951–1956), which lasted 6 years. The drought of record was the most intense long-term drought (-2.32 average PDSI, peaking at about -3.1); however, six other droughts were more intense for shorter durations (PDSI > -3.1) (Mauldin 2003). Therrell (2000), also using tree-ring analysis, concluded that the drought of record was the most prolonged period of sustained drought in the past 347 years. The drought of record represents only 2.1 percent of the 280-year period analyzed and only 2.5 percent of the 40 droughts.

Although the nature of future drought stress remains unclear, for those areas where climate models suggest drying, such as the southwest, including the western half of Texas (Seager et al. 2007), extreme droughts as severe or more severe than those encountered in the instrumental record are more likely (Burke et al. 2006).

## 3.1.5 Likelihood of a Repeat of the Drought of Record Based on Historical Data

In response to concerns about the likelihood of a reoccurrence of a significant drought that could adversely affect spring systems during the term of the permit, the potential for a repeat of the drought of record was analyzed from three perspectives: the long-term regional rainfall pattern, based on tree-ring data; the regional pattern of rainfall from the instrumental rainfall records; and a probabilistic analysis, based on the characteristics of the historic instrumental data.

### 3.1.5.1 Long-term Regional Rainfall Pattern (1500 to 2010)

Based on a recent evaluation using tree-ring data as a proxy for annual rainfall, Cleaveland and Votteler (in preparation) have provided a depiction of the climate in the Edwards Aquifer region of Texas during the past 500 years. They identified the pattern of significant drought events in Divisions 6 and 7, which correspond to the Edwards Aquifer contributing zone and recharge zone, respectively, for this period. Significantly, the period ending in 1956 was the second-driest 5-year period, the fourth-driest 10-year period, and the second-driest 20-year period in both divisions, indicating that it was a significant event of low frequency during this period.

### 3.1.5.2 The Regional Rainfall Record (1895 to 2010)

**Figure 3-5 displays the regional rainfall record from 1895 to 2024.**

### 3.1.5.3 Probabilistic Assessment of Recurrence of the Drought of Record

Although not necessarily intuitive, annual rainfall totals are essentially random, with little evidence for between-year associations (Hershfield 1963; Guttman 1989). The distribution of annual rainfall totals is often nearly normal (or Gaussian) (Hershfield 1963) but also can be represented by other statistical distributions. Guttman (1989) recommends evaluation of the data of interest prior to making assumptions as to the appropriate statistical descriptor.

Rainfall data for the period from 1895 to 2010 (Table 3-1 and Figure 3-6) were evaluated as to their approximation to a normal distribution. The mean rainfall during the period was 25.37 inches per year (s.d. = 6.575), with a minimum of 11.22 inches in 1956.

The distribution of this data was assessed using Microsoft Excel 2010 and the SYSTAT 11 statistical software package. Annual rainfall data were compared with a number of statistical distributions but fit best with and were not significantly different from a normal distribution (see Figure 3-6).

Because the 1956 drought of record was the result of a multi-year sequence of drier-than-average years, the 1895–2010 rainfall data set was also examined by calculating 3-, 5-, 7-, and 10-year running averages (Figures 3-7 through 3-10). Each of these sequences was also normally distributed. With this analysis, it was not possible to identify which sequence (3-, 5-, 7-, or 10-year sequence) would be the best descriptor of what occurred in the drought of record; therefore, all of the sequences were evaluated.

Although the rainfall in 1956 was the lowest annual total for the entire period (11.22 inches), it does not stand out significantly from other years (see Figure 3-6). However, the 3-, 5-, 7-, and 10-year sequences ending in 1956 are distinguishable in the period, particularly the 5- and 7-year sequences.

From the normal distributions for each of these sequences (from the individual yearly totals and the 3-, 5-, 7-, and 10-year totals), the cumulative probabilities for the drought of record were calculated, based on the normal distributions (Table 3-2).

From the data in Table 3-2, it can be inferred that, if the overall climatic regime from the past 11 years were to continue into the near-term future, the probability of a recurrence of a year as dry as 1956 is approximately 1.6 percent in any given year. The probability of a 3- or 5-year period as dry as the drought of record is approximately 0.2 percent, and the probability of a 7- or 10-year period as dry as the drought of record is 0.1 percent or less (Table 3-3).

**Table 3-1. Annual Rainfall Records From Texas Climate Division 6 [update table and source**

**Figure 3-5. Division 6 Rainfall [update figure]**

**Figure 3-6. Division 6 Rainfall Frequency Distribution [update figure]**

**Figure 3-7. Three-year moving average rainfall 1895–2024 [update figure]**

**Figure 3-8. Five-year moving average rainfall 1895–2024 [update figure]**

**Figure 3-9. Seven-year moving average rainfall 1895–2024 [update figure]**

**Figure 3-10. Ten-year moving average rainfall 1895–2024 [update figure]**

**Table 3-2. Probability of Drought of Record, Based on 1895–2010 Annual Rainfall Totals [update table]**

| Number of Years in Drought Sequence | Mean for Drought of Record (inches) | Calculated Cumulative Probability* P(rainfall < drought of record) |
|---|---|---|
| 1 | 11.20 | 0.0161 |
| 3 | 14.60 | 0.00211 |
| 5 | 17.44 | 0.00219 |
| 7 | 17.27 | 0.00034 |
| 10 | 19.38 | 0.00119 |

*Calculated from 1895–2010 rainfall data.

**Table 3-3. Calculated and Modeled Probability of Recurrence of Drought of Record [update table]**

| Number of Years in Drought Sequence | Mean for Drought of Record (inches) | Calculated Cumulative Probability* P(rainfall < drought of record) | Monte Carlo Modeled Cumulative Probability for Future Periods** | | |
|---|---|---|---|---|---|
| | | | 8 Year (2010–2018) | 15 Years (2010–2025) | 25 Years (2010–2035) |
| 1 | 11.20 | 0.0161 | 0.094 | 0.16 | 0.241 |
| 3 | 14.60 | 0.00211 | 0.011 | 0.026 | 0.038 |
| 5 | 17.44 | 0.00219 | 0.009 | 0.009 | 0.041 |
| 7 | 17.27 | 0.00034 | 0 | 0 | 0.005 |
| 10 | 19.38 | 0.00119 | 0.001 | 0.007 | 0.017 |

*Calculated from 1895–2010 rainfall data.
**Based on 1,000 iterations.

### 3.1.5.4 Effects of the Drought of Record on Comal Springs

The severity of the drought of 1956 and its impact on water levels at Landa Lake are unique in the hydrologic record for central Texas. The most critical period of low flow at Comal Springs was during the summer months of 1956 when the springs ceased the artesian flow. Landa Lake went from being "full" in early June to being "dry" (that is, not flowing) in August of that year. A description of what occurs at Comal Springs when water levels drop has been previously described by LBG-Guyton Associates (2004) and is summarized below.

Spring runs #1 and #2 stop flowing at Landa Park with a well water elevation of 622 feet above mean sea level (ft MSL) when total Comal Springs flow is about 130 cubic feet per second (cfs). Spring run #3 stops flowing at Landa Park with a well water level of 620 ft MSL; this is also the current lake level, as controlled by the dam. Total Comal Springs flow at this point is about 50 cfs. Spring runs #1 and #2 went dry during the summer of 1953 as well as from the summer of 1954 until January 1957. Spring run #3 stopped flowing during the summer of 1955 as well as from May until December 1956. Although the flows from spring runs #1, #2, and #3 stop with a Landa Park well level of 620 ft MSL, there was still flow out of Landa Lake due to spring discharge from other spring runs into the lake itself. When the water elevation at the Landa Park well declined to about 619 ft MSL, total spring discharge went to zero. During 1956, spring discharge was zero for 144 consecutive days, from June 13 to November 3. At that point, flow stopped at the New Channel dam, but water was still able to flow though the culvert to the Old

Channel. Below a Landa Park well elevation of approximately 618 ft MSL, the elevation of the lake bottom immediately upstream of the culvert prevented flow from reaching the Old Channel culvert. Spring discharge could presumably still occur at water levels as low as the lowest lake-bottom elevation of 613 ft MSL. However, for such discharge to occur, an outlet at that elevation would need to be constructed that would discharge to a location at a lower elevation (such as Old Channel).

Large parts of the lake bottom emerged at a lake elevation of 618 ft MSL. The north end of the lake, north of Spring Island, also emerged at about 618 ft MSL. Although there were some deeper pools at the north end, flow from north to south was probably interrupted. Figures 3-11a and 3-11b are photographs of the southern end of Landa Lake that were taken in the summer of 1956. The water level in the individual pools within the lake appeared to be about 617to 618 ft MSL. The lowest level of Landa Park well (613.34 ft MSL) was reached on August 21, 1956. The deepest pool, just south of Spring Island, had a bottom elevation of 613 ft MSL. Newspaper clippings indicate that there may have been 6 inches of water left in the deep pools.

### 3.1.5.5 Effects of the Drought of Record on San Marcos Springs

San Marcos Springs is at the end of a flow system for the Aquifer that includes most of the outcrop, streams, and the Blanco River in Hays County. The springs receive recharge from this area, and they often exhibit a rapid flow response to storm events in this region. San Marcos Springs also appears to receive a regional base flow of about 50 to 100 cfs that bypasses discharge at Comal Springs (LBG-Guyton Associates 2004). Although San Marcos Springs did not go dry during the drought of record in the summer of 1956, spring discharge declined to 47 cfs. Increases in seasonal water levels and flows in the artesian section of the Aquifer (San Antonio pool), however, do not always result in increases in discharge at San Marcos Springs.

Most of the spring discharge at San Marcos is through spring complexes in the bottom of Spring Lake. There are few, if any, subaerial springs, such as those that occur at Comal Springs. Although some of the springs have distinct orifices where discharge can be measured, most of the spring discharge appears to be through rock rubble or sand boils in large, flat sand-plain areas. The southern springs appear to discharge groundwater from the regional flow system, while the northern springs receive their discharge from the more localized recharge zone in Hays County. Discharge rates in the southern springs would be expected to be far more stable under varying flow conditions than the northern springs, which should be more variable in proportion to total spring discharge values.

### 3.1.5.6 Effect of Drought on Hueco Springs

Following Barr (1993), only recent drought and springflow data are presented here. The larger of the two springs, Hueco I, typically exhibits constant flow but has been documented to stop flowing during severe droughts (Ogden et al. 1986), such as in 1984. However, Hueco I did not stop flowing during the drought occurring in 1989–1991. Hueco II is an intermittent spring that typically stops flowing during the driest months of the year (Barr 1993). The Permittees do not own or have jurisdiction over these springs or the surrounding ecosystems.

**Figure 3-11a. Historic Photo of Landa Lake [keep figure]**

**Figure 3-11b. Historic Photo of Landa Lake [keep figure]**

# 3.2 Edwards Aquifer-fed Springs

Texas originally had 281 known, major non-saline springs; of those, only four were defined as first-magnitude springs, having a flow of more than 100 cfs. These four consist of Comal Springs, San Marcos Springs, Goodenough Springs, and San Felipe Springs. Goodenough and San Felipe Springs are in Val Verde County, west of the Edwards Balcones Fault Zone Aquifer. Goodenough has since been inundated by the impoundment of Amistad International Reservoir (Brune 1975). Comal and San Marcos Springs remain the largest springs in Texas, and flow from these springs is supplied principally by the Edwards Aquifer. Other spring outlets of the Aquifer within the jurisdiction of the Edwards Aquifer Authority (EAA) include Leona Springs, San Pedro Springs, San Antonio Springs, and Hueco Springs (see Figure 3-12). Total annual discharge from the six most significant springs listed in Table 3-4 during the period of record (1934 to 2009) has varied from 69,800 acre-feet (ac-ft) in 1956 to 802,800 ac-ft in 1992, with an average annual discharge of 385,700 ac-ft (EAA 2010b).

## 3.2.1 Comal Springs Physical Description

Comal Springs, located in the city of New Braunfels in Comal County, is the largest natural spring system in Texas. At 623 ft MSL, Comal Springs is one of the lowest-elevation springs fed by the Aquifer. The springs discharge from four major orifices of varying sizes with associated spring runs as well as from numerous smaller discharge points. In 1847, Comal Springs was impounded to form Landa Lake for irrigation purposes (see Figure 3-12) (Abbott and Woodruff 1986; Linam et al. 1993). Water discharging from Comal Springs has been recharged from numerous areas upgradient in the Aquifer recharge and contributing zones. Longer regional-scale flowpaths primarily originate primarily in Bexar and Medina Counties, while short, localized groundwater contributions to springflow occur in Comal County. Dye tracer tests at Comal Springs suggest that separate flowpaths contribute to individual spring orifices. For instance, spring runs #1, #2, and #3 have been shown to have a larger contribution from localized shallow flowpaths, while spring orifice #7 reflects water emerging from regional deeper flowpaths (EAA 2010).

Although Comal Springs is generally perennial, with a historical average flow for the period 1934 to 2021 of 287 cfs (EAA 2021), individual springs and/or spring runs have ceased flowing during recorded history. Cessation of spring discharge occurred during the drought of record in 1956 for 144 days, from June 13 to November 4 (U.S. Fish and Wildlife Service [USFWS] 1996). In contrast, the record high average annual flow for Comal Springs is 534 cfs in 1973. Throughout implementation of the Edwards Aquifer Habitat Conservation Plan (EAHCP) (2013–2022) and its associated conservation measures, average annual flow for Comal Springs has been 258 cfs.

**Figure 3-12. General Location Map of Springs [refresh figure]**

**Table 3-4. [Update table]**

### 3.2.2 San Marcos Springs Physical Description

San Marcos Springs, near the base of the Balcones Escarpment in the city of San Marcos in Hays County, is the second-largest spring system in the state and the source of baseflow to the San Marcos River (Figure 3-12). At 574 ft MSL, San Marcos Springs exhibits the lowest elevation of the major springs in the San Antonio segment of the Aquifer. Impoundment of San Marcos Springs for irrigation resulted in the creation of Spring Lake in 1849 (Bousman and Nickels 2003). The springs discharge from six major and several minor orifices at the bottom of Spring Lake, including from below and along the side of the Meadows Center for Water and the Environment office building. During wet years, San Marcos Springs receives a greater contribution from local sources; during dry years, San Marcos Springs receives a greater contribution from regional flowpaths (Johnson and Schindel 2008). Local stream recharge from the Blanco and Guadalupe Rivers and the Sink, Purgatory, York, Dry Comal, and Alligator Creeks contributes to San Marcos Springs where it crosses the recharge zone (Brune 1981). San Marcos Springs is also supplied by “regional underflow past the Comal Springs area” (Guyton et al. 1979). Because San Marcos Springs is lower in elevation than Comal Springs and farther down the pathway of the flow of water within the confined artesian Aquifer zone, discharge at Comal Springs appears to dampen spring output at San Marcos Springs. Historical average annual flow for the period 1957 to 2021 was 176 cfs (EAA 2021). Although Comal Springs went dry for approximately 144 days in 1956 (USFWS 1996), San Marcos Springs remained flowing and has historically had the most constant spring discharge. During that same year, the springs did reach a recorded low discharge of 47 cfs. In contrast, the record high average daily flow for San Marcos Springs was 451 cfs in 1992. Throughout implementation of the EAHCP (2013–2022) and its associated conservation measures, average annual flow for San Marcos Springs has been 180 cfs.

## 3.3 Edwards (Balcones Fault Zone) Aquifer

This section provides a general description of the hydrological boundaries of the Aquifer, hydrological zones, and hydraulic properties.

The Aquifer, referred to as the Edwards Balcones Fault Zone Aquifer by the TWDB (2006a), is one of nine major aquifers in Texas, covering approximately 4,350 square miles across parts of 11 Texas counties. The Aquifer has focused recharge zones, enhanced secondary porosity, and excellent geochemical water quality conditions. These factors make the Aquifer one of the most productive groundwater reservoirs in the country (Sharp and Banner 1997). The Aquifer is the primary source of water for a large portion of central Texas with almost 2 million people (EAA 2010b; U.S. Census Bureau 2010). It supports cities, towns, rural communities, farms, and ranches. The water is used for a range of purposes (e.g., to support municipal, industrial, and manufacturing uses; produce steam for generating electricity; facilitate irrigation, mining, and livestock operations; and sustain recreational uses). The Aquifer also supports several major springs that provide habitat for a number of endangered and threatened species.

The Aquifer extends from a groundwater divide in Kinney County, through the city of San Antonio, northeast to Bell County. Within this area, the Aquifer comprises three segments:

the southern (San Antonio) segment, the Barton Springs (Austin) segment, and the northern segment. Historical hydro-geological data support the presence of a groundwater divide running west-northwest from the city of Kyle in Hays County, which, under normal conditions, hydrologically separated the San Antonio and Austin (Barton Springs) segments. At this location, under most conditions, groundwaters from the San Antonio and Austin segments do not mix. Generally, groundwater north of the divide flows north, while groundwater south of the divide flows south. This groundwater divide may be diminished substantially during drought conditions. A recent study (HDR 2010) suggests that as water levels in the Aquifer decline during major droughts and with current levels of pumping, this groundwater divide diminishes, allowing the potential for some groundwater to bypass San Marcos Springs and flow north into the Barton Springs segment of the Aquifer and toward Barton Springs. The third segment of the Aquifer, which is known as the “northern segment,” is hydrologically separated from the Barton Springs segment by the Colorado River. The focus of this groundwater discussion will be on the San Antonio segment of the Aquifer.

The San Antonio segment of the Edwards Aquifer is approximately 180 miles long, stretching from the city of Brackettville in Kinney County to an area north of Kyle in Hays County, Texas (see Figure 3-16). It varies in width from 5 to 40 miles. This segment of the Aquifer extends through all or part of 11 counties: Zavala, Frio, Atascosa, Guadalupe, Kinney, Uvalde, Medina, Bexar, Comal, Caldwell, and Hays. As described in Section 3.2.1, the Aquifer lies under several streams in three major river basins, the Nueces, the San Antonio, and the Guadalupe.

**Figure 3-13. Climate Regions of Texas [keep and refresh figure]**

The San Antonio segment of the Aquifer holds water that drains from approximately 8,000 square miles in some 12 counties in the contributing and recharge zone. The water-bearing body of the Aquifer itself underlies approximately 3,600 square miles in eight counties. The total volume of circulating freshwater in the Aquifer is estimated at 173 million ac-ft (Bureau of Economic Geology 1995), making it one of the most productive aquifers in the United States, although the amount of recoverable groundwater is not known. The Aquifer, which historically has been the sole source of water for the city of San Antonio (USGS 1995; EAA 2001), provides base flow to the three river basins mentioned above (USGS 1999). Annual discharge from springflow and pumping has frequently exceeded average annual recharge. Median annual recharge for the period of record (1934-2021) was 547,000 ac-ft, while median annual discharge from springflow and pumping was 706,900 ac-ft (EAA 2021).

The Aquifer is considered a karst aquifer. Flow in the Aquifer is very complex (USGS 1995) and typical of other karst aquifers. It occurs over a wide range of hydraulic conductivity (e.g., flow through the rock matrix [least conductive], flow in planar fractures and bedding planes, turbulent flow through integrated conduit systems [most conductive]). In general, most storage occurs in the matrix, while most flow occurs in the fractures/faults and conduits. Matrix and conduit components may or may not mix effectively. Thus, groundwater in some components of the Aquifer may have very long residence times and be relatively resistant to surface contamination, while other components of the Aquifer may have extremely rapid travel times and be very vulnerable to contamination. The vulnerable parts of the Aquifer are also the most productive, feeding major springs and wells.

In addition to the variability of flow velocities, flow directions are also variable in karst aquifers. Flow directions are influenced by both regional and local hydraulic gradients, but they are also controlled by the location and orientation of conduit systems. Karst aquifers may be influenced by development and changes in geologic formations that occurred under previous water flow regimes; thus, flowpaths may not follow local topography or surface watersheds. It is common for flow in karst aquifers to cross watershed boundaries, which are typically considered groundwater divides in other types of aquifers. Furthermore, the pattern and direction of flow in a karst aquifer is often water-level dependent because high water levels can utilize older flowpaths and travel in non-linear directions, using conduits formed under older groundwater regimes, which may differ from modern ones.

Generally, the water flows south-southeastward from the recharge zone along low permeabilities and steep hydraulic gradients within the unconfined portion of the Aquifer. As the water flows into the confined portion of the Aquifer, the flow direction changes toward the east and northeast within the low-gradient, highly permeable artesian zone. The water is then discharged from several springs, predominantly Comal and San Marcos Springs (Section 3.2.1). Although the Aquifer contains vast reserves of water, a large volume of water cannot be extracted without affecting springflow and the overall water budget. This is because the springs are higher in elevation than much of the confined artesian zone. This relationship is similar to a bucket of water with holes at the top that are analogous to the spring locations. Although water is available in the lower portions of the bucket, it cannot be extracted without affecting the flow of water through the holes (springs) at the higher levels. The water budget of the Aquifer (recharge, discharge, and springflow) is discussed in Section 3.3.3.

The San Antonio segment of the Aquifer consists of a recharge zone and artesian zone (see Figure 1-1). Each of these components is described below. The Aquifer is also affected by a contributing zone. Development over the contributing and recharge zones of the Aquifer is regulated under rules established by the Texas Commission on Environmental Quality (TCEQ) Edwards Aquifer Protection Program (2010). Section 3.3.2, below, provides an overview of these regulations.

## Contributing Zone

The contributing zone is composed of drainage areas and catchments of surface streams upstream of the recharge zone that subsequently flow over the recharge zone. Much of the contributing zone lies over the older Glen Rose Formation, upthrust by the Balcones faulting. In the upthrown fault blocks, the Edwards Group rocks have been eroded away and are not present. Here, the Upper Glen Rose is exposed and classified as being the “contributing zone” to the Aquifer. The contributing zone of the San Antonio segment of the Aquifer is a surface component, not technically part of the Aquifer, which consists mainly of the drainage areas and catchments of surface streams, creeks, and rivers that subsequently flow over the Aquifer’s recharge zone in the Nueces, San Antonio, and Guadalupe River Basins. The contributing zone encompasses some 5,400 square miles in all or part of Edwards, Real, Kerr, Bandera, Kendall, Gillespie, Blanco, Bexar, Comal, Hays, Kinney, Uvalde and Medina Counties (see Figure 1-1). This area is important because of its substantial contribution to Aquifer recharge. Future development in the contributing zone will affect the quality and quantity of water draining to the recharge zone of the Aquifer.

## Recharge Zone

The recharge zone (also known as the unconfined zone) of the Aquifer is an approximately 1,250-square-mile area where heavily faulted and fractured Edwards limestone outcrops at the land surface allow large quantities of water to flow into the Aquifer. The recharge zone stretches as a band from an area north and west of San Marcos and New Braunfels and then southwesterly to an area north of San Antonio before continuing westerly through the northern portions of Bexar, Medina, Uvalde and Kinney Counties. Recharge occurs when streams and rivers cross the permeable formation and a portion of their flow seeps underground or precipitation or runoff falls directly on the outcrop. Water flows are driven by gravity to discharge at water-table springs, enter deep-flow systems and discharge at artesian springs, or recharge the confined zone of the Aquifer. Surface water reservoirs on the recharge zone, such as Medina Lake, also contribute large amounts of water to the Aquifer. Except for the Guadalupe River, all rivers and streams that cross the outcrop of the Aquifer lose major portions of their flows to the Aquifer through joints, faults, and sink holes as well as other karst features (USGS 1995). Where the Guadalupe River crosses the recharge zone, it may either gain or lose water from the Aquifer, depending on Aquifer levels. This is due to water levels in the river being near the groundwater table, whereas other creeks and streams are generally at significantly higher elevations. Three river basins cross the Aquifer area: the Nueces, the San Antonio, and the Guadalupe River. Extending from the west, the Nueces River Basin covers more than half of the Aquifer area.

Several major tributaries in the Nueces River Basin traverse the Aquifer recharge zone, including the Nueces, West Nueces, Frio, Dry Frio, and Sabinal Rivers as well as Hondo Creek. The portion of the San Antonio River Basin in the recharge zone extends from the Medina River to Cibolo Creek and includes the headwaters of Leon and Salado Creeks. Only a small portion of the Guadalupe River Basin intersects the eastern Aquifer area. However, two of the basin tributaries, the Comal and San Marcos Rivers, are fed primarily by the Aquifer at the Comal and San Marcos Springs.

Under normal conditions, most of the Aquifer recharge occurs in the basins west of Bexar County (USGS 1995) where the Edwards limestone outcrop is very wide at the surface. In the recharge zone, there are no other geologic formations overlying the Edwards limestone. It is therefore exposed at the surface.

Periods of recharge are intermittent because most streams in south-central Texas are ephemeral; however, the recharge capacity of surface water into the Aquifer is extremely efficient due to the karstic nature of the system. Water passing over the contributing zone and into faults, fractures, and swallets of the recharge zone is rapidly transferred directly to the Aquifer with little or no filtration. The geologic mechanisms that form karst are complex, and many factors affect how karst is expressed in current settings. These factors control the way the groundwater system evolves and ultimately how groundwater is recharged, transmitted, and naturally discharged through the Aquifer system.

## Artesian Zone

The artesian zone (also known as the confined zone of the Aquifer) is between two relatively impermeable formations, the Glen Rose Formation below and the Del Rio clay above (Ferrill et al. 2004). The weight of water entering the Aquifer from the recharge zone creates tremendous pressure on water that is already present in the formation. Flowing artesian wells and springs exist where this pressure is strong enough to force water to the surface along faults or through wells. This zone is where the highest capacity wells and largest springs exist (Collins and Hovorka 1997). Examples of natural springs under artesian conditions are San Marcos and Comal Springs in the northeast. Groundwater movement through the Aquifer is generally controlled by a number of barrier faults that disrupt the continuity of the permeable Edwards limestone. This movement tends to be from the higher elevations in the west to discharge areas in the east. The displacement of strata ranges from very large, which causes permeable and impermeable layers to be juxtaposed, to very small. Water moves more freely through the Aquifer when displacement is minimal. In addition, groundwater divides exist in the west near Brackettville and in the east near Kyle; therefore, the central portion of the Aquifer is hydro-geologically separated from Edwards limestones on either side (see Figure 3-16).

## Transition Zone

The transition zone consists primarily of younger bedrock overlying the artesian zone of the Edwards Group that has been down thrust to the east in the Balcones Fault Zone. These younger and generally less permeable rocks of the transition zone overlie and form the upper confining units to the artesian zone of the Aquifer. Although the surface bedrock in the transition zone is generally less permeable and karstified than the rocks of the Edwards Group, it was also extensively fractured and faulted by the Balcones Fault Zone and hosts some high-permeability pathways into the artesian zone. An exception is the Austin Chalk Formation, which is well karstified in some areas and hosts significant springs that discharge Aquifer water, such as San Antonio and San Pedro Springs (Veni 2009).

## Contributing Zone within Transition Zone

The contributing zone within the transition zone is defined in Title 30 of the Texas Administrative Code, Chapter 213, as the area generally south and east of the recharge zone—specifically, those areas where stratigraphic units not included in the Edwards Aquifer crop out at topographically higher elevations and drain to stream courses where stratigraphic units of the Edwards Aquifer crop out and are mapped as the recharge zone.

## Hydraulic Properties

Aquifer transmissivity (i.e., the ability of water to pass through the Aquifer, as measured by hydraulic conductivity and thickness) is high. According to Maclay and Small (1986), transmissivity of the Aquifer in the San Antonio area varies from 1 to 2 million square feet per day, allowing some wells in the city of San Antonio to discharge as much as 10,000 gallons per minute (gpm) or more (USGS 1995). One particular well was documented by the EAA to produce between 25,000 and 36,000 gpm. Highest transmissivity was determined to exceed 4,300,000 square feet per day in Comal County near Comal Springs; the smallest was 130 square feet per day in the saline water zone (Maclay and Land 1988). The linear distance at which water may move through the Aquifer appears to vary greatly, depending on location. Ogden et al. (1986) documented travel from up to 1,000 feet per day to only a few feet per day. Recent tracer tests conducted by the EAA revealed discrete groundwater flowpaths near Panther Springs Creek, with apparent (point-to-point) groundwater velocities ranging from 43 to 17,490 feet per day from the recharge zone to the transition/artesian zone of the Aquifer (EAA 2010a). Other evidence of high porosity of the Aquifer is the ability of Aquifer water levels to quickly respond to rainfall and recharge events as well as the rapid decline in water levels over a large area due to increased pumpage.

The Knippa Gap near Sabinal in eastern Uvalde County (see Figure 1-1) is a major controller of groundwater flow within the western portion of the Aquifer. The Knippa Gap is a geological restriction within the Aquifer that allows a substantial flow of groundwater from west to east but restricts the flow long enough to maintain higher groundwater levels in the Uvalde pool compared with the San Antonio pool (Green et al. 2008). Wells to the west of the Knippa Gap display much less variability in water levels than wells to the east. Water entering the recharge zone in northwestern Uvalde County appears to flow through the gap to reach the main freshwater zones of the Aquifer in Medina and Bexar Counties.

Flow models for the Aquifer show groundwater flowing east-northeast from Uvalde and Medina Counties, eventually discharging at Comal, Hueco, and San Marcos Springs; numerous small springs; or extracted by groundwater pumping from wells (Kuniansky et al. 2001). However, recent tracer studies in northern Bexar County performed by the EAA found that water flows from north to south with very rapid flow velocities (Johnson et al. 2009). In addition, these studies found that flowpaths may be more complex than originally thought, with rapid groundwater transport dominated by karstic conduit flow.

## Freshwater/Saline Water Interface

The freshwater/saline water interface (also known as the “Bad Water Line,” or BWL) delineates the Edwards Aquifer’s eastern and southern boundaries. It is not an actual, well-defined boundary but rather a transition zone on the southern and eastern limits of the Aquifer, extending from west of Kinney County through Bexar County and northward beyond the northern extent of the San Antonio region of the Aquifer. Wells to the south and southeast of this line typically display total dissolved solids (TDS) concentrations greater than 1,000 milligrams per liter (mg/l). Wells on the other side of this line typically have TDS concentrations equal to or less than 1,000 mg/l. The reason the “bad-water line” exists is not clear. In some places, it coincides with geologic features such as faults; in other places, there is no obvious geologic control. The presence of “bad” or more saline water appears to be more associated with relative permeabilities of the Aquifer rather than a density boundary between two different water types, which commonly exists in coastal sand aquifers. Wells in the transition zone have sections of brackish water that overlie freshwater, which, in turn, overlie brackish water, indicating that the type of rock and porosity influences the salinity of the water. It has been hypothesized that increased pumping of freshwater from the Aquifer may lead to an expansion of the bad-water zone, which could be detrimental to existing irrigation and municipal wells. In 1985, the EAA, in cooperation with USGS, TWDB, and the San Antonio Water System (SAWS), began testing in the fresh/saline interface area for possible saline-water encroachment into the freshwater zone. In 1997, the EAA reported that there were no significant changes in water quality in the test wells between 1985 and 1997 and that normal changes in Aquifer water levels have little effect on the quality of freshwater near the interface.

### 3.3.1 Inter-formational Flow into the Edwards Aquifer

The Edwards Aquifer receives most of its recharge directly where the limestone of the Person and Kainer Formations outcrop. However, a significant component of groundwater flow enters the Aquifer directly as inter-formational flow from the Trinity Aquifer. The recent Groundwater Availability Model for the Hill Country Portion of the Trinity Aquifer indicates that as much as 2,400 ac-ft per year for each linear mile of the Edwards-Trinity boundary in Bexar and Comal Counties (Jones 2011) exits the southern boundary of the recent Groundwater Availability Model, indicating possible flow from the Trinity Aquifer into the Edwards Aquifer. This value is lower to the west in Medina and Uvalde Counties (660 ac-ft/year/mile) and lowest farther east in Hays and Travis Counties (350 ac-ft/year/mile). Green (2011) has also demonstrated that losing streams in the contributing zone (Upper Glen Rose outcrop) are much more connected with the Edwards Aquifer than previously thought. In the Barton Springs segment of the Edwards Aquifer, it has been shown that Upper Glen Rose is in close hydraulic connection with the Edwards Aquifer, as documented by monitoring sophisticated multi-port wells (Smith and Hunt 2011). Dye tracer studies in northern Bexar County indicate that a very prolific connection exists between the two aquifers and documented rapid groundwater flow across faults that juxtapose the Edwards and Trinity Aquifers.

### 3.3.2 Groundwater Quality of the Edwards Aquifer

## Rules Governing Groundwater Quality

Regulations governing the quality of groundwater in Texas have interrelated state and federal regulatory functions. In 1974, the federal Safe Drinking Water Act was passed to protect sources of public drinking water. This act, amended in 1996, mandated enforceable drinking water standards, as established by the U.S. Environmental Protection Agency (EPA). The TCEQ has assumed responsibility for enforcement of drinking water standards in Texas and has established standards that meet or exceed those of the EPA. The Edwards Aquifer was designated as a sole-source aquifer, and TCEQ promulgated rules regulating development activity over zones of the Aquifer in eight counties, pursuant to 30 Texas Administrative Code, Chapter 213. The counties are Kinney, Uvalde, Medina, Bexar, Comal, Hays, Travis, and Williamson. Subchapter A applies to all regulated activities (defined as construction-related or post-construction activity) within the recharge zone, certain activities within the surrounding transition zone that stretches along the eastern and southern boundary of the recharge zone, and other activities that may contaminate the Aquifer and hydrologically connected surface streams. Under these rules, developers must submit an application, including an Aquifer protection plan, to the TCEQ prior to certain types of activity in the recharge, transition, or contributing zones of the Aquifer. For proposed development, including any regulated construction-related activity over the recharge zone, a water pollution abatement plan (WPAP) is required. The WPAP must include a geological assessment report, identifying pathways for the movement of contaminants to the Aquifer, and a report on best management practices and measures to prevent pollution in the Aquifer. After the plan is approved, notice must also be filed in the county deed records that the property is subject to an approved Aquifer protection plan. Certain facilities are also prohibited from being built in the recharge or transition zones, such as Type 1 municipal solid waste landfills and waste disposal wells. Subchapter B applies to regulated activities in the Aquifer's contributing zone. All activities that disturb the ground or alter a site's topographic, geologic, or existing recharge characteristics are subject to regulation, which would require either sediment and erosion controls or a contributing zone plan (CZP) to protect water quality during and after construction. Exemptions include construction of single-family residences on lots larger than 5 acres where no more than one single-family residence is located on each lot; agricultural activities; oil and gas exploration, development, and production under the jurisdiction of the Texas Railroad Commission; clearing of vegetation without soil disturbance; and maintenance of existing structures not involving additional site disturbance (30 Texas Administrative Code Section 213.22[6]).

The EAA has implemented a water quality protection program through rulemaking. Well construction rules have been adopted that regulate the construction, operation, maintenance, abandonment, and closure of wells (see EAA Rules, Chapter 713 [Water Quality], Subchapters B [General Provisions], C [Well Construction, Operation, and Maintenance], and D [Well Closures]). The EAA also regulates the reporting of spills (Subchapter E), storage of certain regulated substances (Subchapter F) on the recharge zone and the contributing zone of the Aquifer, and the installation of regulated tanks on the recharge zone of the Aquifer (Subchapter G). The City of San Marcos has also enacted regulations to protect water quality over the Aquifer recharge zone.

## Primary Drinking Water Standards

Primary drinking water standards are enforceable for public water supply systems and often referred to as maximum contaminant levels (MCLs). The MCL for a contaminant is the maximum permissible level of the contaminant in water that is delivered to any user of a public water system. MCLs protect drinking water quality by limiting levels of specific contaminants that can adversely affect public health and are known or anticipated to occur in public water systems. The primary standards are based on concentrations published in Title 30 of the Texas Administrative Code, Chapters 290 and 350. This concentration is the value estimated to be protective of human health and the environment.

## Secondary Drinking Water Standards

Secondary drinking water standards, which are non-enforceable, are set for contaminants that may affect the aesthetic qualities of drinking water, such as odor or appearance.

## Historic and Current Groundwater Quality Monitoring

Historically, the groundwater of the Aquifer has been considered to be of high quality—typically fresh but hard, with an average dissolved solid concentration of less than 500 mg/l (Texas Water Commission [TWC] 1992). Cooperative efforts between the EAA, USGS, and TWDB have resulted in a systematic program of water data collection. Each year the EAA monitors the quality of water in the Aquifer by sampling approximately 80 wells, eight surface water sites, and major spring groups across the region. Collection sites are typically selected to provide representative samples of the recharge zone, the shallow and deep artesian zone, the springs, and the surface streams that flow across the recharge zone as well as areas with historical detections of anthropogenic compounds.

Tests at the wells included measurements of temperature, pH, conductivity, alkalinity, major ions, minor elements (including heavy metals), TDS, nutrients, pesticides, herbicides, volatile organic compounds (VOCs), and other analytes.

## 3.3.3 The Edwards Aquifer Water Budget

Water levels of the Aquifer and associated flows of Comal and San Marcos Springs are affected by the rate of water entering the Aquifer (recharge) and the rate of water exiting the Aquifer (discharge). Recharge occurs as water enters the Aquifer from streams, natural catchments, recharge structures, precipitation events, and subsurface flows from adjacent aquifers. Seasonal rainfall over the region ultimately controls the rate of recharge. Discharge occurs from the withdrawal of water from wells as well as the flow of natural springs and seeps. An unknown smaller quantity is discharged to the saline water zone (USGS 1995). Discharge is greatly affected by water demand and the rate of pumping. If recharge is high, the Aquifer can sustain higher levels of pumping while maintaining higher levels of springflows. However, if low seasonal recharge is followed by reduced rainfall and high rates of pumping, then Aquifer levels will decline, with resulting decreased spring discharges. Historic recharge and discharge of the Aquifer and effects on springflow are discussed below.

## Groundwater Recharge

Estimates of the average annual recharge of the Aquifer vary according to changes in weather cycles and resulting precipitation over the recharge and contributing zones. The USGS (1995) cites an average annual recharge of 635,000 ac-ft. However, Klemt et al. (1979) indicate an average annual recharge of approximately 651,000 ac-ft. Data from the EAA's 2021 Hydrologic Data Report (EAA 2021) indicate an average annual groundwater recharge of 695,000 ac-ft for the period of record (1934–2020) and an even higher annual average of 965,400 ac-ft during the last 10-year period (2000–2009). Estimated contributions of the major river basins to annual recharge during the period of record (1934–2009) are listed in Table 3-5.

Estimated recharge to the Aquifer varied greatly from 1934 to 2009, as indicated in Figure 3-17. Variability was correlated with annual precipitation and corresponding runoff into the major river and creek basins. Lowest annual estimated recharge (44,000 ac-ft) occurred during 1956, at the peak of the drought of record. Highest estimated recharge (2,486,000 ac-ft) occurred in 1992. Rates of infiltration of water carried by the streams across the recharge zone have been estimated by the USACE (1965) to range from 500 to more than 1,000 cfs. Recent modeling studies using the Hydrologic Simulation Program Fortran (HSPF) indicate that land-based recharge outside of stream channels across the nine basins varies from a low of 2 percent to a high of 76 percent (EAA 2010b), whereas 24 to 98 percent of recharge across the nine basins occurs in stream channels as channel loss (LBG Guyton Associates 2005). In addition, some recharge to the Aquifer originates from inter-formational flow from adjacent aquifers, such as the Trinity Aquifer. Recent studies by Green and Bertetti (2010) indicate that a substantial volume of water enters the Aquifer directly through a cross-formational flow of recharged water to the Trinity Aquifer (Glen Rose limestone). Dye tracing conducted by the EAA in northern Bexar County suggests rapid and direct groundwater flowpaths from the Trinity to the Edwards Aquifers (Johnson et al. 2009). Estimates of the contribution from adjacent hydraulically connected aquifers have been estimated by the EAA (2010a) to vary from 5,000 to 60,000 ac-ft/year.

**Table 3-5. Contributions of Major River Basins to Average Annual Recharge of the Edwards Aquifer, 1934–2009 [update table]**

**Figure 3-17. Estimated Annual Recharge and 10-year Floating-average Recharge for the San Antonio Segment of the Edwards Aquifer, [update info and period]**

## Groundwater Discharge

Water is diverted from the Aquifer through wells; it also exits from natural springs and seeps occurring near geological faults along the Edwards Formation and Balcones Escarpment. Wells are the principal source of water for agricultural, municipal, and industrial uses in the region. The depths of wells range from less than 500 feet in the unconfined Aquifer to more than 3,000 feet in the confined Aquifer in the western region (USGS 1995). Wells in the area can be very large, with casing diameters ranging from 10 to 30 inches. These wells are capable of pumping in excess of 35,000 gpm. Average annual discharge from wells over the period of record (1934–2021) was 318,000 ac-ft (44.7 percent of all discharge), in comparison to 384,400 ac-ft (55.3 percent) from springflow (EAA 2021). During droughts, the proportion of well discharge to spring discharge changes considerably. During 1956, at the height of the drought of record, wells contributed 82 percent of the discharge in comparison to 18 percent for springs. During the drought of 2008, wells contributed 51 percent of the total discharge, while spring discharge was 49 percent. Values for average and median discharge are provided in the EAA 2010b.

Well discharge has generally increased over the period of record, from a point beginning in 1968 and running through 1989, with annual discharge consistently exceeding average annual recharge (USGS 1995). Pumping peaked in 1989 at an estimated level of 542,000 ac-ft. Since 1980, as a result of increased pumping, there has been greater fluctuation in springflow, along with increased time required for recovery, even during a period that recorded the two highest levels of Aquifer recharge (1992 and 2004). Examination of Figure 3-18 indicates increases in pumping beginning in 1982,1987, and 1996, resulting in higher fluctuation of springflow.

# 3.4 Description of the Edwards Aquifer, Comal Springs, and San Marcos Springs Ecosystems

The Aquifer and associated springs (Comal Springs, San Marcos Springs, and Hueco Springs) are unique aquatic ecosystems with some of the greatest diversity in groundwater and spring-associated species in the world (Bowles and Arsuffi 1993; Culver and Sket 2000; Holsinger and Longley 1980; Longley 1981; Reddell 1994).

**Figure 3-18. Groundwater Pumping Compared to Springflow to the Edwards Aquifer [update figure].**

## 3.4.1 Edwards Aquifer Ecosystem

The Aquifer lies within the Balcones Fault Zone, on the eastern boundary of the Edwards Plateau. It extends from a groundwater divide in Kinney County, through San Antonio, then continues northeast to Bell County. The recharge zone occurs in the Balcones Fault Zone at the Aquifer outcrop where the cretaceous limestones are exposed at the surface. Dissolution of the Edwards limestone throughout the recharge zone creates defining features such as caves and sinkholes. Groundwater levels typically vary with weather and season and have the potential to rapidly fluctuate following heavy rainfall. Water quality within the Aquifer is generally good because quick recharge through karst features limits water-rock interactions, thereby reducing dissolved solids (TWDB 2016). Within the contributing and recharge zones, water quality is heavily influenced by rainfall, stream infiltration, and increased groundwater velocities. Within the Artesian Zone, however, water quality is more stable because of the slower groundwater velocities and increased volume of water (EAA 2021). Focused recharge, enhanced cavernous porosity, and geochemical water quality conditions makes this one of the most productive groundwater reservoirs in the country (Sharp and Banner 1997). It may be one of the most biologically diverse karst aquifers in the world because of the high degree of interconnectedness between the conduits. Culver et al. (2003) showed that patterns of biodiversity were positively correlated with the number of caves and the distance from the late Cretaceous Sea. In addition, Hutchins et al. 2015 suggested that biological diversity within the Aquifer might be supported through chemolithoautotrophy, the process by which an organism obtains energy through the oxidation of inorganic compounds, a stable energy source that increases resource exploitation and reduces competition.

The Aquifer supports a highly modified biological assemblage that is adapted to deep water environments, including catfish, salamanders, and aquatic crustaceans with vestigial or no eyes. Several studies investigating the occurrence of aquifer-dwelling biota have reported up to 55 aquatic species, taxonomically representing seven phyla, 11 classes, and 17 orders of organisms (Hutchins et al. 2021). Several species are listed by the USFWS as endangered or threatened or have been proposed for listing (see Section 3.5).

The hydrology of the Aquifer is directly related to surface water ecosystems because water in the springs flows from the Aquifer at the base of the Balcones Escarpment (McKinney and Sharp 1995). Therefore, the systems are intertwined by water quantity, quality, and thermal conditions while separate with respect to the biological organisms that directly rely on sunlight and surface energy.

## 3.4.2 Comal Springs Ecosystem

The Comal Springs ecosystem (Figures 3-19a and 3-19b) originates from the Aquifer through multiple spring orifices, primarily in Landa Park in New Braunfels. The system comprises four major springs and several smaller spring runs that feed into Landa Lake. Together, the spring runs and Landa Lake form the headwaters of the Comal River, which covers 3.1 miles before its confluence with the Guadalupe River, making it the shortest river in Texas. From Landa Lake, water flows into two channels, the original "Old Channel" and a "New Channel" created in 1847 when the river was dammed and a millrace was hand excavated to provide water for William Merriweather's saw and grist mill.

**Figure 3-19a/b. Comal Springs Ecosystem [keep figures]**

During low flow conditions, most of the flow is directed to the Old Channel, however, it flows mostly to the New Channel during high flow conditions. The two channels rejoin 1.6 miles downstream from Landa Lake (McKinney and Sharp 1995). The long term (1933–2022) median discharge from the Comal Springs ecosystem, including the Old Channel and New Channel, is 304 cfs (USGS 08169000). The median flow in the Old Channel from 2012 to 2022 was 57 cfs (USGS 08168913). Over the years, extensive urban development along the banks, channel modification, and recreational activities related to parks and tube chutes have altered the Comal Springs system (McKinney and Sharp 1995). Despite a few small dams, channelization, and some diverted springflow for a water park, Schlitterbahn, the Old Channel retains many of its natural characteristics. The New Channel, however, has a more uniform width and, in some areas, a limestone bottom. The New Channel stream modifications are associated with several constructed dams to control overflow and tube chutes to enhance recreational use.

Although bank and channel modifications have occurred because of development and recreation, water temperatures remain near constant in the system overall. Temperatures do display variability among a longitudinal gradient, with more variation as distance from spring source increases. Low variation occurs in spring runs and at Landa Lake, while variation increases in the Old Channel and New Channel from upstream to downstream (BIO-WEST 2022). For example, in 2022, median temperature variation within a reach increased from 1.1°C in Landa Lake, to 1.5 °C in Old Channel, and 2.9°C in New Channel Downstream. Overall, annual median temperature throughout the Comal Springs ecosystem ranged from 23.8°C (74.8°F) upstream of Landa Lake to 23.9 °C (75.0 °F) at the New Channel and 24.4°C (75.2°F) at the Old Channel (BIO-WEST 2022). In addition, the ecosystem exhibits high water quality, with low nutrient and bacteria levels (EAA 2021; USFWS 1996).

The biotic community in Comal Springs includes a diverse assemblage of submerged aquatic vegetation, benthic macroinvertebrates, fishes, and amphibians. Approximately 10 species of submerged aquatic vegetation and several species of bryophyte are dominant in the Comal Springs ecosystem (Williams 2011). Historical accounts of aquatic vegetation indicate that much of the native vegetation in Landa Lake and the Old Channel was displaced with non-native species; therefore, a native aquatic vegetation restoration plan was developed for Landa Lake and the Old Channel in 2013. Prior to EAHCP restoration efforts, Landa Lake was dominated by *Vallsineria*. The Old Channel historically supported large stands of *Ludwigia* and filamentous algae, but those native species were replaced by *Hygrophila*. Post-restoration mapping in 2018 indicated that *Hygrophila* was drastically reduced to only the spillway in Landa Lake and the lower half of the Old Channel; however, because the likelihood of reinfestation is high, continued maintenance is necessary to keep *Hygrophila* from re-establishing (BIO-WEST 2019). Currently, *Vallsineria* dominates the vegetation community in Landa Lake, while bryophytes dominate restored areas of the Old Channel. Flood events, flood pulses along Dry Comal Creek, and high recreational use can yield reduced vegetative cover in the New Channel. Between disturbance events, dominant vegetation within the New Channel often consists of *Cabomba* and *Hygrophila*. Among the fish community, the dominance of spring-associated species (e.g., Guadalupe roundnose minnow [*Dionda nigrotaeniata*], Texas shiner [*Notropis amabilis*], and fountain darter [*Etheostoma fonticola*]) indicates a healthy spring ecosystem (BIO-WEST 2022). Generally stable trends in benthic macroinvertebrate communities suggest a healthy community. Despite urban development, the Comal Springs ecosystem still exhibits high biotic integrity (Munscher et al. 2019; Scanes 2016). Several organisms occurring in the Comal Springs ecosystem are listed by the USFWS as threatened or endangered. The listed species will be discussed in further detail in Section 3.5.

### 3.4.3 San Marcos Springs Ecosystem

The San Marcos Springs ecosystem (Figures 3-20a through 3-20c) originates from several springs throughout Spring Lake in Hays County, forming the headwaters of the San Marcos River. The San Marcos River extends 68.2 miles to its confluence with the Guadalupe River. San Marcos Springs has the most environmental stability and flow reliability of any spring system in the southwestern United States (USFWS 1996). This spring system has never stopped flowing in recorded history, although discharges dropped to approximately 46 cfs during the drought of record in the 1950s. The long-term (1956–2022) median discharge from the San Marcos Spring system was 174 cfs (BIO-WEST 2022). Temperatures in the Upper San Marcos River remain nearly constant year-round (21°C to 23°C [70°F to 73°F]) (BIO-WEST 2022), showing slight variability along a longitudinal gradient as distance from spring sources increases.

As with the Comal River, the San Marcos River is a haven for recreational activities. Upstream flood control dams within the watershed of the San Marcos River have enhanced recharge to the Aquifer by allowing water behind the dams, which would have gone downstream as irretrievable rapid flow, to infiltrate and contribute to the recharge system. Hydrologically, these dams have also reduced the magnitude of scouring flood events downstream, allowing an accumulation of sediments and encroachment of non-native vegetation. A major source of the accumulated sediments is provided by Sessom Creek, which receives runoff from the Texas State University campus (Earl and Wood 2002). These sediments are accumulating at a high rate, and even significant floods are unable to erode and transport them. Because flood control measures on the San Marcos River have prevented large scouring floods from occurring, the deposited sediments remain near the confluence of Sessom Creek and the San Marcos River, about 40 yards downstream from Spring Lake Dam. The sediments act as fill in the natural channel, making the channel downstream shallower than it would otherwise be and creating a spit that extends about halfway across the San Marcos River at the confluence with Sessom Creek. In 2021, the City of San Marcos began an improvement project on Sessom Creek to address the problem of increased sediments in the San Marcos River by creating grade controls and providing bed and bank stabilization. This effort will reduce sedimentation and preserve habitat in the area downstream of Spring Lake Dam.

The biological uniqueness and high degree of endemism found in Spring Lake and in the Upper San Marcos River can be attributed to thermal stability, consistent water chemistry, and a reliable flow (USFWS 1996). Downstream of Spring Lake Dam, the Upper San Marcos River flows over mostly gravel habitats with many shallow riffles and deeper runs. Lemke (1989) documented 31 species of aquatic macrophytes on the Upper San Marcos River, with 23 species being native. Among native vegetation, dominant taxa consist of Texas wild-rice, *Potamogeton*, *Hydrocotyle*, *Cabomba*, and *Sagittaria*. Increasing competition with non-native species, *Hydrilla* and *Hygrophila*, and resulting displacement for native species have been concerns. Control of non-native vegetation, mitigation of floating vegetation mats, and enhancement of Texas wild-rice have occurred as a result of implementation of the EAHCP since 2013 (EAA 2012).

**Figure 3-20a/b/c. San Marcos Springs Ecosystem [keep figure]**

Hydrilla has been greatly reduced to an undetectable level from Spring Lake to downstream of Hopkins Street, and removal efforts for *Hygrophila* are following closely behind. The Upper San Marcos River boasts a diverse fish assemblage, with spring-associated fishes (e.g., Guadalupe roundnose minnow, largespring gambusia [*Gambusia geiseri*], and Texas shiner) dominating community abundance in the upper and middle portions (BIO-WEST 2022). One spring-associated endemic species, the San Marcos Gambusia *Gambusia georgei*, was designated as endangered in 1980 and last collected in 1983. In September 2021, the USFWS proposed to remove this species from the Federal Lists of Endangered and Threatened Wildlife and Plants due to extinction (USFWS 2021). Despite more than 170 years of urbanization and resulting changes to stream morphology, instream habitats, water quantity and quality, and introduced species, the Upper San Marcos River retains a persistent fish community (Kollaus et al. 2014). Stable trends in aquatic life use over time, ranging from “intermediate” in Spring Lake to “exceptional” at Spring Lake Dam and Interstate 35, suggest that a robust benthic macroinvertebrate community exists (BIO-WEST 2022). Several organisms occurring in the San Marcos Springs ecosystem are listed by the USFWS as either threatened or endangered and therefore will be discussed in further detail in Section 3.5.

## Hueco Springs Ecosystem

Hueco Springs is in Comal County, on private property, approximately 4 miles north of New Braunfels, near the junction of Elm Creek and the Guadalupe River. It is the seventh-largest spring in Texas; it includes two main groups of springs, one on each side of River Road. These springs flow from the Hueco Springs fault, which is a major structural feature within the Aquifer with an offset of approximately 400 feet (Guyton and Associates 1979). The springs consist of two orifices at a high elevation (approximately 658 ft MSL); therefore, they have variable flow and often go dry or have long periods of low flow during drought (Abbott and Woodruff 1986). The maximum discharge for Hueco Springs was 260 ac-ft per day (131 cfs) in 1968 (Brune 1975) but has averaged about 70 ac-ft per day. Hueco Springs recharge has both local and regional components, originating from the nearby Dry Comal Creek and Guadalupe River Basins and from longer flowpaths from San Antonio (see Figure 3-13) (Otero 2007). Hueco Springs was documented as having elevated nitrate levels (> 5 parts per million [ppm]) during the drought of the 1950s, but most values since that time have been below 2 ppm. One measurement was just above 2 ppm in 2000 (Johnson et al. 2009).

This spring complex consists of two main groups of springs, issuing from the floodplain of the Guadalupe River. Hueco I (Hueco A) is a large, typically perennial spring on the west side of River Road in an undeveloped area. Hueco II (Hueco B) is an intermittent spring on the east side of River Road located in a campground. Hueco Springs has a local recharge component that could be enhanced by strategically placed recharge dams (Barr 1993). Fauna recorded from this site include the elmid beetle, *Microcylloepus* sp., and the water penny beetle, *Psephenus texanus*, along with surface-dwelling amphipods, oligochaetes, caddisfly larvae, crayfish, clams snails, aquatic isopods, three species of copepod (*Acanthocyclops vernalis, Mesocyclops edax,* and *Skstodiaptomus* sp.), hypogean amphipods (*Stygobromus russelli*) (Zara 2003), an aquifer salamander (possibly *Eurycea rathbuni*), and the federally listed Peck's cave amphipod, *Stygobromus pecki* (Barr 1993).

# 3.5 Listed Covered Species

Seven species that depend entirely on the Aquifer and associated springs are currently listed as endangered or threatened by the USFWS. Incidental take may be allowed for all of these species if covered by an Endangered Species Act (ESA) Section 10(a)(1)(B) permit. The ESA does not prohibit take of listed plants, except on federal lands (16 United States Code [U.S.C.] Section 1532[8] and Section 1532[14]).

Listed species addressed in the HCP include (with date of listing):

## Endangered

- Fountain darter (*Etheostoma fonticola*) (35 FR 16,047 [October 13, 1970])
- Comal Springs riffle beetle (*Heterelmis comalensis*) (62 FR 66,295 [December 18, 1997])
- Comal Springs dryopid beetle (*Stygoparnus comalensis*) (62 FR 66,295 [December 18, 1997])
- Peck's cave amphipod (*Stygobromus pecki*) (62 FR 66,295 [December 18, 1997])
- Texas wild-rice (*Zizania texana*) (43 FR 17,910 [April 26, 1978])
- Texas blind salamander (*Eurycea* [formerly *Typhlomolge*] *rathbuni*) (32 FR 4,001 [March 11, 1967])

## Threatened

- San Marcos salamander (*Eurycea nana*) (45 FR 47,355 [July 14, 1980])

A brief life history of each species covered in the HCP is provided below, including details that are relevant to the HCP.

### 3.5.1 Fountain Darter (*Etheostoma fonticola*)

The fountain darter, a member of the family *Percidae*, is endemic to the San Marcos and Comal Rivers. This species was first collected in 1884 in the San Marcos River just below its confluence with the Blanco River and in 1891 in the Comal River (Schenck and Whiteside 1976). Historically, fountain darter distributions throughout the San Marcos River extended from Spring Lake downstream to just below its confluence with the Blanco River as well as throughout the Comal River from the headwaters downstream to its confluence with the Guadalupe River (Schenck and Whiteside 1976). Currently, fountain darter distributions remain similar and occur in the San Marcos River from Spring Lake downstream to just above its confluence with the Blanco River as well as the entirety of the Comal River, including Landa Lake (BIO-WEST 2022; McKinney and Sharp 1995; Schenck and Whiteside 1976).

Fountain darters are among the smallest darters, belonging to the subgenus *Microperca* within the genus *Etheostoma*. Fountain Darters can be identified by their olive-green coloration, abbreviated lateral line, midlateral row of elongated dark blotches, dark spots at the base of the caudal fin, and suborbital bars (Page and Burr 1979; Schenck and Whiteside 1976). Stenothermal conditions and high water clarity in both spring systems enhance the persistence of fountain darters throughout their range (Kollaus et al. 2014; Schenck and Whiteside 1977; Simon et al. 1995). Fountain darters typically have slack-water affinities and often associate with habitats that include undisturbed sand and gravel substrates, rock outcrops, and submergent vegetation (i.e., algae, bryophytes, vascular plants) for feeding, reproduction, or cover (Alexander and Phillips 2012; McKinney and Sharp 1995; Schenck and Whiteside 1977; USFWS 1996). Young darters are often found in heavily vegetated slack-water habitats, while adults can be found in all habitats (Schenck and Whiteside 1976). Although fountain darters are frequently associated with vegetation, the relationship is not exclusive. The use mechanisms (e.g., feeding, reproduction, cover) remain unknown (Edwards and Bonner 2022). Densities are higher in ornate vegetation such as bryophytes or *Cabomba* (BIO-WEST 2022), suggesting that darters associate with structurally complex habitats. The type and amount of food consumed changes with growth and varies, depending on the invertebrate community composition within the reach (Schenck and Whiteside 1977). Generally, food sources for fountain darters consist of small aquatic invertebrates such as copepods, aquatic insect larvae, and amphipods (McKinney and Sharp 1995; Schenck and Whiteside 1977). Fountain darters are stationary feeders that use visual cues, primarily during the day, as they wait for prey to approach (Schenck and Whiteside 1976; USFWS 1996). Fountain darters are relatively sedentary, moving an average of 10 meters throughout the course of a year under a stable flow regime (Dammeyer et al. 2013). Another study, conducted under low-flow scenarios, similarly suggested that fountain darters remain relatively stationary, moving an average of 20.9 meters, with maximum movement of 131 meters (BIO-WEST 2014).

Some studies suggest that fountain darters exhibit continuous spawning year-round (Hubbs 1985; Strawn 1955); however, a more recent study demonstrated that fountain darters display a protracted annual reproductive cycle, with the optimum reproductive season in the spring

(Nichols 2015). Fecundity is believed to be lower in fountain darters than other species of darters and could be related to the influence of repeated spawnings throughout the year (Nichols 2015; Schenck and Whiteside 1977). This species exhibits sexual dimorphism, with the males having four morphological forms that differ in size, color, and shape (Schenck and Whiteside 1977). Vegetation is considered necessary for egg deposition (Strawn 1956), although fountain darters utilize a variety of substrates, including PVC tubing and glass in the hatchery setting (Brandt et al. 1993). Males produce a small amount of transparent milt (sperm) to fertilize the adhesive eggs (Hubbs 1958). Little or no parental care is provided to the eggs or young (Schenck and Whiteside 1977). Several laboratory studies have shown reductions in egg production between 25°C (77°F) and 26°C (79°F) and in larval production between 24°C (75°F) and 25°C (77°F) (Bonner et al. 1998; Brandt et al. 1993; McDonald et al. 2007). Wild fountain darters often experience a 2°C temperature fluctuation, but this fluctuation might not affect fountain darter recruitment in the wild because darters of less than 15 millimeters (mm) were still observed as temperatures approached 26°C (79°F) (BIO-WEST 2022).

Between 1954 and 1973, the original population of fountain darters was extirpated from the Comal River (Linam et al. 1993; Schenck and Whiteside 1976). It is believed that a combination of a rotenone treatment by the Texas Fish, Game, and Oyster Commission in 1951 to remove non-native Rio Grande cichlids (*Herichthys cyanoguttatus*), a lack of springflow for a 6-month period in 1956, and a flood from Blieders Creek in 1971 all potentially contributed to extirpation (Linam et al. 1993; Schenck and Whiteside 1976). A collection by Hubbs and Strawn (1957) that occurred between the rotenone treatment and the zero springflow conditions of 1956 indicated fountain darter presence in the system but did not indicate abundance. Fountain darters were listed as federally endangered in 1970 (USFWS 1970; 35 FR 16047) and deemed “the little fish that roared” (Votteler 1998) as legislative and judicial battles led to the creation of the Edwards Aquifer Authority to regulate groundwater pumping and protect springflow in San Marcos and Comal Springs. Critical habitat for the fountain darter was designated at Spring Lake and its outflow as well as the San Marcos River downstream to 0.5 mile below the Interstate 35 bridge (45 FR 47355, 47364 [July 14, 1980]). In 1975, a total of 457 fountain darters from the San Marcos River were re-introduced into the Comal River, from which the present Comal population is descended (Linam et al. 1993; Schenck and Whiteside 1976).

Several studies have attempted to provide fountain darter population abundance estimates, but the estimates either have no confidence intervals (103,000) (Schenck and Whiteside 1976) or wide-ranging confidence intervals (15,900–107,700) (Linam et al. 1993), thereby calling the estimates into question. Population abundance is difficult to estimate because of the fountain darter’s small body size, the range of sampling methods used in the past, and the difficulty in accounting for all of the habitat dynamics in calculations. Although recent population estimates have not been generated, long-term monitoring of fountain darters indicate that high densities exist in the San Marcos and Comal Rivers. In the Upper San Marcos River, long-term (2001–2022) median fountain darter densities range from 1.5 darters per square meter ($m^2$) in Spring Lake to 2.0 darters/$m^2$ in City Park and at Interstate 35. In the Comal River, fountain darter densities range from 1.5 darters/$m^2$ in the Upper Spring Run to 11.0 darters/$m^2$ at Landa Lake (BIO-WEST 2022). Furthermore, among vegetation taxa, fountain darter densities are highest in bryophyte (16.8 darters/$m^2$) and *Cabomba* (12.3 darters/$m^2$).

Threats to fountain darters include diminished springflow, poor water quality, and habitat destruction (USFWS 1996). Initially, it was believed that the trematode *Centrocestus formosanus,* hosted by the red-rimmed Melania (*Melanoides tuberculata*), posed a serious threat to the fountain darter after *C. formosanus* was first identified from a fountain darter in the 1990s and later high numbers of encysted metacercariae were observed on the darters (Cantu et al. 2013). This trematode attacks the gills of the fountain darter, causing reddening, swelling, and bleeding that could lead to increased stress and reduced ability to avoid predators. Laboratory studies suggested that, in early stages of infestation and under moderate parasite loads, *C. formosanus* did not affect reproduction (BIO-WEST 2002). In addition, infestation by the trematode *Haplorchus pumilio* has been observed encysted in the connective tissue around the heads and fins (Huston et al. 2014), which may exacerbate the effects of *C. formosanus*. Monitoring studies aimed at understanding distribution and density of *C. formosanus* and *H. pumilio* were conducted from 2013 to 2022. Results suggested that, although flow generally explains density trends for both trematodes through an inverse relationship with densities increasing under low-flow conditions, there has been an overall decrease in cercariae concentrations over time (BIO-WEST 2022). Coupled with stable fountain darter densities over time in both systems, this indicates that *C. formosanus* and *H. pumilio* might pose less of a threat to fountain darter populations than initially believed. However, continued monitoring of parasite concentrations and additional research, particularly during periods of low flow, into snail population trends, as well as infection rates in snail, fish, and bird hosts, would provide deeper understanding of these parasite population dynamics.

### 3.5.2 Comal Springs Riffle Beetle (*Heterelmis comalensis*)

The Comal Springs riffle beetle (Coleoptera: Elmidae) was first collected from Comal Springs in 1976, as described by Huston et al. (1988); it also occurs in San Marcos Springs (Gibson et al. 2008; Gonzales 2008). Although some riffle beetles are capable of flight, the Comal Springs riffle beetle is a flightless aquatic beetle, measuring about 2 mm long (Huston et al. 1988; USFWS 1997). Both larvae and adults are entirely aquatic, with the adults feeding mainly on algae and detritus scraped from submerged weeds and rocks (Brown 1987). Stable isotope analysis indicated Comal Springs riffle beetles derived more than 80 percent of their essential amino acids from bacteria, in contrast to surface species that derived essential amino acids from a mix of algae, bacteria, and fungi (Nair et al. 2021).

Comal Springs riffle beetles are found in the flowing, uncontaminated waters of spring runs but also occupy areas along the Landa Lake shoreline where springflow is present or areas of upwelling springflow, including the deepest portions of Landa Lake (BIO-WEST 2002; Bowles et al. 2003). They have also been documented at spring orifices along the headwaters of Spring Lake (Gibson et al. 2008). They tend to be most abundant within 20 centimeters of spring outlets and prefer a low flow, darkness, and elevated carbon dioxide levels (Cooke et al. 2015). They have a narrow range of thermal tolerance, with a preferred temperature of approximately 23°C (73°F) (Cooke et al. 2015). Relative to other elmid species, they are the most sensitive to thermal stress and have a median lethal temperature of 26.9°C (80.4°F) (Nair et al. 2023). Water flow appears to be important to respiration, thermal tolerance, and survival of this species; therefore, a reduction in water flow or drying of spring runs could be a limiting factor to their survival (USFWS 1997). Individuals tend to orient downward in the substrate and toward flow (BIO-WEST 2002), a behavioral response that may permit individuals to move to suitable habitat when springflow is reduced at the surface. However, because this species was not identified until 1976, well after the documented drought of record and cessation of springflow at Comal Springs during the 1950s, the question of survivability of the species during no-flow periods remains unanswered. In addition to behavioral responses, the presence of individuals in deeper areas of Landa Lake, which are somewhat removed from the spring runs, may have facilitated survival despite loss of habitat and provided a source for recolonization.

The presence of males is necessary for egg production by females. Egg production is a function of their longevity (Kosnicki 2020, 2022), with eggs hatching after an average of 25 days, larvae reaching a final (seventh) instar after 4 months, and adults surviving approximately 1 year (BIO-WEST 2017). The design of captive housing chambers has changed over time as knowledge of their captive survival and propagation requirements has become better known. A manual was recently developed that documents the history of their captive husbandry and current best practices (USFWS 2022). In summary, Comal Springs riffle beetles are housed in different variations of dark flow-through chambers containing leaves and/or conditioned wood as a food source and limestone rocks for habitat complexity; monitoring efforts have been reduced because they are light sensitive, and disturbance increases mortality (USFWS 2022).

In 2007, the USFWS designated 19.8 acres of the Comal Springs complex and 10.5 acres of the San Marcos Springs complex as critical habitat for this species (USFWS 2007); in 2013, this critical habitat designation was revised to 54 acres of surface critical habitat (USFWS 2013). Water withdrawals and pollution from hazardous materials, pesticide use, construction, and stormwater are all listed as threats to this species and its ecosystem (USFWS 2007).

### 3.5.3 Comal Springs Dryopid Beetle (*Stygoparnus comalensis*)

The Comal Springs dryopid beetle (Coleoptera: Dryopidae) is the only known subterranean aquatic (stygobiotic) species in its family; it was first collected in 1987 and described by Barr and Spangler (1992). Specimens have been collected throughout the Comal Springs system, but most adults have been found in spring run #2 and the upwellings around Spring Island. The species has also been collected at Fern Bank Springs in Hays County (Barr and Spangler 1992; Gibson et al. 2008). This species reaches a length of about 3 mm and has a translucent, slightly pigmented appearance. It has evolved vestigial eyes and greatly reduced (non-functional) micropterous wings (Shepard 2019), which are likely to reduce energy expenditure on organs that were not useful in relatively hydrologically stable subterranean and spring habitats (McCulloch et al. 2009). External morphological measurements have not shown meaningful size differences between sexes, but lateral lighting can be used to illuminate internal structures through their translucent exoskeleton, which allows for non-invasive separation of sexes (Barr and Spangler 1992; Kosnicki 2019).

Comal Springs dryopid beetles are hypothesized to be associated with *Platanus* roots, and larvae and pupae maybe dependent on woody material at terrestrial margins for reaching the adult stage (BIO-WEST 2019). Behavioral trials indicated that this species prefers to reside in food resources (*Platanus* leaves), even if it requires moving against flow (BIO-WEST 2019). Females that are caught in the wild lay an egg in captivity every 7 to 8 days, but only approximately 5 percent of the eggs reach pupation after an average of 323 days. Adults produced in captivity have not reproduced (BIO-WEST 2022).

Comal Springs dryopid beetles are able to maintain a mass of small hydrophobic hairs on their underside where they retain a thin air bubble through which gas exchange occurs during respiration (Bexar Metropolitan Water District [BMWD] 1998; Chapman 1982). As water flow decreases, subsequently decreasing dissolved oxygen levels, this method of respiration loses its effectiveness. Thus, the USFWS found that dryopid beetles require flowing, uncontaminated waters for survival (USFWS 1997). Similar to most species in the ecosystem, this species faces threats such as pollution and reduced springflow (Bowles and Arsuffi 1993; USFWS 2007).

In 2007, the USFWS designated 31.8 acres of critical habitat for this species at the Comal Springs complex and 1.4 acres of critical habitat at the Fern Bank Springs complex (USFWS 2007); in 2013, the critical habitat designation was updated to encompass 39.4 acres of surface critical habitat and 139 acres of subsurface critical habitat (USFWS 2013).

### 3.5.4 Peck's Cave Amphipod (*Stygobromus pecki*)

Peck's cave amphipod (Amphipoda: Crangonyctidae) is a subterranean aquatic crustacean, first collected in 1964 by Steward Peck and described by Holsinger (1967). Peck's cave amphipod is known only from the Comal Springs system, including Comal Springs and Panther Canyon Well, and from Hueco Springs (Gibson et al. 2008). Extensive collection efforts have been unable to locate the species in other localities (Barr 1993; Gibson et al. 2008; USFWS 1997). Genetically, there appear to be separate populations of Peck's cave amphipod. Currently, there is sufficient gene flow to prevent isolation (Ethridge et al. 2013; Lucas et al. 2016). The genus *Stygobromus* is highly diverse, with more than 130 described species (all subterranean); at least nine species are in Texas (Ethridge et al. 2013; Gibson et al. 2021). Three species co-occur with *S. pecki*: *S. bifurcatus*, *S. flagellatus*, and *S. russelli*.

Individuals that are caught in the wild and then housed and fed leaves and fish flakes in captivity lived up to 2.7 years, although it appears that *S. pecki* prefers live food more than *S. flagellatus* (Kosnicki and Julius 2019). Heavy morality and cannibalism have been observed in captivity, with the amount of habitat available being more important for reducing mortality than water volume. Fries et al. (2004) indicated that females have multiple broods of about 10 individuals each; newly hatched neonates are approximately 2 mm in length. Kosnicki and Julius (2019) found females produced broods of up to 28 eggs, with no relationship between female size and egg production; high levels of captive egg mortality could be due to female stress. On average, eggs were incubated for approximately 50 days, with 24 percent surviving to free-swimming neonates and having lengths of approximately 2.9 mm. None survived more than 32 days or to first molt (Kosnicki and Julius 2019).

Two critical habitat units have been designated for Peck's cave amphipod: Comal Springs and associated portions of Landa Lake as well as the Hueco Springs complex, which encompasses Hueco Springs and associated satellite springs. In 2013, the critical habitat designation was updated to encompass 38.4 acres of surface and 138 acres of subsurface critical habitat (USFWS 2013). Primary constituent elements of the critical habitat for all three federally listed aquatic invertebrate species include unpolluted, high-quality water; Aquifer water temperatures between 68°F and 75°F; adequate dissolved oxygen levels and food supply; and substrates between 0.3 and 5.0 inches in diameter. Water withdrawals and pollution from hazardous materials, pesticide use, construction, and stormwater are all listed as threats to this species and its ecosystem (USFWS 2007).

### 3.5.5 San Marcos Salamander (*Eurycea nana*)

The San Marcos salamander is a member of the lungless salamanders, belonging to the family Plethodontidae. San Marcos salamanders were first collected from the San Marcos Springs and described in 1938 (Bishop 1943). It was once thought that the San Marcos salamander in the San Marcos River and the Texas salamander (*Eurycea neotenes*) in the Comal River were the same; however, investigations by Chippendale et al. (1992, 1994, and 1998) have suggested that these two populations may be genetically different. The San Marcos salamander was listed as threatened by the USFWS in 1980 (USFWS 1996; 45 FR 47355). Critical habitat has been designated for the San Marcos salamander—specifically, Spring Lake and its outflow as well as the San Marcos River downstream to 50 meters below Spring Lake Dam (USFWS 1996).

San Marcos salamanders are small, reaching a maximum length of 58.4 mm; slender; and light brown in color. Prominent features include large eyes with a dark ring around the lens, well-developed and highly pigmented external gills, moderately short and slender limbs with four toes on the forefeet and five on the hind feet, and a well-developed tail fin. San Marcos salamanders are distinct compared to other neotenic *Eurycea* from Texas in that they are smaller and more slender. They have different coloration, a greater number of costal grooves (i.e., vertical wrinkles in the skin between front and hind legs), larger eyes relative to their head, and fewer teeth (Tupa and Davis 1976; USFWS 1996). As a neotenic species, the San Marcos salamander retains juvenile characteristics such as gills and tail fins throughout its adult life stage. Water issuing from the springs has a low oxygen content (30 to 40 percent saturated), causing the external gills of the San Marcos salamander to have a bright red coloration due to increased blood flow through the gills (Tupa and Davis 1976).

San Marcos salamanders are found in Spring Lake and downstream of the dam at Spring Lake (Tupa and Davis 1976; Nelson 1993). Flowing waters are one of the main components necessary for survival of the San Marcos salamander. They prefer waters that are slightly alkaline (pH 7.2) and thermally constant, approximately 21°C to 22°C (69.8°F to 71.6°F), with oxygen saturation of 40 to 50 percent and little variation in bicarbonate alkalinity (220 to 232 mg/l) (Tupa and Davis 1976). They associate with rocky areas around spring openings, requiring clean, clear waters. In Spring Lake, San Marcos salamanders most often associate with mesohabitats, consisting of gravel, cobble, and boulders with a higher coverage of *Amblystegium* sp. and filamentous algae (Diaz et al. 2015). Individuals can also be found in *Lyngbya* sp., a filamentous blue-green algae that covers shallow, sandy substrates and provides a good hiding place by means of camouflage for the salamanders (BMWD 1998; USFWS 1996). Populations have been found in front of the Meadows Center for Water and the Environment office building on concrete banks and in boulders that are covered with an aquatic moss (*Leptodictyium riparium*) (USFWS 1996). Downstream of Spring Lake in the riverine portion of their range, salamanders frequently associate with bare rock surfaces that lack macrophyte cover (Diaz et al. 2015). Numerous rooted aquatic macrophytes occur on the boundary of the salamander habitat at suitable depths, including *Sagittaria*, *Ludwigia*, and *Vallisneria*. Individuals can be found within these mats of vegetation at the shallow headwater areas because the vegetation houses food sources and offers protective cover for avoidance of predators (i.e., larger fish, crayfish, turtles, and aquatic birds) (Tupa and Davis 1976; USFWS 1996a). The main food source of the San Marcos salamander is amphipods. Stomach content analyses have shown that San Marcos salamanders also feed on tendipedid (midge fly) larvae and pupae, other small insect pupae and naiads, and small aquatic snails. San Marcos salamanders are stationary feeders, waiting for prey to come near, indicating a behavioral response to sensory cues from living prey (Tupa and Davis 1976).

Sexual maturity in male San Marcos salamanders occurs when they reach a snout-vent length of 19 mm or total length of 35 mm (Tupa and Davis 1976). MacKay (1952) found sperm in all mature males from October to May and postulated that they have a breeding season in June and another in the fall. Similarly, Tupa and Davis (1976) and Bogart (1967) performed studies on the San Marcos salamander that suggest they breed most of the year, with a peak in late spring (May and June). Females reach sexual maturity with a snout-vent length greater than 20 mm or total length greater than 35 mm. Females carrying large yellow ova were considered ready for oviposition and found in almost every month of the year. Both male and female San Marcos salamanders utilize chemical cues, in addition to visual cues, to seek out potential mates, a rare behavior in salamanders (Thaker et al. 2006). Courtship and egg deposition have not been observed, and no eggs have been collected from the San Marcos salamander's natural habitat. Typically, *Eurycea* breed in the running water of streams and springs or in caves; their adherent eggs are singly deposited on the bottom and sides of vegetation or rocks (USFWS 1996).

Attempts to estimate population size have also been made. The San Marcos salamander population found in the shallow area of Spring Lake, along the northern bank in front of the Aquarena Springs Hotel, was estimated by Tupa and Davis (1976) to be 20,880. In 1991, the population was estimated at 23,200 in the same area, at 25,238 for rocky substrates around spring openings, and at 5,213 for rocky substrates 492 feet (150 meters) downstream of the Spring Lake Dam, for a total population estimate of 53,651 (Nelson 1993). Long-term density trends indicate that densities in Spring Lake are higher than densities downstream of Spring Lake Dam (BIO-WEST 2022). Threats to the persistence of San Marcos salamander populations include reduced springflow and increased sedimentation.

### 3.5.6 Texas Blind Salamander (*Eurycea rathbuni*)

The Texas blind salamander, a member of Plethodontidae, was first collected in 1895 from the National Fish Hatchery and Technology Center (NFHTC) in San Marcos, Texas, when specimens were expelled from an artesian well drilled to supply the hatchery with water (Longley 1978). Earlier taxonomists supported the recognition of genus *Typhlomolge* (Wake 1966; Potter and Sweet 1981); however, Mitchell and Reddell (1965) stated that the Texas blind salamander represents *Eurycea,* an extreme cave-associated morphology. Based on biochemical, morphometric, and molecular techniques, Chippindale et al. (1994) concluded that the Texas blind salamander is phylogenetically within the Texas *Eurycea* group. This conclusion has been more recently supported by allozyme and mitochondrial genetic (DNA) sequence studies by Chippendale et al. (2000). The USFWS reassigned this species as *Eurycea*. Texas blind salamander was listed as federally endangered in 1967 (32 FR 4001).

The distribution of Texas blind salamander may be the Aquifer beneath and near San Marcos in an area as small as 25.9 square miles (USFWS 1996). All collections of Texas blind salamanders documented in the literature have occurred in Hays County and include the San Marcos NFHTC, Ezell's Cave, San Marcos Springs, Rattlesnake Cave, Primer's Fissure, Texas State University's artesian well, and Frank Johnson's well (Longley 1978; Russell 1976). Previously, it had been found in Wonder Cave; however, searches in 1977 did not discover any individuals (Longley 1978). Recent collections and genetic work support a more widespread distribution of this species, including four additional sites: Hueco Springs, Comal Springs, Panther Canyon Well, and Mission Bowling Well in Comal County (Bendik et al. 2013).

The Texas blind salamander is a smooth, unpigmented troglobitic (cave-adapted) aquatic species. In the wild, maximum length is reported at 145 mm, and maximum age is estimated to be greater than 10 years. However, one female at the San Marcos Aquatic Resources Center (SMARC) was estimated to be 20 years old, measuring 146.5 mm (Vieira et al. 2021). The salamander has a large and broad head, reduced eyes (two small dark spots beneath the skin), and long and slender limbs with four toes on the forelegs and five on the hind legs. Like San Marcos salamanders, Texas blind salamanders are neotenic. External gill branches and cutaneous gas exchange facilitate respiration (Emerson 1905). External characteristics to determine sex are unknown. Because of the presence of juveniles year-round, the Texas blind salamander appears to be sexually active throughout the year, most likely due to the thermally constant waters of the Aquifer. Studies of this species while in captivity have found that the Texas blind salamander differs from other salamanders in that females use chemical cues to seek males or avoid other females as well as initiate courtship (Gabor et al. 2010; Vieira et al. 2021). In addition, studies in captivity noted three spawning events in 1 year, with a clutch size of eight to 21 eggs per spawning (Longley 1978). Unpigmented eggs were attached to gravel either singly or in groups of two or three eggs. It was suggested that a constant water temperature within the Aquifer is essential for normal egg development (Longley 1978), although no thermal minima or maxima have been determined for their various life stages (Berkhouse and Fries 1995; Longley 1978). Eggs hatch within 12 to 16 days after laying, and larvae begin feeding within 1 month after hatching. Young salamanders feed on copepods; larger salamanders eat amphipods, blind shrimp (*Palaemonetes antrorum*) in captivity, daphnia, small snails, and other invertebrates. Cannibalism has also been documented with the Texas blind salamander (USFWS 1996).

## 3.5.7 Texas Wild-Rice (*Zizania texana*)

Texas wild-rice is an aquatic, monoecious perennial grass (Poaceae) that is endemic to the San Marcos River. This species was originally collected in 1892 and identified as southern wild-rice (Z. *aquatica*). However, the plant was later collected and recognized as a distinct species by W. A. Silveus in 1932 (Silveus 1933) and described as Texas wild-rice by A. S. Hitchcock in 1933 (Hitchcock 1933). Texas wild-rice is thought to have evolved in geographic isolation from other species of *Zizania*, although some suggest *Z. texana* represents a relict population that became isolated during the early Holocene (Horne and Kahn 1997). The nearest present-day population is a coastal plain population of Z. *aquatica* in southern Louisiana, approximately 400 miles (640 kilometers [km]) away. It is morphologically different from Z. *texana* (Terrell et al. 1978).

Texas wild-rice attaches to the substrate using short, tightly intertwined spongy roots (Beaty 1975). The linear leaves can be up to 3.3 feet long and 0.5 inch wide (Poole et al. 2007; Terrell et al. 1978). Texas wild-rice forms large clumps that become rooted in sand and gravel sediments, which are overlain by Crawford black silt and clay (Vaughan 1986). This species requires thermally constant temperatures, clear water, undisturbed stream bottom habitat, protection from floods, and protection to allow inflorescence (flower production) during reproduction (McKinney and Sharp 1995). It has two growth forms: submerged, which reproduces asexually, and emergent, which is capable of flowering. Both forms exhibit distinct morphological characteristics (Silveus 1933). The submerged growth form is found primarily at a depth of less than 3.3 feet in swift-moving, shallow runs with coarse sandy substrates in the Upper San Marcos River (Poole and Bowles 1999). Through the help of restoration efforts, flowering plants are now a common occurrence in the wild, as demonstrated by greater genetic diversity than would be predicted in an asexually reproducing species (Richards et al. 2007; Wilson et al. 2017). Flowering typically occurs in the spring and fall but may be seen throughout the year due to constant water temperatures. Texas wild-rice does reproduce vegetatively, from stolons, and appears to re-establish readily when uprooted and relocated during flood events. (BIO-WEST 2003a, 2003b). Texas wild-rice stands are often associated with other aquatic plant species. *Hydrilla verticillata*, *Hygrophila polysperma*, and *Potamogetan illinoensis* are commonly found growing with Texas wild-rice (BIO-WEST 2020). In the lower sections of rivers, Texas wild-rice is found in isolated clumps.

When Texas wild-rice was first described in 1933, it was found in abundance in the upper 4.0 km of the San Marcos River, Spring Lake, and contiguous irrigation ditches, requiring considerable effort by irrigation companies to control its growth (Terrell et al. 1978; Silveus 1933). By 1976, Texas wild-rice was not observed in Spring Lake. The estimated total coverage was 1,131 $m^2$ of habitat in the extreme upper and lower segments of the 1.5-mile reach of the Upper San Marcos River (Emery 1977). Drastic declines in abundance led to the listing of Texas wild-rice as an endangered species in 1978. The species' critical habitat was designated as Spring Lake and its outflow as well as the San Marcos River downstream to its confluence with the Blanco River (USFWS 1980). After the listing, continued decline occurred in the areal coverage of Texas wild-rice until it declined to just 453 $m^2$ (Vaughn 1986). Coverage began to slowly increase in 1989. It greatly increased beginning in 2013, following restoration efforts by the City of San Marcos and Texas State University (Poole et al. 2022). By 2021, Texas wild-rice reached the highest areal coverage ever documented: 17,235 $m^2$ (BIO-WEST 2021). This high coverage was most likely a result of little to no recreation in the river during 2020–2021, which was related to the COVID-19 lockdown. After its peak in April 2021, Texas-wild-rice began a decreasing trend, most likely due to the compounding effects of continued low flows and increased recreation. Historically, the species was present in an area just below a wastewater treatment plant. In 2015, a large flood event drastically reduced coverage throughout this reach, which limited the longitudinal distribution to just downstream of Cape's Dam. Despite several years of post-flood recovery, Texas wild-rice still remains rare downstream of the Interstate 35 bridge. Planting efforts have contributed to increased coverage throughout this reach in recent years. In 2017, the USFWS began maintaining refugia for Texas wild-rice. Its 430 plants are divided between the San Marcos Aquatic Research Center and Uvalde National Fish Hatchery (USFWS 2021).

The main threats to Texas wild-rice include diminished springflow and disturbances to the environment (USFWS 1996). During times of low flow, the upper portions of the culms (stems) and leaves become emergent (Terrell et al. 1978; USFWS 1996) or entirely stranded, leading to desiccation. Diminished springflow results in an increase in sedimentation, water depth, and turbidity and a decrease in current velocities, contributing to a loss of habitat for Texas wild-rice growth—specifically, throughout the lower portions of its historic range (Poole and Bowles 1999). Although water depth and current velocity are a direct result of the influence of springflow into the San Marcos River, the impacts of increased sedimentation and turbidity on Texas wild-rice are largely a result of urbanization within the contributing watershed. Cumulative turbidity caused by recreation is a major concern for Texas wild-rice. This means that impacts from turbidity due to high levels of recreation in upstream reaches (e.g., Sewell Park) will be worse in downstream reaches (e.g., Interstate 35 reach). In addition, impacts from recreationists (e.g., tubing), floating debris (e.g., aquatic vegetation cut at Spring Lake or on the property of landowners), shade that reduces photosynthesis, or interference with pollination and seed maturation can damage the plants (Beaty 1975; Poole 1992). Herbivory by nutria (Myocastor coypus), the introduced giant rams-horn snail (*Marisa cornuarietis*), and waterfowl as well as competition from aquatic plants are believed to be significant factors in reducing the size and vigor of Texas wild-rice stands (McKinney and Sharp 1995). The invasion of water trumpet (*Cryptocoryne beckettii*) in 1993 was thought to be a new threat to Texas wild-rice because it competes for nearly identical habitats. It became established in the section of the San Marcos River from the A. E. Wood State Fish Hatchery to the confluence of the San Marcos and Blanco Rivers. Extensive efforts by USFWS and volunteers have resulted in water trumpet being almost entirely removed from the river (Alexander et al. 2008).

## 3.6 Other Covered Species

There are other species within the Plan Area that are proposed for listing as threatened or endangered. The following two species are recommended for continued coverage by this HCP: Edwards Aquifer diving beetle (*Haideoporus texanus*) and Texas troglobitic water slater (*Lirceolus smithii*). These aquatic invertebrates have similar ranges, habitats, and threats as the listed species described above in Section 3.5.

The following sections summarize the locations, habitat requirements, and morphological descriptions of the two species, for which a USFWS 90-day finding indicates that listing as threatened or endangered may be warranted (74 FR 66,866 [December 16, 2009]).

### 3.6.1 Edwards Aquifer Diving Beetle (*Haideoporus texanus*)

The Edwards Aquifer diving beetle (Coleoptera: Dytiscidae: Hydroporini), also known as the Texas cave-diving beetle, is a small (up to 3.5 mm for adult; up to 5.5 mm for larvae), elongated, oval-shaped, and somewhat flattened species. It was collected as early as 1973 and later described by Young and Longley (1976); larvae were described by Longley and

Spangler (1977). This species is restricted to the subterranean waters of the Aquifer in Hays and Comal Counties where it has been collected from the Texas State University artesian well and from Comal Springs, respectively (Bowles and Stanford 1997; Gibson et al. 2008). Throughout implementation of the EAHCP (2013–2023), approximately 30 individual Edwards Aquifer diving beetles have been collected through drift net sampling over spring orifices in Comal Springs. Collection typically occurs during wet periods with high springflow output. In San Marcos Springs, collections have been confirmed at the Texas State University artesian well, but the numbers are limited. These beetles have reduced, nonfunctional eyes and greater development of the sensory setae (hairs) on their wings, legs, and mouth area (Young and Longley 1976). This species was the first blind, unpigmented, and aquifer-adapted water beetle known from North America, but three other endemic stygobiontic dytiscids are now known from Texas aquifers (Jean et al. 2012; Miller et al. 2009; Spangler and Barr 1995). The biological characteristics of all four species are poorly known. The phylogenetic placement of *H. texanus* is close to *Neoporus* and *Heterosternuta* in the subtribe Hydroporina, with two of the other stygobiontic species more distantly related within the subtribe Siettitiina (Hydroporini) and the third in the tribe Bidessini (Miller et al. 2013).

The USFWS (2009) has declared that substantial information was presented in the petition to list the species as threatened or endangered, indicating that listing of this species may be warranted due to the present or threatened destruction, modification, or curtailment of its habitat or range resulting from water drawdown and loss of water quality due to development.

### 3.6.2 Texas Troglobitic Water Slater (*Lirceolus smithii*)

The Texas troglobitic water slater, as described by Ulrich (1902), is one of four described species of *Lirceolus* in the Edwards Aquifer (Lewis and Bowman 1996; Lewis 2001). Schwartz et al. (2018) provided a key for identification of the species of *Lirceolus* in Texas, based on external morphological characteristics. Phylogeographic work on *Lirceolus* showed patterns of relatedness that follow surface river drainage basins (Krejca 2005); multiple species in the genus occur together at individual sites in the Edwards Aquifer (Schwartz et al. 2018). Members of this genus are not commonly collected. *L. smithii* is known only to discharge from artesian deep-aquifer sites; discharged individuals are typically in poor condition (Schwartz et al. 2018). In captivity, most individuals died within 24 hours, and none have survived more than 1 week (Schwartz et al. 2018).

This species was previously known from two localities in the San Marcos Springs system of Hays County: Diversion Springs and an artesian well. However, more recently, it was found at the Spring Lake outflow well by Schwartz et al. (2018). Only the single San Marcos population is known. The full extent of its range is undetermined because of the lack of other artesian wells in the area from which it could be discharged. Its deep habitat suggests it may be insulated from short-term perturbations in the aquifer; however, it is possible that pollutants in the aquifer may harm the species (Schwartz et al. 2018). Although no *Lirceolus* have formal protection, several of the species are endemic to small areas. A regional HCP in Hays County recognizes *Lirceolus smithii* as a species that could become listed as threatened or endangered in the future (Loomis Partners, Inc. et al. 2010).

The USFWS (2009) has declared that substantial information was presented in the petition to list the species as threatened or endangered, indicating that listing of this species may be warranted due to the present or threatened destruction, modification, or curtailment of its habitat or range resulting from aquifer drawdowns and decreasing water quality.

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