Comal Springs Riffle Beetle
(*Heterelmis comalensis*)
5-Year Status Review:
Summary and Evaluation

U.S. Fish and Wildlife Service
Austin Ecological Services Field Office
Austin, Texas
May 20, 2024

5-YEAR REVIEW

Species reviewed: Comal Springs riffle beetle (*Heterelmis comalensis*)

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1.0 GENERAL INFORMATION

1.1 Reviewers:

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Cooperating Field Office(s):
Not Applicable

Cooperating Regional Office(s):
Not Applicable

1.2 Purpose of 5-Year Reviews:

The U.S. Fish and Wildlife Service (Service or USFWS) is required by section 4(c)(2) of the Endangered Species ESA (ESA) to conduct a status review of each listed species once every 5 years. The purpose of a 5-year review is to evaluate whether or not the species' status has changed since it was listed (or since the most recent 5-year review). Based on the 5-year review, we recommend whether the species should be removed from the list of endangered and threatened species, be changed in status from endangered to threatened, or be changed in status from threatened to endangered. Our original listing as endangered or threatened is based on the species' status considering the five threat factors described in section 4(a)(1) of the ESA. These same five factors are considered in any subsequent reclassification or delisting decisions. In the 5-year review, we consider the best available scientific and commercial data on the species and focus on new information available since the species was listed or last reviewed. If we recommend a change in listing status based on the results of the 5-year review, we must propose to do so through a separate rule-making process including public review and comment.

1.3 Methodology used to complete the review:

The Service conducts status reviews of species on the List of Endangered and Threatened Wildlife and Plants (50 CFR 17.12) as required by section 4(c)(2)(A) of the ESA (16 U.S.C. 1531 et seq.). The Service provides notice of status reviews via the Federal Register and requests new information on the status of the species (e.g., life history, habitat conditions, and threats). Data for this status review were solicited from interested parties through a Federal Register notice announcing this review on May 5, 2021 (86 FR 23976). The Austin

Ecological Services Field Office conducted this review and considered both new and previously existing information from federal and state agencies, municipal and county governments, non-governmental organizations, academia, and the public. The primary sources of information used in this analysis was the final rule listing the Comal Springs riffle beetle as endangered (62 FR 66295), revised critical habitat ruling for the Comal Springs riffle beetle (78 FR 63100), research published in scientific journals, and unpublished reports and data.

1.4 Background:

1.4.1 FR Notice citation announcing initiation of this review:

86 FR 23976 May 5, 2021

1.4.2 Listing history:

Original Listing
FR notice: 62 FR 66295
Date listed: December 18, 1997
Entity listed: Comal Springs riffle beetle (*Heterelmis comalensis*)
Classification: Endangered

Revised Listing, if applicable
FR notice: Not Applicable
Date listed: Not Applicable
Entity listed: Not Applicable
Classification: Not Applicable

1.4.3 Associated Rulemakings:

The original designation of critical habitat, contained in the final rule, was published on July 17, 2007 (72 FR 39248). Critical habitat for Comal Springs riffle beetle was revised on November 22, 2013, in areas of occupied, spring-related aquatic habitat with designations for surface critical habitat but without additional subsurface designations (78 FR 63100). Springs, associated streams, and underground spaces immediately inside of or adjacent to springs, seeps, and upwellings are the primary components of the physical or biological features essential to the conservation of this species (50 CFR 17.95; 78 FR 63123).

1.4.4 Review History:

Not Applicable

1.4.5 Species' Recovery Priority Number at start of 5-year review:

2C

1.4.6 Recovery Plan or Outline

Name of plan or outline: Not Applicable
Date issued: Not Applicable
Dates of previous plans/amendment or outline, if applicable: Not Applicable

2.0 REVIEW ANALYSIS

Section 4 of the ESA (16 U.S.C. 1533) and its implementing regulations (50 CFR part 424) set forth the procedures for determining whether a species meets the definition of “endangered species” or “threatened species.” The ESA defines an “endangered species” as a species that is “in danger of extinction throughout all or a significant portion of its range,” and a “threatened species” as a species that is “likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range.” The ESA requires that we determine whether a species meets the definition of "endangered species" or "threatened species" due to any of the five factors described below.

Section 4(a) of the Act describes five factors that may lead to endangered or threatened status for a species. These include: A) the present or threatened destruction, modification, or curtailment of its habitat or range; B) overutilization for commercial, recreational, scientific, or educational purposes; C) disease or predation; D) the inadequacy of existing regulatory mechanisms; or E) other natural or manmade factors affecting its continued existence.

The identification of any threat(s) does not necessarily mean that the species meets the statutory definition of an “endangered species” or a “threatened species.” In assessing whether a species meets either definition, we must evaluate all identified threats by considering the expected response of the species, and the effects of the threats—in light of those actions and conditions that will ameliorate the threats—on an individual, population, and species level. We evaluate each threat and its expected effects on the species, then analyze the cumulative effect of all of the threats on the species as a whole. We also consider the cumulative effect of the threats in light of those actions and conditions that will have positive effects on the species—such as any existing regulatory mechanisms or conservation efforts. The Service recommends whether the species meets the definition of an “endangered species” or a “threatened species” only after conducting this cumulative analysis and describing the expected effect on the species now and in the foreseeable future.

2.1 Distinct Population Segment (DPS) policy (1996):

This is an invertebrate and DPS policy is not applicable.

2.2 Updated Information and Current Species Status

2.2.1 Biology and Habitat

2.2.1.1 New information on the species’ biology and life history:

Background

On the whole, riffle beetles are most associated with flowing water that has shallow riffles or rapids (Brown 1987, p. 253). The Comal Springs riffle beetle was first collected in 1976 at Comal Springs in Comal County, Texas and later discovered at San Marcos Springs in Hays County, Texas (Bosse et al. 1988, pp. 201-202; Barr 1993, pp. 31, 44; Gibson et al. 2008, p. 79). This species currently does not have a final recovery plan and this is the species' first 5-year review since listing in 1997.

Biology

Adult Comal Springs riffle beetles, which were first described in 1988, exhibit a reddish-brown coloration, possess eyes, and vary in length from 1.7-2.48 millimeters (0.07-0.09 inch) (Bosse et al. 1988, pp. 199, 202; Worsham and Julius 2017, p. 28). They respire through a plastron, facilitated by small, hydrophilic hairs that diffuse oxygen from the water into the body (Bosse et al. 1988, p. 199; Yee and Kehl 2015, pp. 1011, 1030). The hind wings of Comal Springs riffle beetles are short and non-functional, a subterranean characteristic that renders this species incapable of flight (Bosse et al. 1988, p. 201; Bowles et al. 2003, p. 379). Unlike other animals adapted to subterranean environments, Comal Springs riffle beetles do not possess additional features such as reduced or lack of eyes and pigmentation (Cooke et al. 2015, p. 117).

The larvae of Comal Springs riffle beetles are characterized by their elongated bodies, retractable heads, feature dorsal spines and a more flattened head capsule shape. These aquatic larvae develop anal gills used to retrieve oxygen from water (Brown 1987, p. 261). The pupae of Comal Springs riffle beetles are pale in color and possess setae that facilitate oxygen intake into the body. It is unknown whether the hydrophobic setae play a role in facilitating respiration underwater, possibly similar to the plastron observed in adult beetles (Huston and Gibson 2015, pp. 522-523).

Comal Springs riffle beetles are detritivores, feeding on organic matter sourced from terrestrial coarse and particulate materials scraped off substrates of microbial origin, including fungi and bacteria, as well as periphyton. This feeding behavior remains consistent irrespective of the canopy cover (Brown 1987, p. 262; Nowlin et al. 2017, pp. 16-18, 21, 27). A co-occurring listed species, the Comal Springs dryopid beetle (*Stygoparnus comalensis*), derives most of its food from the same organic matter sources but has a niche overlap of less than or equal to 1 percent with the riffle beetle at Comal Springs (Nair et al. 2021, p. 244).

Life History

Surveys of Comal Springs riffle beetles indicate they have asynchronous generations, likely due to the consistent water quality at occupied springs (Bowles et al. 2003, p. 376; BIO-WEST, Inc. 2006, p. 39). Other elmid beetles with stable environmental conditions can affect emergence timings and oviposition based on changes in water velocity or temperature and food availability (Passos et al. 2003, p. 34). There are no known indicators or mechanisms for emergence of the Comal Springs riffle beetle.

Female adult Comal Springs riffle beetles reproduce multiple times annually with up to 121 larvae produced in their lifetime (Kosnicki 2022, p. 2). In an egg deposition study, treatments with biofilm poly-cotton cloth as the substrate contributed to the most eggs hatching into viable larvae, suggesting the biofilms produced on the cotton cloth may be an important nutritional requirement for egg development (Worsham and Julius 2017, p. 12). Additionally, hatching success depends on the nutritional quality females received in captivity (Worsham and Julius 2017, p. 14).

Eggs have translucent shells facilitating damage-free observation of development (Worsham and Julius 2017, p. 11). Egg development and incubation occur for 21-25 days until hatching, which is longer than other riffle beetle species (e.g., 5-15 days) (Brown 1987, p. 254; Worsham and Julius 2017, p. 16). There is no evidence of diapause (i.e., period when development is delayed during unfavorable environmental conditions) during the incubation period either in captivity or in the wild (Bowles et al. 2003, p. 37; Worsham and Julius 2018, p. 3). Egg development starts with globular bodies like early cells of a zygote (i.e., 3 days), to more cell division and smaller cells developing (i.e., 7 days), to tissue differentiation with an embryo visible and budding appendage (i.e., 14-18 days), to a full developed larvae observable inside the egg with a faint red eye (i.e., 21 days) and hatching from the egg after 25 days (Worsham and Julius 2017, p. 15).

Larvae undergo six molts for a total of seven instars, reaching the final instar at 12 weeks (Cooke 2012, p. 28; Worsham and Julius 2017, p. 17). Similar to the adults, Comal Springs riffle beetle larvae feed on allochthonous material and acquire nutrients from associated microbial communities, particularly bacteria (Nair et al. 2021, p. 245). In captivity, larvae have been observed to persist in the final instar phase for over four months before pupating, possibly to assimilate nutrients necessary for the pupation process, due to inadequate habitat conditions, or because of food quality issues (Worsham and Julius 2017, pp. 17, 24). Notably, temperature variations within the range of 19-25 degrees Celsius (°C) (66-77 degrees Fahrenheit [°F]) were not found to significantly affect larval survival (Worsham and Julius 2017, p. 20).

The Comal Springs riffle beetle exhibits an extended period of larval development, leading to the emergence of delicate pupae, thus highlighting the complexity of its metamorphic process. The process of eclosion (i.e., hatching), during which larvae develop into pupae, takes approximately one month (Worsham and Julius 2017, p. 24). However, a more recent study provides detailed insights into the larval development, indicating that pupation occurs 38 weeks (8.8 months) post-hatching, with more than half of that duration spent in the 7th instar (Worsham and Julius 2018, p. 5).

Pupae for this species are capable of eclosing both underwater and right below the waterline possibly due to trapped air in their pupal case (Cooke 2012, p. 38; Huston and Gibson 2015, p. 523). Unfortunately, they are susceptible to damage, causing them to lose their hydrophobic qualities (Huston and Gibson 2015, p. 522). Following eclosion, adult individuals are initially light yellow in color (i.e., teneral) and gradually darken to an orange-brown, typical of mature adults. During this early stage of adulthood, the internal abdominal structure for determining sex is challenging to discern.

Adults in captivity have been reported to live up to a year with an average generation time of two years, although further research is needed (Bowles et al. 2003, p. 376; Worsham and Julius 2017, p. 24). The gut microbiome of captive adults, which is influenced by various factors, including a different and more diverse bacterial community than that of their wild counterparts, may be attributed to human contact, varying sources of water with differing geochemical concentrations within the aquifer, or locations within the aquifer between the two source counties. These factors could potentially alter the microbial community. Additionally, biofilm shedding from well water pipes at captive facilities may play a role (Mays et al. 2021, pp. 3, 9).

2.2.1.2 Abundance, population trends (e.g. increasing, decreasing, stable), demographic features (e.g., age structure, sex ratio, birth rate, seed set, germination rate, age at mortality, mortality rate, etc.), or demographic trends:

Little is known about limiting factors that may impact the abundance and distribution of the Comal Springs riffle beetle. Current abundance estimates only include samples collected at the surface.

Abundance of Comal Springs riffle beetles did not correlate significantly with water depth, current velocity, and distance downstream from the primary spring outlets (Bowles et al. 2003, pp. 370-371). Typical water depth in occupied habitat is 2-10 centimeters (cm) (1-4 inches (in)), but the beetle has been found in slightly deeper areas within the spring runs and around the spring upwellings at the impoundments (Bosse et al. 1988, p. 202; BIO-WEST, Inc. 2007, p. 23). A mark-recapture study retrieved < 1 percent of the 100 beetles marked, suggesting the population in the sampling area (western shoreline of Landa Lake) is large (Huston et al. 2015, p. 797).

Larval and adult Comal Springs riffle beetle populations at Comal Springs may reach their greatest densities (i.e., about five per square meter) in late fall through winter, but all life stages can be found throughout the year, suggesting multiple broods in a season with overlapping generations (Bowles et al. 2003, p. 396). Biomonitoring of all benthic macroinvertebrates in the Comal Springs system occurs biannually, during spring and fall, and was initially established in 2000 using driftnets. Targeted sampling of spring orifices, employing poly-cotton cloth traps, commenced in 2003 (BIO-WEST, Inc. 2003, pp. 37-41; BIO-WEST, Inc. 2004, p. 38). This particular species has been consistently collected within the Comal Springs system since 2003 (BIO-WEST, Inc. 2007, p. 39).

Notably, larvae of this species are captured in lower numbers during biomonitoring using the poly-cotton cloth method, suggesting potential differences in habitat preference or a sampling bias where the biofilms produced on the cloth are not preferred by this life stage (BIO-WEST, Inc. 2005, p. 65). It is important to consider these nuances in sampling methods, especially when interpreting biomonitoring data for different life stages. Additionally, there are no population estimates available for this species, and caution is advised against utilizing the numbers of beetles retrieved with this cloth method to estimate population trends due to the associated high error rate and large natural variability of the Comal Springs population (Huston et al. 2015, p. 796-797; EARIP HCP 2020, p. 4-108–4-109).

San Marcos Springs, another ecosystem where the Comal Springs riffle beetle is present with an established population, lacks comprehensive monitoring data for its springflow and is not included in the Edwards Aquifer Recovery Implementation Program (EARIP) Habitat Conservation Plan (HCP). Unfortunately, the absence of such data makes it challenging to determine the current status of the habitat. The uncertainty surrounding the springflow data for San Marcos Springs emphasizes the need for further investigation to assess and safeguard the habitat of the Comal Springs riffle beetle in this particular ecosystem.

2.2.1.3 Genetics, genetic variation, or trends in genetic variation (e.g., loss of genetic variation, genetic drift, inbreeding, etc.):

Although the Comal Springs riffle beetle is a genetically distinct species, the species is most closely related to but divergent from *H. glabra*; a species capable of flight associated with rivers and streams (Gonzales 2008, pp. 24-25). Bosse et al. (1988, p. 202) speculated that the Comal Springs riffle beetle likely evolved from an isolated population of *H. glabra,* which was substantiated by Gonzales (2008, p. 38).

Three populations of the Comal Springs riffle beetle had high genetic variation: two at Comal Springs (Spring Island and western shoreline of Landa Lake) and San Marcos Springs (Gonzales 2008, p. 32). This isolation is due to the lack of recent gene flow, but historically they had a common ancestral population (Gonzales 2008, p. 32).

Recent genetics suggests an even greater degree of isolation among populations (W. Coleman, unpublished data). The spring runs and backwater spring populations have dried up during drought periods and genetic bottlenecks were apparent (Gonzales 2008, p. 34). Dye tracing studies show a different water source for each of the three high-variance populations and informs the experienced bottlenecks during extensive drought periods (LBG-Guyton and Associates et al. 2004, pp. B-24, B-30; Johnson and Schindel 2008, pp. 12, 49, 59; Musgrove and Crow 2012, pp. 80, 86-87).

2.2.1.4 Taxonomic classification or changes in nomenclature:

Elmidae (Insecta: Coleoptera) is a family of true aquatic beetles distributed worldwide except for Antarctica with approximately 146 genera (Yee and Kehl 2015, p. 1030). There are 35 riffle beetle species in Texas, with four species in the genus *Heterelmis* (Nair et al. 2019, p. 1076; Barr 2021, p. 93).

2.2.1.5 Spatial distribution, trends in spatial distribution (e.g. increasingly fragmented, increased numbers of corridors, pollinator availability, etc.), or historic range (e.g. corrections to the historical range, change in distribution of the species' within its historic range, etc.):

Comal Springs riffle beetle are an epigean (i.e., surface-dwelling), groundwater obligate invertebrate known from two major spring systems: Comal Springs at the spring outlets and Landa Lake (Comal County, Texas) and San Marcos Springs at a few headwater springs of Spring Lake (Hays County, Texas) (Bosse et al. 1988, entire; Barr 1993, pp. 31, 44; Gibson et al. 2008, p. 79).

Due to their flightless nature, these beetles have low dispersal abilities, limiting them to crawling or drifting downstream to habitats with adequate food resources and within their preferred physicochemical range. Their highest abundance is within 20 cm (8 in) from a spring outlet, and they are absent at a 1-meter (m) (3 feet (ft)) distance when sampling the surface with cotton cloth traps (Cooke et al. 2015, pp. 114, 117-118; Huston et al. 2015, p. 797; Worsham and Julius 2017, p. 6). Specific springflow requirements and the extent of subterranean habitat usage by this species remain unknown; therefore, habitat management relies on maintaining historical conditions within the natural habitat for the species (LBG-Guyton and Associates et al. 2004, pp. C-4–C-5).

Comal Springs riffle beetle are also found in deeper habitats where diffuse springflows are present (BIO-WEST, Inc. 2005, p. 51; 2006, p. 39). Within these more lentic habitats, the beetles exhibit higher movement rates compared to a site at Comal Spring Run 3, suggesting their ability to seek more suitable microhabitat conditions despite their inability to disperse via flight (BIO-WEST, Inc. 2006, p. 39).

Previously, it was believed that the existence of this species at Comal Spring Run 4 was unlikely due to the lentic conditions and the dominance of a silt substrate (Bowles et al., 2003, p. 376). No specimens were identified in multiple surveys until 2020, when a few were collected by Texas State University (Nowlin and Worsham, 2015, p. 12; Nowlin, 2022, pers. comm.). Subsequent surveys of Comal Spring Run 4 did not reveal any further instances of this species, indicating that the finding in 2020 may be a one-time occurrence (Gibson, unpublished data).

2.2.1.6 Habitat or ecosystem conditions (e.g., amount, distribution, and suitability of the habitat or ecosystem):

Comal Springs riffle beetles inhabit gravel and cobble-dominated substrates with aquatic vegetation and submerged wood present (Brown 1972, p. 57; Bowles et al. 2003, p. 372). They are best captured within or around spring orifices, even at shallow water depths (Bowles et al. 2003, pp. 367, 373; Gibson et al. 2008, p. 77; Cooke et al. 2015, p. 117). Comal Springs riffle beetles, being ectothermic, exhibit a stenothermal adaption, preferring temperatures between 22.5-25.5°Celsisu (°C) (72.5-78°Fahrenheit (°F)) (Huey and Kingslover 1989, p. 131; Nair et al. 2023, pp. 2, 6). This preference restricts them primarily to these spring outlets because of a narrow tolerance to short-term temperature fluctuations (Nair et al. 2023, p. 6). In addition to their temperature preferences, these beetles are observed to avoid low concentrations of carbon dioxide and prefer dark spaces (Cooke et al. 2015, p. 115).

Continuous groundwater flows in San Marcos Springs result in nearly constant temperatures (2021 average: 22°C [72°F]) (Musgrove and Crow 2012, p. 47; Edwards Aquifer Authority 2022a, pp. 15–16). The flowing spring waters at San Marcos Springs at Spring Lake are clear with varying levels of dissolved oxygen, dependent on amount and source of discharge (less than 40 to 63 percent saturated, 2-7 milligram per liter [mg/L]) and few detections contaminants, such as of personal care products and pharmaceuticals (Tupa and Davis 1976, p. 182; Groeger et al. 1997, pp. 285-286; Nowlin and Schwartz 2012, pp. 65-67; EAA 2015, pp. 58-59). San Marcos Springs receives primarily regional recharge, but can be influenced by minor amounts of local recharge sources and/or saline groundwater for short periods, with water quality representative of shallow groundwater and no seasonality (Ogden et al. 1986, p. 120; LBG-Guyton Associates et al. 2004, p. B-43; Johnson and Schindel 2008, p. 60; Musgrove and Crow 2012, pp. 47, 80, 89; Nowlin and Schwartz 2012, p. 56).

The water temperature remains relatively stable at both the spring runs and Landa Lake at Comal Springs, measuring 20.7°C (69.3°F) and 23.9°C (75°F), respectively (BIO-WEST, Inc. 2021, p. 18). The spring runs maintain specific conductivity (579-587 micro siemens/centimeter (µS/cm)), and dissolved oxygen (5.1-5.2 mg/L), with few detections of contaminants, such as personal care products and pharmaceuticals (BIO-WEST, Inc. 2021, p. 18; EAA 2013, p. 62; EAA 2018, p. 5; EAA 2021a, pp. 27-36, 45-47).

Despite the general groundwater quality at Comal Springs, there has been a noticeable trend since the 1970s. While total dissolved solids and conductivity have been on the rise, they are currently stabilizing. Conversely, nitrates have doubled, with a median concentration of 2 mg/L, since the 1970s (Musgrove et al. 2016, pp. 462, 465, 467; EPA 2023a, unpaginated). These shifts in water quality within both streams and groundwater align with the escalation of impervious cover across the watershed (Kaushal et al. 2005, p. 13518; Baker et al. 2019, pp. 6494–6495; Castaño-Sánchez et al. 2020, p. 6). These alterations in water quality parameters may serve as a long-term indicator of the urbanization that has already transpired in the recharge zone.

2.2.1.7 Other:

The Comal Springs riffle beetle occurs in a limited range at a small number of localities with little or no ability to disperse between or beyond these localities. These characteristics make them susceptible to local extirpation and extinction (McKinney 1997 p. 499; Bowles et al. 2003 p. 380; O'Grady et al. 2004 p. 514). It is speculated that the riffle beetle may be able to retreat into spring openings or burrow down to the hyporheos (groundwater zone below the stream channel) during times of drought (Bowles et al. 2003 p. 359).

A severe drought or water contamination event could eliminate many or all the existing populations (Bowles et al. 2003 p. 380). Having a high number of individuals at a site provides no protection against extinction due to stochastic events. Dispersal beyond their extant range is unlikely, given the isolated nature of the spring headwater system dynamics and aquifer hydraulic connectivity that limit movement of individuals.

The areas inhabited by individuals of the species can be protected through localized conservation measures (e.g., intact riparian zones, springflow protection measures); however, the groundwater that provides water quality and quantity for the species can originate a significant distance from these habitats, and efforts that protect or conserve groundwater may be variable in their success and implementation. Even with the most effective management and recovery plans in place, the species remains vulnerable to devastating stochastic events such as floods or droughts that could eliminate the species.

2.2.1.8 Conservation Measures:

Water Quantity

The Edwards Aquifer Authority (EAA) is charged with protecting terrestrial and aquatic life, domestic and municipal water supplies, the operation of existing industries, and the economic development of the entire Edwards Aquifer (Chapter 626, Laws of the 73rd Texas Legislature, 1993). Aquifer management since these rules were implemented has been successful at controlling groundwater withdrawals to maintain springflows. By EAA estimates, Comal Springs would have likely ceased flowing during the 2014 drought period without current regulations (EAA 2015, p. 62). Currently, these regulations have been effective in managing the Edwards Aquifer and reducing the risk of substantial declines in spring flows at Comal and San Marcos springs.

Another important conservation measure is implementation of the City of San Antonio’s Edwards Aquifer Protection Program (Stone and Schindel 2002, pp. 38-39; City of San Antonio 2023, pp. 3, 6). In 2000, the voters of San Antonio passed Proposition 3, a $65 million sales tax initiative, to fund the acquisition (i.e., fee-simple and conservation easements) of open space to protect the contributing and recharge zones of the aquifer in Bexar County (Romero 2018, p. 2). Protection of open space has the potential to reduce the impacts of development (e.g., run-off form impervious cover, fertilizer applications, and wastewater) on maintain aquifer recharge (Reilly and Carter 2018, pp. 3-2, 3-6; Romero 2018, pp. 5-6). That program was re-approved in 2005, 2010, and 2015 with additional funds to acquire open space (Reilly and Carter 2018, pp. 1-3–1-5). The effort was later expanded to acquire lands in Medina and Uvalde counties that contain larger portions of the contributing and recharge zones (Romero 2018, pp. 5-6, 8). The dedicated sales tax expired in 2021 with 97,124 hectares (240,000 acres) acquired under the Edwards Aquifer Protection Program (Siglo Group 2022, pp. 51-52). The City of San Antonio recently approved an alternative funding stream to support land acquisitions through the commitment of $100 million over ten years (City of San Antonio 2023, pp. 3, 6).

Water Quality

There are several laws and regulations to protect water quality that apply to the Edwards Aquifer. The Federal Safe Drinking Water Act of 1974, as amended, regulates pollution and sedimentation of public drinking water sources, including the Edwards Aquifer. This legislation mandates enforcement of drinking water standards established by the Environmental Protection Agency. The Texas Commission on Environmental Quality (TCEQ) is responsible for enforcement of these standards in Texas. Under the authority of the Texas Administrative Code (TAC) (30 TAC § 213), the TCEQ regulates activities having the potential for polluting the Edwards Aquifer and hydrologically connected surface streams through the Edwards Aquifer Protection Program or “Edwards Rules.” The Edwards Rules require several water-quality protection measures for new development occurring in the recharge zone and portions of the contributing zone of the Edwards Aquifer. The TCEQ also prohibits facilities such as municipal solid waste landfills and waste disposal wells from being built in the recharge or transition zones.

Discharge from non-point residential or agricultural sources is one of the primary sources of pollution in the Edwards Aquifer. Texas has an extensive program for the management and protection of water that operates under State statutes and the Federal Clean Water Act. The Program includes regulatory programs such as the following: Texas Pollutant Discharge Elimination System, Texas Surface Water Quality Standards, and Total Maximum Daily Load Program (under Section 303(d) of the Clean Water Act).

The TCEQ’s Texas Pollutant Discharge Elimination System program regulates discharges of pollutants to Texas surface water. Through the Pollutant Discharge Elimination System program, the TCEQ authorizes the discharge of stormwater and non-stormwater to surface waters in Texas associated with storm sewer systems and construction sites, which must meet the requirements of the Edwards Rules.

A watershed protection plan was accepted in 2018 by TCEQ for the Dry Comal Creek and Comal River Watershed by the City of New Braunfels. Dry Comal Creek has not met state water quality standard for bacteria, and the watershed protection plan is intended to address and reduce the elevated bacteria levels through management (TCEQ 2020, p. 1). Another watershed protection plan for the Upper San Marcos River was approved in 2018 by TCEQ. The watershed protection plan addresses the impairment of the Upper San Marcos River due to elevated total dissolved solids, and proactively addresses bacteria, nutrients, sediment, and future growth scenarios for the watershed (TCEQ 2018, p. 1).

The EAA has additional regulations (EAA rule 713) that apply to the recharge zone and five miles upgradient of the recharge zone. Much of the contributing zone occurs outside of the EAA jurisdiction (EARIP HCP 2020, pp. 1-4-1-5) and is not subject to these regulations. New development in the Edwards Aquifer recharge, transition, or contributing zones is reviewed by the TCEQ Edwards Aquifer Protection Program (30 TAC § 213.1). For the contributing zone, the rule covers activities that disturb more than two hectares (ha) (five acres (ac)) in Medina, Bexar, Comal, Kinney, Uvalde, Hays, Travis, and Williamson counties (30 TAC § 213.20). The contributing zone in Bandera, Kerr, and Kendall counties does not have additional protections under either program.

Several other entities also have measures to protect groundwater from contamination including the EAA’s Aboveground Storage Tank Program, Agricultural Secondary Containment Assistance Program, and Abandoned Well Program among others (EAA 2022, entire). The San Antonio Water System implements several water quality protection measures including development regulations (i.e., Aquifer Quality Protection Ordinance No. 81491) for properties over the contributing and recharge zones, review of building permits and master development plans, regulation of underground storage tanks, commercial/industrial compliance, and an abandoned well program (San Antonio Water System 2022, unpaginated).

In addition to these state and federal regulations, a significant number of local regulations to protect water quality were implemented by the City of San Marcos, City of New Braunfels, EAA, and Texas State University as part of the EARIP HCP (EARIP HCP; see sub-section below). Texas Water Code (Chapter 36) allows groundwater districts, but not cities, to regulate groundwater, including groundwater quality. However, cities can regulate pollution at the surface that ultimately impacts groundwater quality.

Habitat Conservation Plan

The EARIP HCP was finalized in 2013, amended in 2020, and covers incidental take of listed species at Comal and San Marcos Springs for groundwater withdrawal, recreation, and other activities through 2028 (EARIP HCP 2020, entire). Permittees to the plan include the EAA, City of San Antonio acting through the San Antonio Water System, City of New Braunfels, City of San Marcos, and Texas State University (National Research Council 2015, pp. 25–26). The EARIP HCP includes activities to minimize and mitigate impacts and contribute to the recovery of the eleven Covered Species and addresses a variety of aquifer management issues, including ensuring springflow during a repeat of the Drought of Record (Payne et al. 2019, p. 200; EARIP HCP 2020, pp. 4-57–4-59, 4-62–4-66). Long-term commitments to protect listed species in the Edwards Aquifer beyond the HCP and the term of its associated section 10(a)(1)(b) permit are not currently in place.

The current EARIP HCP biological goals that center on management, flow-related, and population objectives for the Comal Springs riffle beetle (EARIP HCP 2020, p. 4-11–4-16). The Comal Springs/River management objectives are “Not exceed a 10 percent deviation (daily average) from historically recorded water quality conditions (long-term average) in the Edwards Aquifer as measured issuing from the spring openings at Comal Springs” and to restore riparian habitat adjacent to spring openings to reduce sedimentation after rain events. Additionally, maintain specific median beetle population densities (as measured by numbers per lure) at three locations within the Comal Springs ecosystem. These biological goals do not include the Comal Springs riffle beetle population at San Marcos Springs.

A captive refugia and associated research is funded by the EARIP HCP through a contract (Contract # 16-822-HCP) with the Service’s San Marcos Aquatic Resource Center and Uvalde National Fish Hatchery (EARIP HCP 2020, p. 5-

3). The contract was established to protect species left vulnerable to extirpation throughout a significant portion of their range due to a limited geographic distribution of the population and will preserve the capacity for these species to be re-established in the event of the loss of population due to a catastrophic event, such as the unexpected loss of springflow or a chemical spill. Research activities expand knowledge on habitat requirements, biology, life histories, and effective reintroduction techniques for the species.

2.2.2 Five-Factor Analysis (threats, conservation measures, and regulatory mechanisms):

2.2.2.1 Present or threatened destruction, modification or curtailment of its habitat or range:

Water Quantity

A primary threat to the habitat of the Comal Springs riffle beetle is the potential loss of springflows and reduced water quantity underground brought on by groundwater withdrawals from the southern segment of the Edwards Aquifer. Springflows at Comal and San Marcos springs ecosystems are tied inseparably to water usage for the southern segment of the Edwards Aquifer. Groundwater pumping to meet municipal, industrial, and irrigation uses, is a widely recognized threat to the persistence of subsurface and surface groundwater-dependent ecosystems (Danielopol et al. 2003, pp. 109-112; Eamus et al. 2016, pp. 317, 333-335; Mammola et al. 2019, pp. 645-646). Removal of groundwater from an aquifer leads to water level decline, especially if discharge of groundwater significantly exceeds recharge (Theis 1940, pp. 278-280; Alley et al. 2002, pp. 1,986; Foster and Chilton 2003, pp. 1,961-1,962). Declining aquifer levels can result in springflow decline or failure, loss of stream and creek base-flow, and/or drying of water-filled caverns (Springer and Stevens 2009, pp. 9-10; Eamus et al. 2016, pp. 316-318, 333-335).

If not replenished through recharge, groundwater discharged through wells and springs is removed from aquifer storage (i.e., total amount of water in aquifer), and with absent or much reduced recharge, persistent groundwater removal would initially lead to decline and/or cessation in springflows (Lindgren et al. 2004, p. 41). Like other karst aquifers, water levels of the Edwards Aquifer fluctuate with recharge (i.e., distribution, amount, and intensity of rainfall) and discharge (i.e., wells or springs) (Petitt and George 1956, p. 49; Buszka 1987, pp. 24-27; Maclay 1995, pp. 48, 52; Worthington et al. 2003, p. 4; Lindgren et al. 2004 pp. 40-41, 45). Prolonged dry periods result in declines in aquifer, but water levels rebound rapidly with return of precipitation (Petitt and George 1956, p. 49). Groundwater pumping has exceeded recharge multiple times with water levels rebounding with increased rainfall (Petitt and George 1956, p. 49). The longest period was the Drought of Record (a three-year period when aquifer recharge was at its lowest recorded level) during the mid-1950s (Arnow 1959, pp. 27-29). At one point, Comal Springs stopped flowing from June 13 through November 3, 1956, during the Drought of Record (Puente 1976, p. 22; Barr 1993, p. 61).

In the early 1990s, federal litigation (i.e., *Sierra Club vs. Secretary of the Interior* [No. MO-91-CA-069] United States District Court for the Western District of Texas) resulted in the creation of the EAA in 1993 by the State of Texas to manage groundwater withdrawals (i.e., by nonexempt wells) from the southern segment and limit Edwards Aquifer pumping authorized through permits (National Research Council 2015, pp. 24-26; Hardberger 2019, pp. 193-194; Payne et al. 2019, p. 199). During the 2007 legislative session, the Texas Legislature increased the annual maximum amount of pumping that could be authorized by permits to 705,551 megaliters (ML) (572,000 acre-feet (af)) and directed the EAA to adopt and enforce a "Critical Period Management" plan establishing targeted withdrawal reductions during times of drought to achieve the water, species, and species habitat conservation goals established in the agency's enabling legislation (80th Texas Legislature, 2007, Senate Bill 3). Aquifer management since these rules were implemented have been successful at reducing groundwater withdrawals, but currently do not account for future droughts that may be worse than the Drought of Record. The Stage V Critical Period Management that currently exists is also tied to the Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan (EARIP HCP) but could be subject to change after species recovery.

Springflows have been protected at Comal and San Marcos springs during recent droughts in the 2000s and 2010s because of groundwater pumping restrictions from the EAA during periods of drought. During the 2008-2009 drought, springflows remained at sufficient levels to maintain resiliency for the EARIP HCP’s Covered Species (above 2.3 cubic meters per second (m^3/s) [80 cubic feet per second (cfs)]) (USGS station 08169000). By EAA estimates, Comal Springs likely would have gone dry during the 2014 drought without the enforcement of Critical Period Management (EAA 2015, pp. 1, 62).

While a repeat Drought of Record has not occurred, modeling indicates that the Critical Period Management plan during Phase II of the EARIP HCP will maintain springflows above 0.85 m^3/s (30 cfs) at Comal Springs and above 1.3 m^3/s (45 cfs) at San Marcos Springs during a Drought of Record. However, the plan is currently unable to return springflows at either spring system to 2.3 m^3/s (80 cfs) within six months (EARIP HCP 2020, pp. 4-58, 4-66). Future droughts may also be more severe than the Drought of Record, and current aquifer management does not account for this.

Groundwater will continue to be a source of water in the future as urban populations increase. Predicted water demands for the four counties within the San Antonio pool (i.e., Hays, Comal, Bexar, Medina) are projected to increase by 48 percent in the year 2070, surpassing the capacity of existing supplies

(Texas Water Development Board 2021, p. A-2–A-3). Strategies identified by the State of Texas and Groundwater Conservation Districts for these counties are contingent on funding and infrastructure availability (Texas Water Development Board 2021, entire).

The springflows required to support resilient populations are species-specific and contingent on habitat use and requirements. According to the biological opinion (USFWS 2013, p. 129) associated with the EARIP HCP, the issuance of the Incidental Take Permit for the EARIP HCP is not likely to jeopardize the continued existence of the Comal Springs riffle beetle or adversely modify its critical habitat. Modeled springflows during Phase II project Comal Spring flows to remain at approximately 1.4 m^3/s (50 cfs) during a repeat Drought of Record, surpassing the springflows during the Drought of Record when it ceased for four months in 1956 (USFWS 2013, pp. 32, 91, 103-108).

Springflows crucial for the survival of the Comal Springs riffle beetle were not considered in the 1995 recovery plan or quantitative delisting criteria. The springflows influencing the Comal Springs riffle beetle and its habitat may vary from those affecting other surface species. For instance, at 0.9 m^3/s (30 cfs) at spring runs 2 and 3 of Comal Springs do not provide surface habitat for invertebrates (EAHCP 2020, pp. 4-97–4-98). The USFWS determined that 0.9 m^3/s (30 cfs) during a repeat Drought of Record is not likely to jeopardize the Comal Springs riffle beetle (USFWS 2013, p. 129).

Water sources such as seeps along the western shoreline of Landa Lake and upwellings near Spring Island, are expected to persistently offer habitat support during low-flow conditions within the Comal Springs ecosystem (USFWS 2013, p. 100). San Marcos Springs at Spring Lake, unlike historical droughts and the Drought of Record, has maintained its flow throughout recorded history (Nace and Pluhowski 1965, pp. 81–87; Ogden et al. 1986, pp. 117–118; LBG-Guyton Associates et al. 2004, p. B45; USFWS 2013, pp. 104-105).

The Comal Springs riffle beetle, despite enduring the severe drought of the mid-1950s without being extirpated, likely suffered adverse effects from unregulated aquifer pumping, given its aquatic nature. Evidence suggests that despite surviving the drought without being extirpated, the Comal Springs population was likely impacted by the prolonged absence of water at the surface during that period (Arnow 1959, pp. 27-29; Barr 1993, pp. 61-62). It is reasonable to expect that individuals could have been stranded and possibly extirpated due to receding groundwater levels. The negative impact on the beetle could have been further exacerbated if adults were confined to the vicinity of spring openings due to potential terrestrial requirements of the immature stages and a narrow tolerance in water quality (Barr 1993, pp. 61-62; Cooke 2012, p. 41).

Moreover, there is uncertainty regarding the riffle beetle's ability to escape unfavorable conditions resulting from catastrophic drought in their habitat.

Studies suggest that the species might attempt to follow the water into the aquifer as drying occurs, but their adaptability to surviving extended periods of drying or stagnation, especially in the absence of a water management plan accommodating their needs, remains questionable (Cooke 2012, p. 30; Nair et al. 2023, p. 6). The current water management plan for the Edwards Aquifer plays a crucial role in the survival of the Comal Springs riffle beetle by ensuring consistent springflow. If this management were to cease, leading to longer periods of drying, the species would face detrimental consequences, as it is not well-equipped to endure extended periods of aridity, exposure to high temperatures (median lethal temperature at 27°C [81°F] for the Comal Springs riffle beetle), or stagnation (Cooke et al. 2015, pp. 119-120; Nair et al. 2023, pp. 4-6).

Water Quality

Water quality at Comal and San Marcos springs ecosystems where the Comal Springs riffle beetle is found are influenced by groundwater and surface water. These two spring ecosystems depend on groundwater flow from the southern segment of the Edwards Aquifer. This segment of the aquifer is fed by many stream systems that enter the aquifer through recharge features. The Edwards Aquifer is vulnerable to contamination because the limestone and carbonate rocks are highly permeable and exposed at the surface in the recharge zone (Clark 2000, pp. 1-2, 8-9; Burri et al. 2019, p. 150). Contaminants, commonly linked to urban and suburban activities such as residential and commercial development, industrial operations, transportation infrastructure, and waste disposal, tend to accumulate in higher concentrations within the shallow areas of recharge zones, especially in regions characterized by urban land uses (Wilson 2011, pp. 1-2; Lin and Gong 2016, pp. 384-385; Opsahl et al. 2018, p. 58).

Abandoned groundwater wells are a source of potential contamination from shallow groundwater into subsurface habitat and affect water quality at the springs. Shallower wells (< 300 m [< 984 ft]) are less likely than deeper wells to intercept older groundwater that received cumulative, diluted inputs of pollutants across the aquifer and therefore are more likely to intercept anthropogenic contaminants coming directly from the surface than deeper wells (Musgrove et al. 2014, pp. 69, 73). The EAA funds a needs-based abandoned well closure assistance program to assist well owners with proper well plugging in cooperation with San Antonio Water System to locate and plug abandoned wells (EAA 2021b, pp. 50-53). Likewise, former oil wells require maintenance decades after plugging (cement plugs in a steel pipe) and can blowout underground and break free under artesian pressure if not properly maintained (Gold 2022, entire).

Oil and gas transmission pipelines are another potential source of hazardous material spills on the contributing and recharge zones of the aquifer. The "development and production of oil, gas, or a geothermal resource within the jurisdiction of the Texas Railroad Commission” are not considered regulated activities “having the potential for polluting the Edwards Aquifer and hydrologically connected surface water in order to protect existing and potential uses of groundwater and maintain Texas Surface Water Quality Standards” (Texas Natural Resource Conservation Commission 1996, p. 1). Consequently, the construction and maintenance of these pipelines are not subject to guidance mitigating impacts to karst features such as voids, and development of these pipelines are not subject to the Edwards Aquifer rules (Texas Natural Resource Conservation Commission 1996, entire).

Nitrogen is highly soluble and a threat to groundwater quality and a stressor to groundwater-dependent taxa (Castaño-Sánchez et al. 2020, pp. 6, 11; Banerjee et al. 2023, pp. 3–6). Panther Canyon well (State well number 6823302), recorded nitrate (2 mg/L) present in 2003 (Texas Water Development Board 2023, unpaginated). Nitrate concentrations over 1 mg/L are indicative of anthropogenic inputs, which have been recorded historically at Comal Springs and have doubled over the last 70 years (median concentration 2 mg/L) (Dubrovsky et al. 2010, p. 79; Musgrove et al. 2016, pp. 462, 465, 467; Castaño-Sánchez et al. 2020, p. 6). These changes in water quality in streams and groundwater correspond with increases in impervious cover over a watershed (Kaushal et al. 2005, p. 13,518; Baker et al. 2019, pp. 6494–6495; Castaño-Sánchez et al. 2020, p, 6). These water quality parameter changes may be a long-term indication of urbanization that has already occurred across the recharge zone.

Nitrates and orthophosphate consistently emerge from Spring Run 1 at Comal Springs, and are typically present at low concentrations (2 mg/L) (U.S. Geological Survey 2023, unpaginated). The current drought has significantly decreased flow, and thus dilution of contaminants are slowed at Comal Springs; recent data resulted in 3 mg/L of nitrate measured at Spring Run 2 at Comal Springs (West 2023, unpaginated). While safe for humans, it is unknown what effect these elevated nutrients will have over time within the aquifer food web and if conditions would become more favorable for surface species to colonize further underground (Notenboom et al. 1994, pp. 482–484, 490; Opsahl et al. 2018, p. 3).

Riffle beetles, including the Comal Springs riffle beetle, generally thrive in highly oxygenated water near saturation, and any contamination that poses a threat to diminish this water quality could have adverse effects on their survival (Elliott 2008, pp. 198-199). Despite the environmental tolerances of the Comal Springs riffle beetle being unknown, hindering quantitative assessments of stressors on its populations, other riffle beetle species worldwide are recognized as indicators of good water quality and are sensitive to contamination (Brown 1972, p. 53; USFWS 2019, p. 16; Sotomayor et al. 2023, p. 1).

Volatile organic compounds have been detected at one spring ecosystem and generally these events are rare (Johnson and Schindel 2014, p. 21). There is one documented diesel spill (i.e., naphthalene) that occurred in 2000 at Spring Run 7 at Comal Springs (Ogden et al. 1986, p. 126; Gibson et al. 2008, p. 75). It is unknown what effect this had on the subterranean community.

Although water quality in the Edwards Aquifer is generally good, several studies have detected contaminants in groundwater from the southern segment including nitrates, herbicides, pesticides, and polycyclic aromatic hydrocarbons, among many others (Fahlquist and Ardis, 2004 pp. 7-8, 10; Johnson et al. 2009, pp. 10-13, 23-26, 31-35; Musgrove et al. 2014, pp. 67, 69-71; Opsahl et al. 2018, p. 58; Opsahl et al. 2020, pp. 17-30). For example, contaminants have exceeded public drinking water standards in springwater and surface water recharging the aquifer, including antimony, arsenic, lead, lithium, and tetrachloroethene (Johnson et al. 2009, p. 45). However, groundwater contamination has not been shown to be widespread or with large numbers of substances present in concentrations that exceed drinking water standards (Bush et al. 2000, pp. 1-2, 14-21; Fahlquist and Ardis 2004, pp. 7-8, 10; Johnson et al. 2009, 44, 47; Opsahl et al. 2018, p. 58; Opsahl et al. 2020, pp. 17-30; EARIP HCP 2020, pp. 3-40-3-42).

Some of the sources of water quality degradation include impervious cover and stormwater runoff, construction activities, recharge from irrigation return flow (i.e., water that is not lost from evapotranspiration on laws or to stream runoff), wastewater discharge, transportation infrastructure, and hazardous materials spills resulting from development within the watersheds that contribute groundwater flows to spring habitats (van der Kamp 1995, pp. 11-15; Cantonati et al. 2012, entire; Passarello et al. 2012, pp. 29–34; Lapworth et al. 2012, entire). Land-use changes, particularly increases in impervious cover, are known stressors to aquatic systems and are difficult to predict, model, and remediate (Sharp 2010, p. 3; Coles et al. 2012, p. 65). Future development in the recharge and contributing zones are likely to decrease water quality because of the increased risk of contamination entering the aquifer.

Forested land with limited human disturbances contributes to high-quality recharge (Dudley and Stolten, 2003, pp. 11, 58; Shah et al. 2022, p. 120, 396), while rural and exurban land uses contribute to groundwater contamination from leaking sewage, refuse dumping, and dead, decaying livestock (Sui et al. 2015, p. 21; Katz 2019, p. 565; EARIP HCP 2020, pp. 5-43). Septic systems are a likely source of nutrients (EARIP HCP 2020, p. 5-43; Sui et al. 2015, p. 21). Once a source of pollution enters groundwater, it can be difficult if not impossible to track, intercept, and remediate because of karst conduit complexity (Humphreys 2011, p. 297). Since water quality in the Edwards Aquifer is generally good, this indicates that local sources of water pollution can disproportionately affect water quality in portions of the aquifer.

Urban and agricultural land uses dominate the artesian zone in the southern segment. Low- to high-density urban development occurs across much of the former, while agriculture dominates the latter county. Land use across the southern segment of the Edwards Aquifer plays a major role in groundwater and surface water quality. The presence of agriculture, residential and commercial developments, industrial facilities, military installations, and transportation infrastructure are correlated with increased presence of many contaminants (Bush et al. 2000, pp. 6-9; Fahlquist and Ardis 2004, p. 7; Johnson et al. 2009, p. 46; Wilson 2011, pp. 1-2; Musgrove et al. 2014, pp. 69-71; Opsahl et al. 2018, p. 58; Opsahl et al. 2020, pp. 17-30).

To examine projected land-use changes in the urban centers intersecting Edwards Aquifer groundwater, we used the U.S. Environmental Protection Agency's (EPA 2019, unpaginated) Integrated Climate and Land-Use Scenarios. These outputs produce spatially explicit projections of population and land-use that are based on the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios. The combination of SSP5-RCP8.5 illustrates a higher population growth and higher emissions, and a faster rate of human population growth consistent with the Texas Demographic Center population projections for Bexar County and the San Antonio-New Braunfels Metropolitan Area (EPA 2017, pp. 34-35, 46; Texas Demographic Center 2022, unpaginated). Within the Edwards Aquifer artesian, recharge, and contributing zones (543,498 has [1,343,014 ac]), developed land-use classes are projected to grow from 21 percent in 2020 to 27 percent developed by 2050. When examining delineated areas at a finer scale around Comal and San Marcos springs using the Integrated Climate and Land-Use Scenarios, the area around Comal Springs is projected to increase in development from 66 percent to 82 percent developed and the San Marcos Springs area is projected to increase from 44 percent to 65 percent developed by 2050. These areas may be important to assess more immediate impacts from groundwater contamination.

Based on the Integrated Climate and Land-Use Scenario results, projections of developed land-uses and population growth will continue to expand outward outside of the major metropolitan areas, San Antonio and Austin, Texas. Over time, these alterations have the potential to affect recharge rates, leading to deteriorating groundwater quality as a result of heightened runoff from impervious surfaces in suburban and urban areas or septic systems that are poorly managed and prone to leakage in exurban areas (Berube et al. 2006, pp. 10, 38; Barkfield 2022, p. 2).

The U.S. Census Bureau (2020, unpaginated) ranked several of the counties in the recharge and contributing zones of Comal and San Marcos springs (adjacent to Sessom Springs in Hays County, Texas) among the fastest growing in the United States from April 2010 to July 2019: Hays County was the second fasting growing county with a 46.5 percent population increase, Comal County the fourth fastest growing county with a 43.9 percent population increase, and

Kendall County the fifth fastest growing county with a 42.1 percent population increase. Since 2000, these three counties have doubled in population and have seen substantial associated development. Projections indicate that the human population of Bexar, Comal, Hays, and Kendall counties will continue to increase substantially over the next three decades.

Conversion of natural habitat to urban, suburban, and exurban development is likely to accompany this population growth. Under a high human population growth scenario, land use projections suggest that large areas west and north of Bexar County will be converted to increasingly more urbanized land-use classes by 2100 (EPA 2019, unpaginated). Much of the exurban and suburban development is postulated to occur outside of municipal boundaries in unincorporated areas of counties where land use regulations (e.g., restrictions on impervious cover) are non-existent (Siglo Group 2022, pp. 13-14). Run-off from existing and expanded impervious cover in sensitive areas of the aquifer could affect groundwater quality over time. New contaminant sources are expected to be added to the region as increased human populations and expanded development continues; many existing contaminant sources will persist.

A review of research studies found that impacts to aquatic species are seen with impervious cover of 10 percent or more (Center for Watershed Protection 2003, p. 97). Although the studies were focused on stream systems, we assume that shallow groundwater habitats would have similar impacts because shallow groundwater ultimately flows into streams through discharge features. While physical parameters may be different (e.g., higher oxygen, lower temperatures, higher conductivity) in the shallow groundwater, pollutants entering both systems would be the same.

The EAA does not have explicit impervious cover limits in the recharge zone, with the intent that structural best management practices will protect water quality (Greater Edwards Aquifer Alliance 2010, p. 3). The TCEQ shares responsibility in protecting the Edwards Aquifer through impervious cover limits through a construction permit review process for development proposals of more than 20 percent impervious cover that includes structural best management practices (30 TAC § 213).

Hays County also limits impervious cover to 15 percent within conservation lands on the recharge zone confined and limits impervious cover to 20 percent outside of the recharge zone (Hays County 2017, p. 204). Lastly, Hays County limits commercial property within the recharge zone not exceed 35 percent impervious cover or 65 percent if outside of the recharge zone (Hays County 2017, p. 207). Comal County has goals to minimize impervious cover within the city of New Braunfels to limits of 26 percent per parcel (Design Workshop, Inc. 2012, pp. 4–5).

While the efforts to implement such limits are intended to help ameliorate at least some water quality impacts, these percentages are nonetheless higher than 10 percent, and each project approval does not account for the cumulative impact of combined impervious cover amounts within each county. Likewise, most lands over the contributing zone are not managed with land use regulations (e.g., impervious cover restrictions) (Siglo Group 2022, pp. 13–14).

Habitat Disturbance- Flooding

Surface habitat modification can occur as the result of flooding. Flash flooding is common throughout the Edwards Plateau (Woodruff and Wilding 2008, pp. 614-616). However, channel modification and the elimination of riparian zones can increase the severity of flooding (Schoof 1980, p. 697). Depending on the severity of floods, they can either deposit or increase suspended sediment loads over species habitat or scour substrate and vegetation from species habitat under high velocities (Griffin 2006, pp. 57-58, 61, 64; BIO-WEST, Inc. 2016, p. 26; BIO-WEST, Inc. 2019b, pp. 14, 17; Schwartz et al. 2020, pp. 12). It is possible that species may also be washed away in floods, though this has not been studied for the Comal Springs riffle beetle. Record flooding occurred in the San Marcos River in 2015 and scoured large amounts of aquatic vegetation (BIO-WEST, Inc. 2016, p. vi, 48). Floods have deposited finer sediments (e.g., silt) over invertebrate surface habitat at Comal and San Marcos springs, reducing springflow and quality of habitat (BIO-WEST, Inc. 2002, p. 11; Gibson 2022, pers. comm.).

2.2.2.2 Overutilization for commercial, recreational, scientific, or educational purposes:

Comal Springs riffle beetle specimens are collected for scientific study and two refugia populations. Such collections have not been documented to negatively impact total wild population numbers. At present, this species is not recognized for their commercial worth, and there is no evidence of overexploitation, making overutilization insignificant as a threat.

2.2.2.3 Disease or predation:

Fungal bodies have been observed growing outside of live riffle beetle joints, but not in Comal Springs riffle beetles (Gibson 2022, pers. comm.). Fungi have not been observed on living Comal Springs riffle beetles, but benign fungal parasites on *Dryops* species have been documented (Brown 1987, p. 266). Filamentous fungi have been documented on deceased wild and captive Comal Springs riffle beetle larvae and adults, but whether the fungi were the cause of the mortality or occurred post-mortem is uncertain (Worsham and Gibson 2022, pers. comm.).

Obligate ectoprotozoans are found around the mouth and faces of wild Comal Springs riffle beetles which decrease in number over time in captivity where access to wild, living food resources are not provided. It is uncertain what extent of parasitism has on this species, but the protozoans are likely receiving shredded food from the beetles and are benign (Brown 1987, pp. 266, 269).

The amount of predation that occurs in the wild has not been examined for this species. Blind, fragile subterranean species such as the Comal Springs riffle beetle may be more susceptible to predation once the species enter surface waters (Brown 1987, p. 263; Barr 1993, pp. 63-64). Fishes compete for prey expelled from the aquifer at discharge features (e.g., spring openings). Researchers have seen Mexican tetras (*Astyanax mexicanus*), sunfish (*Lepomis* sp.), and mosquitofish (*Gambusia* sp.) congregating at spring openings waiting for the driftnet to be removed and consuming the bycatch, including subterranean invertebrates (BIO-WEST, Inc. 2003, p. 42). Macroinvertebrates such as the Comal Springs riffle beetle are a part of the food chain, and it is assumed any number of individuals removed from the listed macroinvertebrate populations through typical levels of predation are likely to be negligible.

2.2.2.4 Inadequacy of existing regulatory mechanisms:

Under this factor, we examine the stressors identified within the other factors as ameliorated or exacerbated by any existing regulatory mechanisms or conservation efforts. Section 4(b)(1)(A) of the ESA requires that the Service consider "those efforts, if any, being made by any State or foreign nation, or any political subdivision of a State or foreign nation, to protect such species…" In relation to Factor D under the ESA, we interpret this language to require the Service to consider relevant Federal, State, and Tribal laws, regulations, and other such binding legal mechanisms that may ameliorate or exacerbate any of the threats we describe in threat analyses under the other four factors or otherwise enhance the species' conservation. Our consideration of these mechanisms is described in detail within each of the threats or stressors to the Comal Springs riffle beetle (see discussion under the other Factors). Much of the information under Section 2.2.2.1 should also be considered as relevant here because it is often the inadequacy of existing regulations that contributes to habitat loss and degradation for this species.

The recharge and contributing zones to the Edwards Aquifer continue to experience rapid human population growth and conversion of natural habitat to developed land-use types, which continues to threaten water quality. Much of the contributing zone is not under the same regulations to protect water quality as the recharge zone, even though much of the water that recharges the aquifer originates in the contributing zone. Regulatory mechanisms that protect water in the Edwards Aquifer are crucial to the future survival of the Comal Springs riffle beetle. Federal, State, and local laws and regulations have improved water quality and quantity protection but could be insufficient to prevent ongoing impacts to the species and their habitats from water quality degradation, reduction in water quantity, and surface disturbance of spring sites, and are unlikely to prevent further impacts to the species in the future. Knowledge of the source, accumulation, and transport of these compounds in the aquifer are lacking and investigations into their effects on the habitat quality are necessary for the recovery of the Comal Springs riffle beetle and for sustainable use of the aquifer (Danielopol et al. 2004, pp. 187-188; Opsahl et al. 2018, p. 2).

Under Texas Parks and Wildlife Code (Chapter 68) and TAC (31 TAC § 65.171-65.176), the Texas Parks and Wildlife Department is authorized to add species to the agency’s List of State Threatened and Endangered Nongame Species and List of State Endangered, Threatened, and Protected Native Plants. The Comal Springs riffle beetle is also state listed. The Texas Parks and Wildlife Department prohibits the taking, possession, transportation, or sale of any animal species that are state listed as threatened or endangered. No protections are provided for habitat required by species.

While the EAA was granted regulatory authority by the Texas Legislature, there have been several legal challenges to the EAA permitting program. For example, in court cases *Edwards Aquifer Authority v. Day* (2012, Supreme Court of Texas No. 08-0964) and *Edwards Aquifer Authority v. Bragg* (2013, Court of Appeals of Texas No. 04-11-00018-CV), courts awarded landowners compensation for groundwater permits that were denied by the EAA due to lack of historical usage. The ruling for *Edwards Aquifer Authority v. Day* by the Texas Supreme Court argued that there was no reason to treat groundwater differently than oil and gas and recognized groundwater as real property. In both cases, landowners owned the land prior to enactment of new groundwater pumping regulations. There remains a lack of clarity with Texas groundwater law that results in ongoing legal challenges regarding groundwater regulation, and these could impact the EAA’s ability to regulate the aquifer in the future.

The EAA manages and issues permits for groundwater withdrawals within the Edwards Aquifer through conservation and drought management. The EAA’s jurisdiction is limited to the Edwards Aquifer in Uvalde, Medina, Bexar, and portions of Comal, Guadalupe, Hays, and Caldwell counties. The contributing zone in Bandera, Kerr, and Kendall counties do not have additional protections under either program. Thus, the EAA’s water quality regulations do not protect most of the contributing zone, which may ultimately reduce the water quality of the Edwards Aquifer.

As described above, TCEQ regulates activities that have the potential to pollute the Edwards Aquifer and hydrologically connected surface streams under the same Edwards Aquifer Protection Program or “Edwards Rules” and for the same counties. This means areas of the contributing zone do not have additional protections that could affect the amount and quality of recharge that enters the

Edwards Aquifer, resulting in lower water quality protection for the aquifer and the Comal or San Marcos ecosystems.

Likewise, this agency does not address development or other land use, impervious cover limitations, some nonpoint source pollution, or application of fertilizers and pesticides over the recharge zone (30 TAC § 213.31). Changes to how surface water and the Trinity Aquifer are managed are likely to change the amount that can be sustainably pumped from the Edwards Aquifer during drought conditions. For example, the Hays-Trinity Groundwater Conservation District also manages groundwater that influences the water at the San Marcos Springs ecosystem.

2.2.2.5 Other natural or manmade factors affecting its continued existence:

Global climate change is already affecting many regions' biodiversity, with stressors driven by increasing temperatures and extreme climatic events and will continue to in the near-term (Intergovernmental Panel on Climate Change 2023, pp. 5, 15). Over the last 115 years, the global averaged surface air temperature has increased by 1.0°C (1.8°F) with recent decades being the warmest in 1,500 years (Vose et al. 2017, pp. 186, 188). With the highly karstic permeability of the Edwards Aquifer, climate change and variability strongly influence this vulnerable aquifer that relies heavily on rainfall for recharge (Mace and Wade 2008, p. 659; Taylor et al. 2013, p. 312; Ding and McCarl 2019, p. 11; Nielsen-Gammon et al. 2020, p. 9). The Fourth U.S. National Climate Assessment (U.S. Global Change Research Program 2018, pp. 1,002-1,003) presents the Edwards Aquifer as a case study in vulnerability to climate change, citing the shallow karst aquifer as especially sensitive to climate change, and the regional population growth and development as exacerbating the effects of decreased water supply during droughts. While average rainfall is not projected to change significantly in central Texas, the distribution of precipitation is anticipated to change with more extreme droughts and extreme rain events (Geos Institute 2016, pp. 14-15).

Increasing temperatures will also create drier conditions due to increased evapotranspiration (Loáiciga and Schofield 2019, p. 224). Extreme droughts in Texas are more likely than they were 40-50 years ago (Rupp et al. 2012, p. 1,054; Nielsen-Gammon et al. 2020, entire). A recent study predicts megadroughts in Texas, more severe than have been seen for the past thousand years, that will occur before 2100 (Nielsen-Gammon et al. 2020, entire). Droughts worse than the Drought of Record occurred since the 1600s and are not uncommon in the region (Mauldin 2003, entire; Cleaveland et al. 2011, entire). It is not possible to ensure that there will be adequate flow to these springs without planning for more extreme droughts than the Drought of Record (Loáiciga and Schofield 2019, p. 236; Mace 2019, p. 212). The sustainable water yield for the Edwards Aquifer will decrease in a dry climate (EARIP HCP

2020, pp. 3-12, 3-31, 3-43; Loáiciga and Schofield 2019, pp. 223, 235-236) while human demand for groundwater will increase (EARIP HCP 2020, pp. 3-10–3-11), making it more challenging to balance groundwater use for human needs and ecosystem function. In 2010, Texas set a record for lowest rainfall with similar conditions persisting until 2013 (Nielsen-Gammon 2012, p. 59; National Research Council 2015, p. 168). Heavy rainfall leading to floods may also become more common from extreme precipitation events and may result in increased habitat disturbance due to movement of materials and scouring.

Average air temperature in Texas has risen 1.5°C (2.7°F) since the early 1900s (National Oceanic and Atmospheric Administration 2022, unpaginated). Future air temperature changes will depend on the amount of future greenhouse gas emissions (U.S. Global Change Research Program 2018, p. 995). Based on current projections of greenhouse gas emissions, air temperature is projected to increase 2.0-2.8°C (3.6-5.1°F) by 2050, and 2.4–4.7°C (4.4–8.4°F) by 2100 for the southern Great Plains (U.S. Global Change Research Program 2018, p. 995). Projections by Sharif (2018, p. 4) predict a greater rise in air temperature by 2100, 2.7-5.6°C (5-10°F). Studies have not explicitly addressed groundwater temperature increases for the Edwards Aquifer. Based on other research into changes in groundwater temperature, it is reasonable to expect that groundwater temperature will increase as air temperature increases, with a possible lag in groundwater temperature increase (Mahler and Bourgeais 2013, p. 295). Groundwater temperature also increases with urbanization and vegetation removal (Benz et al. 2017, entire). This could further increase groundwater temperatures as more development occurs. Groundwater temperature typically increases with depth due to geothermal heat flow, although this also varies locally with other variables such as vertical groundwater flow (Bense and Kurylyk 2017, pp. 1, 8). This suggests that deeper water would not provide a long-term buffer to increasing temperatures.

Surface water temperature will also increase during warm months. Data from the EAA indicates greater temperature fluctuations downstream from the springs due to increased exposure time to ambient temperatures and runoff from rain events (BIO-WEST, Inc. 2019a, p. 20; BIO-WEST, Inc. 2019b, p. 16). Low spring discharge is also a mechanism that increases the water’s exposure time to ambient temperature. Thus, both future droughts and increased ambient temperature are likely to increase the surface water temperature. Thus, both future droughts and increased ambient temperature are likely to increase the surface water temperature. Continuous temperature data for the springs began in 2000, and groundwater temperature at Comal and San Marcos springs are relatively constant (BIO-WEST, Inc. 2019b, p. 16). Continuous water temperature monitoring in the Comal River should indicate whether water temperatures rise in the future.

Comal Springs riffle beetles are ectothermic macroinvertebrates with a limited thermal tolerance and a confined habitat centered around freshwater springs originating from the aquifer (Cooke et al. 2015, pp. 114, 117-118; Huston et al. 2015, p. 797; Worsham and Julius 2017, p. 6; Nair et al. 2023, entire). Due to the reduction of functioning wings for rapid dispersal, these beetles encounter difficulties when exposed to short periods of elevated temperatures (~ 3°C increase [5.4°F]). Such temperature spikes can adversely affect their metabolic response, overall longevity, and their ability to migrate to habitats with more favorable and less stressful conditions (Bosse et al. 1988, p. 201; Bowles et al. 2003, p. 379; Nair et al. 2023, p. 6).

Groundwater-dependent species with similar thermal tolerances and adaptive traits are constrained by their inability to migrate and face challenges relocating due to specific habitat requirements (Kløve et al. 2014, p. 263; Castaño-Sánchez et al. 2020, p. 7; Simčič and Sket 2021, entire; Becher et al. 2022, pp. 4–5). Some groundwater-dependent species would likely be incapable of adapting to modified temperatures in the medium to long-term and less capable, due to restricted dispersal capabilities, to flee rising temperature conditions than more generalist surface species (Culver and Pipan 2009, pp. 207–208; Taylor et al. 2013, pp. 324–325; Mammola et al. 2019, p. 646). Moreover, de-watered voids may emerge, prompting speculation that the species will attempt to follow the receding water into the aquifer, presumably seeking preferable water quality conditions (Cooke 2012, p. 30; Nair et al. 2023, p. 6). The potential for these riffle beetles to escape unfavorable conditions resulting from catastrophic drought in their habitat is uncertain. Nonetheless, considering the known challenges faced by this stenothermal, groundwater-dependent species in terms of migration and adapting to modified temperatures, it seems unlikely that the Comal Springs riffle beetle possesses a high degree of adaptability.

An assessment by U.S. Geological Survey evaluated the projected future vulnerability through 2050 of the Comal Springs riffle beetle and rated it as moderately vulnerable to climate change (Stamm et al. 2015, pp. 1, 40, 42, 47). Moderately vulnerable is defined as “abundance and/or range extent within geographical area assessed likely to decrease by 2050.” While the rate of water temperature change in their habitat remains unknown, its potential impacts on water quality are significant. Increased water temperature can lead to the alteration of contaminant mobilization, changes in recharge rates, stimulation of metabolic processes, and disruption of biogeochemical processes such as the carbon or nitrogen cycle (Kløve et al. 2014 p. 263; Castaño-Sánchez et al. 2020 p. 7; Simčič and Sket 2021 entire; Becher et al. 2022 pp. 4–5). These mechanisms collectively contribute to a decline in water quality, affecting both subsurface and surface environments.

Therefore, the adaptive capacity ectothermic animals have to environmental changes is presumed to be low. For ectothermic macroinvertebrates, vulnerability to climate change depends on thermal sensitivity and the speed at which their buffered environment undergoes alterations (Pallarés et al. 2021, p. 487; Delić et al. 2022, p. 2). This will require more research globally to fully understand vulnerability of these aquifer ecosystems and their subterranean communities (Mammola et al. 2019, pp. 646–647; Hose et al. 2022, entire).

2.3 Synthesis

There are currently two genetically isolated populations of the Comal Springs riffle beetle in Texas. Demographic data, captive refugia research, and the five-factor threats analysis (Section 2.2.2) are collectively not indicative of the need for a change in listing status recommendation for the Comal Springs riffle beetle. Comal Springs riffle beetle populations rely on continuous management and protective measures to preserve habitat, prevent silt accumulation, manage groundwater pumping for optimal springflow, supply terrestrial organic matter for the food web, and maintain sufficient water availability and quality for overall ecosystem health. In conclusion, it is our recommendation that a change in classification is not warranted at this time.

3.0 RESULTS

3.1 Recommended Classification:

No change is needed

3.2 New Recovery Priority Number (indicate if no change; see 48 FR 43098):

No Change Recommended; see 48 FR 43098, September 21, 1983 & 48 FR 51985, November 15, 1983 - Correction)

Brief Rationale:

Primary stressors to Comal Springs riffle beetle populations are the loss of springflows and decreases in subsurface habitat due to drawdown of the Edwards Aquifer and reductions in water quality from development and land-use changes. Research suggests that contamination of groundwater has not been historically widespread, is at relatively low concentrations currently, and the subterranean ecosystems do not exhibit significant signs of degradation (Hutchins 2018, pp. 481–482). Current conservation, flow protection, and water quantity optimization measures in place have been effective in meeting biological objectives for EARIP HCP Covered Species, including the Comal Springs riffle beetle (National Research Council 2018, p. 109). Given projected human population increases, associated expansion of exurban, suburban, and urban development and climate change-induced droughts for south-central Texas, the impact on groundwater habitat quality and aquifer recharge into the future remains uncertain (Loáiciga and Schofield 2019, p. 224; National Oceanic and Atmospheric Administration 2022, unpaginated). The sustainable water output for the Edwards Aquifer could decrease in a dry climate while human demand for groundwater would increase, making it more challenging to balance groundwater use for human needs and ecosystem function, and thus, the EARIP HCP's Comal Springs riffle beetle's viability (Loáiciga and Schofield 2019, pp. 223, 235–236; EARIP HCP 2020, pp. 3-10–3-11, 3-12, 3-31, 3-43; Nielsen-Gammon et al. 2020, pp. 9–10).

In terms of viability, the Comal Springs riffle beetle occupies a restricted range of two genetically distinct populations as a narrow endemic species only occurring in groundwater-dependent spring ecosystems supplied by the Edwards Aquifer and are highly susceptible to extinction from perturbations that would affect water quantity and quality in the Edwards Aquifer and ongoing management is needed to maintain resiliency. Further, the absence of data to inform how these threats directly impact Comal Springs riffle beetle populations precludes a more detailed assessment of these impacts. Thus, our analysis does not warrant a change in recommended classification or recovery priority number. Therefore, we recommend the Comal Springs riffle beetle retain its classification as endangered due to its conservation-reliant status.

3.3 Listing and Reclassification Priority Number, if reclassification is recommended (see 48 FR 43098):

Reclassification (from Threatened to Endangered) Priority Number:
Reclassification (from Endangered to Threatened) Priority Number:
Delisting (Removal from list regardless of current classification) Priority Number:

Brief Rationale:

Not applicable

4.0 RECOMMENDATIONS FOR FUTURE ACTIONS

- Incorporate habitat-centered biological goals and objectives during EARIP HCP renewal process to promote protection of suitable habitat quality and quantity and species resiliency.
- Continue water quantity and quality monitoring at accessible spring and well sites within and the areas that recharge the occupied spring ecosystems for habitat quality.
- While there is a general understanding habitat quality decreases as silt accumulates and reduces springflow and water quality, the absence of quantitative studies linking variations in silt-free habitat to Comal Springs riffle beetle population estimates adds complexity, highlighting the need for research to understand the direct and indirect impacts of sedimentation on habitat suitability and food resources (National Research Council 2018, p. 46).
- Currently, there is a lack of sufficient biological and habitat data for the San Marcos Springs population. It is recommended that status surveys of the San Marcos ecosystem in Hays County, Texas are conducted to assess the health and status of this Comal Springs riffle beetle population. Texas State University's Meadows Center for Water and the Environment, responsible for overseeing Spring Lake which houses a genetically distinct population of the species, plays a pivotal role in their conservation efforts. The recent decrease in flow from Hotel Spring during the summer of 2023 underscores the vulnerability of this beetle population, which heavily depends on consistent, high-quality spring flow at San Marcos Springs (BIO-WEST, Inc. 2023, pp. vii, 15; Nair et al. 2023, p. 6). Collaboration with the Meadows Center for Water and The Environment and the EAA is essential to addressing these challenges which would improve our knowledge

regarding current population resiliency and the assurance of redundancy of this genetically distinct population into the future.

- Conduct research to reduce sources of nitrate into the Comal Springs ecosystem through coordination with agencies, public education, and other non-governmental organizations.
- Establish conservation easements or fund land purchases within the contributing and recharge zones of the Edwards Aquifer for the benefit of the Comal Springs riffle beetle and to ensure adequate springflow is sustained through droughts. Additionally, a site-prioritization tool could be developed to support decision making about strategic land acquisitions.
- To the extent possible, reduce increases in impervious surfaces or clearing of forest within the recharge areas supporting the species.
- Continue captive propagation research:
    - Conduct ongoing research to enhance captive propagation techniques.
    - Implementing a targeted microbial management strategy in captivity, informed by comprehensive microbiome analyses, to mitigate potential disruptions caused by factors described in Mays et al. (2021, pp. 3, 9), such as human contact and biofilm shedding from well water pipes. This proactive measure is essential for ensuring the resilience and sustainability of the captive populations over the long term.
    - Develop the capacity to produce offspring on-demand, anticipating standard operating procedures to inform action for potential catastrophic events or extirpation in the wild.
    - Formulate a comprehensive reintroduction plan based on research findings, ensuring the ability to replenish populations as needed.

5.0 REFERENCES

Alley, W.M., R.W. Healy, J.W. LaBaugh, and T.E. Reilly. 2002. Flow and storage in groundwater systems. Science 296: 1,985-1,990.

Arnow, T. 1959. Ground-water geology of Bexar County, Texas. Texas Board of Water Engineers Bulletin 5911. 52 pp.

Baker, M.E., M.L. Schley, and J.O. Sexton. 2019. Impacts of Expanding Impervious Surface on Specific Conductance in Urbanizing Streams. Water Resources Research 55: 6482–6498.

Banerjee, P., P. Garai, N. C. Saha, S. Saha, P. Sharma, and A. K. Maiti. 2023. A critical review on the effect of nitrate pollution in aquatic invertebrates and fish. Water, Air, & Soil Pollution 234(6):333.

Barkfield, R. F. 2022. Infrastructure consequences of exurb growth in Texas. Texas A&M University, The Bush School of Government and Public Service, Mosbacher Institute White Paper Spring 2022, 11 pp.

Barr, C.B. 1993. Survey for two Edwards Aquifer invertebrates: Comal Springs dryopid beetle *Stygoparnus comalensis* Barr and Spangler (Coleoptera: Dryopidae) and Peck's cave amphipod *Stygobromus pecki* Holsinger (Amphipoda: Crangonyctidae). Report prepared for the U.S. Fish and Wildlife Service. 70 pp.

Barr, C.B. 2021. Revision of *Macrelmis* Motschulsky, 1860 in the Southwestern United States and Northern México with description of four new species (Coleoptera: Elmidae: Elminae). The Coleopterists Bulletin 75.

Becher, J., C. Englisch, C. Griebler, and P. Bayer. 2022. Groundwater fauna downtown – Drivers, impacts and implications for subsurface ecosystems in urban areas. Journal of Contaminant Hydrology 248:104021.

Bense, V. and B.L. Kurylyk. 2017. Tracking the subsurface signal of decadal climate warming to quantify vertical groundwater flow rates. Geophysical Research Letters 44: 1-10.

Benz, S.A., P. Bayer, and P. Blum. 2017. Identifying anthropogenic anomalies in air, surface and groundwater temperatures in Germany. Science of the Total Environment 584-585: 145-153.

Berube, A., A. Singer, J.H. Wilson, and W.H. Frey. 2006. Finding exurbia: America's fast-growing communities at the metropolitan fringe. The Brookings Institution, On the Record, Washington, D.C. 47 pp.

BIO-WEST, Inc. 2002. Comal Springs riffle beetle habitat and population evaluation. Project 802, Task 13. BIO-WEST, Inc. Prepared for the Edwards Aquifer Authority, Variable Flow Study, 11 pp.

BIO-WEST, Inc. 2003. Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the Comal Springs/River aquatic ecosystem. Final 2002 Annual Report. Edwards Aquifer Authority, 45 pp.

BIO-WEST, Inc. 2004. Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the Comal Springs/River aquatic ecosystem. Final 2003 Annual Report. Edwards Aquifer Authority, 40 pp.

BIO-WEST, Inc. 2005. Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the Comal Springs/River Aquatic Ecosystem. Final 2004 Annual Report. BIO-WEST, Inc., Comal County, Texas. 70 pp.

BIO-WEST, Inc. 2006. Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the Comal Springs/River Aquatic Ecosystem. Final 2005 Annual Report. BIO-WEST, Inc., Comal County, Texas. 42 pp.

BIO-WEST, Inc. 2007. Variable Flow Study: Seven years of monitoring and applied research. Prepared for Edwards Aquifer Authority, 70 pp.

BIO-WEST, Inc. 2016. Habitat Conservation Plan Biological Monitoring Program. San Marcos Springs/River Aquatic Ecosystem 2016 Annual Report. Prepared for Edwards Aquifer Authority, 53 pp.

BIO-WEST, Inc. 2019a. Habitat Conservation Plan Biological Monitoring Program. San Marcos Springs/River Aquatic Ecosystem 2019 Annual Report. Prepared for Edwards Aquifer Authority, 50 pp.

BIO-WEST, Inc. 2019b. Habitat Conservation Plan Biological Monitoring Program. Comal Springs/River Aquatic Ecosystem 2019 Annual Report. Prepared for Edwards Aquifer Authority, 53 pp.

BIO-WEST, Inc. 2021. Biological Monitoring Program Comal Springs/River Aquatic Ecosystem Annual Report. Prepared for Edwards Aquifer Authority, 52 pp.

BIO-WEST, Inc. 2023. Habitat Conservation Plan biological monitoring program: San Marcos Springs/River aquatic ecosystem annual report. 2023 Edwards Aquifer Authority Reports Appendix G3. BIO-WEST, Inc. Prepared for the Edwards Aquifer Authority, 57 pp.

Bosse, L.S., D.W. Tuff, and H.P. Brown. 1988. A New Species of *Heterelmis* from Texas (Coleoptera: Elmidae). The Southwestern Naturalist 33: 199–203.

Bowles, D.E., C.B. Barr, and R. Stanford. 2003. Habitat and phenology of the endangered riffle beetle *Heterelmis comalensis* and a coexisting species, *Microcylloepus pusillus*, (Coleoptera: Elmidae) at Comal Springs, Texas, USA. Archiv für Hydrobiologie 156: 361–383.

Brown, H.P. 1972. Trials and tribulations of a riffle beetle buff (or why didn't I stick with the protozoa?). Bios 43: 51–60.

Brown, H.P. 1987. Biology of riffle beetles. Annual Review of Entomology 32: 253–273.

Burri, N.M., R. Weatherl, C. Moeck, and M. Schirmer. 2019. A review of threats to groundwater quality in the Anthropocene. Science of The Total Environment 684: 136–154.

Bush, P.W., A.F. Ardis, L. Fahlquist, and P.B. Ging. 2000, Water quality in south-central Texas 1996-98: U.S. Geological Survey Circular Report 1212, 32 pp.

Buszka, P.M. 1987. Relation of water chemistry of the Edwards Aquifer to hydrogeology and land use, San Antonio region, Texas. U.S. Geological Survey Water-Resources Investigations Report 87-4116. 100 pp.

Cantonati, M., L. Füreder, R. Gerecke, I. Jüttner, and E.J. Cox. 2012. Crenic habitats, hotspots for freshwater biodiversity conservation: toward an understanding of their ecology. Freshwater Science 31: 463–480.

Castaño-Sánchez, A., G.C. Hose, and A.S.P.S. Reboleira. 2020. Ecotoxicological effects of anthropogenic stressors in subterranean organisms: A review. Chemosphere 244:125422.

Center for Watershed Protection. 2003. Impacts of impervious cover on aquatic systems. Center for Watershed Protection, Ellicot City, MD. 142 pp.

City of San Antonio. 2023. Capital improvements program FY2023 FY2028. 241 pp.

Clark, A.K. 2000. Vulnerability of ground water to contamination, Edwards Aquifer recharge zone, Bexar County, Texas, 1998. Water-Resources Investigation Report 00-4149. U.S. Geological Survey, Austin, Texas. 9 pp.

Cleaveland, M.K., T.H. Votteler, D.K. Stahle, R.C. Casteel, and J.L. Banner. 2011. Extended chronology of drought in South Central, Southeastern and West Texas. Texas Water Journal 2: 54–96.

Coles, J.F., G. McMahon, A.H. Bell, L.R. Brown, F.A. Fitzpatrick, B.C. Scudder Eikenberry, M.D. Woodside, T.F. Cuffney, W.L. Bryant, K. Cappiella, L. Fraley-McNeal, and W.P. Stack. 2012. Effects of urban development on stream ecosystems in nine metropolitan study areas across the United States. U.S. Geological Survey, Circular 1373, 138 pp.

Cooke, M. 2012. Natural history studies on the Comal Springs riffle beetle (*Heterelmis comalensis*). Texas State University, San Marcos, Texas, 65 pp.

Cooke, M., G. Longley, and R. Gibson. 2015. Spring association and microhabitat preferences of the Comal Springs riffle beetle (*Heterelmis comalensis*). The Southwestern Naturalist 60: 110–121.

Culver, D.C., and T. Pipan. 2009. The biology of caves and other subterranean habitats. Oxford University Press, New York.

Danielopol, D.L., M. Creuzé des Châtelliers, F. Moeszlacher, P. Pospisil, and R. Popa. 1994. Adaptation of crustacea to interstitial habitats. Academic Press, San Diego, California.

Delić, T., P. Trontelj, V. Zakšek, A. Brancelj, T. Simčič, F. Stoch, and C. Fišer. 2022. Speciation of a subterranean amphipod on the glacier margins in South Eastern Alps, Europe. Journal of Biogeography 49(1):38-50.

Design Workshop, Inc. 2012. New Braunfels stormwater management strategy. Phase I Report, 48 pp.

Ding, J., and B. A. McCarl. 2019. Economic and ecological impacts of increased drought frequency in the Edwards Aquifer. Climate 8(1): 2.

Dubrovsky, N.M., K.R. Burow, G.M. Clark, J.M. Gronberg, P.A. Hamilton, K.J. Hitt, D.K. Mueller, M.D. Munn, B.T. Nolan, L.J. Puckett, M.G. Rupert, T.M. Short, N.E. Spahr, L.A. Sprague, and W.G. Wilber. 2010. The quality of our nation’s waters: Nutrients in the nation’s streams and groundwater, 1992-2004. U.S. Geological Survey, Circular 1350. 174 pp.

Dudley, N., and S. Stolten. 2003. Running pure: The importance of forest protected areas to drinking water. A report to the World Bank and WWF Alliance for Forest Conservation and Sustainable Use, 112 pp.

EAA (Edwards Aquifer Authority) 2013. Hydrologic data report for 2011. Report No. 13-01, San Antonio, Texas, 73 pp.

EAA (Edwards Aquifer Authority) 2015. Hydrologic data report for 2014. Report No. 15-01, San Antonio, Texas, 69 pp.

EAA (Edwards Aquifer Authority) 2018. 2017 water quality summary. San Antonio, Texas, 6 pp.

EAA (Edwards Aquifer Authority). 2021a. EAHCP annual expanded water quality monitoring report. Appendix F of 2021 Edwards Aquifer Authority Reports.

EAA (Edwards Aquifer Authority). 2021b. Plugging away at the EAA. Edwards Aquifer Authority News Drop (Summer 2021):56. Retrieved on April 14, 2022, from: https://user-qzm76pf.cld.bz/NewsDrop-Summer-2021/.

EAA (Edwards Aquifer Authority). 2022. Aquifer Protection. Retrieved on May 3, 2022, from: https://www.edwardsaquifer.org/aquifer-protection/.

Eamus, D., B. Fu, A.E. Springer, and L.E. Stevens. 2016. Groundwater dependent ecosystems: classification, identification techniques and threats. Pages 313-346 *in* Jakeman, A.J., O. Barreteau, R.J. Hunt, J. Rinaudo, and A. Ross, editors. Integrated groundwater management: concepts, approaches, and challenges. Springer Open. 762 pp.

EARIP HCP (Edwards Aquifer Recovery Implementation Program Habitat Conservation Program). 2020. Prepared by RECON, Environmental, Inc.; Hicks & Company; Zara Environmental, LLC; and BIO-WEST, Inc. 423 pp.

Elliott, J.M. 2008. The Ecology of riffle beetles (Coleoptera: Elmidae). Freshwater Reviews 1: 189–203.

EPA (U.S. Environmental Protection Agency). 2017. Updates to the demographic and spatial allocation models to produce Integrated Climate and Land Use Scenarios (ICLUS) (Final Report, Version 2). EPA/600/R-16/366F. Office of Research and Development U.S. Environmental Protection Agency, Washington, DC. 134 pp.

EPA (U.S. Environmental Protection Agency). 2019. Integrated Climate and Land-Use Scenarios Version 2.1 Land Use Projections. Retrieved on September 16, 2022, from https://www.epa.gov/gcx/iclus-downloads/.

EPA (U.S. Environmental Protection Agency). 2023. Comal Springs #1 (DX-68-23-301/ LR-68-23-301) monitoring report. Available at: https://mywaterway.epa.gov/monitoring-report/NWIS/USGS-TX/USGS-294300098080001/ (August 9, 2023).

Fahlquist, L., A.F. Ardis. 2004. Quality of water in the Trinity and Edwards Aquifers, south-central Texas, 1996-98: U.S. Geological Survey Scientific Investigations Report 2004-5201, 25 pp.

Foster, S.S.D. and P.J. Chilton. 2003. Groundwater: the processes and global significance of aquifer degradation. Philosophical Transactions of the Royal Society B 358: 1957–1972.

Geos Institute. 2016. Hot enough yet? The future of extreme weather in Austin, Texas. Ashland, OR. 26 pp.

Gibson, J.R., S.J. Harden, and J. Fries. 2008. Survey and distribution of invertebrates from selected springs of the Edwards Aquifer in Comal and Hays Counties, Texas. The Southwestern Naturalist 53: 74-84.

Gibson, J.R. 2022. Phone call on invertebrate threats for species biological report. November 29.

Gold, R. 2022, January 12. A forgotten oil well births a 100-foot geyser in West Texas. Texas Monthly. Retrieved on April 14, 2022, from: https://www.texasmonthly.com/news-politics/west-texas-geyser-oil-well-chevron/.

Gonzales, T.K. 2008. Conservation genetics of the Comal Springs Riffle Beetle (*Heterelmis comalensis*) populations in Central Texas, with examination of molecular and morphological variation in *Heterelmis* sp. throughout Texas. Master of Science. Texas State University, San Marcos, Texas. 67 pp.

Greater Edwards Aquifer Alliance. 2010. Permanent stormwater pollution prevention systems within the Edwards Aquifer Recharge Zone in Bexar County, Texas. An overview and assessment of current regulatory agency processes, 48 pp.

Griffin, K.L. 2006. An Analysis of changes in Texas wild rice distribution following the 1998 flood of the San Marcos River, Texas. M.A. Geo. Thesis, Texas State University, 68 pp.

Groeger, A.W., P.F. Brown, T.E. Tietjen, and T.C. Kelsey. 1997. Water quality of the San Marcos River. Texas Journal of Science 49: 279–294.

Hardberger, A. 2019. Texas groundwater law and the Edwards Aquifer. Pages 189–197 *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America.

Hays County. 2017. Hays County development regulations. Available at: https://hayscountytx.com/download/departments/development_services/regulations/2017-Hays-County-Development-Regulations.pdf (April 7, 2022).

Hose, G.C., A.A. Chariton, M.A. Daam, T. Di Lorenzo, D.M.P. Galassi, S.A. Halse, A.S.P.S. Reboleira, A.L. Robertson, S.I. Schmidt, and K.L. Korbel. 2022. Invertebrate traits, diversity and the vulnerability of groundwater ecosystems. Functional Ecology 36(9): 2200-2214.

Huey, R.B., and J.G. Kingsolver. 1989. Evolution of thermal sensitivity of ectotherm performance. Trends in Ecology & Evolution 4: 131–135.

Humphreys, W.F. 2011. Management of Groundwater Species in Karst Environments. Springer, Dordrecht, Netherlands.

Huston, D.C., and J.R. Gibson. 2015. Underwater pupation by the Comal Springs riffle beetle, *Heterelmis comalensis* Bosse, Tuff, and Brown, 1988 (Coleoptera: Elmidae), with an update on culture techniques. The Coleopterists Bulletin 69: 521–524.

Huston, D.C., J.R. Gibson, K.G. Ostrand, C.W. Norris, and P.H. Diaz. 2015. Monitoring and marking techniques for the endangered Comal Springs riffle beetle, *Heterelmis comalensis* Bosse, Tuff, and Brown, 1988 (Coleoptera: Elmidae). The Coleopterists Bulletin 69: 793–798.

Hutchins, B.T. 2018. The conservation status of Texas groundwater invertebrates. Biodiversity Conservation 27: 475–501.

Intergovernmental Panel on Climate Change. 2023. Summary for policymakers. Climate change 2023: Synthesis report, pp. 1–34. IPCC, Geneava, Switzerland.

Johnson, S.B., and G.M. Schindel. 2008. Evaluation of the option to designate a separate San Marcos pool for critical period management. Report No. 08-01. 63 pp.

Johnson, S., G. Schindel, and J. Hoyt. 2009. Water quality trends analysis of the San Antonio segment, Balcones Fault Zone Edwards Aquifer, Texas. Edwards Aquifer Authority Report No. 09-03.

Johnson, S., and G.M. Schindel. 2014. Water quality trends analysis of the San Antonio Segment, Balcones Fault Zone Edwards Aquifer, Texas. 2014 Update. Edwards Aquifer Authority, 65 pp.

Katz, B.G. 2019. Nitrate contamination in karst groundwater. Pages 756–760 *in* Encyclopedia of Caves. Academic Press. London, United Kingdom.

Kaushal, S.S., P.M. Groffman, G.E. Likens, K.T. Belt, W.P. Stack, V.R. Kelly, L.E. Band, and G.T. Fisher. 2005. Increased salinization of fresh water in the northeastern United States. Proceedings of the National Academy of Sciences 102: 13517–13520.

Kløve, B., P. Ala-Aho, G. Bertrand, J. J. Gurdak, H. Kupfersberger, J. Kværner, T. Muotka, H. Mykrä, E. Preda, P. Rossi, C. B. Uvo, E. Velasco, and M. Pulido-Velazquez. 2014. Climate change impacts on groundwater and dependent ecosystems. Journal of Hydrology 518:250–266.

Kosnicki, E. 2022. Fecundity of first-generation captively reared *Heterelmis comalensis* (Coleoptera: Elmidae) M. Chaudhury [ed.]. Journal of Insect Science 22: 5.

Lapworth, D. J., N. Baran, M. E. Stuart, and R. S. Ward. 2012. Emerging organic contaminants in groundwater: A review of sources, fate and occurrence. Environmental Pollution 163: 287–303.

LBG-Guyton Associates, BIO-WEST, Inc., Espey Consultants, Inc., and URS Corporation. 2004. Evaluation of Augmentation Methodologies in Support of In-Situ Refugia at Comal and San Marcos Springs, Texas, 1182 pp.

Lin, Y. and X. Gong. 2016. Risk assessment of water pollution exposure to hazardous waste sites: a case study in Bexar County, Texas. Papers in Applied Geography 2(4): 383–394.

Lindgren, R.J., A.R. Dutton, S.D. Hovorka, S.R.H. Worthington, and S. Painter. 2004. Conceptualization and simulation of the Edwards aquifer, San Antonio region, Texas: U.S. Geological Survey Scientific Investigations Report 2004–5277, 143 pp.

Loáiciga, H. A., and M. Schofield. 2019. Climate variability, climate change, and Edwards Aquifer water fluxes. Pages 223-238 *In* The Edwards Aquifer: The past, present, and future of a vital water resource. Abbott, P.L. and C.M. Woodruff, Jr., editors. Geological Society of America. 312 pp.

Mace, R.E. 2019. The use of water from the Edwards Aquifers, Texas. Pages 207–212 *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America.

Mace. R.E. and S.C. Wade. 2008. In hot water? How climate change may (or may not) affect the groundwater resources of Texas, Texas, Gulf Coast Association of Geological Societies Transactions, 58: 655-668.

Mammola, S., P. Cardoso, D. C. Culver, L. Deharveng, R. L. Ferreira, C. Fišer, D. M. P. Galassi, C. Griebler, S. Halse, W. F. Humphreys, M. Isaia, F. Malard, A. Martinez, O. T. Moldovan, M. L. Niemiller, M. Pavlek, A. S. P. S. Reboleira, M. Souza-Silva, E. C. Teeling, J. J. Wynne, and M. Zagmajster. 2019. Scientists' warning on the conservation of subterranean ecosystems. BioScience 69(8): 641–650.

Maclay, R.W. 1995. Geology and hydrology of the Edwards Aquifer in the San Antonio area, Texas. Geological Survey Water-Resources Investigations Report 95-4186, 54 pp.

Mahler, B. J., and R. Bourgeais. 2013. Dissolved oxygen fluctuations in karst spring flow and implications for endemic species: Barton Springs, Edwards aquifer, Texas, USA. Journal of Hydrology 505: 291–298.

Mays, Z., A. Hunter, L.G. Campbell, and C. Carlos-Shanley. 2021. The effects of captivity on the microbiome of the endangered Comal Springs riffle beetle (*Heterelmis comalensis*). FEMS Microbiology Letters 368: fnab121.

McKinney, M.L. 1997. Extinction vulnerability and selectivity: combining ecological and paleontological views. Annual Review of Ecology and Systematics 28: 495–516.

Musgrove, M., and C.L. Crow. 2012. Origin and Characteristics of Discharge at San Marcos Springs Based on Hydrologic and Geochemical Data (2008–10), Bexar, Comal, and Hays

Counties, Texas. 2012–5126. U.S. Geological Survey in cooperation with San Antonio Water System, Report, Bexar County, Comal County, Hays County, 94 pp.

Musgrove, M., B.G. Katz, L.S. Fahlquist, C.A. Crandall, and R.J. Lindgren. 2014. Factors affecting public-supply well vulnerability in two karst aquifers. Groundwater–Focus 52: 63–75.

Musgrove, M., S. P. Opsahl, B. J. Mahler, C. Herrington, T. L. Sample, and J. R. Banta. 2016. Source, variability, and transformation of nitrate in a regional karst aquifer: Edwards aquifer, central Texas. Science of The Total Environment 568: 457–469.

Nair, P., P.H. Diaz, and W.H. Nowlin. 2021. Interactions at surface–subterranean ecotones: structure and function of food webs within spring orifices. Oecologia 195:14.

Nair, P., J.R. Gibson, B.F. Schwartz, and W.H. Nowlin. 2023. Temperature responses vary between riffle beetles from contrasting aquatic environments. Journal of Thermal Biology 112: 103485.

Nair, P., A.H. Hunter, M.L.D. Worsham, M. Stehle, J.R. Gibson, and W.H. Nowlin. 2019. Sexual Dimorphism in Three Species of *Heterelmis* Sharp (Coleoptera: Elmidae). The Coleopterists Bulletin 73: 1075–1083.

Nace, R.L., and E.J. Pluhowski. 1965. Drought of the 1950's with special reference to the Midcontinent. Geological Survey Water-Supply Paper 1804. 88 pp.

National Oceanic and Atmospheric Administration. 2022. NOAA National Centers for Environmental Information. State climate summaries 2022: Texas. Available at: https://statesummaries.ncics.org/chapter/tx/ (September 1, 2022).

National Research Council. 2015. Review of the Edwards Aquifer Habitat Conservation Plan: Report 1. National Academies Press, Washington, D.C. 174 pp.

National Research Council. 2018. Review of the Edwards Aquifer Habitat Conservation Plan: Report 3. National Academies Press, Washington, D.C. 190 pp.

Nielsen-Gammon, J. 2012. The 2011 Texas drought. Texas Water Journal 3: 59–95.

Nielsen-Gammon, J., J.L. Banner, B.I. Cook, D.M. Tremaine, C.I. Wong, R.E. Mace, H. Gao, Z. Yang, M.F. Gonzalez, R. Hoffpauir, T. Gooch, and K. Kloesel. 2020. Unprecedented drought challenges for Texas water resources in a changing climate: What do researchers and stakeholders need to know? Earth's Future 8: 20.

Notenboom, J., S. Plénet, and M.-J. Turquin. 1994. Groundwater contamination and its impact on groundwater animals and ecosystems. Pages 477–500 *in* J. Gibert, D.L. Danielopol, and J.A. Stanford [eds.], Groundwater ecology. Academic Press. San Diego, California.

Nowlin, W.H., and M.L.D. Worsham. 2015. Comal Springs riffle beetle habitat connectivity study. Texas State University and BIO-WEST, Inc. prepared for the Edwards Aquifer Authority, San Marcos, Texas. 76 pp.

Nowlin, W.H. 2022. E-mail: “Comal Springs SR4 and CSRB.” July 6.

Nowlin, W.H., and B. Schwartz. 2012. Spring Lake watershed characterization and management recommendations final report. Nonpoint Source Protection Program CWA §319(h). Texas State University, San Marcos, Texas. 130 pp.

Nowlin, W.H., D. Hahn, P. Nair, and F. Alfano. 2017. Evaluation of the trophic status and functional feeding group status of the Comal Springs riffle beetle. 148-15-HCP. Texas State University prepared for the Edwards Aquifer Authority, 30 pp.

O’Grady, J.J., D.H. Reed, B.W. Brook, and R. Frankham. 2004. What are the best correlates of predicted extinction risk? Biological Conservation 118: 513-520.

Ogden, A.E., R.A. Quick, and S.R. Rothermel. 1986. Hydrochemistry of the Comal, Hueco, and San Marcos Springs, Edwards Aquifer, Texas. Geological Society of America.

Opsahl, S.P., M. Musgrove, B.J. Mahler, and R.B. Lambert. 2018. Water-quality observations of the San Antonio segment of the Edwards Aquifer, Texas, with an emphasis on processes influencing nutrient and pesticide geochemistry and factors affecting aquifer vulnerability. Scientific Investigations Report 2010-16. U.S. Geological Survey in cooperation with San Antonio Water System, 67 pp.

Opsahl, S.P., Musgrove, M., and Mecum, K.E. 2020. Temporal and spatial variability of water quality in the San Antonio segment of the Edwards aquifer recharge zone, Texas, with an emphasis on periods of groundwater recharge, September 2017–July 2019: U.S. Geological Survey Scientific Investigations Report 2020–5033, 37 pp.

Pallarés, S., R. Colado, M. Botella-Cruz, A. Montes, P. Balart-García, D.T. Bilton, A. Millán, I. Ribera, and D. Sánchez-Fernández. 2021. Loss of heat acclimation capacity could leave subterranean specialists highly sensitive to climate change. Animal Conservation 24(3): 482-490.

Passarello, M. C., J. M. Sharp, and S. A. Pierce. 2012. Estimating urban-induced artificial recharge: A case study for Austin, TX. Environmental & Engineering Geoscience 18(1): 25–36.

Passos, M.I.S., J.L. Nessimian, and L.F.M. Dorvillé. 2003. Life strategies in an elmid (Insecta: Coleoptera: Elmidae) community from a first order stream in the Atlantic Forest, southeastern Brazil. Acta Limnologica Brasiliensia 15: 29–36.

Payne, S., N. Pence, and C. Furl. 2019. The Edwards Aquifer Habitat Conservation Plan: Its planning and implementation. Pages 109–206 *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America.

Petitt, B.M., Jr. and W.O. George. 1956. Ground-water resources of the San Antonio area, Texas: a progress report on current studies. Texas Board of Water Engineers Bulletin 5608. Volume 1, 80 pp.

Puente, C. 1976. Statistical analysis of water-level springflow, and stream data for the Edwards aquifer in south-central Texas: Open-File Report 76-393. U.S. Geological Survey, San Antonio, Texas, 59 pp.

Reilly, F.J., Jr. and K.A. Carter. 2018. Program study and analysis services for the Edwards Aquifer Protection Program. Report for the City of San Antonio, Texas' Parks and Recreation Department, 45 pp.

Romero, F.S. 2018. San Antonio's Edwards Aquifer Protection Program: overview and analysis. Texas Water Journal 1–15.

Rupp, D. E., P. W. Mote, N. Massey, C. J. Rye, R. Jones, and M. R. Allen. 2012. Did human influence on climate made the 2011 Texas drought more probable? Explaining extreme events of 2011 from a climate perspective. Bulletin of the American Meteorological Society 93(7): 1041–1067.

San Antonio Water System. 2022. Aquifer Protection and Evaluation. Retrieved on January 12, 2023, from: https://www.saws.org/protecting-our-environment/water-resource-compliance-protection/aquifer_protection/.

Schoof, R. 1980. Environmental impact of channel modification. Water Resources Bulletin 16(4): 697-701.

Schwartz, B., W.H. Nowlin, T. Hardy, J. Jeong, and J. Wolfe, III. 2020. Sessom Creek sediment export study. Texas State University; Edwards Aquifer Research and Data Center; Texas A&M AgriLife Research, EAHCP proposal no. 160-17-TESS, San Marcos, TX. 7 pp.

Shah, N.W., B.R. Baillie, K. Bishop, S. Ferraz, L. Högbom, and J. Nettles. 2022. The effects of forest management on water quality. Forest Ecology and Management 522: 120397.

Sharif, H. 2018. Climate projections for the City of San Antonio. University of Texas at San Antonio, San Antonio, TX. 17 pp.

Sharp, J.M. 2010. The impacts of urbanization on groundwater systems and recharge. Aqua Mundi 2020, 6 pp.

Siglo Group. 2022. State of the Hill Country: 8 key conservation and growth metrics for a region at a crossroads, Produced for the Texas Hill Country Network, 60 pp.

Simčič, T., and B. Sket. 2021. Ecophysiological responses of two closely related epigean and hypogean *Niphargus* species to hypoxia and increased temperature: Do they differ? International Journal of Speleology 50(2): 111-120.

Sotomayor, G., J. Romero, D. Ballari, R.F. Vázquez, I. Ramírez-Morales, H. Hampel, X. Galarza, B. Montesinos, M.A.E. Forio, and P.L.M. Goethals. 2023. Occurrence prediction of riffle beetles (Coleoptera: Elmidae) in a tropical Andean basin of Ecuador using species distribution models. Biology 12: 473.

Springer, A.E. and L.E. Stevens. 2009. Spheres of discharge of springs. Hydrogeology Journal 17(1): 83-93.

Stamm, J.F., M.F. Poteet, A.J. Symstad, M. Musgrove, A.J. Long, B.J. Mahler, and P.A. Norton. 2014. Historical and projected climate (1901–2050) and hydrologic response of karst aquifers, and species vulnerability in south-central Texas and western South Dakota. 2014–5089. U.S. Geological Survey in cooperation with the Department of Interior South-Central Climate Science Center, Scientific Investigations Report, 59 pp.

Stone, D., and G.M. Schindel. 2002. The application of GIS in support of land acquisition for the protection of sensitive groundwater recharge properties in the Edwards Aquifer of south-central Texas. Journal of Cave and Karst Studies 64: 38–44.

Sui, Q., X. Cao, S. Lu, W. Zhao, Z. Qiu, and G. Yu. 2015. Occurrence, sources and fate of pharmaceuticals and personal care products in the groundwater: A review. Emerging Contaminants 1(1): 14-24.

Taylor, R. G., B. Scanlon, P. Döll, M. Rodell, R. van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J. S. Famiglietti, M. Edmunds, L. Konikow, T. R. Green, J. Chen, M. Taniguchi, M. F. P. Bierkens, A. MacDonald, Y. Fan, R. M. Maxwell, Y. Yechieli, J. J. Gurdak, D. M. Allen, M. Shamsudduha, K. Hiscock, P. J.-F. Yeh, I. Holman, and H. Treidel. 2013. Ground water and climate change. Nature Climate Change 3(4): 322–329.

TCEQ (Texas Commission on Environmental Quality). 2018. Upper San Marcos River Watershed Protection Plan. TCEQ Nonpoint Source Program Fact sheet, 2 pp.

TCEQ (Texas Commission on Environmental Quality). 2020. Dry Comal Creek and Comal River Watershed Protection Plan Implementation. TCEQ Nonpoint Source Program Fact sheet, 1 pp.

Texas Demographic Center 2022. Texas Population Projections Program. Retrieved on July 28, 2023, from: https://demographics.texas.gov/data/tpepp/projections/.

Texas Natural Resource Conservation Commission. 1996. Chapter 213 - Edwards Aquifer Rule Log No. 97105-213-WT.

Texas Water Development Board. 2021. 2022 State Water Plan, 167 pp.

Texas Water Development Board. 2023. Groundwater Database Report and Downloads. Retrieved on May 24, 2023, from: http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp/.

Theis, C.V. 1940. The source of water derived from wells. Civil Engineering 10: 277–280.

Tupa, D.D., and W.K. Davis. 1976. Population-dynamics of San-Marcos salamander, *Eurycea nana* Bishop. Texas Journal of Science 27: 179–195.

U.S. Census Bureau. 2020. Resident population estimates for the 100 fastest-growing U.S. Counties with 10,000 or more population in 2010: April 1, 2010 to July 1, 2019 (COEST2019-CUMGR).

USFWS (U.S. Fish and Wildlife Service). 2013. Biological and conference opinions for the Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan-Permit TE-63663A-0 (Consultation No. 21450-2010-F-0110). Ecological Services Field Office, Austin, TX, 169 pp.

USFWS (U.S. Fish and Wildlife Service). 2019. Species Status Assessment Report Scott Riffle Beetle (*Optioservus phaeus*). Kansas Ecological Services Field Office, 27 pp.

U.S. Geological Survey. 2023. USGS Surface-Water Daily Data for the Nation. USGS 08168710 Comal Spgs at New Braunfels, TX. Available at: https://waterdata.usgs.gov/monitoring-location/08168710 (February 28, 2023).

U.S. Global Change Research Program. 2018. Impacts, risks, and adaptation in the United States. Pages 987–1035 *in* Fourth National Climate Assessment. Washington, D.C.

van der Kamp, G. 1995. The hydrogeology of springs in relation to the biodiversity of spring fauna: A review. Journal of the Kansas Entomological Society 68: 4–17.

Vose, R.S., D.R. Easterling, K. E. Kunkel, A.N. LeGrande, and M.F. Wehner. 2017. Temperature changes in the United States. U.S. Global Change Research Program, Washington, D.C.

West, B. 2023. E-mail: "Edwards Aquifer Refugia Program Peck's cave amphipod and Comal Springs riffle beetle collection TODAY."

Wilson, J.T. 2011. Assessment of selected contaminants in streambed- and suspended-sediment samples collected in Bexar County, Texas, 2007–09: U.S. Geological Survey Scientific Investigations Report 2011–5097, 57 pp.

Woodruff, C.M. and L.P. Wilding. 2008. Bedrock, soils, and hillslope hydrology in the central Texas Hill Country, USA: implications on environmental management in a carbonate rock terrain. Environmental Geology 55: 605-618.

Worsham, M.L.D., and E. Julius. 2017. Comal Springs riffle beetle (*Heterelmis comalensis*): Life history and captive propagation techniques. BIO-WEST, Inc. prepared for the Edwards Aquifer Authority, 36 pp.

Worsham, M.L.D., and E. Julius. 2018. Evaluation of life history of the Comal Springs riffle beetle: Pupation! BIO-WEST, Inc., Texas State University, Desert Research Institute, and the San Marcos Aquatic Resources Center prepared for the Edwards Aquifer Authority, 10 pp.

Worsham, M.L.D., and J.R. Gibson. 2022. E-mail "*Stygobromus* diseases." August 25.

Worthington, S.R.H. 2003. Conduits and turbulent flow in the Edwards Aquifer. Report prepared for the Edwards Aquifer Authority. 42 pp.

Yee, D.A., and S. Kehl. 2015. Order Coleoptera. Pages 1003–1042 *in* J.H. Thorp and A.P. Covich [eds.], Ecology and general biology. 4th edition. Elsevier/AP, Academic Press is an imprint of Elsevier. San Diego, California.

U.S. FISH AND WILDLIFE SERVICE

5-YEAR REVIEW of Comal Springs riffle beetle (*Heterelmis comalensis*)

Current Classification: Endangered

Recommendation resulting from the 5-Year Review:

No change needed

Appropriate Listing/Reclassification Priority Number, if applicable:

FIELD OFFICE APPROVAL:

Acting Lead Field Supervisor, Fish and Wildlife Service, Austin Ecological Services Field Office

Approve CATHERINE YEARGAN Digitally signed by CATHERINE YEARGAN Date: 2024.07.25 17:02:24 -05'00' ____________________