CENTRAL TEXAS REGIONAL
MOBILITY AUTHORITY

Karst Species Technical Report

Barton Skyway Ramp Relief

(CSJ 3136-01-193)

Central Texas Regional Mobility Authority

June 2021

The environmental review, consultation, and other actions required by applicable federal environmental laws for this project are being, or have been, carried out by TxDOT pursuant to 23 USC 327 and a Memorandum of Understanding dated December 16, 2019, and executed by the Federal Highway Administration and Texas Department of Transportation.

Contact Information

This document is released for the purpose of interim review under the authority of Kemble White, Ph.D., P.G. (Texas Geoscience License #3863; USFWS 10(a)(1)(B) scientific permit covering Central Texas karst invertebrates and *Eurycea* salamanders (TE 37416B-0/ESPER0005108) and Heather Beatty, P.G. (Texas Geoscience License #1350). It is not to be used for permitting, final planning decisions, bidding or construction.

Revision History

The following table shows the revision history for this document.

Effective Date Month Year	Reason for and Description of Change
June 2021	Version 1 released

Table of Contents

List of Figures

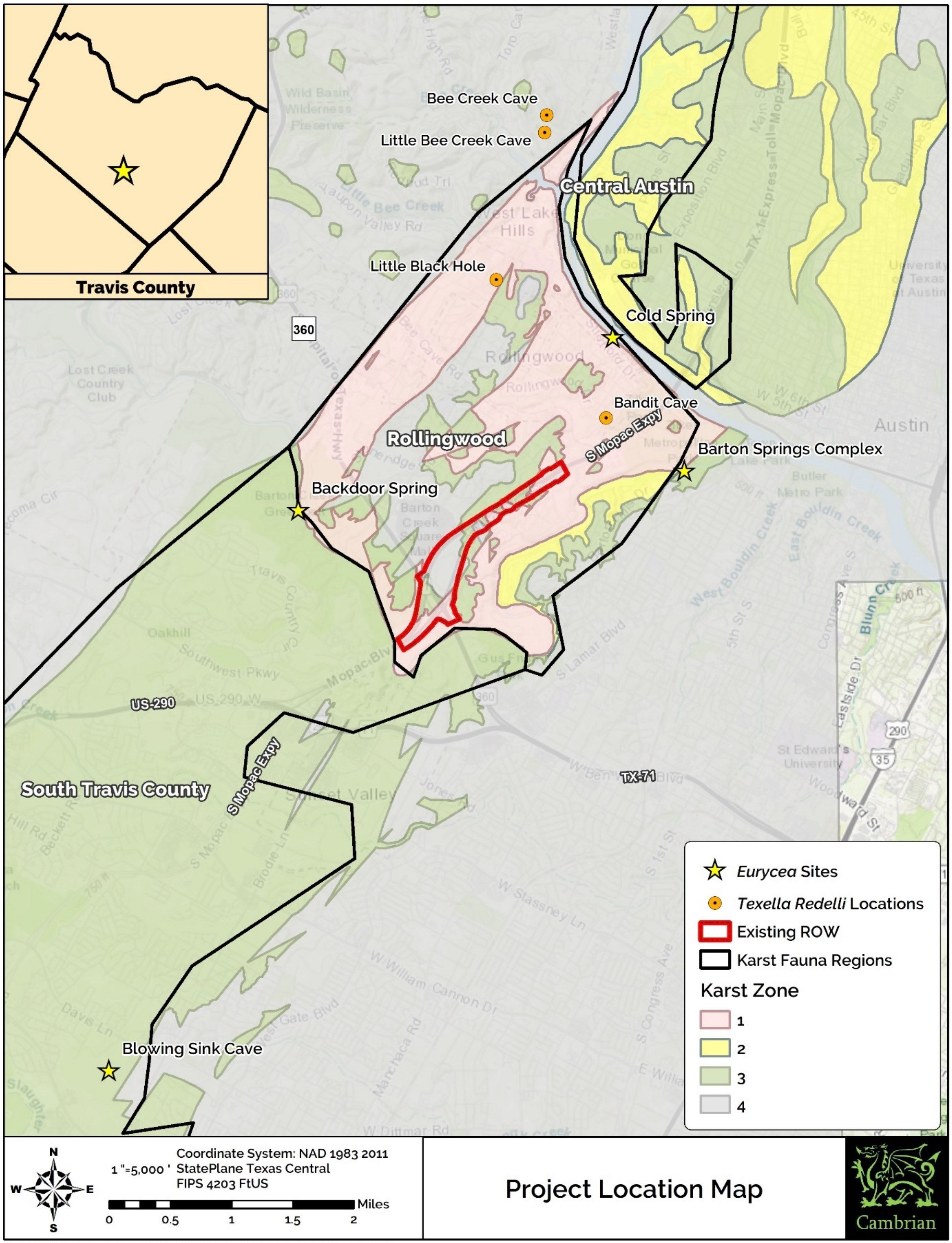
List of Tables

I. Introduction

The Central Texas Regional Mobility Authority (CTRMA) is currently in the planning stages of proposed ramp improvements that would add a southbound auxiliary lane to a 1.55-mile section of State Loop 1 (MoPac Expressway) from Barton Skyway to State Loop 360 (SL 360 or Lp 360) located in Austin, Travis County (Figure 1). This section of the MoPac Expressway (MoPac) had main lanes constructed in the late 1970's and frontage roads built in the late 1980's. Recent improvements in the Project Area were completed in 2014 and 2015 that added a shared use path along MoPac with bridges over SL 360 (Lp 360) and bridge and roadway widening along Lp 360. All of the proposed improvements would take place within the existing MoPac right of way (ROW). The entire Project Area (approximately 220.2 acres) lies within the recharge zone of the Barton Springs Segment of the Edwards Aquifer and within the broader Balcones Escarpment which is a geographic region known to be occupied by endemic karst species including two salamanders restricted to groundwater and springs, and approximately 45 species of rare and endangered karst invertebrates. The purpose of this report is to assess the potential effects of the project on any of these species and to evaluate if take of endangered taxa is likely to occur.

The Edwards Aquifer is the primary focus of this report because it is exposed in the Project Area and it is well known for dynamic interactions between surface water and groundwater. The aquifer discharges primarily at Barton Springs and Cold Springs which are known habitat for listed *Eurycea* salamanders. The Edwards Aquifer is a focus of conservation concerns due to its ecological significance and vulnerability to contamination as a karst aquifer. Karst refers to the modification of bedrock by chemical dissolution resulting in a landscape characterized by caves, sinkholes and springs. Due to the recognized environmental sensitivity of the Edwards Aquifer karst hydrogeologic system, the Texas Commission on Environmental Quality (TCEQ) requires water quality controls for regulated development activities. Stormwater runoff from the Project Area is conveyed by open ditches and storm sewer pipes where it ultimately joins Barton Creek. Listed *Eurycea* salamander species are the Barton Springs Salamander and Austin Blind Salamander (BSS; *Eurycea sosorum* and ABS; *Eurycea waterlooensis*) which were listed as federally endangered in 1993 and 2013, respectively, due to threats from urbanization, including loss of habitat, degraded water quality, and reduced water quantity (USFWS 1997, 2013a). The USFWS designated Critical Habitat Units (CHUs) for ABS around each of the four springs that comprise the Barton Springs Complex at the time of federal listing (USFWS 2013b). BSS has not had critical habitat designated, and the USFWS has not developed a survey protocol for either taxa. The project is located within the Rollingwood Karst Faunal Area (KFA), which is associated with the Edwards Aquifer and known for endemic cave dwelling species. This report also addresses potential effects to the endangered Bee Creek Cave Harvestman (*Texella reddelli*) which is thought to occur in the vicinity of the project beneath karst terrain. Critical Habitat has not been designated for the Harvestman.

The degree of subsurface excavation is related to the likelihood of encountering a previously undetected karst void. Project excavation estimates from the 30% schematic level design indicate that the likelihood of encountering karst voids is low because the underlying geologic units are generally non-cavernous to poorly cavernous in most of the Project Area. Planned excavation consists of the installation of storm sewer pipe, electrical conduit, drilled shafts for an overhead sign structure and for illumination poles.



Credits: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO,

Figure 1. Project location map relative to karst management areas, cave sites known to contain *Texella Reddelli*, and spring sites known to contain *Eurycea* salamanders.

II. Site Description and Hydrogeologic Setting

A. Topography and Drainage

Topography within the Project Area consists primarily of rolling uplands dissected by the Skunk Hollow Creek tributary to Barton Creek. Elevation within the Project Area along southbound MoPac is highest at a point about 1,000 feet north of the Lp 360 intersection where the land surface is approximately 685 feet above mean sea level (amsl). The elevation is lowest at the north and south ends of the Project Area at approximately 568 feet amsl. Surface water runoff in the Project Area drains to Barton Creek which is south and east of the ROW. On the south end Barton Creek is about 200 feet south of the project while on the north end, the creek is about 1,000 feet away. Drainage near Lp 360 flows south along grass lined ditches at the base of road cuts. Drainage within the Skunk Hollow Creek tributary to Barton Creek is conveyed across the ROW in a storm sewer pipe. Within this drainage area surface runoff flows along grass lined slopes and ditches to two outfalls on the east side of the ROW. Towards the north end of the Project Area, runoff flows northeast along the ROW in grass lined ditches and is conveyed in storm sewer to an outfall about 500 feet north of Barton Skyway. Grass lined ditches are equivalent to grassy swales that function as water quality best management practices (BMPs).

Barton Springs is downstream of the project, where surface water in Barton Creek eventually joins the Lower Colorado River in Austin. The Barton Creek watershed is 74,647acres from the vantage of the Lp 360 stream gaging station just south of the Project Area (Zhu and Glick 2017, Table 2.1). Stormwater discharges from the Project Area that eventually reach Barton Creek represent less than 1% of the contribution to the total storm flows within the watershed.

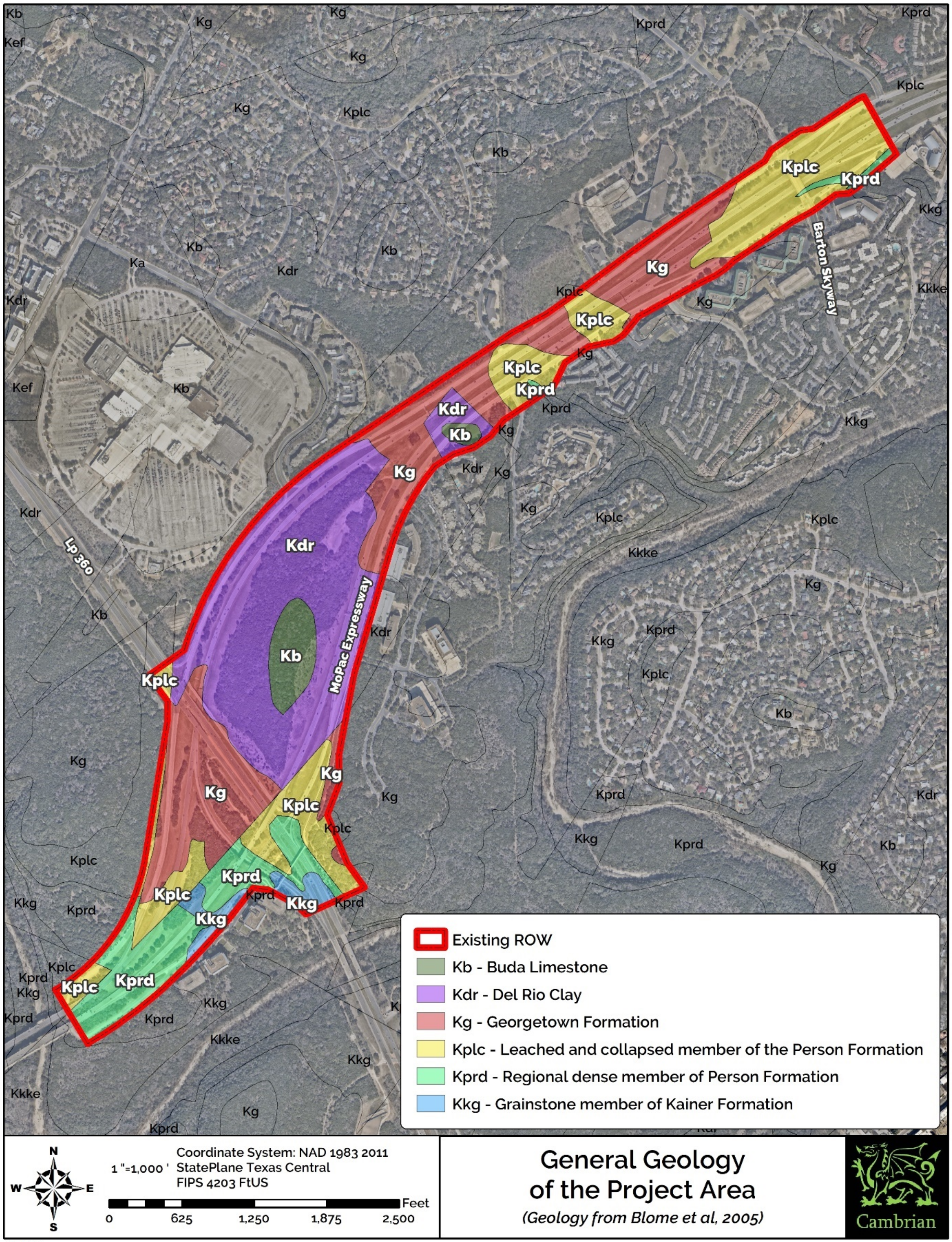
B. Geology

The Project Area lies within the Balcones Escarpment on the eastern margin of the Edwards Plateau. The Project lies within the Balcones Fault Zone (BFZ), which is a major geologic expression of a structural hinge characterized by mostly normal, down to the coast faulting. Approximately one and a half miles west of the project, the northeast trending Mount Bonnell Fault is the dominant fault near the project. The project occurs within the mapped Edwards Aquifer recharge zone where outcropping units in the unsaturated zone rapidly transmit water to the karst aquifer. Although several of the outcropping units are stratigraphically younger than the lithologies that make up the Edwards Aquifer, they occur at topographic highs and contribute surface water runoff to the aquifer outcrop.

Bedrock geology of the Project Area consists of Cretaceous age sedimentary rocks (limestone, marl, and clay) that were deposited in a marine shelf or shelf-margin environment. The upper Cretaceous Del Rio Clay and Buda Limestone overlie the lower Cretaceous Kainer, Person and Georgetown Formations. The Kainer and Person Formations are subdivided into seven hydrostratigraphic members. Within the Project Area the Grainstone member of the Kainer Formation, Regional dense and the undivided Leached and collapsed members of the Person Formation are present (Figures 2 and 3). The occurrence of the Cyclic and marine member of the Person Formation is absent or limited in this part of Travis County due to erosion prior to Georgetown Formation deposition (Hauwert 2009).

Period	Stratigraphic Unit				Thickness (ft)
Quaternary	Alluvium (Qal)				10-30
Upper Cretaceous	Navarro and Taylor Groups (Knt)				600
	Austin Group (Ka)				275
	Eagle Ford Group (Kef)				40
	Buda Limestone (Kb)				40
	Del Rio Clay (Kdr)				60
Lower Cretaceous	Edwards Aquifer	Georgetown Fm. (Kg)			50
		Edwards Group	Person Fm. 50–170 feet thick	Cyclic and Marine mbr (Kpcm)	0-70
				Leached and Collapsed (Kplc)	30-80
				Regional Dense mbr (Kprd)	20
			Kainer Fm. 270–335 feet thick	Grainstone mbr (Kkg)	45-60
				Kirschberg Evaporite mbr (Kkke)	65-75
				Dolomitic mbr (Kkd)	110-150
				Basal Nodular/Walnut Fm. (Kkbn)	50
	Upper Glen Rose mbr (Kgru)				450

Figure 2. Stratigraphic Column. Abbreviations from Blome (2005). Stratigraphic nomenclature and thickness from Hunt et al. (2019) and Small et al. (1996).



Credits:

Figure 3. General geology of the Project Area.

The Del Rio Clay is essentially non-karstic and forms the upper hydrologic cap of the aquifer. Karst features are uncommon in the Georgetown Formation which is the uppermost unit of the Edwards Aquifer. The Leached and collapsed member is karstic and can form extensive caves especially at the base just above the Regional dense member because it is resistant to solution and locally functions as an aquitard (Russell 2007, Hauwert 2009, Hunt et al. 2019). The Regional dense member can be frequently breached with vertical fissures (Hauwert 2009). The Grainstone member forms few caves (Small et al., 1996). There are no project excavation sites located on mapped outcrops of the Regional dense or Grainstone members.

Most of the soil associations within the Project Area occur on hillside slopes of ridges and have a slow to very slow rate of water transmission. Mass grading associated with roadway construction has altered natural soil such that it supports a uniform grass cover. The Del Rio Clay, which exhibits a very low permeability and is the upper confining unit above the Edwards Aquifer, occurs along the hillsides north of Lp 360 between the widely separated main lanes. Here the Buda Limestone caps the top of the hill, at the base of which is a fault that juxtaposes the Georgetown Formation and upper confining units to the west with members of the Edwards Group to the east. Of the multiple faults that cross the Project Area, this fault is distinct and the only one that is observable on the ground (Fault F-14; Cambrian Environmental, 2020a).

C. Recharge to the Edwards Aquifer

The addition of water (recharge) into the unconfined portion of the Edwards Aquifer does not occur uniformly. Recharge enters the Barton Springs Segment of the Edwards Aquifer through caves, sinkholes, or through fractures within the channels of creeks (Slade et al. 1986). Karst features, which are often formed along fault-related fractures, provide avenues for point recharge. While a relatively small amount of recharge does occur through diffuse infiltration across the aquifer outcrop, most recharge in the Barton Springs Segment occurs where overland flow of water is concentrated by topography within drainage and creek channels and within internally draining sinkholes (Hauwert et al. 2005, Hauwert 2009, Hauwert and Sharp 2014). The conditions for recharge are dependent on the amount of storage in the aquifer. Dye trace studies have shown that much of the recharge entering from Barton Creek, upstream of Loop 360, feeds Cold Springs, rather than the Barton Springs complex (Hauwert et al. 2004, Hauwert 2009).

The geologic assessment conducted for the project, as well as previous geologic and karst feature surveys that were reviewed, have identified no major karst recharge features within the Project Area. Two karst features sensitive to recharge (MPS-7 and MPS-19) occur within the Project Area but not within the proposed limits of construction along the southbound direction, and therefore the features will not be affected by the project (Cambrian Environmental 2021 *in progress*).

D. Subsurface Water Levels

Groundwater levels provide critical information about the hydrologic relationships of recharge and discharge to storage within an aquifer, and the direction of groundwater flow. Water level measurements can be expressed as depth to water (DTW) as feet from the land surface, or water-level elevation amsl (BSEACD, 2017). The elevation of groundwater varies based on climatic factors that affect spring discharge rate. Due to the karstic nature of the Edwards Aquifer, water levels fall during seasonal dry weather conditions when there is little or no recharge. In contrast, water levels rise rapidly in response to rainfall events especially in the unconfined portion of the aquifer. A network of water wells in Travis County south of the Lower Colorado River are monitored in partnership with well owners, BSEACD, City of Austin, Travis County, Texas Water Development Board, U.S. Geological Survey, and other area scientists (BSEACD, 2017). Water levels are recorded with automated equipment or by manual measurement.

During a range of flow conditions, groundwater beneath the project generally flows northeast towards Barton Springs, Cold Springs and smaller springs associated with the Lower Colorado River (Hunt et al. 2019). The water table gradient is steep on the western side of the recharge zone and flattens more towards the east and south towards Barton and Cold Springs.

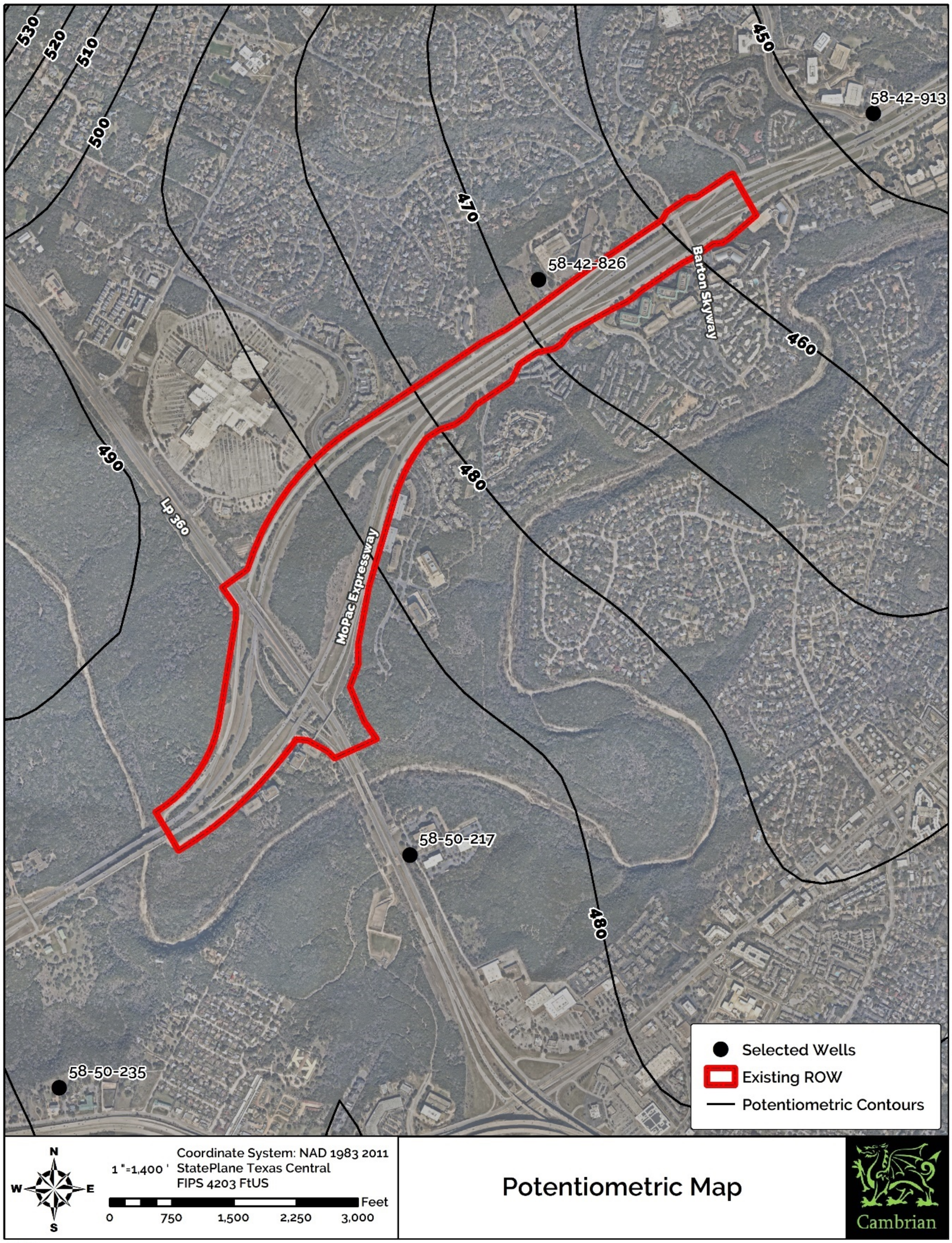
A potentiometric map representing the Edwards Aquifer water level surface during high-flow conditions at Barton Springs (February 2002) is presented in Figure 4. Water storage in the aquifer is highest during such high-flow conditions which also means water levels are closest to the land surface. Using water level data from a time when the water table elevation is high allows for a conservative approach to analyze potential project impacts since areas of closest proximity to the water table can be identified. Comparison of land surface and water table elevations in the Project Area reveals they are separated by approximately 100 to 200 feet. The maximum extent of project excavation would not be more than 20 feet deep (for high mast illumination poles) which is at least 110 feet above the water table at high-flow conditions (Figure 5). Identifying the vertical separation distance between construction activities and the water table can assist in developing impact avoidance best management practices.

E. Groundwater Flow Paths to Springs

The great majority of natural groundwater discharge from the Barton Springs Segment of the aquifer occurs at two locations downstream of the Project Area; Cold Springs and a group of springs collectively known as the Barton Springs Complex. Cold Springs is a major spring that discharges from the south bank of the Lower Colorado River 1.8 km (1.1 mi) north of the project and 2.3 km (1.4 mi) upstream from the mouth of Barton Creek. Barton Springs, made up of Old Mill, Main, Upper, and Eliza Springs, discharge from within Zilker Park northeast of the project about 1.0 km (0.6 mi) upstream of the confluence of Barton Creek and the Lower Colorado River.

These spring sites are shown in Figure 6, along with two springlets in the utility corridor between Lp 360 and Barton Creek Mall west of the Project Area. *Eurycea* salamanders were not detected in these springlets during recent surveys (Cambrian Environmental 2020b).

The Barton Springs Segment of the Edwards Aquifer has been divided into three groundwater basins based on the results of dye tracing (Hauwert et al. 2004; Hauwert 2009; Zappatello and Johns, 2018). Dye trace studies indicate that groundwater within the Barton Springs Segment generally flows northeast towards the Lower Colorado River (Hauwert et al. 2004). Groundwater discharged at Cold Springs originates from the Cold Springs



Credits:

Figure 4. Potentiometric map of the project area. The linework used to make the map consisted of 172 wells that were measured within a month (BSEACD 2017, 2020). The contour interval is 10 feet. Inconsistences in the provided linework (i.e., repeated 480 feet contours) depict a more or less flat water table. Separation between the project area and the water table is between 100 and 200 feet.

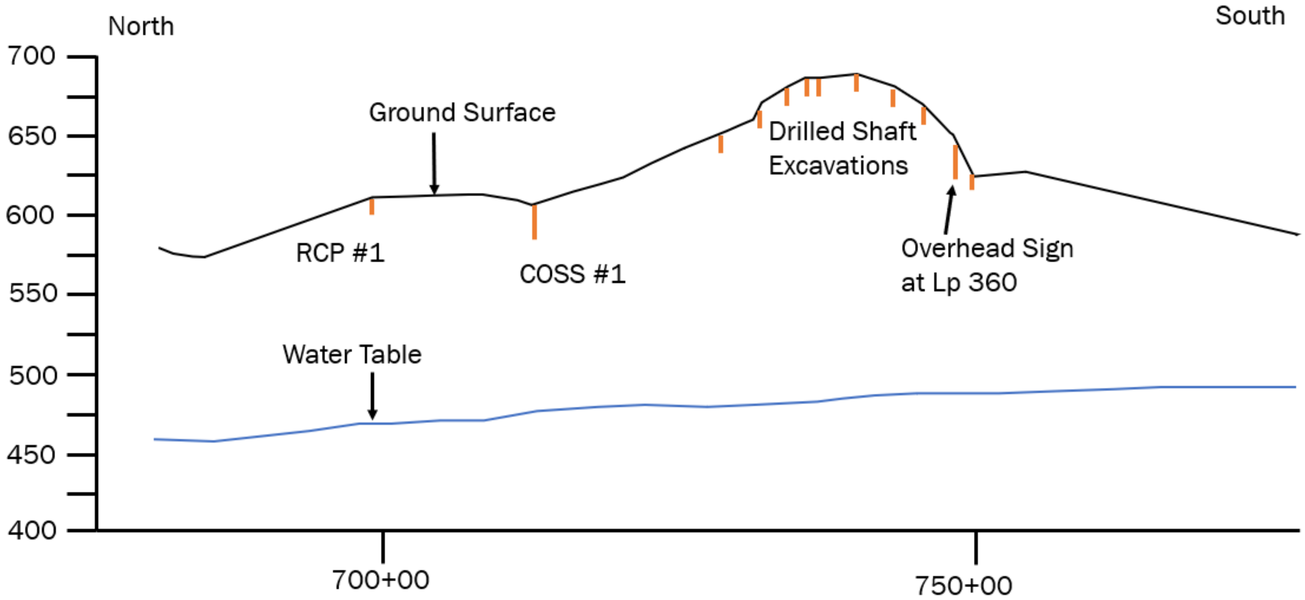


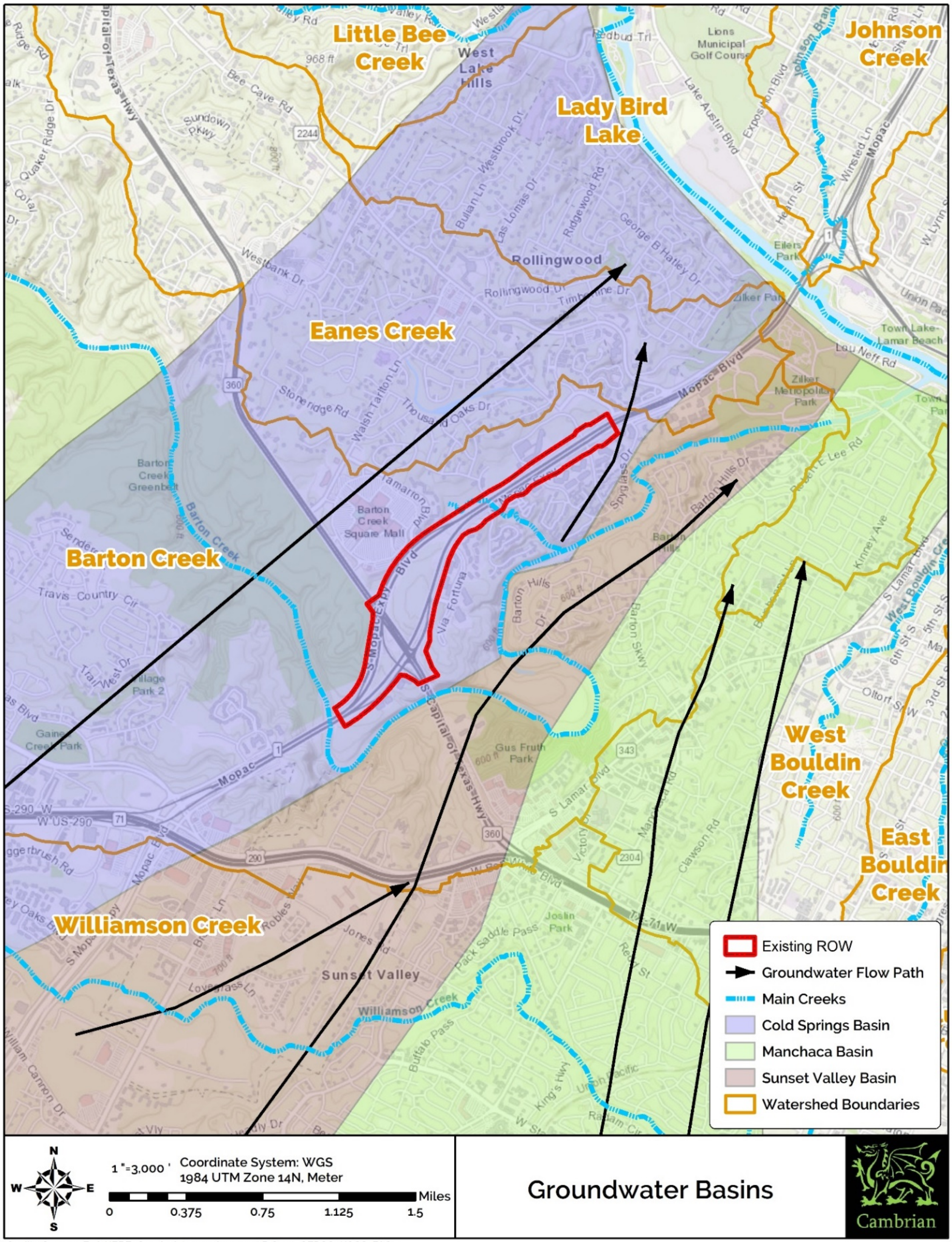
Figure 5*.* Separation between the ground surface and the water table along southbound MoPac roadway stationing. Locations of excavation sites are shown in orange. The water table (blue) surface during high-flow conditions is 110 ft or more below the estimated depth of excavations

Basin. The Barton Springs Complex discharges from the Sunset Valley and Manchaca Basins. The understood boundary joining the Cold Springs and the Sunset Valley basins occurs east of the Project Area therefore, the entire Project Area lies within the Cold Springs groundwater flow basin (Figure 7).

Jones Sink occurs in the bed of Barton Creek approximately 500 feet southwest of the Project Area and 325 feet downstream of the existing bicycle and pedestrian bridge over Barton Creek. Recharge to this feature reaches Cold Springs within several days (Hauwert et al. 2004). See the complete Cambrian Environmental Geologic Assessment for this project for more refined details for these features.

Credits:

Figure 6. Barton Springs, Cold and Backdoor Springs are *Eurycea* locations. Mall Spring 1 and 2 are springlets (very low flow rate) near the Project Area that does not contain suitable habitat for *Eurycea*.



Credits: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO,

Figure 7. The Project Area lies within the Cold Springs groundwater basin.

III. Barton Springs and Austin Blind Salamanders

BSS and ABS are neotenic, permanently aquatic plethodontid salamanders restricted to groundwater and springs within or upstream of the Barton Springs segment of the Edwards Aquifer (Devitt and Nissen 2018, Devitt et al. 2019). At the time of description, BSS were only known from Barton Springs (Chippindale et al. 1993). BSS are currently suggested to occur at 16 springs and one cave (Blowing Sink Cave) in Hays and Travis counties, Texas (Devitt and Nissen 2018, Devitt et al. 2019). ABS were described in 2001 and are only known from Barton Springs (Hillis et al. 2001). Hybridization had been suggested to rarely occur between BSS and ABS, despite their sympatry (Chippindale 2012), but more recent studies substantiate the occurrence of hybridization (Corbin 2020). Populations of BSS at Barton Springs, Cold Spring, and Blowing Sink are reported to demonstrate high levels of gene flow, relative to other central Texas *Eurycea* salamanders (Chippindale 2012). The purpose of this section is to assess the potential impacts the proposed project may have on nearby populations of BSS and ABS, and their habitats. Cold Spring and the Barton Springs complex are located approximately 1.1 miles and 0.9 miles downgradient from the Project Area respectively, while Backdoor spring is located approximately 1.2 channel miles upstream of the Project Area along Barton Creek. All other known locations for the BSS are more than 4 miles upgradient of the Project Area.

A. Habitat Description

ABS are subterranean and are rarely found in the surface habitat at Barton Springs (Hillis et al. 2001, Dries et al. 2013). Subsequently, little is known regarding the natural history of this taxon. The ecology and natural history of BSS is well-studied in comparison to other central Texas *Eurycea* salamanders, but all of the available information comes from laboratory experiments or the wild population at Barton Springs which is located approximately one mile east of the Project Area. The natural history of this taxon at smaller and less anthropogenically modified springs is not yet described.

BSS are found in and underneath a variety of structure objects including cobble, gravel, leaf litter, woody debris, and vegetation, but the interstitial spaces between cobble and gravel are considered optimal habitat (Dries et al. 2013, Dries and Colucci 2018). BSS abundance is negatively correlated with sediment cover, which can fill these interstitial spaces (Bendik and Dries 2018, Dries and Colucci 2018). No data are available regarding the distribution of BSS downstream of spring outlets, but most central Texas *Eurycea* are found in close proximity to springs (Sweet 1982, Bowles et al. 2006, Bendik et al. 2014, Bendik et al. 2016). BSS occur at densities ranging from 0.093/m2 to 4.32/m2 within the Barton Springs complex, and salamander abundance is positively correlated (with a 5 to 14-month lag) to increases in spring discharge quantity (Bendik and Dries 2018, Dries and Colucci 2018). BSS diet is dominated by planarians, chironomid larvae, and amphipods, but they show the ability to diet switch based on resource availability (Gillespie 2013). Crayfish and centrarchid sunfish are documented predators of BSS (DeSantis et al. 2013, Owen et al. 2016, Devitt and Owen 2016, Zabierek and Gabor 2016, Davis et al. 2017). However, these predators are abundant and overlap with BSS at Barton Springs (Dries et al. 2013).

BSS require aquatic habitats with a narrow range of water chemistry and temperature associated with karst aquifers (USFWS 1997). For example, BSS lose their righting response (ability to turn their body upright) in high water temperatures, at approximately 32 ºC (Berkhouse and Fries 1995, Crow et al. 2016). Additionally, BSS demonstrate decreased growth rate when water temperatures are above 24 ºC (Crow et al. 2016). BSS are also sensitive to dissolved oxygen (DO) concentrations below 4.5 mg/L (Woods et al. 2010) and DO is positively correlated with abundance of other *Eurycea* species (Willson and Dorcas 2003, Turner 2004). Currently, no studies have directly investigated BSS tolerance of varying pH or specific conductivity conditions. On average, Barton Springs demonstrates neutral pH and specific conductivity of approximately 600 µS/cm (Dries et al. 2013). Bowles et al. (2006) reported higher counts of the closely related Jollyville Plateau Salamander (*E. tonkawae*; JPS) from springs with conductivity approximately 600 µS/cm compared to springs with conductivity around 900 µS/cm and above. However, Adcock et al. (2016) documented increased JPS relative abundance and density at sites with conductivity greater than 900 µS/cm.

Several publications document a decrease in the abundance of stream dwelling salamanders due to changes in water quality (e.g., temperature, pH, DO) associated with urbanization (see Barrett and Price 2014). Willson and Dorcas (2003) and Bowles et al. (2006) reported that water conductivity increases in areas with increased impervious cover (a measure of urbanization) and is associated with a decrease in aquatic salamander density. Urbanization can also lead to increased siltation in water bodies from stormwater runoff, which can fill the interstitial spaces (and increase embeddedness) thought to be important refugia for *Eurycea* salamanders (Martin et al. 2012, USFWS 2013a). BSS and ABS were listed as federally endangered in 1993 and 2013, respectively, due to threats from urbanization, including loss of habitat, degraded water quality, and reduced water quantity (USFWS 1997, 2013a). The USFWS designated Critical Habitat Units (CHUs) for ABS around each of the four springs at Barton Springs at the time of federal listing (USFWS 2013b). BSS has not had critical habitat designated, and the USFWS has not developed a survey protocol for either taxa.

B. Vulnerability of *Eurycea* Species to Roadway Construction Activities

Activities occurring directly within spring runs known to be occupied by *Eurycea* salamanders could directly affect individuals present at the site. However, the proposed Project Area does not include any areas of known occurrence for BSS or ABS. Therefore, no direct surface effects are expected through physical contact with animals or their preferred habitat. Direct surface effects could only occur during construction of the proposed project if previously undetected *Eurycea* habitat were encountered within the Project Area.

Indirect surface effects are possible if stormwater runoff attributable to the proposed Project reaches an occupied site outside of the Project Area, such as Barton Springs. This may change *Eurycea* habitat so that the breeding, feeding, or sheltering behaviors are adversely modified. Stormwater leaving the Project Area will pass through improved vegetative water quality controls (filter strips) designed to meet or exceed all applicable water quality standards prior to being released. These controls are designed to achieve or exceed the non-degradation water quality standard set by TCEQ and would ideally prevent adverse effects.

Subsurface effects are possible through interaction with the Edwards Aquifer. The extent to which BSS or ABS occur within the Edwards Aquifer is not known. Salamanders are expected only to occur within the wetted portions of the subsurface. The depth at which groundwater occurs is not uniform (Figure 4 - Potentiometric map), and relies on surface topography as well as morphology of the subsurface. Thus, the risk of encountering groundwater during proposed actions varies along the Project Area. Impacts to the subsurface do not rely entirely on contacting groundwater directly. For example, proposed actions may interact with a subsurface void that provides a pathway to the aquifer. An example of this occurred in 2018 during drilling for a geothermal project East of the Barton Springs Complex, which resulted in sedimentation reaching the springs and clouding water. City of Austin investigators found turbidity, but no adverse impact on aquatic life from this event[1].

---

[1] https://www.austintexas.gov/faq/2018-sediment-discharge-springs

IV. Karst Invertebrates

A. Cave Dwelling Karst Invertebrate Species

The entire Project Area lies within the recharge zone of the Barton Springs Segment of the Edwards Aquifer and within the broader Balcones Escarpment which is a geographic region known to be occupied by approximately 45 species of rare and endangered karst invertebrates. The purpose of this report is to assess the potential effects of the project on any of these species, evaluate if take of endangered taxa is likely to occur, and if the proposed project is likely to jeopardize the continued survival and recovery of the species.

Central Texas is an internationally-recognized hotspot of biodiversity due largely to cavernous habitat developed within the Balcones Escarpment. This diversity includes sixteen species of karst invertebrates including cave-adapted beetles and arachnids that have been listed as endangered by the U.S. Fish and Wildlife Service (USFWS). Seven of the endangered taxa are endemic to Travis and Williamson counties. The seven listed species are: Bee Creek Cave harvestman (*Texella reddelli*), Bone Cave harvestman (*Texella reyesi*), Tooth Cave pseudoscorpion (*Tartarocreagris texana*), Tooth Cave spider (*Tayshanneta myopica*), Tooth Cave ground beetle (*Rhadine persephone*), Kretschmarr Cave mold beetle (*Texamaurops reddelli*), and Coffin Cave mold beetle (*Batrisodes texanus*). These species occur nowhere else on the planet and the karst outcrop in which their habitat occurs is threatened by the rapidly expanding communities of the Greater Austin Region. In an attempt to balance development impacts with conservation, Regional Habitat Conservation Plans (RHCPs) addressing karst invertebrates have been developed in both Travis and Williamson counties. These plans, coordinated between local governments and the USFWS, have successfully protected dozens of known locations not only for the endangered taxa but for many of the other rare cave-adapted species who share the same habitat and who might otherwise become candidates for endangered status. Several species occurring in the vicinity of the project are identified under the Balcones Canyonlands Conservation Plan (BCCP) as species of concern (SOC) (Table 1).

Table 1. Endemic troglobitic fauna of Travis County

Common Name	Species Name	Number of Cave Occurrences	Pertinent Information
Bandit Cave spider	*Cicurina bandida*	16	BCCP SOC
Spider	*Cicurina Cueva*	22+	BCCP SOC
Spider	*Cicurina ellioti*	1	BCCP SOC
Spider	*Cicurina reddelli*	1	BCCP SOC
Spider	*Cicurina reyesi*	1	BCCP SOC
Spider	*Tayshaneta "Neoleptoneta" concinna*	2	BCCP SOC
Spider	*Tayshaneta "Neoleptoneta" devia*	6	BCCP SOC
Tooth Cave spider	*Tayshaneta "Neoleptoneta" myopica*	6	Endangered
Spider	*Eidmannella reclusa*	3	BCCP SOC
Pseudo-scorpion	*Tartarocreagris comanche*	4	BCCP SOC
Pseudo-scorpion	*Tartarocreagris intermedia*	1	BCCP SOC
Pseudo-scorpion	*Tartarocreagris texana*	5	Endangered
Ground beetle	*Rhadine austinica*	30	BCCP SOC
Tooth Cave Ground beetle	*Rhadine persephone*	61	Endangered
Kretschmarr Cave Mold beetle	*Texamaurops reddelli*	9	Endangered
Harvestman	*Texella mulaiki*	12+	BCCP SOC
Bee Creek Cave harvestman	*Texella reddelli*	4+	Endangered
Bone Cave harvestman	*Texella reyesi*	203+	Endangered
Harvestman	*Texella spinoperca*	2	BCCP SOC
Millipede	*Speodesmus N. Sp. 2*	6	BCCP SOC
Millipede	*Speodesmus bicornourus*	33	Wilco RHCP Additional Species
Isopod	*Caecidotea reddelli*	Unknown	BCCP SOC
Isopod	*Miktoniscus N. Sp.*	Unknown	BCCP SOC
Isopod	*Trichoniscinae N. Sp*	Unknown	BCCP SOC

Common Name	Species Name	Number of Cave Occurrences	Pertinent Information
Silverfish	*Texoreddellia texensis*	100+	Widely distributed troglobite
Collembola	*Arrhopalites texensis*	7	Wilco RHCP Additional Species
Collembola	*Oncopodura fenestra*	5+	Wilco RHCP Additional Species
Flatworm	*Sphalloplana mohri*		BCCP SOC
Ostracod	*Candona sp. nr. stagnalis*	Unknown	BCCP SOC
Entotroph	*Mixojapyx reddelli*	14	Widely distributed troglobite

Only one of the federally listed species (the Bee Creek Cave Harvestman) is known to occur south of the Lower Colorado River. Its range could potentially include the northern approximately 3,800 feet of the Project Area, although no karst features occupied by any of the listed species have been identified within the Project Area. Several caves containing BCCP SOC have been identified adjacent to the Project Area. Undetected karst voids may occur beneath the Project Area. Even though the Project Area is generally heavily urbanized, unexpected impacts to karst fauna are possible due to the cryptic nature of their subterranean habitat.

B. Karst Invertebrates and Cave Ecology

Troglobites are obligate cave-dwelling organisms that include more than 1,200 species worldwide (Barr 1968). They are characterized by a number of anatomical and physiologic adaptations to cave life collectively referred to as troglomorphy. Troglomorphic characteristics include loss of pigment and sclerotization (thickness of the exoskeleton in invertebrates), reduction or loss of eyes, elongation of appendages, lengthened life span, modified fecundity, and metabolic adaptation to nutrient-poor habitat conditions. The cave environment is relatively monotonous compared to surface invertebrate habitats and is characterized by stable temperatures close to the mean surface temperature, constant near-saturation humidity, low evaporation rates, and the absence of photosynthetic nutrient production. Photo Illustrations 1 through 5 show troglomorphic characteristics of central Texas cave fauna including some species and genera known from the Project Area.

Due to the lack of light for photosynthesis, most cave communities lack primary producers. Instead they rely on nutrient input from the surface ecosystem, and as such they are an extension of the surface ecosystem. Nutrients are introduced into the subsurface in the form of plant detritus washed in by floodwater, roots that penetrate the habitat through cracks in the bedrock, organisms that enter the cave under their own power, and the eggs and waste of trogloxene species such as cave crickets. These types of cave communities are essentially decomposer communities (Culver 1982). Other cave ecosystems have been found to derive

Photographic Illustration 1. The vestigial eye (right) of this central Texas *Rhadine* sp. beetle is an example of regressive troglomorphic traits exhibited by cave-adapted fauna. *Rhadine austinica* (left) occurs in the general Project Area and is a BCCP SOC.

nutrients from chemoautotrophs that produce energy by breaking chemical bonds in sulfur minerals. However, no evidence of this process playing a significant role in the ecology of Central Texas terrestrial troglobites has been found. As a result of adaptation to this low-energy environment, many troglobites are K-selected (Culver 1982). K-selected species are characterized by delayed reproduction, increased longevity, smaller total egg production, and larger egg size.

The origin and geographic distribution of troglobites have important general implications for researchers of evolutionary biology (Holsinger 1988). Study of cave organisms has long been of interest because of the regressive evolutionary traits associated with troglomorphy that are shared by a wide variety of taxa. Regressive evolution is especially significant to the field of evolutionary biology because of the possibility that it results from conditions under which the accumulation of neutral mutations (genetic drift) dominates over environmental selection pressures in term of their influence on the composition of the genome (Culver 1982).

Many troglobitic species are considered to be relicts persisting in subsurface refugia long after their surface ancestor species abandoned their geographic region due to climate change (Barr 1968). Most terrestrial troglobites are thought to have evolved from a surface ancestor that was pre-adapted for cave life because it belonged to a species adapted to living in cool, moist soil or leaf-litter. Repetitive climatic oscillations, such as those during the Pleistocene, periodically brought suitable habitat conditions for these species into and out of geographic areas south of the glacial maxima (Christman and Culver 2001). During warmer, drier intervals, populations inhabiting caves and sinkholes were able to survive in isolated pockets whereas other populations were forced to migrate to suitable habitat conditions or go extinct. The resulting geographic isolation, reduced population size, and restriction of gene flow combined with troglomorphic selection pressures to produce endemic species. Most of the local endemic karst invertebrates are thought to have arisen through similar processes (Barr 1968, Cokendolpher 2004, Culver 1982, Holsinger 1988, Mitchell and Reddell 1971).

Photographic Illustration 2. Surface-adapted (left) and cave-adapted (right) spiders of the genus *Cicurina* show dramatic differences in eye development. Whereas the surface species *Cicurina varians* (left) has the normal 8-eyed configuration, the cave-adapted species of the subgenus *Cicurella* (right) lacks even the vestigial eyes exhibited by many troglobites. The troglobitic species *Cicurina bandida* occurs within the Project Area and is a BCCP SOC.

Photograph Illustration 3. The millipedes of the genus *Speodesmus* lack eyes and pigment and exhibit elongated legs. *Speodesmus* N.S. occurs in the vicinity of the Project Area and is a BCCP SOC.

Photographic Illustration 4. The rare harvestman *Texella mulaiki* occurs in the vicinity of the Project Area and is among the most troglomorphic species in central Texas.

Photographic Illustration 5. *Texella reddelli* in Little Bee Creek. Image from the 2020 BCCP Annual Report, Appendix U11, https://www.traviscountytx.gov/tnr/nr/2020-annual-report.

Centers of troglobitic biodiversity in the United States include Texas, the southeast (Appalachian Mountains, Cumberland Plateau, Central Basin of Tennessee, and the Bluegrass and Mammoth Cave regions of Kentucky), and the Sierra Nevada foothills of California. Among all of these areas, Texas ranks second in terrestrial troglobite diversity (Peck 1998). The diversity of troglobitic fauna in Central Texas caves has been attributed in part to its latitude being south of the maximal advance of glacial ice and north of the stable tropical zone (Culver et al. 2005). Caves were never covered by ice during Pleistocene glaciations as caves in northern latitudes were and the climatic oscillations associated with climate change continuously brought potential colonizers into and out of contact with caves habitats. The composition of the troglobitic community indicates that glacial periods were more important to producing the overall biodiversity in Texas caves. Eleven genera of troglobites share affinities with northern and northeastern fauna whereas only three genera share affinities with tropical and subtropical fauna (Mitchell and Reddell 1971). Tooth Cave, which has the highest level of biodiversity known in any Texas cave, is located approximately 10 miles north of the Project Area. Table 1 presents a list of karst invertebrate species known from southern Travis including those identified as BCCP SOC.

C. Regulatory Framework

Seven species of invertebrates known only from caves in Travis and Williamson Counties, Texas, are listed by the USFWS as endangered species under the provisions of the Federal Endangered Species Act of 1973, as amended (ESA). The seven species are Bee Creek Cave harvestman (*Texella reddelli*), Bone Cave harvestman (*Texella reyesi*), Tooth Cave pseudoscorpion (*Tartarocreagris texana*), Tooth Cave spider (*Neoleptoneta* *myopica*), Tooth Cave ground beetle (*Rhadine persephone*), Kretschmarr Cave mold beetle (*Texamaurops reddelli*)., and Coffin Cave mold beetle (*Batrisodes texanus*). The USFWS considers potential threats to these species to include: destruction and/or deterioration of habitat by commercial, residential, and road construction; filling of caves; loss of permeable cover; contamination from such things as septic effluent, sewer leaks, runoff, and pesticides; predation by and competition with non-native fire ants; and vandalism.

Section 9 of the ESA prohibits the "take" of threatened and endangered species; take is defined as actions that "harass, harm, pursue, shoot, wound, kill, trap, capture, or collect, or attempt to engage in any such conduct." Generally, the USFWS considers modification of regularly occupied endangered species habitat to constitute "harm" and, therefore, a violation of the ESA. In the case of the cave invertebrates, the USFWS may consider any unauthorized activities that result in the realization of any of the aforementioned threats to be "take" and a violation of the ESA.

Generally, habitat requirements for these species include subsurface void spaces in permanent darkness, moisture input sufficient to maintain high humidity, and a source of organic material from the surface. Organic material can be washed into the void by surface water or brought into the void by small mammals or trogloxene species such as cave crickets (*Ceuthophilus secretus*) and daddy longlegs (*Lieobunum townsendii*). Features that can host these organisms include caves, enlarged rock joints, sinkholes, and smaller karst conduits. All seven species are believed to be restricted to karst features within the Edwards Limestone and associated formations.

The USFWS commissioned studies (Veni and Associates 1992, 2007) that delineated geographic zones according to their potential to provide suitable habitat for karst invertebrates. The zones were based on lithology, distributions of known caves and cave fauna, and geologic controls on cave development. The zones were delineated as follows:

Zone 1: Areas known to contain endangered cave species.

Zone 2: Areas having a high probability of endangered or other endemic invertebrate cave fauna.

Zone 3: Areas that probably do not contain endangered cave species.

Zone 4: Areas that do not contain endangered cave species.

The Project Area includes areas designated as Karst Zones 1, 2, and 3. As depicted in Figure 1, the distribution of karst zones within the Project Area are more or less equivalent (37% in zone 1, 28% in zone 2 and 35% in zone 3); however, karst zone 4 is more prevalent within the anticipated limits of construction in the southbound direction.

The studies also discussed the overall karst geography of the Austin region as well as potential geologic and geographic barriers to karst invertebrate dispersal and limits to their distribution. Distinct Karst Fauna Regions (KFRs) have been delineated within Travis, Williamson, Hays, and Burnet counties based on "geologic continuity, hydrology, and the distribution of 38 rare troglobites" (USFWS 1994:67). Figure 1 depicts the proposed Project Area in relation to the KFRs and karst zones. The project would occur within the Rollingwood KFR.

The northeastern half of the Rollingwood KFR is known to be occupied by the Bee Creek Cave Harvestman. The Rollingwood KFR is a more discrete, clearly delineated karst area. To the northwest and southeast it is bounded by faults which limit the exposure of cavernous rock. To the northeast and southwest the KFR is bounded by significant topographic incision by the canyons of Barton Creek and the Lower Colorado River. On the southbound side of the Project Area, two discrete areas are mapped as karst zone 1. Both are associated with the Skunk Hollow Creek tributary to Barton Creek (Figure 1). Of the seven listed invertebrates, only the Bee Creek Cave Harvestman is considered to occur south of the Lower Colorado River and it is not known to range south of Barton Creek.

D. Karst Invertebrate Habitat in the Project Area

The potential for karst invertebrate habitat to occur in the Project Area is directly dependent on the degree of karst void development within the underlying bedrock. The habitat for cave-adapted fauna in the Balcones Escarpment is the byproduct of the evolution of the Edwards Aquifer, a hydrogeological process acting across approximately 20 million years of evolutionary time. The paleoaquifer developed along the structural grain imparted by the Balcones Fault Zone and the primary porosity of the Edwards Limestone which is the host rock for the great majority of caves in the area. During the Miocene, as the ancestral Gulf of Mexico was subsiding to the southeast, the escarpment was created along a belt of weakness where episodic faulting produced more than 1,000 feet of displacement. The resultant Balcones Escarpment is essentially a fault-line scarp consisting of a series of northeast-trending, predominantly normal, nearly vertical, en-echelon (closely-spaced, parallel or subparallel, step-like) faults that are down-thrown toward the coast (Senger et al. 1990).

In the approximately 20 million years since faulting ceased, drainage systems adjusted to this change in topography by accelerating denudation rates along the escarpment. Erosion was particularly focused on fault scarps with the highest displacement. Acting essentially like a giant head-cut, regional drainage systems stripped more than 900 feet of overlying Comanche and Gulf Series strata away from the topographic break, toward the Gulf of Mexico. The top of the Edwards Group Limestones, the dominant cave-forming units in the area, were exposed and had begun to be incised on the San Marcos Platform (a high point in the geological structure) by the middle Miocene on the order of 10 million years ago (Wilson 1956, Ely 1957).

As subsequent portions of the confined aquifer were gradually exhumed by erosion, discrete zones of cavernous porosity became air-filled and were available for progressive colonization by terrestrial fauna (White 2006). Being closest in proximity to karst habitats, it was the edaphobitic (soil dwelling) fauna that first entered the subterranean voids. That the troglobite community is descended from paleo-soil and paleo-leaf-litter fauna is apparent from the fact that both communities share the same basic faunal components (Reddell 1994). Bacteria and actinomycetes were followed by protozoa, nematodes, and rotifers. Mites and springtails formed the base of the scavenger/predator community and, in turn, provided a prey base for insects, myriapods, arachnids, and diplurans. It is this last group of animals who followed convergent evolutionary pathways leading to the remarkable diversity of troglobitic fauna now known from Texas caves. Today the descendants of early cave colonists comprise at least 45 species of obligate terrestrial troglobites in Travis and Williamson counties (Reddell 1993, 1994). They are the living descendants of the surface fauna of the late Miocene sheltered for 10 million years by their subterranean habitat. However, not all voids in the Edwards Limestone are occupied by troglobitic fauna. While troglobitic fauna are known to inhabit mesocavern habitat (small voids connected to the larger caves and sinkholes through which nutrients are able to enter the subsurface), some mesocaverns are interstitial in nature (essentially sealed off from biological activity). Photographic Illustration 6 depicts the interior of an interstitial cavern encountered in a sewer line trench. Although this cave had no natural entrance, mesocaverns allowed BCCP SOC access to the cave habitat.

Photographic Illustration 6. Interior of a cave encountered during construction on a site within the South Austin Karst Fauna Region.

E. Literature Review and Field Studies

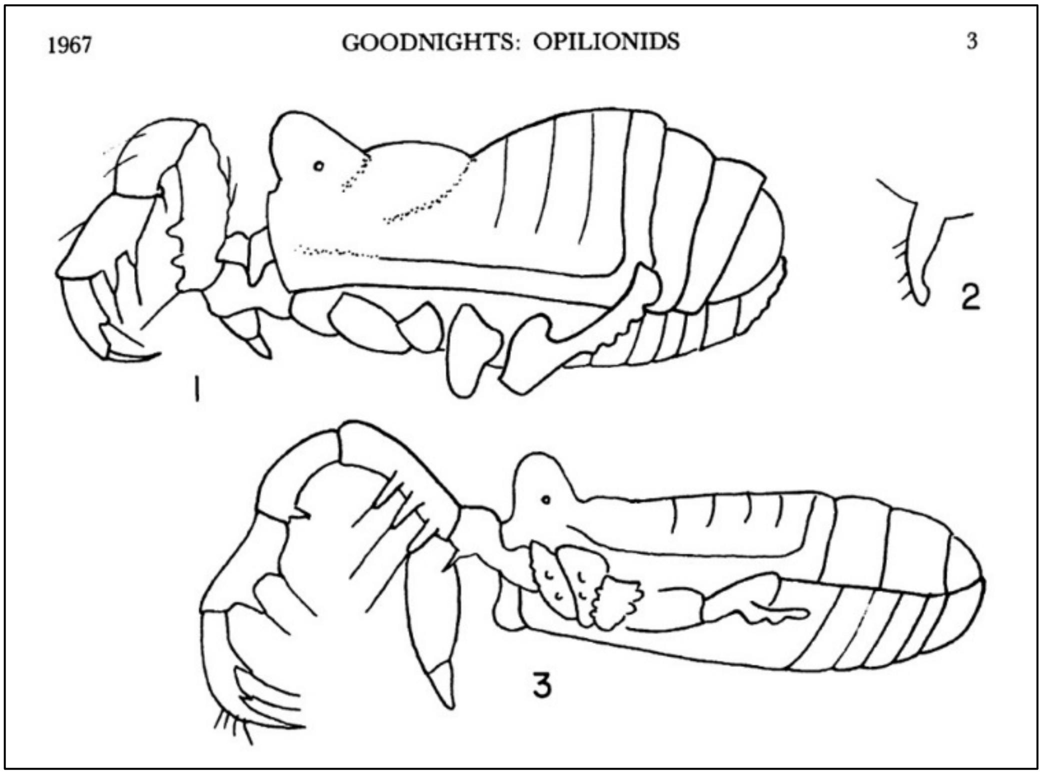
A literature review was conducted as part of the Project Geologic Assessment investigation (Cambrian Environmental 2021) which incorporated the results of previous studies, most notably the karst invertebrate studies conducted early in project development (Zara Environmental 2016). The literature review incorporated karst feature locations and species records from the Texas Speleological Survey, the Texas Commission on Environmental Quality, the City of Austin, and the BCCP. This included consideration of significant caves occurring within 0.25 miles of the ROW which may be relevant to the biological goals and objectives of the BCCP. One nearby cave (Bandit Cave) is known to contain the endangered Bee Creek Cave Harvestman (Figure 1). Several caves surrounding the Project Area are known to contain endemic karst invertebrates and BCCP SOCs. They include Five Pocket Cave and Spyglass Cave; Table 2 provides a summary of six significant karst features known to occur within 500 feet of the project ROW. Hobo Hotel Cave is identified in the COA database as occurring in the ROW; however, the cave is thought to be filled or mislocated. A dimensional analysis of 28 cave maps located within a mile of the MoPac ROW south of the Project Area showed that 86% have longest segments that are less than 100 feet (TxDOT, 2014). Although no maps were available for caves within 500 feet of the project ROW, the analysis suggests that these caves will not intersect the Project Area.

Table 2. Significant karst features within 500 feet of the project ROW within the Rollingwood Karst Fauna Region.

Feature	Distance from project ROW (ft)	BCCP Species of concern	Surface Basin Delineated?	Subsurface Basin Delineated?	Comment
Barton Skyway Cave	177	No data available	no	no	Sealed
Five Pocket Cave	141	*Rhadine austinica*	no	no	Two endemic species
Spyglass Cave	443	*Rhadine austinica*	no	no	Sealed
Jones Sink	500	No data available	no	no	Located in creek bed
Hobo Hotel	Within ROW	No data available	no	No	Filled
Ben White Shelter	200	No data available	no	no	Located above creek bed

Biological data are included where available, but it appears that most of these caves were not thoroughly surveyed for biota. Therefore, these caves represent both known and potential habitat for karst invertebrates.

See the Geologic Assessment (Cambrian Environmental 2021) for full details of all features located within the right of way. Approximately the northeastern half of the Project Area appears to occur within the range of *T. reddelli*. Predicting the occurrence of the Bee Creek Cave Harvestman beyond confirmed locations is difficult, however, due to poorly understood biogeography. In the half century since *T. reddelli* was initially described the concept of the species identity, range and distribution have been in constant flux due to new collection work and the perceived relationship between *T. reddelli* and other *Texella* species. In 2020, the first genetics data on *Texella* sp. upended long-held ideas about the species' range, taxonomy and distribution (Hedin and Derkerabetian 2020). Appendix A contains maps of the distribution of *T. reddelli* over six decades and illustrates the chaotic fluctuation of the species concept and biogeography over time. The taxonomic history of cave harvestmen in central Texas began with a description of a single specimen identified as *Texella mulaiki* from Hays County (Goodnight and Goodnight 1942). By 1967 increased sampling from the area produced a second species, *T. reddelli* (Goodnight and Goodnight 1967) (Figure A-1). This pair of species formed morphological bookends on the spectrum of cave adaptation with *T. mulaiki* being highly troglobitic with elongated appendages, eye loss, etc., and with *T. reddelli* being much less so (Figure 8). *T. reddelli* is only slightly troglomorphic and has well developed eyes, and relatively short legs (Ubick and Briggs 1992).



1967 GOODNIGHTS: OPILIONIDS 3

Figure 8. Anatomical Illustrations of local *Texella* sp.. Excerpted from the original descriptions of *T. reddelli* (1) and *T. mulaiki* (3) both of which occur in the vicinity of the project (Goodnight and Goodnight 1967, p.3).

By 1971 collections included cave-adapted harvestmen from across the Edwards Aquifer region most of which were intermediate forms in terms of troglomorphism (Mitchell and Reddell 1971). By 1992 growing collections allowed for the identification of 18 *Texella* species in Texas, three hierarchical groups[2] and for the re-description of *T. reddelli* (Ubick and Briggs 1992) (Figure A-2). By the 2000's additional collection work in disparate locations created a significant amount of confusion regarding the biogeography of the species. This was particularly because specimens identified as *T. reddelli* had been reported from non-karst environments located well outside of delineated KFRs and as far afield as Burnet County. These locations included leaf litter on talus slopes in western Travis County, caves in karst systems not related to the Edwards Aquifer, and in a man-made mine. Not surprisingly, the first genetics study of central Texas *Texella* species included a comment on the "conspicuously discontinuous distribution" of *T. reddelli*. *T. reddelli* was also the only listed karst invertebrate with reported locations both north and south of the Lower Colorado River (Figures A-3 and A-4). Because of the species low-degree of exhibited troglomorphy some in the taxonomic community began to speculate that at least some of the sampled populations were not actually troglobites at all, but had simply been collected in caves and had been assumed to be cave-adapted.

Twenty-twenty saw the development of the first genetics data on central Texas *Texella* species in a study sponsored by the USFWS (Hedin and Derkerabetian 2020). The data had significant implications for the conservation of *T. reddelli*. Most significantly the study found that all *T. reddelli* specimens from north of the Lower Colorado River actually belong to *T. reyesi*, not *T. reddelli*. Secondly, rejection of the northern disjunct populations strongly suggests that other disjunct populations do not belong to *T. reddelli* despite morphological similarities.

Other results were significant to the *Texella* biogeography of the Project Area. All three of the hierarchical groups have representatives in the vicinity of the Project Area which poses logistical issues for identifying any cave harvestmen found there. Construction monitoring for karst voids is a common conservation measure on roadway projects, but identifying a specimen to species level can be very difficult, especially if the specimen is immature. Developing a rapid diagnostic method of identifying specimens is highly important to conservation of these species. The genetics results indicate clearly that *T. mulaiki* from the Southern Travis County KFR is highly distinct taxon. Also, while *T. grubbsi* and *T. spinoperca* are distinct from *T. reddelli* and *T. mulaiki*, specimens assigned to these species are nested within the same terminal clade. *T. grubbsi* and *T. spinoperca* are closely related enough to raise the possibility that they are synonyms. The geographic relationships between these taxa are illustrated in the Appendix, Figure A-5. Practical implications of this issue are expanded upon in Section V. Veni and Jones (2021) indicated that the southwestern half of the Rollingwood KFR may be occupied by the non-listed species *Texella spinoperca* instead of *T. reddelli*.

---

[2] The Reddelli infragroup contains *T. reddelli*, *T reyesi, and T. mulaiki,* the Spinoperca infragroup contains *T. spinoperca* known only from one or two localities in Travis County south of Cave Y, and the Brevidenta infragroup includes *T. grubbbsi* known from Cave Y (formerly identified as *T. reddelli*), but also from a cave in north Travis County and in several location in Hays and Burnett Counties.

Determining whether a geographic area is occupied by listed karst invertebrates is inherently difficult. Habitat for the invertebrates can be highly obscure within the landscape especially where development activities have occurred. Cave entrances are often concealed by thick brush or blocked by natural or man-made materials, which have to be removed to make the habitat accessible to researchers. Once accessed, the habitat is a difficult working environment and individuals belonging to listed species are often cryptic within the habitat because they are small (some species are less than 2 millimeters [mm] long), because they occur in small numbers, because they retreat beneath rocks or within inaccessible parts of the cave, or because they enter the humanly accessible part of the cave only on a seasonal basis. Some listed species (like the *Texella*) also have non-listed congeners (other species within the same genus) that occur in the same region (Figure A-6). Often these congeners can be difficult to tell apart due to limits in available taxonomic methods. In some instances it can be difficult to tell whether a troglobite recovered from a given cave is a listed species or not. Genetic techniques have been developed for the identification of some listed spiders (Paquin and Hedin 2004, White et al. 2006, Hedin 2014, Hedin and Derkerabetian 2020).

In an attempt to define a due diligence standard that manages the uncertainty inherent to karst studies, the USFWS has developed protocols for determining the presence or absence of listed karst invertebrates (USFWS 2006, 2011, 2014). These protocols provide guidance on when you might be at risk of “taking” a species while conducting karst invertebrate surveys and when it is advisable to have a Section 10(a)(1)(A) permit issued by the USFWS under the ESA to be covered for “take.” The first step in the due diligence process is to survey the surface for karst terrain features that may indicate the potential for habitat in the subsurface. The second step is to investigate any identified karst terrain features for the potential to contain endangered species habitat. This step often involves excavating sinkholes or potential blocked cave entrances. Should potentially suitable habitat be found within a cave, the third step is to conduct a presence/absence survey for listed species within the cave.

Cambrian Environmental professional geologists conducted a karst terrain feature survey within Project Area during the Geologic Assessment investigation in 2021 (Cambrian 2021). The pedestrian survey was completed by walking parallel transects spaced approximately 50 feet apart. Closer spacing was used where vegetation inhibited clear observation. All potential karst features, including depressions, holes, and animal burrows, were carefully examined for evidence of subsurface extent. A number of techniques were used for this effort, including probing with a digging implement to determine the thickness and consistency of fill material and feeling for the presence of air flow, which may indicate the presence of a subsurface void space. Other techniques included making observations of any notable characteristics of the feature such as the presence of various types of vegetation or a semi-circular burrow mound produced by the activities of small mammals.

Karst investigations conducted during a previous planning effort for the MoPac South project resulted in the detection of no occupied habitat for either endangered karst invertebrates or BCCP SOC within the ROW (Zara Environmental 2016). Of 22 potential karst features identified in the ROW, six were determined to have potential for habitat. Following excavation and biological surveys where warranted no obligate karst fauna were detected. Cambrian (2021) incorporated the results of these earlier studies and conducted additional excavation and habitat assessment work to support the results of this updated study. While none of the features investigated in the ROW was found to contain endangered karst invertebrates, they are illustrative of the potential for karst development within the subsurface in the Project Area.

Seven karst features occur in the Project Area, including sinkholes and solution enlarged fractures: MPS-7, MPS-19, MPS-20, MPS-21, MPS-22, MPS-23, and MPS-32 (Table 3). Of these seven, two features were determined to be sensitive with a potential for rapid recharge according to TCEQ guidance: MPS-7 (solution cavity) and MPS-19 (solution enlarged fracture). Sensitive feature MPS-7 has a drainage basin of about 1 acre and is located between the MoPac mainlanes south of SL 360. Feature MPS-19 drains less than 1 acre and is located on an isolated pinnacle east of the MoPac northbound mainlanes within the SL 360 ROW. Feature MPS-21 was previously identified as having a potential karst origin but it was determined to be a non-karst depression. Each of the features are outside the expected limits of construction for the project.

Bandit Cave is the nearest cave to the Project Area known to contain the endangered Bee Creek Cave Harvestman. It is located on private land approximately 510 feet from the edge of TxDOT ROW along MoPac. The nearest point of the project though, at the north end, is more than 3,000 feet from the cave. Bandit Cave lies within the Eanes Creek watershed to the north of the Barton Creek watershed where surface drainage from the project flows.

Table 3. Karst features identified within the Project Area with equivalent feature numbers as a previous geologic assessment. Feature MPS-6 (previous GA feature MP-011) was downgraded to a non karst closed depression because the feature is in the Del Rio Clay. Faults are not included for simplicity. NB=northbound, SB=southbound, ML=mainlanes, FR=frontage road.

Karst Feature ID Geologic Assessment[3]	Previous GA Feature Identification[4]	Karst Feature type and setting	Status
MPS-7	MP-012	Sinkhole between the MoPac ML south of Lp 360	No listed species found in presence/absence survey. Sensitive to recharge.
MPS-19	MBB-12	Solution enlarged fracture on isolated pinnacle east of the MoPac NBML within Lp 360 ROW	No listed species found in presence/absence survey. Sensitive to recharge.
MPS-20	MBB-14	Solution cavity in roadcut east of MoPac NBML at Lp 360	No listed species found in presence/absence survey. Not sensitive to recharge.

---

[3] Cambrian Environmental (2021)
[4] Zara Environmental (2016)

MPS-21	MBB-20	Non-karst depression east of the MoPac NBML	Not sensitive to recharge.
MPS-22	MBB-21	Solution cavity in roadcut along the MoPac NBFR at Lp 360	Not sensitive to recharge.
MPS-23	MBB-22	Solution cavity in roadcut along the MoPac NBFR at Lp 360	Not sensitive to recharge.
MPS-32	Not previously identified	Solution cavity between MoPac ML south of Lp 360	Not sensitive to recharge.

F. Vulnerability of Karst Invertebrates to Roadway Construction Activities

Troglobitic fauna are vulnerable to impacts from development activities due to their absolute dependence on environmental conditions present only in the caves. The cave environment is relatively monotonous compared to surface habitats and is characterized by stable temperatures close to the mean surface temperature, constant near-saturation humidity, low evaporation rates, and the absence of photosynthetic nutrient production (Barr 1968, Culver 1982). Any activity that breaches the architecture of a cave system has the potential to interrupt the relative stasis of temperature and humidity required by troglobites.

Most threats described below alter the stable physical environment of the cave, alter nutrient input, or introduce substances and/or organisms that have the potential to adversely affect karst invertebrate species.

- Entrances to caves can be filled-in or collapse during development activities or activities for agricultural purposes. Covering cave entrances can alter the physical cave environment, as well as impede or eliminate nutrient input.

- Chemical contamination from ground water and/or surface drainages, including pesticides, fertilizers, sewage, hazardous materials spills, various pipeline leaks, storage tanker leaks, landfills, and urban run-off, could adversely affect karst invertebrates. Trash dumping also may be a source of chemical contamination.

- Altering surface drainage via alterations in topography, impervious cover, etc. could lead to drying of karst features and changes in nutrient inputs.

- Loss or alteration of surface communities can potentially adversely affect karst invertebrates by altering nutrient inputs, altering the stable physical environment of the cave, and introducing potentially harmful organisms. When changes in surface community plant composition occur, there is the potential to alter the type and quality of nutrient input into the cave system from the alteration of vegetation. Moreover, changes in surface plant species composition can in turn alter the surface animal species composition. Alterations in animal species composition may lead to less nutrient input into caves via a decrease of troglophiles and trogloxenes. If the surface plant community is denuded (replaced with impervious cover, left as bare ground, etc.) this could lead to fluctuations in cave temperatures and moisture regimes that are outside the normal range of variability for the system. Lastly, disturbance of the soil may lead to increased density of red imported fire ants (*Solenopsis invicta*) and alter the physical environment of the cave through increased sedimentation.

- Materials excavation operations have the potential to alter the stable physical environment of the cave ecosystem by increasing the number of cave entrances, which could have a drying effect, increase sedimentation, and change water drainage patterns to the system. Furthermore, caves can be completely destroyed through this type of activity.

The Project Area consists almost entirely of previously developed land within one of the most urbanized corridors in the Austin area. Most of the project components are unlikely to adversely affect karst invertebrate habitat.

G. Discussion

In order to monitor for undetected habitat encountered during construction activities, karst voids encountered during construction should be evaluated by scientists permitted by the USFWS for karst invertebrate biota surveys (USFWS 2014a).

Relevant BMPs and measures include contractor awareness training so that voids are recognized and response actions are implemented uniformly, notification to the project team and TCEQ, drainage controls to minimize sediment deposition into a void, covering an exposed void to maintain pre-discovery atmospheric conditions, investigations by scientists permitted by the USFWS for karst invertebrate biota surveys (USFWS 2014a), and proper void mitigation designed to protect water quality and provide structural support for the roadway. Incorporating void response and mitigation procedures in construction plans is becoming standard practice for development within the aquifer recharge zones in Central Texas.

The potential for impacts to unanticipated karst features would be minimized from both project construction activities and from post-construction spills on the proposed roadway by the implementation of a Water Pollution Abatement Plan (WPAP) and the use of BMPs in accordance with the TCEQ Edwards Aquifer Protection Program (EAPP) and associated Edwards Rules for the entire Project Area.

V. Impacts Analysis

The proposed project occurs entirely within an area where both construction practices and roadway operation are required to attain minimum performance standards to prevent water quality degradation within the Edwards Aquifer. The proposed project would meet or exceed TCEQ standards and water quality BMPs would match or improve upon sediment controls and TSS removal efficiencies attained by the current facility. There are no known locations for listed species within or adjacent to the proposed Project Area. Therefore, this analysis focuses on the potential for impacts to listed species from the types of direct effects that could result from encountering subgrade karst features not currently known to occur within the Project Area. This starts with a detailed analysis of the geologic and man-mad material present in the shallow subsurface.

A. Geologic Interpretation of Near Surface Materials

Geologic maps were reviewed to determine which areas occur within karstic geologic units. Detailed field surveys were conducted to verify mapped geologic elements in relation to the current roadway and right of way conditions. In particular, the locations and extents of project excavation based on the 30% schematic level design were examined to determine which geologic units would be disturbed during construction. Trenching sites for storm sewer pipe and electric conduit, as well as drilled support shafts for overhead sign structures and illumination poles are estimated to involve excavation between six and 20 feet deep. The locations are generally located between the southbound main lanes and the frontage road or close to the southbound intersection with Lp 360 (Figure 8).

The extent of mapped karst zones was reviewed in the Project Area (Veni 2007). Various published geologic maps and available aerial imagery within the Project Area were reviewed (Rodda 1974, Garner and Young 1976, Blome et al. 2005). The most current available City of Austin geologic map of the Austin area (City of Austin 2014) was reviewed and used as in field maps to aid in site-specific geological interpretation.

As-built construction plans were reviewed (particularly 3136-01-027, and -058) to determine where previously undisturbed karstic bedrock may occur in the subsurface. The degree of grading and the resulting cut of fill was noted (Table 4, Figure 9).

A karst terrain feature survey was conducted within the Project Area during the geologic assessment investigation in 2020 (Cambrian 2020). Licensed professional geoscientists (Texas license numbers 1350 and 3863) along with staff conducted a pedestrian survey of the ROW between January and April 2020. All potential karst features, including depressions, holes, and animal burrows, were carefully examined for evidence of subsurface extent. A number of techniques were used for this effort, including probing with a digging implement to determine the thickness and consistency of fill material and feeling for the presence of air flow, which may indicate the presence of a sub-surface void space. Other techniques included making observations of any notable characteristics of the feature site such as the presence of various types of vegetation or a semi-circular burrow mound produced by the activities of small mammals.

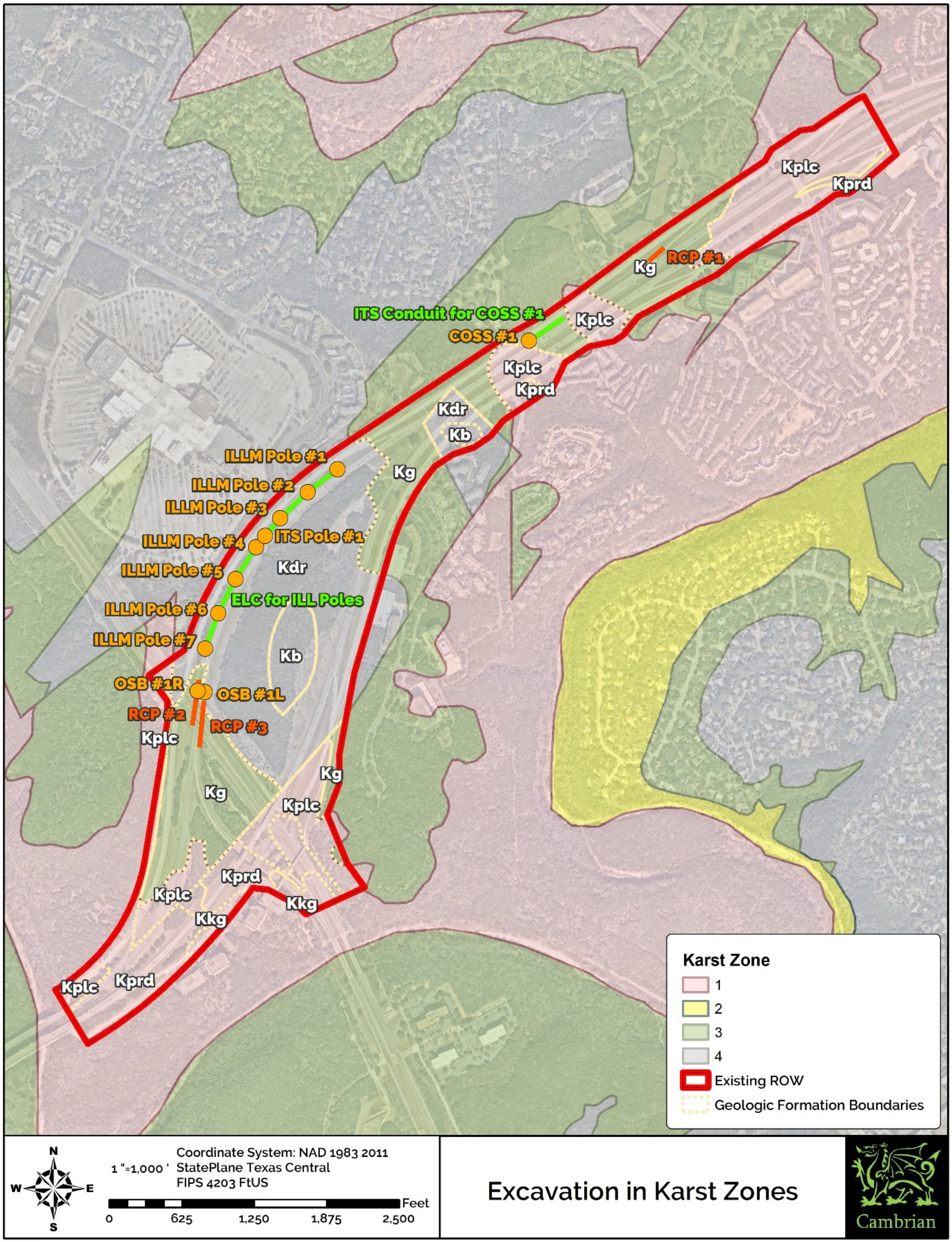
Each of the geologic maps and field studies indicated that the project would be constructed within the Del Rio Clay, Georgetown Formation or Leached and Collapsed member of the Edwards Group (31.5%, 28%, and 23% of the Project Area respectively).

As illustrated in Figures 3, 5, and 9 the majority of the Project Area and all but one of the vertical shaft installations would occur either within existing fill, or within underlying strata that are poorly-karstic to non-karstic. The likelihood of encountering a karst feature in one of these excavation sites is low and conservation measures employed at the time of discovery could dramatically reduce the likelihood of any impact to subterranean habitat. Construction of the project is therefore very unlikely to result in any adverse effect to the Edwards Aquifer.

Impacts to listed karst species are not expected except in the very unlikely event that a significant karst void is encountered during construction and that void is determined to be occupied by one of the listed species. In order to monitor for undetected habitat encountered during construction activities, karst voids encountered during construction should be evaluated by scientists permitted by the USFWS for karst invertebrate biota surveys (USFWS 2014a). The potential for impacts to unanticipated karst features would be further minimized from both project construction activities and from post-construction spills on the proposed roadway by the implementation of a WPAP and the use of BMPs in accordance with the TCEQ Edwards Aquifer Protection Program and associated Edwards Rules for the entire Project Area.

Table 4. Maximum depth at the various excavation locations.

Name	Type	Maximum Depth (ft)	Likely to Encounter Karstic Strata
COSS #1	Drilled shaft for Cantilever Overhead Support Structure	20	Yes
Illumination Poles #1 through 7	Drilled shaft	10	No
ITS Pole #1	Drilled shaft	10	No
OSB #1R and #1L	Overhead Sign Board Structure	20	Possible
RCP #1	Reinforced Concrete Pipe (storm sewer)	8	No
ITS for COSS #1	Conduit	6	Yes
ELEC for Illumination Poles	Conduit	6	No
RCP #2 and #3	Reinforced Concrete Pipe (storm sewer)	8	Possible



Credits:

Figure 9. Excavation locations within the Project Area relative to mapped karst zones per Veni and Associates, 2007.

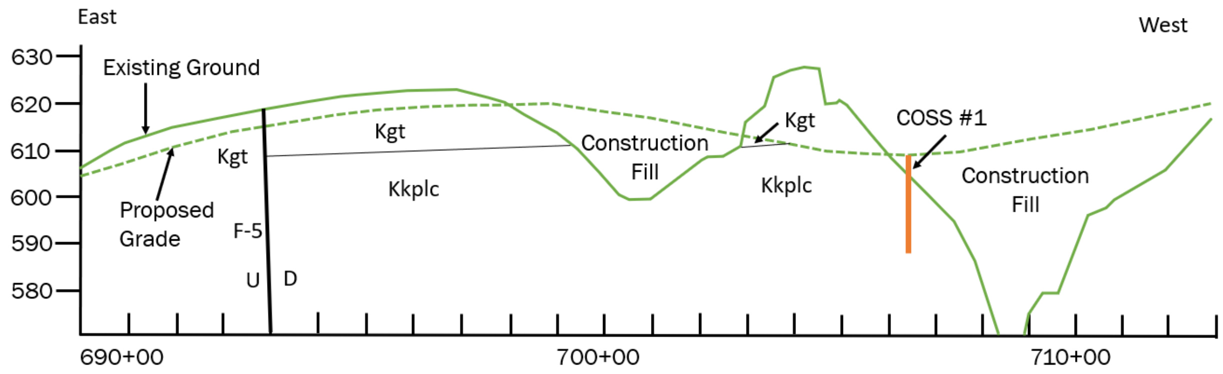


Figure 10. As built southbound main lanes profile along MoPac stationing from 1978 (CSJ: 3136-01-027). Drilled shaft COSS #1 (orange), an excavation site within karst zone 1, would penetrate the Leached and Collapsed Member (Kkplc) of the Edwards Group. Elevations are shown in feet above mean sea level; VE=10x. During high-flow conditions at Barton Springs, the water table elevation is 476 ft amsl.

VI. Literature Cited

Barr, T.C., 1968. Cave ecology and the evolution of troglobites. Evolutionary Biology 2: 35-102.

Berkhouse, C.S. and J.N., Fries. 1995. Critical thermal maxima of juvenile and adult San Marcos Salamanders (*Eurycea* nana). The Southwestern Naturalist 40:430–434.

Berkhouse, C., 2005. Summary of Information for Assessing the Status of the Tooth Cave Ground Beetle (Rhadine persephone). HNTB Corporation, Austin, Texas.

Barton Springs Edwards Aquifer Conservation District (BSEACD), 2020. Edwards Aquifer Potentiometric Database. Provided electronically on August 4, 2020.

BSEACD (Gary, R., Camp, J. and Hunt, B.), 2017, Monitor Wells, BSEACD Fact Sheet 0817, 4p. https://bseacd.org/uploads/BSEACD_MonitorWellFactSheet_2017_final.pdf

BSEACD (Hunt, B and Gary, R.), 2014. Water Level Maps of the Edwards Aquifer and Middle Trinity Aquifers, Central Texas, BSEACD Fact Sheet 0314. https://bseacd.org/uploads/BSEACD_FS0314_WaterLevelMaps.pdf

Blome, C.D., Faith, J.R., Pedraza, D.E., Ozuna, G.B., Cole, J.C., Clark, A.K., Small, T.A., and Morris, R.R., compilers (Blome et al., 2005). Geologic Map of the Edwards aquifer recharge zone, south central Texas: U.S. Geological Survey Scientific Investigations Map 2872, scale 1:200,000. (ArcGIS files publication date 2005) https://pubs.usgs.gov/sim/2005/2873/

Cambrian Environmental. 2021. Geologic Assessment, Barton Skyway Ramp Relief (*in progress*). Report for the Central Texas Regional Mobility Authority, June 2021.

——. 2020a. Draft Geologic Assessment, Mopac South from Cesar Chavez Street to Slaughter Lane, Travis County, Texas (CSJ: 3136-01-176). Report for the Central Texas Regional Mobility Authority and the Texas Department of Transportation, August 2020.

——. 2020b. Biological Technical Report, Barton Springs Salamander (*Eurycea sosorum*) and Austin Blind Salamander (*Eurycea waterlooensis*) Surveys for the SL360 Corridor Study in Austin, Travis County, Texas (CSJ: 0113-13-170). Report for the Texas Department of Transportation, January 2020.

City of Austin (COA), 2014. Geologic Map of the Austin area (ArcGIS files 9/11/2014 version). Provided electronically by the City of Austin Watershed Protection Department One Texas Center, 505 Barton Springs Road, 11th Floor, Austin, TX 78704.

Christman, M. C. and Culver, D. C., 2001. The relationship between cave biodiversity and available habitat. J. Biogeogr. 28: 367–380.

Cokendolpher, J.C., 2004. Cicurina spiders from caves in Bexar County, Texas (Araneae: Dictynidae) Texas Memorial Museum Speleological Monograph 6: 13-58.

Culver, D.C., 1982. Cave Life; Evolution and Ecology. Harvard University Press, Cambridge, Massachusetts.

Culver, D.C., Deharveng, A.B., Lewis, J.J., Madden, M., Reddell, J.R., Sket, B, Tronjel, P., and White, D., 2005. The Mid-latitude Biodiversity Ridge in Terrestrial Cave Fauna. Ecography. 9 November 2005. https://doi.org/10.1111/j.2005.0906-7590.04435.x

Ely, L.M., 1957. Microfauna of the Oakville Formation, LaGrange Area, Fayette County, Texas. University of Texas at Austin M.A., 118 pp.

Garner, L.E., K.P. Young, P.U. Rodda, G.L. Dawe, and M.Y. Rogers, 1976. Geologic Map of the Austin Area, Texas. *in*; Environmental Geology of the Austin Area: an Aid to Urban Planning. Bureau of Economic Geology Report of Investigations No. 86, The University of Texas at Austin.

Goodnight, C.J. and M.L Goodnight, 1967. Opilionids from Texas caves (Opiliones Phalangodidae). American Museaum Novitates No. 2301. 8 pp.

Hauwert, N.M., Sansom, J.W., Johns, D.A., Aley, T.J., (Hauwert et al.), 2004. Groundwater Tracing Study of the Barton Springs Segment of the Edwards Aquifer, Southern Travis and Northern Hays Counties, Texas. Report by the Barton Springs Segment, City of Austin and the Ozark Underground Laboratory. September 2004. https://bseacd.org/uploads/Hauwert_COA_2004_BS-Groundwater-Tracing-Study-final_web.pdf

Hauwert, N.M., 2009. Groundwater flow and recharge within the Barton Springs segment of the Edwards Aquifer, southern Travis and northern Hays counties, Texas. The University of Texas at Austin.

Hedin, M., 2014. Using novel genetic markers and multigenic species delimitation methods to resolve the species status of the cave-dwelling spider species *Cicurina wartoni* Gertsch from Travis County, Texas. FINAL REPORT FOR USFWS CONTRACT #F13PX00770. Department of Biology, San Diego State University San Diego, CA 92182.

Hedin, M. and Derkarabetian, S., 2020. Resolving the Species Status of *Texella* reyesi (Opiliones Phalangodidae) Using Sequence Capture of Ultra-conserved Elements. Final report of pilot study funded by U.S. Fish and Wildlife Service.

Hunt, B.B., Smith, B.A., and Hauwert, N.M., (Hunt et al.) 2019. Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer, central Texas, in Sharp, J.M., Jr., Green, R.T., and Schindel, G.M., eds., The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource: Geological Society of America Memoir 215. https://bseacd.org/uploads/Hunt-et-al.-2019-Barton-Springs-aquifer-GSA-Memoir-215.pdf

Mitchell, R.W. and J.E. Reddell, 1971. The invertebrate fauna of Texas caves. In The Natural History of Texas Caves.

Paquin, P., and Hedin, M., 2004. The power and perils of ‘molecular taxonomy’: a case study of eyeless and endangered Cicurina (Aranea: dictynidae) from Texas caves. Molecular Ecology 2004, 13, 3239-3255.

Peck, S.B., 1998. A summary of diversity and distribution of the obligate cave-inhabiting faunas of the United States and Canada. Journal of Cave and Karst Studies, April 1998: 18-26.

Reddell, J.R. 1993. The Status and Range of Endemic Arthropods from Caves in Bexar County, Texas. Prepared for Texas Parks and Wildlife Department and U.S. Fish and Wildlife Service. 25 October 1993.

——. 1994. The cave fauna of Texas with special reference to the western Edwards Plateau in eds. W. R. Elliott and G. Veni: The Caves and Karst of Texas: A Guidebook for the 1994 Convention of the National Speleological Society with emphasis on the southwestern Edwards Plateau: 31-49.

Rodda, P.U., 1970. Geology of the Austin West Quadrangle, Travis County, Texas. University of Texas, Bureau of Economic Geology. Quadrangle Map No.38.

SWCA Environmental Consultants (SWCA), 2008. Williamson County Regional Habitat Conservation Plan. Prepared for the Williamson County Conservation Foundation, the Honorable Lisa Birkman, President and Commissioner, Precinct 1. SWCA Project No. 10622-139-AUS. August 15, 2008.

Small, T.A., Hanson, J.A., and Hauwert, N.M., (USGS, 1996). Geologic Framework and Hydrogeologic Characteristics of the Edwards Aquifer Outcrop (Barton Springs segment), northeastern Hays and Southwestern Travis Counties, Texas, Water-Resources Investigations Report 96-4306 https://pubs.er.usgs.gov/publication/wri96430690

Ubick, D and T.S. Briggs, 1992. The harvestman family Phalangodidae. 3. Revision of *Texella* Goodnight and Goodnight (Opiliones: Laniatores). Texas Memorial Museum, Speleological Monographs, 3:155-240.

U.S. Fish and Wildlife Service (USFWS). 1994. Recovery plan for endangered karst invertebrate in Travis and Williamson counties, Texas: U.S. Fish and Wildlife Service Region 2. 154 pp.

——. 1994a. Recovery plan for endangered karst invertebrates in Travis and Williamson counties, Texas. 25 August 1994. USFWS Region 2 Office, Albuquerque, NM. 154 pp.

——. 2001. Environmental Assessment for Issuance of two Endangered Species Act Section 10(a)(1)(B) Permits for the Incidental Take of a Troglobitic Ground Beetle (Rhadine exilis) and Madla's Cave Meshweaver (Cicurina madla) During the Construction and Operation of Commercial Development on the Approximately 1,000-Acre La Cantera Property, San Antonio, Bexar County, Texas. March 9, 2001.

——. 2006. United States Fish and Wildlife Service, Section 10(a)(1)(A) Scientific Permit Requirements for Conducting Presence/Absence Surveys for Endangered Karst Invertebrates in Central Texas. U.S. Fish and Wildlife Service, Austin Ecological Services Field Office, Austin, Texas.

——. 2009a. 5-Year Review: Bone Cave Harvestman (*Texella* reyesi). USFWS Austin Ecological USFWS Field Office, Austin, TX. 22 pp.

——. 2009b. 5-Year Review: Bee Creek Cave Harvestman (*Texella* reddelli). USFWS Austin Ecological USFWS Field Office, Austin, TX. 13 pp.

——. 2009c. 5-Year Review: Tooth Cave Spider (Neoleptoneta myopica), Kretschmarr Cave Mold Beetle (Texamaurops reddelli), and Tooth Cave Pseudoscorpion (Tartarocreagris texana). USFWS Austin Ecological USFWS Field Office, Austin, TX. 15 pp.

——. 2011. United States Fish and Wildlife Service, Section 10(a)(1)(A) Scientific Permit Requirements for Conducting Presence/Absence surveys for Endangered Karst Invertebrates in Central Texas. U.S. Fish and Wildlife Service, Austin Ecological Services Field Office. Revised September 8, 2011. Access 03/17/14 from: https://www.fws.gov/southwest/es/Documents/R2ES/Karst_Survey_Protocols_20110908.pdf

——. 2014a. United States Fish and Wildlife Service, Section 10(a)(1)(A) Scientific Permit Requirements for Conducting Presence/Absence surveys for Endangered Karst Invertebrates in Central Texas. U.S. Fish and Wildlife Service, Austin Ecological Services Field Office. Revised September 8, 2011. Access 11/03/14 from: http://www.fws.gov/southwest/es/Documents/R2ES/Karst_Survey_Procedures_20140508.pdf

______.2014b. Biological Opinion for the Intersection of State Highway 151 and Loop 1604. Bexar County, Texas. Section 7 Consultation Number 02ETAU00-2012-F-0023. 26 August 2014.

______.2014c. Endangered Karst Invertebrate Taxonomy of Central Texas. U.S. Fish and Wildlife Service, Austin Ecological Services Field Office. Revised March 5, 2014. Accessed from: http://www.fws.gov/southwest/es/documents/r2es/bexar_rp_taxo_module.pdf

——. 2015. United States Fish and Wildlife Service, Section 10(a)(1)(A) Scientific Permit Requirements for Conducting Presence/Absence surveys for Endangered Karst Invertebrates in Central Texas. U.S. Fish and Wildlife Service, Austin Ecological Services Field Office.

_____. 2018a. Species Status Assessment for the Bone Cave Harvestman (*Texella* reyesi). Version 1.0 April, 2018. Austin, TX. 159 pp.

_____. 2018b. Bone Cave Harvestman (*Texella* reyesi). 5-Year Review: Summary and Evaluation. USFWS Austin Ecological Services Field Office, Austin, TX. 40 pp. July 6, 2018.

_____. 2018c. Bee Creek Cave Harvestman (*Texella reddelli*). 5-Year Review: Summary and Evaluation USFWS Austin Ecological Services Field Office, Austin, TX. 39 pp. July 6, 2018.

_____. 2018d. Tooth Cave Pseudoscorpion (Tartarocreagris texana). 5-Year Review: Summary and Evaluation. USFWS Austin Ecological Services Field Office, Austin, TX. 34 pp. July 6, 2018.

_____. 2018e. Tooth Cave Spider (Tayshaneta myopica=Neoleptoneta myopica). 5-Year Review: Summary and Evaluation. USFWS Austin Ecological Services Field Office, Austin, TX. 34 pp. July 6, 2018.

_____. 2018f. Kretschmarr Cave Mold Beetle (*Texamaurops reddelli*). 5-Year Review: Summary and Evaluation. USFWS Austin Ecological Services Field Office, Austin, TX. 33 pp. July 6, 2018.

_____. 2018g. Tooth Cave Ground Beetle (*Rhadine persephone*). 5-Year Review: Summary and Evaluation. USFWS Austin Ecological Services Field Office, Austin, TX. 37 pp. July 6, 2018.

Veni, G, Jones, M., 2021. Statistical analysis and Revision of Endangered Karst Species Distribution, Austin Area, Texas. National Cave and Karst Research Institute Report of Investigation 10, Carlsbad, New Mexico, 55 pages. http://www.nckri.org/about_nckri/investigations/NCKRI_RI_10.pdf

Veni and Associates, 2007. Revision of Karst Species Zones for the Austin, Texas, Area. Prepared for the Texas Parks and Wildlife Department. 8 July 2007. https://www.fws.gov/southwest/es/Documents/R2ES/TX_Karst_Veni_2007_Austin_area_karst_zones.pdf

Veni and Associates, 1992. Geologic controls on cave development and the distribution of cave fauna in the Austin, Texas, region. Revised February 1992. USFWS Austin, Texas. 77 pp.

White, K., 2006. Paleohydrology of the Edwards Aquifer Karst and the Evolution of Rare and Endangered Cicurina Cave Spiders, South-Central Texas. University of Mississippi Dissertation. Oxford, Mississippi.

White, et al. 2009 Hydrologic evolution of the Edwards Aquifer recharge zone (Balcones fault zone) as recorded in the DNA of eyeless Cicurina cave spiders, south-central Texas. Geology, April 2009; v. 37; no. 4; p.339-342; doi:10.1130/G25373A.1;3 figures.

Wilson, J.A., 1956. Miocene formations and vertebrate biostratigraphic units. Texas Coastal Plain: American Association of Petroleum Geologists Bulletin. 40:2233-2246.

Small, T. A., Hanson, J. A., & Hauwert, N. M., 1996. Geologic framework and hydrogeologic characteristics of the Edwards aquifer outcrop (Barton Springs segment), northeastern Hays and southwestern Travis Counties, Texas (Vol. 96, No. 4306). US Department of the Interior, US Geological Survey.

Texas Department of Transportation (TxDOT), 2014. Additional Geologic Studies for the MoPac (State Loop 1) Intersections, Austin District. October 2014.

Texas Water Development Board (TWDB), 2020. Groundwater Data Viewer, an interactive data viewer published by the TWDB, 1700 North Congress Avenue, Austin, TX 78701.

Zappitello, S.J., Johns, D.A., and Hunt, B.B., 2019. Summary of Groundwater Tracing in the Barton Springs Edwards Aquifer from 1996 to 2017, City of Austin Watershed Protection Report, DR-19-04. https://bseacd.org/uploads/Zappitello-et-al.-2019-Dye-Tracing-Summary.pdf

Zara Environmental, 2016. Draft: Karst Invertebrate and Salamander Technical Report. Mopac South Project, Austin, Travis County, Texas. Prepared for Jacobs Engineering, Inc. 2705 Bee Cave Road, Suite 300, Austin, TX 78746. 28 January 2016

Zhu, W., and Glick, R., 2017. An Examination of Stormwater Quality and Quantity in Austin Area Creeks. City of Austin Watershed Protection Report SR-17-05, September 2017, 351 p. http://www.austintexas.gov/watershed_protection/publications/document.cfm?id=283712

VII. Appendices

Appendix A:

Known Range and Distribution of *T. reddelli* Over Time

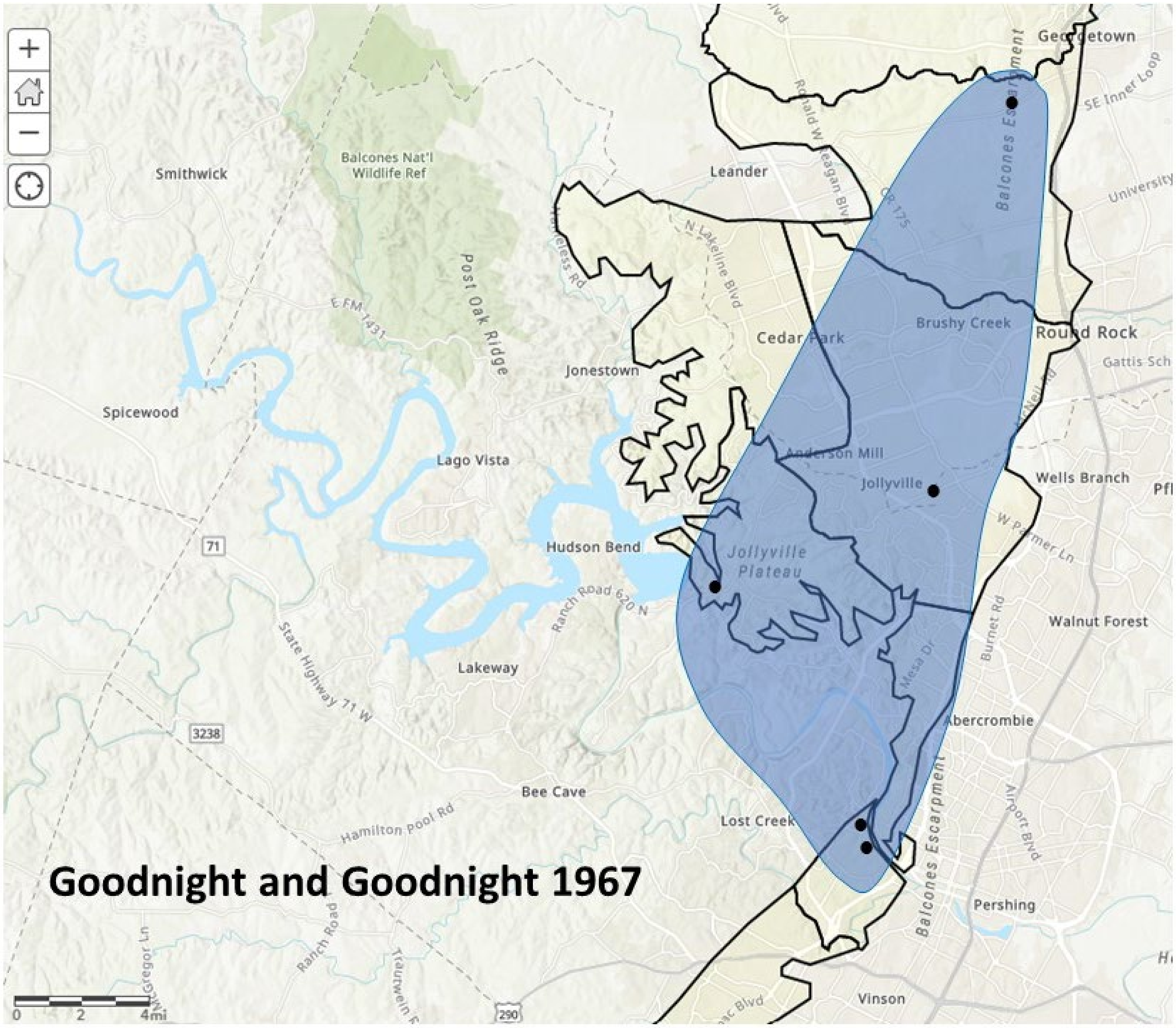


Figure A-1. Range of *T. reddelli* as originally described.

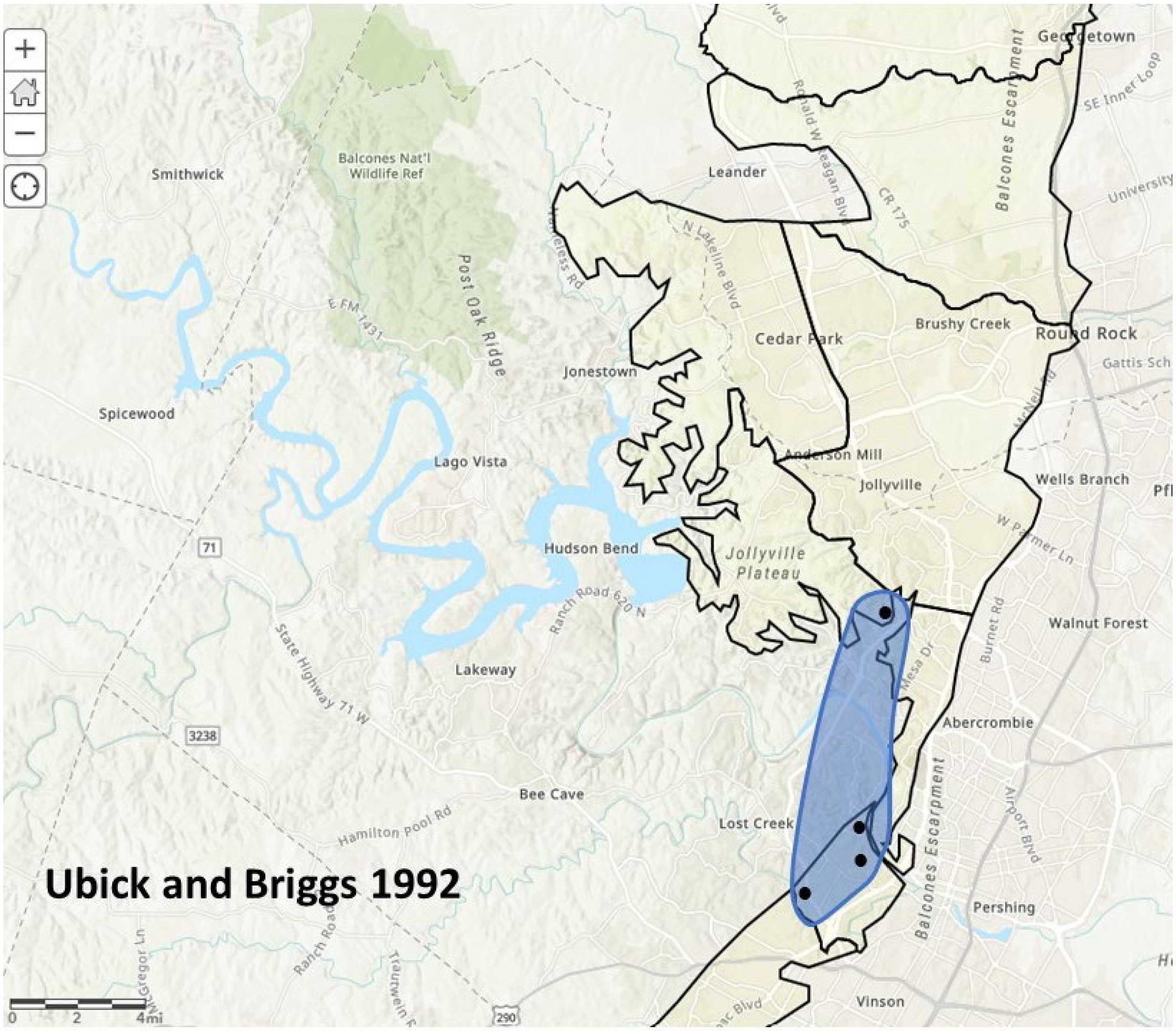


Figure A-2. Range of *T. reddelli* as re-described in 1992. This range reduction was due primarily to specimens being re-assigned to the newly described species *T. reyesi*.

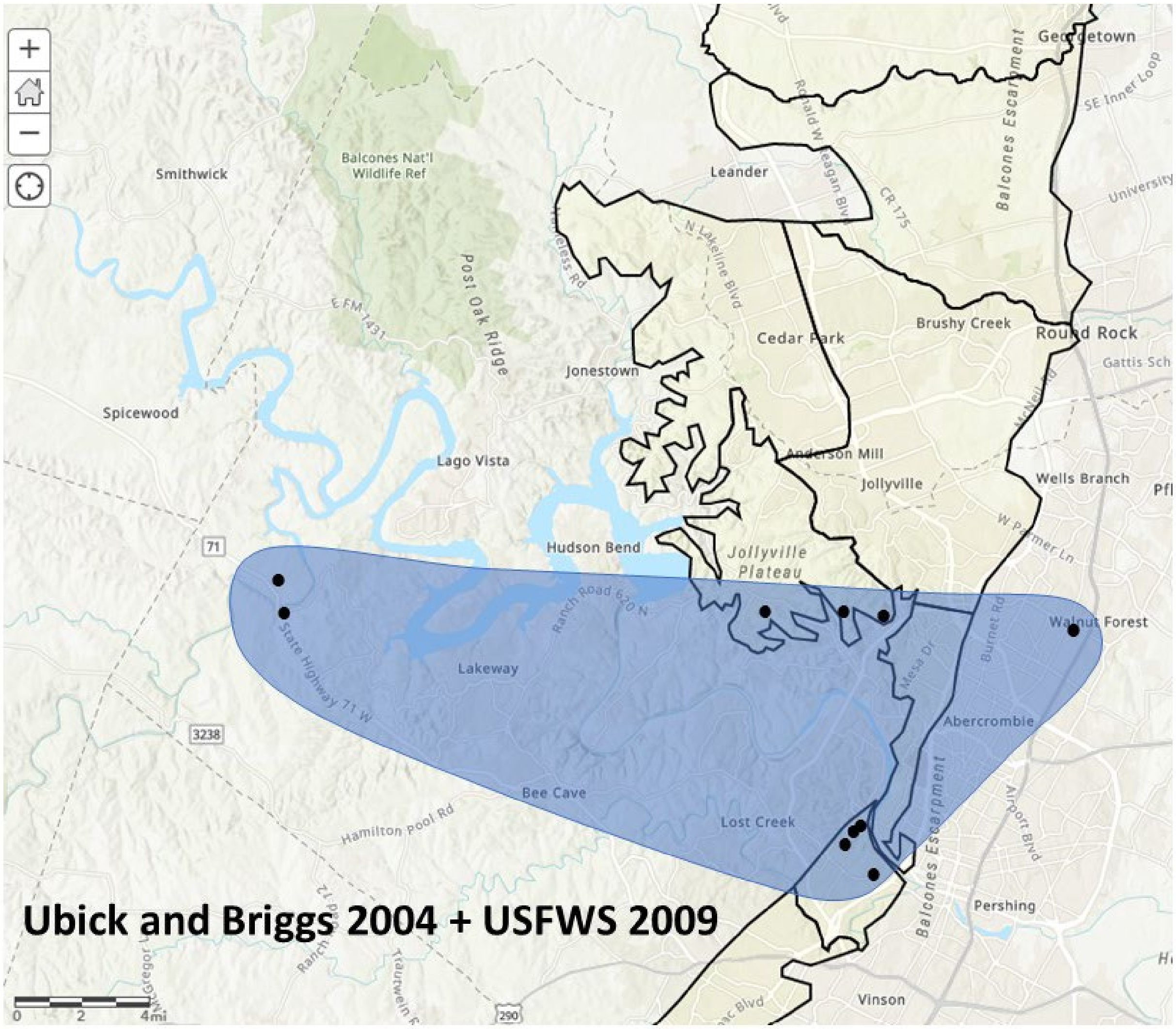


Figure A-3. Range of *T. reddelli* as reported in the 2000's. This range expansion was due primarily to new collections.

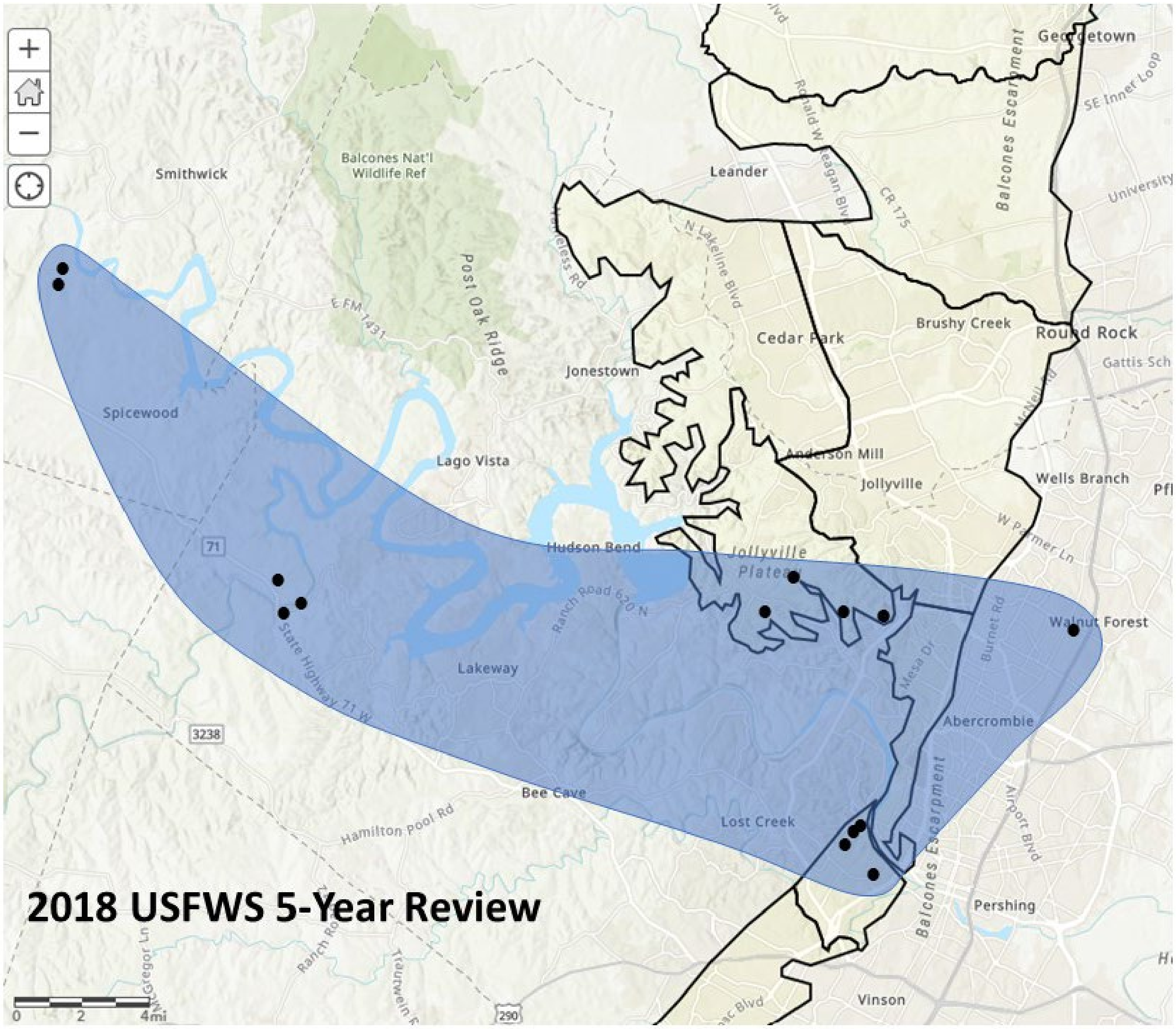


Figure A-4. Range of *T. reddelli* as reported in the USFWS 5-Year review. This range expansion was due primarily to new collections.

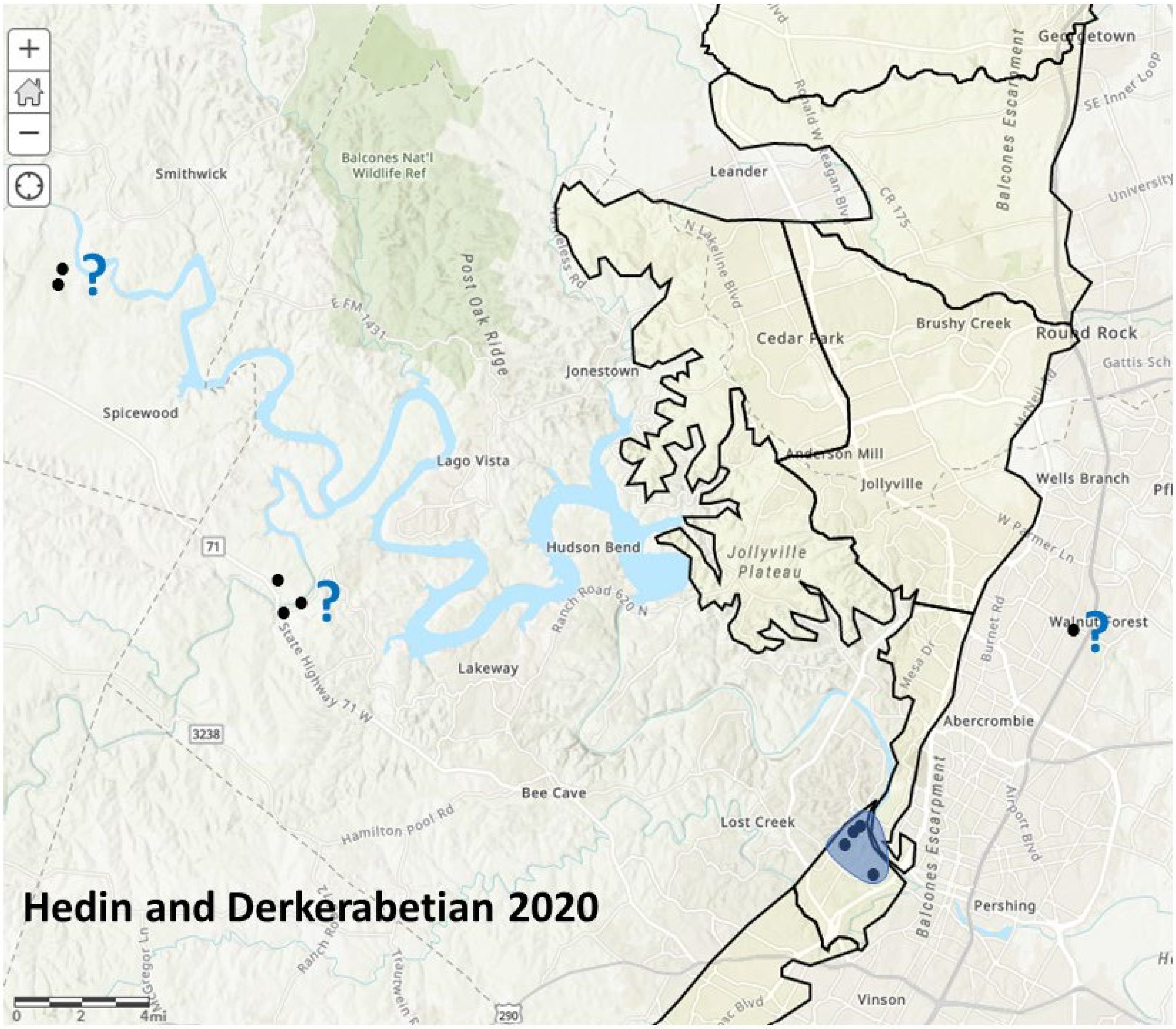


Figure A-5. Range of *T. reddelli* as indicated by recent USFWS-sponsored genetics study (Hedin and Derkerabetian 2020).

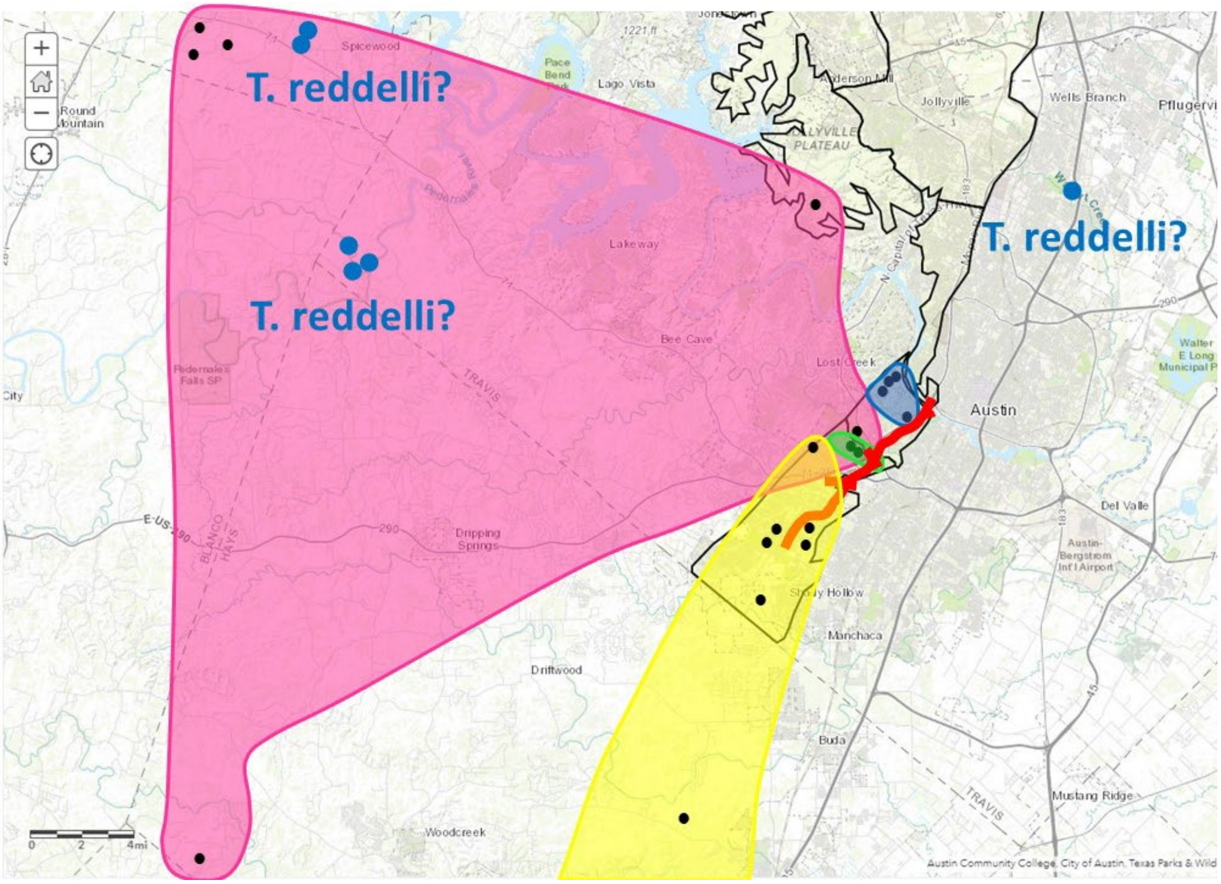


Figure A-6. Range of *T. reddelli* as indicated by recent USFWS-sponsored genetics study. *Texella grubbsi* (Pink), *Texella mulaiki* (Yellow), *Texella spinoperca* (Green).