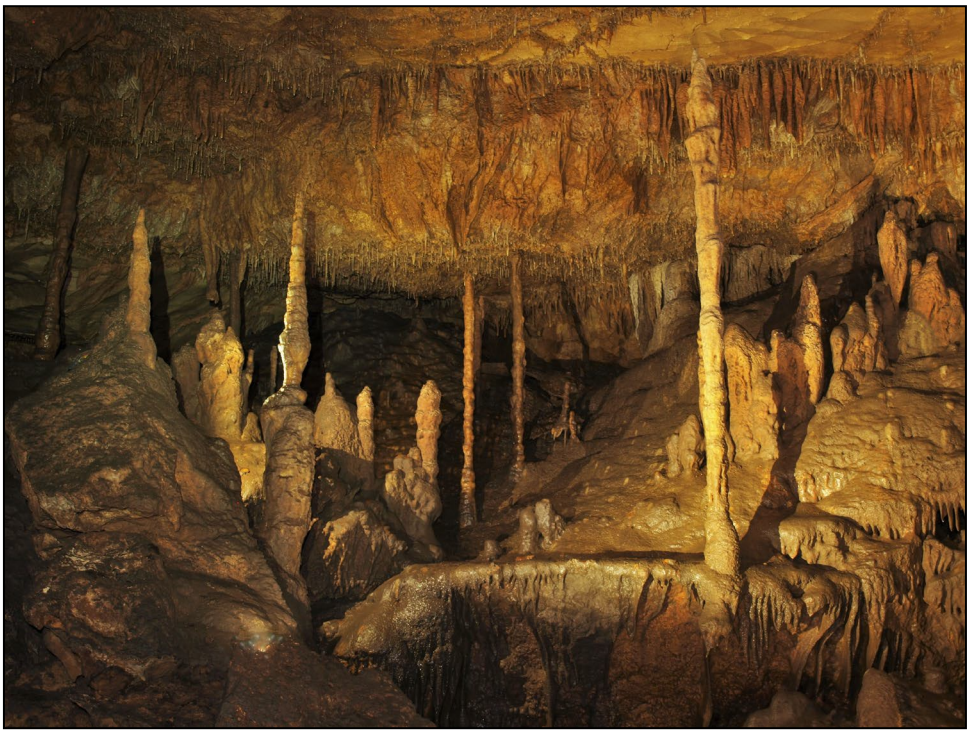
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SURFACE AND SUBSURFACE DRAINAGE BASIN DELINEATION OF PIPELINE CAVE, WEST SLAUGHTER LANE CORRIDOR, AUSTIN, TRAVIS COUNTY, TEXAS



Cave formations within Pipeline Cave.

Prepared in partnership with the
City of Austin, Wildland Conservation, Austin Water

Prepared for
AECOM
9400 Amberglen Boulevard
Austin, Texas 78729

and the
City of Austin
Public Works Department

8 February 2021

SURFACE AND SUBSURFACE DRAINAGE BASIN DELINEATION OF PIPELINE CAVE, WEST SLAUGHTER LANE CORRIDOR, AUSTIN, TRAVIS COUNTY, TEXAS

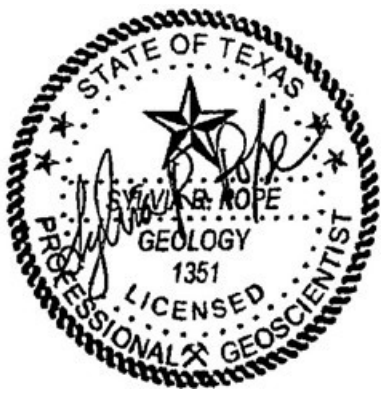
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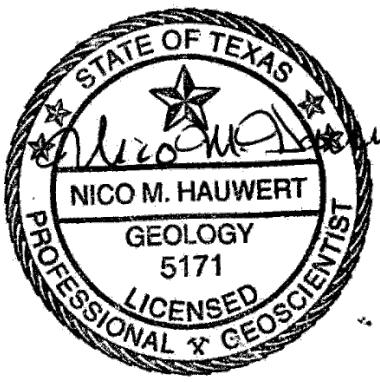
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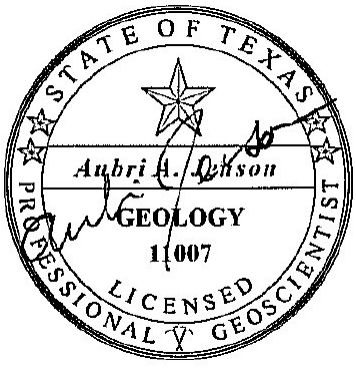
In accordance with the Texas Board of Professional Geologists rules at 22 Texas Administrative Code, Part 39, Chapter 851, Subchapter C, §851.156, this report is signed and sealed on the title page to assure the user that the work has been performed by or directly supervised by the following professional geologists who take full responsibility for this work.

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Acknowledgements

This study was supported in funding and labor by the Mobility Corridor Project of City of Austin Public Works Department and Austin Water Balcones Canyonlands Preserve Program. The study would not be possible without the generous access permission and support from Melissa Beatty of Whitestone Reit on behalf of Parkside Village South Shopping Center and Tim League, founder of Alamo Drafthouse Cinema. The authors gratefully acknowledge the following individuals for helping bring this project to completion: City of Austin Watershed Protection Department for providing precipitation data from FEWS rain gauge #1190, fire hose for tracer study, and fluorimeter data from Eliza Springs; Saj Sappitello for assistance with report writing; Brian Cowan for preliminary project design; Rich Zaria, Drew Thompson, Lucas Pustka, Bill Larsen, Jet Joost, Colin Strickland, Mark Sanders, and Christopher Francke for assistance with cave excavation; Joe Diaz park manager for the City of Austin Parks and Recreation Department for facilitating access to caves and dye injection features; Lucas Pustka and Liza Colucci for help with field work; Kevin Thuesen program manager for AW Water Quality Protection Lands and biologist Devin Grobert for site access and project assistance; and others. Lara Williams constructed the geologic cross section. Colin Strickland, Aubri Jenson, and Drew Thompson surveyed and produced a cave map of Pipeline Cave. Brian Smith, Barton Springs/Edwards Aquifer Conservation District, provided suggestions for groundwater monitoring and approved the proposal for the dye trace injection. Justin Camp, Barton Springs/Edwards Aquifer Conservation District, provided access and technical information for groundwater monitoring. All assistance is appreciated.

Abstract

This project was conducted to support environmental permitting requirements for the Slaughter Lane Corridor Transportation Improvement Project, initiated by the City of Austin. Transportation improvements are proposed within in the West Slaughter Lane Corridor between Loop 1 South and Escarpment Boulevard. These improvements may affect the existing land surface and subsurface conditions in the vicinity of Pipeline Cave, located south of West Slaughter Lane and west of Loop 1 South. Pipeline Cave is listed on the City of Austin/Travis County Balcones Canyonlands Conservation Plan federal endangered species permit for the protection of karst invertebrate species. Since 2018 this cave has been managed by the City of Austin's Balcones Canyonlands Preserve Program. Per the Balcones Canyonlands Preserve Management Plan, hydrogeologic investigations are required if infrastructure development is proposed within 0.25 mile of a cave. Otherwise, construction may be limited to areas that are at an elevation greater than that of the floor of a cave. A hydrogeologic investigation had not been conducted for Pipeline Cave, prior to this project.

This project delineated the surface and subsurface drainage basins of Pipeline Cave by mapping hydrostratigraphic characteristics, determining geologic framework, conducting pedestrian karst feature surveys, excavating karst features, surveying caves, characterizing cave drips and pools, characterizing source water and cave drip water quality, analyzing cave drip rates, and conducting a dye tracer study. The goal of the hydrogeological study is to map the cave's water source areas with high confidence. The project began in November 2019 and ended in December 2020.

The result of this project is the determination that the probable extent of the surface and subsurface drainage basins of Pipeline Cave is relatively local and outside of the area of the proposed transportation improvements. The construction associated with these improvements is unlikely to affect Pipeline Cave, or the karst invertebrate habitat within the cave, due to the limited disturbance to the land surface occurring outside of the surface and subsurface drainage basins. Furthermore, in the course of the hydrogeologic study, the accessible habitat portion of Pipeline Cave was expanded 20 times its pre-2018 trash-filled volume. The excavation revealed that Pipeline Cave housed a bat colony prior to its filling with trash in the 1950's and 1960's as part of the former Covert Ranch.

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Introduction

This study supports environmental permitting requirements for the Slaughter Lane Corridor Transportation Improvement Project, initiated by the City of Austin. Proposed transportation improvements, such as traffic signal installation and bicycle/pedestrian lane construction, will be constructed in the Slaughter Lane Corridor to facilitate non-motorized vehicle transportation. These improvements may affect the existing surface and subsurface conditions in the vicinity of Pipeline Cave, located south of West Slaughter Lane and west of Loop 1 South.

Pipeline Cave is listed on the City of Austin/Travis County endangered species permit; warranting protection of the cave to maintain habitat for karst invertebrate species. The management of the cave is a component of the Balcones Canyonlands Conservation Plan (BCCP), administered by the City of Austin and Travis County. The cave is located within the Recharge Zone of the Barton Springs segment of the Edwards Aquifer (BSEA), as shown in Figure 1. Pipeline Cave contains a species of concern (*Speodesmus N.S.*) listed on the City of Austin/Travis County endangered species permit and is habitat for troglobitic invertebrates. Identifying water and nutrient flowpaths that sustain habitat in caves such as Pipeline Cave is an important part of the management plan. In addition, few BSEA studies have examined groundwater flowpaths within the shallow subsurface, and this additional information about local infiltration and groundwater flow will assist regional groundwater managers in protecting the aquifer. This study delineates the surface and subsurface drainage of Pipeline Cave and further constrains east-west groundwater flow paths in the BSEA.

Caves receive two types of groundwater recharge: 1) direct recharge, within the surface catchment area, via runoff into one or more entrances to the cave; and 2) indirect recharge, within the subsurface drainage basin, via water infiltration through soil percolation or subsurface karst features, which enters the cave as drips and conduit flow. A cave's surface drainage basin is delineated by visually examining topography and signs of surface runoff (e.g., stranded debris and vegetation that has been bent down by flow), and by remote sensing (e.g., LiDAR) or surveying techniques. In contrast, the subsurface drainage basin is more difficult to delineate, as it cannot be determined by a visual examination. The size of the cave footprint and surface topography do not necessarily coincide with the footprint of the subsurface drainage basin (Hauwert, 2009).

Additional factors such as the characteristics of the geologic units, the occurrence and orientation of faults and fractures, the dip of the strata, and the location and activity of cave drips, all influence the subsurface drainage basin of a cave. Groundwater tracing, typically using non-toxic fluorescent dyes, is an established method for delineating the subsurface drainage basin of a cave, spring, or other groundwater resource. Identification of the source-water supplying cave drips and/or cave streams is important for protecting and maintaining water quality through the proper management of the cave and its surface and subsurface drainage basins (Hauwert and Cowan, 2013).

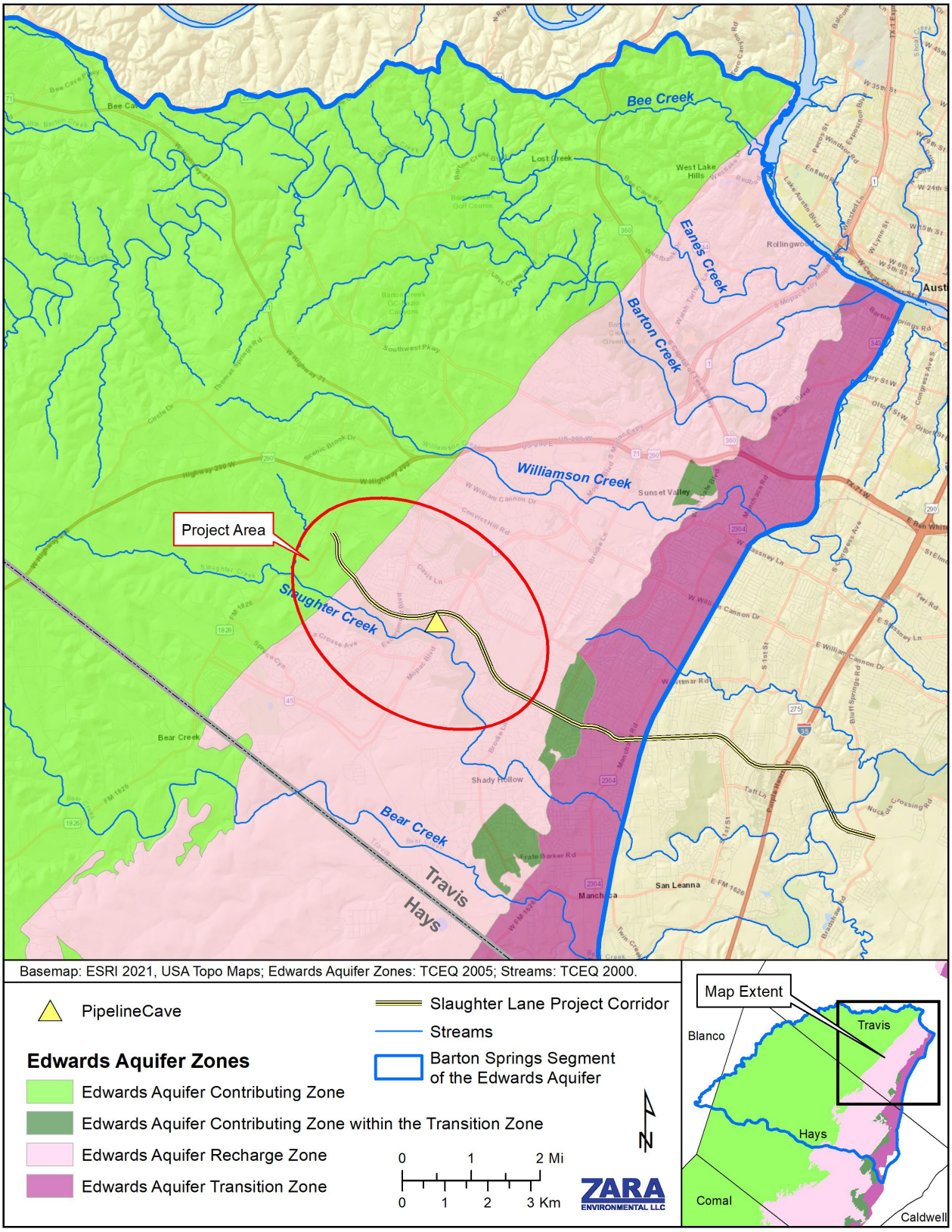


Figure 1. The location of the Slaughter Lane Project Corridor and Pipeline Cave are within the Barton Springs segment of the Edwards Aquifer.

Zara Environmental LLC (Zara) was contracted by the City of Austin to conduct a groundwater tracing study of Pipeline Cave and nearby caves in the West Slaughter Lane vicinity. Zara and the City of Austin, Balcones Canyonlands Preserve (COA BCP) staff worked together on all aspects of the project. This report includes data from both parties. Work was initiated November 2019 and concluded in December 2020.

Permission to conduct dye tracer injections was obtained from the Barton Springs/Edwards Aquifer Conservation District (BS/EACD), the COA Parks and Recreation Department and the COA Water Quality Protection Lands prior to injection on 9 October 2020.

Geologic and Hydrologic Setting

Surface Geology & Stratigraphy

Pipeline Cave lies within the Recharge Zone of the BSEA. In this area, uplift has exposed the limestone containing the unconfined portion of the aquifer: the Edwards Group (Person and Kainer Formations) and the Georgetown Formation (Rose 1972, Small et al 1996). These Cretaceous-age rocks are developed from the accumulation of thick sequences of marine sediments deposited in a lagoon environment on the San Marcos Platform protected by a barrier reef during the Cretaceous about 100 million years ago (Rose 1972). Within the roughly 10 mile (mi) wide Balcones Fault Zone, the strata are relatively flat or dip in various directions, but faulting down drops the rock units over 1,000 feet (ft) to the southeast (Hauwert, 2009). The porous, soluble limestone layers contain sinkholes, solution cavities, vertical and horizontal fissures, caves, swallets, springs, and rock shelters. The surface is typically covered by patchy, thin soils derived from weathered limestone and modern organic material. A research site 1 mi south of the study area found soil depths varied from 0 to 2 ft [61 centimeters (cm); Hauwert, 2009], although much greater soil depths can be found in filled sinkholes that are widespread across this area.

From youngest to oldest, the strata at the surface and in the subsurface of this region consists of the Del Rio Formation clay, Georgetown Formation limestone, Edwards Group Limestone (Person and Kainer Formations), and the Glen Rose Formation limestone. A stratigraphic column showing the regional geology is included as Figure 2.

The Person Formation is about 130 ft thick in southern Travis County. The composition of the Person Formation ranges from crystalline limestone to grainstone to mudstone and is divided into three informal hydrogeologic units: The Cyclic and Marine members, undivided; the Leached and Collapsed members, undivided; and the Regional Dense member. The Cyclic and Marine members are chert-bearing wackestones and can be somewhat variable in thickness because of the erosional unconformity between the Person and Georgetown Formations. In southern Travis County these layers are less than 5 ft thick or are not present at all (Hauwert 2009). The Leached and Collapsed members are a light colored wackestone with interbedded mudstone and grainstone intervals that form one of the more porous and permeable subdivisions of the Edwards Aquifer. The leached member is a dense, bioturbated micrite, and the collapsed

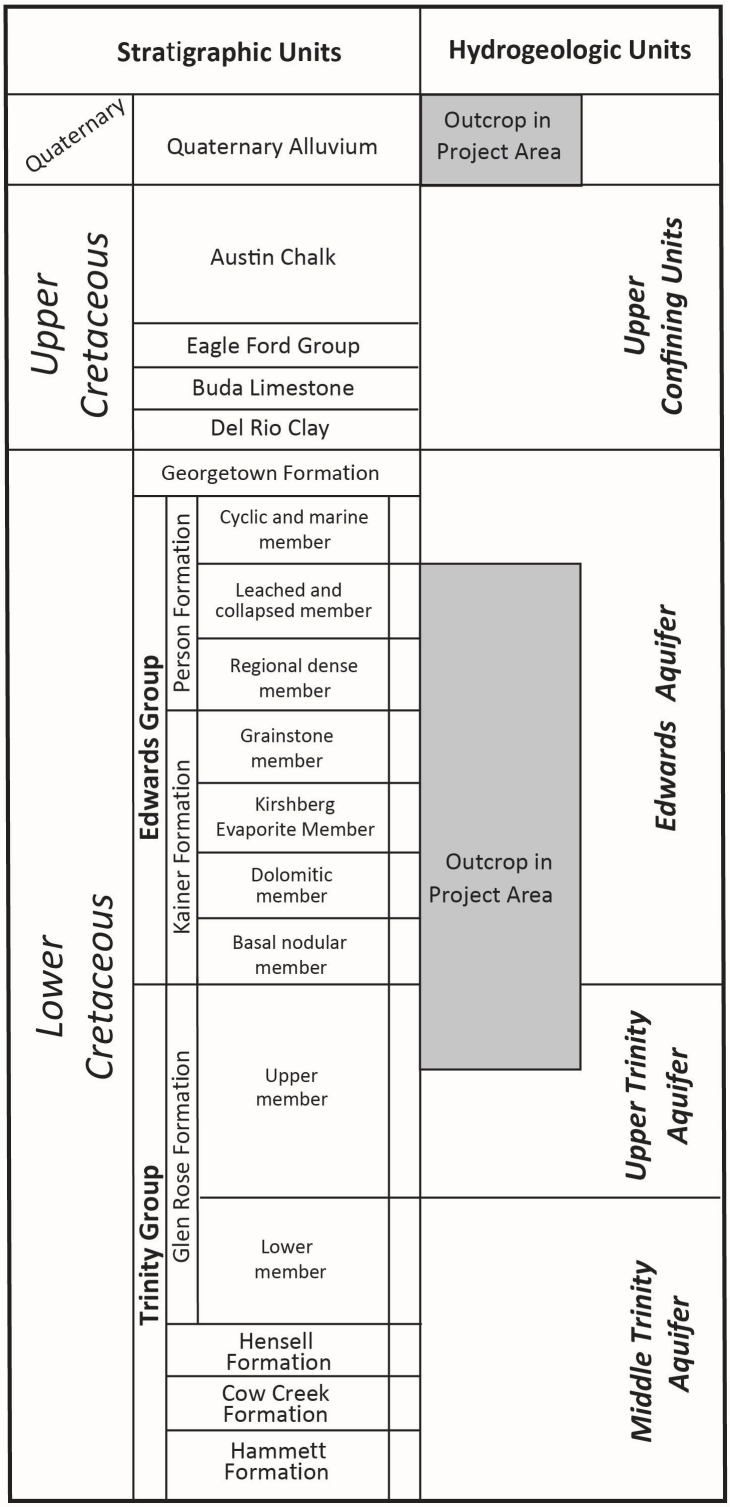


Figure 2. Stratigraphic column of the Slaughter Lane Corridor project area, Austin, Travis County, Texas.

member is composed of several 0.3 to 1.5 ft thick zones of collapsed stromatolitic limestone (Rose 1972). The combined thickness of the two members ranges from 70 ft in northern Hays County to less than 25 ft near the Colorado River in Travis County (Hauwert 2009). The lowermost member of the Person Formation is the Regional Dense Member (RDM), which has a thickness of 15 to 32 ft in southern Travis County and thins towards the Colorado River (Hauwert 2009). The RDM is composed of a dense argillaceous mudstone and is easily identified in the outcrop and on a variety of geophysical logs. Most of the fractures that penetrate the RDM do not appear to be solution enlarged. Caves that breach the RDM are usually vertical shafts with horizontal caverns developed above or below the RDM. The RDM can function as a confining unit between the upper and lower portions of the Edwards Aquifer (i.e., between the Kainer and the Person Formations); however, caves, faults, and fractures may greatly reduce the vertical confining ability of the RDM. The RDM is probably not an effective barrier to lateral flow at faults as flowing water tends to circumvent less permeable layers.

The Kainer Formation has an approximate total thickness of 300 ft in southern Travis County. The lithology of the Kainer Formation ranges from mudstone to miliolid grainstone to crystalline limestone. The Kainer is subdivided into four informal members that include the Grainstone, Kirschberg Evaporite, Dolomitic, and Basal Nodular members. The Grainstone member is the uppermost unit of the Kainer Formation and is 45 to 60 ft thick in southern Travis County (Hauwert 2009). It is composed of thick sequences of dense, tightly-cemented miliolid grainstone. Primary matrix porosity, as measured on geophysical logs, is some of the lowest in the Edwards Aquifer. Secondary fracture porosity accounts for the bulk of effective porosity in this aquifer unit. The Kirschberg evaporite member underlies the Grainstone member and is 40 to 75 ft thick in this area. This hydrogeologic unit consists of crystalline limestone and chalky pulverulite with chert nodules and lenses (Hauwert 2009). Solution and collapse features are common. The porosity has been described as boxwork (Maclay and Small 1976) because of the configuration of the voids and the secondary neospar and travertine deposits. The boxwork porosity does not seem to be prevalent throughout the entire thickness or extent of the member but occurs sporadically within more massive limestone. Dissolution of evaporite minerals, such as gypsum and anhydrite, and the existence of contorted beds in the Kirschberg evaporite result in extensive secondary porosity, which creates one of the most permeable subdivisions in the Edwards Aquifer. The Dolomitic member is a resistant, highly-bedded wackestone with interbedded grainstone, burrowed mudstone, and some chert nodules. The Dolomitic member has a total thickness of about 140 ft in this area (Hauwert 2009). Effective porosity and probable pathways of water in this unit are restricted to solution enlarged bedding planes, joints, fractures, and faults. The basal nodular member is the lowermost unit of the Edwards Group and is 45 to 65 ft of fossiliferous, nodular limestone (Hauwert 2009). In the subsurface, the basal nodular member has negligible porosity and permeability (Maclay and Small 1984) and can function as part of the lower confining unit; however, in outcrop the basal nodular member often displays extensive karstification, which has generated secondary porosity in the form of large lateral caves.

Geologic units that are below the Edwards Aquifer or outcrop west of the Recharge Zone in the Contributing Zone, are considered lower confining units. The Walnut Formation and/or the Glen

Rose Formation are less transmissive, although studies have established hydraulic connection between the Upper member of the Glen Rose Formation and the Edwards Aquifer (Wong et al., 2014). The Walnut Formation is described as a gray to tan, dense, fine to medium-grained fossiliferous limestone containing patchy beds of clay and calcareous shale (GAT 2010). Fossils include extensive oyster beds of *Exogyra texana* and *Texigryphaea mucronata*. Strata bedding is massive to thin and shale-like. The Walnut Formation is less permeable than the Glen Rose Formation and Edwards Limestone, but is not necessarily a confining layer. It is up to 175 ft thick but thins to the south toward Bexar County, where it is has mostly been eroded at the surface (Arnow 1963). The Glen Rose Formation has been divided informally into two members, Upper and Lower. The Upper member of the Glen Rose Formation is an alternating sequence of limestone and marly clay that, when weathered, creates the distinctive "stair-step" topography found throughout much of the Hill Country.

Structural Features

The Balcones fault zone is the major structural feature influencing the geology of the Edwards Aquifer and it delineates the boundary between the Edwards Plateau and the Gulf Coastal Plain. The zone is a system of mostly southeast-dipping *en echelon* normal faults that initiated within the last 24 to 5 million years ago. The arcuate zone extends from southwest central Texas to Dallas, Texas and generally coincides with the subsurface Ouachita orogenic belt. Regionally the Balcones fault zone trends E-NE and down drops 98 to 1200 ft with increasing net displacement toward the Gulf of Mexico. Fault orientation of relay ramps or oblique faults trends vary from E-NE due to differences in lateral fault displacement. Overall, the Balcones fault zone is important because it controls the outcrop of Edwards Group carbonates and influences preferential pathways for groundwater within the aquifer (Ferrill et al. 2019). Within the vicinity of the study area, prior direct tracing at Wildflower Cave (2010) and Midnight Cave (1999) show that groundwater flow paths travel eastward in the direction of down dropping fault blocks, rather than along faults (Hauwert et al., 2004a, 2012b).

Regional Hydrogeology

The Edwards Aquifer is one of the most permeable and productive limestone aquifers in the United States. In the Austin, Texas area, the BSEA supplies drinking water to nearly 60,000 people and provides habitat for several endangered aquatic species (Hunt et al. 2019). Karst aquifers are, by their nature, extremely vulnerable to contamination. Soils in karst areas tend to be thin and patchy, and the soil filtration capacity is low and is only decreased by human activity. Recharge in karst systems commonly occurs as point recharge into specific karst features, bypassing what little filtration a limited soil zone might afford. The project area is located in the BSEA, which extends south from Barton Springs in Austin towards the southern extent of Onion Creek, although the groundwater divide shifts as far south as the Blanco River during drought periods (Hunt et al 2019).

Over 40 aquifer-wide groundwater traces have been conducted in the BSEA since 1996 (Hauwert et al. 2004a, Hunt et al. 2005, Smith et al. 2006, Hauwert 2015, Johnson et al. 2012, Smith et al. 2012, Hunt et al. 2013, Zappitello and Johns 2018, Zappitello et al. 2019). These tracing studies

have shown that groundwater in the BSEA within the Recharge Zone generally flows perpendicular to faulting to the east along secondary flow routes and join primary groundwater flow routes trending northeast parallel to fault trends within the confined zone and within 5 mis of the regional base level discharge at the Colorado River. Most of these tracing studies have focused on regional-scale groundwater flow and identifying watersheds that contribute to the major springs (Zappitello et al. 2019). Hauwert and Cowan (2013) describe 8 unsaturated (vadose) zone traces recovered in cave drips, cave streams or local caves. An additional 10 vadose traces have been successfully recovered in Flint Ridge Cave and two additional trace recoveries at Barton Springs have been conducted but not extensively reported yet (City of Austin 2016). The aquifer segment has been divided up into three basins, known as Cold Springs, Sunset Valley, and Manchaca (Hauwert et al 2004). The Cold Springs Groundwater Basin discharges at Cold Springs on the Colorado River, while the other two basins feed different springs within the Barton Springs complex. Groundwater flow within the BSEA occurs through a well-developed karst conduit network, resulting in very rapid flow rates on the order of 1 to 7 mi per day. These rapid flow rates are typical of karst aquifers and contrast with other types of aquifers, where water may reside for long periods and be filtered by other matrices such as sand. Groundwater flow rates to Barton Springs, within the Slaughter Creek area of the BSEA, range from 7,900 to 45,400 ft/day, and vary as aquifer discharge rates change (Zappitello et al. 2019).

Recharge and Vadose Zone Flow

Edwards Aquifer recharge occurs primarily within losing streams, where surface water flows from the Contributing Zone flow over faults, fractures, and karst features that have been solutionally enlarged (Sharp and Banner 1997), and also from infiltrating precipitation in upland areas. Central Texas is a semi-arid environment with mean annual precipitation of 32 in per year (NOAA 2018). Evaporation of 40 to 65 in per year removes much of this water prior to recharging the aquifers. Many of the rainfall events occur as thermal convection thunderstorms that can produce large amounts of precipitation in short periods of time. A study by Hauwert and Sharp (2014) documented that about 68% of rainfall that falls on the BSEA Recharge Zone enters the atmosphere from evapotranspiration, about 29% recharges, and 3% is runoff. Periods of recharge are intermittent, as most streams in central Texas are ephemeral; however, the recharge capacity of surface water into the aquifer is highly efficient due to the karstic nature of the system.

In karst systems, groundwater flow in the unsaturated volume above the water table (vadose zone), can be quite complex and highly heterogeneous due to variability in hydrostratigraphic units, structural features, karst feature presence, rainfall intensity, antecedent conditions, and soil characteristics (Hauwert and Cowan 2013; Cowan and Hauwert 2013; Hauwert 2009; Cowan et al. 2007). Flow within the vadose zone occurs through a network of interconnected pores formed by macropores in the soil zone, and fissures, conduits, fractures, faults, caves, and other solutional features in the rock matrix. Flow in the vadose zone is generally down dip with some deviation due to the influence of structural features such as fractures and faults, whereas flow below the water table tends to be lateral along strike. Where hydrostratigraphic units are more massive and less soluble they tend to perch vadose flow, whereas more soluble

hydrostratigraphic units typically develop conduits and cave passages through which vadose waters can easily travel downward.

In addition to the aquifer-wide aquifer traces, additional vadose traces were conducted to determine cave drip source areas, some of which were also detected at Barton Springs. A vadose groundwater tracer study conducted in support of the Davis Lane roadway realignment and improvements project, located approximately 1.3 mi east of the Pipeline Cave project area, identified flow paths in the vadose zone that connected to caves located in the William Russell Karst Preserve. Fluorescent dye tracers were detected within 4 to 8 days after injection at a distance of 3,000 ft in Blowing Sink Cave. The tracers were detected at Barton Springs, Eliza Springs, and Old Mill Springs within 17 to 18 days after injection (Hauwert, 2012).

Hauwert and Cowan (2013) conducted a groundwater tracer study of vadose zone flow to cave drips within Barker Ranch Cave #1, located on City of Austin Water Quality Protection Land approximately 2.5 mi south of the Pipeline Cave project area, in order to delineate the cave subsurface drainage basin. One chemical tracer (KBr) was detected in water collected from a cave drip within 3 to 7 hours. Pyranine, a dye tracer, was detected within 4 weeks at a well located 3.3 mi northeast of the injection site. The tracer detections and geological mapping conducted within the project area assisted the authors in delineating the cave subsurface drainage basin and establishing groundwater flow from the study location to flowpaths within the BSEA.

Methods

Surface Drainage Basin Delineation, Pipeline Cave

Surface drainage basin delineation methods were adapted from Hauwert and Cowan (2013). A 2001 walking survey of the pre-development topographic boundaries of the surface drainage basin of Pipeline Cave resulted in the delineation of an approximate 3.0-acre (ac) area shown in Figure 3. The delineation with a handheld Trimble XRS Global Positioning System (GPS) unit was conducted on June 28, 2001 by Nico Hauwert, when West Slaughter Lane had been widened to the current extent and two petroleum pipelines trended west to east north of the cave, but prior to the construction of the Parkside Village Shopping Center. The site was also examined by Nico Hauwert under runoff conditions following rain events on January 16, 2001 and July 1, 2002. In 2001 and 2002 it was noted that two petroleum pipelines cross the natural surface catchment area for Pipeline Cave, the closest within 100 ft of Pipeline Cave sinkhole entrance, and that slight mounding with these easements may act to divert some natural runoff from the entrance. No runoff was observed reaching the Pipeline Cave entrance in 2001-2002, although a small amount of runoff entered the cave entrance during a rain event in 2020. For the construction of Parkside Village, runoff from the impervious northern portion of the site was diverted to a water-quality pond, that is irrigated west of Pipeline Cave in order to comply with City of Austin stormwater control regulations for the Barton Springs Zone. In 2020, the surface catchment was assumed to be the same as the natural catchment field mapped in 2001, but truncated for the impervious cover surfaces of Parkside Village Shopping Center, resulting in an area of approximately 1.85 ac.

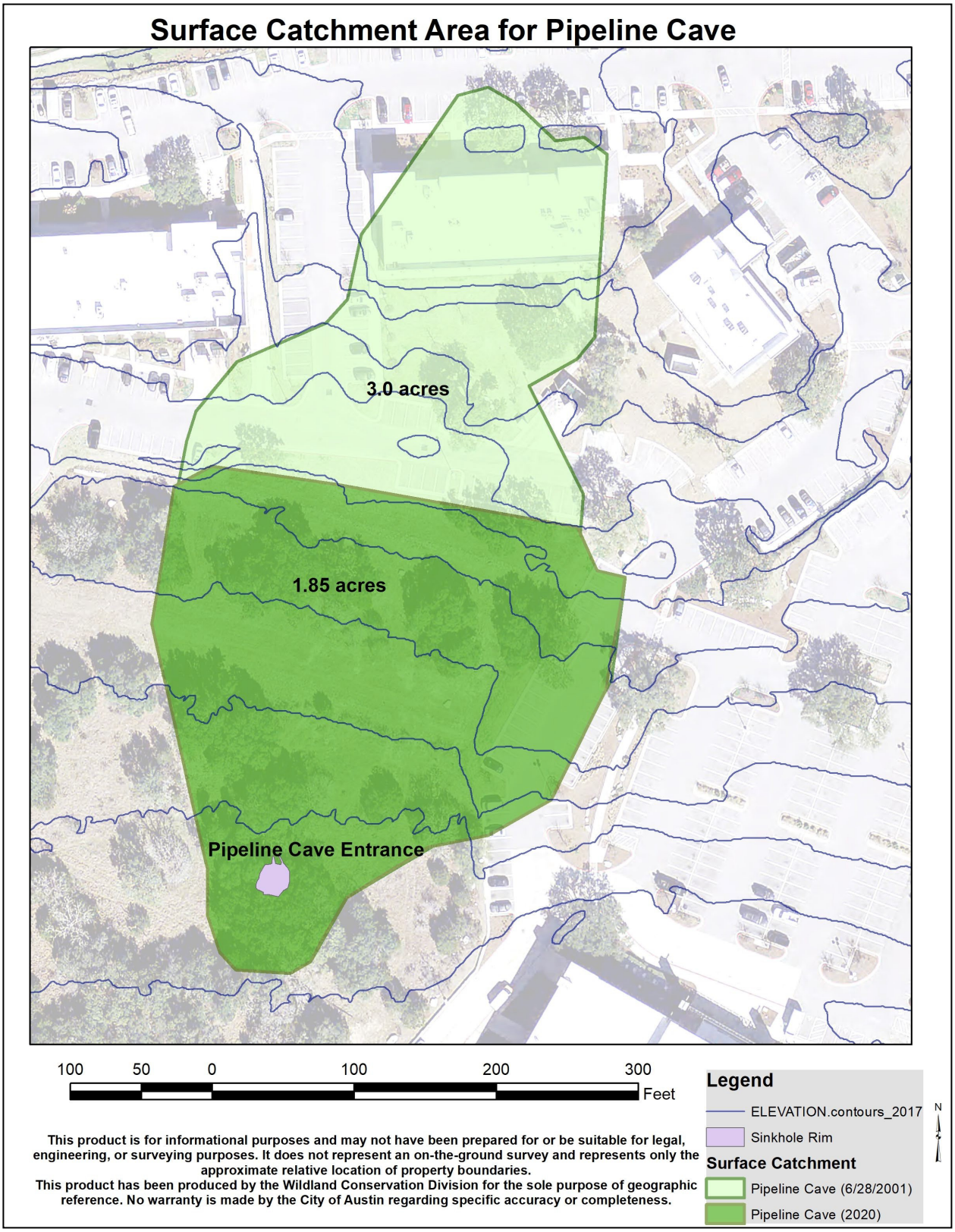


Figure 3. Surface drainage basin map for Pipeline Cave, surveyed in 2001 and analyzed in 2020.

Karst feature pedestrian survey results

Karst feature pedestrian surveys were conducted in the vicinity of Pipeline Cave, Midnight Cave, and an area to the west of Midnight Cave within the Slaughter Creek watershed. Karst features were documented and evaluated for potential use as groundwater dye tracer injection site. Several dozen features were identified in the pedestrian survey. The names and locations of a subset of the identified karst features are shown on Figure 4.

Cave and karst feature excavation for potential use as groundwater tracer injection sites.

Karst feature excavation was proposed for this study in order to remove unconsolidated material to allow examination of the cave passage extent and evaluate potential use as a groundwater tracer injection site. Overland flow of stormwater runoff transports soil and sediment into karst features. Over decades or centuries, this infill material may reduce the accessible portion of a cave and the recharge capacity of a cave or karst feature. Also, it was common practice for landowners to fill caves and sinkholes as a convenient rubbish disposal method, to modify large sinkholes as stockponds, or to reduce the risk of livestock injury or death due to a fall into an open feature (Hauwert, 2009). Another benefit of excavating unconsolidated material from a recharge feature is to reduce the potential that dye will be retained in the fines rather than mobilizing into the karst system (Aley, 2019).

<u>Pipeline Cave Excavation.</u>

Excavation within Pipeline Cave was initiated on August 10 and 17, 2018 and February 12, 2019 by the removal of about 120 ft^3 of trash (BCP, 2020). The trash that was identified and dated was potentially created as long ago as 1940 and as recently as 1980 (Thompson, 2018). November 2019 following observations of raccoon access through a narrow, soil-filled passage. Removal of infill from a narrow passage at the bottom of an upper chamber revealed additional passages of Pipeline Cave that enlarged the known extent of the cave approximately twentyfold. The cave volume calculated by Elliott (1997) at 1,000 ft^3 was increased in this study 20 times to 20,000 ft^3. A large, lower chamber is now accessible. The full extent of the cave is 275 ft longer, 8.2 ft deeper, and 5,085 ft^2 larger than the previously known extent. The newly discovered room contained bat guano, suggesting that a bat colony inhabited the cave prior to its use as a ranch trash dump in the 1950's and 1960's.

<u>Confusion Cave Excavation.</u>

Confusion Cave is located approximately 307 ft south of the surface opening of Pipeline Cave. Confusion Cave was excavated in order to observe the cave morphology and to evaluate use as a potential groundwater dye tracer injection site. Excavation occurred in October 2019. Cave infill was removed to reveal interior passage to an approximate depth of 30 ft. Analysis of the cave passage morphology and drip feature elevation revealed that the floor of Confusion Cave was lower than the elevation of cave drips in Pipeline Cave. Therefore, Confusion Cave was not selected as a tracer injection site nor a tracer monitoring site.

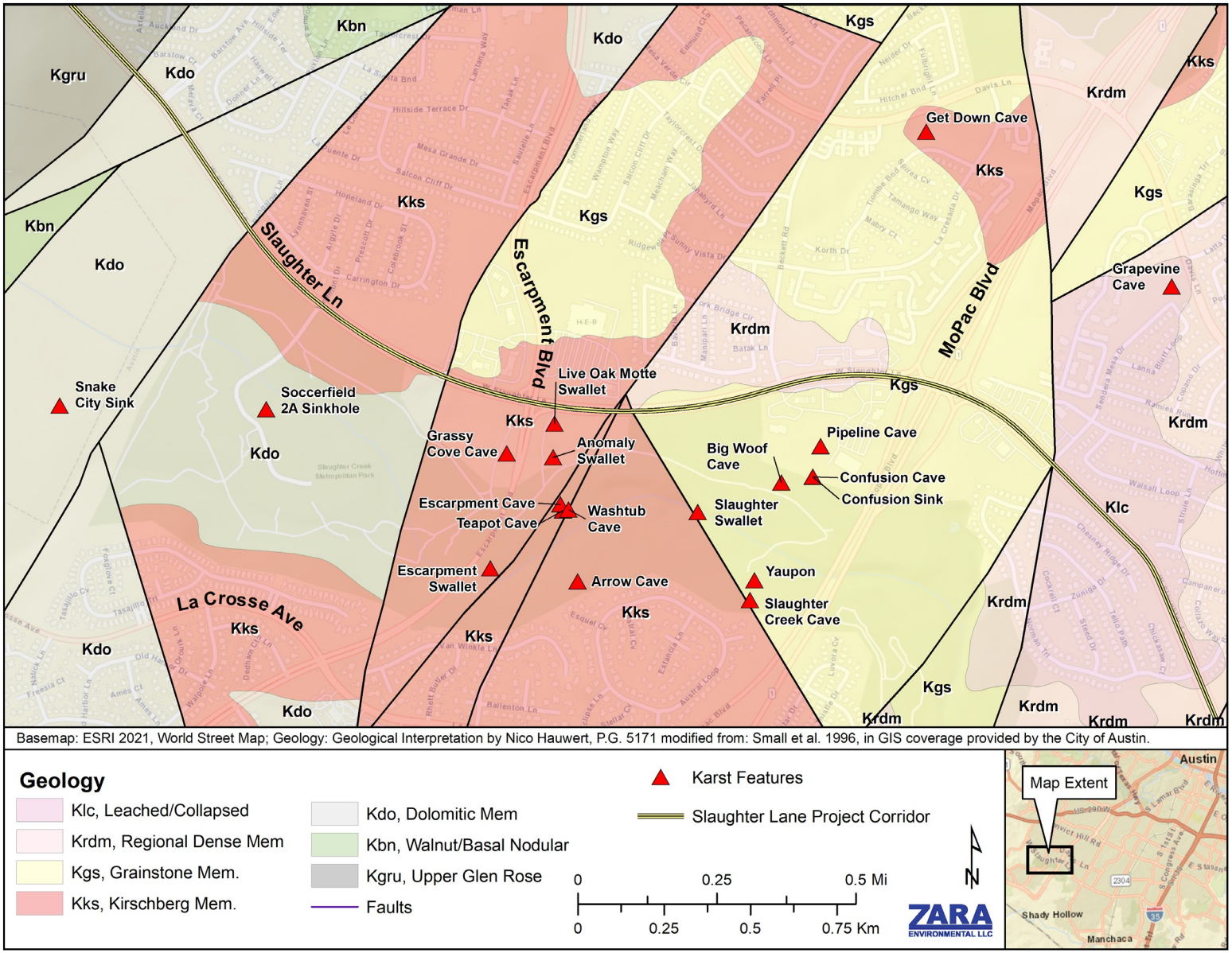


Figure 4. Karst features identified within the project area.

Additional Karst Feature Excavation.

Five additional karst features were excavated during this project for the purpose of evaluating their use as a potential groundwater dye tracer injection site. These features include: Big Woof Cave, Escarpment Cave, Anomaly Swallet, Soccerfield 2A Sinkhole, and Snake City Sink. These feature locations are shown in Figure 4. Hand excavation to a vertical-trending opening, such as a fracture or conduit, continued until a bedrock horizon was encountered.

Big Woof Cave, located within approximately 500 ft southwest of Pipeline Cave, was excavated. Big Woof Cave was eliminated as a dye tracer injection site because the cave floor elevation is lower than the cave drip elevations in Pipeline Cave.

Escarpment Cave, previously referred to as Escarpment Sink, is located 2,530 ft southwest of Pipeline Cave within an unnamed tributary to Slaughter Creek. Sediment, modern soil fill, and an admixture of weathered limestone/clay was excavated from an initial swallet depth of 4 ft to a depth of 16 ft. This swallet was selected for tracer injection based on the morphology of the cave passage, the depth of the cave, and observations of post-storm runoff flow entering the swallet. All upgradient stormwater runoff from a 1-in precipitation event on 3 April 2020 entered the swallet (Figure 5) indicating a probable connection to the local groundwater flow system. Flow in this tributary is initiated by precipitation rate, volume, and antecedent soil moisture conditions that exceed soil infiltration capacity.



Figure 5. Post-storm runoff entering Escarpment Cave on 3 April 2020. Photo credit: Jeff Watson, Zara.

Anomaly Sink, a solution-enlarged fracture located in the unnamed tributary upgradient of Escarpment Cave, was hand excavated to approximately 2 ft deep. The fracture contained compacted, clayey soils and sediment and tapered to a narrow width. This feature, initially chosen as a tracer dye injection site, drained too slowly on 9 October 2020 to be used for tracer injection.

Soccerfield 2A Sinkhole, located at the center of a broad, shallow topographic depression and approximately 536 ft northeast of the entrance of Midnight Cave, was hand excavated to an approximate depth of 2.3 ft. Removal of compacted, clayey soils terminated at a weathered rock floor. This feature was used to inject pyranine dye on 12 November 2020.

Snake City Sink was excavated with hand tools to an approximate depth of 5.5 ft. Removal of modern soil, clayey infill and weathered rock terminated at a competent rock horizon. A fracture influenced preferential solution-enlargement along the western wall of the sinkhole. This feature was used to inject fluorescein dye on 9 October 2020.

Unconsolidated material removed from each feature excavation was dispersed on the nearby ground, in a manner compliant with U.S. Fish and Wildlife Service (USFWS) protocol for conducting Presence/Absence Surveys for Endangered Karst Invertebrates in Central Texas (USFWS 2015), in order to minimize potential red imported fire ant activity.

Subsurface drainage basin delineation, Pipeline Cave

Subsurface drainage basin delineation methods were adapted from Hauwert and Cowan (2013), which outlines a multi-step approach to delineating a cave's subsurface drainage basin. These steps include: cave surveys, characterization of cave drips and cave streams, hydrostratigraphic mapping, determining geologic framework, water quality characterization, and groundwater tracing. Hydrostratigraphic mapping and geological framework are combined here for brevity and are referred to collectively as Geological Framework.

Groundwater tracing methods were adapted from Dole (1906), Smart (1988), Quinlan (1990), Hauwert et al (2004), and Aley (2019). Groundwater tracing is an important component of subsurface drainage basin delineation in karst systems where conduits and cave passages develop along preferential pathways that cannot be determined by analysis of current surface topography. Development of karst flow paths, sometimes spanning thousands of years, may result in groundwater flow directions that cross surface drainage divides, divert in a direction counter to overland drainage patterns, and activate only with certain potentiometric surface elevation increases (Quinlan, 1990).

<u>Cave Surveys</u>

A cave survey was completed as a component of the delineation of the subsurface drainage basin of Pipeline Cave. COA BCP project personnel surveyed and mapped Pipeline Cave, following excavation by COA BCP and Zara that revealed greater subsurface extent through a previously blocked passage. The current extent of Pipeline Cave is 34.8 ft deep, 377.3 ft long and as wide as

44.3 ft, as shown in Figure 6. The subsurface drainage basin of Pipeline Cave is constrained by the depth and lateral extent of the cave. The cave's lowest elevation can be used to eliminate areas on the surface that are lower in elevation and are, therefore, outside the subsurface drainage area of the cave.

Existing cave surveys of other caves within the project area were used to estimate the elevations of cave drips with respect to the elevation of the lowermost passage of Pipeline Cave, 790 ft above mean sea level (msl). The cave drip elevations are provided in subsequent sections of this report.

Characterization of Cave Drips and Cave Pools

Many caves have "wet areas" where cave pools and drips are present, and "dry areas" where cave pools and drips are not present. In caves with both wet and dry areas, the elevation of the lowest point within the cave in which the visible source for a drip or pool is present can be used to further eliminate areas on the surface that are lower in elevation and are, therefore, outside the subsurface drainage basin (rather than using the elevation of the bottom of the cave). Caves within the vicinity of Pipeline Cave were evaluated for potential inclusion in the groundwater tracer study based on observations of active drips and the elevation of the drips, relative to the presumed subsurface catchment area of Pipeline Cave based on the lowest elevation, 240.8 m msl, within the cave. Cave drips and cave pools within Arrow Cave, Grassy Cove Cave, Slaughter Creek Cave, Midnight Cave, and Get Down Cave that occur at an elevation greater than 790 ft msl were selected as monitoring sites for tracer dye detection for this study.

Cave Drip Catchment and Tipping Bucket Rain Gauge Installation

Cave drip monitoring stations were installed in Arrow Cave and two locations within Pipeline Cave, as the initial phase of this hydrogeological study. The stations were positioned to measure drip rates from active drips observed during cave visits in November 2019 and January 2020. Each station had a Rainwise tipping bucket connected to a HOBO data logger that recorded the tip counts from cave drips. Data were downloaded with HOBOWare software to a laptop on a periodic basis.

Pipeline Cave Drip 1 monitoring station was installed on 9 November 2019 in the lowermost chamber of the cave. A collection "tent" of plastic sheeting directed water from cave drips to a tipping bucket device connected to a HOBO data logger. Pipeline Cave Drip 2 monitoring station was installed on 18 December 2019 in an upper passage of the cave. A tipping bucket was positioned to capture water from several overhead cave drips. Due to suspected logger malfunction and animal disturbances of the tipping bucket, the HOBO data logger was replaced on 1 October 2020.

Pipeline Cave

Travis County, Texas

Surveyed by Aubri Jenson, Drew Thompson & Colin Strickland March 2020 with Leica Disto X2
Sketched & Drafted by Colin Strickland
Length: 115 m, 377 ft. Depth: 10.6 m, 35 ft.

The vertical scale is zero at the cave gate which is at approximately 825 ft. above mean sea level. The surface topography trends downward as you proceed towards the end of the cave. Therefore the depth to the surface at the end is less than that which is indicated by the scale

Gate is at approximately 825 ft. above mean sea level

Entrance
Level A
Level B
Level C
Behind main passage
Behind main passage

Projected Profile
(Lined up with plan view below)

Behind main passage

Entrance Room in Relation to Lower Level (Level C)

Level B in Relation to Entrance Room (Level A)

Contorted Crawl

Mulaiki Balcony

Coon Tomb

Equitable Hindrance

Plan View

The Basement of The Alamo

Travelers Respite

Treasure Trove

Contorted Crawl

Level B in Relation to Lower Level (Level C)

slope
floor change
ceiling change
passage underneath/behind
passage above/in front of
passage continues too small
bedrock
sediment
mud
pulveriolite
roots
branches
breakdown
water pool
flowstone
stalactites
soda straws
draperies
bacon
stalagmites
totems
columns
ceiling height (m)
pit depth (m)

Magnetic declination: 3.70 E

Both the profile and plan are rotated -30° from magnetic north

Figure 6. Pipeline Cave map, plan and profile view.

The Arrow Cave drip monitoring station was installed on 10 February 2020 in a passage called Zone 2. A collection "tent" of plastic sheeting directed water from cave drips to a tipping bucket device connected to a HOBO logger. The equipment, data collection procedures, and collection tent set ups at Pipeline Cave Drip 1 and Arrow Cave were based on methods described by Schreiber et al. (2015) and Cowan and Hauwert (2013).

Recorded tip counts from the HOBO data loggers were downloaded using HOBOWare software to a laptop on a periodic basis, starting in December 2019 and ending 8 December 2020. Zara personnel conducted all data downloads and maintained the tipping bucket monitor stations. HOBO data loggers were used to record tip counts. Files were downloaded to a laptop in comma-separated format (.csv). Zara conducted quality assurance reviews of the data files to identify potential problems of tipping bucket performance, lapses in data collection, or other issues. Calibration of the per-tip volume of each station was conducted at the initiation of cave drip monitoring. At Arrow Cave, a second calibration occurred on 15 April 2020 to reset tip counts recorded by the data logger. The per-tip calibration volume was used to calculate daily drip volumes for drip data graphs for each station.

Precipitation data was obtained from the City of Austin Flood Early Warning System gauge #1190, located at Escarpment Boulevard (City of Austin, 2020). Daily precipitation totals, converted from inches (in) to centimeters (cm), were compared to cave drip volumes for graphical analysis.

Geological Framework

Geologic structure and the hydrostratigraphic characteristics of all caves and surface outcrops of Edwards Formation were recorded. Observations included important structural and hydrostratigraphic characteristics such as vuggy or high porosity zones which may act as preferential flow zones; fracture and fault orientations and infill which may influence groundwater flow direction; and fractures, faults, and geologic contacts that guide cave passage geometry and orientation. In the project area, faults are located in near proximity to more than half of the karst features shown in Figure 4. The majority of the cave passage development was within the Kirschberg Member of the Edwards Group. This hydrostratigraphic unit contains evaporite horizons that readily dissolve from contact with atmospheric-derived water. A geologic cross-section of the project area (Figure 7) shows the subsurface extent of Pipeline, Midnight, Grassy Cove, and Blowing Sink Caves within the hydrostratigraphic members of the BSEA and the elevation of the potentiometric surface (shown as a blue line). The geologic cross-section was used to identify possible geological constraints on the subsurface catchment area of Pipeline Cave.

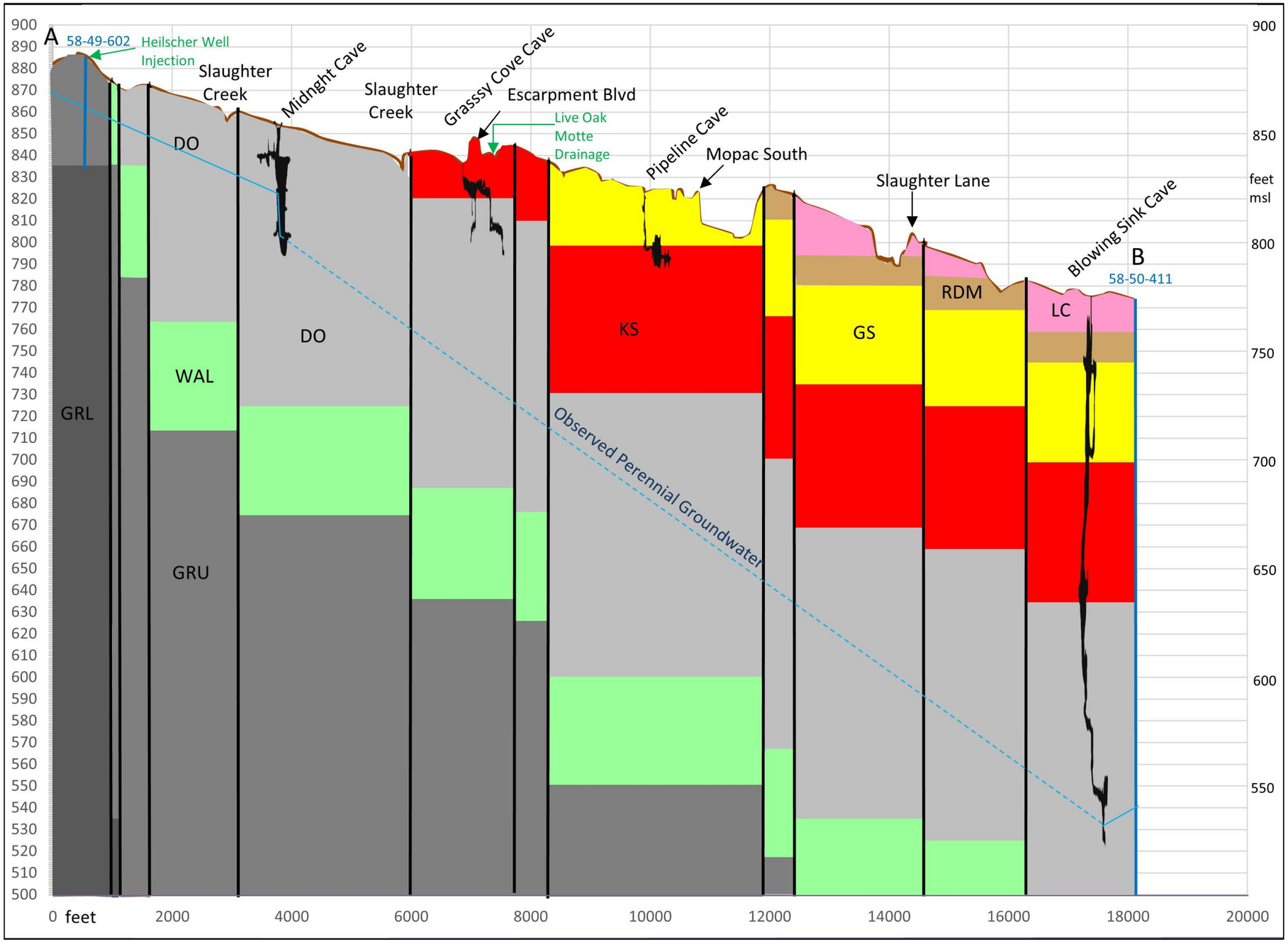


Figure 7. Geologic cross-section of the project area. Pipeline Cave is located in the center of the land surface profile. Cross-section created by Lara Williams.

Water Quality Characterization

Water Sample Collection and External Data Source

In order to evaluate potential urban impacts to water quality of cave drips, a series of water samples were collected from caves, streams, and urban runoff locations across the project area. Water samples were collected by Zara and BCCP technical staff (Table 1). All sample bottles were provided by Lower Colorado River Authority (LCRA) Environmental Laboratory and samplers used nitrile gloves for sample collection. All Zara water samples were unfiltered and preserved on ice prior to laboratory drop-off. BCCP Samples were filtered and preserved on ice prior to laboratory drop-off.

Table 1. Summary of water samples collected by Zara and BCCP staff during study period.

Collection Entity	Location	Date	Sample Type
Samples collected by Zara Staff	Bear Creek	3/22/2020	Surface Stream
	Grassy Cove	2/12/2020	Cave Drip
	Grassy Cove Drainage	2/12/2020	Urban Runoff
	Grassy Cove Drainage	5/28/2020	Urban Runoff
	Midnight Cave	2/20/2020	Cave Pool
	Pipeline Cave	3/3/2020	Cave Drip
	SL @ 1826	5/28/2020	Surface Stream
	Wetland S. of Drafthouse	5/29/2020	Wetland
Samples collected by BCCP staff	Midnight Cave	8/25/2020	Cave Pool
	Get Down ACTR Drip A	5/19/2020	Cave Drip
	Get Down ACTR Drip B	5/19/2020	Cave Drip
	Get Down Drip A	5/19/2020	Cave Drip
	Get Down Drip A	8/25/2020	Cave Drip
	Get Down Drip B	8/25/2020	Cave Drip
	Get Down SCC Drip A	5/19/2020	Cave Drip
	Grassy Cove Drainage	5/16/2020	Urban Runoff

Additionally, water quality data from Porras et al. (2016) was downloaded from the City of Austin Water Quality Sampling Database (City of Austin, 2020b). These samples were used as representative treated wastewater endmembers for geochemical comparison to samples collected for this study.

LCRA Environmental Laboratories, Austin, Texas, conducted all laboratory analyses of background water chemistry parameters. All samples were analyzed for major ions (Alkalinity, Chloride, Sulfate, Calcium, Magnesium, Potassium, and Sodium), Total Organic Carbon, Nitrate/Nitrite, Total Phosphorus, Fluoride, Bromide, Boron, Iron, and Strontium. Some samples were also analyzed for E. coli, Ammonia, and Total Dissolved Solids (TDS).

Laboratory Data Analysis

Water quality laboratory data was compiled, reviewed for quality assurance, and analyzed to determine geochemical facies of the different water samples collected. This geochemical analysis was accomplished by calculating the charge concentration of major cations and anions (Calcium, Magnesium, Sodium, Potassium, Sulfate, Chloride, Bicarbonate) reported in units of millequivalents-per-liter (meq/L). In addition, a molar comparison of sodium vs chloride was generated to evaluate potential influence from urban run-off or impacts from irrigation of reclaimed water in the vicinity of the project area.

Groundwater Tracing

Groundwater tracing methods were adapted from Dole (1906), Smart (1988), Quinlan (1990), Hauwert et al (2004), and Aley (2019). Ozark Underground Laboratories, located in Protem, Missouri, conducted all laboratory analyses for dye tracer detection.

Five fluorescent dye tracers (Fluorescein, Eosine, Rhodamine WT (RWT), Sulfarhodamine B (SRB), and Pyranine) were chosen based on their low toxicity, limited occurrence in the environment, and relatively conservative properties compared to other tracers. These dyes are non-toxic to humans and are non-reactive to other water-borne constituents. The types and amounts of dye were chosen in collaboration with Ozark Underground Laboratories (OUL). The dyes, charcoal receptors (packets of activated charcoal enclosed in nylon mesh), and 50 milliliters (mL) water vials were purchased from OUL.

Background Tracer Dye Monitoring

Two rounds of background monitoring for the presence of Fluorescein, Eosine, and RWT occurred. Background charcoal receptors were deployed at sites within four caves: Pipeline, Arrow, Midnight, and Get Down Caves. During the first round of background monitoring in February 2020, Fluorescein dye was detected at 0.185 parts per billion (ppb) concentration from a charcoal receptor retrieved from Arrow Cave. Fluorescein was not detected in the second round of background monitoring in a charcoal receptor retrieved 15 April 2020, nor from a water sample collected 10 March 2020 at Arrow Cave. No other dyes were detected at any other site.

A third round of background receptors were collected and sent to OUL to hold for future analyses. This round of receptors, placed in March and April, in anticipation of a late spring tracer dye injection, were collected in September or October in advance of the 9 October 2020 injection. Table 2 lists the results of the background monitoring.

Background sampling for SRB and Pyranine was not conducted prior to tracer injection, as initial plans did not include these tracers. If pyranine or SRB had been detected, the plan was to re-analyze charcoal receptors that had been submitted earlier in the study and stored at the laboratory.

Table 2. Background tracer dye monitoring results.

Collection Site	Sample ID	Sample Type	Placed Date & Time (military)	Collected Date & Time (military)	Fluorescein (ppb)	Eosine (ppb)	RWT (ppb)
Arrow Cave	AC-1	Charcoal	2/10/20 0945	3/10/20 0945	0.185	ND	ND
	AC-1b	Charcoal	3/10/20 0945	4/15/20 1030	ND	ND	ND
	AC-1W	Water	3/10/20 0935	3/10/20 0935	ND	ND	ND
Midnight Cave	MC-1	Charcoal	1/30/20 1000	2/20/20 1030	ND	ND	ND
Get Down Cave	GD-1	Charcoal	1/30/20 1100	2/20/20 1130	ND	ND	ND
Pipeline Cave	PC-1	Charcoal	2/10/20 1130	3/3/20 1000	ND	ND	ND
	PC-1 (DUP)	Charcoal	2/10/20 1130	3/3/20 1000	ND	ND	ND
Surface Runoff (Austral Loop)	SR-1	Water	NA	2/10/20 0930	ND	ND	ND
Grassy Cove Runoff (from Slaughter Lane)	GC-1	Water	NA	2/12/20 1135	ND	ND	ND
Field Blank 1	FB-1	Charcoal	3/27/20 0900	3/27/20 1300	ND	ND	ND
Field Blank 2	FB-2	Charcoal	4/15/20 0900	4/15/20 1300	ND	ND	ND

Tracer Dye Preparation

Fluorescein, Eosine, SRB and Pyranine were shipped from OUL to project personnel as powders. The dyes were mixed with potable water in advance of injection and in accordance with instructions provided by OUL. RWT was shipped from OUL as a pre-mixed liquid. As a precautionary measure to prevent sample cross-contamination, project personnel that mixed and handled tracer dyes were not involved in collecting samples.

Tracer Dye Injection

Tracer dyes were injected (applied) at five sites in the project area, as two injection events (Figure 8). The sites included four karst features (Escarpment Cave, Live Oak Motte Swallet, Snake City Sink, Soccerfield 2A Sinkhole) and a shallow water well with an open bottom (Hielscher Well No. 58-49-602). The four karst features were previously hand excavated to enhance fluid movement into the subsurface. The hand-dug, shallow water well, with an upper rock wall enclosure, had a measured water level depth of 6.8 ft below ground surface (bgs) and a total depth of 52 ft bgs on 29 July 2020. The injection sites were thought to be within the shallow subsurface drainage area of the system due to base elevations greater than that of the surveyed elevation of drips in Pipeline Cave. Injection features were also selected within an area that overlies an east-west direction of groundwater flow in this portion of the aquifer, as identified from a previous groundwater tracer injection conducted in Midnight Cave in 1999 (Hauwert et al., 2004a), and associated aquifer studies (Hauwert et al., 2004b). A 2010 injection in Wildflower Cave just south of the study area and east of Mopac South was recovered from Blowing Sink Eileens River Cave Stream about 1 mi east.

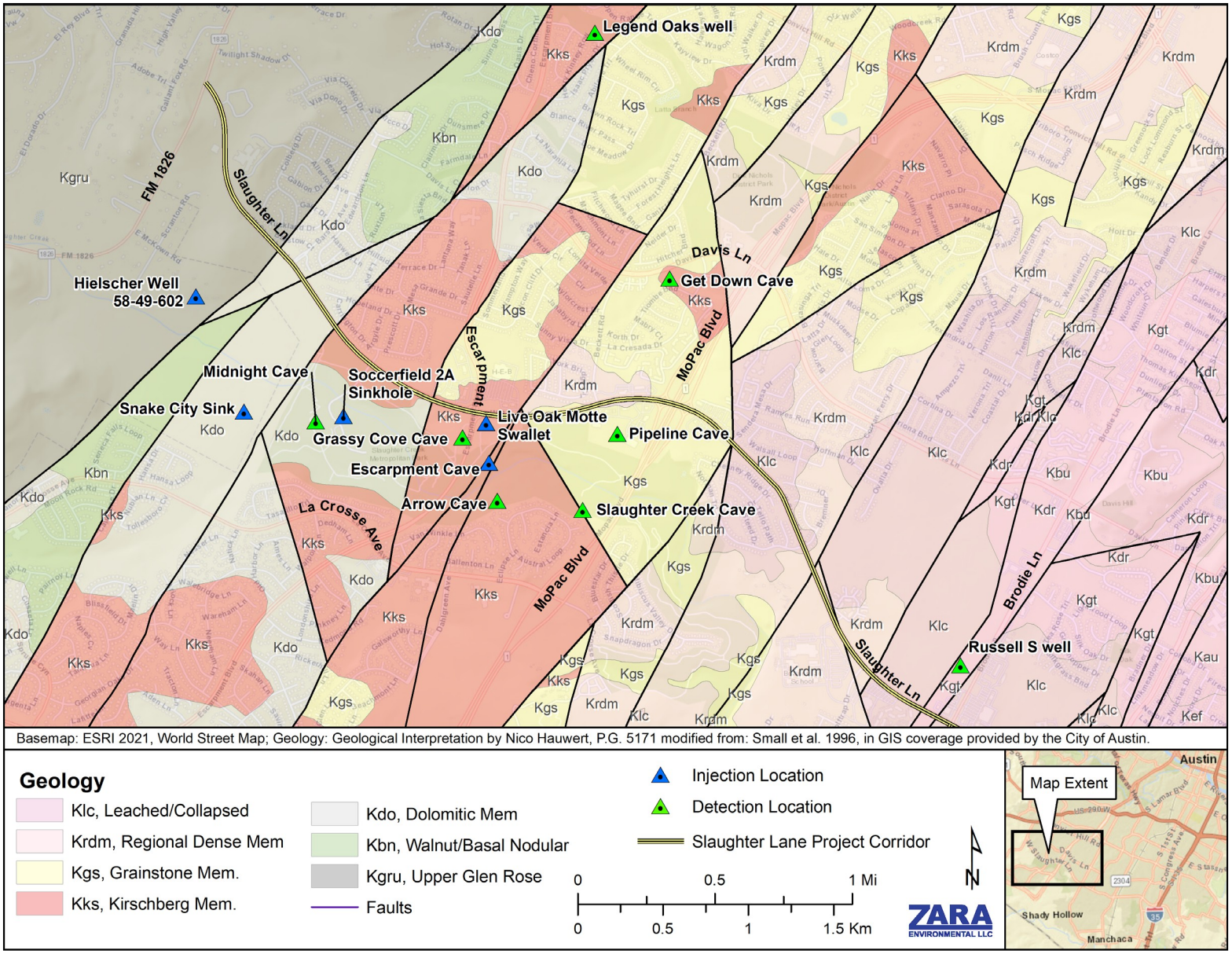


Figure 8. Map of tracer injection and monitoring sites.

The conditions that USGS-reported for Barton Springs discharge on October 9, 2020, was 38 ft^3/s, which is below a low flow threshold of about 40 ft^3/s where changes to Barton Springs chemistry occurs and travel times are significantly diminished. By the day of the final tracer injection on November 12, 2020, USGS-reported Barton Springs discharge had diminished to about 32 ft^3/s. Under similar flow conditions of 37 ft^3/s on September 28, 1999, 10 pounds of eosine injected further south of the study area within the Little Bear Creek watershed, first arrival at Barton Springs took 21 days. Five pounds of fluorescein and 10 pounds of RWT injected on the same day in that area were never detected at Barton Springs, although the RWT was detected in a local well 21-28 days later (Hauwert, 2009). In addition, the much small masses of dye injected during this study that was intended for local recovery in caves, meant that recovery at Barton Springs was expected to be unlikely.

Based on previous tracing at Midnight Cave in 1999 and Wildflower Cave in 2010, it was anticipated that tracers injected in our study would rapidly descend to the water table of the Edwards Aquifer and flow east through Eileens River cave stream in Blowing Sink (240 ft below the surface) and travel east to reach a major flow path for the Manchaca Flow Route that supplies Main, Eliza, and Old Mill Spring of Barton Springs. Unfortunately, the passages descending into Eileens River in Blowing Sink Cave were filled in during a flood in October 2013 and could not be accessed during this study for monitoring.

The first injection event of four dyes was initiated on 9 October 2020. Potable water was used to flush the dyes into three karst features and one shallow water well. Two Texas Commission on Environmental Quality certified bulk water haulers were contracted to convey City of Austin water to the injection sites via truck-mounted 2,000 gallon tanks and fire hose. The first injection was into Escarpment Cave; a feature observed by Jeff Watson (Zara) to be receiving water following heavy rain on 3 April 2020, an indication of connection to the local groundwater flow system.

Supplemental water was injected in one of the karst features, Snake City Sink, on 13 October 2020 in order to increase the total injection volume. Figure 9 is a photo of the injection into Snake City Sink on 9 October 2020.

A second injection of pyranine dye was conducted on 12 November 2020. Potable water from a City of Austin tap was used to flush dye into a karst feature, Soccerfield 2A Sinkhole, located in Circle C Ranch Metropolitan Park on Slaughter Creek. Figure 10 illustrates this injection.



Figure 9. Photo of fluorescein dye tracer injection into Snake City Sink, 9 October 2020. Photo credit: Jessica Gordon, City of Austin Watershed Protection Department.



Figure 10. Photo of Pyranine injection into Soccerfield 2A Sinkhole. Photo credit: Sylvia Pope, Zara.

Table 3 reports the tracer dye injection sites, dye types and masses, pre-injection potable water flush volume, potable water flush volume, flush rate, and injection date and start time.

Table 3. Tracer dye injections on 9 October 2020, 13 October 2020 and 12 November 2020.

Injection Feature Name	Dye	Amount (lb)	Pre-injection Flush Vol (gal)	Flush Vol (gal)	Flush rate (gal/min)	Injection Date & Time (military)
Escarpment Cave	Eosine	2	2,000	8,000	66.7	10/09/20 11:00
Live Oak Motte Swallet	Sulforhodamine B	4	20,000	3,500	116.7	10/09/20 14:45
Hielscher Well	Rhodamine WT	4	1,000	3,400	16.1	10/09/20 13:35
Snake City Sink	Fluorescein	1	2,000	2,000	66.7	10/09/20 17:30
	n/a	-	-	5,500	26.7	10/13/20 09:20
Soccerfield 2A Sinkhole	Pyranine	1	300	5,505	6	11/12/20 18:20

Tracer dye detection monitoring

Dye-absorbing charcoal receptor packets allowed for continuous dye monitoring at the cave drip sampling locations and two water well locations, and were placed at each detection site (Table 4). Duplicate receptors were placed at detection sites in accordance with a sampling plan calling for approximately 10% duplication. The 10-week monitoring period began 16 October 2020 and concluded 21 December 2020. Receptors were collected and replaced once a week for three weeks after dye injection, and then three more times at approximate two-week intervals. A 50 mL water sample was collected whenever sufficient drip water was available at the time that the receptors were retrieved. A grab sample of water was collected from pooled drip water or a catch basin placed below a tipping bucket. One water sample was collected from each water well location, Legend Oaks Well (State well no. 58-50-127) and Russell South Well (State well no. 58-40-411). A field blank charcoal receptor was carried by Zara and COA BCP personnel during each sample collection event, in order to identify any potential dye cross-contamination.

Table 4. Monitoring stations where charcoal receptors were placed and water samples were taken.

Site	Site ID	Notes
Pipeline Cave Drip 1	PC Basement	Station located at ~799 ft amsl. Drip tent captures water that drains to a tipping bucket.
Pipeline Cave Drip 2	PC Zone 2	Station located at ~801 ft amsl. A tipping bucket captures water.
Pipeline Cave Alamo Balcony Pool	PC Alamo	Station located at ~806 ft amsl. A drip pool located on the north side of the Alamo Room.
Get Down Cave Center Drip	GDC Center	Station located at ~ 760 ft amsl.
Get Down Cave Contortion Drip	GDC Contort	Station located at ~ 760 ft amsl.
Get Down Cave Column Drip	GDC Column	Station located at ~ 760 ft amsl.
Arrow Cave Zone 2 Drips	AC Zone 2	Station in collection pan under drip tent ~827 ft amsl.
Arrow Cave Totem Drip	AC Totem	Receptor placed directly below drip ~827 ft amsl
Slaughter Creek Cave	SCC	Receptor placed directly below drip
Midnight Cave Fall	MC Fall	Station located at base of flowstone waterfall, at bottom of pit ~797 ft amsl.
Grassy Cove Cave, Packsaddle Pit	Grassy PP	pool at bottom of Packsaddle Pit in Grassy Cove Cave at ~ 820 ft amsl
Legend Oaks Well	LO Well	Suspended in water at ~ 720 ft amsl
Russell South Well	Williams South Well	Suspended in water at ~ 480 ft amsl

COA BCP staff collected receptors and water samples at all the sites except Midnight Cave Fall and Legend Oaks Well. Zara staff conducted monitoring at those two locations. After collection, charcoal receptors and water samples were stored out of direct sunlight, on ice and in refrigerators, and then shipped to OUL with “blue” ice packs in coolers. Sample shipments arrived at OUL within two days. Chain-of-custody protocol was followed for all sample collection and shipment.

Charcoal receptors and water samples were analyzed for the presence and concentration of tracer dyes at OUL following the methods outlined in Aley et al (2015). Samples were analyzed on a spectrofluorophotometer under synchronous scan protocol. Post processing of the fluorescence intensity and wavelength (corresponding to each dye) yielded the concentration of each dye in each charcoal and water sample.

COA WPD provided technical assistance to this study by deploying a Eureka™ fluorimeter sonde at Eliza Springs, within the Barton Springs complex. The fluorimeter sensor is calibrated to detect 10 ppb RWT and 10 ppb Fluorescein. Readings were recorded at 15-minute intervals during a 9-week period from 16 October 2020 through 14 December 2020.

Results

The results of this hydrogeological investigation were used to delineate the subsurface catchment area of Pipeline Cave. The hydrogeologic analysis of the project area, the cave drip volume data, and the geochemistry of the cave drip water yielded sufficient information to delineate the subsurface catchment area, despite the negative results of the tracer dye test component of the study.

A number of conditions can lead to a failure to recover a tracer at any monitoring site (Jones 1976). These factors include:

1. Downstream discharge site(s) which were not monitored,
2. An insufficient amount of tracer or flush water was used,
3. Complete sorption losses occurred on fine-grained sediment or organic matter,
4. Very slow, diffuse groundwater flow causing the tracer to arrive at a concentration below the detection limit,
5. An insufficient duration or frequency of sampling,
6. High background concentrations or arrival of similar wavelength tracer obscured the tracer arrival,
7. Receptors were coated or saturated,
8. Tracer concentration was reduced by photo-decay or other degradation,
9. Tracer was diluted due to flooding, and
10. An inadequate amount of time was provided to allow purging of the same tracer from previous tests

For this study, the failure to recover tracer at any of the monitoring sites is suspected to be due primarily to dry soil conditions prior to and during the monitoring period.

Pipeline Cave occurs within the Grainstone Member, in the upper passages, and the Kirschberg member, in the extensive lower chambers, of the Edwards Group. The propagation of the cave interior as narrow, nearly vertical passages through the Grainstone Member, and significant enlargement of primarily horizontal chambers and passages within the Kirschberg member is similar to cave morphology observed at other locations within the BSEA (Hauwert, 2009). Two nearby caves, Confusion Cave and Big Woof Cave, were excavated and surveyed as part of this study are drier than Pipeline Cave. Confusion Cave is reported to be within strata that is loose white powder, that is likely dolomite crystals cemented with easily soluble calcite within pulverulitic beds expected in the uppermost beds of the Kirschberg Member below the Grainstone Member. The same beds may be expressed as extensive horizontal cave passages in the lower levels of Pipeline Cave, but the pulverulite may not be visible because of heavy flowstone deposition on its walls.

Cave excavations and cave surveys were used for geological framework analysis and for tracer dye injection and monitoring site selection. Pipeline Cave was excavated to reveal a substantially larger extent than what was humanly accessible prior to this study. The connection to the lower

chamber of Pipeline Cave contributed to the delineation of the subsurface catchment area and revealed cave drips and pools monitored for this project.

Characterization of Cave Drips and Cave Pools

At all monitoring stations, the drip flow volume generally decreased as precipitation declined after May 2020. Cave drip flow volumes were compared to records of stream flow in Slaughter Creek and discharge at Barton Springs during the initial 4 months of the project. Data did not reveal paired responses between cave drip volumes and stream flow or spring discharge. This reduces the likelihood that post-rainfall flow in Slaughter Creek or a local groundwater potentiometric surface change has an effect on cave drip responses in the project area.

Drip locations, drip flow rate data, and drip water chemistry within Pipeline Cave suggest that the water source of the cave drips are local. The muted or absent response of Drips 1 or 2 to precipitation events compared to periodic, cyclical increases in drip volume indicated a local, non-precipitation water source. Irrigation water applied to the land surface west of Pipeline Cave is the probable source of drip water, as an irrigation schedule would explain the cyclicity of the data and the occurrence of drip responses during dry periods. Cave drip flow rate monitoring indicates a probable artificial source of water to cave drips in Pipeline Cave.

Arrow Cave drip observations

Observed responses to precipitation are recorded as 1 to 3 day lag interval cave drip volume increases in Arrow Cave, as shown in Figure 11 and Figure 12. The March 2020 data file recorded all zeros, despite suitable soil moisture conditions and precipitation to induce drips at the monitor station. At Arrow Cave, a second calibration occurred 15 April 2020 to reset tip counts recorded by the data logger. The graph for the monitoring period of 8 September to 8 December 2020 (Figure 12) shows no cave drips 3 weeks prior to the Eosine tracer and flush water injection. A cave drip peak on 16 October 2020, in absence of rainfall, may be a response to the Escarpment Cave injection. However, no Eosine was detected at this location and a subsurface groundwater flow path has not been confirmed. Drip volume peaks in November displayed in Figure 12 reflect a manual adjustment of the data, as recorded observations of liters of water flow was not confirmed by personnel deploying/collecting charcoal receptors. Water samples were not collected in Arrow Cave in November due to dry conditions. It is possible that the tipping bucket was disturbed by animals, resulting in false readings. The drip volume peak recorded on 7 December 2020 may be a response to rainfall of 27-28 November 2020. The recorded drip rates throughout the project period ranged from 0 to 1.52 mL/min, as reported in Table 5.

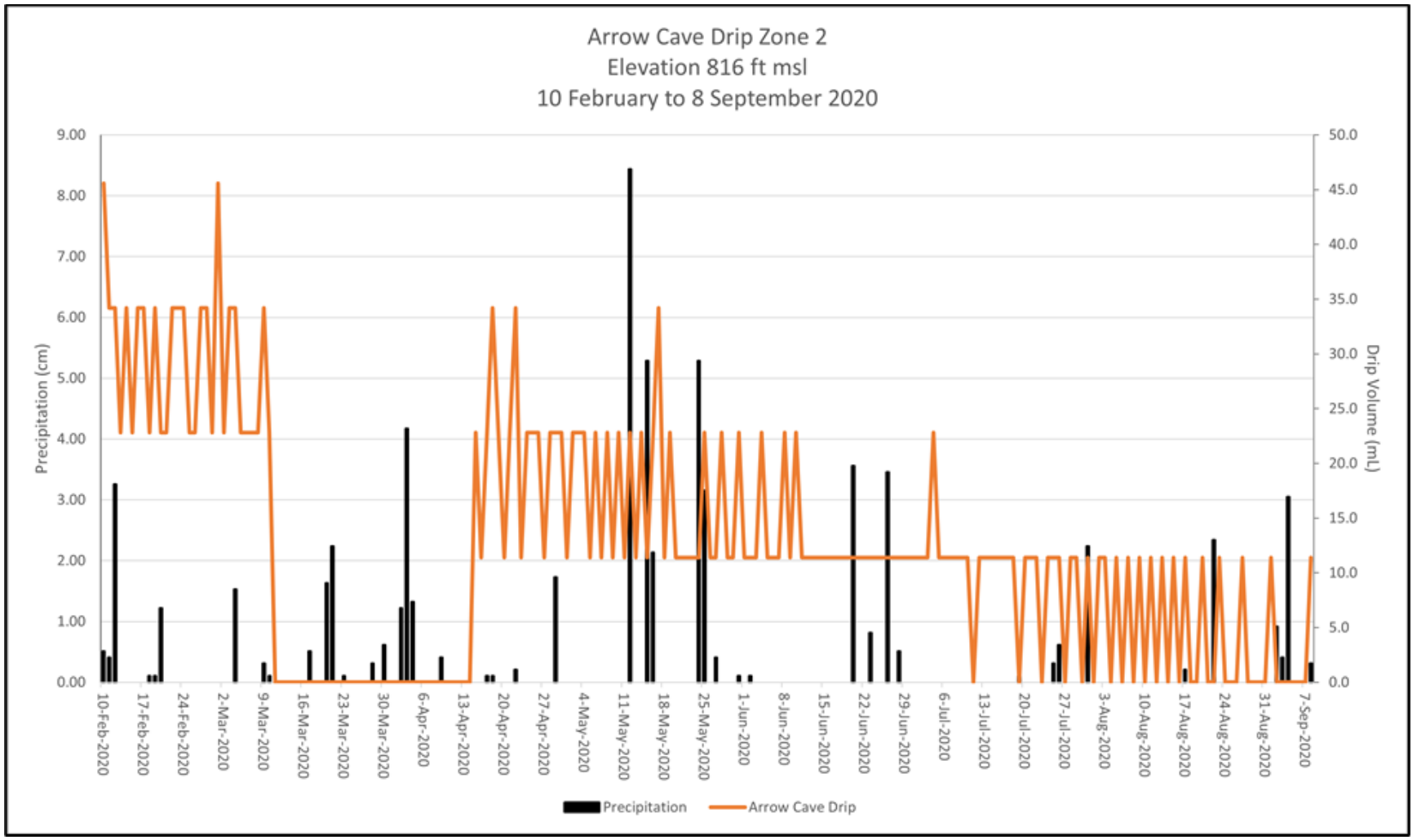


Figure 11. Arrow Cave drip data and precipitation record, 10 February to 8 September 2020.

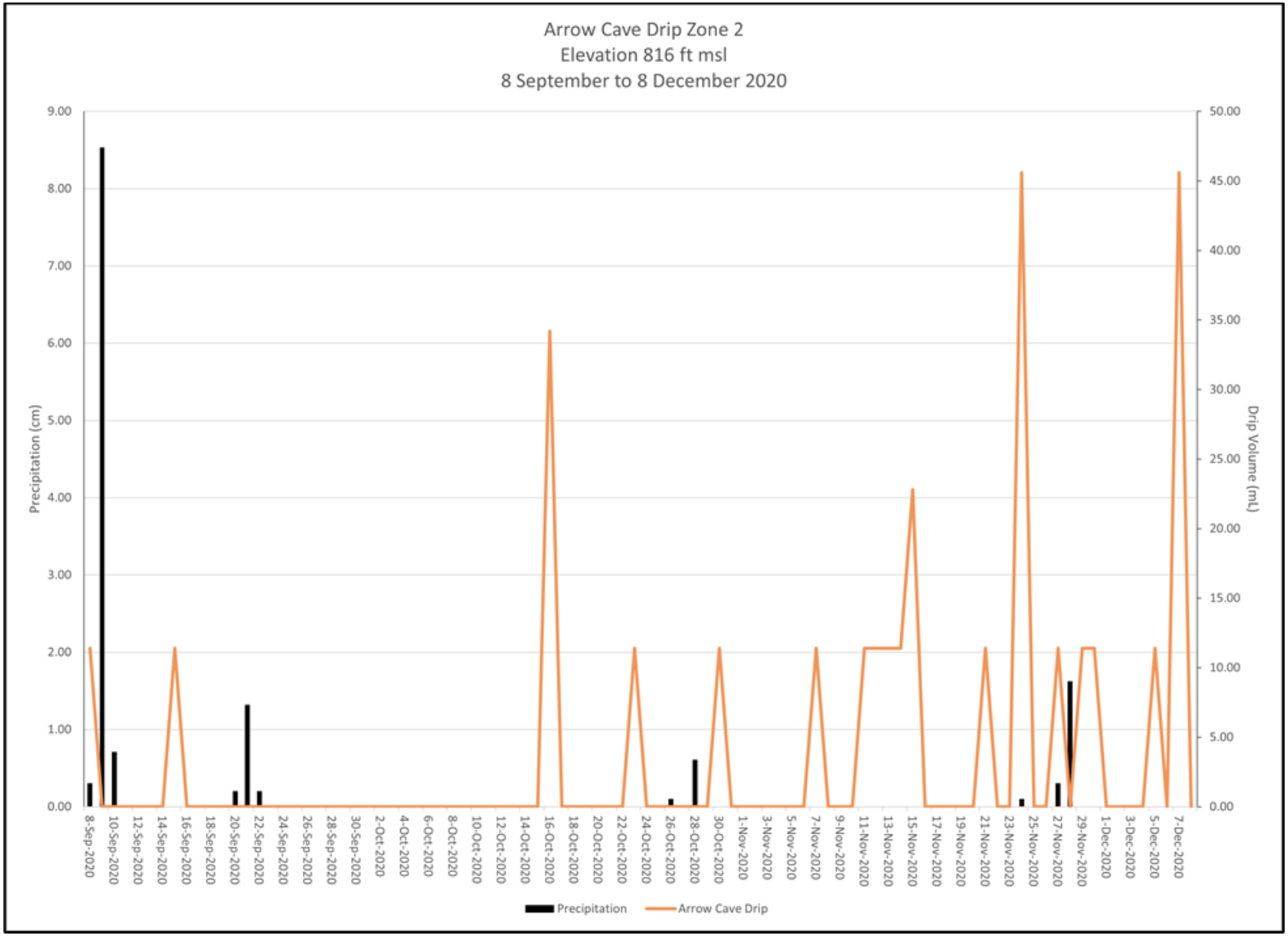


Figure 12. Arrow Cave drip and precipitation record, 8 September to 8 December 2020.

Table 5. Cave Drip Characteristics and Observed or Measured Drip Rates.

Cave	Drip Name	Elevation (ft msl)	Hydrostrat Unit	Type	Minimum	Drip Rate (ml/min)	
						Average	Maximum
Pipeline	Capillary	820	Grainstone mbr	Seepage	0		
Pipeline	Drip 2 (Raccoon)	801	Kirschberg mbr	Discrete	0	0.057	2.26
Pipeline	Alamo Pool	806	Kirschberg mbr	Discrete to pool			
Pipeline	Drip 1 (Basement) 11/19 – 4/15	801	Kirschberg mbr	Discrete	4.8	12.16	18.24
Pipeline	Drip 1 (Basement) 7/20 -10/20	801	Kirschberg mbr	Discrete	0	9.6	12.8
Midnight	Waterfall source	823	Dolomitic mbr	Discrete			
Midnight	Waterfall Base	803	Dolomitic mbr	Discrete to Pool			
Arrow	Totem	819	Kirschberg mbr	Discrete	0		
Arrow	Zone 2 (East Room)	816	Kirschberg mbr	Discrete	0	0.009	1.52
Slaughter Creek	Entrance	806	Kirschberg mbr	Discrete	0		
Grassy Cove	Packstrap Pool	801	Dolomitic mbr	Pool			
Get Down	Cascade	759	Kirschberg mbr	Discrete	0		
Get Down	Center	759	Kirschberg mbr	Discrete	0.18	0.23	0.27
Get Down	Contortion	759	Kirschberg mbr	Discrete	0.67	5.0	9.0

Pipeline Drip 1 observations

The muted or absent response of Drip 1 to precipitation events compared to periodic, cyclical increases in drip volume indicated a local, non-precipitation water source. Figure 13, Figure 14 and Figure 15 show frequent, cyclical peaks in drip volume that do not correspond to the occurrence or volume of rainfall within the project area. Observation of other non-precipitation water sources in the vicinity of Pipeline Cave include a drainage channel, stormwater control structures, a wetland area, and a designated irrigation area. The drainage channel and wetland were ruled out as potential sources. It is unknown if the irrigation water applied to the land surface west of Pipeline Cave is from accumulated water from the stormwater control structures. The irrigation area is the probable source of drip water, as an irrigation schedule would explain the cyclicity of the data and the occurrence of drip responses during dry periods.

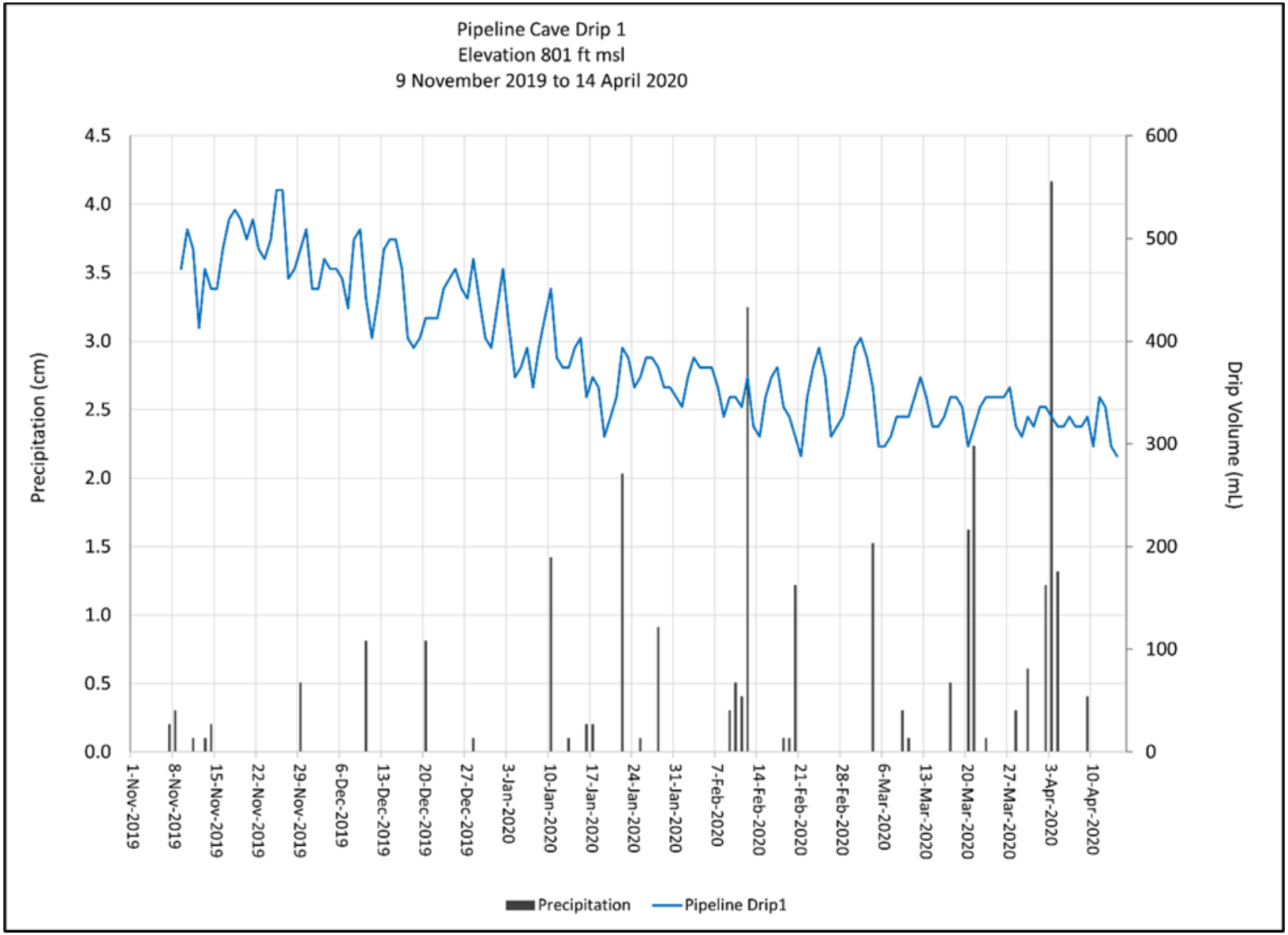


Figure 13. Pipeline Cave Drip 1 data and precipitation record, 9 November 2019 to 14 April 2020.

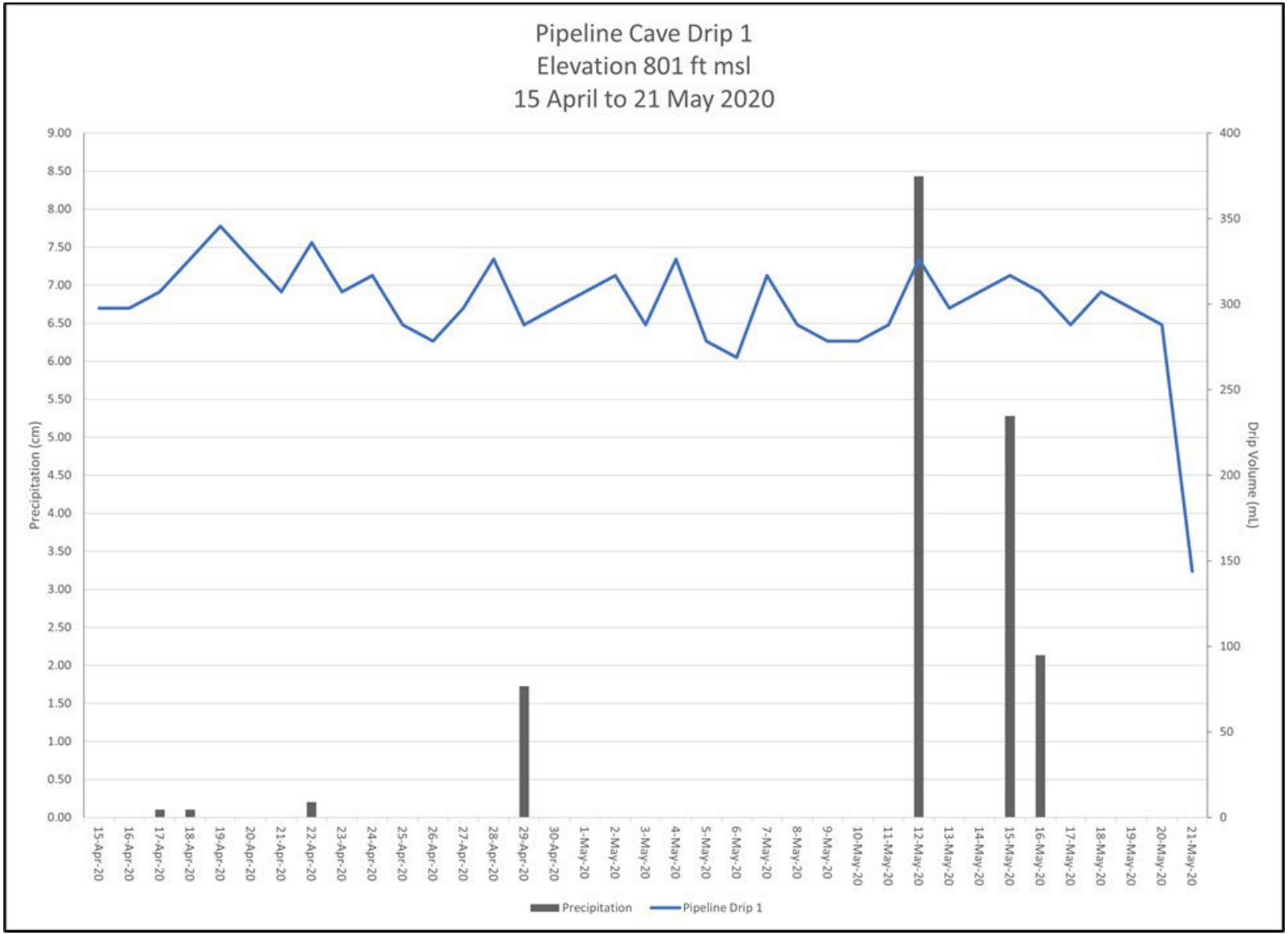


Figure 14. Pipeline Cave Drip 1 data and precipitation record, 15 April to 21 May 2020.

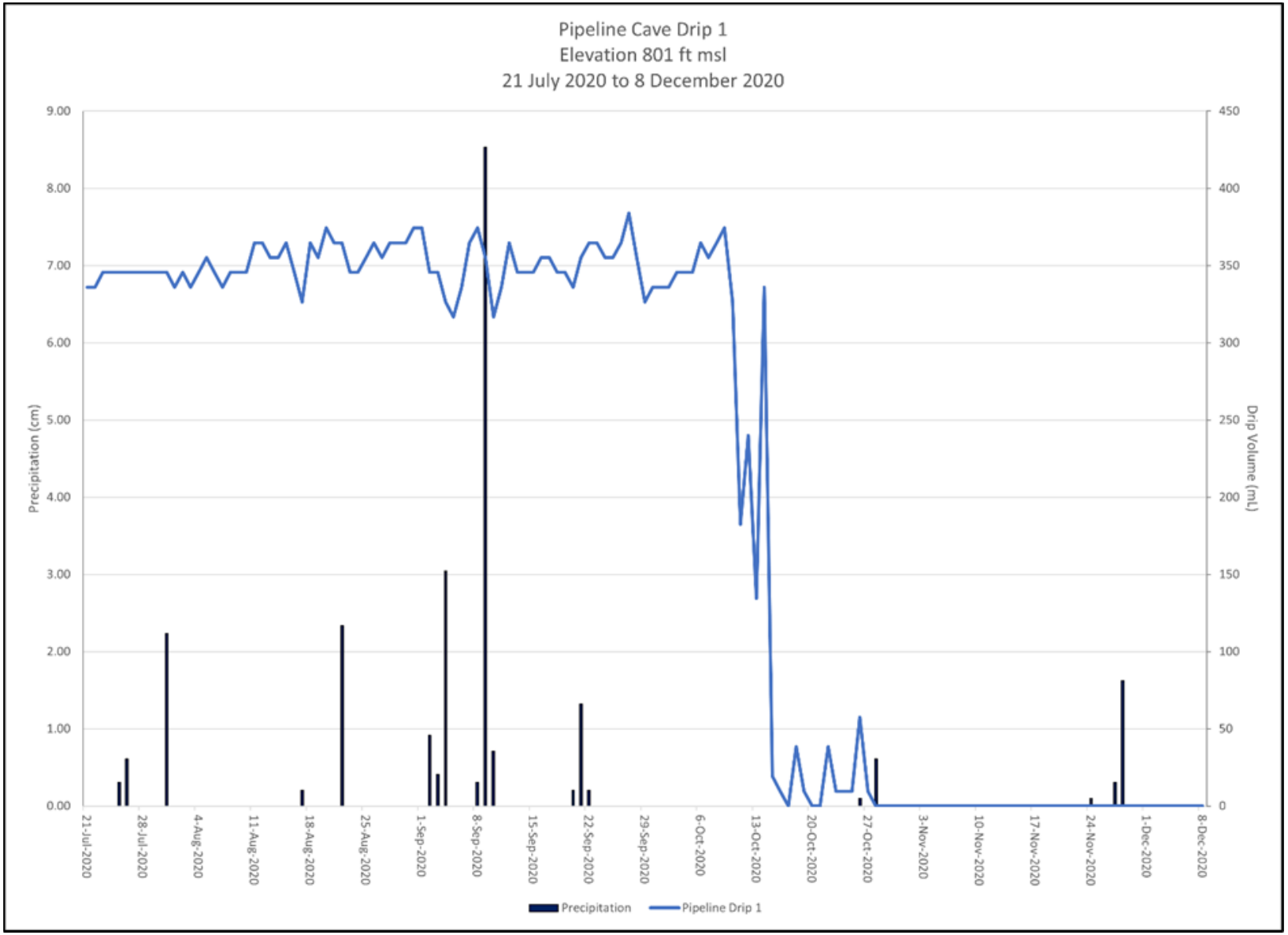


Figure 15. Pipeline Cave Drip 1 data and precipitation record, 21 July to 8 December 2020.

Pipeline Drip 2 observations

Initial observations at the Drip 2 station were eliminated from evaluation due to HOBO data logger malfunctions and probable animal interference with the tipping bucket. The HOBO data logger was replaced and the tipping bucket was recalibrated on 1 October 2020. Figure 16 shows the drip volume responses to precipitation between 1 October to 8 December 2020. The peak response pattern is different lacks obvious correlation to precipitation occurrence.

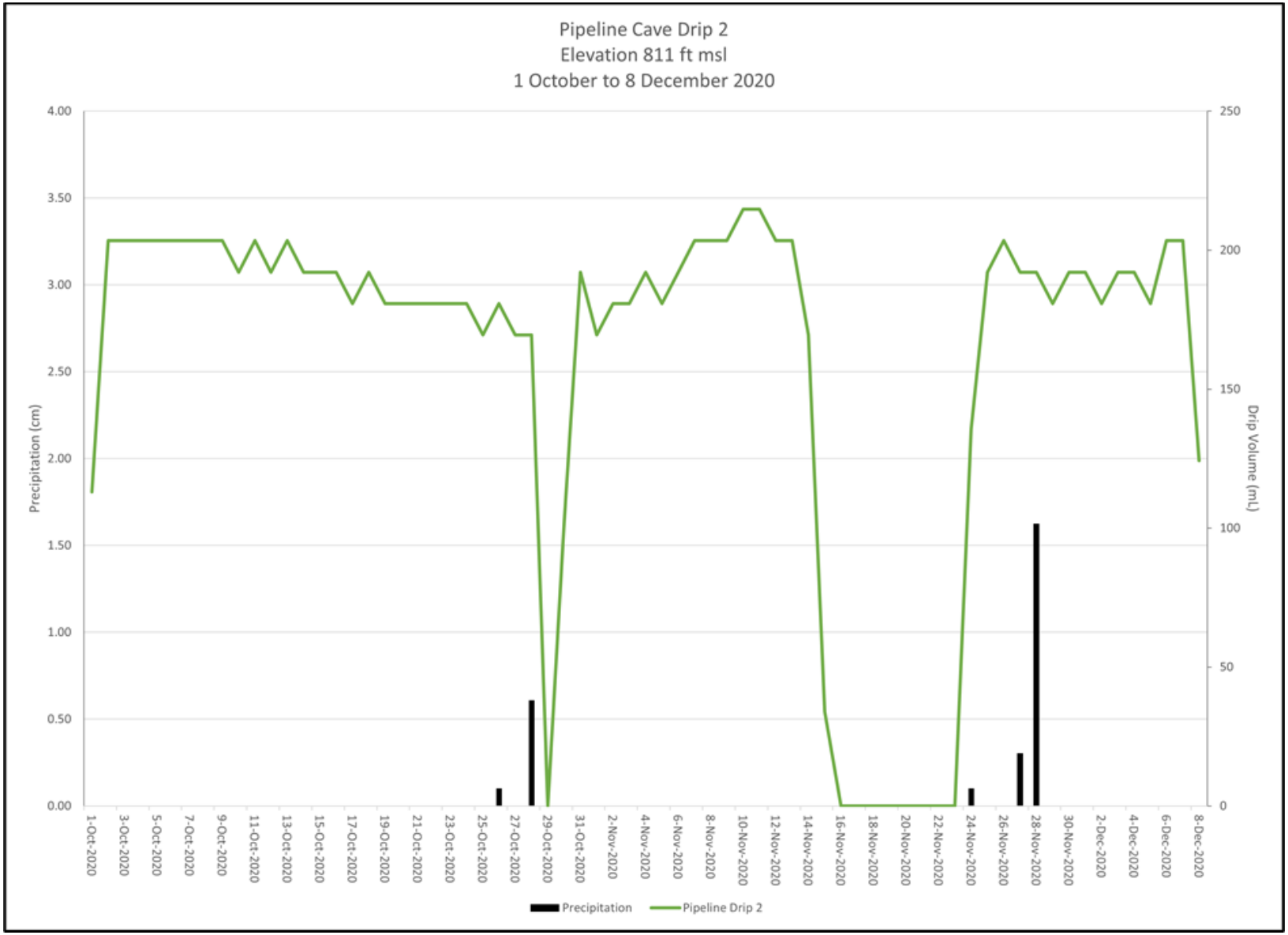


Figure 16. Pipeline Cave Drip 2 data and precipitation record, 1 October to 8 December 2020.

Drip Characterization

Cave drip types are described as seepage, discrete, discrete to pool, or pool in Table 5. Drip type was based on drip elevation, drip rate, and the hydrostratigraphic unit. Drip rates are reported for all observations documented during this project period. Drip rates ranged from a minimum of 0, when dry soil conditions led to a cessation of drips, to a maximum of 18.24 mL/min. This maximum was observed at Pipeline Drip 1 between November 2019 and April 2020. The average drip rate ranged from 0.009 mL/min measured at Arrow Cave Zone 2 to 12.16 mL/min measured at Pipeline Drip 1 between November 2019 and April 2020. Measured total daily drip volumes were lower in Arrow Cave than those of Pipeline Drip 1 or Drip 2.

Water Quality Characterization

Water samples of urban runoff, stream water, and cave drip water collected during the study period all fell within the Ca-Mg-HCO_3 geochemical facies (Figure 17). Cation charge concentration was dominated by Ca, and to a lesser extent Mg; while anion charge concentration was dominated by bicarbonate (HCO_3^-). This facies is indicative of water chemistry dominated by carbonate mineral dissolution (Calcite and Dolomite in particular). The Midnight Cave and Slaughter Creek at 1826 samples were distinguished from the other samples by slightly higher Sulfate charge concentration percentage (~18-24% of total anion charge). 2015 reclaimed water samples reported by Porras et al. (2016) had a markedly different geochemistry than the study samples, being more representative of a Na-Cl geochemical facies.

Comparison of Na and Cl molar concentrations showed most of the study samples with roughly equivalent concentrations (i.e. plotting on the 1:1 line) (Figure 18). The exception to this was the Slaughter Creek Cave drip sample, which plotted on the Cl side of the 1:1 line.

Phosphorus, Total Organic Carbon, and Nitrate data are presented in . Elevated nitrate was reported in the Midnight Cave Pool for both the February and August 2020 samples (18.5 and 8.16 mg/L respectively). The Pipeline Cave water sample showed elevated Total Phosphorus (0.546 mg/L). The Slaughter Creek Cave drip sample had relatively high concentrations of Total Organic Carbon (4.92 mg/L), as did all of the surface water and urban runoff samples (2.99-9.35 mg/L).

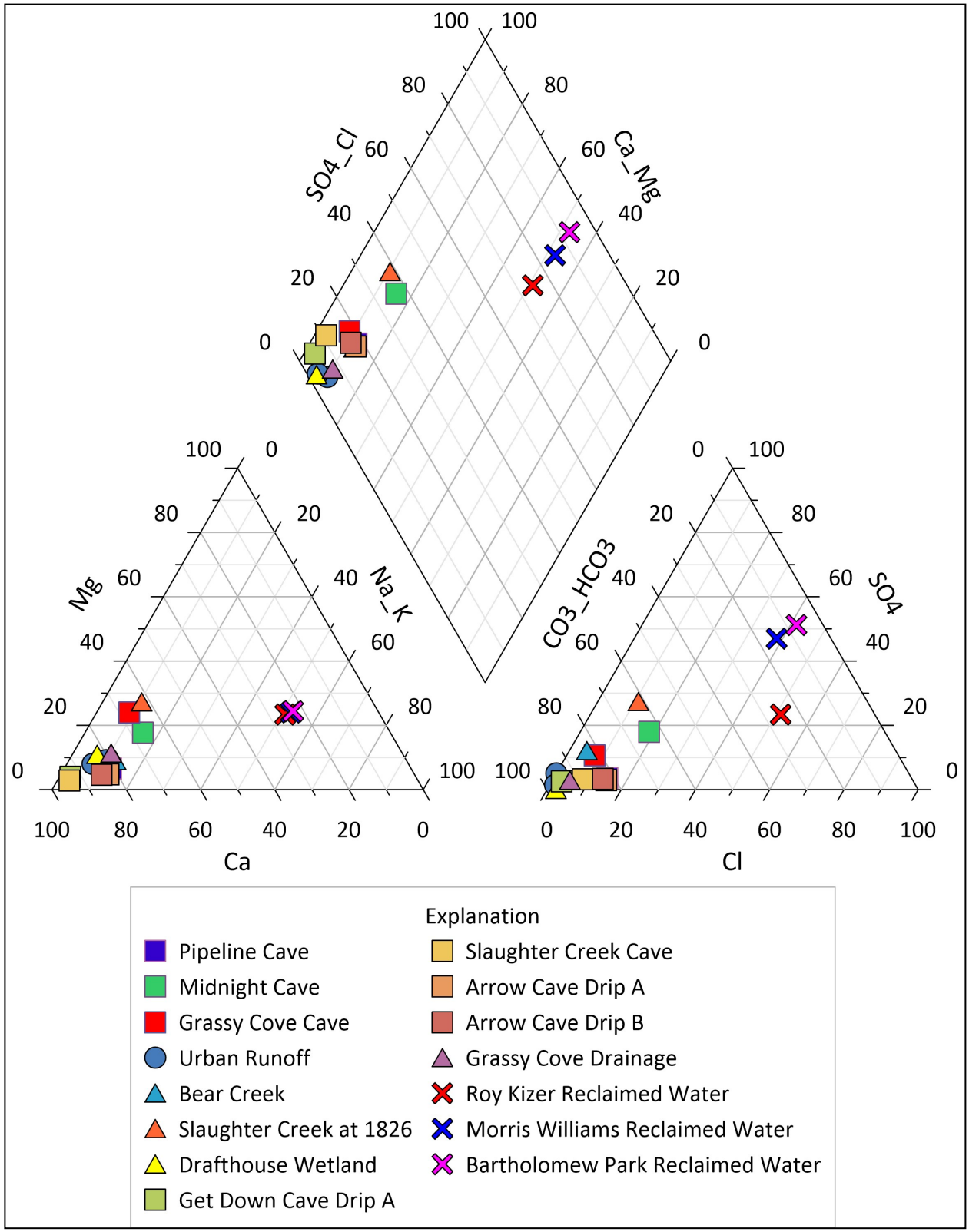


Figure 17. Piper Plot summarizing geochemistry of water samples collected during the study period. Data points symbolized as 'X's represent reclaimed water samples collected by City of Austin staff in 2015 and reported in Porras et al. (2016).

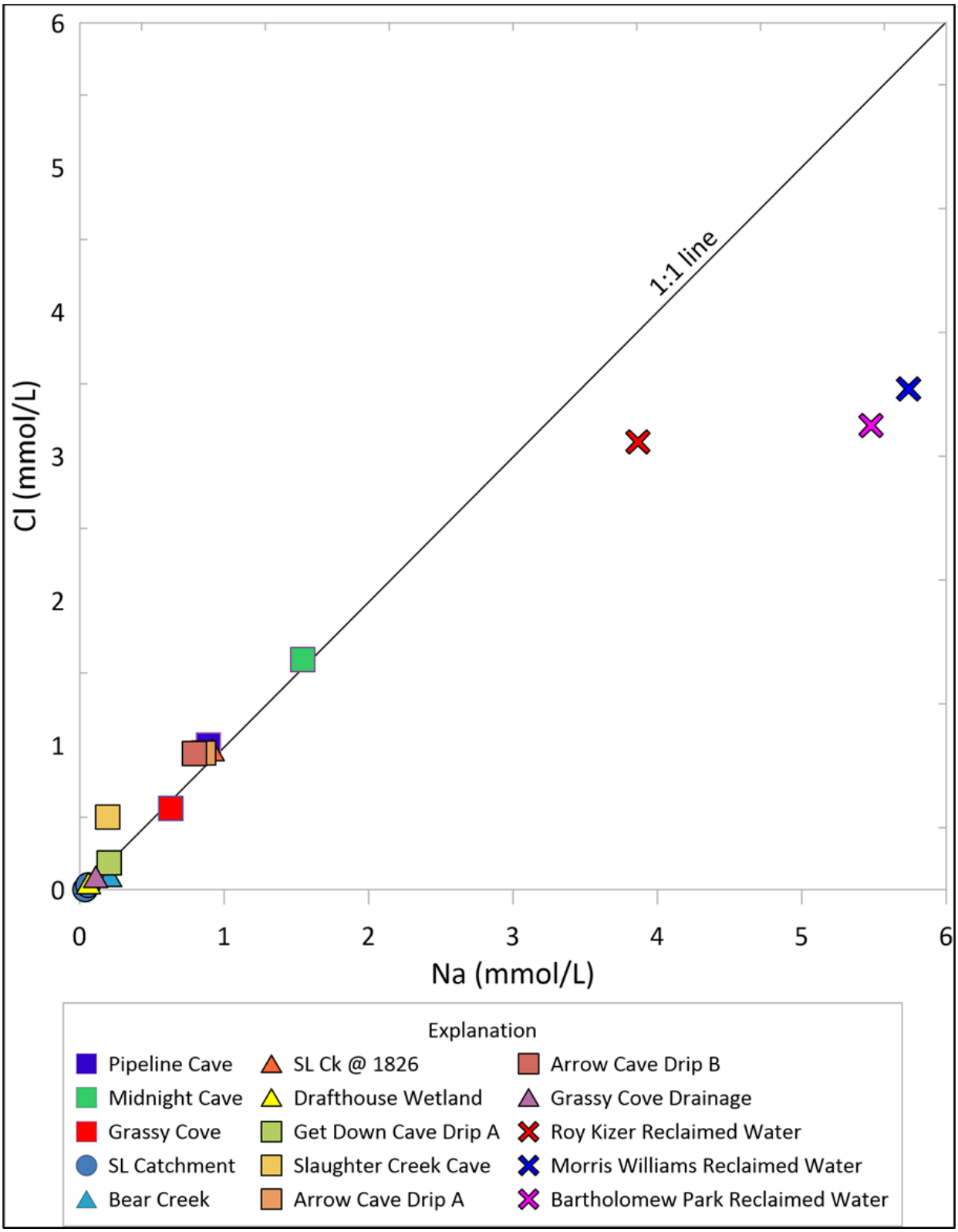


Figure 18. Molar concentration of Chloride versus Sodium of water samples collected during study timeframe.

Table 6. Summary of nitrate, phosphorus, and Total Organic Carbon of samples collected during the study period. All values are reported in milligrams per liter.

Site	Date	Nitrate/ Nitrite	Total Phosphorus	Total Organic Carbon
Pipeline Cave (Zara)	3/3/2020	0.339*	0.546	2.79
Midnight Cave (Zara)	2/20/2020	18.5*	<0.0200	1.12
Midnight Cave (BCP)	8/25/2020	8.16	0.0166	1.38
Grassy Cove (Zara)	2/12/2020	2.66*	<0.0200	0.931
Get Down Drip A (BCP)	5/19/2020	0.72	<0.008	0.924
Get Down Drip A (BCP)	8/25/2020	1.51	<0.008	0.952
Get Down Drip B (BCP)	8/25/2020	2.77	<0.008	1.07
Slaughter Creek Cave Drip A (BCP)	5/19/2020	<0.02	0.0217	4.92
Arrow Cave Drip A (BCP)	5/19/2020	0.49	<0.008	2.45
Arrow Cave Drip B (BCP)	5/19/2020	0.6	0.0169	2.25
Grassy Cove Drainage (Zara)	2/12/2020	0.165*	0.12	2.4
Bear Creek (Zara)	3/22/2020	0.185*	0.114	6.25
Grassy Cove Drainage (Zara)	5/28/2020	0.0511*	0.114	7.29
Grassy Cove Drainage (BCP)	5/16/2020	0.39	0.144	5.11
SL @ 1826 (Zara)	5/28/2020	0.195*	<0.02	2.99
Wetland S. of Drafthouse (Zara)	5/29/2020	<0.01*	0.0555	9.35
Morris Golf Pond (COAWPD)	8/27/2015	26.5	3.66	7.66
Roy Kizer Golf Pipe (COAWPD)	8/27/2015	15.7	1.78	6.11
Bartholomew Park (COAWPD)	8/27/2015	28.6	4.75	8.13

*Nitrate/nitrite values reported by EPA laboratory method 300.0. All other values report method SM4500-NO3-H.

All charcoal receptors and water samples analyzed were non-detect for all dyes.

COA WPD provided technical assistance to this study by deploying a fluorimeter sonde at Eliza Springs. The sonde data indicate possible detections of RWT on 1 December 2020 and of Fluorescein on 2 December 2020 at very low concentrations. Figure 19, a graph of the fluorimeter sonde readings from 1 December 2020 to 3 December 2020, shows small peaks in RWT and Fluorescein. The injection of RWT in the Hielscher Well and associated flush water, completely filled the well and declined at a slow rate. The dye was visible in the well on 13 October 2020, suggesting poor connectivity to the local water table or fractures or conduits. Randomly located well sites are not representative of faster flow routes that naturally develop in karst aquifers and transport the majority of flow (Quinlan, 1989).

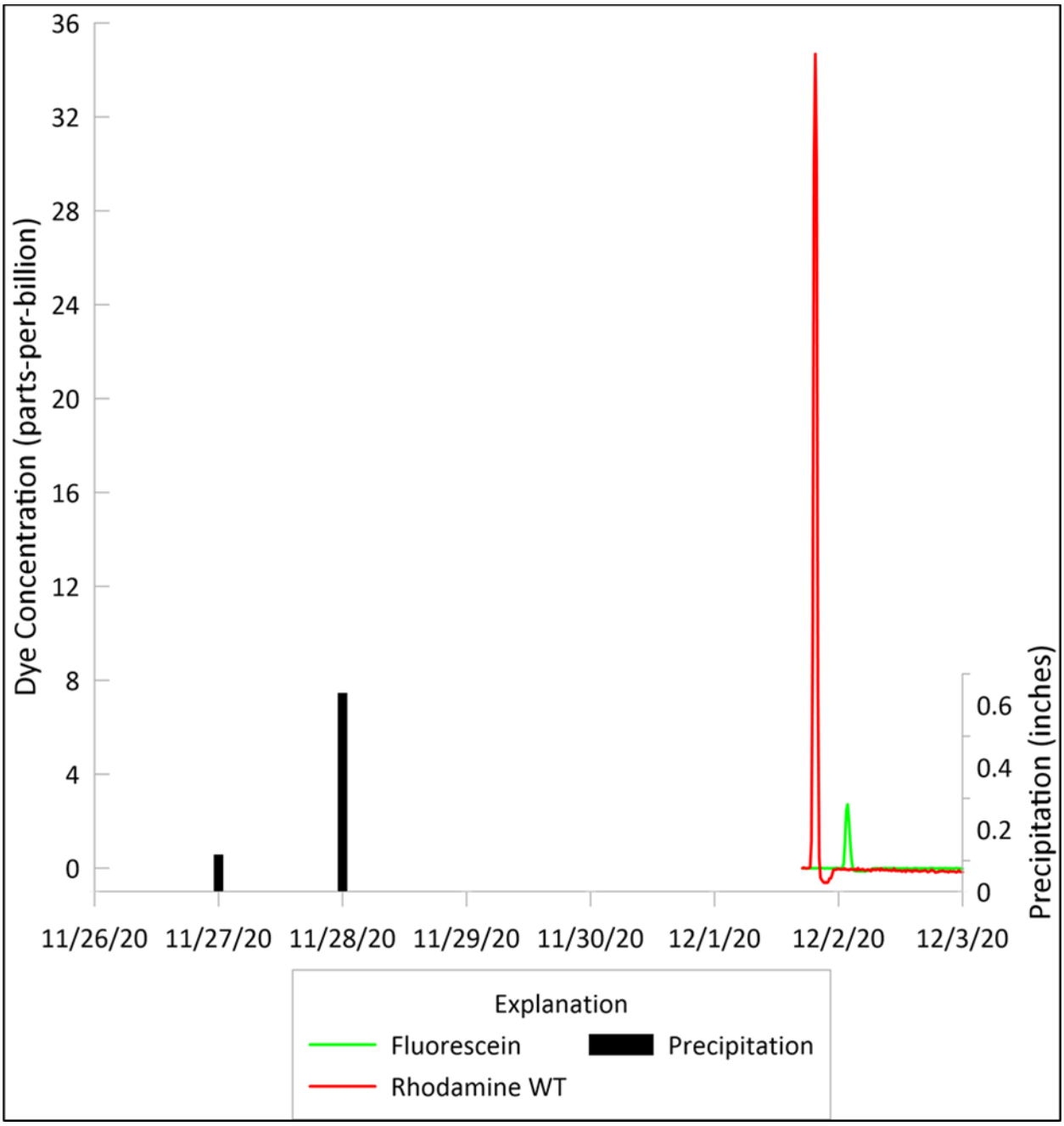


Figure 19. Graph of the fluorimeter sonde readings from 1 December 2020 to 3 December 2020 and antecedent precipitation.

Due to the limited transmissivity indicated by the slow post-injection dispersion of RWT at the Hielscher well and the non-detect results in Midnight Cave, the closest monitoring site, the RWT peak observed at Eliza Springs may be unrelated to the 9 October 2020 injection of RWT for this study. Even though no RWT pulses were observed in the prior 44 days of monitoring following injection, it is also possible that the four pounds of RWT dye and/or the flush volume was insufficient for detection at local monitoring sites yet arrived at Eliza Springs. RWT characteristically breaks into two components, one of which is more strongly sorbed by sediment than Fluorescein (Hauwert 2009, Appendix I). Note that following a 5-pound injection of RWT tracer in nearby Midnight Cave in 1999, it took 7-8 days to arrive at Barton Springs under a discharge rate of 83 ft^3/s with a calculated 17% recovery. Consequently, this study's 4-pound injection on 9 October 2020, under Barton Springs discharge of 38 ft^3/s, would require significantly more travel time (i.e., weeks) for a lower recovery or no detection.

Fluorescein was detected at Eliza Springs on 2 December 2020, 54 days after injection and 4.5 days after a 0.76-in rain. It is possible that the peak of Fluorescein at a low concentration of less than 4 ppb may be unrelated to the 9 October 2020 injection of Fluorescein at Snake City Sink, due to the slow rate of infiltration of flush water and the common finding of Fluorescein in urban stormwater runoff. It is possible that the flush volume used to "push" the tracer dyes into the system was insufficient, and a series of rain events was necessary to flush the dye through local groundwater flow paths. However, the detection of both RWT and Fluorescein within the same timeframe after injection, and not during background monitoring, suggests these detections may be associated with this study's dye injections. It is possible that a portion of the injected dye reached a prominent flow path that did not include Midnight Cave and reached Eliza Springs. Note that the injection mass of 1 pound of Fluorescein is substantially lower than the 20-30 pounds that would typically be injected from this distance for a clear recovery at Barton Springs. It is also possible that the December 2020 detections of RWT and Fluorescein are due to mobilization of residual dye from a previous tracer injection, the last known injection within the BSEA occurring in 2017.

Subsurface drainage basin delineation, Pipeline Cave

The subsurface drainage basin of Pipeline Cave is constrained by the depth and lateral extent of the cave. The cave's lowest elevation can be used to eliminate areas on the surface that are lower in elevation and are, therefore, outside the subsurface drainage area of the cave. The lowest surveyed elevation of Pipeline Cave is 790 ft above mean sea level (amsl). The dip of the Kirschberg HSU strata potentially extends the subsurface drainage basin approximately 1700 ft amsl towards the west to where it is truncated by a fault. This may mark the western boundary of the subsurface catchment area of Pipeline Cave, as none of the injected fluorescent dye tracers were detected in Pipeline Cave drips.

The subsurface catchment area, as delineated here, is a conservative over-estimation of the actual infiltration source area for drips within the known extent of Pipeline Cave with high confidence, based on existing data. With additional local tracing, the subsurface catchment area could potentially be constrained to a smaller area. Runoff from Parkside Village impervious cover surfaces are routed via drains to a water quality pond southeast of Pipeline Cave. As designed, these impervious cover surfaces would not currently supply flow to Pipeline Cave: however, the potential subsurface catchment for Pipeline Cave is extended across this area because it could not be ruled out that the subsurface area didn't naturally extend within this area. This pond was historically in the location of a stockpond for Covert. The lowest critical source elevation is about 801 ft amsl. The expected source direction is west due to the hydraulic gradient from eastward down-dropping faults, as shown in the geological cross-section of the project area in Figure 7. The down-dropping fault blocks to the east tend to focus groundwater flow eastward rather than westward, as shown by previous local groundwater traces. Surface topography slopes south over the cave, declining surface elevation of about 1 ft per 40 ft. Consequently, there is a greater potential infiltration area to the north than to the south. The Pipeline Cave Alamo Pool drip sample collected on 3 March 2020 had relatively high chloride, sodium, and iron concentrations of 35.6 mg/l, 20.5 mg/l, and 0.856 mg/l, respectively. These findings are interpreted to be from an urban runoff source, and may be attributed to runoff or infiltration from an irrigation field located approximately 250 ft west of Pipeline Cave. A water-quality pond with base elevations ranging from approximately 814 ft amsl to approximately 820 ft amsl is located approximately 200 ft southeast of Pipeline Cave.

Hydraulic gradient is the angle of surface features to underlying cave drips, as described by Hauwert and Cowan (2013). The magnitude of hydraulic gradient relates to the likelihood that an overlying feature or area might contribute flow to an underlying cave drip and varies with the permeability characteristics of the intervening rock unit. A feature that directly overlies a cave drip (90˚) is highly likely to infiltrate and contribute flow to the cave drip. Table 7 lists the calculated hydraulic gradients for potential source water features to Pipeline Cave Drip 1.

Table 7. Hydraulic gradients for potential source water feature to Pipeline Cave Drip 1.

Feature	*Elevation (ft amsl)	Height Above 801 ft msl (ft)	Distance (ft)	Gradient (radians)	Gradient (degree)	Direction	Intervening Hydro-stratigraphic Unit
Parkside Village WQ Pond (base)	814	13	200	0.06491	3.72	SE	Grainstone Mbr
Parkside Village WQ Pond (full)	820	19	200	0.09472	5.43	SE	Grainstone Mbr
Drainage West of Pipeline Cave	826	25	700	0.0357	2.05	W	Grainstone Mbr
Irrigation Field	830	29	250	0.11548	6.62	W	Grainstone Mbr
Slaughter Lane	842	41	600	0.06823	3.91	N	Grainstone Mbr
Slaughter Creek	816	15	1400	0.01071	0.61	SW	Grainstone Mbr
Escarpment Cave Injection	827	26	2500	0.0104	0.60	SW	Grainstone/Kirschberg Mbrs
Live Oak Motte Swallet Drainage Injection	842	41	2500	0.0164	0.94	W	Grainstone/Kirschberg Mbrs

*Elevations were based on 2-ft surface contour elevations derived from City of Austin GIS shapefiles and were not directly surveyed.

Because the Grainstone and Kirschberg Members have the highest permeability of the Edwards Aquifer, infiltrating water tends to descend to the water table at relatively higher angles generally greater than 12˚, based on direct tracing (Hauwert and Cowan 2013). Since the 2013 publication, a dye tracer study from cave a half-mile away reached drips in Flint Ridge Cave through the highly permeable Kirschberg Member at a low gradient of about 1˚, which was surprising but indicative that hydraulic gradients are not definitive delineation of subsurface catchment area and exceptions are possible. Similarly, a high value of hydraulic gradient does not prove that the site contributes to a referenced cave drip.

The elevation of the lowest known drip horizon in Pipeline Cave of about 801 ft amsl was used in calculating hydraulic gradient. An irrigation field located about 200 ft west of Pipeline Cave has a hydraulic gradient of about 2˚-7˚ from the drip horizon in Pipeline Cave. The two dye tracers injected in two sites (Escarpment Cave and Live Oak Motte Swallet, located approximately 2,500 ft west and with hydraulic gradients of 0.6-0.9˚) were not detected in Pipeline Cave or other monitored sites. The edges of the subsurface catchment area defined in this study has a hydraulic gradient of 8˚ north, 2˚ west, 4˚ south, and 15˚ east of Pipeline Cave.

A northwest to southeast drainage from Slaughter Lane (Figure 20) was evaluated as a possible source to Pipeline Cave, and no evidence of its contribution was found. The channel lies about 700 ft west of Pipeline Cave and its channel has an elevation of about 826 ft amsl, which is higher than the lowest drip horizon in Pipeline Cave of 801 ft amsl. During a roughly 2-in rain event on 3 April 2020, Drew Thompson entered Pipeline Cave to measure drips and did not observe outstanding flow that could be attributed to focused recharge such as from the channel west of Pipeline Cave. A few days later, on 6 April 2020, Jeff Watson walked the drainage west of Pipeline Cave and did not observe obvious flow loss. The hydraulic gradient between this drainage and lowermost drip horizon in Pipeline Cave (799 ft amsl) is two degrees. It is interpreted that this drainage is outside of the subsurface catchment area for drips in the known extent of Pipeline Cave.

Based on these analyses, the natural subsurface catchment area of Pipeline Cave should be constrained within the conservatively overestimated potential subsurface catchment basin of 10.8 acres shown in Figure 20.



Figure 20. Map of Pipeline Cave Footprint, Surface Catchment, and Subsurface Drainage Basin.

Discussion

The tracer test was hampered by very dry soil moisture percentages that began in July and persisted through mid-December 2020 (NOAA, 2020). These conditions, combined with the small mass of the tracer dyes selected for a short distance trace, may have resulted in limited movement of the dye. The tracer test was designed to identify shallow, subsurface groundwater flow paths to cave drips within Pipeline Cave from karst features located upgradient of the cave. The initial scope of the project included two dye tracer tests but was reduced to one test due to time and budget constraints. The known challenges of conducting dye tracer tests in the epikarst zone are believed to be responsible for the non-detects for this project. Cave drips are generally classified as either having a diffuse source, such as infiltration through overlying soil and rock strata, or a conduit source, such as a conduit or fracture that is of karst-origin. In this project, all the cave drips occur at an elevation that is above the potentiometric surface (water table elevation) reported in the vicinity, as depicted in the geologic cross-section provided as Figure 7. The dry soil conditions reduced the potential for recharge from direct precipitation or stormwater runoff to vertically migrate to discrete cave drips or to mobilize along preferential flowpaths in the unsaturated zone.

Water Quality

Overall water chemistry of cave drips and cave pools in the project area reflects a Ca-Mg-HCO3 geochemical facies, which indicates dissolution of rocks containing carbonate minerals (such as Limestone and Dolomite) that outcrop over the entirety of the project area. Stream water and urban runoff water samples also fell within this geochemical facies.

In order to evaluate possible source water types, samples collected during the study period were compared to representative reclaimed water samples collected by City of Austin staff in 2015 (Porras et al., 2016). Samples collected during the study period had a distinctly different geochemical facies composition than the 2015 reclaimed water samples, which had a much larger proportion of sodium and chloride (Figure 17). Reclaimed water samples also had a significantly higher sodium/chloride ratio. A plot of molar concentration of sodium versus chloride shows that study samples generally plotted on the 1:1 line while reclaimed water samples plotted well right of the 1:1 line (Figure 18). This suggests that the major ion composition of water samples collected during the study period do not indicate obvious influence from reclaimed water.

Waters from the Midnight Cave pool and Slaughter Creek at 1826 surface water both indicate higher proportion of sulfate as a percentage of dissolved constituents (Figure 17). This elevated sulfate in Midnight Cave may be a result of cross aquifer flow from the Upper Glen Rose unit of the Trinity Aquifer, which is juxtaposed against Edwards Aquifer units to the west and upgradient of the Cave on the upthrown side of the Mount Bonnell Fault. The Upper Glen Rose generally has higher proportion of soluble sulfate-bearing minerals such as gypsum and anhydrite (Wong et al., 2014). This generally leads to higher sulfate and total dissolved solids in groundwater of the Upper Trinity Aquifer. Thus, cross aquifer flow from the Upper Trinity Aquifer into the Edwards may provide a reasonable explanation for elevated sulfate in Midnight Cave.

High levels of nitrate were present in water samples collected from the Midnight Cave Pool in February and August 2020 (18.5 and 8.16 mg/L, respectively). These nitrate levels were significantly higher than other BCCP caves in the project area (<0.02-2.77 mg/L). Private septic systems are located west of and upgradient of Midnight Cave, and may provide one possible explanation for elevated nitrate levels. Elevated levels of Phosphorus in a cave drip water sample collected from Pipeline Cave may indicate possible urban contamination, such as fertilizer.

The surface catchment area providing runoff to the entrance of Pipeline Cave was mapped as a 3-acre natural catchment area from field observations in 2001 and 2001 and a 1.85-acre current surface catchment area. Based on the geological framework of eastward down-dropping fault blocks, the presence of highly permeable Grainstone and Kirschberg Members, the elevations of cave drips and hydraulic gradient from surface areas, the limited drip rate, rain-event observations, water chemistry of the drips, and dye tracing from specific surface sites, the potential subsurface catchment basin for drips within Pipeline Cave is constrained within a 10.8-acre area mapped in Figure 7. Based on the estimated boundaries of these catchment areas and the limited land surface disturbances associated with proposed transportation improvements of the West Slaughter Lane Corridor project, we conclude that the proposed transportation improvements are likely to have little to no impact on Pipeline Cave habitat for karst invertebrate species. In the course of this study, with the support of the property owner, tremendous improvement to the cave was made through the removal of trash fill and extending the accessible cave habitat volume 20 times its pre 2018 volume.

Literature Cited

Aley and Thomas. 2019. The Ozark Underground Laboratory's Groundwater Tracing Handbook. Ozark Underground Laboratory, Protem, Missouri, 35p.

Aley, Thomas, Beeman, and Shiloh L. 2015. Procedures and Criteria, Analysis of Fluorescent Dyes in Water and Charcoal Samplers: Fluorescein, Eosine, Rhodamine WT, and Sulforhodamine B Dyes. Ozark Underground Laboratory, Inc., Protem, Missouri, 20 p.

Balcones Canyonlands Preserve Karst Monitoring and Management FY 2020 Annual Report, Appendix I: Travis County Natural Resources and Austin Water Balcones Canyonland Preserve. P, 48-52.

Brune, G. and Duffin, G. L. 1983. Occurrence, availability, and quality of groundwater in Travis County, Texas: Texas Department of Water Resources, Report 276, 219 p.

City of Austin. 2016. State of Our Environment Report. 31 p.

City of Austin, Watershed Protection Department. 2020. Flood Early Warning System (FEWS) gauge #1190 measurements. Gauge #1190, Escarpment Boulevard, Austin, TX. Data provided 4 December 2020.

Collins, E.W. 1987. Characterization of fractures in limestones, northern segment of the Edwards aquifer and the Balcones Fault Zone, central Texas. Gulf Coast Association of Geological Societies Transactions, V. 37, p. 43-54.

Cowan, B.D., Banner, J.L., and Musgrove, M. 2007. Geochemical and physical tracing of rapid response in the vadose zone of the Edwards karst aquifer, Geological Society of America Abstracts with Programs, Denver, CO, Vol. 39, No. 6, p. 190.

Cowan, B.D. and Hauwert, N.H. 2013. Use of physical and chemical response in cave drips to characterize upland recharge in the Barton Springs Segment of the Edwards Aquifer, central Texas, USA, Proceedings of the Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Carlsbad, New Mexico, May 6-10, 2013.

Dole, R.B. 1906. Use of fluorescein in the study of underground waters. *In* Fuller, M.L. ed., Underground-Water Papers. U.S. Geological Survey Water-Supply and Irrigation Paper 160, p. 73-85.

Ferrill, D. M., Morris, A.P., and McGinnis, R.N. 2019. Geologic Structure of the Edwards (Balcones Fault Zone) Aquifer, 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, p. 171-188, https://doi.org/10.1130/2019.1215(14).

Geologic Atlas of Texas (GAT). 2019. Available at: https://txpub.usgs.gov/txgeology/. Accessed January 2019.

Hauwert, N., Johns, D., Aley, T., and Sansom, J. 2004a. Groundwater Tracing Study of the Barton Springs Segment of the Edwards Aquifer, Southern Travis and Northern Hays Counties, Texas: Report by the Barton Springs/Edwards Aquifer Conservation District and City of Austin Watershed Protection and Development Review Department. 110 pp. and appendices.

Hauwert, N., Johns, D., Hunt, B., Berry, J., Smith, B., and Sharp, J. 2004b. Flow Systems of the Edwards Aquifer Barton Springs Segment Interpreted from Tracing and Associated Field Studies. Symposium Proceedings of Edwards Aquifer in Central Texas, Retrospective and Prospective, San Antonio, Texas. Hosted by the South Texas Geological Society and Austin Geological Society. 18 p.

Hauwert, N.M. 2009. Groundwater flow and recharge within the Barton Springs Segment of the Edwards aquifer, southern Travis and northern Hays counties, Texas. PhD Dissertation in Geology at The University of Texas at Austin, Austin, Texas. 346 p.

Hauwert, N.M. 2012a. Summary of Initial Hydrogeologic Study Results, Evaluation of Impacts from Davis Lane, and Proposed Solutions to Protect Water Sources to Goat, Maple Run, and Blowing Sink Balcones Canyonland Preserve Caves. City of Austin, Watershed Protection Department. 27 p.

Hauwert, Nico. 2012b. Dye Trace Simulation of an Accidental Spill Phase 10: State Highway 45 Southwest and MoPac South into the Barton Springs Segment of the Edwards Aquifer Travis County, Texas: City of Austin Watershed Protection Dept. short report SR13-01. 75 p. http://www.austintexas.gov/watershed_protection/publications/document.cfm?id=196481

Hauwert, N.M. and Cowan, B.D. 2013. Delineating source areas to cave drips and cave streams in Austin, Texas, USA. Proceedings of the 13th Sinkholes Conference, NCKRI Symposium 2, Carlsbad, NM. Pp. 353-365.

Hauwert, N.M. and Sharp, J. 2014. Measuring Autogenic Recharge over a Karst Aquifer Utilizing Eddy Covariance Evapotranspiration. Journal of Water Resource and Protection, vol. 6, p. 869- 879.

Hunt, B., Smith, B., Campbell, S., Beery, J., Hauwert, N., and Johns, D. 2005. Dye tracing recharge features under high-flow conditions, Onion Creek, Barton Springs Segment of the Edwards Aquifer, Hays County, Texas. Austin Geologic Society Bulletin, Vol. 1, p. 70-86.

Hunt, B., Smith, B., and Hauwert, N. 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.

Johnson, S., Schindel, G., Veni, G., Hauwert, N., Hunt, B., Smith, B., and Gary, M. 2012. Tracing Groundwater Flowpaths in the Vicinity of San Marcos Springs, Texas. Edwards Aquifer Authority, Report No. 12-01. 145 p.

Jones, W.K. 1976. Dye tracer tests in karst areas: National Speleological Society Bulletin, v. 46, pp. 3-9.

National Oceanic and Atmospheric Administration (NOAA). 2018. Local Climatological Data Annual Summary with Comparative Data at Austin/Bergstrom, TX (KAUS). 2017. Available at:ftp://ftp.ncdc.noaa.gov/pub/data/lcd/annual/2017/01201713AUS.pdf. Accessed December 2018.

National Oceanic and Atmospheric Administration (NOAA). 2020. Monthly soil moisture conditions maps, July through December 2020. Available at: https://www.cpc.ncep.noaa.gov/products/Soilmst_Monitoring/US/Soilmst/Soilmst.shtml#. Accessed December 2020.

Porras, A., Richter, A., Heirs, S., Clamann, A., Scoggins, M., Herrington, C., Burdick, W. and S. Sudduth. 2016. Reclaimed water irrigation water quality impact assessment. City of Austin Watershed Protection report: SR-16-06, 50p.

Quinlan, James F. 1989. Groundwater Monitoring in Karst Terranes: Recommended Protocols & Implicit Assumptions: EPA/600/X-89 /050, 79 p.

Quinlan, James F. 1990. Special Problems of Ground-Water Monitoring in Karst Terranes: Ground Water and Vadose Zone Monitoring, ASTM STP 1053, D. M. Nielsen and A.I. Johnson, Editors, American Society for Testing and Materials, p. 275-304.

Schreiber, M.E., Schwartz, B.J., Orndorff, W., and Doctor, D.H. 2015. Instrumenting Caves to Collect Hydrologic and Geochemical Data: Case Study from James Cave, Virginia. 28 p. in Advances in Watershed Science and Assessment, The Handbook of Environmental Chemistry 33, DOI: 10.1007/978-3-319-14212-8_8. T. Younos, T.E. Parece (eds.).

Small, T.A., Hanson, J.A., and Hauwert, N.M., 1996, Geologic framework and hydrogeologic characteristics of the Edwards Aquifer outcrop (Barton Springs Segment), northeastern Hays and southwestern Travis Counties, Texas: U.S. Geological Survey Water Resources Investigations 96-4306.

Smart, C.C. 1988. Artificial Tracer Techniques for the Determination of the Structure of Conduit Aquifers. Groundwater. Vol. 26, p. 445-453.

Smith, B., Hunt, B., and Beery, J. 2006. Summary of 2005 Groundwater Dye Tracing, Barton Springs Segment of the Edwards Aquifer, Hays and Travis Counties, Central Texas. BSEACD Report of Investigations 05012006. 31 p.

Smith, B., Hunt, B., and Johnson, S. 2012. Revisiting the Hydrologic Divide Between the San Antonio and Barton Springs Segments of the Edwards Aquifer: Insights from Recent Studies: Gulf Coast Association of Geological Societies Journal, Vol. 1, p. 55-68.

Texas Speleological Survey (TSS). 2014. TSS Map CD. Austin: Texas Speleological Survey.

Thompson, D. 2018. Trash Log of Pipeline Cave Fill. Excel spreadsheet logging date ranges for trash recovered from Pipeline Cave in 2018 and 2019. Austin Water BCP file.

United States Fish and Wildlife Service (USFWS). 2015. Section 10(a)(1)(A) Scientific Permit Requirements for Conducting Presence/Absence Surveys for Endangered Karst Invertebrates in Central Texas. USFWS Ecological Services Field Office, Austin, Texas. Revised 21 May 2015. 24 p.

Wong, C., Kromann, J., Hunt, B., Smith, B. and Banner, J. 2014. Investigating Groundwater Flow Between Edwards and Trinity Aquifers in Central Texas. Groundwater, v. 52, p.624-639. doi:10.1111/gwat.12106

Zappitello, S. and Johns, D. 2018. 2017 Groundwater Tracing in the Barton Springs Edwards Aquifer: Onion Creek and Little Bear Creek. City of Austin Watershed Protection Department Short Report SR-18-10. 29 p.

Zappitello, S., Johns, D., and Hunt, B. 2019. Summary of Groundwater Tracing in the Barton Springs Edwards Aquifer from 1996 to 2017. City of Austin Watershed Protection Department Data Report DR-19-04. 30 p.