Workshop #2

Delineation of Potential Management Areas within Bell County, Texas

Prepared for

Clearwater Underground Water Conservation District

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INTRODUCTION

Over the past several years Clearwater Underground Water Conservation District ("CUWCD") has directed hydrogeologic investigations of its managed aquifers. These investigations have helped further quantify the observations of local landowners and area water well drillers regarding the difference in the hydrogeologic conditions in southwestern Bell County compared to other parts of the county. To synthesize the scientific investigations into policy recommendations, members of CUWCD's technical consulting team applied our respective area of expertise to delineate a distinct management area in southwestern Bell County.

Our study area for this investigation focused on southwestern Bell County. The study area extended into northwestern Williamson County to allow for the investigation of the geology, structure, historical water levels, and hydraulic properties that informed how groundwater moves through the subsurface into Bell County. We also reviewed information from previous investigations across the county and extending into McLennan County. Using this information, we delineated proposed management areas with recommendations for the modification of the District Rules to account for policy variations in different parts of Bell County. Within this report, we briefly discuss the variations in hydrogeologic characteristics that dictated our recommendations for the proposed management zones.

HYDROSTRATIGRAPHY

Standen and Clause (2021) built upon their previous research to refine the understanding of the lithology, stratigraphy, and structure of the Trinity Aquifer in southwestern Bell County. Their study area was 491 square miles and included portions of southwestern Bell County, northwestern Williamson County, and eastern Burnet County (see Figure 1). Within this area, they conducted a detailed stratigraphic investigation to identify possible geologic variabilities within the units making up the Trinity Aquifer, particularly, those units of the Middle and Lower Trinity as identified on Table 1.

The Cretaceous Hosston, Pearsall, Hammett Shale, Cow Creek Limestone, and Hensell Sand Members have historically been referred to as the Travis Peak Formation. However, this generalized classification does not account for differences in hydraulic characteristics, groundwater chemistry, and water levels between hydrologic units. Instead, the aquifer system is better described as the Middle Trinity Aquifer comprised of the Hensell Sand and Cow Creek Limestone, and the Lower Trinity Aquifer comprised of the Hosston.

Figure 1. Study area for Standen and Clause (2021).

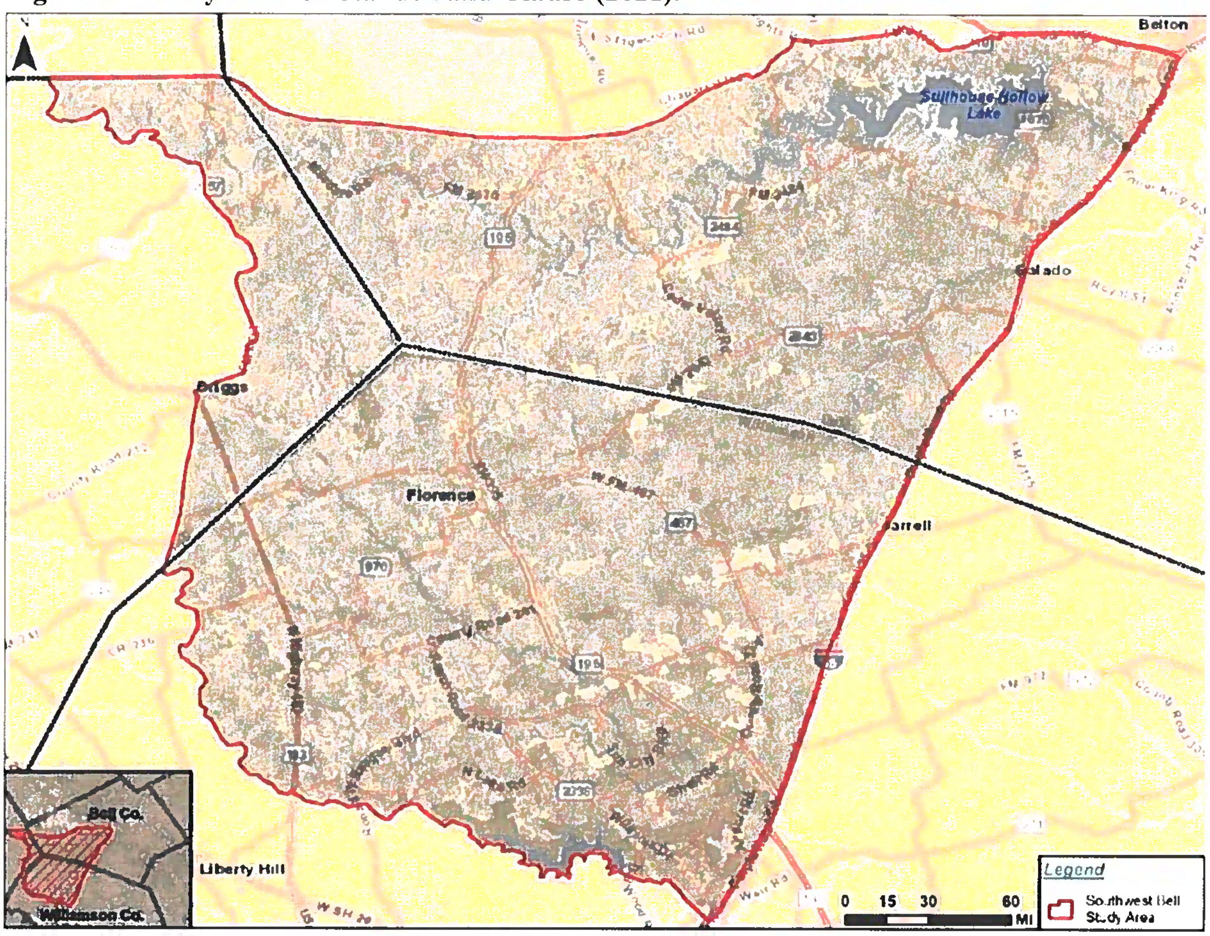


Table 1. Study Area Middle and Lower Trinity Stratigraphic Column. Modified from Klemt and others (1975) and Duffin and Musick (1991).

System	Group	Stratigraphic Units		Hydrologic Unit	Lithologic Description
Cretaceous	Middle Trinity	Travis Peak Formation	Hensell Sand Member	Middle Trinity Aquifer	Composed of sands and sandstones, gravels and conglomerates that are poorly to well cemented, and sometimes interbedded with sandy limestone lenses, multicolored clays, and gray to green shales.
			Cow Creek Limestone Member		Cream to tan color limestones that are fossiliferous, sometimes sandy, and can locally contain fractures and cavities.
			Hammett Shale / Pearsall Member	Aquitard	Hammett Shale: Gray to dark gray silty sandy shale with streaks of dolomite. / Pearsall Member: "Redbeds" Limestones, multi-colored clays, and sand lenses
	Lower Trinity		Hosston Member	Lower Trinity Aquifer	"Lower Trinity Sand," composed of poorly sorted multicolored conglomerate, poorly sorted to well sorted fine and coarse grain sand and sandstones, streaks of shale and occasional limestone.

The stratigraphic units of the Middle and Lower Trinity are present at depth and underlie the entire study area. These units dip to the east being shallower in the northwestern portion of the study area and deeper to the east. Along the eastern edge of the study area, the Middle and Lower Trinity are approximately 900 and 1,100 feet below land surface, respectively, while in the northwestern portion of the study area along the Lampasas River, the Middle and Lower Trinity is less than 100 and 200 feet below land surface, respectively.

The Middle Trinity is composed of both the Hensell Sands and Cow Creek Limestone. It is hydrologically separated from the Lower Trinity Aquifer by the Hammett Shale or Pearsall Member. The Lower Trinity Group includes the Hosston Member which lies unconformably on an irregular erosional surface of Paleozoic strata. Within the study area, sand grain size decreases in a westward direction and calcium carbonate materials increase in both the Hensell Sands and Hosston Member, while the Cow Creek Limestones grades into the Pearsall formation. These changes occur in the Middle and Lower Trinity calcareous facies transition zone that primarily occurs west of Texas Highway 195 in Bell County.

Middle and Lower Trinity faults with a NE-SW orientation are present throughout the study area. These are normal faults with the up blocks located along the west side of each fault that follow the known Balcones Fault Zone structure and surface faults mapped in the Geologic Atlas of Texas. Although faults are observed throughout the study area, only faults near and around Stillman Valley Road and FM 2484 appear to form a noticeable boundary condition for water chemistry, groundwater production, and water level surfaces.

HYDRAULIC CHARACTERISTICS

Through evaluations of the well spacing requirements (Keester, 2020), we have considered the hydraulic characteristics of the Middle and Lower Trinity aquifers based on the datasets used in the groundwater availability model (Kelley and others, 2014; Keester and Konetchy, 2016; Konetchy and Beach, 2020). Based on these datasets, the transmissivity of the Middle Trinity Aquifer decreases to the west and south (Figure 2). The Middle Trinity Aquifer transmissivity data for the eastern portion of the county is uncertain due to a lack of available pumping test results. However, the lower transmissivity values in the southwestern portion of the county are consistent with recent pumping test results from RS Materials and River Ridge Ranch which had transmissivity values of 1,800 gallons per day per foot (gpd/ft) and 31 gpd/ft, respectively.

For the Lower Trinity Aquifer, the transmissivity dataset from Kelley and others (2014) was not consistent with available pumping test data. To improve the transmissivity dataset, CUWCD updated the model within Bell County (Keester and Konetchy, 2016; Konetchy and Beach, 2020). The results of this work showed generally increasing transmissivity values from west to east across the county (Figure 3). However, results from recent pumping tests associated with the Brookings Ranch (Yelderman, Jr. and others, 2022) and Stillman Valley Ranchettes (Worsley, 2021) wells indicate the transmissivity values for the southwestern portion of the county are overestimated.

The pumping test at the Brookings Ranch location indicated transmissivity values of about 160 gpd/ft (Yelderman, Jr. and others, 2022) while the results at the Stillman Valley Ranchettes test was about 85 gpd/ft (Worsley, 2021). Both of these tests demonstrated our understanding of the hydraulic properties of the Lower Trinity Aquifer need to be updated. In addition, the test at the Brookings Ranch site showed the existence of a negative flow barrier which impeded flow to the well. Based on the hydrostratigraphic understanding of the area, we believe this barrier is a fault located between the wells (Figure 4).

The hydraulic properties observed in the southwest area of the county are consistent with the hydrostratigraphy for the area. The pumping tests indicate at least some of the faults identified are barriers to groundwater flow. While barriers to groundwater flow have been observed in pumping test data in other areas of the county, the low transmissivity of the aquifers in the southwest corner of Bell County along with the barriers contribute to low aquifer productivity.

Figure 2. Middle Trinity Aquifer transmissivity (Kelley and others, 2014).

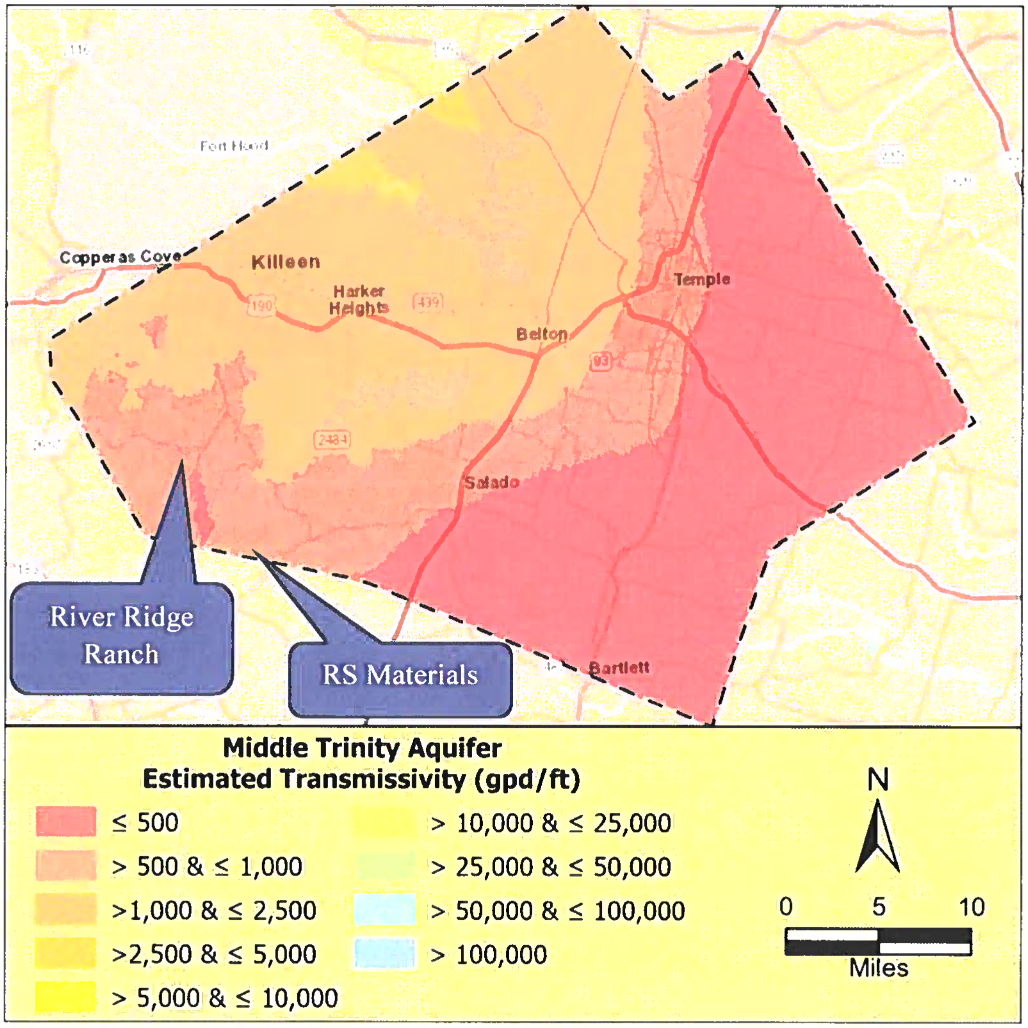


Figure 3. Lower Trinity Aquifer transmissivity.

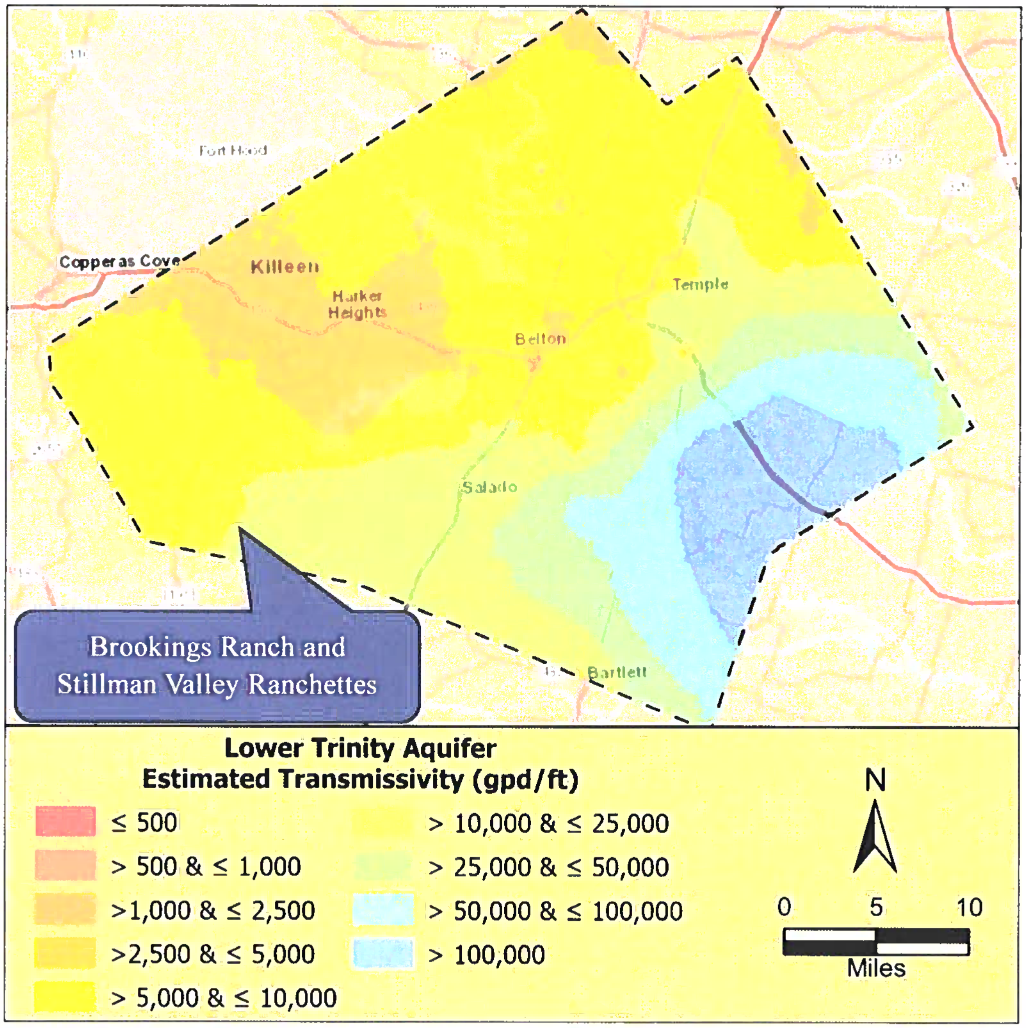
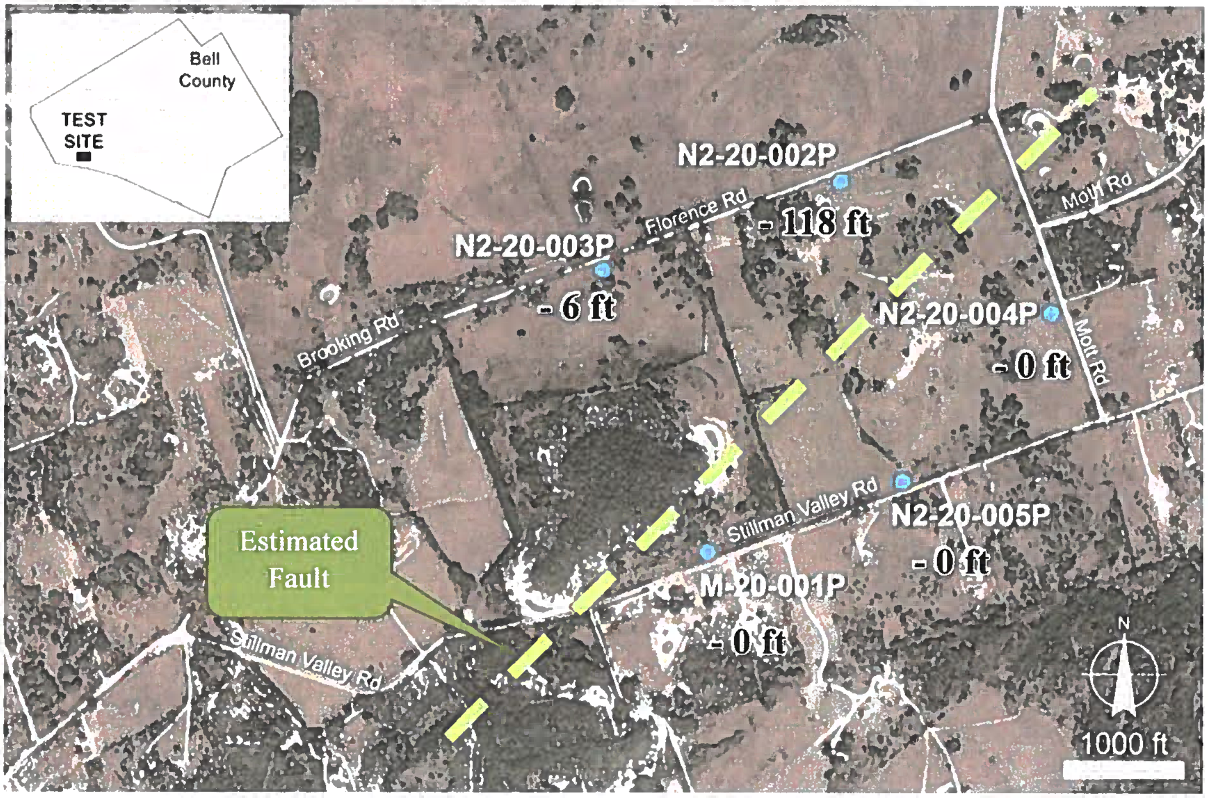


Figure 4. Drawdown in wells completed in the Lower Trinity Aquifer at the Hines site.



WATER LEVELS

Since 2006, water levels in the Middle Trinity have declined by more than 150 feet in the southwest portion of Bell County (Figure 5). These declines in water levels are due to groundwater production in the area as well as in Williamson County. The water level declines in the Middle Trinity are nearly 10 feet per year in some wells and recent measurements suggest similar declines are occurring in the deeper Lower Trinity Aquifer.

In southwestern Bell County, water levels in the Middle Trinity are deeper than water levels in the Lower Trinity. As Figure 6 indicates, the depth to water is more than 700 feet in an area of southwestern Bell County with the top of the screen interval only about 50 feet below the water level. Due to the dip of the aquifer and a lower ground surface elevation, the depth to the top of the screen is deeper and the depth to water is shallower, respectively. However, in both areas we observe a general decline in water level over time.

In southwestern Bell County, water levels in wells completed the Lower Trinity Aquifer are closer to the surface than they are in wells completed the Middle Trinity. In the northern and eastern portions of the county the water levels are generally deeper due to more production from the Lower Trinity in these areas. Water levels in the Lower Trinity are deepest in the northern portion of the county exceeding 500 feet locally (Figure 7). In eastern Bell County there is an area of locally shallow water levels (less then 200 feet) associated with high-capacity water wells completed to the base of the Hosston.

Figure 5. Middle Trinity Aquifer water level declines from 2006 through 2019.

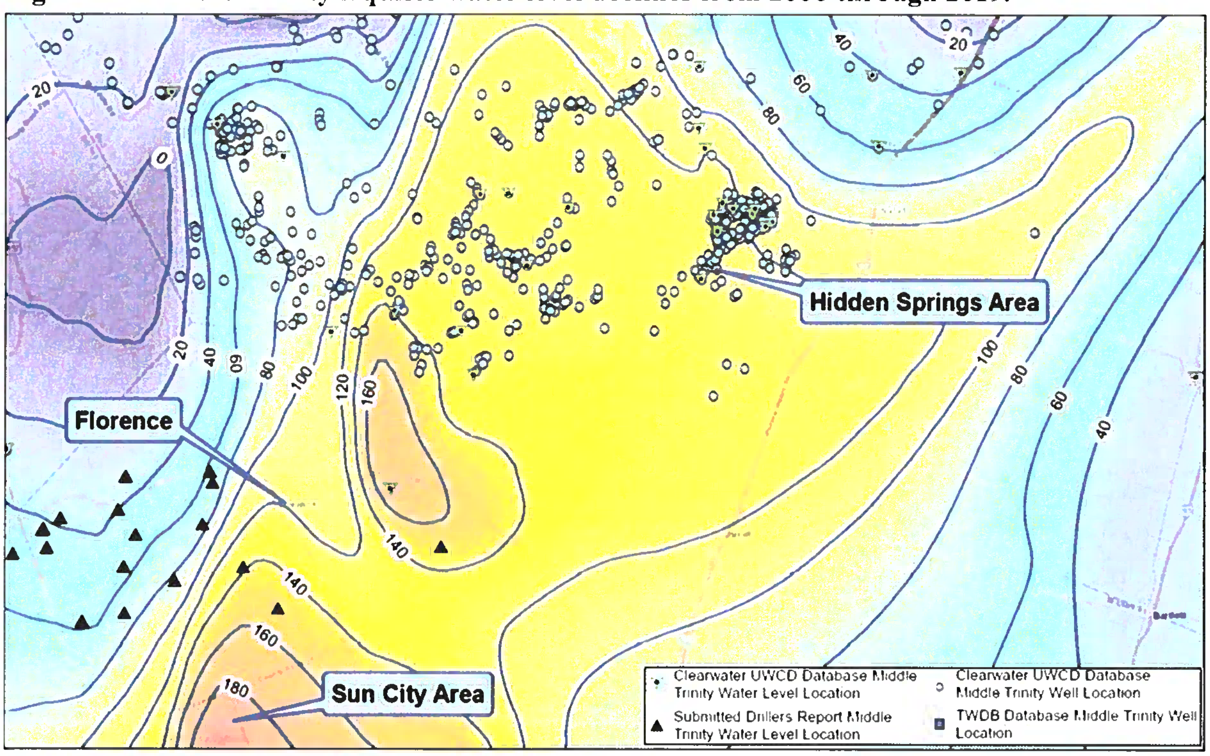


Figure 6. December 2021 Middle Trinity Aquifer measured (hydrographs) and estimated (contour map) depth to water.

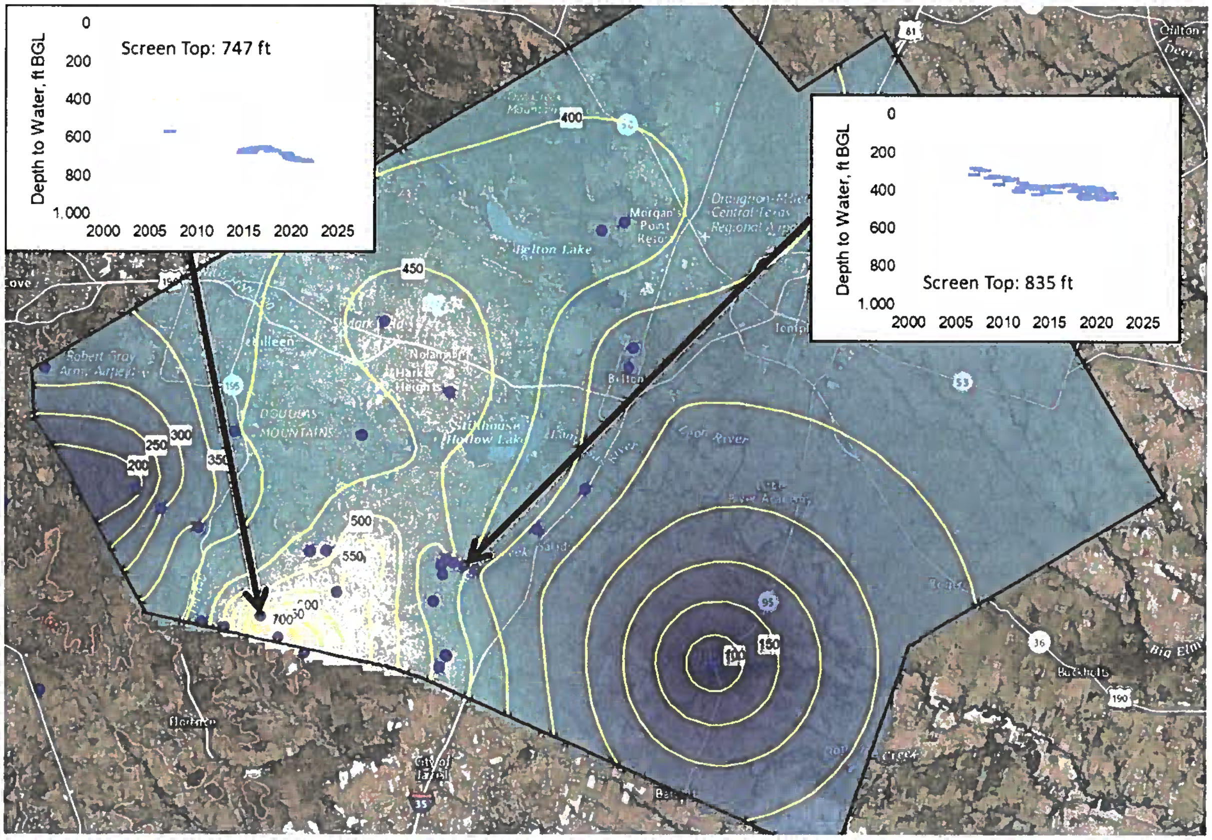
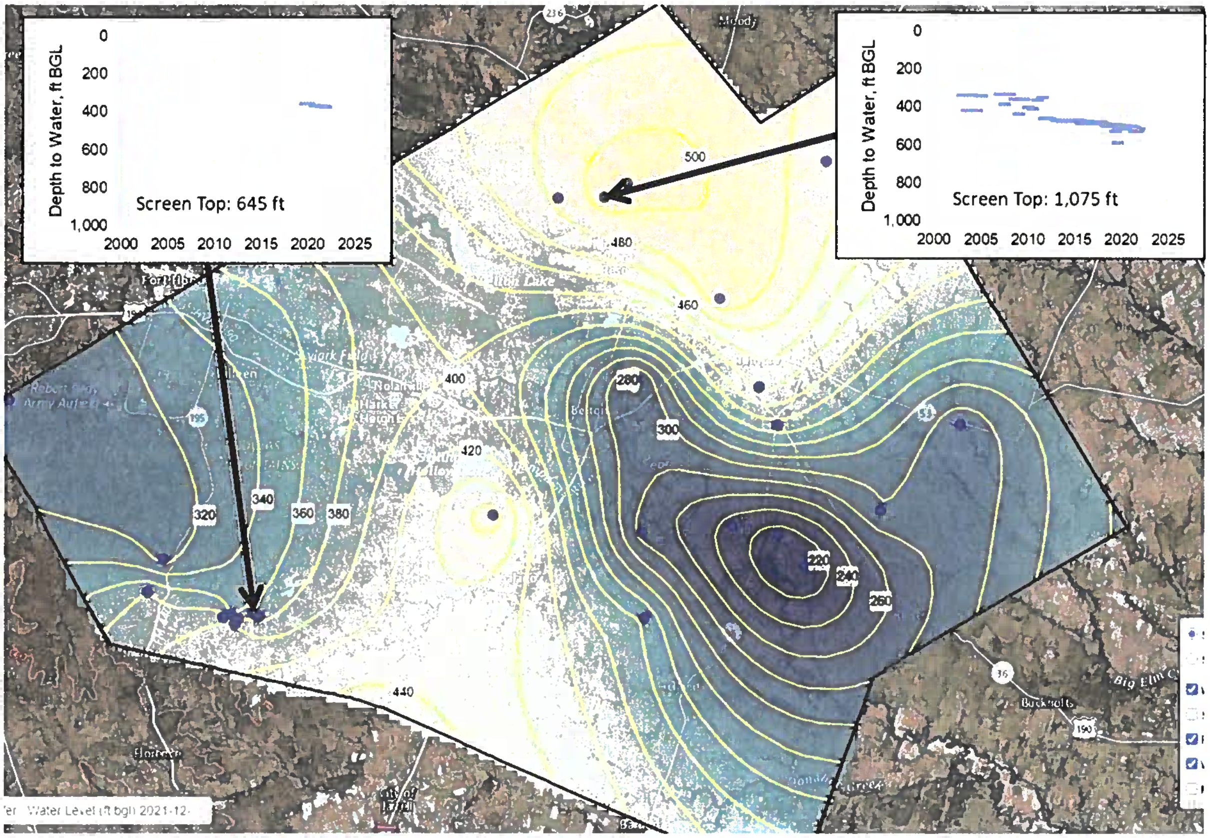


Figure 7. December 2021 Lower Trinity Aquifer measured (hydrographs) and estimated (contour map) depth to water.



WATER QUALITY

Tucker (2018) discussed variations in water quality within the Middle Trinity Aquifer throughout Bell and McLennan counties. He identified an area of increasing total dissolved solids (TDS) and changing ionic concentrations from south to north across Bell County. These higher TDS concentrations are reflected in the increasing conductivity values as measured in microSiemens per centimeter (μS/cm). Figure 8 illustrates the change in groundwater conductivity and ionic concentrations in the Middle Trinity Aquifer. Figure 9 is an example of the Stiff Diagrams shown on Figure 8 illustrating the ionic constituents symbolized.

The cause of the water quality changes in the Middle Trinity Aquifer is not known. However, it may be related to surface water infiltrating through the subsurface and dissolve soluble minerals in the shallower formations. As the water seeps downward, these minerals are carried into the deeper Middle Trinity Aquifer. Additional research is needed to assess this hypothesis.

Groundwater samples from wells completed in the Lower Trinity Aquifer are mostly in the southwest portions of the county (Figure 10). There are two wells from which collected samples had a TDS concentration of more than 2,000 mg/L. However, most of the samples indicated TDS concentrations of less than 1,500 mg/L with two samples in the deeper portions of aquifer in eastern Bell County have concentrations of less than 1,000 mg/L which is indicative of fresh water.

Figure 8. Groundwater quality in the Middle Trinity Aquifer. Modified from Tucker (2018).

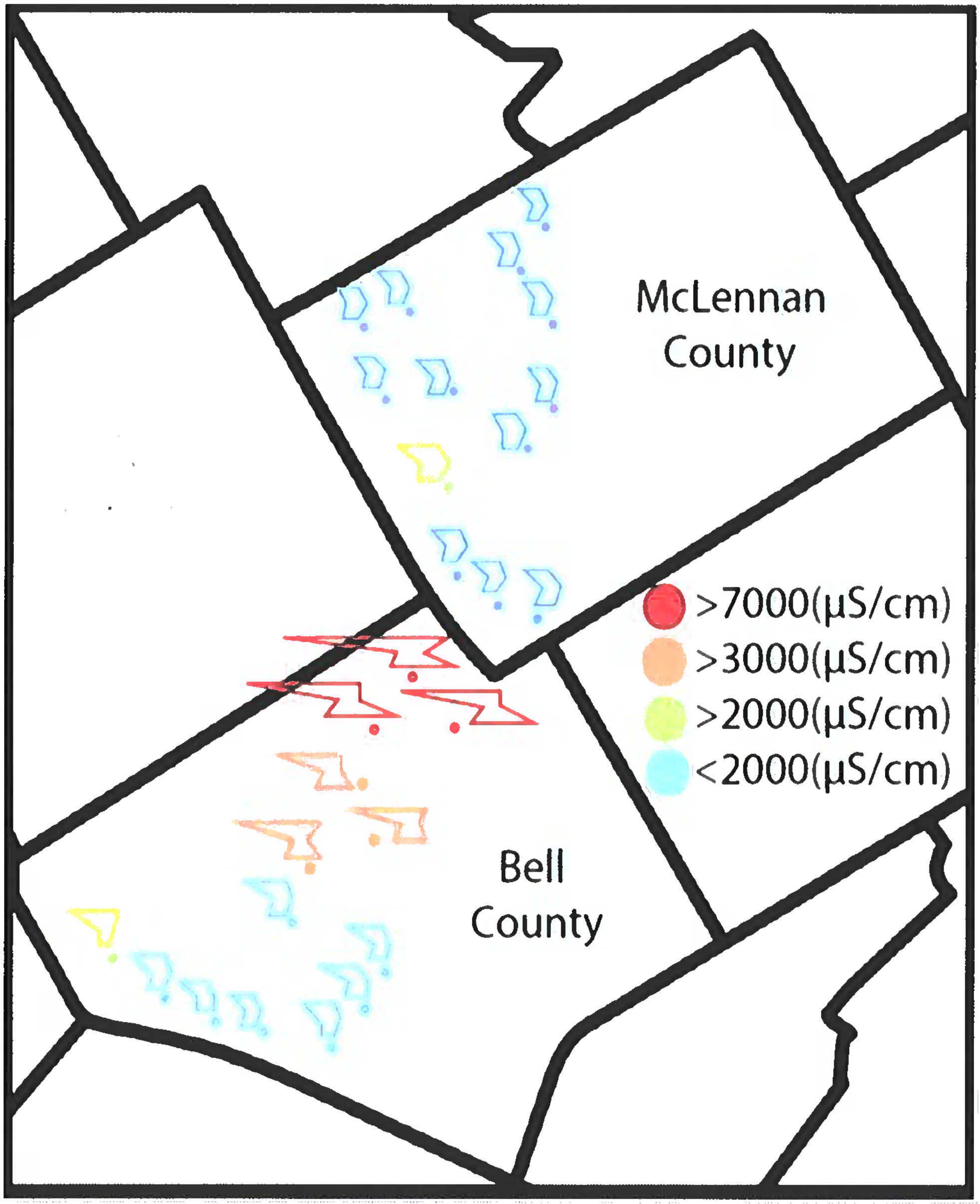


Figure 9. Stiff diagram of the common Middle Trinity water type ($Na^+ + K^+$ and $HCO_3^- + CO_3^-$ dominated).

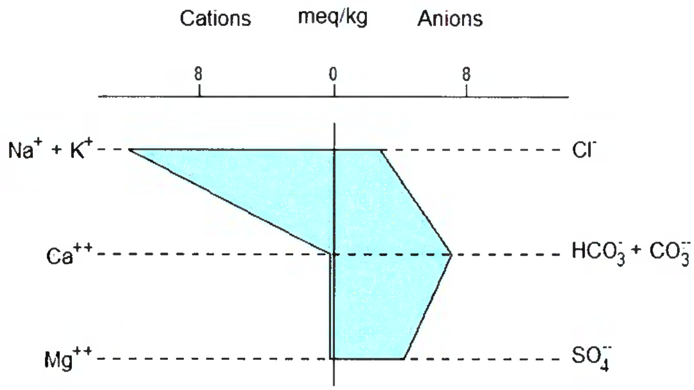
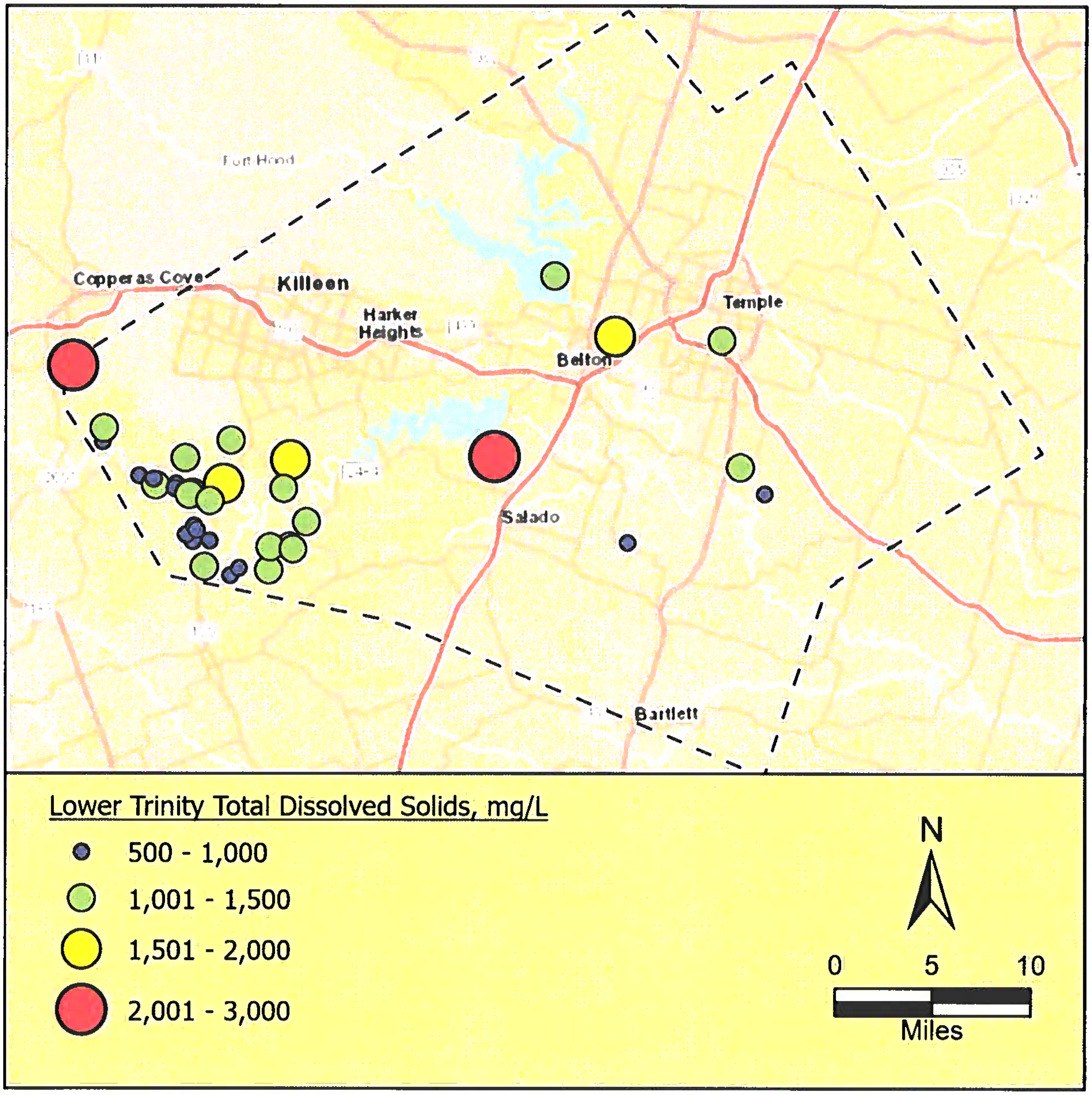


Figure 10. Groundwater total dissolved solids concentration for samples collected from wells completed in the Lower Trinity Aquifer.



PROPOSED MANAGEMENT AREAS

Based on our current understanding of the hydrogeologic characteristics of the Trinity Aquifer, we identified four proposed management areas. We identified these areas based on the hydrogeologic characteristics unique to the area. We then delineated the area using existing roads and the county line to provide recognizable landmarks for each boundary and for consistency with CUWCD Rule 7.1. Figure 11 illustrates the location of each proposed Trinity Aquifer management area.

Figure 11. Proposed Trinity Aquifer management areas.

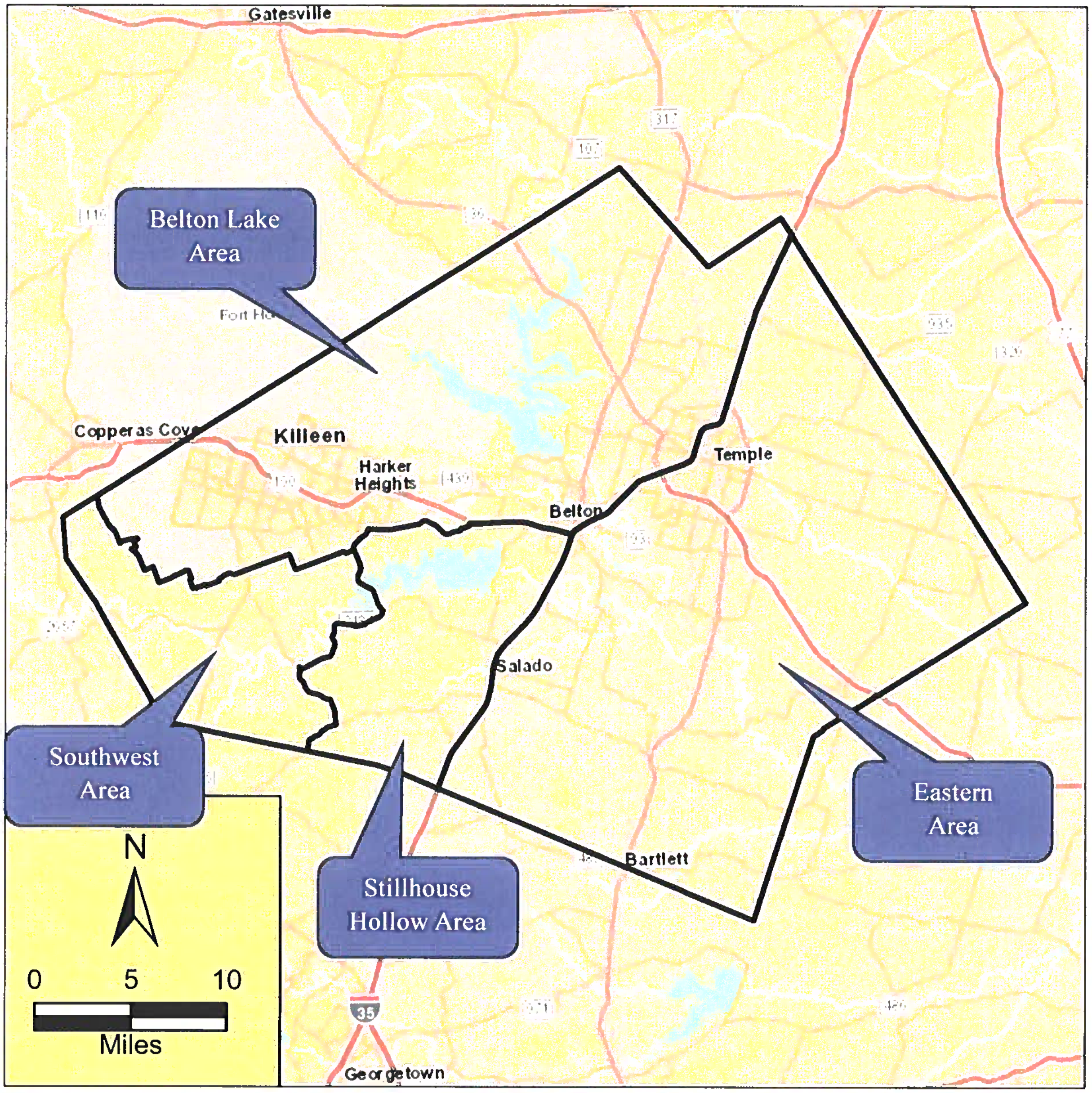


Table 2 and Table 3 summarize the aquifer characteristics for each proposed management area based on our current understanding. Each table provides the range in values for the area followed by the median value in parentheses. The depth to the top of the aquifer and aquifer thickness are based on the structural data developed for CUWCD. The transmissivity values are based on input datasets for the groundwater availability model. The available drawdown values are based on estimated water levels and the proposed definition discussed in the following section of this report.

Table 2. Middle Trinity summary aquifer characteristics per proposed management area.*

Management Area	*Depth to Top (ft)*	*Thickness (ft)*	*Transmissivity (gpd/ft)*	*Available Drawdown (ft)*
Southwest	190–820 (470)	0–170 (40)	370–1,600 (830)	70–210 (140)
Stillhouse Hollow	490–1,080 (800)	20–110 (50)	180–1,670 (940)	110–730 (330)
Belton Lake	400–1,580 (770)	10–280 (40)	300–3,040 (1,610)	70–1,110 (300)
Eastern	900–2,520 (1,960)	20–300 (80)	20–1,500 (140)	570–2,480 (1,840)

*Values shown as: minimum–maximum (median)

Table 3. Lower Trinity summary aquifer characteristics per proposed management area.*

Management Area	*Depth to Top (ft)*	*Thickness (ft)*	*Transmissivity (gpd/ft)*	*Available Drawdown (ft)*
Southwest	190–1,060 (570)	40–150 (90)	3,160–17,430 (6,660)	180–590 (250)
Stillhouse Hollow	680–1,410 (1,070)	40–290 (100)	3,020–23,320 (10,960)	350–1,040 (640)
Belton Lake	450–1,840 (920)	0–190 (60)	1,880–12,780 (5,750)	190–1,320 (450)
Eastern	1,080–3,050 (2,230)	40–540 (260)	1,520–247,470 (32,330)	830–2,850 (1,980)

*Values shown as: minimum–maximum (median)

The Southwest Area generally has the lowest amount of available groundwater for users. The transmissivity values in the aquifers are low and there have been large water level declines over the last several years. The stratigraphy and structure in the area are not conducive to rapidly transmitting groundwater in the subsurface to wells for production. Numerous faults and changing lithology inhibit the flow of groundwater. The range and median depth to the top of the aquifer are the lowest of the four areas. While the transmissivity range is similar to the other proposed areas, the available drawdown is lower which limits the long-term groundwater availability.

For the Lower Trinity in the Southwest Area, the transmissivity values shown in Table 3 are likely too high. Recent aquifer tests indicate the lower range of the transmissivity values in the area should be lower with recent aquifer tests indicating a transmissivity value of less than 100 gpd/ft. While these new data are not yet incorporated into the model datasets, they are applied to our understanding of the local hydrogeologic conditions.

In the Stillhouse Hollow Area, water levels have declined by more than 100 feet in the Middle Trinity Aquifer since 2006. However, due to the dip of the stratigraphic units there is more water above the top of the aquifer than there is in the Southwest Zone. As shown in Table 2, there is more than 700 feet of available drawdown in some areas with a median value of more than 300 feet. While water levels will continue to decline and reduce the available drawdown, the stress on the aquifer is not as significant as in the Southwest Zone due to less development and the availability of groundwater from the shallower Edwards Aquifer in some parts of the area.

The Lower Trinity Aquifer in the Stillhouse Hollow Area is not well understood at this time. There are few wells in this deeper zone of the aquifer. However, indication of the aquifer conditions at the Doc Curb Well near the Stillhouse Hollow Lake dam indicate the aquifer may not be as transmissive as Table 3 suggests. Also, the quality of the water from this non-exempt well does not meet potable water standards.

For the Belton Lake Area, there are some observed changes in the water quality in the Middle Trinity Aquifer compared to the areas to the south. The salinity of the groundwater generally increases from south to north within the aquifer. However, the water quality in the Lower Trinity remains fresh and is used by public water suppliers such as Moffat Water Supply Corporation and the City of Troy.

The Eastern Area is primarily for the Lower Trinity Aquifer. The area east of Interstate 35 has fewer users of the aquifer due to the depth of the formations and associated cost for completing a well. As suggested by the median transmissivity value shown in Table 3, the Lower Trinity Aquifer in the area generally is highly productive with transmissivity values several times greater than in areas to the west and well yields may exceed 1,000 gallons per minute. Faulting may limit the flow of groundwater from the west to the east, but the high transmissivity and height of water above the top of the aquifer allow for a large amount of groundwater availability.

PROPOSED RULE MODIFICATIONS

With the unique hydrogeologic conditions associated with each Trinity Aquifer proposed management area, the groundwater resources in these areas may be managed differently. The variations in resource management may be addressed through different rules for each zone. The following provides proposed rule changes associated with each management zone.

Proposed Management Area Rule Changes

CUWCD Rule 7.2 addresses adjusting groundwater withdrawals in a management area based on an assessment of availability. Considerations of availability in this Rule focus on the amount of recharge available for withdrawal from each aquifer in the management area. Based on the determination of the amount of recharge available for production from wells, permitted pumping may be adjusted to equal the amount of recharge available. The term "recharge" in the Rule suggests the total amount of inflows to the management area rather than just the amount of precipitation that infiltrates into the aquifer.

While we have not developed the groundwater availability values per CUWCD Rule 7.2, we have prepared proposed well spacing rules following the current framework of CUWCD Rule 9.5.2. The revised spacing requirements are designed to minimize interference drawdown as much as practicable. As the focus is on minimizing the interference drawdown between wells, we focused on the spacing from existing wells completed in the same aquifer with spacing based on column pipe size. While we propose revised spacing requirements below, we also recommend that the rules allow for an exemption when physical conditions may not allow the landowner to meet the spacing requirements.

Middle Trinity Aquifer

For the Middle Trinity Aquifer, we would not expect a well to be completed with a column pipe of more four inches in diameter (Keester, 2020). As such, based on the hydrogeologic characteristics of the Middle Trinity Aquifer, we recommend the rules prohibit completion of well in the Middle Trinity Aquifer with a column pipe of more four inches in diameter. In lieu of a prohibition, the minimum spacing should be at least 5,280 feet from an existing well completed in the Middle Trinity Aquifer if the proposed well will have a pipe of more four inches in diameter. For smaller diameter column pipe diameters, Table 4 provides the recommended spacing between a new well completed in the Middle Trinity Aquifer and an existing well completed in the same aquifer.

Table 4. Middle Trinity Aquifer proposed minimum spacing for a new well from existing wells completed in the same aquifer.

Management Area	***District Column Pipe Diameter Range (in)****			
	1¼ (≤18 gpm)	***1½ (≤35 gpm)***	***2 (≤60 gpm)***	***>2 to 4 (≤225 gpm)***
Southwest	150 feet	660 feet (1/8 mile)	Not Allowed	Not Allowed
Stillhouse Hollow			1,320 feet (1/4 mile)	Not Allowed
Belton Lake				Not Allowed
Eastern				5,280 feet (1 mile)

*rate (gpm) associated with column pipe is for reference only

In addition to the spacing requirement, for a new Middle Trinity well in the Belton Lake area we recommend requiring water quality analysis of the produced groundwater once the well is completed. We also recommend requiring the driller to obtain a geophysical log of the open borehole prior to well completion. These items will aid in assessing the cause of the poorer water quality in the northern part of Bell County in the aquifer. As data are collected, the District may determine that new wells completed in the Middle Trinity Aquifer for domestic use in the Belton Lake should be prohibited to protect human health.

For the Stillhouse Hollow Area, all Middle Trinity wells should be completed with a measuring tube to allow for continued monitoring of water level declines. As development continues in the area, production may need to be limited to extend the duration of groundwater availability. For permitted wells in the Middle Trinity Aquifer in the Stillhouse Hollow Area, we recommend the applicant consider the duration of groundwater availability taking into consideration the current trend in water level decline, anticipated drawdown associated with the new pumping, and the minimum pumping water level to obtain the proposed pumping.

Lower Trinity Aquifer

Unlike the Middle Trinity Aquifer, there are areas where production from the Lower Trinity Aquifer may require a column pipe of more than 10 inches in diameter. Generally, the current spacing requirements are sufficient for proposed wells with a column pipe diameter of 6 inches or less (Keester, 2020). However, we recommend increasing the spacing requirement for consistency with the Middle Trinity and preservation of groundwater availability. Recent pumping tests suggest wells with a proposed column pipe of more than two inches in diameter are not feasible in the Southwest Area. Table 5, for column pipe sizes up to four (4) inches, and Table 6, for column pipe sizes greater than four (4) inches, provides the recommended spacing between a new well completed in the Lower Trinity Aquifer and an existing well completed in the same aquifer based on the local hydrogeologic conditions.

Table 5. Lower Trinity Aquifer proposed minimum spacing for a new well with a column pipe up to four (4) inches from existing wells completed in the same aquifer.

<table>
<tr><th rowspan="2">Management Area</th><th colspan="4">District Column Pipe Diameter Range (in)*</th></tr>
<tr><th>1¼ (≤18 gpm)</th><th>1½ (≤35 gpm)</th><th>2 (≤60 gpm)</th><th>>2 to 4 (≤225 gpm)</th></tr>
<tr><td>Southwest</td><td rowspan="4">150 feet</td><td>660 feet (1/8 mile)</td><td colspan="2">Not Allowed</td></tr>
<tr><td>Stillhouse Hollow</td><td rowspan="3">330 feet (1/16 mile)</td><td rowspan="3">660 feet (1/8 mile)</td><td rowspan="2">1,320 feet (1/4 mile)</td></tr>
<tr><td>Belton Lake</td></tr>
<tr><td>Eastern</td><td>660 feet (1/8 mile)</td></tr>
</table>

*rate (gpm) associated with column pipe is for reference only

Table 6. Lower Trinity Aquifer proposed minimum spacing for a new well with a column pipe greater than four (4) inches from existing wells completed in the same aquifer.

<table>
<tr><th rowspan="2">Management Area</th><th colspan="3">District Column Pipe Diameter Range (in)*</th></tr>
<tr><th>>4 to 6
(≤450 gpm)</th><th>>6 to 8
(≤800 gpm)</th><th>>8
(>800 gpm)</th></tr>
<tr><td>Southwest</td><td colspan="3">Not Allowed</td></tr>
<tr><td>Stillhouse Hollow</td><td rowspan="2">2,640 feet
(1/2 mile)</td><td rowspan="2">5,280 feet
(1 mile)</td><td rowspan="3">5,280 feet
(1 mile)</td></tr>
<tr><td>Belton Lake</td></tr>
<tr><td>Eastern</td><td>1,320 feet
(1/4 mile)</td><td>2,640 feet
(1/4 mile)</td></tr>
</table>

*rate (gpm) associated with column pipe is for reference only

For the Stillhouse Hollow Area, we recommend the driller be required to obtain a geophysical log of the well, preferably with the open borehole though local subsurface conditions may require the well be obtained through the cased well. We also recommend obtaining a water quality sample once the well is completed to assess changes in water quality in the aquifer.

Hydrogeologic Report

CUWCD Rule 6.9.2(e) requires the submission of a hydrogeologic report in support of an operating permit application for use of more than 37 acre-feet per year. Subsequent District Rule 6.9.2(f) lists four requirements of the hydrogeologic report which are summarized as follows:

1. Pumping test results (which can be deferred under certain circumstances)
2. Identify impacts to nearby wells
3. Describe local geology and aquifer
4. Be completed in compliance with the hydrogeologic report guidelines

The current hydrogeologic report guidelines were last revised on March 24, 2009. Since the most recent revision, CUWCD has gained additional information and understanding regarding the aquifers within Bell County. In addition, the District has developed several tools to assist with evaluating the aquifer conditions at the location where pumping associated with a proposed operating permit would occur. To take advantage of the data and analysis tools developed since the last revision of the guidelines, we recommend the District consider updating the hydrogeologic report guidelines.

Hydrogeologic Report Related Rules Revisions

Before considering revisions to the hydrogeologic report guidelines, we must first consider potential revisions to the District's Rules. First, we recommend the District add a definition for a "Hydrogeologic Report" to clarify exactly what the phrase means within the Rules. A possible definition to include is:

> "Hydrogeologic Report" means a report prepared by a professional engineer or professional geoscientist licensed in the State of Texas for the purpose of improving the best available science related to the groundwater resources managed by Clearwater Underground Water Conservation District.

The District Rules currently define "best available science" as "conclusions that are logically and reasonably derived using statistical or quantitative data, techniques, analyses, and studies that are publicly available to reviewing scientists and can be employed to address a specific scientific question." By defining that the purpose of a hydrogeologic report is to improve the best available science, the report is not simply a technical hurdle for obtaining an operating permit. Rather, it is a joint effort by the applicant and the District to improve understanding of the groundwater resources and to answer the specific questions the Board may have related to the proposed production.

When acting on a permit application, the Board must consider several items including whether "the proposed use of water does or does not unreasonably affect existing groundwater and surface water resources or existing permit holders" (Rule 6.10.24(c)). It is this specific consideration that a hydrogeologic report can help to address. However, currently the Board can only consider this issue qualitatively because an "unreasonable affect" is not defined in the Rules. To quantitatively address this consideration, a possible definition to include in the District Rules or a possible addition to current District Rule 6.10.24(c) is:

To "unreasonably affect" means:

- To cause or likely cause the District to exceed an adopted Desired Future Condition;
- To cause or likely cause a reduction in water level that prevents use of the resource by existing users;
- To cause or likely cause more than one (1) percent reduction in available drawdown in wells completed in the same aquifer that are located beyond the spacing requirement after one (1) year of operation;
- To cause or likely cause degradation of water quality that makes the resource unsuitable for use by existing users; or,
- To cause or likely cause land surface subsidence that damages existing infrastructure due to land deformation or flooding resulting from land deformation, or prevents use of the land by existing users.

The third point in the above list will require the addition of a definition for "available drawdown" in the District Rules. To define "available drawdown" we recommend the District rely on its geologic model and the water level analysis tools. The geologic model provides the top and bottom elevation of the aquifer and the water-level analysis tool provides the estimated elevation of the water level in the aquifer. Using these elevations we are able to calculate the aquifer thickness, the saturated thickness (if unconfined), artesian head (if confined), or the water level above any point in the aquifer.

To account for aquifer conditions ranging from unconfined to confined, a possible definition to include in the District Rules is:

"Available drawdown" is the amount of water-level decline that could potentially occur within an aquifer and is calculated as follows:

- If the water level elevation is 200 feet or more above the top of the aquifer, it is the water level minus the top of the aquifer;
- If the water level elevation is less than the top of the aquifer, it is the water level minus the 30 percent saturated thickness level in the aquifer; and,

- If the water level elevation is less 200 feet above the top of the aquifer and greater than the top of the aquifer, it is the water level minus the 30 percent saturated thickness level in the aquifer with a maximum value of 200 feet.

Figure 12 illustrates how the available drawdown declines with the declining water level. Based on the declining available drawdown, at no more than a one (1) percent reduction in available drawdown the impact on well could be no more than about four (4) feet after one (1) year. In wells with less available drawdown, the allowable impact would be less. Figure 13 illustrates how the pumping rate also declines when the available drawdown and the saturated thickness decline. However, Figure 13 does not consider the effect of increased lift on a pump which would likely cause pumping rates to approach zero faster than Figure 13 suggests.

Figure 12. Illustration of changing available drawdown with changing water levels assuming the top and bottom of the aquifer are at 100 and 0 feet MSL, respectively.

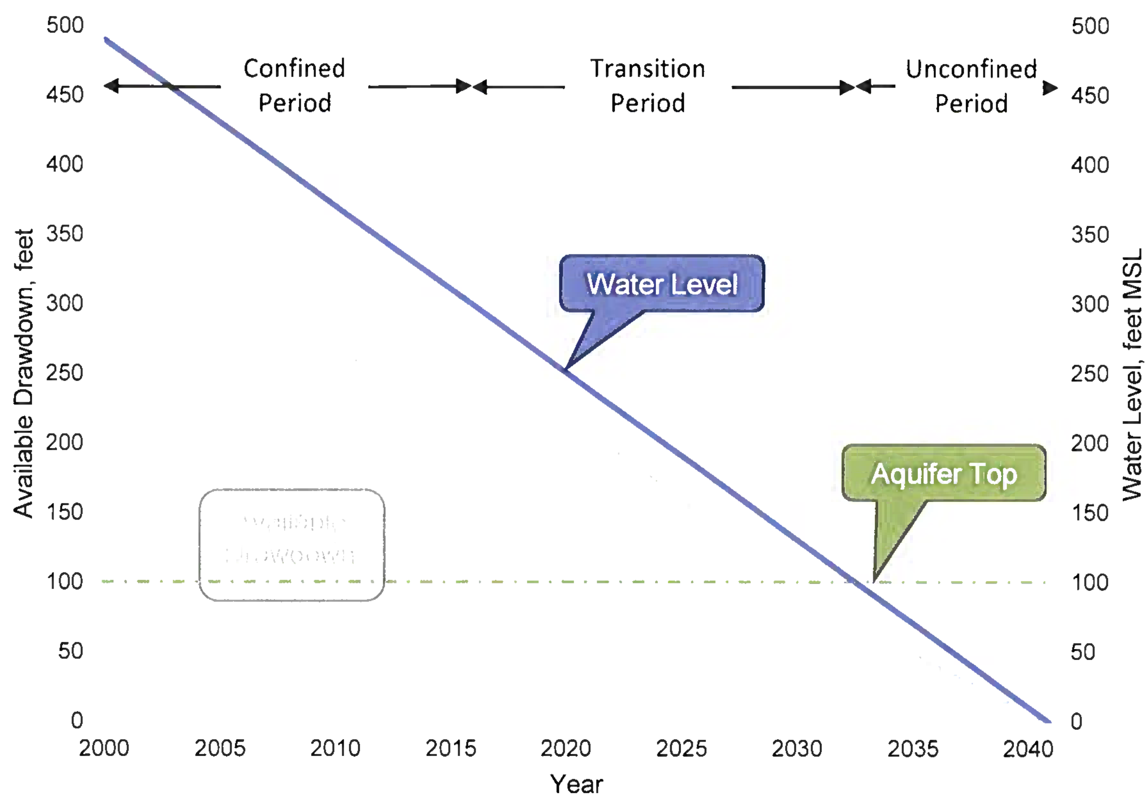
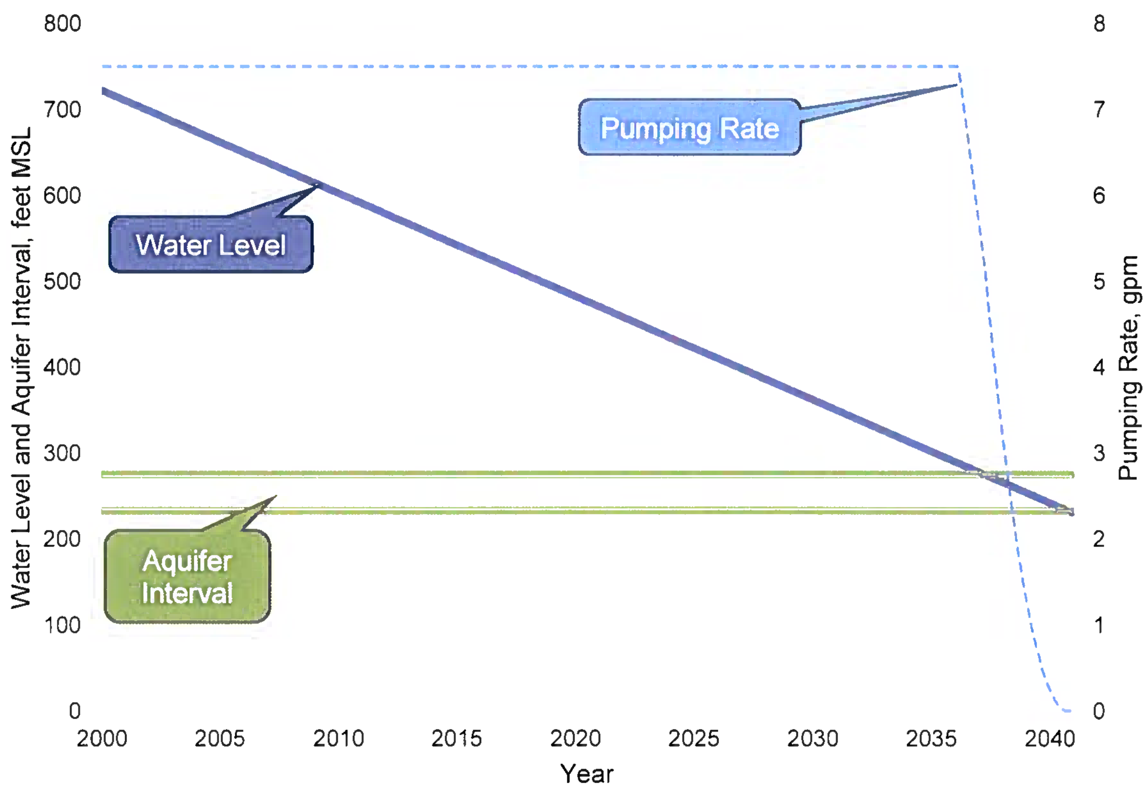


Figure 13. Illustration of changing water levels relative to the aquifer interval. The change in pumping rate reflects the effect of declining available drawdown and the change in aquifer transmissivity with the declining water level.



The variables presented provide a starting point for District consideration. For future permit applications, inclusion of these definitions will help the Board quantifiably consider whether "the proposed use of water does or does not unreasonably affect existing groundwater and surface water resources or existing permit holders." In addition, for the hydrogeologic report to address each of the potential unreasonable effects, the list of hydrogeologic report requirements under current District Rule 6.9.2(f) should be expanded to include: "Describe the results of a water quality analysis for a sample collected from the well for which a permit is being requested."

Hydrogeologic Report Guideline Revisions

We recommend a simplification of the Hydrogeologic Report Guidelines so that they reflect both the District's need for site-specific aquifer data and the District's practical approach to permit application review. As such, for a new well we recommend that in lieu of a hydrogeologic report the District require a well completion report as part of the operating permit application for production greater than annual volume defined by the Board. This well completion report should include:

- A lithology log based on the cuttings collected during drilling;
- Chip trays containing samples of the formation cuttings collected during drilling with depth interval for each sample clearly marked;

- Geophysical log with the well name, location, depth, and drilling fluid properties recorded on the log header
- Well completion diagram identifying (as applicable) the open and cased intervals, casing and screen type and size, filter pack interval, cement interval, pump and motor (model number, pump bowls, horsepower, etc.), pump setting, column pipe type and size, pump head, and other pertinent information related to the well construction
- Pump curve for the final or proposed pump
- Data and analysis from a minimum 24-hour pumping test
- Water quality analysis results

While the report may also include the predicted impacts of the proposed production from the well, District staff or consultants will also perform an analysis of the predicted effects of production using analytical or numerical modeling tools. As such, it may not be necessary for the applicant to perform the impact analysis and the applicant may focus on providing the well and aquifer data to the District.

SUMMARY AND CONCLUSIONS

The hydrogeologic investigations directed by CUWCD over the last several years have verified distinct hydrogeologic conditions in different parts of Bell County. Pumping tests associated with permit applications have also informed the District's understanding of groundwater flow. In addition, ongoing monitoring efforts have shown water level declines in some areas that may soon limit the ability of landowners to produce groundwater.

The conditions identified support the delineation of management areas within Bell County. For effectively managing the groundwater resources of the District, we have delineated these proposed management areas. Within each of these areas, CUWCD may adopt different rules or guidelines for permitting and assessing groundwater availability.

As a first step, we recommend adopting revised spacing requirements to help minimize the interference drawdown on existing wells from a proposed well being completed in the same aquifer. While we recommend revised spacing requirements, we also recommend that the rules allow for an exemption when physical conditions may not allow the landowner to meet the spacing requirements.

Along with the spacing requirement, we recommend CUWCD work with its legal council to develop a definition of what it means to the Board to "Unreasonably Affect" an existing user. Including such a definition in the District Rules would help clarify the District's management of the groundwater resources.

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Workshop #3

Salado Salamander Monitoring Final Report 2020

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Acknowledgements
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Executive Summary

Monitoring of the Salado salamander concluded in January of 2021 finalizing the sixth year of monitoring by the Texas Fish and Wildlife Conservation Office (TXFWCO) at the Salado Downtown Spring Complex (DSC) and at Robertson Springs in Bell County. A total of 14 Salado salamanders were detected this year at Robertson and the DSC. Almost all salamanders were captured at the DSC (n = 11). Within the DSC, Side Spring had the most detections of salamanders over the course of the year (n = 10). Only three detections were documented at Robertson Springs during 2020, due to the lack and loss of discharge from springs on the property in August, and a missed sampling event in Spring due to Covid-19. As of January, Robertson has flow from only a small number of low flowing springs below Ludwigia Spring. All salamanders were captured during active searches.

Monitoring continued at Solana Ranch Spring #1 (SR1), providing a second year of quarterly count data. Monitoring producing a total of 123 detections producing, including 87 individual salamanders (determined through photographic analysis) over the quarterly monitoring period. The majority of salamanders captured at Solana were adults. There was a recapture of an individual salamander caught in September of 2017 and then recaptured again this year in August.

Other monitoring conducted in 2020 included sampling wells within the southern portion of Bell County. This sampling produced no salamanders or aquatic invertebrates. Well sampling in 2021 will include a net similar to a plankton tow net, instead of passive bottle traps. A drift net was deployed at the Gault Archeological Site in September to collect data for future aquifer studies. The population genetics project, in collaboration with Dr. Chris Nice at Texas State University, has been accepted to the journal Conservation Genetics.

Introduction

The Salado salamander (*Eurycea chisholmensis*) was first described as a species in 2000 (Chippendale et al. 2000). Although the salamander had been discovered earlier and was in a collection kept at Baylor University by B.C. Brown, no formal description had been made. In addition, collecting individuals from this population proved to be difficult (Chippendale et al. 2000). Due to the limited knowledge about the species (population density, life history patterns), potential threats (dewatering and urbanization), and limited geographical range, this species was listed as threatened by the U.S. Fish and Wildlife Service (USFWS) on February 21, 2014. The USFWS is in the process of designated critical habitat for this species.

The Salado salamander is highly restricted geographically and is hypothesized to have a very low population within Central Texas (Norris et al. 2012). It has been proposed, that a much more streamlined phylogenetic hypothesis may apply to Central Texas *Eurycea*, (Forstner et al. 2012) and that the additional *Eurycea* within the Central Texas area had not been analyzed in context with congeners, but that is not the case. A peer-reviewed publication by Pyron and Weins (2011) genetically examined all Spelerpines, a subfamily under the family Plethodontidae, which included all *Eurycea* (*E. chisholmensis, E. naufragia, and E. tonkawae*). Pyron and Weins (2011) suggests that the phylogenetic analysis by Chippendale et al. (2004) was appropriate and that indeed these are distinct species. In addition, a recent study, funded through a Section 6 grant (#443022) by Dr. Hillis of the University of Texas, confirms the species designation was indeed scientifically valid (Devitt et al. 2019).

Before monitoring by Texas Fish and Wildlife Conservation Office (TXFWCO), there was no active research or monitoring program in place for this species. The TXFWCO proposes to conduct long term monitoring of the species within its known geographical range. A long-term data set will eventually provide a statistically valid sample size to base future management

Methods

Sampling was conducted quarterly this year at the DSC, Robertson Springs, and SR1 (Figure 1). Timed searches were used at Robertson, while Side and Anderson spring were searched entirely due to the small area of the springs. Solana Ranch Spring #1 was sampled from the spring orifice to a location where the spring run fans and enters the main channel. Areas where the water emerged from under the gravel and cobble pile were searched. Another smaller spring adjacent to the main spring was also searched each visit. All springs were actively searched by turning over rocks and debris. Captured salamanders were placed into mesh bags and kept in the spring run for processing. During timed searches all mesohabitats were searched for salamanders.

Drift nets with 250 μm mesh were used for passive sampling used at a number of locations at Robertson and SR1. Nets were left in place for seven days as part of the passive sampling for the monitoring regime. Aquatic invertebrates captured during drift netting were taken back to the lab, sorted, identified, and enumerated. Most taxa were photographed using a dissecting scope with certain taxa sent to experts for identification.

If a salamander was captured during any survey the primary substrate and vegetation were documented. If a salamander was captured in the drift net placed over an orifice, a designation of cave conduit was applied for substrate. All captured salamanders had two sets of photographs taken. First, photographs alongside a ruler were taken to determine total length of the salamander (mm) using the program ImageJ (Schneider et al. 2012). Following that, a close-up photograph of the head was taken to be used with the program WildID (Bolger et al. 2012) to determine if any individuals were recaptures (Bendik et al. 2013).

Due to low surface densities encountered at the sites over the years, the data have been collapsed and examined cumulatively. As in previous reports the overall dataset has been updated to include the 2020 collections. Data was grouped into seasonal blocks for a size distribution analysis. The relative abundance of the salamanders was calculated for each season based upon size classes. Size classes are from 0-19, 20-29, 30-39, 40-49, 50-59, 60-69 mm. Associated substrate and vegetation percentages were updated to reflect the new collections.

The salamanders from Solana Ranch Spring #1 were examined by creating a probability from the 2019 and 2020 capture history of each salamander. These years were selected as there are quarterly data available for each. This data is from six sampling events, including 64 individuals in 2019, and five sampling events with 80 individuals in 2020. Each time a salamander was captured and identified, it received a 1, therefore the capture history of a salamander for 2019 may resemble 101001 (six number places for six events, 0 = not detected, 1 = detected). For this example the probability is just the sum of the captures divided by the number of events, therefore, 0.5. By examining average probabilities of the capture history for the salamanders, there might be some insight into the effort of sampling between years.

Other sampling that occurred this year and over the history of the monitoring program are presented in the results. These data include sampling at the Gault Archeological Site (Gault Site) and from wells in the southern portion of Bell County. The Gault Site is located within the know range of the Salado salamander. Passive sampling techniques were used at the Gault Site to detect the presence of salamanders and collect aquifer invertebrates using drift nets. Compared to the Gault Site, the wells were sampled used bottle traps to collect samples at 14 sites.

Water level and flow data were collected from the Cemetery Well (Monitor well #5804628) and from the USGS gauge on the Salado Creek (USGS #08104300) from 2014 to 2020. This data was plotted with the total collection of salamanders from each year of sampling since 2015. This analysis was conducted to determine if there is an indicator for the issuance of spring flow at Robertson, and to identify preliminary trends associated with the salamander collections.

Results

Robertson and Downtown Spring Complex

A total of 14 salamanders were detected at Robertson and the DSC (Table 1). Of these 14, three were juveniles (< 25 mm total length; Bowles et al 2006) and 10 were adults, with one escaping before it could be photographed. Most salamanders were captured from the DSC at Side Spring (n = 10) with one additional specimen from Anderson Spring (n = 1). Robertson Springs produced three salamanders, two at Middle Spring (n = 2), and one at Ludwigia (n =1) (Figure 2). By June of 2020, flow at Robertson Springs complex was only issuing from the lowest downstream orifice at the Ludwigia spring zone. Flows at Robertson had still not returned to the Headwater, Middle, or Ludwigia zones by January 12, 2021. Drift netting captured zero salamanders at Robertson Springs. No orifice were netted at the DSC in 2020.

A total of 171 Salado salamanders have been captured since 2015. Some salamanders do not have associated substrate or vegetation data, leaving 168 salamanders to examine the substrate and vegetation associations. A total of 65 (38%) salamanders have been captured in drift nets, presumably leaving the aquifer. Of the remaining 103 salamanders caught on the surface, 66 (64%) have been caught in gravel as the primary substrate, and 28 (27%) have been caught in cobble as the primary substrate (Table 2). Data from past habitat sampling at Robertson Springs has shown around 50% of the substrate to be silt (Diaz et al. 2016). Salamanders have been captured in many types of vegetation, but 43 (41%) have been shown to associate with watercress (*Nasturtium* sp.), and 38 (36%) have been captured in areas with no vegetation.

From the 171 total individuals detected, 163 were used to examine the temporal shift in size for surface populations at the DSC and Robertson. The updated temporal shift in size of the surface population show a classic size progression from smaller to larger, over the course of the year (Figure 3). In spring, the majority of salamanders captured were in the smallest size class ranging from 10 to 19 mm. The line for spring is minimally expressing a bimodal hump, with a smaller hump in the fifth size class. In summer, the smallest size class is still prevalent, however, the second hump is comparable in the third size class. During fall, the bimodal hump resembles the inverse of the spring line as the 4th size class is the most expressed. The winter line is similar to the fall line except the initial hump of the line is in the first size class other than the second size class as in fall. Overall, the most salamanders have been detected in spring, with the least detected in winter (Figure 4).

There appears to be a trend with juvenile salamanders and their appearance on the surface. While juvenile salamanders have been captured throughout the year, there is some clustering from spring to summer, indicating young of the year being detected on the surface (Figure 5). To test for this we ran a chi-squared test, where we assume that juvenile salamanders should be present equally over the course of the year. This would be the case if there is no breeding season. To estimate the age of the juvenile salamanders, we used growth curves from the San Marcos Aquatic Resource Center that show a salamander under 20 mm is about a month old (unpublished data). Therefore, using these assumptions a chi-squared test was run and a significant difference was detected with season and juvenile salamanders under 20 mm in total length which are hypothesized to be around 30 days old (x-squared = 37; df = 3; p = <0.0001).

Solana Ranch Spring #1

A total of 123 salamanders were captured at SR1 during 2020. After removing recaptures of individual adult salamanders, the capture history shows that 94 individual adult salamanders were detected and photographed during 2020. In 2019, 64 individual adults were detected and photographed. Monitoring data from 2020 identified two recaptured salamanders dating back to September 2017. The average capture probability for detecting an individual at SR1 this year was 0.24 compared to 0.27 from 2019.

Twelve salamanders were considered juveniles (<25 mm). Reviewing the salamanders capture data at SR1, dating back to 2017, the majority of the surface population were adults (85%). The size average, based on the 317 salamanders detected since 2017, is 48.18 mm. The largest Salado salamander (87 mm), captured to date, was captured at SR1 in October 2020. This was the first detection of this "large" individual salamander.

The temporal shifts in size class follow the same trends as the DSC and Robertson data, but the overall population exhibits larger salamanders on the surface year round (Figure 6).

During the fall there have been no documented occurrences of salamanders in the first or second size class.

Cannibalism was documented in 2019 during the mark and recapture work. One individual salamander was caught with three eyes at first glance (Photo 1). Following a closer inspection a juvenile salamander was seen with the head out of the other salamanders mouth. The juvenile salamander appeared incapacitated and was left in place.

Aquifer Invertebrates

Drift net sampling at a number of springs within the Robertson and at Anderson springs has been conducted in order to examine surface recruitment and detect juveniles exiting the aquifer. It has also provided a detailed data set of the karst invertebrates present at each spring opening or complex. Sampling the springs with drift nets has shown large range extensions for a number of aquifer dwelling taxa (Alvear et al. 2020[a]) and provided samples of undescribed species (Alvear et al. 2020[b], Gibson et al. 2021) present within this section of the Northern Edwards Aquifer.

Based on samples collected since 2015, we have a basic understanding of the stygofaunal (aquifer dwelling taxa) community structure at the springs studied in Bell County. Drift net sampling examined cumulatively over a sampling period of over 2,100 days (2015 to June of 2018), collected over 4,500 aquifer dwelling individuals (Table 3). Data shows that the majority of the community is comprised of *Stygobromus* spp. (45%; Amphipoda; three species) and aquifer snails (28%; five species). Two families of snails were the most abundant out of the 32%, the first family Hydrobiidae (*Phreatodrobia conica*; 14%) and then the family Lithoglyphidae (*Phreatocerus taylori*; 9%). The isopod, *Lirceolus* spp. was at 16% and has three different species present in the community (Schwartz et al. 2020). All of these stygofauna are within the size range, during all life stages, to be prey items for salamanders. Two studies suggest that there are increases in other aquifer snails, although a different family, during the summer (Johnson et al. 2019) and spring (Diaz et al. 2020). In addition to the aquifer invertebrates, many terrestrial karst invertebrates have been captured over the monitoring period. Most interesting from the terrestrial group include specimens of *Cicurina* sp, *Speodesmus* sp., and *Lymantes nadineae* (Photo 2). In the 2015 report, *Myrmecodesmus reddelli*, was stated as being present at Robertson Springs. Paul Marek, a millipede expert at Virginia Tech, was sent the specimens and in May of 2019 a determination was made that the *Myrmecodesmus* in question is indeed, M. formicarius, **not** *Myrmecodesmus reddelli*, which would have been a large range extension.

Well Sampling

This year a series of 14 wells were sampled in collaboration with the Texas Water Development Board (TWDB). The wells ranged in depth from 1010 ft to 95 ft and were sampled using bottle traps to examine other areas not accessible by spring orifice for Salado salamanders and aquifer dwelling invertebrates. Traps were deployed on March 3, 2020, with the intent of checking them periodically (once every two weeks). On March 10th traps were checked and no salamanders or aquifer invertebrates were detected. The traps were left in place and then Covid-19 restrictions occurred. Traps remained in the wells until June 6th and June 16th 2020. No salamanders or aquifer invertebrates were detected in the duration of the well work. All wells will be sampled again using active sampling methods with a device similar to a plankton tow net in 2021.

Stream Flow and Well Height Data

This analysis shows the tracking of the Cemetery Well with the capture of salamanders (Figure 7). Although there have been varying levels of effort over the years, if the springs are dry no salamanders will be surfacing. Once the springs on the Robertson property go dry a large percentage of salamanders are removed from the overall potential total at year end. Only when flows return to the springs at the Robertson property do the probabilities of capturing a salamander return. This year, the flows did not return at the end of the year as they have in the past and flows from the productive spring zones at Robertson began to fade out in early June. This graph shows the tracking of the Cemetery Well with the capture of salamanders and the mirroring of the USGS guage (Figure 8).

Gault Archeological Site

No salamanders have been captured at the Gault Site. Drift nets have been used as the primary sampling technique for a total of 183 days to determine the presence of salamanders at this site. The karst aquatic invertebrate community is typical for the area of Bell County, based off of collections made at other spring locations over the last four years (Table 3). Certain spring adapted taxa occur at the Gault Site and include aquifer snails, *Heterelmis* sp. (Riffle beetle), and *Stygobromus* sp. (Amphipoda). One of the Hydrobiidae snails may potentially be a new species (Photo 3). Samples of this specimen have been sent to Dr. Kathryn Perez at the University of

Texas Rio Grande Valley. The other hypothesis is that these groups of snails have been neglected for the past 50 to 100 years by science and it is part of another known species, just showing some variation within the species. Dr. Perez will run genetic tests to determine the outcome.

Population Genetic Study

Collection for the population genetics project during 2018 was productive at most sites. Minimum sampling sizes for genetic material (~ 30 individuals) were achieved at Cowan and Twin springs on the Williamson County Conservation Foundation land. Collections at SR1 were also successful, yielding 29 salamanders. Collections at all historic Salado salamander locations were accomplished in 2018 within ranges of the maximum genetic target of 30 salamanders per site. Two sites that would have been of interest to the population genetics project were not represented in this data set by genetic material due to lack of access (Cobbs Spring) or the inability to capture any animals (Bat Well Cave). A total of 183 genetic samples were collected from seven locations. . The project has been published in the journal Conservation Genetics and is available at https://doi.org/10.1007/s10592-021-01364-z.

Discussion

The collection of salamanders in 2020 was low for a number of reasons. The spring season of quarterly sampling (March 16, 2020) was cancelled due to Covid-19. This sampling period is typically one of the most productive of all the seasons (Figure 8). Flows at Robertson Springs began to decline in May of 2020. By June of 2020, the only producing salamander spring flowing was the lowest spring in the Ludwigia spring zone. By August of 2020, the flows at Robertson had ceased to flow in the upper and mid sections. The lack of flow at Robertson during the spring, summer, and leading into the winter, is responsible for a significant decline in the total amount of salamanders captured in 2020.

The temporal shifts in size class for the Salado salamander appear to echo other research for the northern group of *Eurycea* sp. indicating a season for breeding. This pulse in the northern salamander group seems unique and could be facilitated by the shallowing of the aquifer as the limestone tends to decrease in depth as the aquifer moves north. This type of shallowing of the limestone could cause the influx of recharge to inhabited areas more quickly than in deeper portions of the aquifer.

Other research by Bendik et al. (2017) on the Jollyville Plateau salamander (*E. tonkawae*) and Pierce et al. (2014) on the Georgetown salamander (*E. naufragia*) both showed a peak time for gravidity in December, with Pierce et al. (2014) showing an additional peak in February or March for the Georgetown salamander. However, gravidity has not been observed in the Salado salamander in the number of observations necessary to elucidate any trends. What would be expected is to see a lag time between the gravid females observed by the two other authors and the observation of the salamanders in the first size class. Growth curves in captive San Marcos salamanders show that it takes about 60 days to reach around 15 mm. Therefore, if there was to be a peak in Salado salamander gravidity in December, the juveniles would be on the surface and up to about 15 mm at the earliest in late February. The Salado salamander seasonal dynamics graph shows the largest percentages of juveniles occur during spring, which runs from March to May. In other words, we might hypothesize that there is some peak in gravidity for the Salado salamander sometime in December or January, although undetected.

Habitat associations, given the smaller data set collected for the Salado salamander, compared to the other species to the south, are consistent with their reports of habitat associations taken from a larger sample sizes with more robust surface populations present (Bowles et al. 2006; Diaz et al. 2015). Due to the small surface populations at the monitoring sites, examining the data is statistically challenging, however, thinking about observed versus expected may be one way to look at the overall Salado salamander data set. Observed would be the data set for the Salado salamander (e.g. habitat associations). Expected would be the larger established and published data sets with more years of data collection and then anecdotally examining the congruence of the patterns within the two data sets to provide evidence of those observations collected in the Salado. For example, substrate and diet data collected from 2015 to 2018 mentioned in the results is congruent with what is known and published about other southern salamander species (Bowles et al. 2006; Diaz et al. 2015). This published evidence does provide some further validity to the Salado data despite the smaller sample size of salamanders.

Insights into why the surface densities of these salamanders are historically small (Norris et al. 2012), with estimates by the author that surface populations are around 10 salamanders at the DSC and Robertson Springs sites, could be based on five years of monitoring observations. The hydroperiod of the springs (i.e. the duration of discharge over time) and proximity to larger order streams, (i.e. ecological disturbance) may play a large part of influencing surface densities at historic Salado salamander sites (Robertson Springs and DSC). Salado Creek's hydroperiod includes large pulses of water after large rain events in the watershed. These pulses cause Salado Creek to rise high enough that it floods the spring outlets at the DSC and at Robertson Springs.

The spring flows in the DSC appear to be stable except for Little Bubbly Springs which has been intermittent during the study. However, Robertson Springs has a large fluctuation in hydroperiod and was not flowing in 2015, and resumed discharging at many of the orifices in 2016. In 2017, the discharge began to decline again and ceased to flow in 2018. Flow returned to the springs at the beginning of 2019. In 2020 the flows began to subside in May and by August no salamander producing mapped spring zones were flowing. In addition, Robertson and the DSC springs are at the known northern fringe of *Eurycea* distribution in Texas and the Edwards Aquifer. In comparison, the surface population present at SR1, just south of Salado, over the last three visits has always been detectable and consistent with regards to count data. Solana Ranch Spring #1 has had a consistent hydroperiod, is not near a larger order stream or river, and is south of the known northern locations for these salamanders.

These factors may be a large part of why the surface densities are low at the historic Salado salamander sites. In addition, the small surface recruitment of salamanders seen at Robertson and Anderson springs, based on the drift net data, suggest that the populations at these sites may be slow to recover from natural disturbances like a flood or cessation in flows. Given that surface densities are low but appear to be consistent given the flows over the last five years (2015- 2019), it is likely that a large proportion of the Salado salamander population is below the surface within the aquifer. The ongoing genetics project, mentioned earlier, is likely to provide insights into the subterranean population densities when it is completed. In addition, if there is a catastrophic event that affects the aquifer, a long cessation in flows, or there is a need to simply examine changes in the next ten years based on population density, this genetic analysis can be repeated and genetic bottle neck events or recalculation of site population estimates can be reexamined with more certainty.

The views expressed in this paper are the authors and do not necessarily reflect the view of the U.S. Fish and Wildlife Service or Texas Parks and Wildlife Department.

Table 1. Number of Salado salamanders collected during quarterly monitoring data using active and passive sampling techniques in Bell County, TX. (NS = not sampled)

Season	Robertson	Downtown Spring Complex	Solana Ranch Spring #1
Winter	0	4	37
Spring	NS	NS	26
Summer	3	6	28
Fall	0	1	13

Table 2. Habitat associations of the Salado salamander determined by 168 salamanders collected from 2015 to 2020 at the downtown and Robertson springs.

	#	%
Cave Conduit	65	38.69
Substrate		
Silt	3	2.91
Sand	2	1.94
Gravel	66	64.08
Cobble	28	27.18
Boulder	4	3.88
Vegetation		
***Sagittaria* sp.**	1	0.97
***Nasturtium* sp.**	43	41.75
Filamentous Algae	4	3.88
***Ludwigia* sp.**	3	2.91
***Amblystegium* sp.**	5	4.85
***Hydrocotyle* sp.**	2	1.94
none	38	36.89
Organic Debris	5	4.85
Grass	2	1.94

Table 3. Aquifer invertebrates collected from the Downtown Spring Complex and Robertson Springs. The Lirceolus with an astrix does not designate a new species, but the lack of species determination at the site.

Taxa	Downtown Spring Complex	Robertson	Gault Site	Hidden Spring
Blind Dytiscidae sp. nov.		X		
Caecidotea reddelli	X	X	X	X
Caecidotea bilineata		X		
Lirceolus* sp.	X		X	X
Lirceolus bisetus		X		
Lirceolus hardeni*		X		
Lirceolus pilus		X		
Microcerberidae		X		
Parabogidiella americana	X	X		
Stygobromus bakeri	X	X		
Stygobromus bifurcatus	X	X		X
Stygobromus russelli	X	X		X
***Texanobathynella bowmani* cf**	X	X	X	
Bathynellacea Type II		X		
Phreatoceras taylori	X	X	X	X
Phreatodrobia conica	X	X	X	X
Phreatodrobia micra	X	X		
Phreatodrobia nugax	X	X	X	
Sphalloplana mohria	X	X		X
Schornikovdona bellensis	X	X	X	X
Uchidastygacarus sp.	X	X		

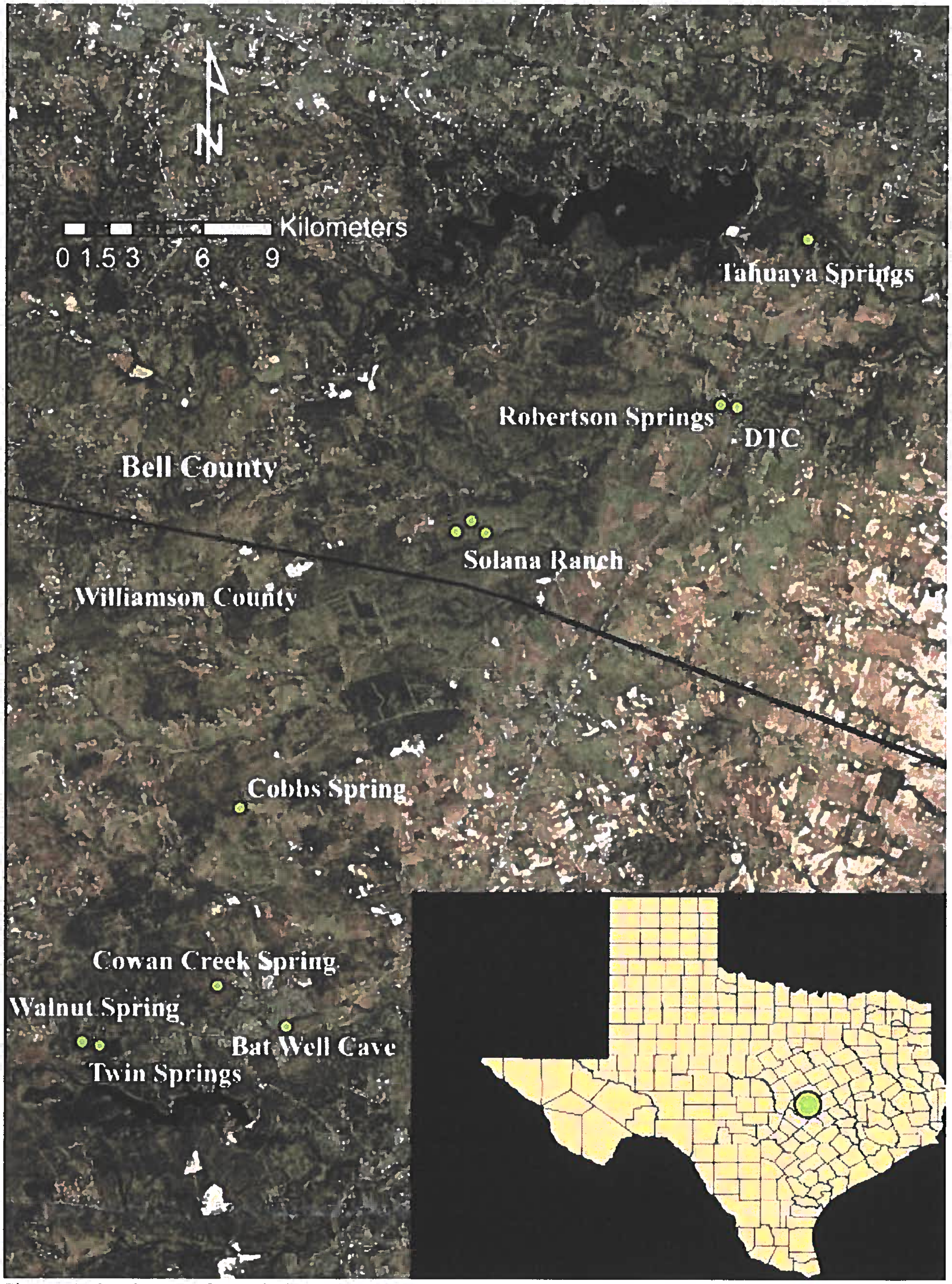

Figure 1. Study area for Salado salamander monitoring conducted from 2015 to 2020.

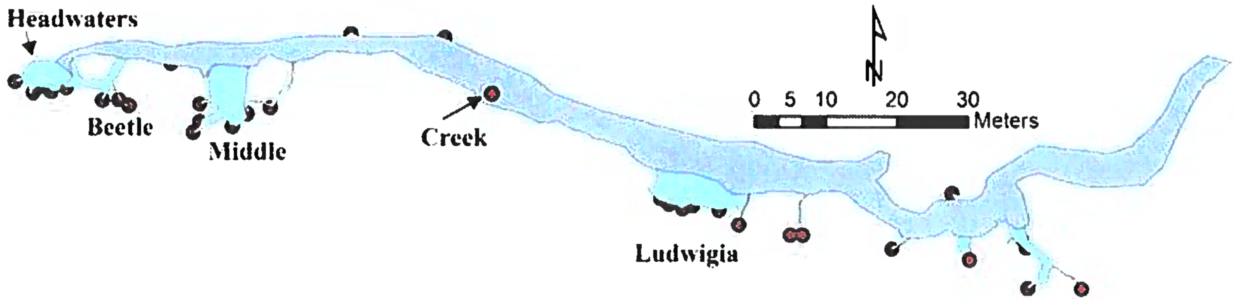

Figure 2. Map of Robertson Springs showing spring zones mapped in 2016 during optimal flow conditions at the site. Light blue zones are spring zones, red dots are orifice, and the blue is the spring run terminating into Salado Creek.

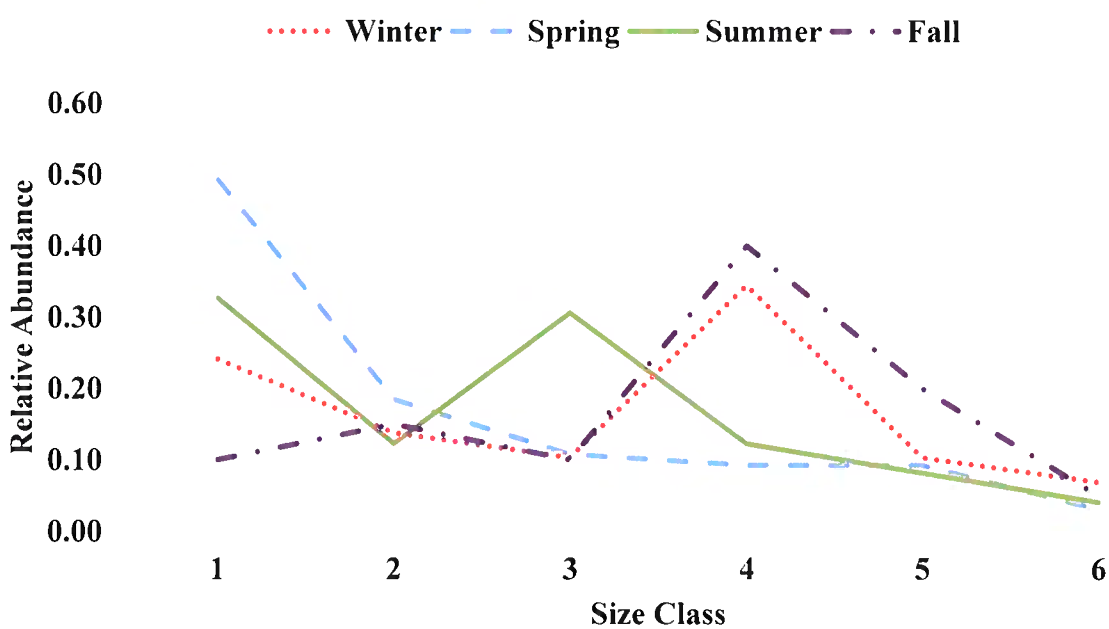

Figure 3. Relative abundance of Salado salamanders reflecting the dominant size class captured from the Downtown Spring Complex and Robertson springs by season 2015 to 2020 for 163 salamanders. Size classes range from 10 -19.99 = 1; 20 -29.99 = 2; etc.

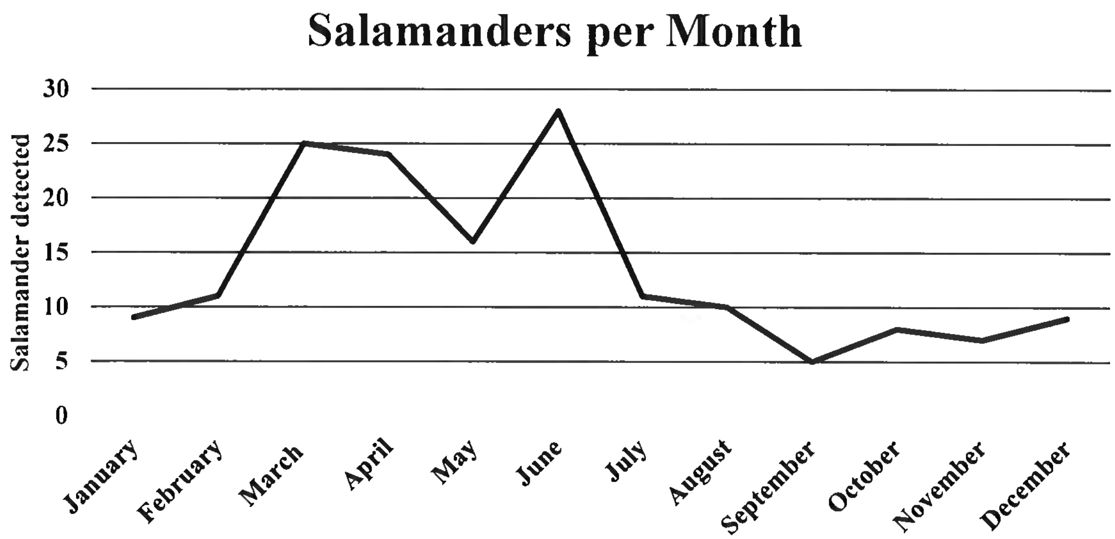

Figure 4. Pooled collections by month of 163 Salado salamanders collected from 2015 to 2020.

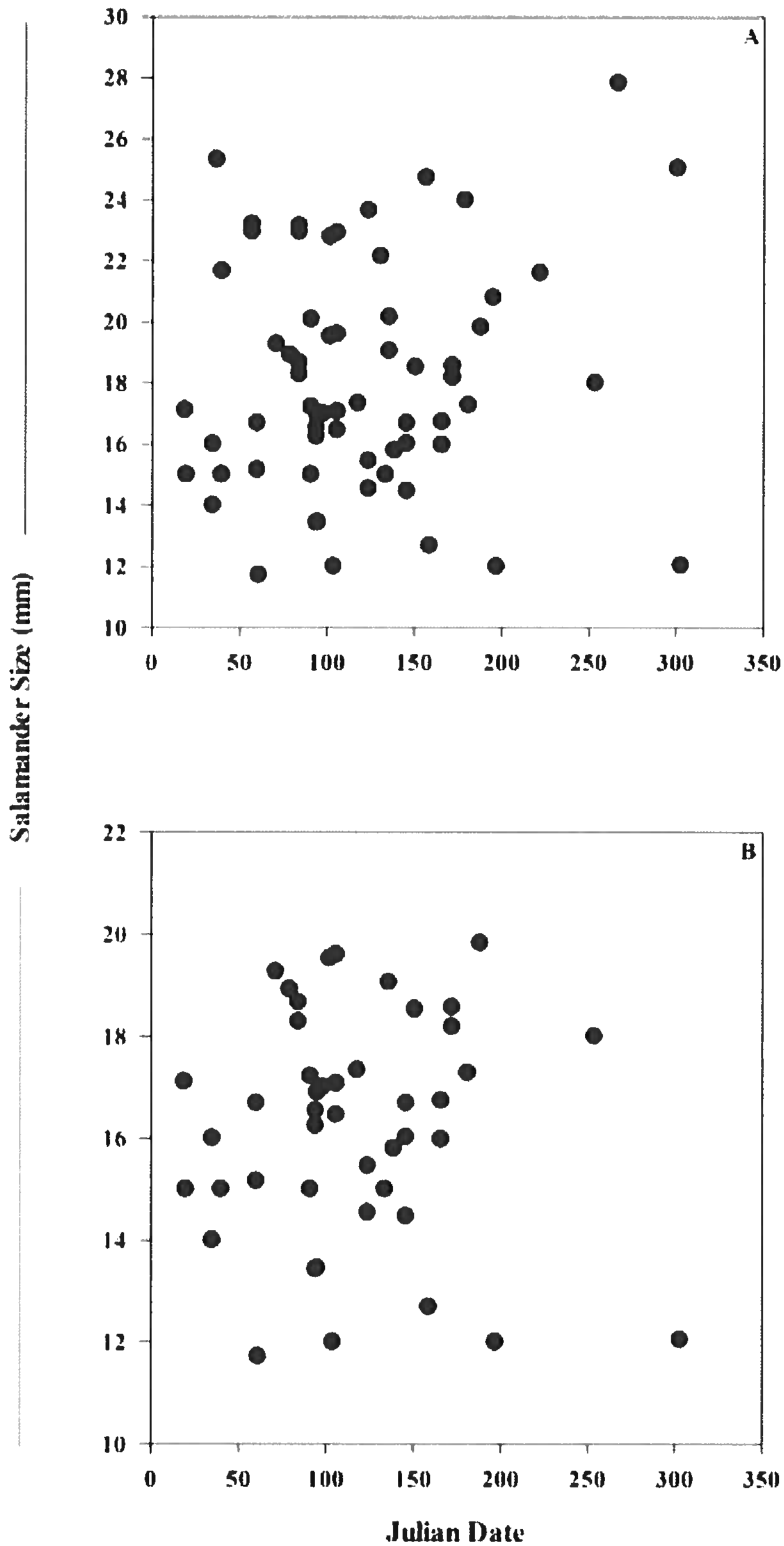

Figure 5. Timing of the capture of juvenile salamanders (< 25 mm) at the Downtown Spring Complex and Robertson Springs. Panel A is all juvenile salamanders and Panel B is only salamanders below 20 mm estimated to be around 55 days old.

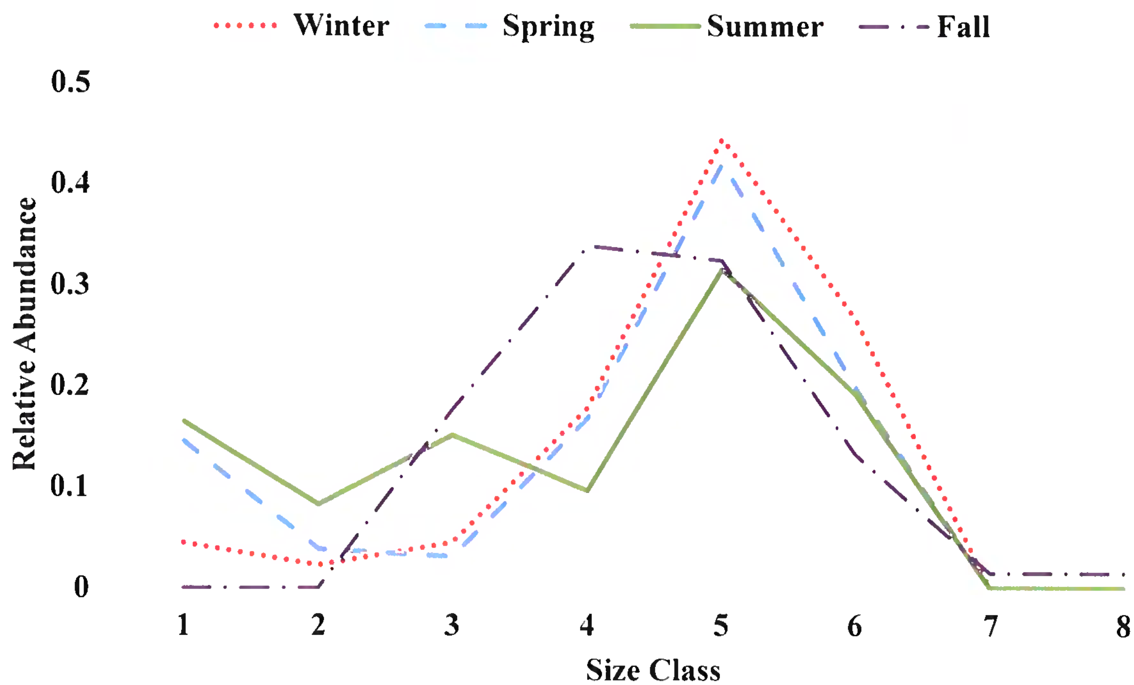

Figure 6. Relative abundance of Salado salamanders reflecting the dominant size class captured from the Solana Ranch Spring #1 by season 2015 to 2020 for 317 salamanders. Size classes range from 10 -19.99 = 1; 20 -29.99 = 2; etc.

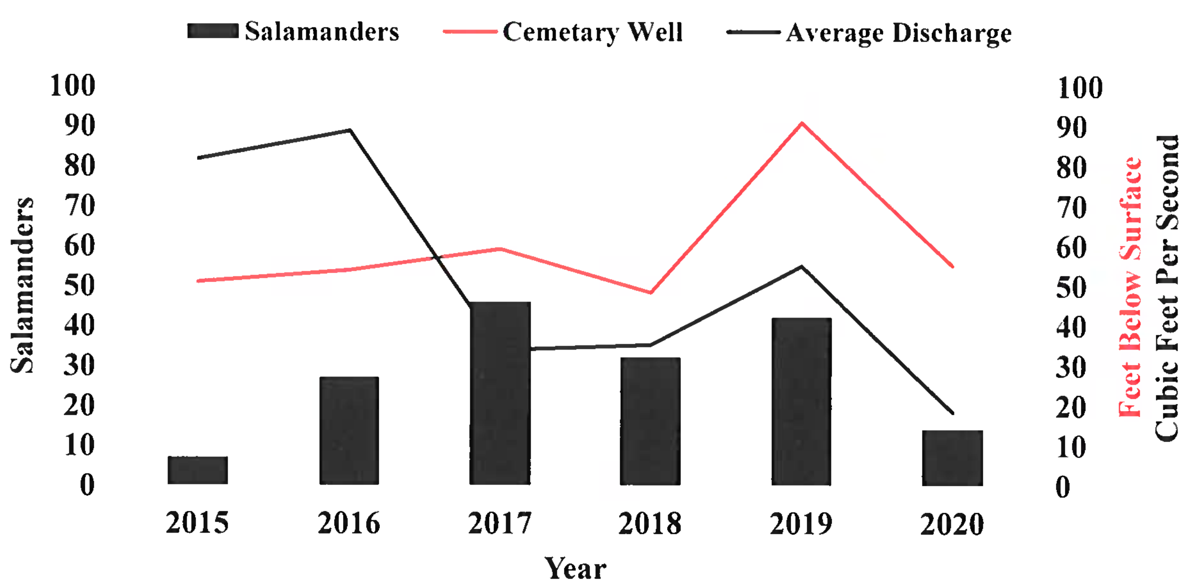

Figure 7. Data collected from the Cemetery Well (Monitor well #5804628) and from the USGS gauge on the Salado Creek (USGS #08104300) plotted with the total collection of salamanders from each year sampled at the Downtown Spring Complex and Robertson springs.

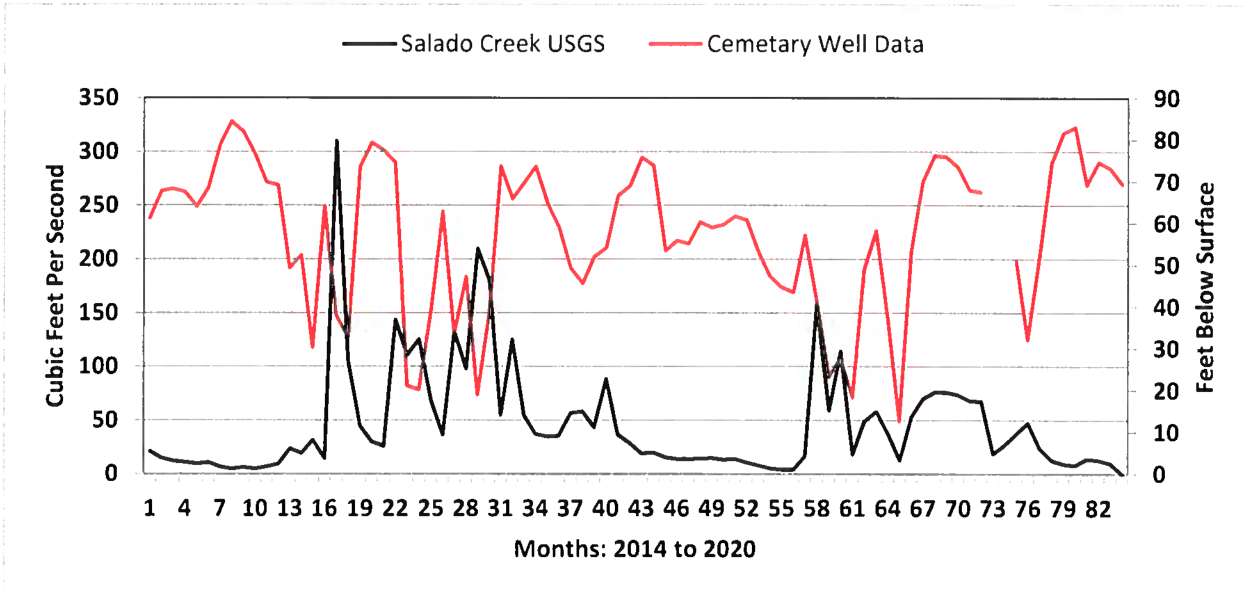

Figure 8. Data from the Cemetery Well (Monitor well #5804628) and from the USGS gauge on the Salado Creek (USGS #08104300) displayed monthly from 2014 to 2020.

Photo 1. Salamander captured during a mark and recapture event showing evidence of cannibalism at Solana Ranch Spring #1.

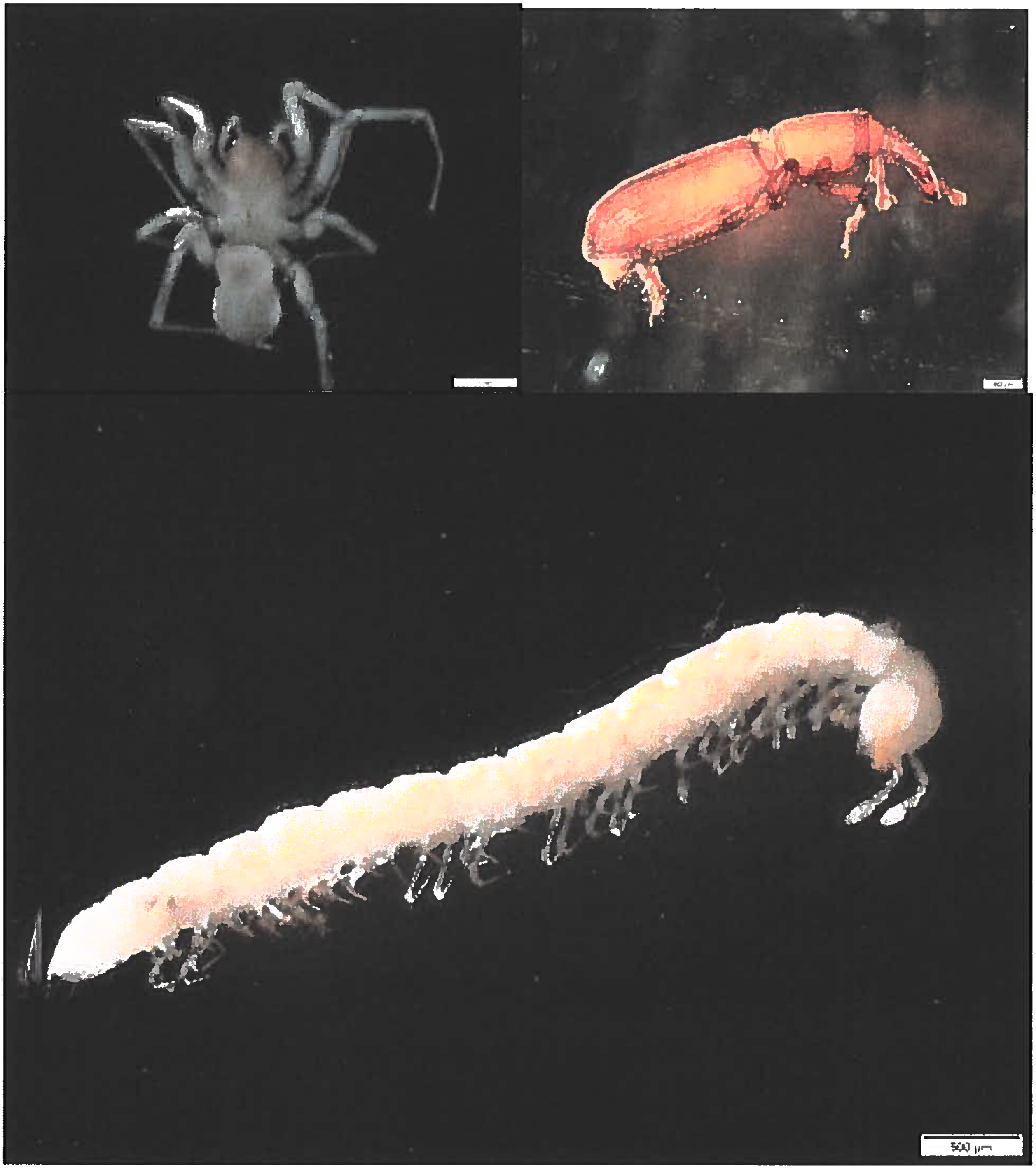

Photo 2. Terrestrial karst invertebrates captured while drift netting springs in Bell County Tx. Top left is a blind spider in the genus *Cicurina*. The top right image is of a blind weevil, *Lymantes nadineae*. The bottom photo is of a blind millipede in the genus *Speodesmus*.

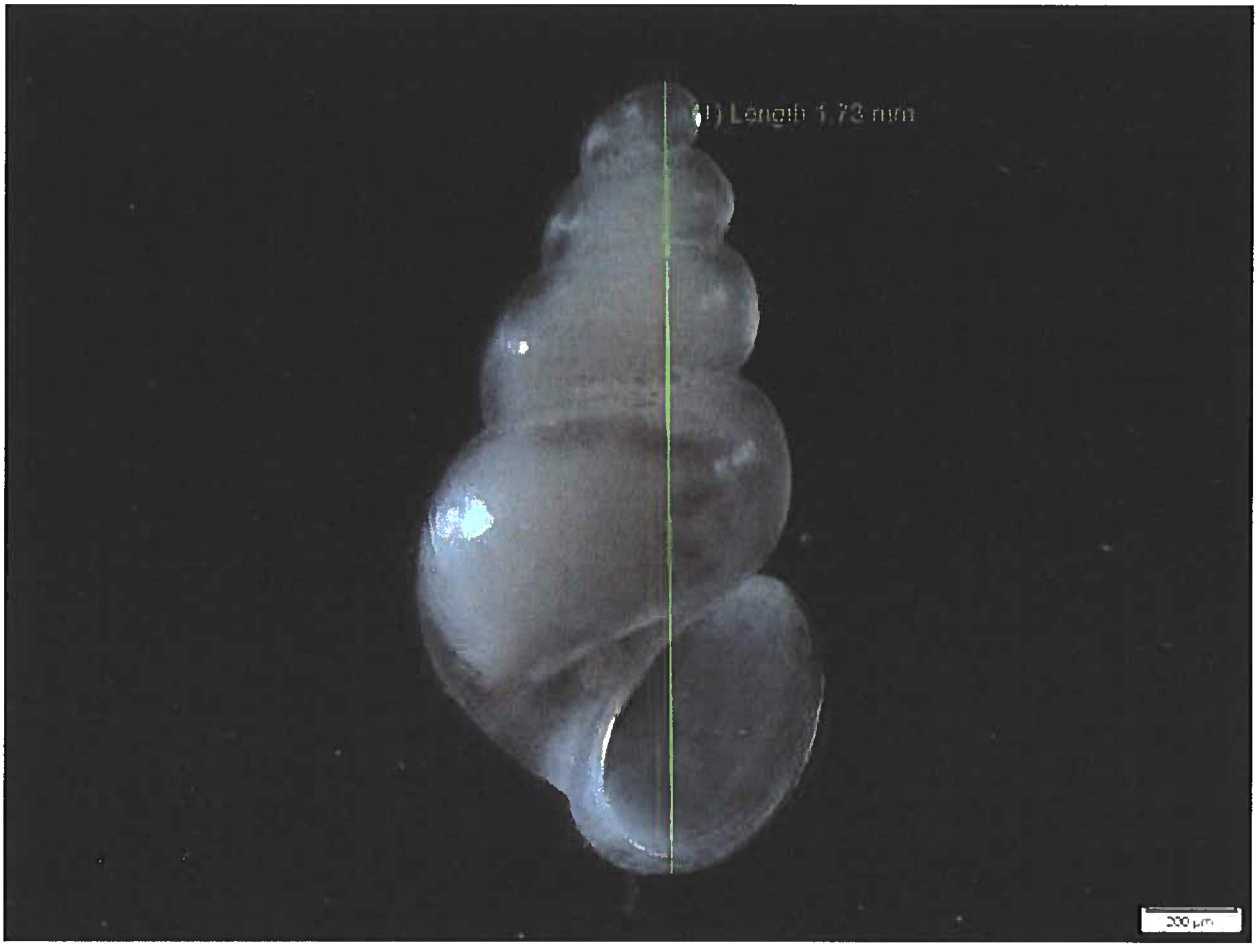

Photo 3. Potential new aquifer snail collected from the Gualt Archeological Site from drift nets during sampling.

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