Evaluation for the Development of a Jacob's Well Groundwater Management Zone in Hays County, Texas

Technical Report prepared for the Hays Trinity Groundwater Conservation District, Hays County, Texas

Report: 2019-05

July 2019

The Meadows Center for Water and the Environment
Texas State University

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Acknowledgments

We would like to acknowledge the Hays Trinity Groundwater Conservation District's Board of Directors for requesting this technical evaluation to inform policy decisions. We would like to acknowledge input and discussions we have had with the dedicated Stakeholder Advisory Committee led by Robin Rather. Anna Huff of The Meadows Center is credited with the graphic design of this report. Finally, we acknowledge reviews and valuable comments from Robert E. Mace, Paul Bertetti, and Alex S. Broun.

Funding for this report was provided in part by Peter and Mary Faye Way.

Suggested citation:

Gary, M.O., Hunt, B.B., Smith, B.A., Watson, J.A., and Wierman, D.A., 2019, Evaluation for the Development of a Jacob's Well Groundwater Management Zone Hays County, Texas. Technical Report prepared for the Hays Trinity Groundwater Conservation District, Hays County, Texas. Meadows Center for Water and the Environment, Texas State University at San Marcos, TX. Report: 2019-05. July 2019. 58 p.

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EXECUTIVE SUMMARY

Jacob's Well is a karst spring originating from the Lower Cretaceous, Middle Trinity Aquifer and is located in the Cypress Creek watershed near Wimberley, Texas. The Middle Trinity Aquifer is the primary groundwater resource for water supply in the region. Jacob's Well flow responds to climatic variations of both short- and long-term cycles. Groundwater pumping from the Middle Trinity Aquifer also directly influences flow at Jacob's Well. The combination of periodic drought cycles and increased groundwater pumping has significantly diminished springflow in recent years.

The Hays Trinity Groundwater Conservation District (District) is charged with managing the groundwater resources within its jurisdictional boundaries. Jacob's Well provides baseflow to Cypress Creek, which in turn provides ecological, hydrological, and financial benefits to the Wimberley region. Recognizing the importance of springflow from Jacob's Well, the District's Board of Directors formed the Scientific Technical Committee of groundwater scientists and tasked the committee with evaluating a potential groundwater management zone in collaboration with the Stakeholder Advisory Committee. The primary goal of this evaluation is to apply a scientifically-based approach to delineate an area in which strategies could be applied that lead to the preservation of springflow and baseflow in Cypress Creek during periods of drought.

The Scientific Technical Committee identified three areas that have a strong hydrologic connection to Jacob's Well (**Figure ES-1**). In other words, Jacob's Well springflow is very sensitive to recharge and pumping influences in these areas. Each area has unique hydrologic and hydrogeologic features that influence the flow to Jacob's Well. These features were considered as the basis for creating groundwater management zones. Evaluations indicate that most of the flow to Jacob's Well can be explained by recharge occurring in an area defined as the Jacob's Well Springshed, and that pumping in that area has direct effects on springflow. However, recharge to the Middle Trinity Aquifer likely occurs in a larger area of western Hays County, and thus may also provide some flow to Jacob's Well under certain conditions. We define this additional area as the Regional Recharge Area, which corresponds to a portion of the springshed for Pleasant Valley Spring. The Tom Creek Fault Area represents an area in hydrologic communication with the upgradient Jacob's Well Springshed and potentially the Regional Recharge Area.

We combined the three hydrologic areas into two groundwater management zones (**Figure ES-1**). A reduction of pumping during drought periods from current levels of pumping will result in increased springflows. A variety of demand reduction and alternative supply strategies having various levels of time and scale will need to be implemented to achieve the desired Jacob's Well flow goals.

A regional strategy includes developing an effective drought-trigger methodology that uses Jacob's Well as one of the drought indicators. Specifically, within the Jacob's Well Groundwater Management Zone, strategies could include increased drought curtailments based on existing non-exempt pumping. These curtailments could be offset with alternate water supplies such as aquifer storage and recovery, interconnections, development of the Lower Trinity quifer and rainwater harvesting. Future Middle Trinity Aquifer pumping would need to be capped and alternative supply options promoted.

The Regional Recharge Area Groundwater Management Zone presently has less non-exempt pumping, and thus has less impact to Pleasant Valley Spring and Jacob's Well. However, with anticipated growth and associated increases in pumping in the area, negative effects on future springflow at Pleasant Valley Spring are expected similar to those observed at Jacob's Well. Additional monitoring and water-balance studies to determine sustainable pumping rates are recommended. Implementing proactive management and rules to limit future pumping in the Middle Trinity Aquifer to encourage alternative water supplies is also recommended.

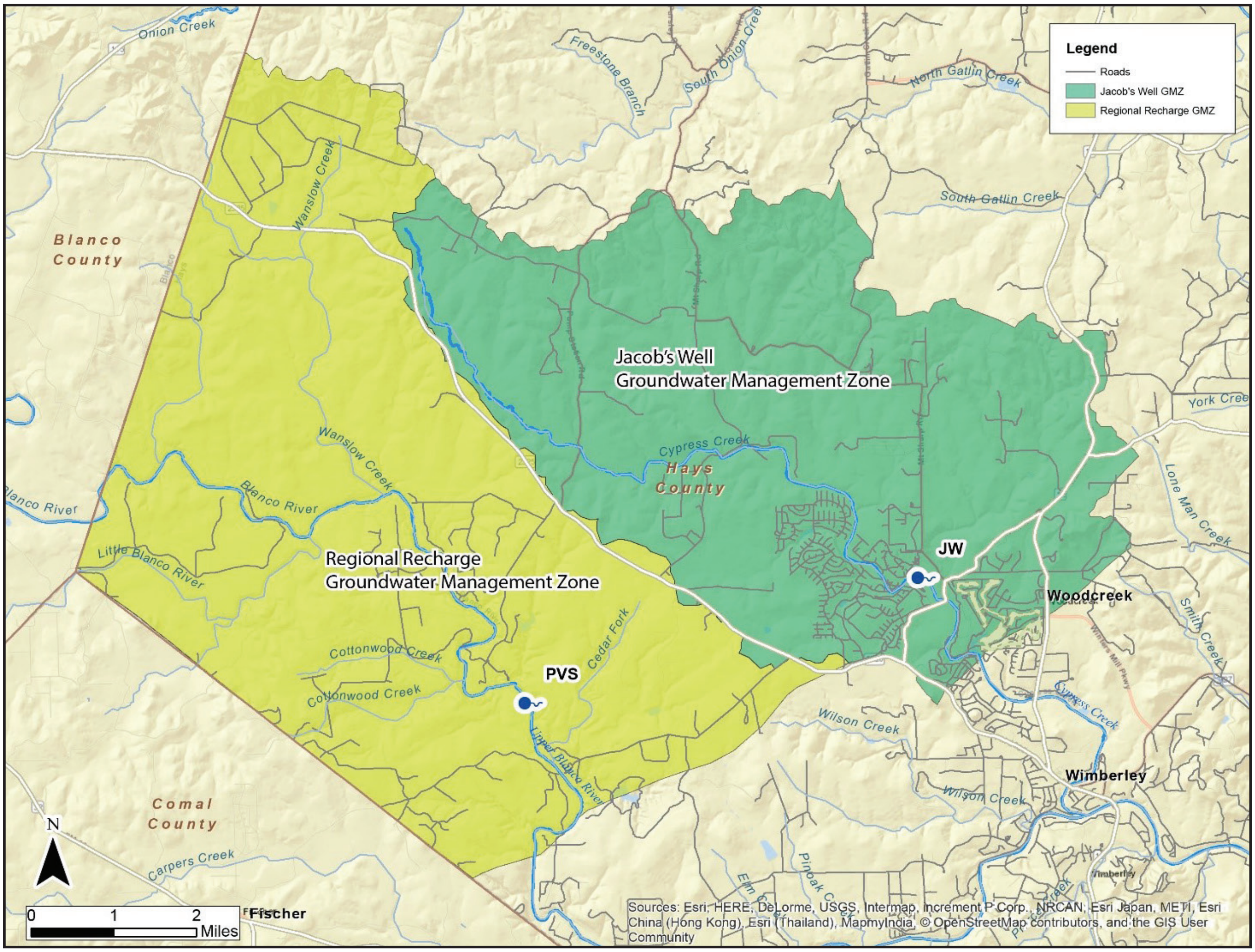

Figure ES-1. Areas of hydrologic influence to Jacob's Well shown in hatched areas. Potential groundwater management zones are shaded green and yellow. The area of the Jacob's Well Groundwater Management Zone is 34 square miles and the area of the Regional Recharge Groundwater Management Zone is 56 square miles.

PREFACE

// Photo 1. Blue Hole on Cypress Creek. Jacob's Well is the primary source of water for Cypress Creek and Blue Hole.

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The Hays Trinity Groundwater Conservation District (District) is charged with managing the groundwater resources within its jurisdictional boundaries (**Figure 1**). In recognition of the importance of maintaining springflow from Jacob's Well, the District's Board of Directors formed a technical committee of groundwater scientists tasked with evaluating hydrogeologic data and identifying alternatives related to the delineation of a Jacob's Well Groundwater Management Zone. The primary goal of the evaluation is to delineate a scientifically based area in which to apply strategies that lead to the preservation of springflow and baseflow in Cypress Creek, particularly during periods of drought. Developing a framework for protecting Jacob's Well flow requires a detailed understanding of springflow, groundwater pumping, effectiveness of current drought management practices, and other potential management strategies. This document summarizes the hydrogeologic data used to define the spatial extent of springsheds and hydrogeologic connections in the area of study, and ultimately recommends potential groundwater management zones. This report also reviews possible effects and strategies related to mitigating pumping to protect springflow.

INTRODUCTION

The Lower Cretaceous Trinity Aquifer is the sole aquifer in the project area and provides critical water resources to central Texas, supporting the ecology and economy of the region. Streams that create the Texas Hill Country landscape are hydrologically linked to the aquifer (groundwater) systems. Rainfall and runoff recharge the aquifers, which provide springflows that sustain baseflows of the streams in the Hill Country and recharge the downstream Edwards Aquifer (Wierman and others 2010, Smith and others 2015, Hunt and others 2017, Smith and others 2018). Because surface and groundwater resources are hydrologically connected, groundwater pumping has an effect on both of these resources.

Jacob's Well, located in the Cypress Creek watershed near Wimberley, Texas, is a karst spring originating in the Middle Trinity Aquifer. The Middle Trinity Aquifer is also the primary groundwater resource for water supply in the region. The spring is the primary source of base flow to Cypress Creek, which flows though the towns of Woodcreek and Wimberley (**Photo 1**) and into the Blanco River upstream of the Edwards Aquifer Recharge Zone. Cypress Creek and Jacob's Well provide wildlife habitat and water for instream flows and financial benefits to Wimberley, Woodcreek and surrounding areas due to the intrinsic character and "natural services" provided by the creek and springs. The Cypress Creek Watershed Protection Plan indicated that a target flow of 4 to 6 cubic feet per second flow in Cypress Creek is necessary to maintain acceptable water quality in the creek (Vogl 2011).

Two major Middle Trinity Aquifer springs are located within the study area, Jacob's Well and Pleasant Valley Spring, which sustain the baseflows to Cypress Creek and the Blanco River, respectively (**Figure 1**). Pleasant Valley Spring is the largest documented spring of the Hill Country Trinity Aquifer system and is located 5 miles WSW from Jacob's Well. Both springs have similar surface elevations, geochemistry, hydrogeologic settings, and emerge from the same structural fault block (Hunt and others 2013).

An important difference between Jacob's Well and Pleasant Valley Spring is the amount of pumping occurring near each. There is relatively little permitted and exempt pumping in the vicinity of Pleasant Valley Spring as compared to Jacob's Well. Historically, Jacob's Well flow was perennial, contributing up to 25 percent of the baseflow to the Blanco River, and continued to flow during the 1950s drought (see Section 4). Jacob's Well flow was measured at 2.6 cubic feet per second in March 1955 (TBWE 1960) and estimated as low as 0.2 cubic feet per second in August 1955. However, over the past 20 years, increases in permitted and exempt pumping upgradient (area of higher groundwater elevation) of Jacob's Well has resulted in capture of springflow during drought periods. This capture has resulted in cessation of Jacob's Well flow during droughts much less severe than the 1950s drought. The combination of periodic drought and increased groundwater pumping has made Jacob's Well more of an intermittent spring than a perennial spring. Watershed characterization studies on Cypress Creek conducted during development of the Cypress Creek Watershed Protection Plan concluded that flow rates of 4 to 6 cubic feet per second are required to maintain healthy dissolved oxygen levels for the aquatic environment (Vogl 2011). While those springflow rates were likely common in the past, the median flow values since 2005 are less than 3 cubic feet per second (Meadows, 2014).

Presently, the source areas (springsheds) for Jacob's Well and Pleasant Valley Spring, including the areas of greatest influence (capture) from pumping, are poorly defined. Delineation of springsheds and areas of hydrologic connection is important to understand the hydrogeologic functioning of the aquifer system and critical to the management and protection of springflow.

Developing a framework for protecting Jacob's Well flow requires a detailed understanding of the geology, hydrogeology, springflows, groundwater pumping, effectiveness of current drought management practices, and other potential management strategies. All of these topics are discussed in this report. The results of this study can be used by stakeholders and policy makers to develop a management zone approach to preserve flows at Jacob's Well.

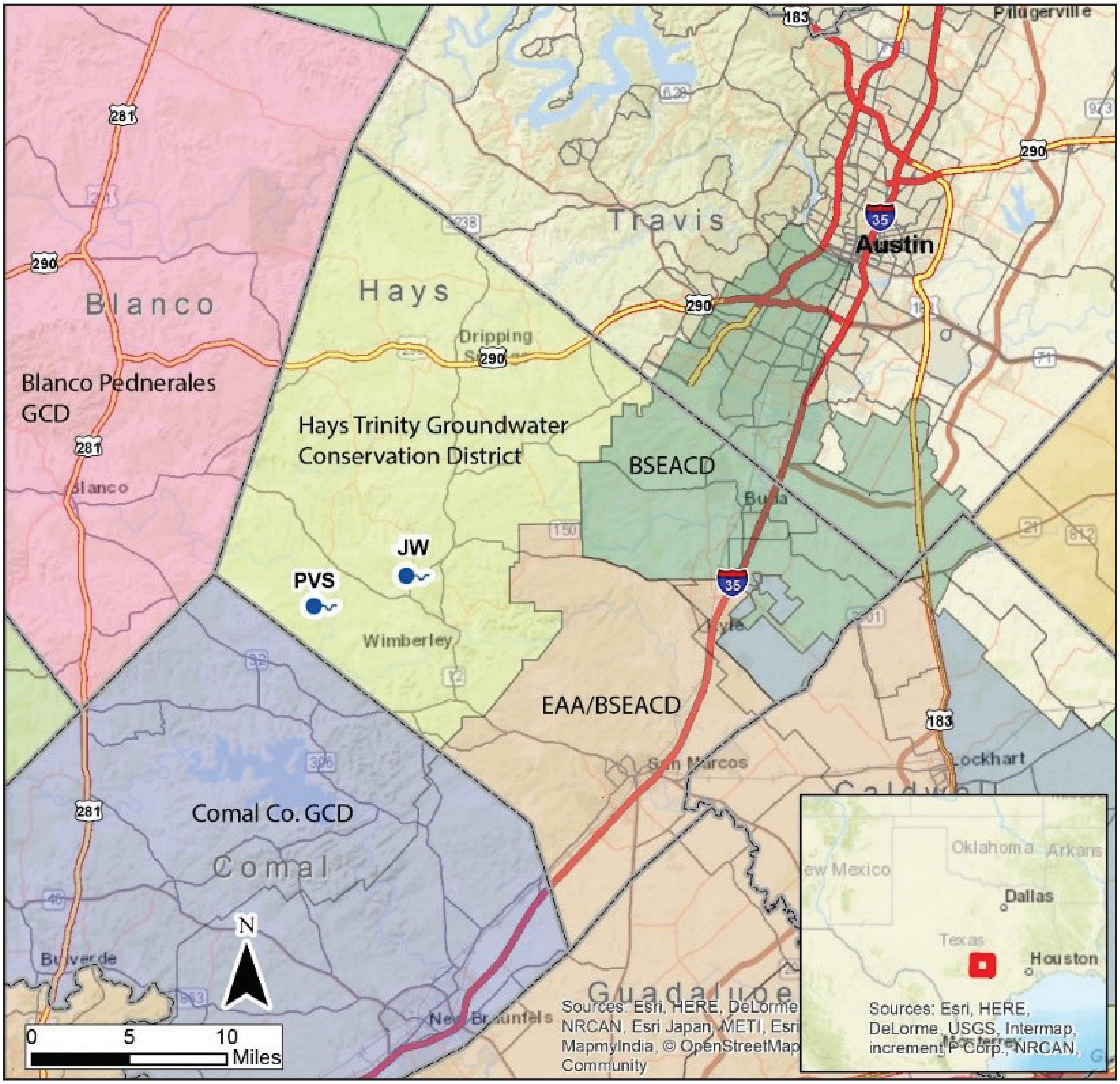

Figure 1. Location map of the Hays Trinity Groundwater Conservation District showing the locations of the major springs in the District, Pleasant Valley Spring (PVS), and Jacob's Well (JW).

GEOLOGIC & HYDROGEOLOGIC SETTING

The study area includes central and western Hays County within the Blanco River watershed (**Figure 2**). Cypress Creek is a tributary watershed of the Blanco River watershed. Often this study area is referred to as the Wimberley Valley. The hydrogeologic setting of the study area has been described in numerous publications including Bluntzer (1992), Wierman and others (2008), Wierman and others (2010), Watson and others (2014), Hunt and others (2010), Hunt and others (2017), and Smith and others (2018).

The geologic units of the of the study area exposed at the surface consist of gently dipping Lower Cretaceous limestone and dolomite strata (**Figures 3 - 6**). Except where remnants of the Edwards Group are present on hill tops, the dominant uppermost unit present is thin-bedded limestone and dolomite of the Upper Glen Rose member of the Glen Rose Formation. Where the Upper Glen Rose has been eroded in the Blanco River and Cypress Creek watersheds, the Lower Glen Rose is the dominant surficial unit.

The Lower Glen Rose is exposed west of the Tom Creek Fault Area and exhibits extensive karst development within the thicker fossiliferous limestone beds (**Figure 2**).

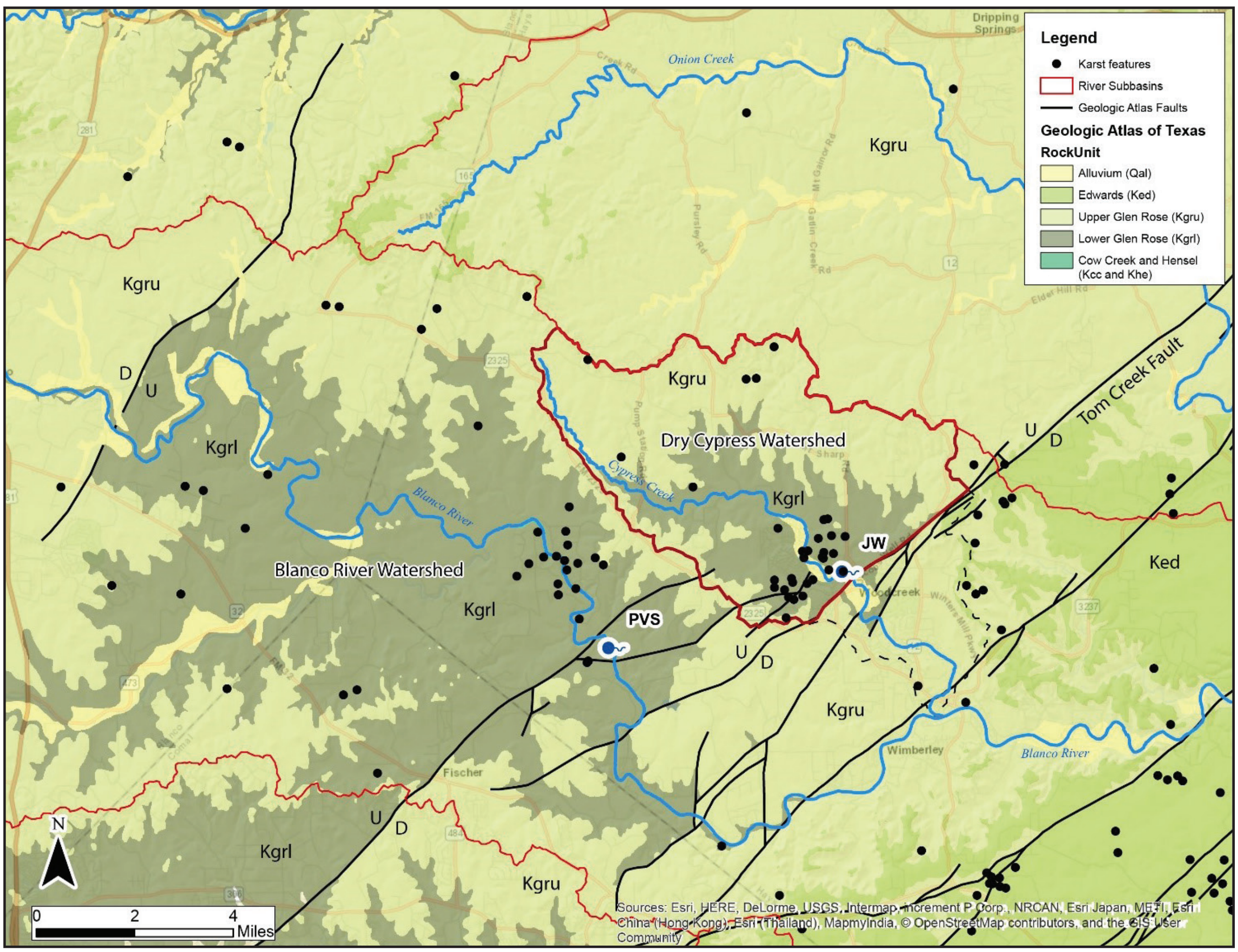

Figure 2. Geologic map of the region around Jacob's Well (JW) and Pleasant Valley Spring (PVS) and their respective watersheds. The area outlined in dark red is upgradient of Jacob's Well and is defined in this report as the Dry Cypress Creek watershed (31 square miles). The Lower Glen Rose carbonates are exposed in the dark green area and contain the majority of known karst (recharge) features in the Trinity Group units.

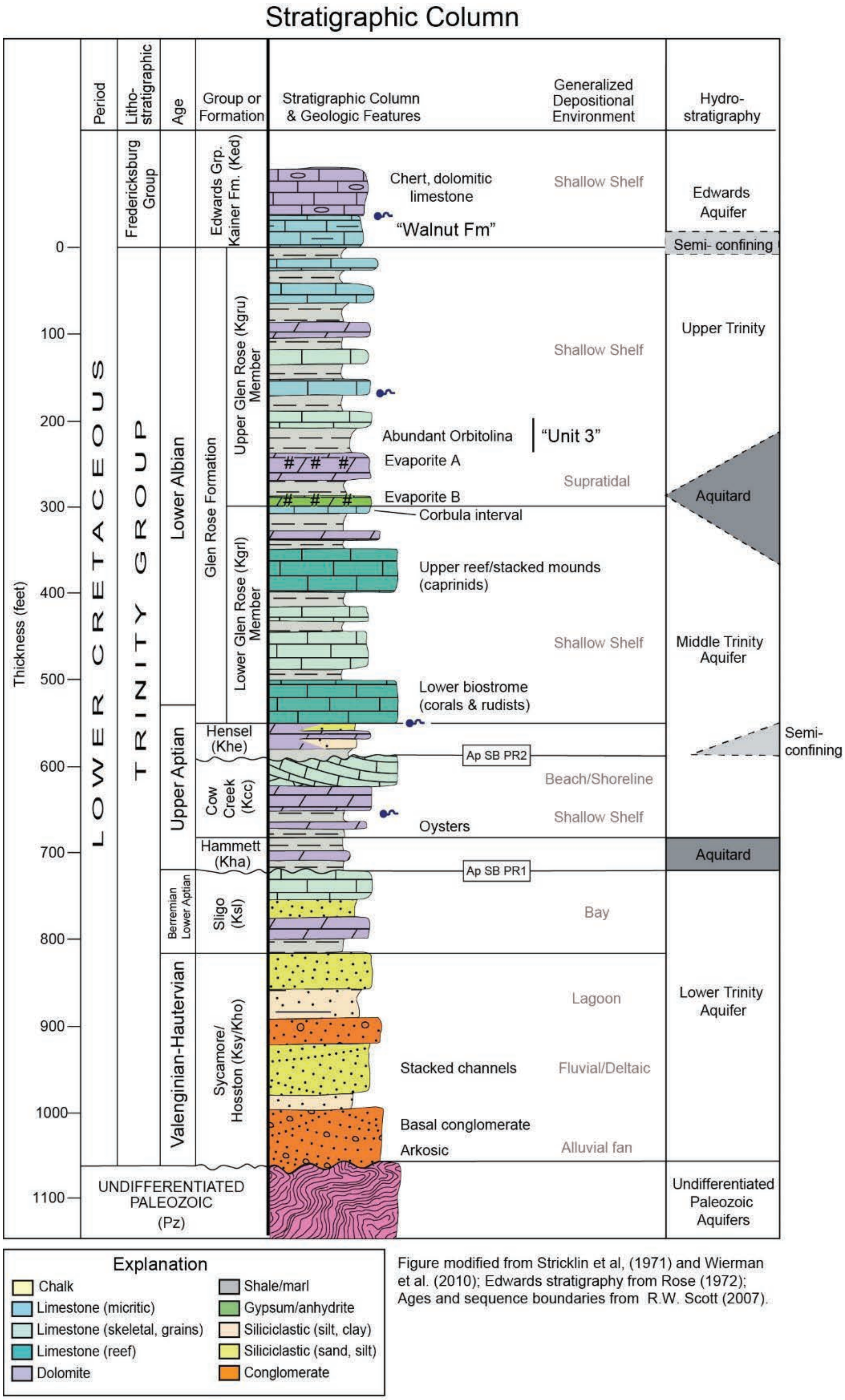

Figure 3. Stratigraphic column of the study area. The primary units of interest are those comprising the Middle Trinity Aquifer (figure from Hunt and others, 2017).

The Hensel Formation is a thin silty dolomite unit below the Lower Glen Rose that can behave locally as an aquitard except where breached with fractures and dissolution features. The Cow Creek Formation is a (grain) limestone and is the primary aquifer unit of the Middle Trinity Aquifer. The Hammett Shale separates the Cow Creek from the underlying Sligo and Hosston formations of the Lower Trinity Aquifer (**Figures 3 and 4**).

The Upper Trinity Aquifer is composed of the Upper Glen Rose limestone (**Figure 3**). Where present, the Upper Glen Rose generally consists of shallow perched water tables. There are often small seeps and springs associated with the Upper Glen Rose within the headwaters of drainages. The underlying Middle Trinity Aquifer is the primary aquifer in the study area and is composed of the Lower Glen Rose, Hensel, and Cow Creek formations (**Figure 3**). The Middle Trinity Aquifer is the water supply for most of the groundwater production in the study area and is the source of water for Jacob's Well and Pleasant Valley Spring (**Figure 4**). The Lower Glen Rose is exposed throughout much of the study area and is highly karstic. The Hensel is a locally confining unit above the Cow Creek. The Cow Creek is a highly transmissive (karstic) unit and the primary aquifer unit within the Middle Trinity Aquifer (**Photo 3**). The Cow Creek is the source of flow to Jacob's Well and Pleasant Valley Spring.

The Hammett Shale is an aquitard separating the Middle and Lower Trinity aquifers. The Lower Trinity Aquifer is composed of the Sligo and Hosston formations (**Figure 3**). Although the Lower Trinity Aquifer is increasingly targeted for production, it generally has less yield and poorer water quality than the Middle Trinity Aquifer. These factors, and the increased depth and cost of well completion, have resulted in less pumping in the study area from the Lower Trinity compared to the Middle Trinity.

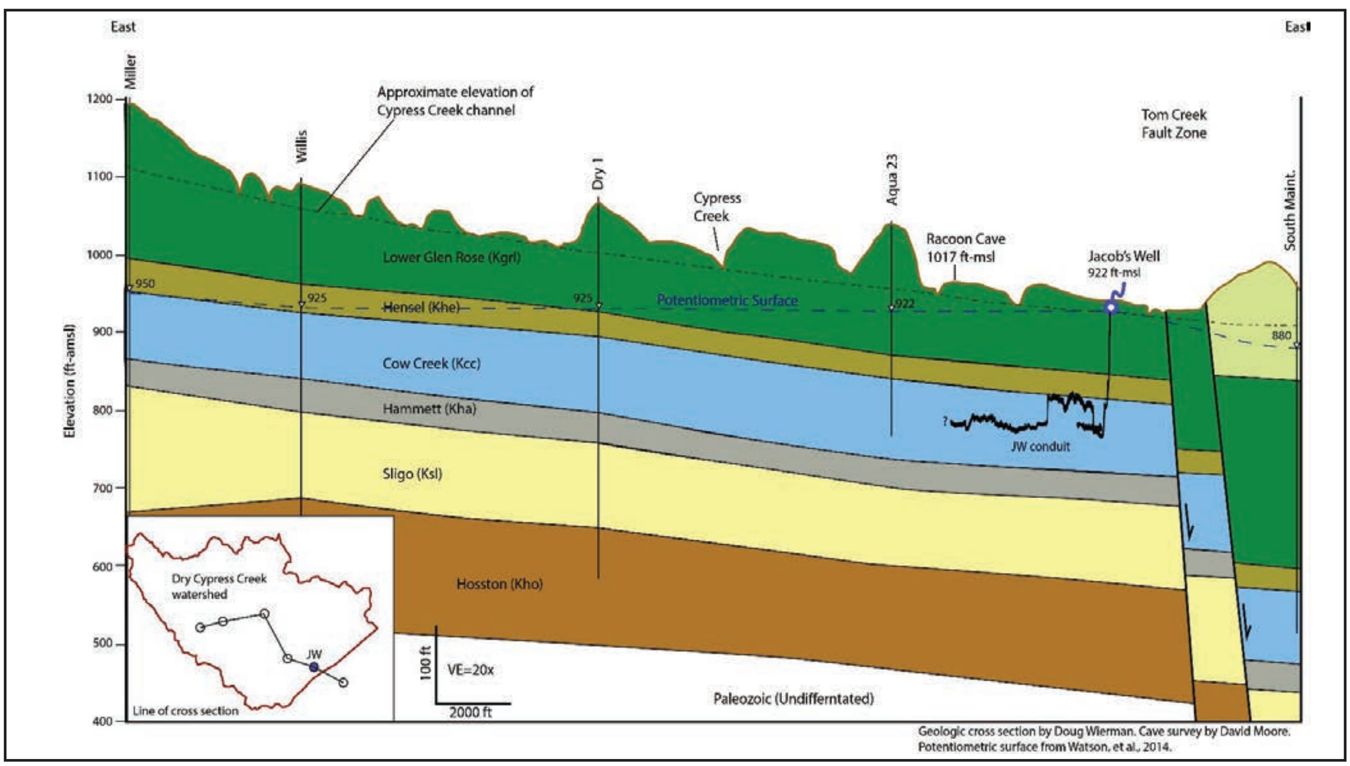

Figure 4. Geologic cross section through Dry Cypress Creek watershed. The potentiometric surface is for the Middle Trinity Aquifer.

STRUCTURE

Geologic maps (BEG 1992, Collins 2002a, and Collins 2002b), outcrops, and geophysical logs provide the foundation of our geologic and structural mapping of the study area. Structure contours of the top of the Cow Creek were created using outcrops and geophysical logs (**Figure 5**) (Al Broun, unpublished data).

The geology of Wimberley Valley is composed of gently southeast dipping Lower Cretaceous limestone and dolomite strata (**Figures 4 and 5**). Geologic maps and structure contours indicate the presence of a horst feature (uplifted block) bound between a NNW-trending west-dipping fault within Blanco County, and a series of en-echelon east-dipping faults, known as the Tom Creek Fault Zone, near the town of Wimberley (**Figure 5**). Vertical displacement across the faults varies from just a few feet to a few hundred feet. The Blanco River has incised deep into the horst structure—exposing all three geologic units of the Middle Trinity Aquifer (**Figure 6**).

The Middle Trinity Aquifer dips gently from west to east through the study area until reaching the Tom Creek and Balcones fault zones. East of Jacob's Well the structural dips (gradients) increase related to faulting (**Figures 4-6**). Some of the faults completely offset geologic and hydrogeologic units and may act as barriers to flow. However, faults often have variable offset and create relay-ramp structures that can provide lateral continuity of geologic units (and flow) into and through the fault zone (Hunt and others 2015). In addition, fractures associated with faults can locally increase the lateral and vertical permeability of the units.

Within the Dry Cypress Creek Watershed, the geologic units dip to the southeast (**Figures 5 and 6**). Additional structure includes an anticline trending west to east across the watershed (Wierman and others 2010). Schumacher and Saller (2008) describe the most prevalent orientation of jointing in the direction of the region's minor stress axis (310° to 330°, a northwest to southeast orientation) and perpendicular to the orientation of normal faulting. This alignment of jointing and the dip of bedding to the southeast strongly influences groundwater flow in the Middle Trinity Aquifer.

// Photo 2. Diver in Jacob's Well cave. The cave passage is developed within the Cow Creek Formation and is the primary aquifer unit of the Middle Trinity Aquifer and source of water for Jacob's Well and Pleasant Valley Spring.

© Jacob's Well Exploration Project

GROUNDWATER FLOW

Groundwater-level (potentiometric surface) maps can provide critical information about recharge, discharge, and storage within an aquifer, and the direction of groundwater flow. **Figure 7** depicts a potentiometric surface for the Middle Trinity Aquifer during March 2018 (Hunt and others, 2019) and is similar to other maps made during 2009 drought conditions (Hunt and others 2010). Regional groundwater flow within the Middle Trinity Aquifer is generally west to east from Gillespie and Blanco counties and into Hays County. The overall flow direction and potentiometric gradients generally follow the structure contour gradients, which reflect dip and faulting (Wierman and others 2010; **Figure 5**). In other words, groundwater flow in the Middle Trinity Aquifer is generally from the northwest to southeast following the regional dip of the rocks. In the vicinity of Jacob's Well, the Cow Creek is under artesian pressure, and groundwater discharges through the Hensel and Lower Glen Rose to the surface, along conduits developed along fractures. Flow from Jacob's Well sustains baseflow to Cypress Creek, which ultimately contributes to flow in the Blanco River. During severe drought conditions the flow in the Blanco River is the only source of continuous surface recharge to the downdip Edwards Aquifer in Hays County.

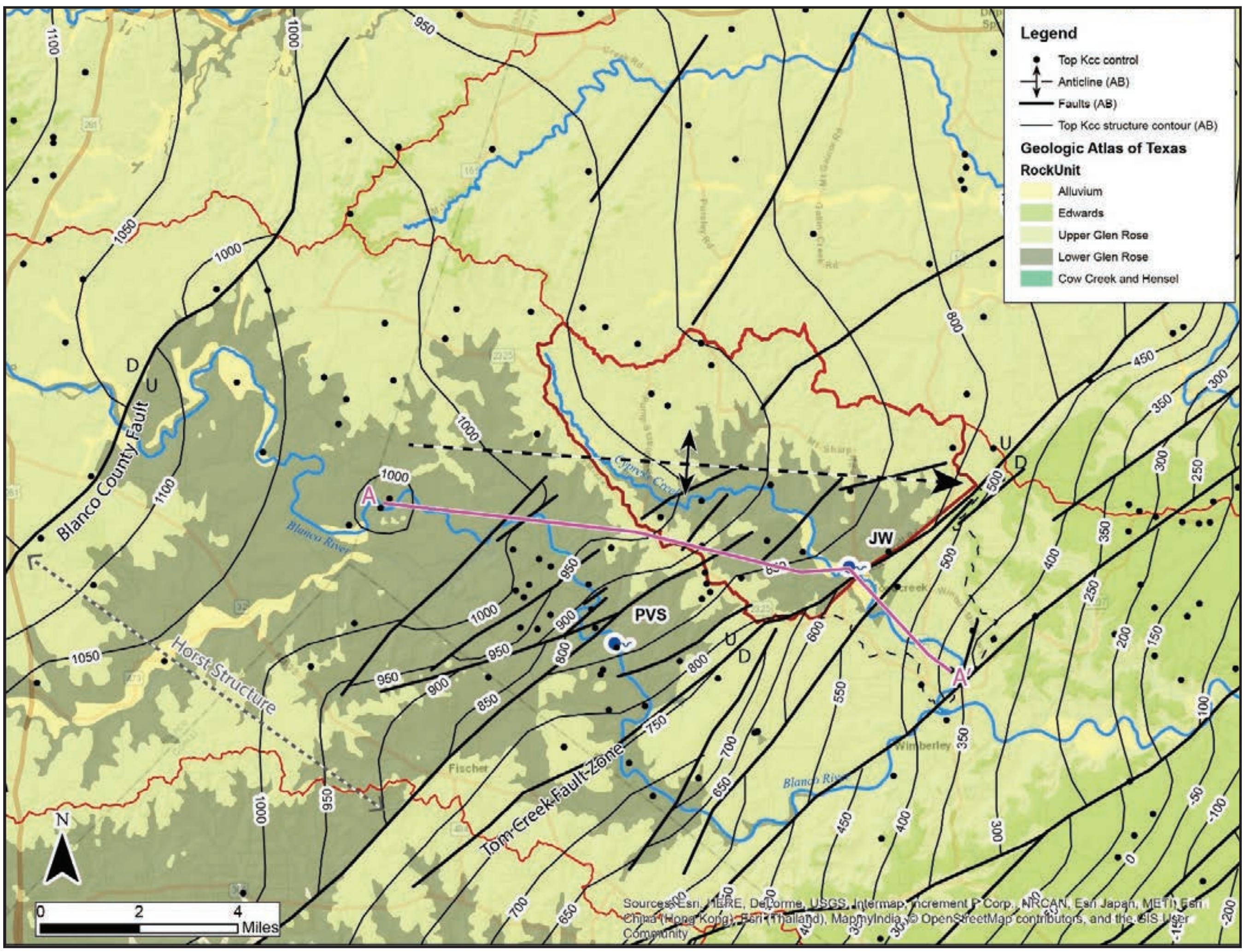

Figure 5. Structure contour map of the top of the Cow Creek (contours in feet above mean sea level). Contours, control, and faults from Al Broun (unpublished data). Figure modified from Wierman and others, 2010. Cross section A to A′ is shown in Figure 6.

Unique features in the potentiometric map are related to structural and hydrogeologic influences. For example, the low gradient and broad potentiometric ridge within central Hays County occurs coincident within the horst complex (**Figure 2**). A significant trough in the potentiometric surface is located upgradient from Jacob's Well along Cypress Creek (Watson and others 2014, Hunt and others 2019; **Figure 7**). The trough indicates focused and converging groundwater flow and is likely related to the Jacob's Well conduit, which extends northwest, parallel to Cypress Creek and beneath the trough. These types of potentiometric troughs are common in karst areas (Hunt and others 2007). A groundwater tracing study (BSEACD 2018, Smith and others 2018) and other data suggest recharge into the Lower Glen Rose within Dry Cypress Creek watershed contributes to discharge at Jacob's Well along this potentiometric trough.

// Photo 3. Flow measurement using acoustic Doppler profiler on the Blanco River at Ranch Road 12 in Wimberley after the 2015 floods.

Faulting appears to influence the groundwater gradients (**Figure 7**). Steeper gradients coincident with the Tom Creek Fault Zone suggest that these faults in the zone may act as a partial barrier to eastward flow, or a change in the permeability of the aquifer. This may be related to the larger magnitude of displacement along certain portions of faults in this zone. However, faults do not appear to be barriers to eastward flow as the potentiometric contours continue to the east with variable gradients, indicating lateral groundwater flow slows in this zone (**Figures 5 and 7**). Regional lateral flow to the east may be facilitated by the relay-ramp structures discussed in Hunt and others (2015).

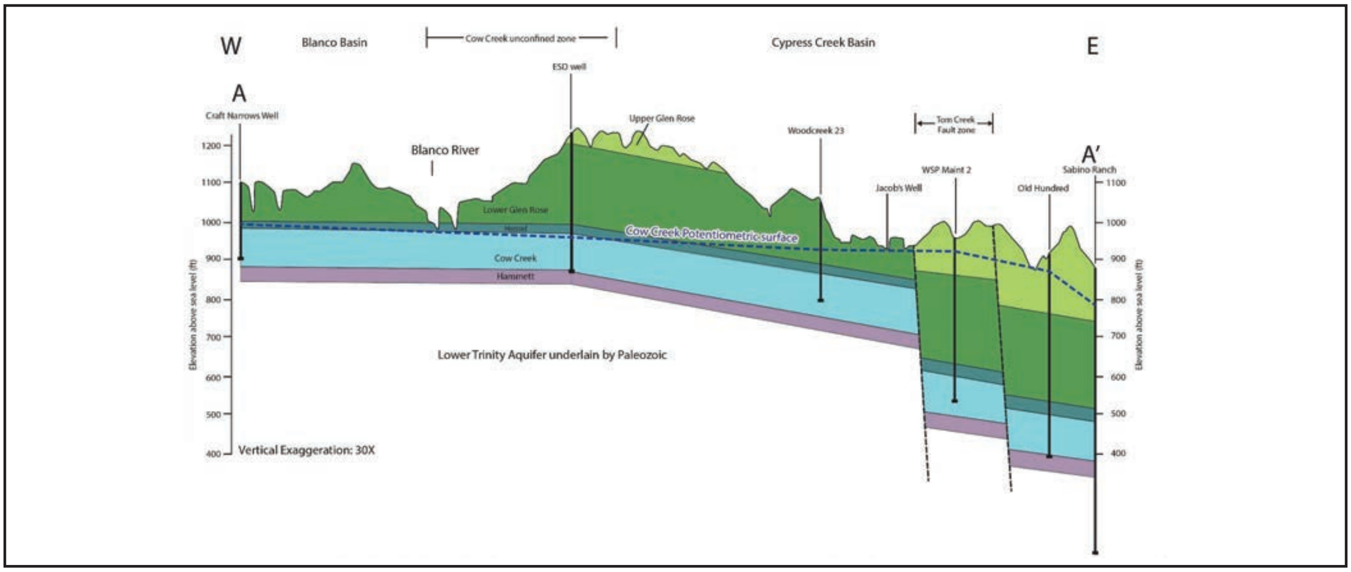

Figure 6. Structural cross section and October 2018 potentiometric surface. Figure from Broun and Watson (2018). Line of cross section shown in Figure 7.

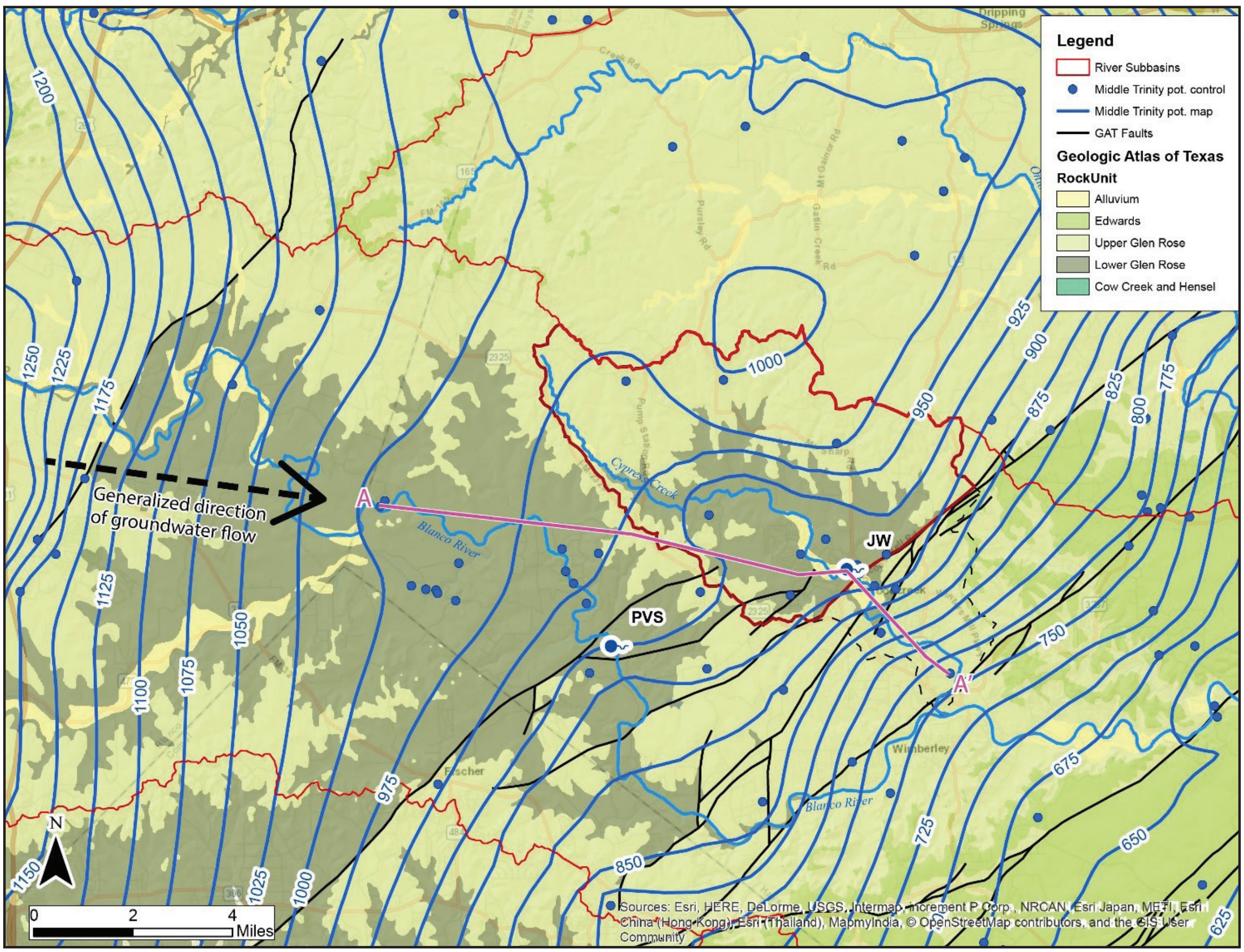

Figure 7. Regional potentiometric (water level) surface of the Middle Trinity Aquifer in March 2018. Elevations in feet above mean sea level. Data from Hunt and others (2019). Cross Section A to A' shown in Figure 6.

Along the southern boundary of Dry Cypress Creek watershed, a potentiometric ridge, defined by the 925-foot elevation contour between Pleasant Valley Spring and Jacob's Well, suggests a potential hydrologic divide exists between these two major springs (**Figure 7**). Data shown in **Figure 8** present a compelling case for hydrologic separation between the Blanco River/Pleasant Valley Spring and Jacob's Well. The hydrograph illustrates a response in the Blanco River (at RR12) and Pleasant Valley Spring to significant rainfall in May and June 2013. However, during that same period the hydrograph at Jacob's Well was unresponsive to the rainfall and the change in river stage in the Blanco River. This suggests that the Blanco River, under those conditions, was not a source of springflow at Jacob's Well. Other publications (Wierman and others 2008) noted similar evidence for hydrologic separation for the reverse situation in April 2006 and again in January 2007 when discharge at Jacob's Well peaked while flow in the Blanco River remained constant.

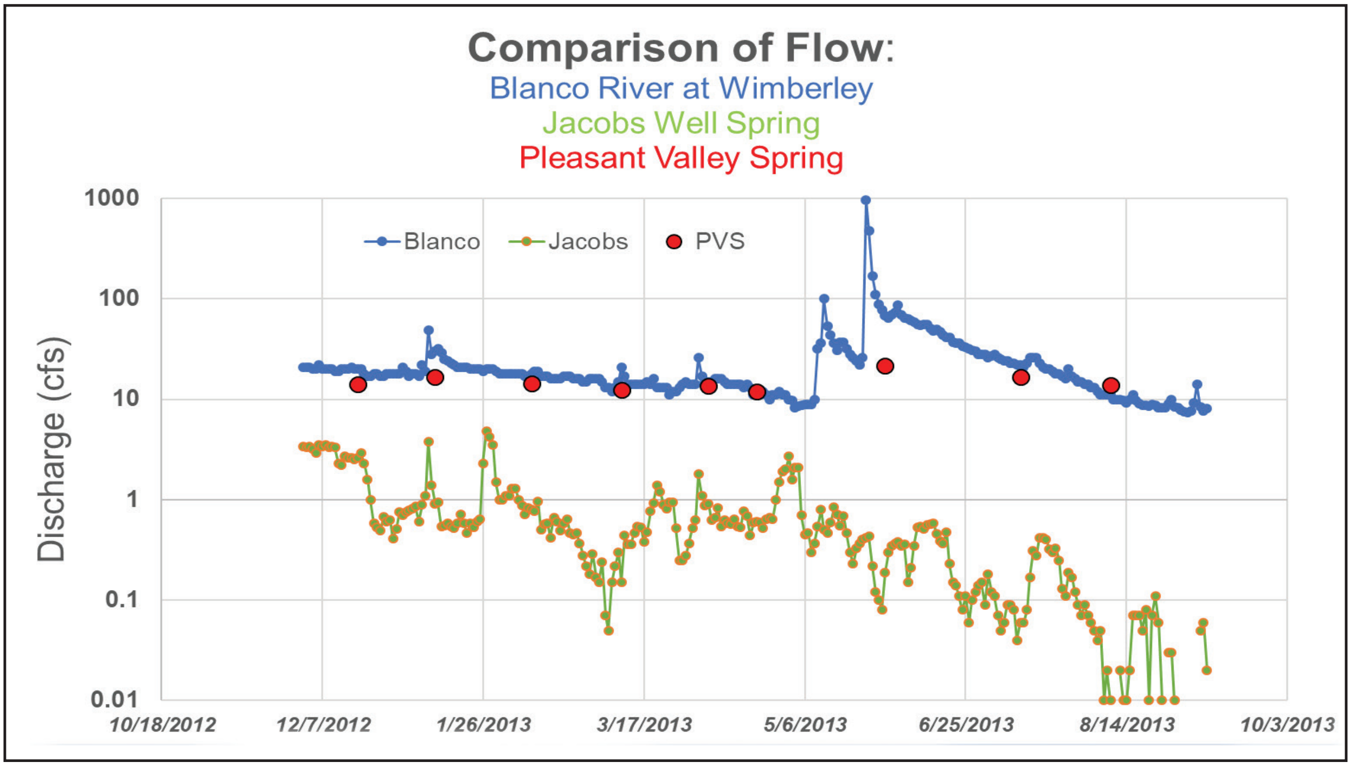

Figure 8. Springflows and Blanco River (at RR12) hydrograph. Note the increased Pleasant Valley Spring springflow and Blanco River response in May to June 2013, while Jacob's Well had no corresponding response. Source data from USGS (2017a, 2017b) and Marcus Gary (unpublished data).

ZONES OF HYDROLOGIC INFLUENCE

We have identified and evaluated three areas that are hydrologically linked to Jacob's Well in this report. Each area has unique hydrologic and hydrogeologic features that influence flow to Jacob's Well. These features are considered as the bases for delineating groundwater management zones.

JACOB'S WELL SPRINGSHED AREA

A springshed is an area that contributes flow to a spring. The term is often used synonymously with source, catchment, or recharge area. Previously, the springshed of Jacob's Well was ill-defined with conflicting conclusions from studies. For example, the Blanco River was reported to be the source of recharge to Jacob's Well based on geochemistry (Steinhauer and others 2006) and published recharge values and water budget estimates (Wierman and others 2008). Budge (2008) used correlations of NEXRAD rainfall data and springflow to estimate the springshed of Jacob's Well and identified an area similar in extent to the Dry Cypress Creek surface watershed. Davidson (2008) suggested two potential source areas including the area within Dry Cypress Creek watershed and another from the Blanco River.

Various data and methods help constrain the area that contributes flow to Jacob's Well. Geologic, structural, and potentiometric data indicate a convergence of groundwater flow to Jacob's Well that is generally constrained within the Dry Cypress Creek watershed (**Figures 5 and 7**). Furthermore, published evaluations indicate the Dry Cypress Creek watershed as the primary source of water for Jacob's Well (Budge 2008, Davidson 2008). This hypothesis is tested as a first-order estimation of the springshed using a variety of water budget calculations. **Table 1** provides some key statistics for the study area and corresponds to area shown in **Figure 2** that are relevant to the evaluations discussed below.

Table 1. Surface areas and geology within the study area. Areas correspond to Figure 2.

Name	Surface Areas (square miles)	Area (square kilometers)	Comment
Cypress Creek (HU-12) Watershed	38	98	entire watershed to the Blanco River
Dry Cypress Creek Watershed	31	79	area upstream of Jacob's Well
Lower Glen Rose Outcrop within Dry Cypress Watershed	12	31	upstream of Jacob's Well, includes Alluvium (Qal) in stream

WATER-BALANCE METHODS

We estimated the springshed for Jacob's Well using a water-balance approach with recharge equaling Jacob's Well discharge. Effective annual recharge, as a percentage of precipitation, and the area of contribution (the springshed) are the unknown variables, while discharge is relatively well known due to the U.S. Geological Survey gage at Jacob's Well. Effective recharge includes all infiltrating surface water including diffuse recharge (infiltrating through soils) and discrete recharge (via karstic features).

A water-balance method was used to estimate a first-order area for the Jacob's Well

Springshed (Bonacci and Andric, 2015). A range of assumed annual effective recharge values, as a percentage of precipitation, results in a range of potential springshed areas (**Figure 9**). An annual effective recharge of up to 25 percent of annual precipitation corresponds to a springshed size equivalent to the area of the exposed Lower Glen Rose within the Dry Cypress Creek watershed (**Table 1**; 12 square miles). An annual effective recharge of up to 10 percent of precipitation results an estimated area that is about the size of the Dry Cypress Creek watershed (**Table 1**; 31 square miles).

Similar results were achieved using another water-balance approach consisting of NEXRAD (Next-Generation Radar) maps of daily precipitation for the area upgradient of Jacob's Well. We selected daily rainfall totals from six NEXRAD grids that cover Dry Cypress Creek (~6.25 square miles per grid) for a period of 561 days (1.5 years) during which Jacob's Well discharge varied from 0.0 cubic feet per second on August 22, 2011, to 0.24 cubic feet per second on March 4, 2013. Using this period minimizes effects of changing aquifer storage in a water-balance equation. The volume of springflow for this period is calculated to be 328,000,000 cubic feet, and the volume of rainfall for this same period was calculated for each grid. Results indicate that if 25 percent of the rainfall is recharge, then an area equal to two grids, or 12.5 square miles, matches Jacob's Well discharge volumetrically over the 1.5-year period. If 10 percent of the rainfall is assumed to recharge, then an area equal to six grids, or 38 square miles, matches Jacob's Well discharge volumetrically over the 1.5-year period. These results suggest Dry Cypress Creek watershed could account for most of the recharge area for Jacob's Well; Budge (2008) reached a similar conclusion by who also using a correlation of NEXRAD rainfall to Jacob's Well springflow. A tool called ESPERE (Lanini and others 2015) allows the estimation of recharge (in inches) using published empirical and analytical methods. Results indicate the annual effective recharge as a percentage of rainfall for three empirical methods ranged from 5 to 63 percent for the 10-year period. Average annual recharge ranged from 26 to 42 percent (**Table 2**).

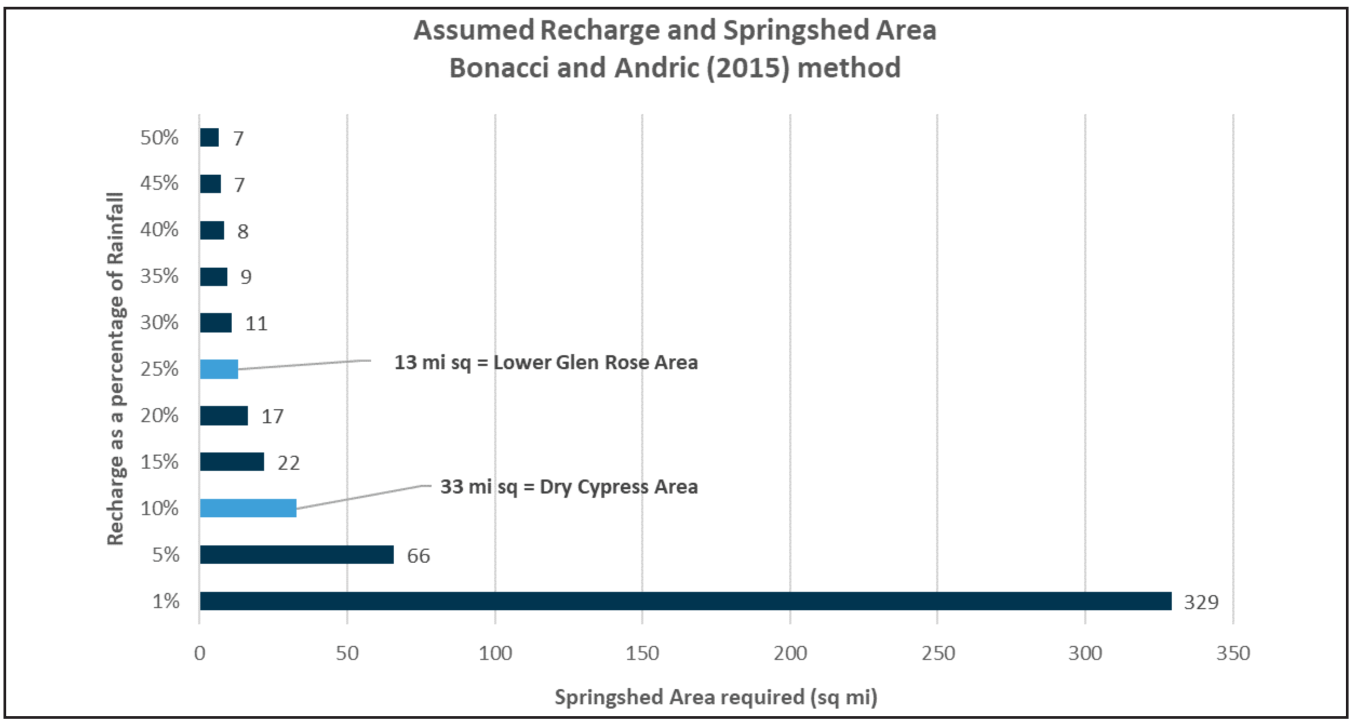

Figure 9. Results of assumed recharge as a percentage of precipitation and the calculated springshed area. The area of Dry Cypress Creek watershed is about 31 square miles, or about 10 percent of precipitation. The Lower Glen Rose has an area within Dry Cypress Creek watershed of 12.1 square miles, or about 25 percent of precipitation.

The annual effective recharge, as a percentage of rainfall, was annualized into a flow rate (cubic feet per second) by assuming a recharge area of 12 square miles for comparison to Jacob's Well flow (**Figure 10**). Despite the different methods, the data correlate reasonably well and indicate relatively high annual average effective recharge for the Dry Cypress Creek watershed (**Table 2, Figure 10**).

Table 2. Table of annual average flow from three different empirical methods summarized in Lanini and others (2015) that estimate annual effective recharge. Values of Jacob's Well flow and recharge are shown in Figure 10.

Year	Flow (cfs)	Annual Recharge (cfs)		
	Jacob's Well	Turc (1954)	Guttman & Zuckerman (1995)	Kessler (1967)
6/1/2006	2.79	2.41	5.46	
6/1/2007	18.65	19.11	25.22	18.34
6/1/2008	4.45	0.61	2.82	4.55
6/1/2009	1.42	7.77	11.97	6.08
6/1/2010	16.25	13.83	19.16	17.81
6/1/2011	2.79	0.70	3.07	5.69
6/1/2012	10.41	7.96	12.93	13.74
6/1/2013	1.67	9.41	13.94	9.26
6/1/2014	4.20	2.90	5.79	6.60
6/1/2015	14.05	22.40	29.49	17.36
6/1/2016	25.55	9.92	14.97	17.34
Min*		5%	22%	22%
Max*		48%	63%	55%
Average*		26%	42%	40%
Coefficient of determination (R^2) **		0.41	0.42	0.80

**Annual recharge as a percentage of rainfall; **R2 value of Jacob's Well discharge compared to annual recharge (cfs = cubic feet per second)*

These estimated effective recharge values are much higher than regional recharge values reported from modeling studies of the Trinity Aquifer, which are 4 to 6 percent of precipitation (Jones and others 2011). However, field studies in geologically similar terranes report annual effective recharge of between 13 to 34 percent of precipitation (Banta and Slattery 2011, Dugas and others 1998). Similarly, Hauwert and Sharp (2014) report 28 percent of precipitation as effective recharge for the karstic Edwards Aquifer.

// Photo 4. (left) Recharge event in Lower Glen Rose cave near Jacob's Well.

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Photo 5. (right) Dye injection in Lower Glen Rose cave near Jacob's Well (same location pictured in photo 4).

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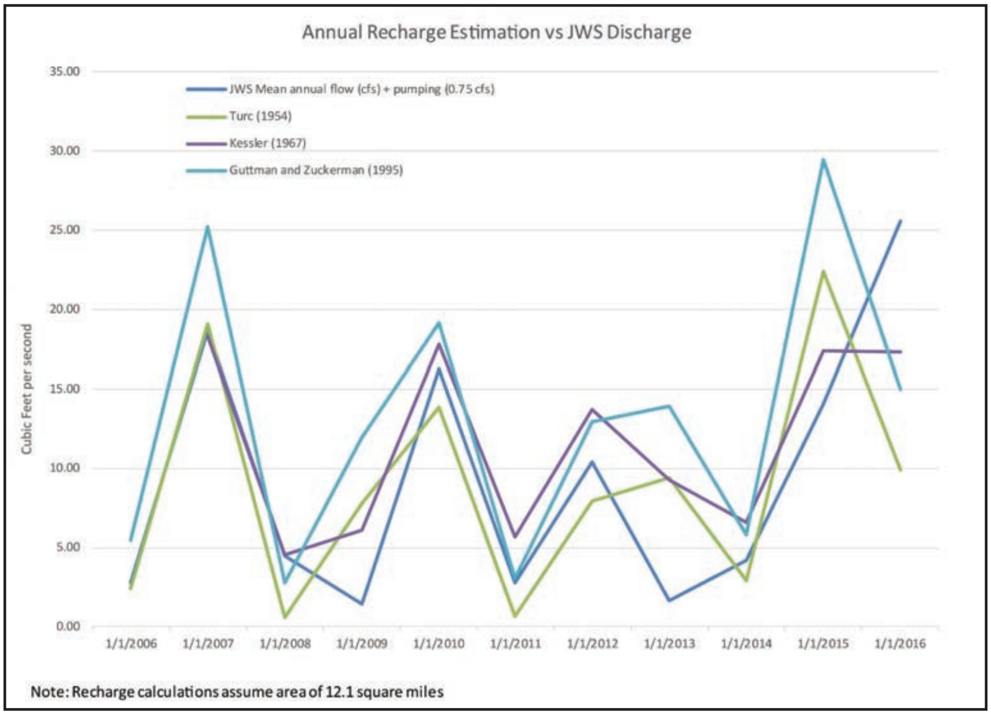


Figure 10. Comparison of annual average flow from three different empirical methods that estimate annual effective recharge summarized in Lanini and others (2015). Values are shown in Table 2. (JWS = Jacob's Well Spring, CFS = cubic feet per second)

JACOB'S WELL SPRINGSHED SUMMARY

Geologic, structural, and potentiometric data indicate a convergence of flow to Jacob's Well that is generally constrained within the Dry Cypress Creek watershed. Water-balance results indicate 10 to 25 percent of precipitation for the annual effective recharge to Jacob's Well is a reasonable assumption for this highly karstic watershed. This range represents the temporal variation in effective recharge that is dependent on residual moisture in the soils and vadose zone. By applying this range of effective recharge to observed springflow volumes at Jacob's Well, a close correlation to the outcrop area of the Lower Glen Rose within Dry Cypress Creek (12 square miles) and total Dry Cypress Creek watershed (31 square miles) exists. Thus, the evaluations presented here generally support the hypothesis that most of the flow to Jacob's Well can be explained by recharge occurring in the Dry Cypress Creek watershed (31 square miles). This area is defined in this report as the Jacob's Well Springshed (**Figure 11**). We assessed additional areas surrounding the Jacob's Well Springshed to address the uncertainty of regional groundwater flow and pumping wells (current or future) that could influence Jacob's Well flows. Those areas are discussed in detail in other sections of this report.

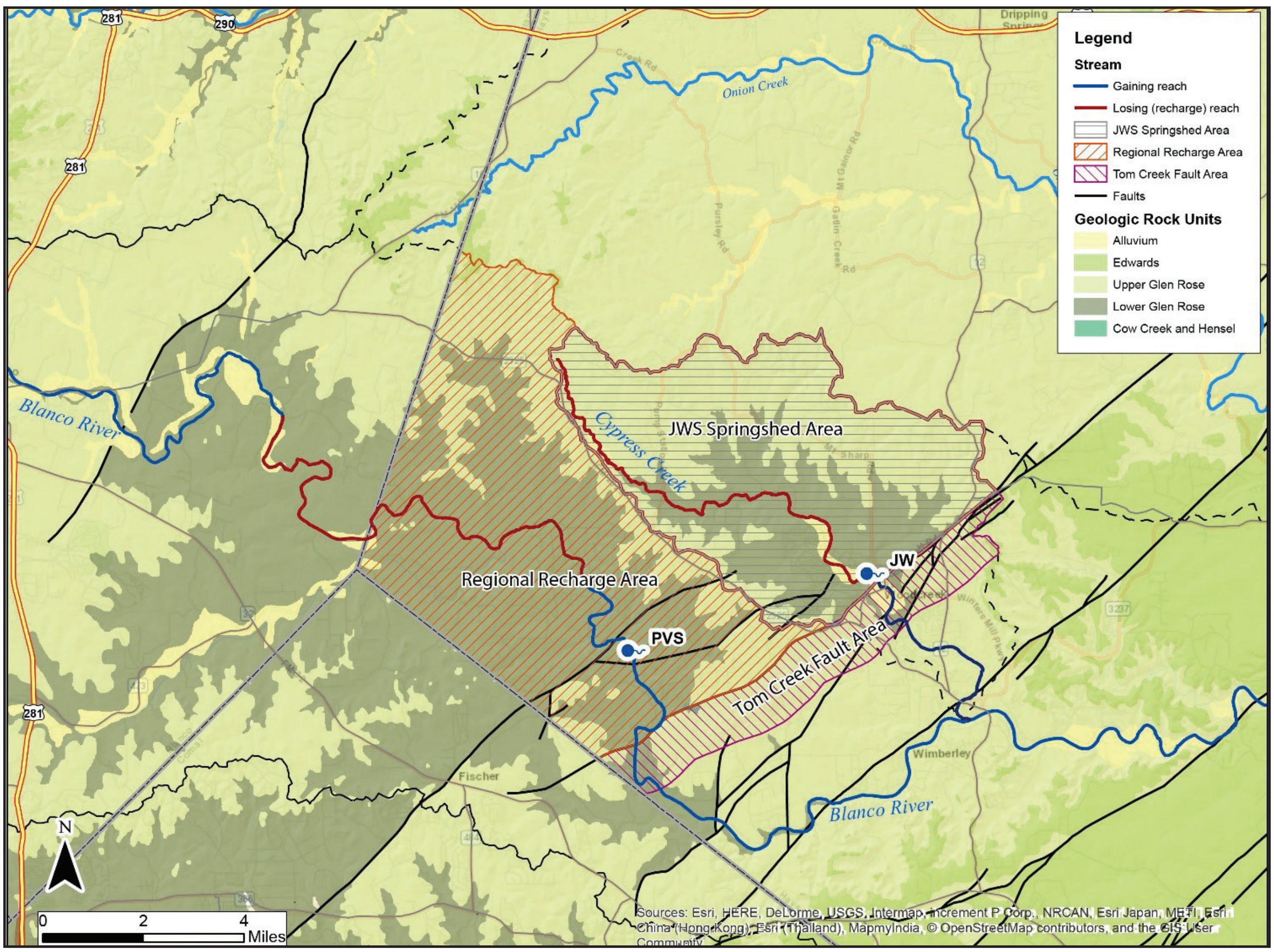
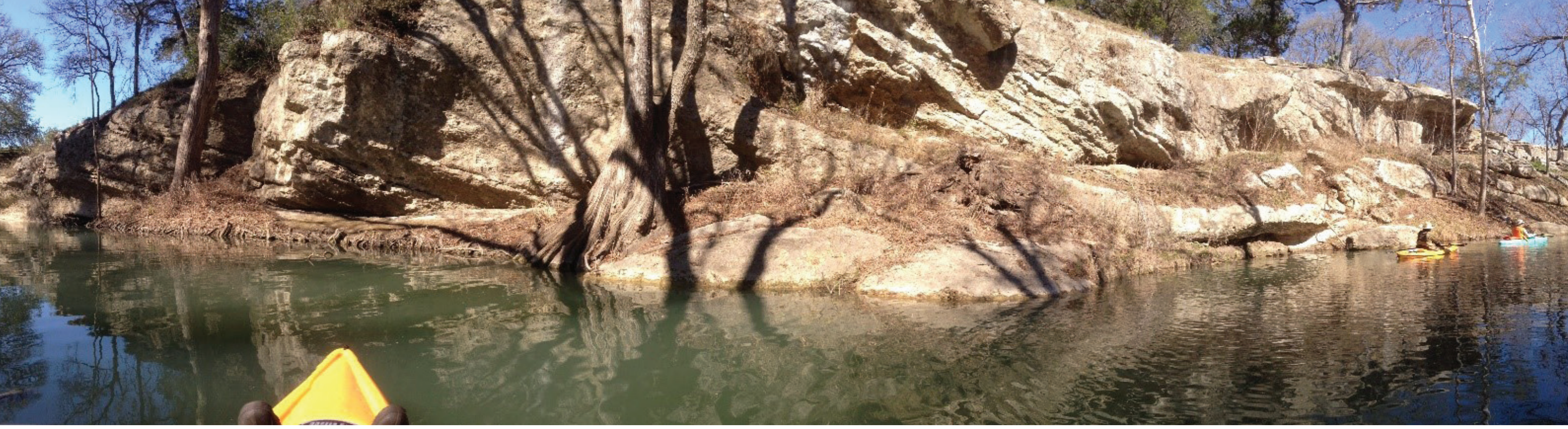


Figure 11. Summary map of defined hydrologic areas related to Jacob's Well springflow.



// Photo 6. Titled beds of Lower Glen Rose in Tom Creek Fault Zone.

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TOM CREEK FAULT AREA

The Tom Creek Fault Area is an area down gradient from Jacob's Well and extends approximately one mile southeast of the Jacob's Well Springshed (**Figure 11**). The Tom Creek Fault area is mapped to the southwest below the Regional Recharge Area. Pumping data and water-level monitoring data collected since 2008 in the Jacob's Well Springshed and portions of the Tom Creek Fault Area indicate these areas are hydraulically connected (Wierman and Hunt 2018). This applies to the Tom Creek Fault Area within the Cypress Creek watershed.

Wells located south and east of the Tom Creek Fault Area (down dip) are more deeply confined and show a different water-level response to recharge events than updip wells within the Jacob's Well Springshed and Tom Creek Fault Area (**Figure 13**). In some places east of the Tom Creek Fault Area, the water levels are as much as 200 feet lower than water levels in the Jacob's Well Springshed. The difference in water levels and hydrologic response indicates that the eastern edge of the Tom Creek Fault Area represents a partial hydrologic barrier or a relatively impermeable restriction to horizontal flow in certain areas. East of the Tom Creek Fault Area, pumping is less likely to have a short-term impact on Jacob's Well flow. Additional studies are necessary to determine how long-term drawdown of the aquifer due to pumping in this region would impact springflow.

Pumping Test Data

The following description from Wierman and others (2008) of a pump test performed in 2007 indicates the relationship of large-scale pumping and discharge at Jacob's Well (**Figures 12 and 13**).

In December 2007, a pump test (Wet Rock 2008) performed at a proposed public water-supply well near Jacob's Well indicated that the pumping of high capacity wells in the vicinity of Jacob's Well caused cyclical variations in base flow discharge. A daily cycle of base flow increases and decreases occurs at Jacob's Well. There are typically three cycles per day with a magnitude of approximately 1 cubic feet per second. The test well (WC23) is located approximately 5,800 feet northwest from Jacob's Well. During the pump test, transducers were placed in two other nearby public water-supply wells, WC 21 and WC22, to observe changes in water levels. WC23 was pumped at 325 gallons per minute for approximately two days. WC21 and WC22 continued their normal pumping cycles during the pump test. When water levels for WC21 and WC23 are overlain with Jacob's Well discharge for the same period of time, WC21 shows a direct correlation between pumping cycles and cycles of Jacob's Well discharge. Discharge from Jacob's well is reduced by approximately 1 cubic feet per second during each pumping cycle from WC21. Drawdown from pumping at WC23 caused a decrease in discharge at Jacob's Well. The pump test indicates that WC21 and WC23 are in direct communication with Jacob's Well and discharges from the water-supply wells cause a reduction flow at Jacob's Well and Cypress Creek. Pumping from WC23 during the test did not appear to have a significant impact on water levels at WC22, possible because WC22 is significantly further away from Jacob's Well and WC23 than WC21.

Transducer (Continuous Monitoring) Wells

We evaluated groundwater-level data in the vicinity of Jacob's Well to aid in characterizing the hydrogeologic relationship between structure, hydrostratigraphy (aquifers), and Jacob's Well. The District has deployed a number of pressure transducers in wells (transducer wells) in the Jacob's Well Springshed and Tom Creek Fault Area to automate groundwater-level data collection (**Figure 13**). Operators of public water-supply system wells are required to measure water levels monthly and report the results on a quarterly basis. The monitoring results provide insight into the hydrogeologic relationship of the wells to the spring and aquifers (Wierman and Hunt 2018).

During major rainfall (recharge) events, groundwater levels and discharge from Jacob's Well rise very rapidly due to the karstic nature of the Middle Trinity Aquifer units (**Figure 14**). Groundwater elevations in wells in the Jacob's Well Springshed and Tom Creek Fault Area within Cypress Creek (referred to as the updip area) have similar levels in the 920 to 925 feet range and fluctuate only a few feet except during major

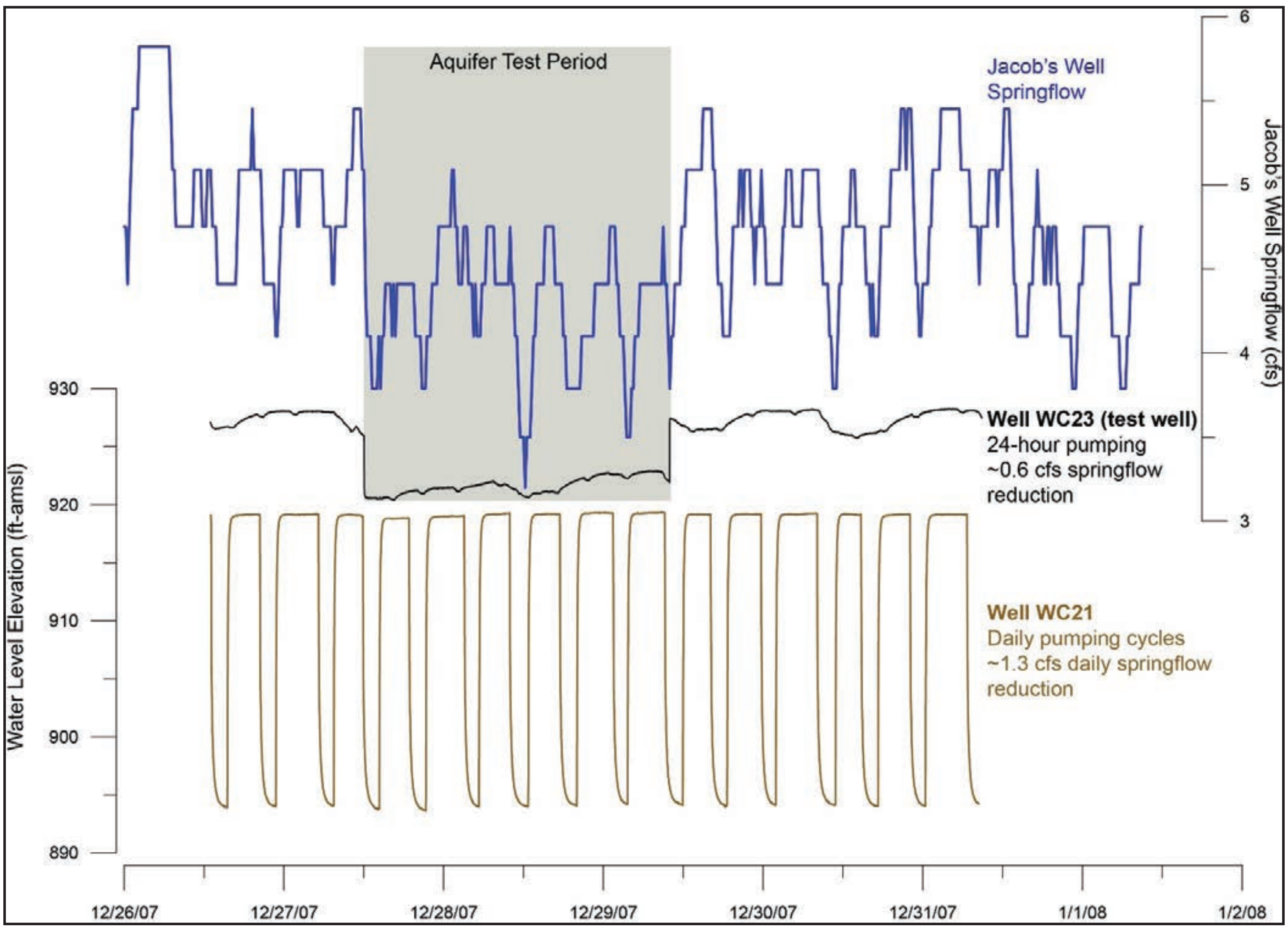


Figure 12. Hydrograph of the WC23 pump test with the test period shaded. Both wells WC21 and WC23 show an influence on the flows at Jacob's Well. Location of wells shown on Figure 13. (cfs = cubic feet per second, ft-amsl = feet above mean sea level)

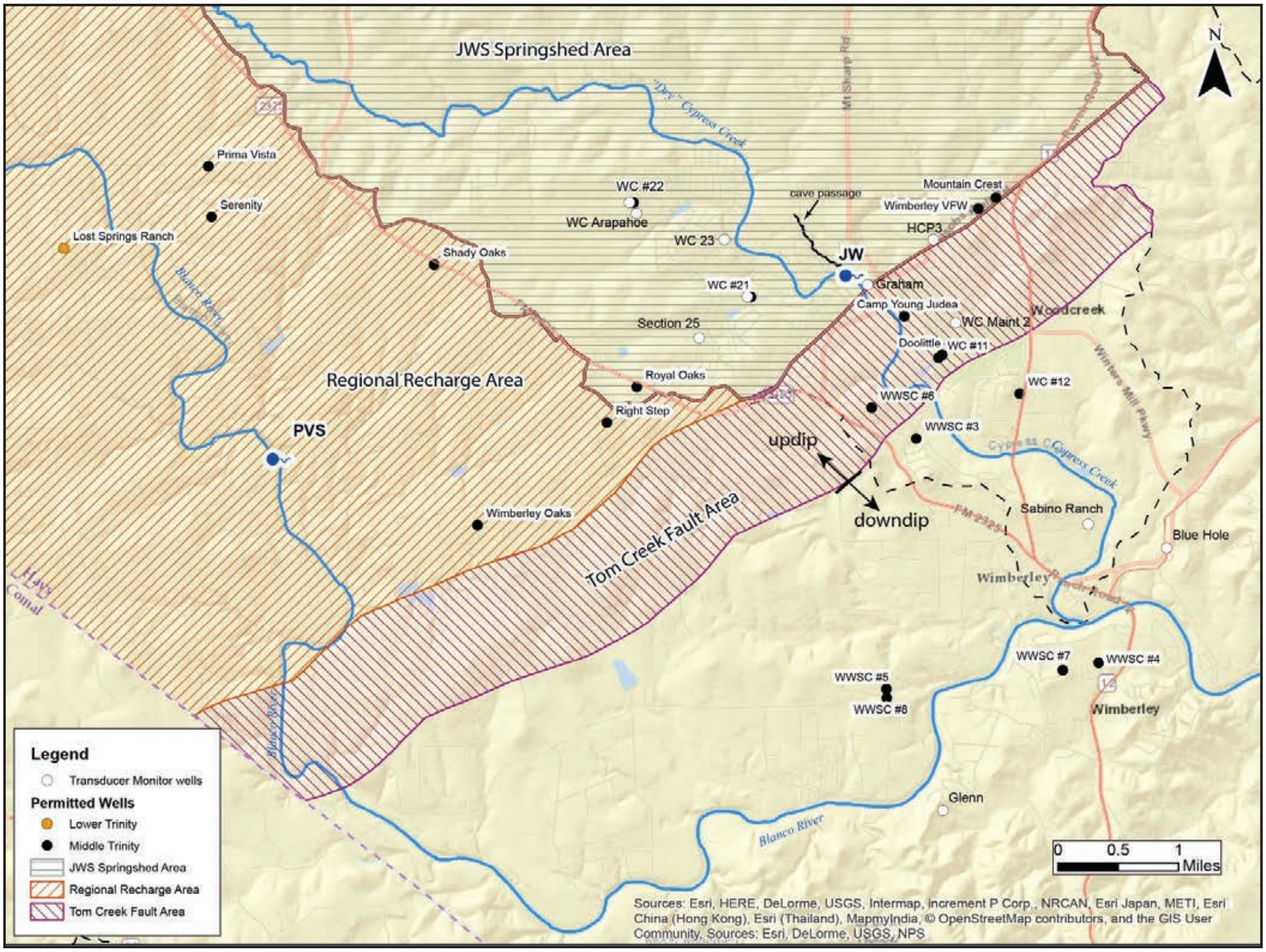


Figure 13. Location of transducer (monitor) and public water system wells in the study area. Note the up-dip area corresponds to wells located within the Tom Creek Fault Area and Jacob's Well Springshed areas. (JW = Jacob's Well Spring)

precipitation events. These potentiometric elevations are very similar to and only slightly higher than the elevations of Jacob's Well and Pleasant Valley Spring. It appears the opening of Jacobs Well and the karst conduits is a dominant hydrologic feature that controls the heads upgradient of the spring within Cypress Creek (Watson and others 2014). To use an analogy from hydraulics, Jacob's Well acts as a "relief valve" for head build up in the Middle Trinity Aquifer. Dynamic and large magnitude head changes have been observed in wells in the Jacob's Well Springshed and Tom Creek Fault Area during major precipitation events and are accompanied by rapid increases in discharge at Jacob's Well, but these increased water levels and discharge dissipate quickly.

Groundwater levels located down dip and east of the Tom Creek Fault Zone (down dip wells) show a very different behavior to recharge events. Two Middle Trinity wells located down dip of the Tom Creek Fault Zone, Glenn and Sabino Ranch, have water-level elevations as much as 200 feet lower than the up-dip wells (**Figure 13**). The difference in water levels indicates the fault is acting as a partial hydrologic barrier, or relatively impermeable restriction to horizontal flow, in that area. Due to several hundred feet of displacement across the fault zone, the Upper Glen Rose may be juxtaposed against the Middle Trinity (**Figure 4**). Water-level trends in down-dip wells generally do not mimic the flat trend of water levels in the Jacob's Well Springshed and the Tom Creek Fault

Area and appear to fluctuate more gradually to wet and drought cycles than individual precipitation events.

The difference in water-level response between wells in the Jacob's Well Springshed and the Tom Creek Fault Area and wells in the down dip area may be related to recharge and groundwater flow rates. The up-dip area is characterized by surface exposure of the Lower Glen Rose member with well-developed karst. Infiltration of precipitation is rapid, as evidenced by the rapid water-level rises and increased discharge at Jacob's Well (**Figure 14**). The Middle Trinity Aquifer monitored in the down-dip wells is significantly deeper within the geologic section resulting in a longer, slower, vertical or lateral recharge pathway. As discussed in the following section, in contrast to the public water-supply wells, no long-term trends are clearly demonstrated by the two transducer wells down dip of the fault zone.

Public Water-Supply Well Water-Level Data

Groundwater elevations in the public water-supply wells (**Figure 15**) show a similar trend to the transducer wells (**Figure 14**). Wells located in the up-dip area tend to maintain water levels close to the level of Jacob's Well and do not significantly fluctuate over time, similar to the up-dip transducer wells. Public water-supply wells in the up-dip area are likely to impact flow from Jacob's Well. Major precipitation events are not as noticeable in the public water-supply wells as with the transducer wells, which is likely due to the data collection frequency and short-term drawdown "noise" from the

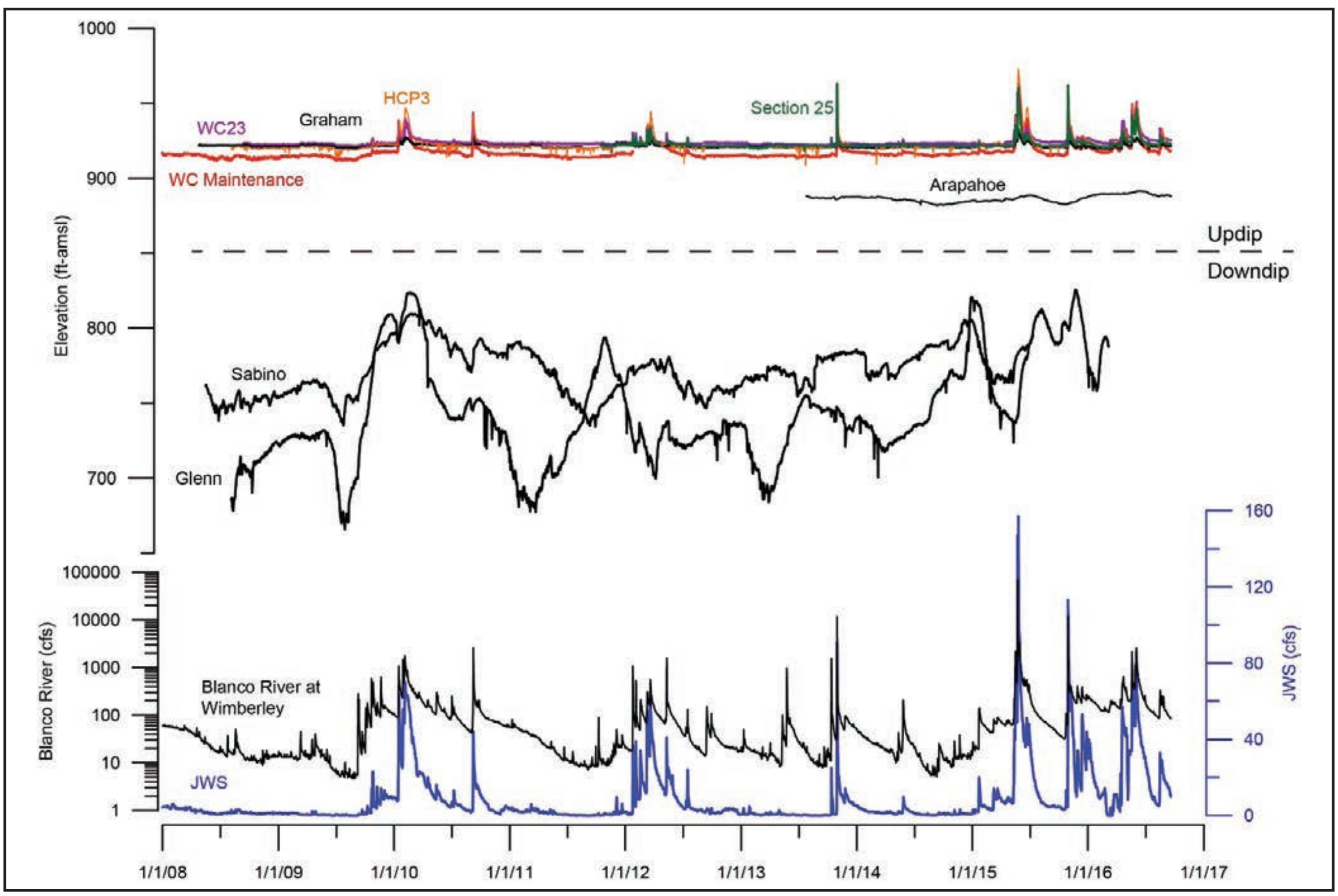


Figure 14. Daily hydrographs of transducer (monitor) wells and Jacob's Well and Blanco River discharge. (cfs = cubic feet per second, ft-amsl = feet above mean sea level, JWS = Jacob's Well Spring)

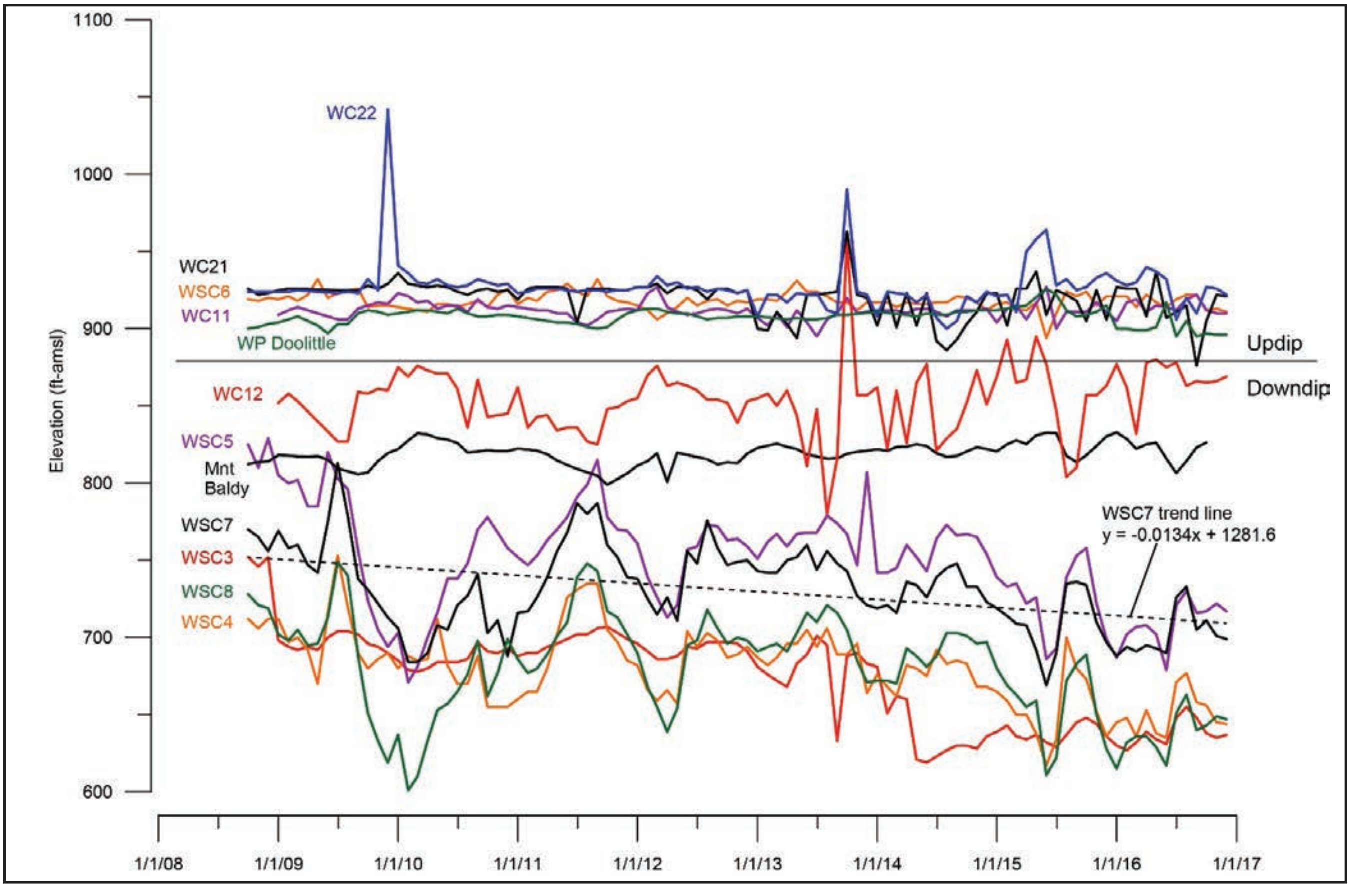
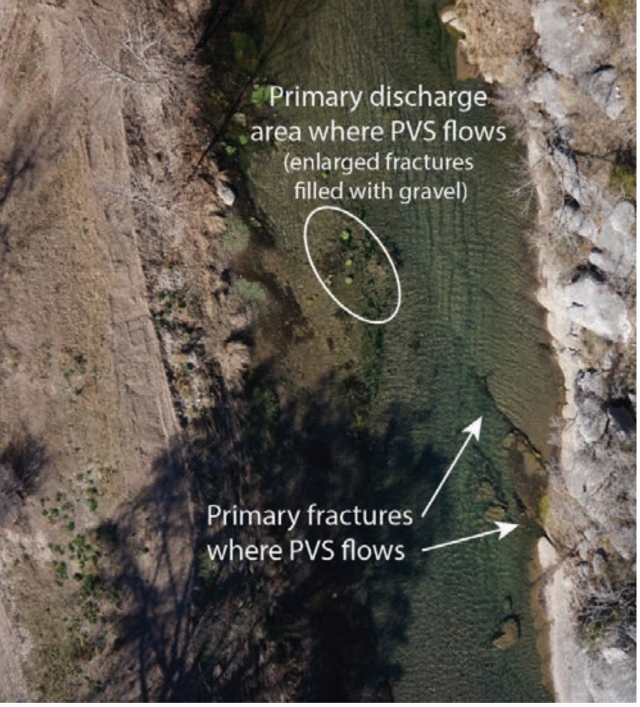


Figure 15. Monthly water-level hydrographs from public water-supply wells in the Wimberley Valley. From Hunt and Wierman (2017). Several public water-supply wells in the downdip portion have decreasing trends. A trend line for WSC7 indicates a declining water level trend of about 4.9 feet per year.

pumping wells. Public water-supply wells on the downdip side of the Tom Creek Fault Area follow the same trends as the down dip transducer wells (Glenn and Sabino). The long-term water level trend in five of the six public water-supply wells on the down dip side of the fault is downward. Water levels decrease between 3 to 11 feet per year, whereas wells on the up-dip side of the fault in the Jacob's Well Springshed and Tom Creek Fault Area do not show a trend either upwards or downwards. However, the lack of clear trend in the updip wells may be a function of the small range of fluctuation and the precision of instruments to measure small changes.

REGIONAL RECHARGE AREA

Most recharge sustaining Jacob's Well originates from the Jacob's Well Springshed (**Figure 11**). However, recharge to the Cow Creek unit of the Middle Trinity Aquifer occurs over a much larger area of western Hays, Blanco, Comal, and Kendall counties. During drought periods, this area may also provide some flow to Jacob's Well when recharge in the springshed is diminished. The area of this regional recharge within the jurisdiction of the District that may contribute flows to Jacob's Well is shown in **Figure 11** and defined here as the Regional Recharge Area. This area is bounded by the Guadalupe (Blanco) River Basin watershed to the north, the Hays-Blanco county line to the west, the Hays-Comal county line to the southwest, the Tom Creek Fault Area to the southeast, and the Jacob's Well Springshed to the east. This area also corresponds to a portion of the springshed for Pleasant Valley Spring, another important karst spring



// Photo 7. (left) Aerial view of Pleasant Valley Spring on the Blanco River (PVS = Pleasant Valley Spring).

© Marcus Gary

Photo 8. (right) Spring orifice of Pleasant Valley Spring in the bed of the Blanco River.

discharging into the Blanco River upstream of the City of Wimberley. During drought, Pleasant Valley Spring is the sole contributor of baseflow to the Blanco River in Hays County.

The surface geology for the Regional Recharge Area consists primarily of the Lower Glen Rose limestone except for higher elevations along the ridge between the Blanco River and Cypress Creek where Upper Glen Rose is present (**Figures 2 and 4**). Some smaller exposures of Cow Creek limestone and the Hensel are present in some areas in the riverbed of the Blanco River in the Burnett Ranch Estates, near the Valley View Road low water crossing. Although these outcrops of Cow Creek are spatially limited, they are important for directly recharging the Cow Creek section of the Middle Trinity Aquifer (Smith and others 2018). From the Burnett Ranch Estates downstream to the Fischer Store Road bridge is the "spring reach" of the Blanco River. This reach is characterized by a number of mostly-perennial springs in the upper segment and, ending at Pleasant Valley Spring, the largest documented spring from the Hill Country Middle Trinity aquifer. Flow from the Blanco River spring reach provides all the flow in the river in the Wimberley area under most conditions, and particularly during drought conditions.

The relevance of the Regional Recharge Area to springflow at Jacob's Well is related to the eastward dip of geologic units, fracturing/faulting, and the extensive karstification in this area. The areas where the Lower Glen Rose is exposed in the Blanco River and Cypress Creek watershed closely link the surface water and groundwater systems. Indeed, both the Blanco River and Cypress Creek are losing (recharging the aquifer) streams within these areas (**Figure 11**). Additionally, regional groundwater flow in the Middle Trinity Aquifer is from west to east along the geologic dip of the beds in eastern Blanco and western Hays counties, indicating that some portion of recharge occurring in the Regional Recharge Area moves toward the Jacob's Well Springshed.

Groundwater-Surface Water Interaction

Groundwater flow in the Regional Recharge Area is described under the Geologic and Hydrogeologic Setting Section, and its direction is shown in **Figure 7**. In the Regional Recharge Area, groundwater in the Middle Trinity Aquifer and surface water in the Blanco River are closely integrated. To the west of Hays County, flow in the Blanco River generally increases with distance downstream. This increase in flow is from numerous small springs that emerge from (listed upstream to downstream) the base of the Edwards (Plateau) limestone, Upper Glen Rose limestone, and Lower Glen Rose limestone. As the Blanco River enters Hays County, water enters a reach that rapidly recharges the Middle Trinity Aquifer. This reach extends from upstream of the Narrows near Chimney Valley Road down to the low water crossing at Valley View Road in Burnett Ranch Estates. This reach has outcrops of Lower Glen Rose, Hensel, and Cow Creek Limestone, and is dry or has ephemeral low flow rates. Downstream of Valley View Road, a series of Middle Trinity Aquifer springs emerge (spring reach), and provide base flow to the Blanco River downstream of this location until the river encounters the Edwards Aquifer recharge zone (**Figure 16**). These springs flow from the Cow Creek portion of the Middle Trinity Aquifer, as does Jacob's Well, and appear to be associated with faults. The first spring in the spring reach of the Blanco River is Little Park Spring, which has flow rates ranging from 0 to 3 cubic feet per second under most conditions and short-term higher rates following large recharge events. This spring ceases to flow under drought conditions. Just below Little Park Spring, Park Spring contributes 0.5 to 8 cubic feet per second under most conditions and maintains some small flow even during drought periods. Downstream of Park Springs, a series of smaller springs and recharge features exist in the Blanco River that contribute flow to the river in wetter periods but collect water from Park Springs under drier conditions. Miller Spring is a large ephemeral spring with flows up to 50 cfs, which stops flowing and recharges the aquifer during low-flow periods (this type of feature is known as an estavelle, **Figure 17**). Finally, the terminal perennial Middle Trinity spring on the Blanco River is Pleasant Valley Spring, just upstream of the Fischer Store Road bridge.

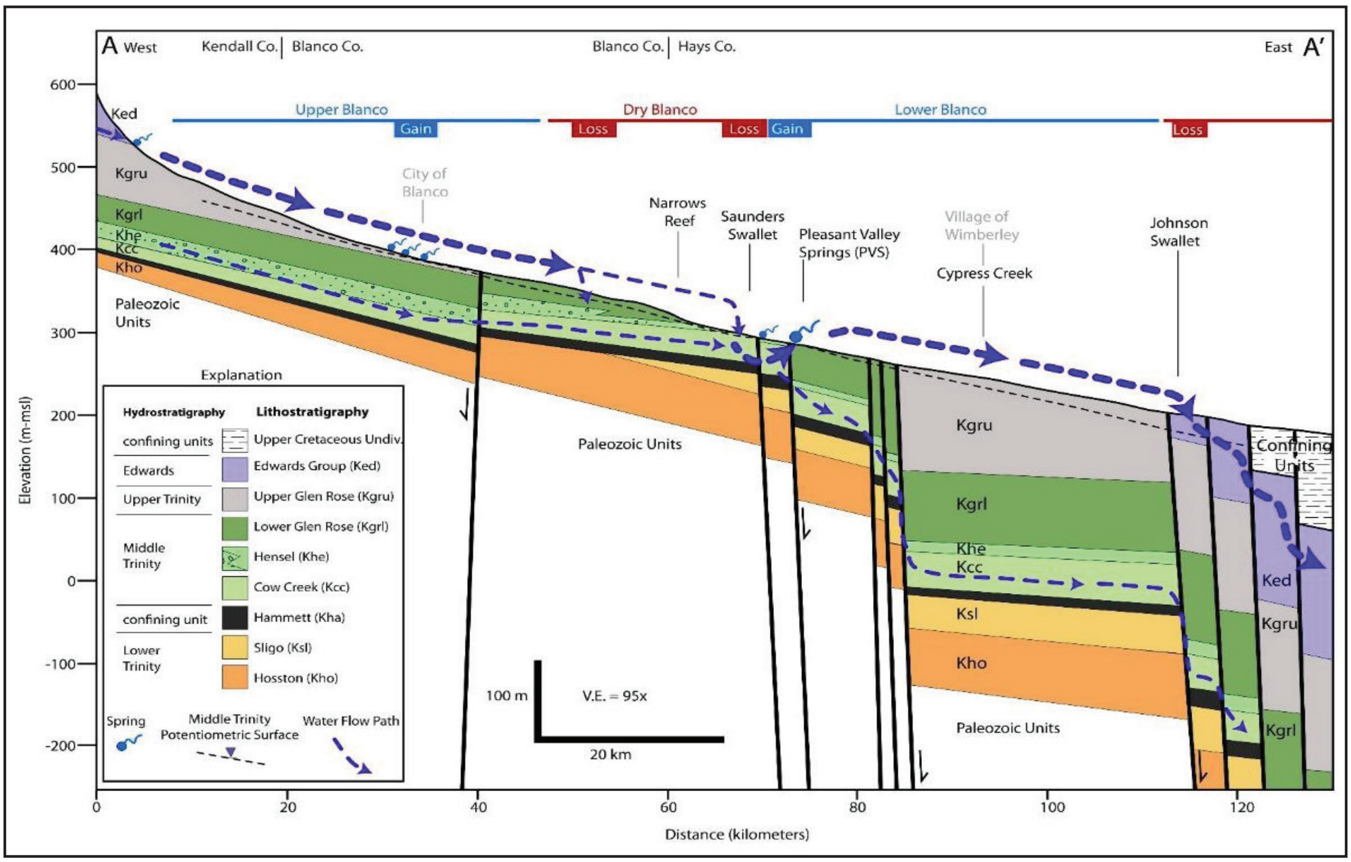


Figure 16. Conceptual cross section of the entire Blanco River showing surface-water/groundwater interaction (from Smith and others, 2015). (co. = county, km = kilometers, m = meters, m-msl = meters above mean sea level, undiv. = undivided, V.E. = vertical exaggeration)

These alternating gaining and losing segments of the Blanco River are shown in **Figure 11 and 16**, and a detailed cross section of the Middle Trinity spring reach is shown in **Figure 17**.

Pleasant Valley Spring is the largest documented spring in the Hill Country Trinity Aquifer. This perennial spring has a measured range from 12 to 60 cubic feet per second but most notably maintains high rates of springflow under all hydrologic conditions, including drought (**Figure 8**). Pleasant Valley Spring's elevation is nearly the same as Jacob's Well's elevation, and it appears to lie in the same fault block as Jacob's Well, immediately up-dip of the Tom Creek Fault. Although the karst conduit is not accessible by cave divers at Pleasant Valley Spring, it is hypothesized that the Cow Creek formation is the primary contributor to flow at the spring and was recently confirmed by dye tracing (Smith et al. 2018). Flow from the spring reach of the Blanco River can be quantified by a pair of U.S. Geological Survey stream gages that bracket this reach. The difference in flow at the upstream gage at Valley View Road and flow at the downstream gage at Fischer Store Road can be used to quantify to total Middle Trinity Aquifer springflow in the Blanco River.

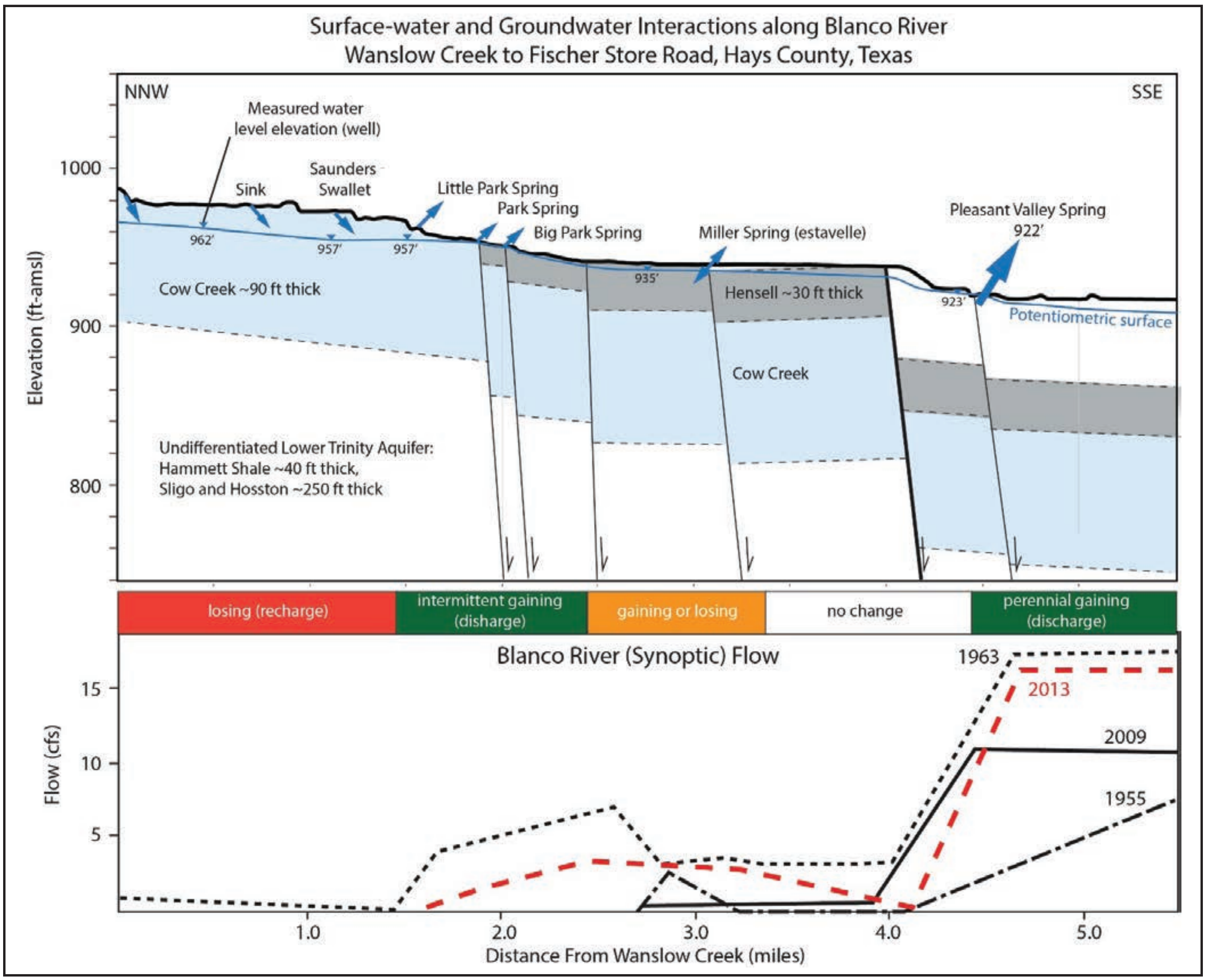


Figure 17. Detailed cross section and flow rate graph show the surface-water/groundwater interaction of the spring reach of the Blanco River from Gary and others, 2013). Synoptic Blanco River flows indicates flows that occurred within a short period of time, generally less than a few weeks. Synpotic flow events were made during low-flow conditions.

SPRINGFLOW AND PUMPING

Developing a framework for protecting Jacob's Well flow requires a detailed understanding and quantification of the springflow and how it has changed over time. Jacob's Well flow has been measured by various entities since 1924 (Brune 2002, TBWE 1960, USGS 2017a). Historic flow measurements and estimates between 1924 and 1974 show Jacob's Well flow ranging between 0.2 (estimated) and 12.1 cubic feet per second (**Table 3**). In addition, the U.S. Geological Survey has periodically measured flow at the Blanco River downstream of its confluence with Cypress Creek since 1924 (USGS 2019b). This gage is known as the Blanco River at Wimberley gage (**Figure 14**) and provides some control on Jacob's Well flow values because measured flow at the gage represents the sum of Cypress Creek flow (sustained by Jacob's Well baseflow) and the Blanco River. During dry conditions, baseflow in the Blanco River at Wimberley are mostly derived from Pleasant Valley Spring about 12 miles upstream of the gage (**Figures 2 and 8**).

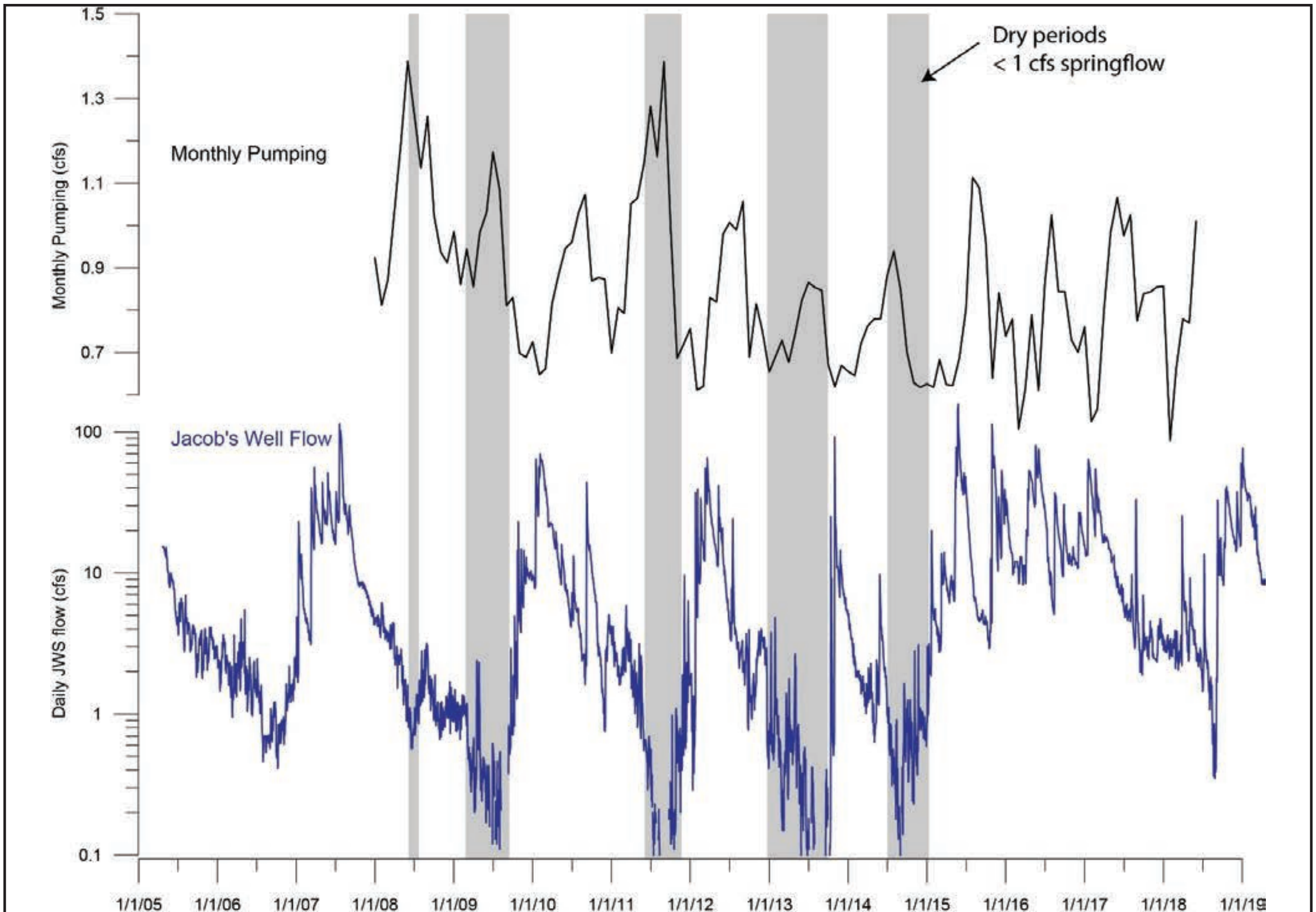
In April 2005, the U.S. Geological Survey installed a gage at Jacob's Well which reports continuous flow data (USGS 2019a). Data from this gage allow the evaluation of how Jacob's Well responds to drought and wet periods over the gage's 13-year period of record. Like other karst springs, Jacob's Well flow is sensitive to extreme climate events such as drought and flooding, which are reflected in the range of flow values. Jacob's Well flow reflects the effects of drought periods and pumping. Since April 2005, Jacob's Well flow has ceased during four drought periods (2009, 2011, 2013, and 2014; **Figure 18**).

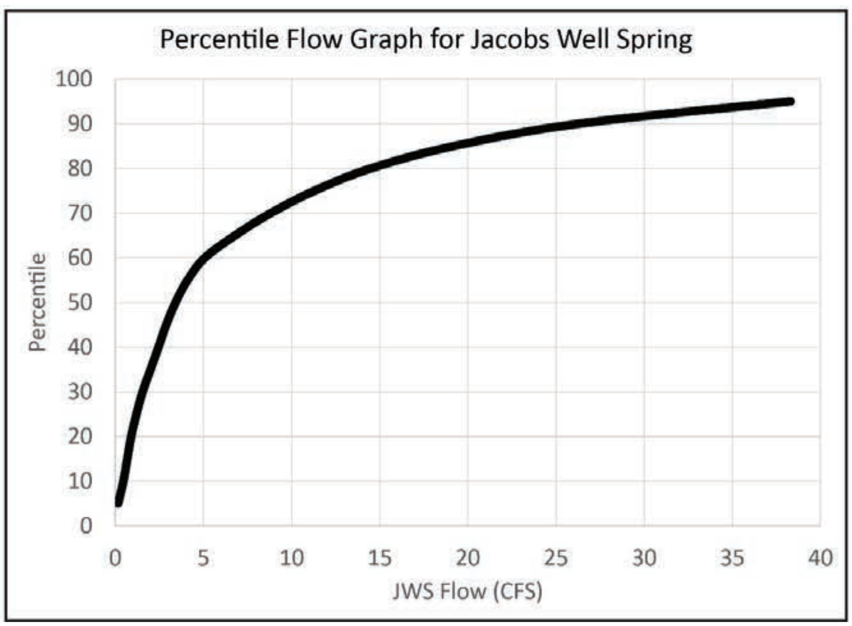
Since 2005, measured daily flow values at Jacob's Well range from 0 to greater than 150 cubic feet per second (Figure 18). Jacob's Well daily average flow is 9.2 cubic feet per second and the median flow value is 3.4 cubic feet per second. The range of monthly mean flows reported by the U.S. Geological Survey is 0 to 55 cubic feet per second with an average of 9.2 cubic feet per second and a median of 3.6 cubic feet per second. Some of the higher flow values are likely biased high as they include storm event runoff of surface water in Dry Cypress Creek.

Table 3: Historic manual flow measurements available for Jacob's Well between 1924 and 1974.

Date	Jacob's Well Flow (cfs)	Source
8/5/1924	6	Brune (2002)
10/28/1937	6	Brune (2002)
12/6/1937	2.9	Brune (2002)
1/6/1955	2.4	Brune (2002)
1/24/1955	2.6	TBWE (1960)
3/5/1955	2.6	TBWE (1960)
7/10/1955	12.1	TBWE (1960)
8/15/1956	0.2*	Inferred from (USGS 2019b); end of the 1950's Drought of Record
4/4/1962	4.2	Brune (2002)
7/10/1974	3.5	Brune (2002)

**Estimate by the authors based on reported flow at the Blanco River Gage was 0.86 cubic feet per second for this date. Jacob's Well flow is inferred to be 25 percent of Blanco River flow based on Jacob's Well flow measurements during 1955 drought of record (TBWE 1960).*





Percentile Analysis	
Percent	Flow (CFS)
95	38.3
90	26.3
85	19.2
80	14.5
75	11.3
70	8.8
65	6.78
60	5.1
55	4.1
50	3.4
45	2.9
40	2.5
35	2.0
30	1.6
25	1.2
20	0.9
15	0.7
10	0.5
5	0.2

Figure 18. (Top) Hydrograph of daily mean Jacob's Well flow from April 2005 to April 2019 and monthly pumping data from major public water-supply wells near to Jacob's Well. Jacob's Well has stopped flowing on four occasions during this period (2009, 2011, 2013, and 2014). Shaded areas indicate periods of drought with springflow less than 1.0 cfs. (Bottom) Cumulative probability plot of daily average Jacob's Well flow from April 2005 to April 2019. (cfs, CFS = cubic feet per second, JWS = Jacob's Well Spring)

Because Jacob's Well springflow is particularly vulnerable during times of drought, it is during these periods that the spring is likely to be most impacted by groundwater pumping (**Figure 12**). Understanding pumping trends in the vicinity of Jacob's Well provides an important step toward quantifying potential impacts of pumping on springflow.

Groundwater production within District can be divided into two categories: (1) exempt, defined as domestic or agricultural use and (2) non-exempt, defined as commercial, industrial, or other business use. As specified by the District's enabling act, non-exempt water users are required to obtain an operating permit and report metered monthly pumping to the District, while exempt users do not have these requirements.

EXEMPT PUMPING IN JACOB'S WELL SPRINGSHED

We conducted an evaluation to estimate the number of exempt wells and an associated volume of pumping for those wells. We constrained the evaluation to the Dry Cypress Creek Watershed (**Figure 2**) with a 1-mile buffer applied to its boundaries. This area captures all of the Jacob's Well Springshed and the Tom Creek Fault Area within the Cypress Creek area.

State well records indicate there are about 326 wells in the Jacob's Well Springshed and Tom Creek Fault Area. These consist of 53 wells listed in the Texas Water Development Board Groundwater Database and 273 wells listed in the Submitted Well Driller's Report database (which only includes wells drilled since 2001). To provide a better estimate of the number of the exempt wells in the area of interest, we used geographic information system software to select lots (Hays Central Appraisal District data from 2018) that had acreage within the area of interest and were outside an area with a certificate of convenience and necessity such as Woodcreek and Wimberley Water Supply Corporation. Hays Central Appraisal District data provides a general description of improvements on a lot, such as residential, commercial, mobile home, or miscellaneous. It is assumed that any lot outside of the certificate of convenience and necessity with an improvement must have a well for water supply. Using geographic information system and Microsoft Access databases, we counted those lots with improvements. We estimate that the total number of wells to be about 1,082 (**Table 6**). **Table 7** provides a range of estimates of pumping from these exempt wells using a high and low per capita value.

Table 4. Types of improvements and estimated number of exempt wells.

Description	Count
Commercial	33
Misc. Improvement	150
Mobile Home	70
Residential	829
Total	**1,082**

Table 5. Pumping estimates using two different usage per capita estimates.

Number of Houses	Use per House (gal/yr)	Volume (gal/yr)	Vol (gal/d)	Vol (MGD)	cfs
1082	120,450 (330 gpd*)	130,326,900	357,060.00	0.36	0.55
1082	70,000**	75,740,000	207,506.85	0.21	0.32

**based on the TWDB per capita water use estimates. **based on City of Austin residential use.*

cfs = cubic meters per second, gal/yr = gallons per year, gpd = gallons per day, MGD = million gallons per day, TWDB = Texas Water Development Board

NON-EXEMPT PUMPING IN JACOB'S WELL SPRINGSHED AND TOM CREEK FAULT AREA

Within the delineated Jacob's Well Springshed there are four non-exempt wells (**Table 4; Figure 13**). Two of these wells are larger-production wells: WC #21 and WC #22 from the Woodcreek phase II permit operated by Aqua Texas. These wells account for about 85 percent of non-exempt pumping within the Jacob's Well Springshed. Total annual permitted volume within the Jacob's Well Springshed is 394.3 acre-feet per year (**Table 5**).

Six non-exempt wells are located within Tom Creek Fault area (WC #11-Woodcreek Phase I permit, Doolittle-Wimberley Springs Partners, and WWSC #6-Wimberley Water Supply Corporation) and account for most of the total reported non-exempt production (**Figure 13**). Total annual permitted volume within the Tom Creek Fault Area is 1,228 acre-feet per year (**Table 5**).

Two of the permit holders within the Tom Creek Fault Area operate wells both inside and outside the boundaries of the delineated Jacob's Well Springshed and Tom Creek Fault Zone. We had to make assumptions to estimate total monthly production within the zone because District permit holders report total monthly production instead of production from individual wells. For the Woodcreek Phase I permit, we assumed that well WC11 accounted for 50 percent of reported production (lumped well #11 and well #12 pumping). For the Wimberley Water Supply Corporation permit, Wimberley Water Supply Corporation provided well-specific pumping data from the WWSC #6 well going back to February 2015. Prior to this date WWSC #6 and WWSC #3 were on the same meter, and Wimberley Water Supply Corporation provided lumped monthly production from both wells. For the lumped data, we assumed WWSC #6 accounted for 50 percent of lumped WWSC #3 and WWSC #6 production.

The Regional Recharge Area has significantly less non-exempt production than the other two delineated areas. There are six non-exempt wells operating within the Regional Recharge Area with a total of 34.3 acre-feet of permitted volume. Up to 16.25 acre-feet is produced from the Lower Trinity Aquifer (Lost Springs Partners permit). Lower Trinity Aquifer pumping is unlikely to influence Jacob's Well flow and was excluded from the analysis.

Table 6. Inventory of non-exempt wells in the vicinity of the Jacob's Well areas of hydrologic influence. Hydrologic area codes: Jacobs's Well Springshed (JW); Tom Creek Fault Area (TCF); Regional Recharge Area (RRA).

Well Name	Permit	Hydrologic Zone	TWDB SWN*	Latitude (DD)**	Longitude (DD)**	Producing Formations
WWSC #3	Wimberley WSC	None	5764707	30.01444	-98.1175	Lower Glen Rose, Cow Creek
WWSC #4	Wimberley WSC	None	6808102	29.98667	-98.09278	Lower Glen Rose, Cow Creek
WWSC #5	Wimberley WSC	None	6808103	29.98389	-98.12222	Lower Glen Rose, Cow Creek
WWSC #6	Wimberley WSC	TCF	5764708	30.01833	-98.12361	Lower Glen Rose, Cow Creek, Cow Creek
WWSC #7	Wimberley WSC	None	6808108	29.98583	-98.09778	Lower Glen Rose, Cow Creek
WWSC #8	Wimberley WSC	None	6808109	29.98278	-98.12222	Lower Glen Rose, Cow Creek, Cow Creek
WC #11	Woodcreek Phase I	TCF	5764702	30.024318	-98.114198	Lower Glen Rose, Cow Creek, Cow Creek
WC #12	Woodcreek Phase I	None	5764711	30.019722	-98.103056	likely Lower Glen Rose, Cow Creek, Cow Creek

Table 6 continued.

Well Name	Permit	Hydrologic	TWDB	Latitude	Longitude	Producing
WC #21	Woodcreek Phase II	JW	5763904	30.03212	-98.14007	LGR, Cow Creek
WC #22	Woodcreek Phase II	JW	NA	30.04387	-98.15613	NA
Doolittle	Wimberley Springs Partners	TCF	NA	30.02463	-98.11373	NA
Mountain Crest	Mountain Crest	JW	NA	30.04376	-98.10591	NA
Right Step	Right Step	RRA	NA	30.01705	-98.16034	NA
Serenity	Serenity	RRA	NA	30.042978	-98.214694	Lower Glen Rose, Cow Creek, Cow Creek
Wimberley VFW	Wimberley VFW	JW	NA	30.042435	-98.108347	NA
Lost Springs Ranch	Lost Springs Ranch	RRA	5763702	30.0394	-98.23522	Hosston (Lower Trinity)
Camp Young Judea	Camp Young Judea	TCF	5764714	30.029444	-98.118889	Lower Glen Rose, Cow Creek, Cow Creek
Shady Oaks	Shady Oaks	RRA	NA	30.036686	-98.183902	NA
Prima Vista	Prima Vista	RRA	NA	30.04917	-98.215	NA
Wimberley Oaks	Wimberley Oaks	RRA	NA	30.004751	-98.178517	NA
Royal Oaks	Royal Oaks	JW	NA	30.021334	-98.15612	NA

NA= not available. Where NA is listed under producing formations those are likely completed in the Middle Trinity

** SWN = State Well Number; ** DD = Decimal Degrees, WSC = water supply corporation.*

Table 7. Non-exempt permitted volume and average production (2016-2018) for delineated areas of hydrologic influence to Jacob's Well (total volume shown on Figure 18).

Hydrologic Area/Permit Holder	Permitted Volume (acre-ft/yr)	Average Production (acre-ft/yr: 2016-2018)
Woodcreek Phase II (WC #21, WC #22)	339	265.9
Royal Oaks	0.043	NA
Wimberley VFW	1.26	0.46
Mountain Crest	54	39.0
JW Catchment Area (total)	**394.3**	**305.4**
WWSC (WC#6)	645	470.7
Woodcreek Phase I (WC#11)	321	220.8
Wimberley Springs Partners	250	47.8
Camp Young Judea	12	17.5
Tom Creek Fault Area* (total)	**1,228**	**756.8**
Lost Springs Ranch**	16.25	7.7
Right Step	9	4.3
Serenity	2.48	2.5
Shady Oaks	1.5	0.3
Prima Vista	0.178	NA
Wimberley Oaks	6.33	4.8
Regional Recharge Area (total)	**35.7**	**19.6**

**Includes all WWSC and WC phase I permitted wells and production, both inside and outside of the delineated TCF area. The WWSC and WC phase I permits each have only one well inside the area (WWSC #6 and WC #11). **Lost Springs Ranch permit produces from a Lower Trinity Aquifer well and is unlikely to influence Jacob's Well.*

Evaluating monthly non-exempt pumping data over time reveals a seasonal pattern of increased groundwater use in the summer months (**Figures 18 and 19**). Over the last 10 years of reporting, permitted pumping has consistently peaked in the summer months (May to September) and remained relatively low in the winter months (**Figure 19**). Because rainfall in Central Texas is typically lower during the summer months, pumping peaks often coincide with periods of hydrologic drought, which are also correlated with periods of low flow at Jacob's Well (**Figures 18 and 20**).

Comparing reported non-exempt and estimated exempt pumping volumes to measured Jacob's Well flow over time allows a quantitative evaluation of potential impacts of pumping to the spring. **Figure 21** provides a graphical representation of monthly pumping estimates and Jacob's Well flow from 2011, a drought year. During the first five months of 2011, average monthly Jacob's Well flow was greater than reported non-exempt pumping (red bar) and estimated exempt pumping (yellow bar) within the Jacob's Well delineated springshed. From June through November 2011, pumping exceeded springflow. In September 2011, non-exempt pumping was approximately double what it was in January 2011 while mean Jacob's Well flow was <0.1 cubic feet per second.

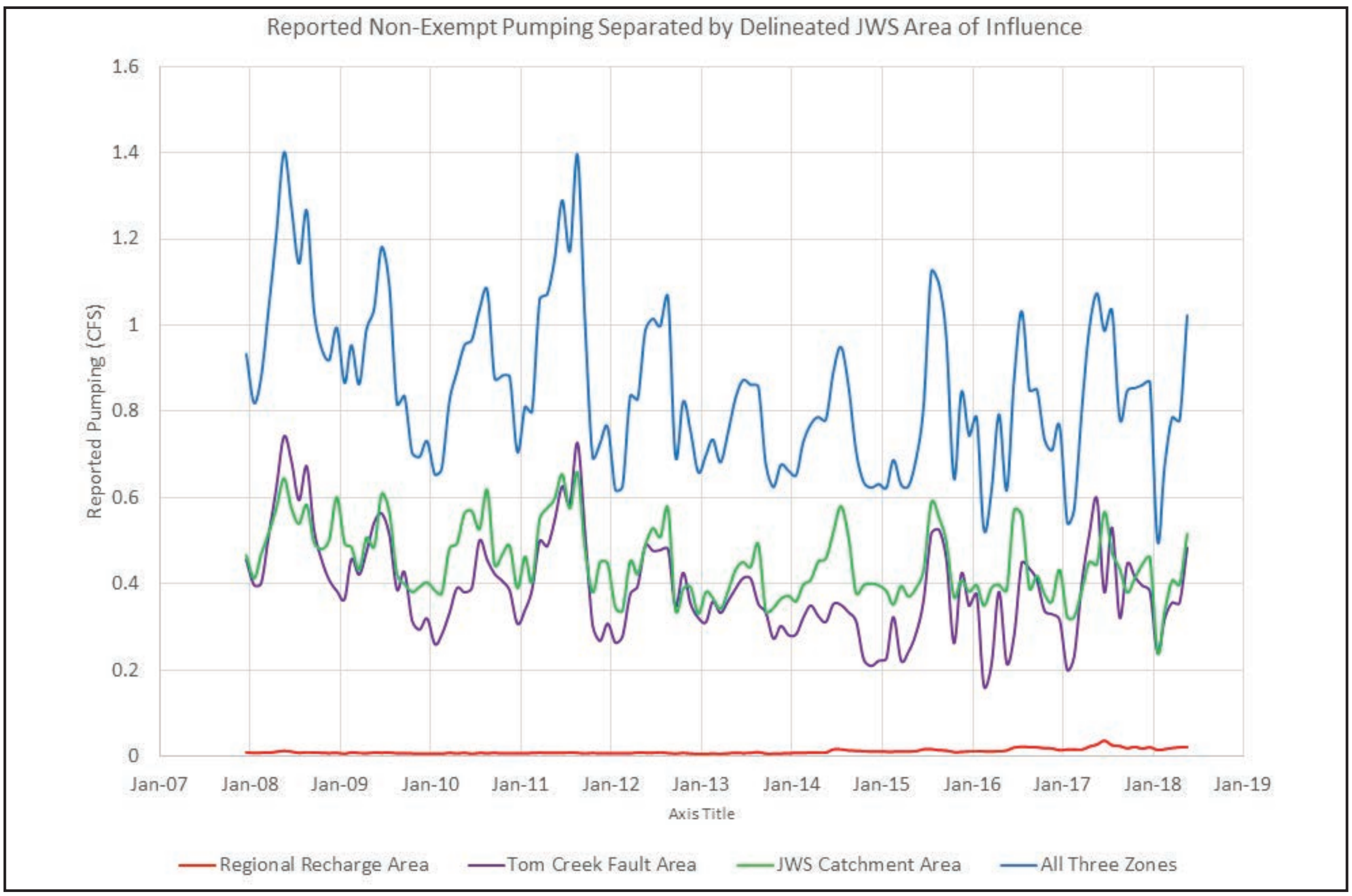


Figure 19: District reported non-exempt pumping in each delineated Jacob's Well area of influence. Distinctive peaks in pumping coincide with the summer months. Tom Creek Fault Area production is estimated. CFS = cubic feet per second, JWS = Jacob's Well Spring

NON-EXEMPT PUMPING DISCUSSION

Curtailment of pumping could be an opportunity to increase flow during drought at Jacob's Well (**Figures 20 and 21; Appendix A**). In practice, the current District drought curtailment measures have not been effective in reducing pumping during the various drought stages (**Appendix A**), and implementing this approach of existing drought reductions may be challenging under the current framework of the District rules. Reported non-exempt pumping within the delineated Jacob's Well areas of influence is significantly lower than the total annual volume permitted (**Table 5**). On average, mean annual groundwater production reported by permit holders is approximately 60 percent of the total permitted volume of 1,871 acre-feet per year. Under current District rules, mandatory drought cutbacks for permit holders curtail pumping based on total permitted volume (not actual pumped volume). As such, the District's mandatory drought cutback rules have a limited effect on reducing pumping within the Jacob's Well Springshed.

Another possible strategy for sustaining Jacob's Well flow in the long-term could be to limit the amount of non-exempt permitted pumping granted for new permit applications in the Jacob's Well Springshed. Reported permitted pumping has not increased from 2008 through 2018 (**Figure 20**). However, pumping could increase if the District granted new permits within the Jacob's Well Springshed. Thus, limiting non-exempt permitted volumes, or implementing conditional permits with stricter cutbacks for future non-exempt applications, could help to sustain flow to Jacob's Well. Similarly, reducing existing non-exempt permitted volumes to be more closely in line with current pumping could help to sustain flow to Jacob's Well by making drought curtailments more effective.

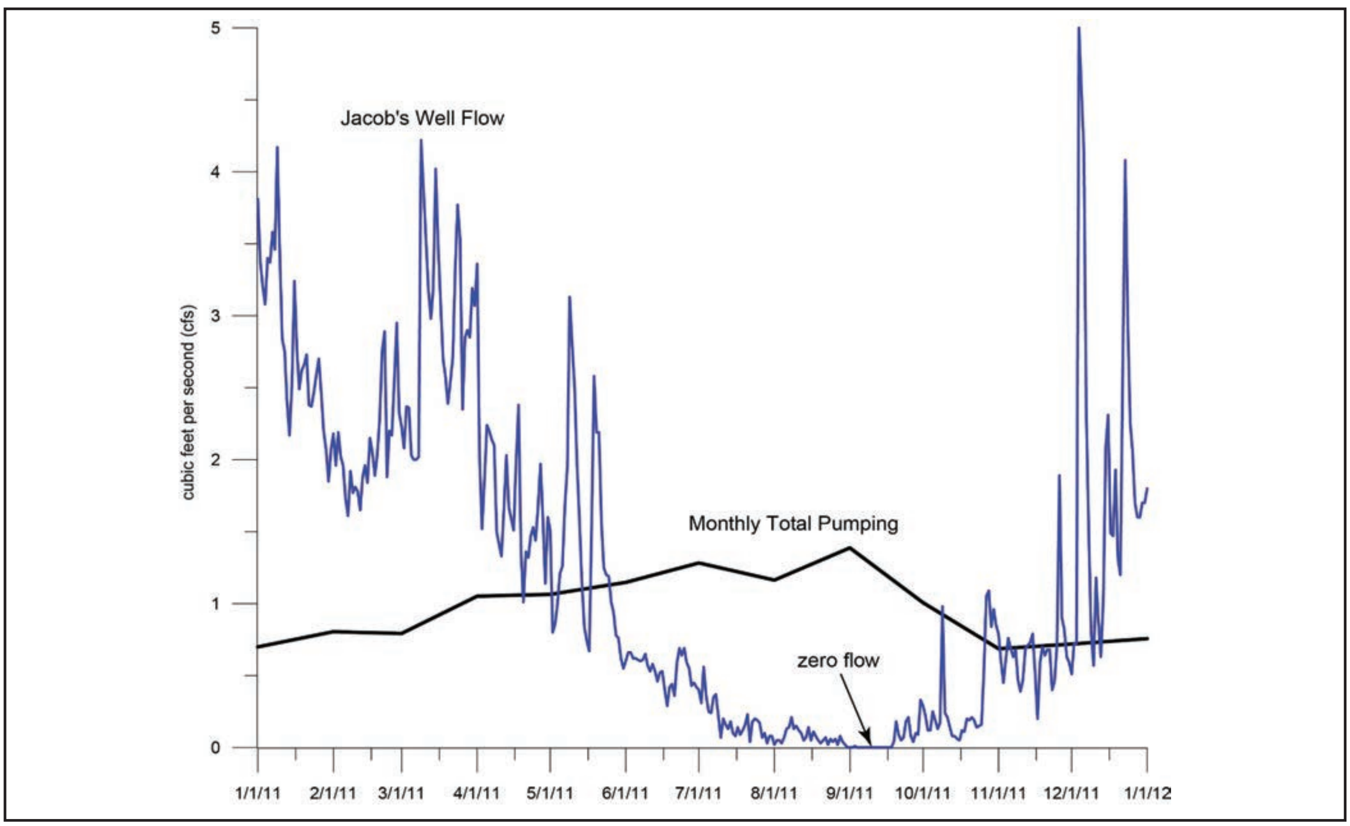


Figure 20. Reported non-exempt pumping in all three areas of influence to Jacob's Well (Jacob's Well Springshed, Tom Creek Fault Area, and Regional Recharge Area) and daily mean Jacob's Well flow during 2011 drought.

// Photo 9. Cypress Creek during drought.

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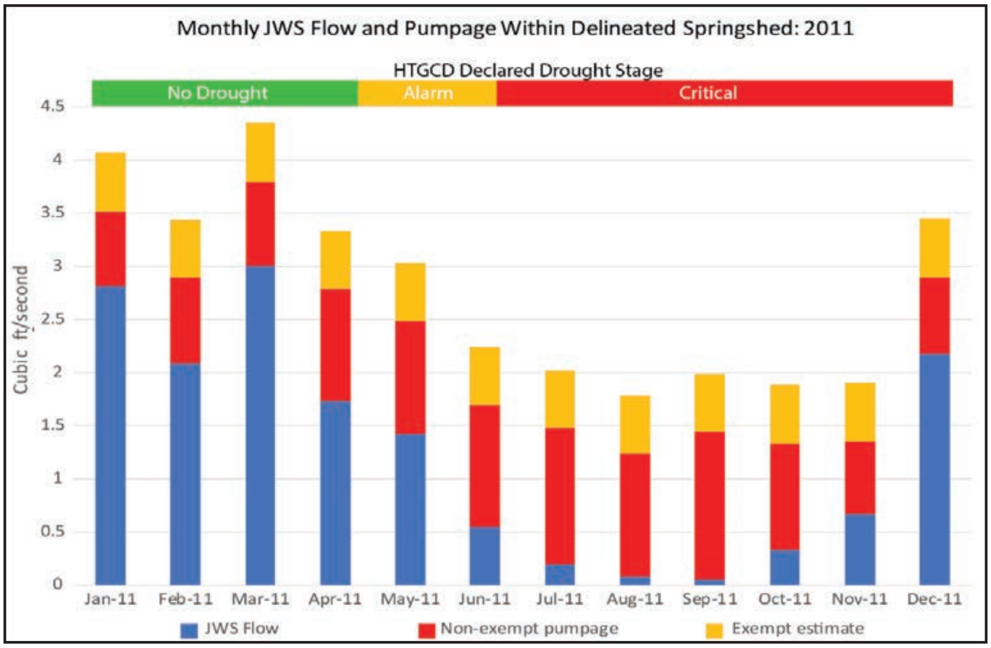

Figure 21. Comparison of Jacob's Well flow and pumping (reported non-exempt and estimated exempt) for 2011, a significant drought year. Monthly pumping values have been averaged to cubic feet per second to allow comparison. (ft = feet, HTGCD = Hays Trinity Groundwater Conservation District, JWS = Jacob's Well Spring)

GROUNDWATER MANAGEMENT ZONES, STRATEGIES, UNCERTAINTIES, AND FUTURE STUDIES

Based on the technical evaluations summarized in this document, we have delineated areas of hydrologic influence to Jacob's Well (**Figure 2**). Jacob's Well flow is most sensitive to recharge and pumping in these areas. As shown in **Figure 22**, the Scientific Technical Committee, with input from the stakeholder group, combined portions of these hydrologic areas into two possible groundwater management zones (**Figure 23**).

INTEGRATION OF STAKEHOLDER INPUT WITH TECHNICAL ANALYSIS

Successful implementation of a Jacob's Well Groundwater Management Zone is based on both technical analyses and input from affected groundwater resource stakeholders in western Hays County. As part of the process the District undertook to evaluate the feasibility and effectiveness of a Jacob's Well Groundwater Management Zone, two committees were formed in 2018, a Scientific Technical Committee and a Stakeholder Advisory Committee. Whereas the roles of these two committees are clearly unique, they both worked in parallel to produce the recommendations provided to the District.

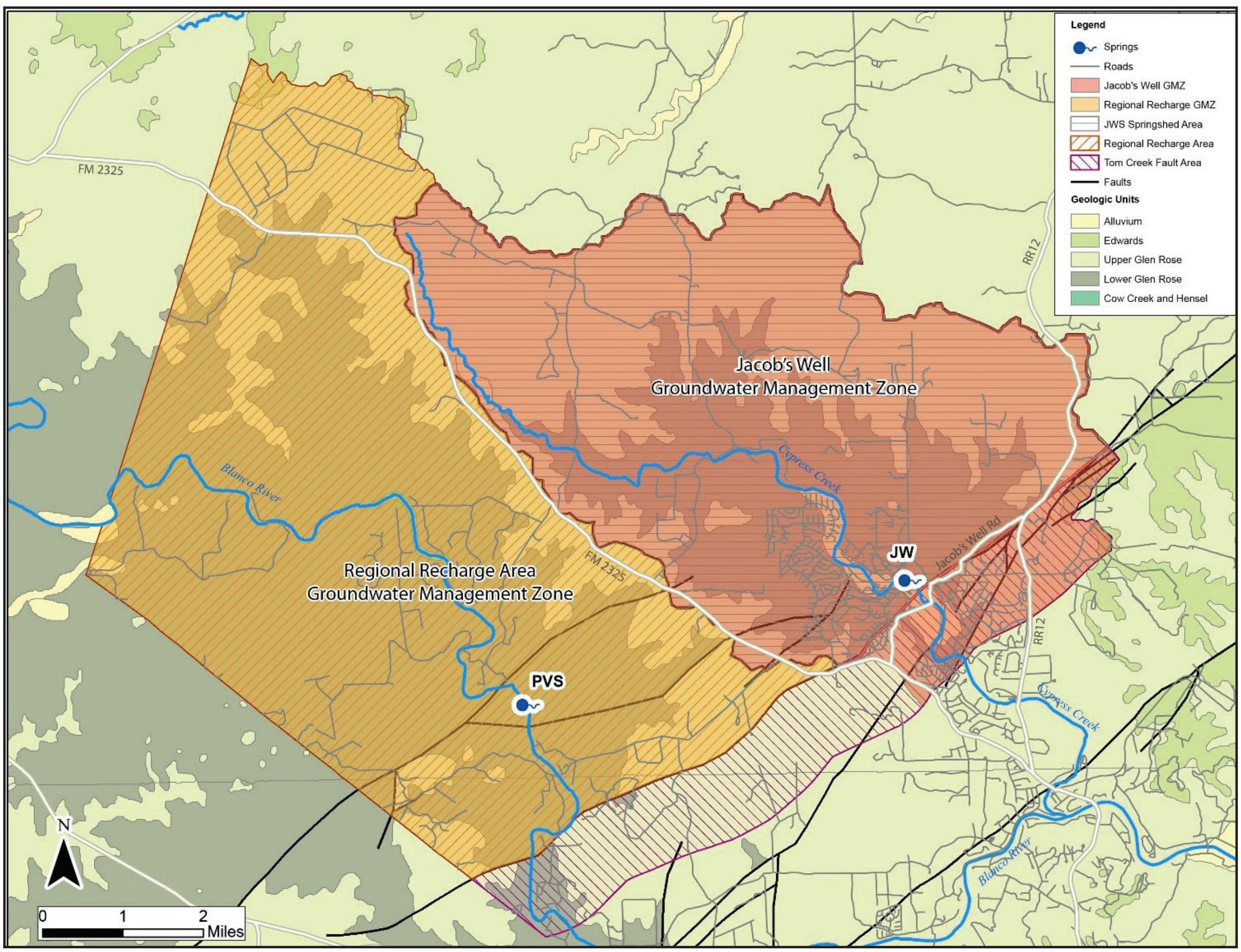

Figure 22. Areas of hydrologic influence to Jacob's Well shown in hatched areas, and potential groundwater management zones shaded orange and red. (GMZ = groundwater management zone, JW = Jacob's Well, PVS = Pleasant Valley Spring)

The Scientific Technical Committee provided a series of presentations to the Stakeholder Advisory Committee throughout the year-long process and regularly interacted with the Stakeholder Advisory Committee facilitator and key members.

This two-way interaction provided a useful dialog between the two committees, guiding the direction of analyses, data evaluation, map development, and many other related topics. The final areas recommended include the Jacob's Well Groundwater Management Zone and Regional Recharge Area Groundwater Management Zone. The Scientific Technical Committee presented an initial area to the Stakeholder Advisory Committee in late 2018 to receive feedback from the stakeholders. This resulted in a re-evaluation of how we described the areas of hydrogeologic connection to Jacob's Well, and which we presented to the Stakeholder Advisory Committee in early 2019. The Stakeholder Advisory Committee was then able to critically evaluate the information and decide on a preferred option for defining the spatial extent of a Jacob's Well Groundwater Management Zone and a Regional Monitoring Zone.

DISTRICT STRATEGIES

Reduction of pumping during drought periods from current levels of pumping will almost certainly result in increased springflows. There are several potential strategies to protect and increase baseflows that have both technical merit and, based on stakeholder discussions, are feasible. Some potential strategies and tools that could provide maximum benefit to springflows are outlined in **Tables 8 and 9**.

Table 8. Demand reduction tools for maintaining sustainable base flow at Jacob's Well Spring through a Jacob's Well Groundwater Management Zone.

Strategy	Description
Drought Curtailments	Implementation of a simple, representative drought declaration methodology using Jacob's Well as one of the triggers.
Education	Effective communication to the public related to water resources, drought, and conservation efforts the public can take.
Conservation	Measures and actions taken to reduce the use of water. These could include watering schedules.
Permit Reductions and Restrictions	Right-sizing and placing ceilings on permitted pumping during non-drought periods.
Infrastructure and Efficiency	Reduce line loss and fix other water infrastructure problems that may waste groundwater.

Table 9. Alternative water-supply tools for maintaining sustainable base flow at Jacob's Well Spring through a Jacob's Well Groundwater Management Zone.

Strategy	Description
Conjunctive Use	Use of surface water and groundwater sources
Aquifer storage and recovery (ASR)	Injection of surface or other water supplies into the Lower Trinity Aquifer for withdrawal during drought periods.
Lower Trinity	Development of the Lower Trinity Aquifer to (1) temporarily or permanently replace pumping from the Middle Trinity and (2) use as a sole-source for future permitted
Rainwater	Promotion of the use of rainwater for commercial and domestic uses.
Alternative Water Supplies	Importing water from more distant sources.
Temporary interconnections and Pipelines	These could alleviate pumping in certain areas.

There will be no single solution to protect and increase baseflows. It will take the combined effects of multiple strategies, along with efforts from District, stakeholders, and agencies outside of District over a number of years to reach full potential benefit.

An effective way to get uniform pumping reductions is through drought declarations and corresponding reductions (EAA 2019). One of the first tasks is to evaluate and develop a simple and representative drought-trigger methodology that uses Jacob's Well flow as one of the drought indicators and drought curtailment triggers. A drought-trigger methodology could be implemented without use of management zones and would have benefits throughout the region. In order for drought reductions to be effective, we suggest the following components need to be a part of the strategy

- monthly reporting of meter readings with enforced monthly goals or targets and
- drought reductions based on actual monthly usage rather than total permitted volume.

Additional regional strategies would include education and communication of the drought declarations and actions the general public (exempt well users) can take to reduce water use during droughts. Additional components would include enhancing overall conservation, improving efficiency of infrastructure, and encouraging use of rainwater as a supply.

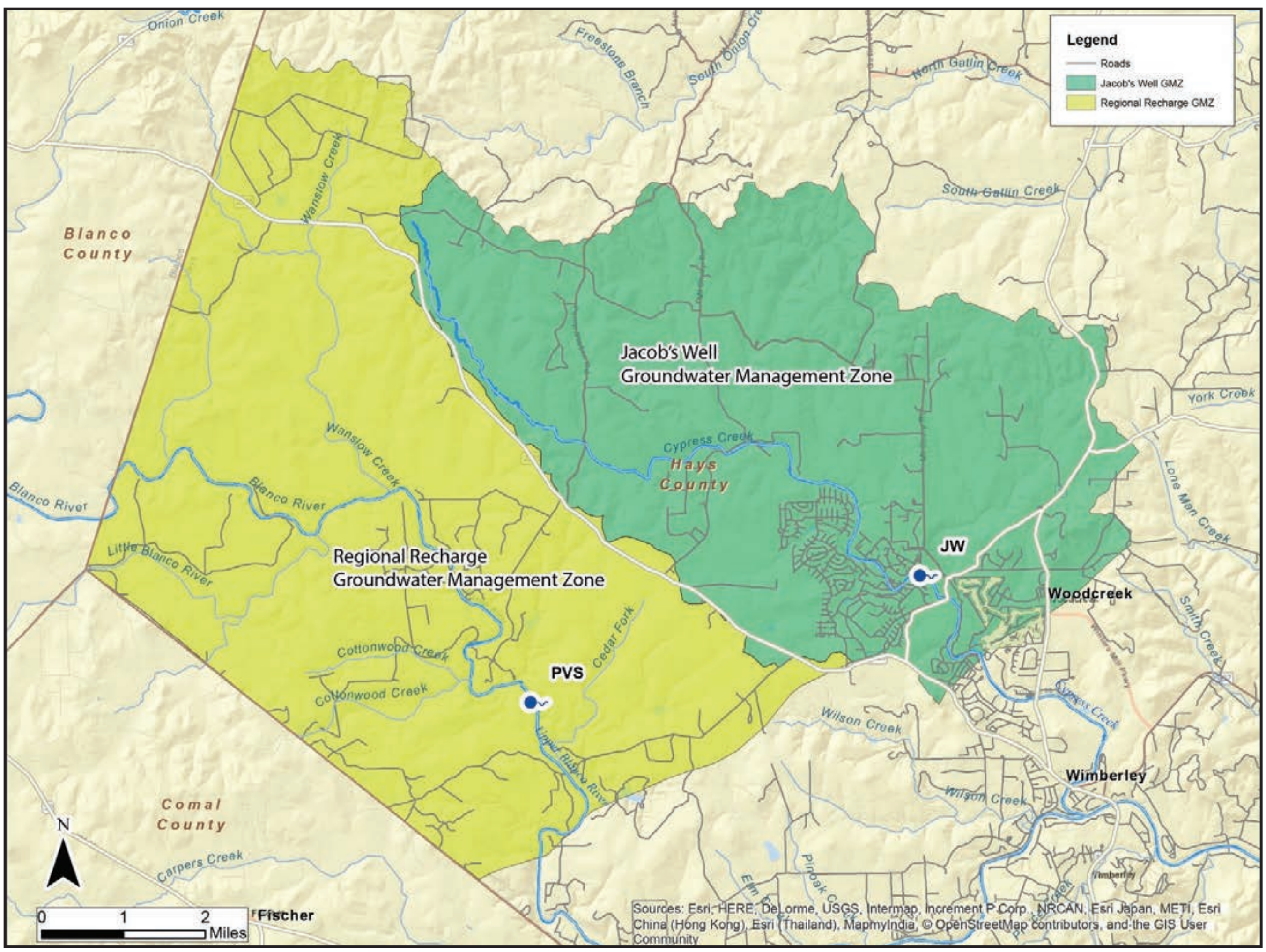

Figure 23. Recommended potential groundwater management zones shaded yellow and green. This maps is the same as Figure 22, but simplified to just the groundwater management zones.

JACOB'S WELL SPRINGSHED GROUNDWATER MANAGEMENT ZONE

The Jacob's Well Groundwater Management Zone is the area where pumping is most influential on the flow at Jacob's Well. Pumping in this area is assumed to have a nearly one to one effect on Jacob's Well flow during drought conditions. This area includes the Jacob's Well springshed and the portion of the Tom Creek Fault Area within Cypress Creek watershed (**Figures 22 and 23**). In this area, current levels of pumping would need to be reduced significantly during drought conditions. To meet existing and some future demand, additional water supplies would need to be developed conjunctively with significant pumping reductions. In order to protect springflows and to increase baseflows, additional strategies could be developed and deployed in this area including

- increased drought curtailments;
- right-sizing existing non-exempt operating permits (reduce the size of permits in which actual annual pumping is significantly lower than permitted volume),
- limiting future permitted pumping within the Middle Trinity Aquifer in this area,
- development and implementation of aquifer storage and recovery during drought periods, and
- interconnections to other water supplies and pipelines to deliver water from outside of the area for use during drought periods.

REGIONAL RECHARGE AREA GROUNDWATER MANAGEMENT ZONE

This area contributes flow to Pleasant Valley Spring and also may provide some flow to Jacob's Well under certain conditions (**Figures 22 and 23**). There is significantly less non-exempt pumping in this area, and no direct influence of pumping on Pleasant Valley Springflow has been observed. Because of the lesser amount of pumping in this area, springflow at Pleasant Valley Spring has not yet experienced the decreased flow observed at Jacob's Well. However, with anticipated growth, we anticipate that flows at Pleasant Valley Spring will decrease with increased pumping in its springshed. In addition, large-scale pumping within this zone could also capture flow to Jacob's Well. Some strategies for this area could include

- implementing management rules to limit future pumping to limit negative impacts on Pleasant Valley Spring, the Blanco River, and Jacob's Well;
- developing a water budget to sustain baseflows and inform future permits in the Middle Trinity Aquifer in this area; and
- encouraging development of alternative supplies such as the Lower Trinity, aquifer storage and recovery, and rainwater.

UNCERTAINTIES

As with any hydrogeologic study, there are assumptions and uncertainties involved in the evaluation. This report is meant to document the rationale and the data on which conclusions are based so that they can be critically reviewed. The best and latest information available was used in this study. One of the largest assumptions is a nearly one-to-one proportional effect of pumping with springflow. This is a basic hydrogeologic concept that is often used in other karst spring areas (Smith and Hunt 2004). This relationship generally holds under drought conditions within the Jacob's Well springshed and the portion of the Tom Creek Fault Zone within Cypress Creek. The relationship is likely not as directly proportional in the Regional Recharge Zone area or farther southwest within the Tom Creek Fault Area. These uncertainties can be addressed in some of the proposed studies below.

Another uncertainty is the potential effects of climate change. Observed and modeled reductions in springflows in several major springs in the area (such as Barton Springs and Comal Springs) due to increases in air temperature are predicted to continue (Stamm and others 2015).

Much of the analyses performed in this report reflect current pumping of the Middle Trinity Aquifer. Current permitted pumping levels are significantly higher than actual pumping. Significant additional growth is expected in the area. Prediction of the rate of growth and the resulting effects on springflow from increases in demand and pumping due to future growth is difficult.

// Photo 10. Jacob's Well at night.

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FUTURE STUDIES

There are a number of studies that could to be conducted to refine the hydrogeologic understanding, address some of the uncertainties, and possibly influence the management and strategies presented here. These studies include

- aquifer tests to refine our understanding of the permeability and hydrologic connectivity of the various areas and wells to Jacob's Well;
- dye tracing to identify preferential pathways and test the hydrologic connection of areas and wells to Jacob's Well;
- installation of additional monitor wells, coupled with more frequent monitoring of public water-supply wells and multiport wells to characterize hydrogeology and system responses to recharge and pumping;
- development of sustainable pumping volumes (water balance) for the springshed of Pleasant Valley Spring;
- aquifer storage and recovery pilot testing; and
- numerical modeling studies incorporating the latest hydrogeologic information to support management decisions. An existing study, started in 2018, to develop a "Tool to assess how the Blanco River interacts with its aquifers" through The Meadows Center for Water and the Environment (Meadows Center 2018) is an example of one such modeling approach.

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APPENDIX A: DROUGHT MANAGEMENT WITHIN JACOB'S WELL AREAS OF HYDROLOGIC INFLUENCE

The District's current drought management strategy includes mandatory drought curtailments for non-exempt permit-holders during times of drought. When the District declares a given drought stage, permit-holders are required to observe pumping cutbacks depending on the severity of the drought stage (**Table A-1**). For a given permit holder, mandatory drought cutbacks are applied based on the permit holder's drought contingency plan, which specifies allocated monthly pumping based on month of the year and level of drought stage declaration (**Figure A-1**). If a given permittee exceeds their annual allocated pumping after mandatory curtailments have been applied under the drought contingency plan, that permittee is assessed a fine by the District at the end of the year.

Table A-1: Current drought stages with associated percentage curtailment. Pumping curtailments are applied to total annual permitted volumes. (ft^3/s = cubic feet per second, NA = not applicable)

Drought Stage	Percentage Curtailment	Pedernales River Trigger (ft^3/s)	Blanco River Trigger (ft^3/s)
No Drought	0	NA	NA
Alarm Stage	20	31.6	28.5
Critical Stage	30	10.2	14.5
Emergency Stage	40	2.23	9.28

Permitee

645 Acre Feet

Drought Contingency Plan Production Cutback Chart

2017- 2019 Permit

210,173,895 Gallons

	Actual Use Gallons		**Baseline Gallons**	Stage 1 Voluntary 10%	Stage 2 Alarm 20%	Stage 3 Critical 30%	Stage 4 Emergency 40%	Gallons Over
January		6%	12,610,434	11,349,390	10,088,347	8,827,304	7,566,260	
February		7%	14,712,173	13,240,955	11,769,738	10,298,521	8,827,304	
March		7%	14,712,173	13,240,955	11,769,738	10,298,521	8,827,304	
April		7%	14,712,173	13,240,955	11,769,738	10,298,521	8,827,304	
May		8%	16,813,912	15,132,520	13,451,129	11,769,738	10,088,347	
June		10%	21,017,390	18,915,651	16,813,912	14,712,173	12,610,434	
July		12%	25,220,867	22,698,781	20,176,694	17,654,607	15,132,520	
August		12%	25,220,867	22,698,781	20,176,694	17,654,607	15,132,520	
September		10%	21,017,390	18,915,651	16,813,912	14,712,173	12,610,434	
October		8%	16,813,912	15,132,520	13,451,129	11,769,738	10,088,347	
November		7%	14,712,173	13,240,955	11,769,738	10,298,521	8,827,304	
December		6%	12,610,434	11,349,390	10,088,347	8,827,304	7,566,260	
Totals	0		210,173,895	189,156,506	168,139,116	147,121,727	126,104,337	0

Figure A-1: Example of permit holder drought contingency plan production cutback chart.

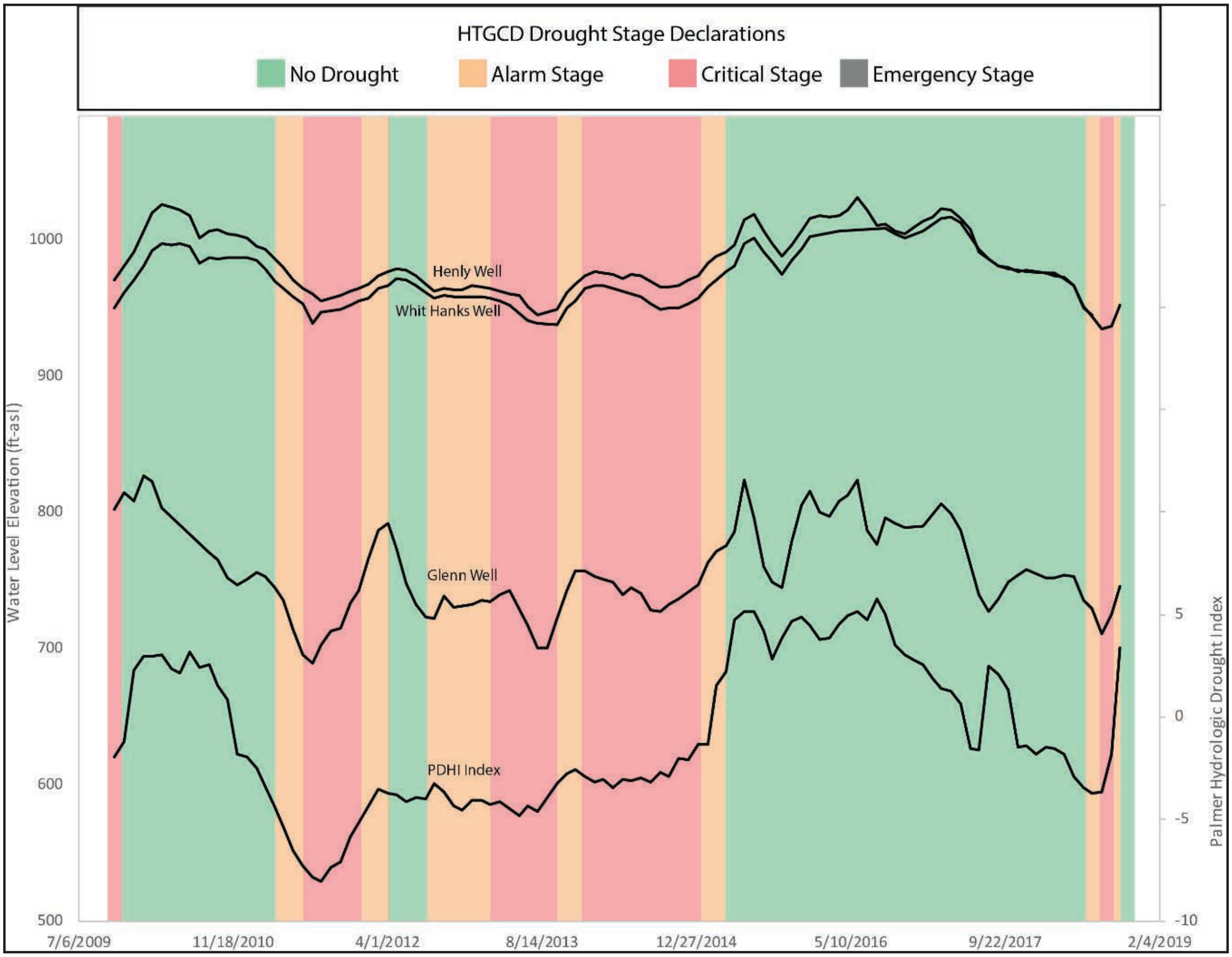


Figure A-2: Drought declaration history since implementation of drought-trigger methodology in November 2009. Time series of selected well water levels and Palmer Drought Hydrologic Index show fluctuations that roughly correspond to drought declarations. (ft-asl = feet above mean sea level, HTGCD = Hays Trinity Groundwater Conservation District, PDHI = Palmer Hydrologic Drought Index)

The District developed and implemented drought stage declarations in its rules starting November 2009. Since then the District has been in declared drought 46 percent of the time (**Figure A-2**). To date, the District has not been in emergency stage declared drought. The timing of drought stage declaration is determined by the District's drought-trigger methodology, which is laid out in District Rule 13. Currently, the District uses river flow from the Blanco River at Wimberley (USGS ID: 08171000) and the Pedernales River at Johnson City (USGS ID: 08153500) as drought-triggers. The District declares a drought stage when river flow at both rivers drops below the specified flow triggers for 30 consecutive days (**Table A-1**). Additionally, the District may use the Palmer Hydrologic Drought Index to inform drought declaration.

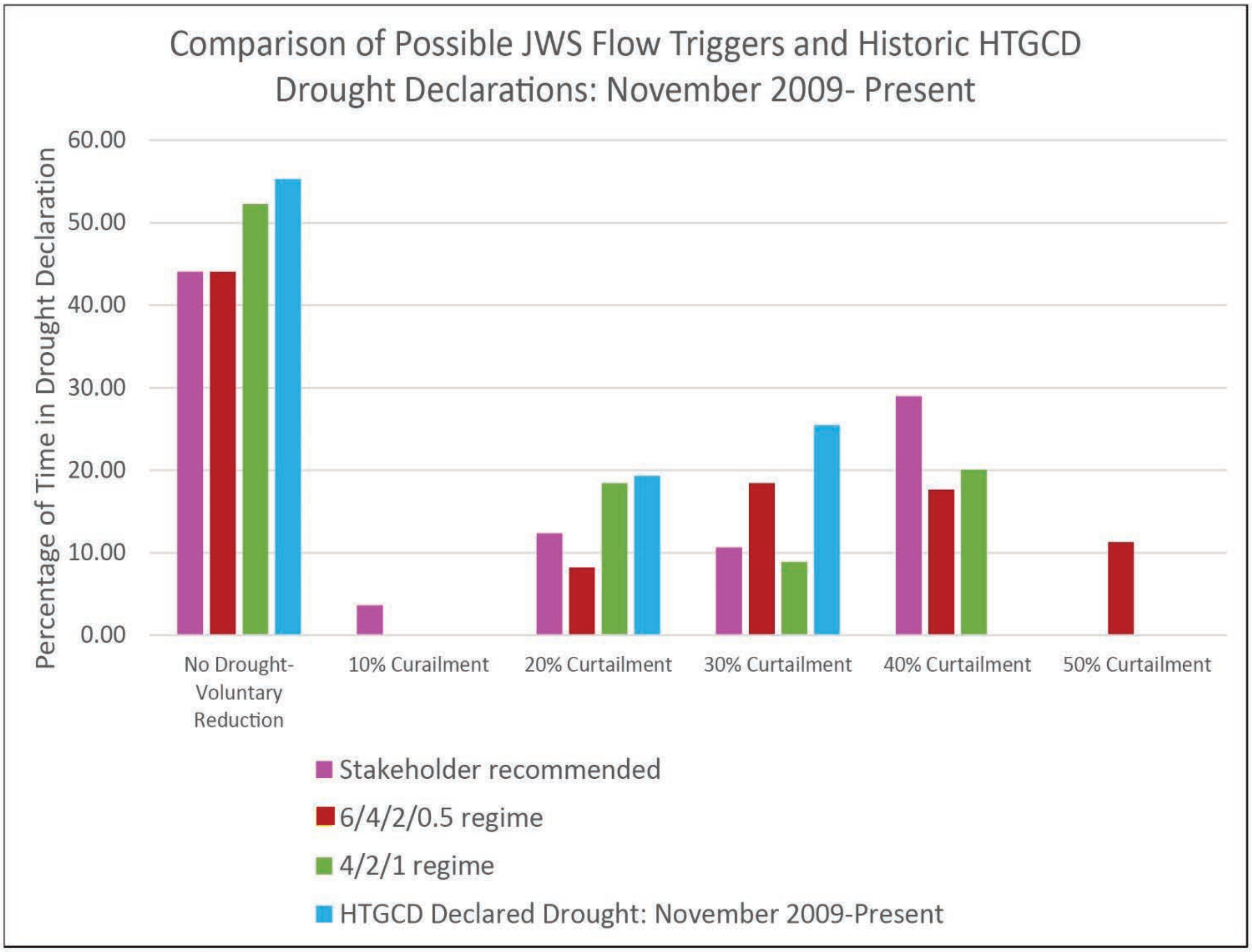
One of the management strategies discussed during the Jacob's Well groundwater management zone stakeholder process was adopting flow at Jacob's Well, as reported by the U.S. Geological Survey (USGS ID: 08170990), as a drought-trigger, either for the entire District or only for the groundwater management zone. This would tie drought declarations directly to Jacob's Well, making District drought declarations more responsive to Jacob's Well flow. The flow gage at Jacob's Well has been in operation since

April 2005 and provides a detailed record of springflow over the last 14 years (Figure 18). **Table A-2** presents a cumulative percentage analysis of Jacob's Well flow for the available period of record from the gage. This analysis could be used by stakeholders to identify target flow values below which drought declarations and mandatory District pumping curtailments would be triggered. **Figure A-3** shows potential Jacob's Well drought-triggers, which have been proposed by the stakeholders, and the percentage of time that each trigger regime put the District in declared drought going back to November 2009. The stakeholder committee voted to recommend this trigger regime at their May 1, 2019, meeting.

Table A-2: Percentile analysis of Jacob's Well flow from the available period of record provided by the U.S. Geological Survey gage. The right column shows the springflow value in cubic-feet/second associated with the percentage of time Jacob's Well flow has been below that value (left column). (CFS = cubic feet per second)

Percent	Flow (CFS)
95	38.3
90	26.3
85	19.2
80	14.5
75	11.3
70	8.8
65	6.9
60	5.2
55	4.1
50	3.4
45	2.9
40	2.5
35	2
30	1.6
25	1.2
20	0.9
15	0.7
10	0.5
5	0.2

Evaluation of the percentage of time the proposed Jacob's Well flow triggers would have caused drought declaration from November 2009 to present allows comparison of the proposed Jacob's Well triggers and historic drought declarations over this time period. When the first Jacob's Well curtailment stage drought-trigger is set to 4 cubic feet per second, total time spent in declared drought versus no-drought (regardless of drought stage severity) would be similar to the current drought-trigger methodology (45 to 48 percent of time in declared drought). When this initial drought-trigger is set to 6 cubic feet per second (the recommended regime), total time spent in declared drought increases to 55 percent. The primary difference between currently established drought-triggers and those presented in **Figure A-3** is the amount of time spent at different stages of drought. The Jacob's Well flow triggers would make drought declarations responsive to Jacob's Well flow and change the distribution of time in declared drought between different percentage curtailment drought stages. Another key difference is that proposed triggers would put the District in 40 to 50 percent pumping curtailments for a significant amount of time. The recommended regime would result in a 40 percent curtailment about 29 percent of the time between November 2009 and present. In contrast, to date the District has not been in 40-percent curtailment (emergency stage drought declaration) since implementing drought declarations.



Curtailment Regimes (JWS Flow Values in Cubic-Feet/second)			
Recommended	6/4/2/0.5 Regime	4/2/1 Regime	Curtailment Percentage
-	-	-	0%
6	-	-	10%
5	6	4	20%
3	4	2	30%
2	2	1	40%
-	0.5	-	50%

Figure A-3: Evaluation of proposed Jacob's Well flow triggers and the District's historic drought declarations from November 2009 to present. Bars represent the percentage of time drought would be declared if these triggers had been in effect over this time period. The magenta bars represent the triggers recommended by the Jacob's Well Groundwater Management Zone stakeholder committee on May 1, 2019. (HTGCD = Hays Trinity Groundwater Conservation District, JWS = Jacob's Well Spring)

EVALUATION OF CURRENT DROUGHT CURTAILMENT EFFECTIVENESS

Since the District implemented drought stage declarations in November 2009, the District has been in declared drought 46 percent of the time. Additionally, total reported non-exempt pumping has remained relatively steady over this period with no obvious rising or falling trend (**Figure 19**). Because annual pumping has been relatively stable and the total duration of drought and no-drought declarations is close to 50 percent, this allows a coarse-scale comparison of non-exempt pumping during drought and no-drought periods.

Figure A-4 presents a comparison of average pumping by month for non-exempt pumping from the three largest permit holders in the vicinity of Jacob's Well (Aqua Texas, Wimberley Water Supply Corporation, and Wimberley Springs Partners). These permit holders account for more than 90 percent of pumping in areas of influence to Jacob's Well. Since the District started implementing drought declarations in November 2009, the District has been in a declared state of drought 46 percent of the time. Despite these declarations, total reported actual (non-exempt) pumping has remained relatively stable over this period; therefore, drought declarations appear to have had little to no effect on pumping (**Figure A-4**). The dotted brown line in **Figure A-4** indicates what

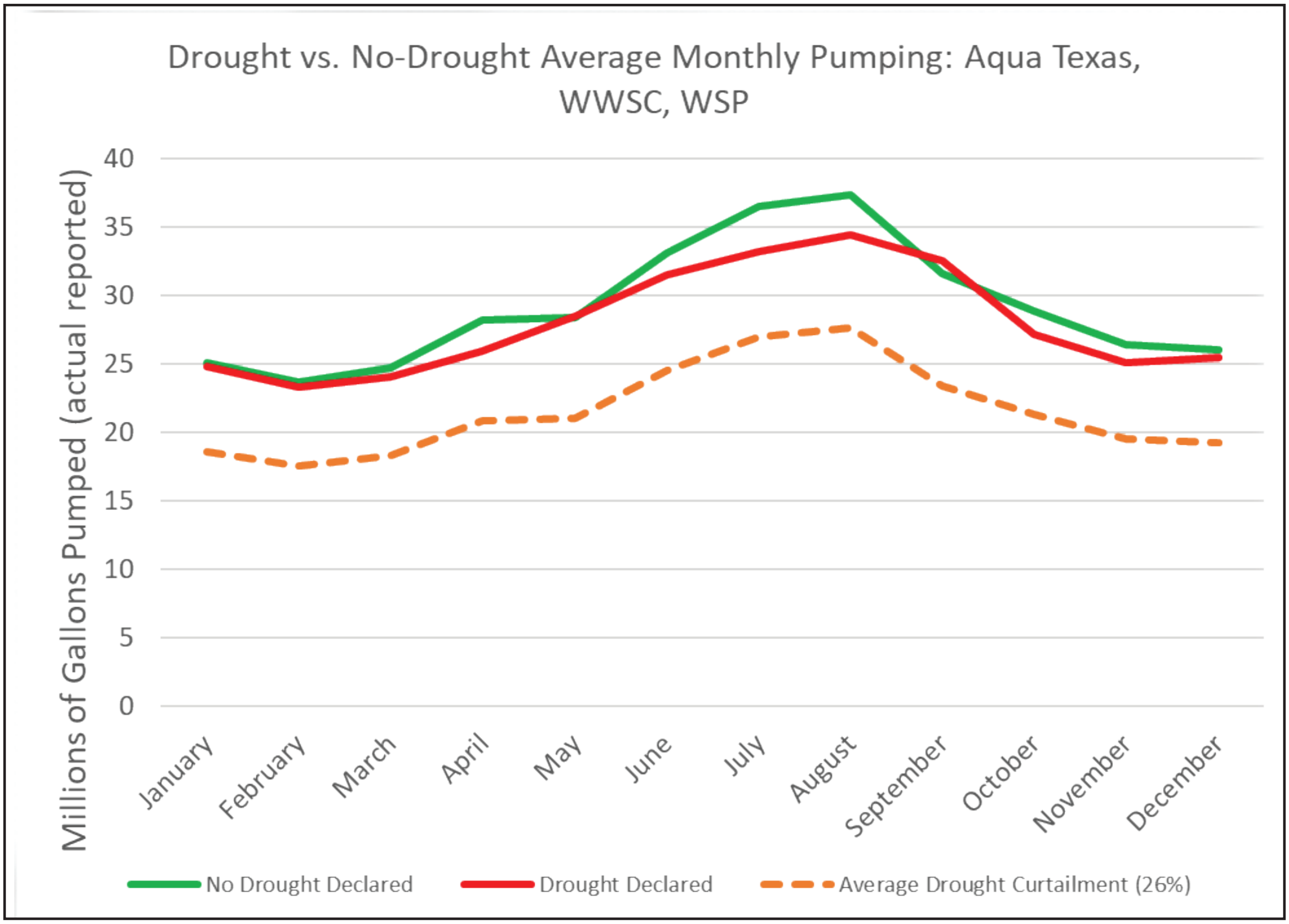


Figure A-4: Comparison of average non-exempt pumping by month during drought declarations versus no-drought declaration. This chart indicates that pumping remained about the same regardless of the drought declaration and indicates that drought declarations have had little to no effect on pumping. The dashed line is where pumping should be if 26 percent of the average monthly pumping was curtailed during drought. (WSP = Wimberley Springs Partners, WWSC = Wimberley Water Supply Corporation) the pumping with a drought curtailment of 26 percent (using data since November 2009) of average pumping during no-drought years. In other words, the dashed line is what pumping levels would be with reductions implemented from normal monthly pumping. During this period, average drought curtailment during declared drought months was 26 percent. Applying this average curtailment to average monthly pumping during the same month when no-drought was declared, a reduction in average monthly pumping equivalent to 0.17 to 0.27 cubic feet per second would have resulted if actual curtailments had been achieved.

The District's mandatory drought curtailments are based on total annual permitted volumes and not actual monthly usage. **Figure A-5** presents a comparison of reported mean annual pumping from non-exempt permits and total permitted volume. Annual permitted volume generally exceeds actual pumping (actual pumping for all large permits is about 73 percent of total permitted volume). Because drought curtailments are based on total permitted volume, they are unlikely to incentivize non-exempt pumping reductions for permits that have a permitted volume significantly higher than mean actual pumped volume.

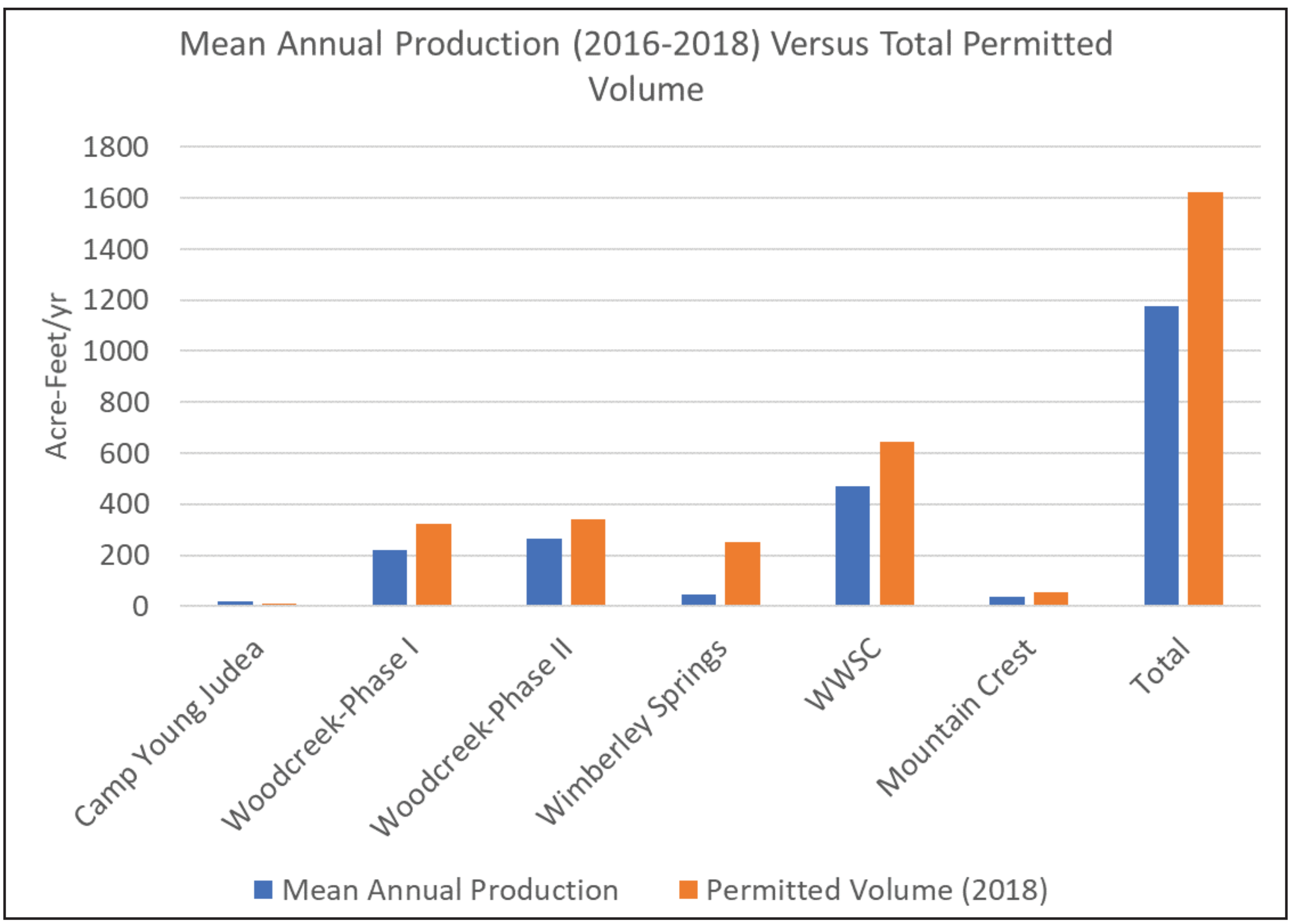


Figure A-5: Comparison of permitted annual volume versus average reported actual pumping (2016 through 2018) for large permit holders with wells in one of the three delineated Jacob's Well areas of influence. Total permitted volume is significantly larger than average reported pumping for most of the large permits.

APPENDIX B: GIS AND GOOGLE EARTH DATA FILES

Download the GIS and Google Earth data files for the groundwater management zones online at http://bit.ly/JWGMZReportAppendixB.

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