Blanco River Aquifer Assessment Tool

A Tool to Assess How the Blanco River Interacts With Its Aquifers: Creating the Conceptual Model

Technical Report prepared for The Meadows Center for Water and the Environment - Texas State University

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Authors:

Nicholas D. Martin, P.G., P.H., Ronald T. Green, Ph.D., P.G., Kindra Nicholaides, S. Beth Fratesi, Ph.D., Rebecca R. Nunu, and Mauricio E. Flores
Earth Science Section, Southwest Research Institute®

Technical Committee:

Douglas A. Wierman, P.G., Robert E. Mace, Ph.D., P.G.
The Meadows Center for Water and the Environment, Texas State University

Brian B. Hunt, P.G., Brian A. Smith, Ph.D., P.G.
Barton Springs /Edwards Aquifer Conservation District

Ronald G. Fieseler, P.G.
Blanco-Pedernales Groundwater Conservation District

Marcus O. Gary, Ph.D., P.G., F. Paul Bertetti, P.G.
Edwards Aquifer Authority

Alex S. Broun, P.G. , Jeffery A. Watson, P.G., Phillip Webster
Hays Trinity Groundwater Conservation District

THE MEADOWS CENTER
FOR WATER AND THE ENVIRONMENT
TEXAS STATE UNIVERSITY

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Vanessa Puig-Williams, Executive Director and General Counsel for the Trinity Edwards Springs Protection Association (TESPA), first envisioned the need for the Blanco River Aquifer Assessment Tool project. Ms. Puig-Williams enlisted the assistance of Chris Hale, Brian Hunt, Ronald Green, Marcus Gary, Doug Wierman, Brian Smith, Paul Bertetti, Nick Martin, Al Broun, and Robert Mace to form an exploratory working group and to formulate the goals, objectives, and scope of the Blanco River Aquifer Assessment Tool. A Technical Committee was assembled that included Barton Springs Edwards Aquifer Conservation District, Blanco-Pedernales Groundwater Conservation District, Edwards Aquifer Authority, and Hays Trinity Groundwater Conservation District with the Meadows Center for Water and the Environment as the lead agency. Ron Fiesler, Jeff Watson, and Phillip Webster joined the Technical Committee to assist in the fulfillment of the project goals.

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Cover Photo: Blanco River after flood event by Kindra D. Nicholaides

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S. Beth Fratesi, Ph.D., Rebecca R. Nunu, and Mauricio E. Flores
Earth Science Section
Southwest Research Institute®

September 2019

601 University Drive, San Marcos, Texas 78666

512.245.9200 | MeacowsCenter@txstate.edu | www.MeadowsWater.org

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Executive Summary

The Blanco River watershed spans five counties through the Texas Hill Country and supplies water to some of the fastest growing population centers in Texas, if not the country (**Figure ES - 1**). Over this reach, the Blanco River is both fed by and feeds the Trinity and Edwards aquifers, blurring the line between groundwater and surface water. It is a source of water to iconic springs such as Pleasant Valley Springs, Jacob's Well Spring, and San Marcos Springs. Even outside of its own watershed, the Blanco River watershed has been shown to contribute to flow in Barton Springs of the Edwards Aquifer during periods of low flow and drought. This makes the Blanco River an essential consideration in maintaining the delicate environmental flow balance of these springs and water courses.

The relationship of the Blanco River with the underlying Trinity and Edwards aquifers is complex, in part due to offset associated with the Balcones Fault Zone, and in part due to rock facies that transition across the watershed. The Trinity Aquifer, in particular, introduces complexity within the Blanco River watershed in that the formations that make up the aquifer exhibit a broad range of properties and that these formations exhibit broad transgressions that transition from the uplands associated with the Edwards Plateau and which dip and thicken toward the Gulf of Mexico. This complexity causes the Blanco River and its tributaries to transition between sections or reaches where the Blanco River typically gains water from the underlying aquifers and reaches where the Blanco River normally loses water to the underlying aquifers.

There are impending threats to the health of the Blanco River and the aquifers it overlies. A growing population is placing increased demands on water resources. Pumping from the Trinity Aquifer, with much of this coming from the Middle Trinity Aquifer, has continuously increased and already lowered aquifer water levels. In 2000, 2008, 2009, 2011, 2013, 2014 and 2018 Jacob's Well Spring temporarily ceased to flow as a result of increased pumping combined with periods of drought. Local demands on groundwater will only increase with development compounded by commercial interests that seek to extract large quantities of water from the Trinity Aquifer to sell and transport it elsewhere. Combined with changing weather patterns, threats to the water resources of this fragile area can only be expected to increase with time.

With unknown effects of changing weather patterns due to global climate change combined with the threat of increased pumping, there is a need to better understand the Blanco River and groundwater interactions. During recent periods, local groundwater conservation districts, including the Edwards Aquifer Authority, have collected data and studied the hydrogeology of the region. Although much effort has been undertaken to compile and comprehend the significance of these vast quantities of data, additional challenges remain. Of particular need are tools that would enable comprehensive management of the combined surface water and groundwater resources. Given the inherent linkage of these water resources, it is imperative that these tools accommodate the inter-relationship between surface water and groundwater. Of critical need is an integrated hydrologic model with sufficient capability to replicate the impact that changes in weather patterns (i.e., precipitation and recharge) and water-management scenarios (i.e., groundwater extraction for local or external uses) will have on both surface water and groundwater in light of the complex relationship between the Blanco River and the underlying aquifers. At this time, no such comprehensive models or tools are available.

The geographical extents of the Blanco River and Onion Creek watersheds are illustrated in **Figure ES - 1** and **Figure ES - 2**. What is not as clearly defined are the extent of the aquifers which underlie and interact with the Blanco River watershed and the downstream extent of the aquifers which are hydraulically connected and impacted by the lower Blanco River. Defining the extent of the study domain of this project is of critical importance to ensure that the tools developed by this project are capable of and appropriate to address the technical and programmatic questions facing the Blanco River watershed. Of concern is how far beyond the Blanco River watershed should the model domain extend to appropriately represent groundwater flow in the Trinity and Edwards aquifers as it pertains to interaction with Blanco River system. Accordingly, the study area has been extended outside of the Blanco River watershed to include the Onion Creek watershed to the northeast and the headwaters of the San Marcos River and other areas to the south and east. This extension, which also includes a fault-bounded section of the Edwards Aquifer, enables the model to address periods of drought when the direction of groundwater flow within the Balcones Fault Zone can change with the result of a relocation of the groundwater divide that separates the contributing zone for San Marcos Springs from the contributing zone for Barton Springs.

A conceptual model of the Blanco River watershed and the underlying Trinity and Edwards aquifers was assembled to bring together disparate data and combine it into a framework that is useful for policy makers to have a better understanding of the complex relationship of the Blanco River and the underlying aquifers **Figure ES - 3**.This conceptual model describes the connections between the Blanco River and the underlying aquifers and the constraints between surface water and groundwater flow in the study area. It is the first stage in developing an integrated hydrologic computer model to be used for examining and optimizing water-management practices with respect to expected increases in groundwater pumping and changes in long-term average weather, or climate.

A critical question regarding the Blanco River watershed is to what degree increased development will affect the environmental health of flow in the Blanco River and its tributaries and discharge of the major springs, including Pleasant Valley Springs, Jacob’s Well Spring, San Marcos Springs, and Barton Springs. Although the refined conceptual framework model described in this report provides insight on these questions, rigorous evaluation of these impacts can only be undertaken if an integrated hydrologic model of the study area is developed. The conceptual framework model described in this report and the supporting geodatabase provide the basis for development of an integrated hydrologic model of the desired model domain.

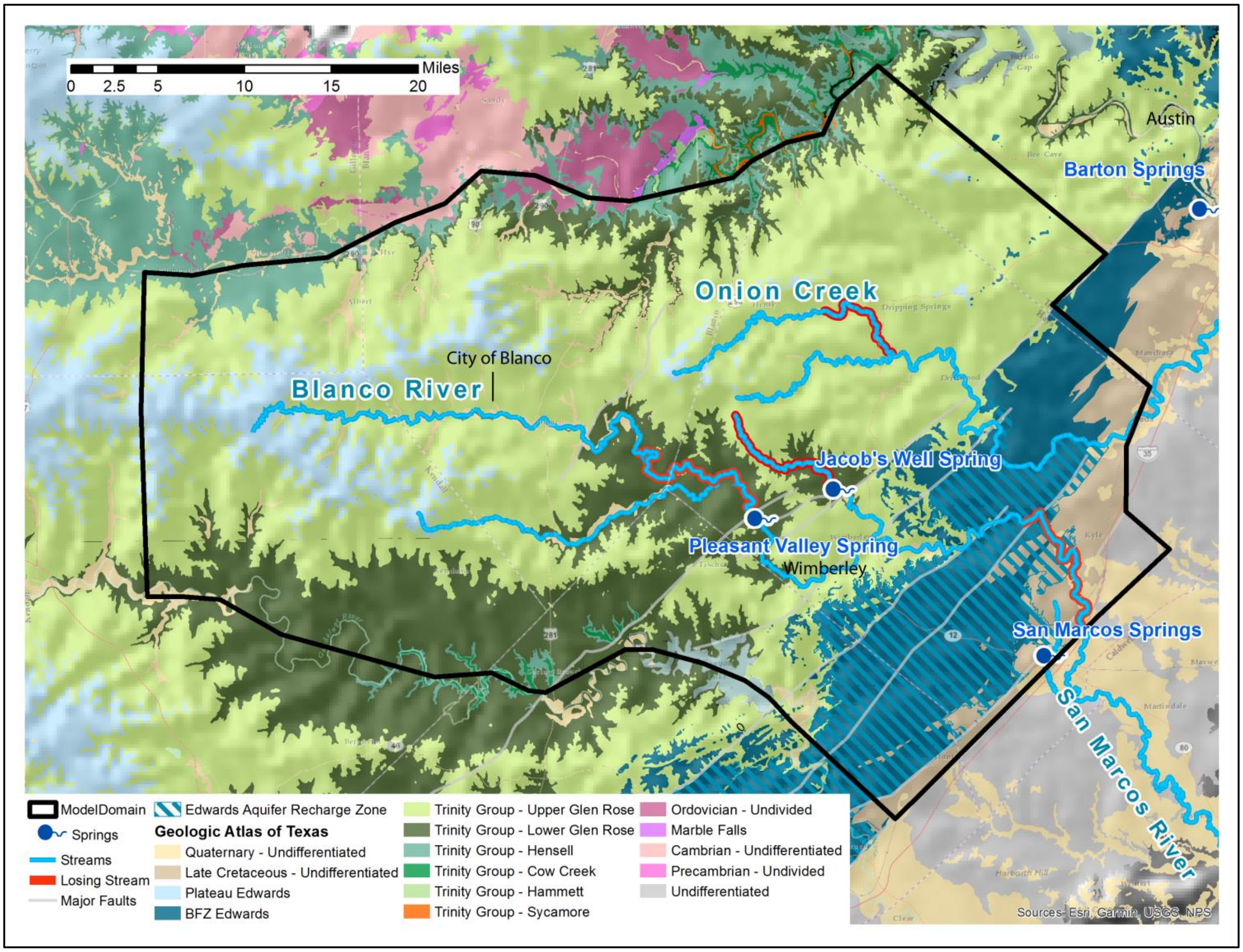

Figure ES - 1: Plan view of the study area. Losing sections of the Blanco River and Onion Creek, or where the rivers are thought to feed into the Trinity and Edwards aquifers, are outlined in red. The Edwards Aquifer recharge zone is indicated by blue hatch markings. Four major springs are also shown.

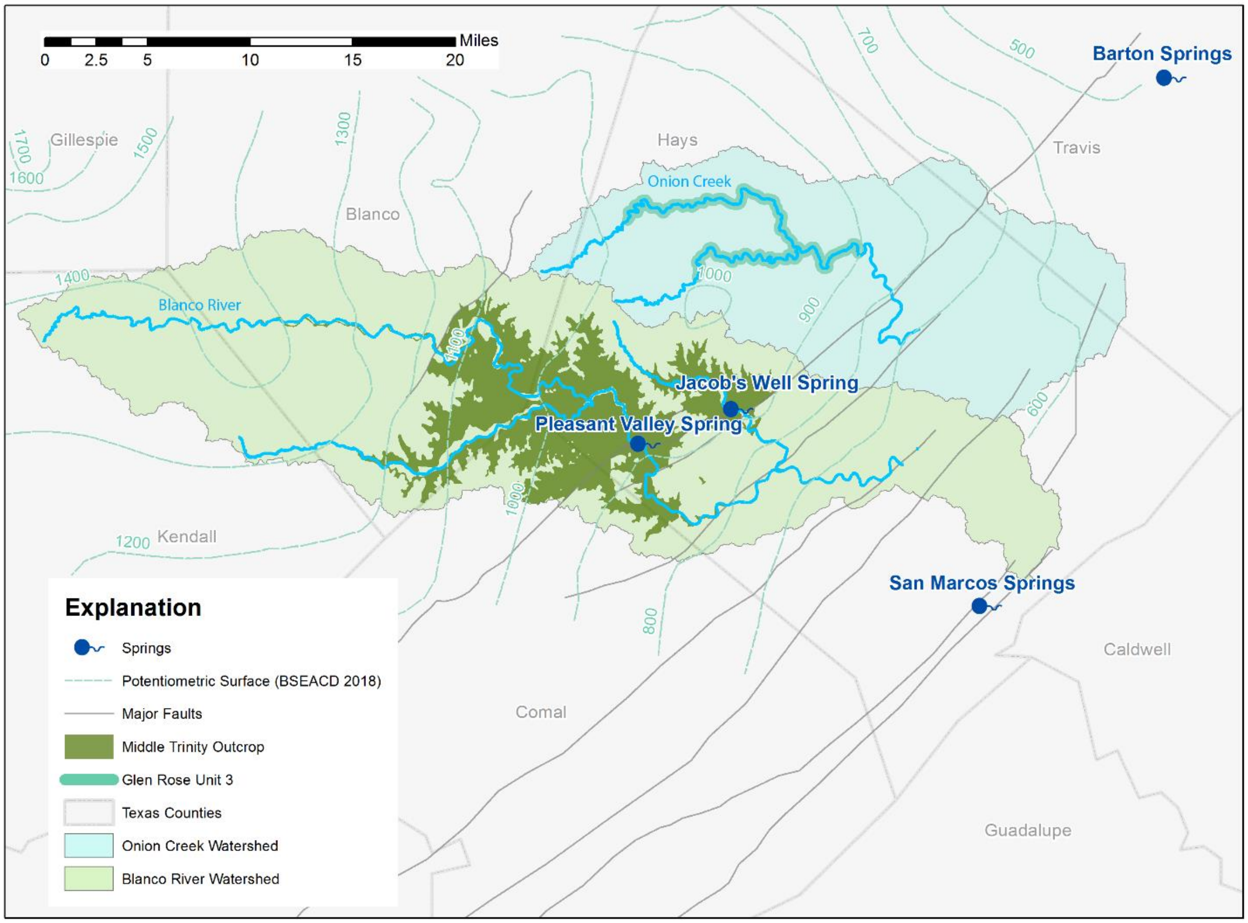

Figure ES - 2: Plan view showing the Middle Trinity Aquifer Outcrop in olive green and Middle Trinity Aquifer water-level contours from 2018.

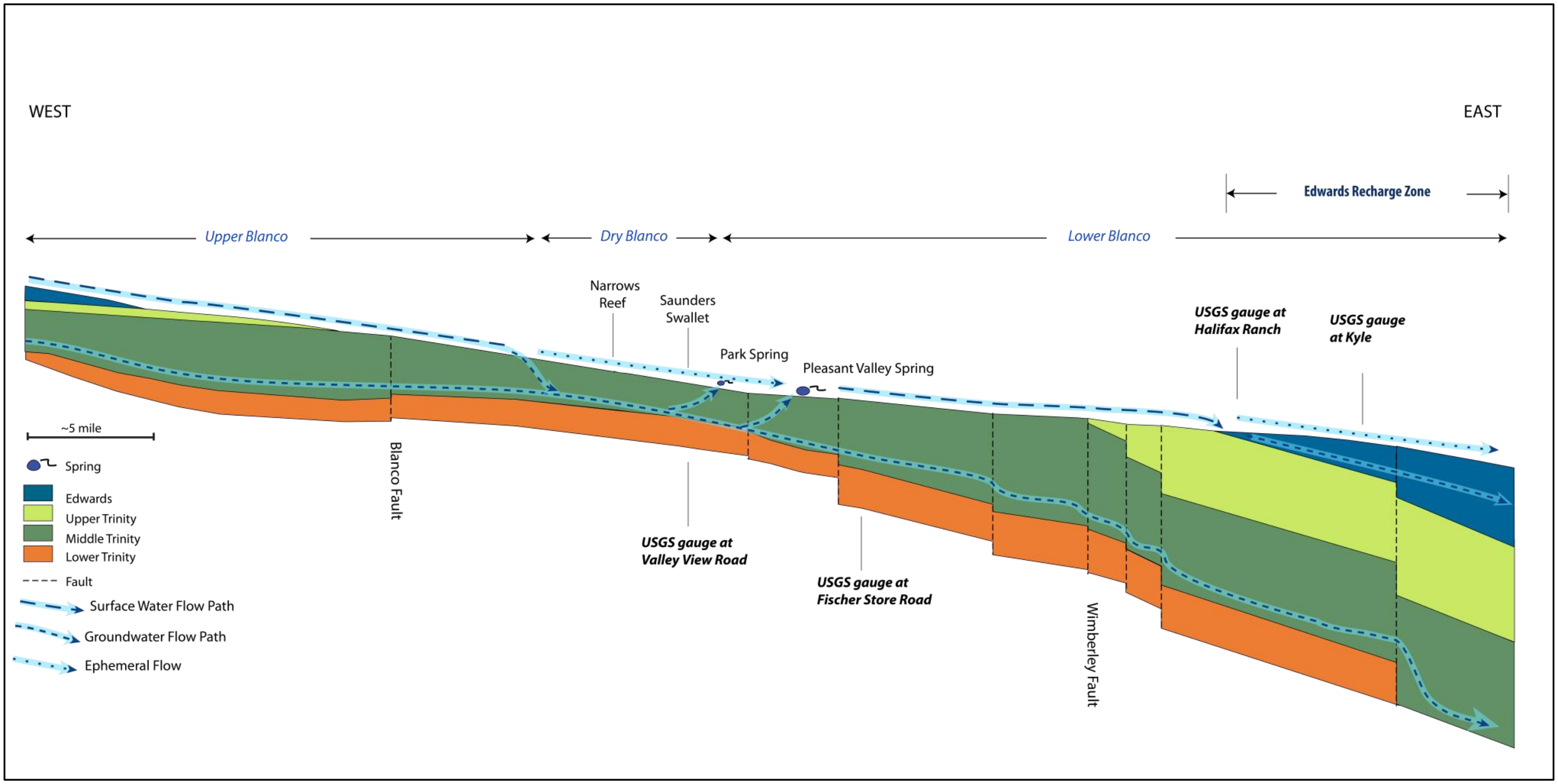

Figure ES - 3: Conceptual section along the Blanco River from west to east. Surface water and groundwater flow paths are shown as they interact in the Trinity and Edwards aquifers

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Appendices

Appendix A: Project Arc Hydro Groundwater Database

Appendix B: Possible Calibration Wells and Hydrographs

1 Introduction

The headwaters of the Blanco River are in northern Kendall County, TX. The river flows eastward for about 87 miles across the Texas Hill Country to join the San Marcos River just southeast of San Marcos, TX (**Figure 1)**. Along the way, the river flows both above and below ground and interacts with the Trinity and Edwards aquifers (Ferguson 2017). The Blanco River watershed provides water to supply spring flow at iconic central Texas springs including Barton Springs, San Marcos Springs, Pleasant Valley Springs, and Jacob’s Well Spring.

The Blanco River basin includes some of Texas’ and the nation’s fastest growing counties. With increases in population come increased demands on the water resources in the basin. Increased extraction of water to meet growing demand has the potential to reduce flow in the Blanco River and discharge from Barton Springs, San Marcos Springs, Pleasant Valley Springs, and Jacob’s Well Spring (Gary et al. 2019).

One way to plan for increased water demand and to effectively manage water resources is to employ a numerical, computer model to simulate the changes in amount of water in Blanco River basin over time given projected changes in water demand with continuing growth. A computer model provides a means to test the impact of economic development hypotheses on the water resources in the basin and to analyze the utility of water-management strategies.

The Texas Water Development Board (TWDB) developed a numerical, computer model of groundwater flow in the Trinity Aquifer in the Hill Country. However, this model: 1) simulates groundwater flow and does not explicitly simulate or account for surface water considerations; and 2) is regional in scope with the main purpose of estimating available groundwater volumes for the entire Trinity Aquifer, which extends beyond Blanco River basin to the north, west, and south.

A new tool needs to be developed that is specific to the Blanco River basin and explicitly accounts for surface water in the basin. The purpose of the new tool is to allow local landowners, communities, and groundwater conservation districts to better understand and manage groundwater resources in the Hill Country by providing understanding and quantification of the interaction of groundwater and surface water in the Blanco River basin. "Surface water" as used in this report comprises water in surface water bodies such as streams and lakes (lumped together in this report as "streamflow"). In this study, surface water also includes water flowing at or near the land surface outside of such water bodies, typically referred to as "runoff". Runoff and other near-land surface processes are included in the "land-surface processes" category in this study.

Although this new tool will also be a numerical, computer model, this new, more local model would not replace TWDB’s groundwater availability model. Instead, it will supplement the TWDB model with more detailed data that local groundwater conservation districts can use to not only inform local management decisions but to inform decisions on desired future conditions and to improve subsequent updates of the regional model.

Development of a numerical, computer model to test hypotheses relating to potential impacts of increased pumping and water extraction on groundwater levels, springs, and river flows is a substantial undertaking. Consequently, the development effort is divided into two phases.

- **Phase 1**: Create a conceptual model of the Blanco River system and use this to generate a blueprint for the numerical, computer model.
- **Phase 2**: Develop, calibrate, and validate the numerical, computer model.

The new tool is called the **B**lanco **R**iver **A**quifers **T**ool for **W**ater and **U**nderstanding **R**esiliency and **S**ustainability **T**rends (BRATWURST). It is likely that there will be subsequent phases to test hypotheses related to future pumping and changes in future weather patterns on the Blanco River system.

The purpose of this document is to present the results of Phase 1: Creation of the Conceptual Model.

1.1 Hypothesis testing

"All models are wrong but some are useful" (Box and Draper 1987, p. 474). Models are wrong because they are an abstraction from reality and it is impossible to exactly and correctly represent reality. But, models can be useful by approximating reality sufficiently to provide illuminating insight into what-if questions and hypotheses.

The purpose of BRATWURST is to examine a series of what-if questions to provide insight into the future of Blanco River water resources. A list of specific questions that BRATWURST is designed to address includes the following.

- **What** is the hydraulic relationship among the Blanco River and the four iconic Hill Country springs and, by extension, the aquifers that provide water to these springs?
    - Pleasant Valley Springs (Middle Trinity Aquifer)
    - Jacob's Well Spring (Middle Trinity Aquifer)
    - San Marcos Springs (Balcones Fault Zone (BFZ) Edwards Aquifer)
    - Barton Springs (Barton Springs Segment of the Edwards Aquifer)
- **If** there are external changes in the future that affect the Blanco River and the associated aquifers, how do the hydraulic relationships change among the river and the springs and what are the potential impacts to river flow, spring discharge, and aquifer water levels?
    - Two important external changes that need to be addressed in this study include:
        1. Increased groundwater extraction (i.e. pumping) from the Middle Trinity Aquifer in conjunction with growth and development in Hays and Blanco Counties; and
        2. Changes in long-term average weather or changes in climate.
    - What are the impacts to river and stream flow from an environmental perspective given these external changes?

These what-if questions guide the region that BRATWURST will be applied to and determine the logic and processes that need to be included as part of BRATWURST (see Sections **7** and **8**).

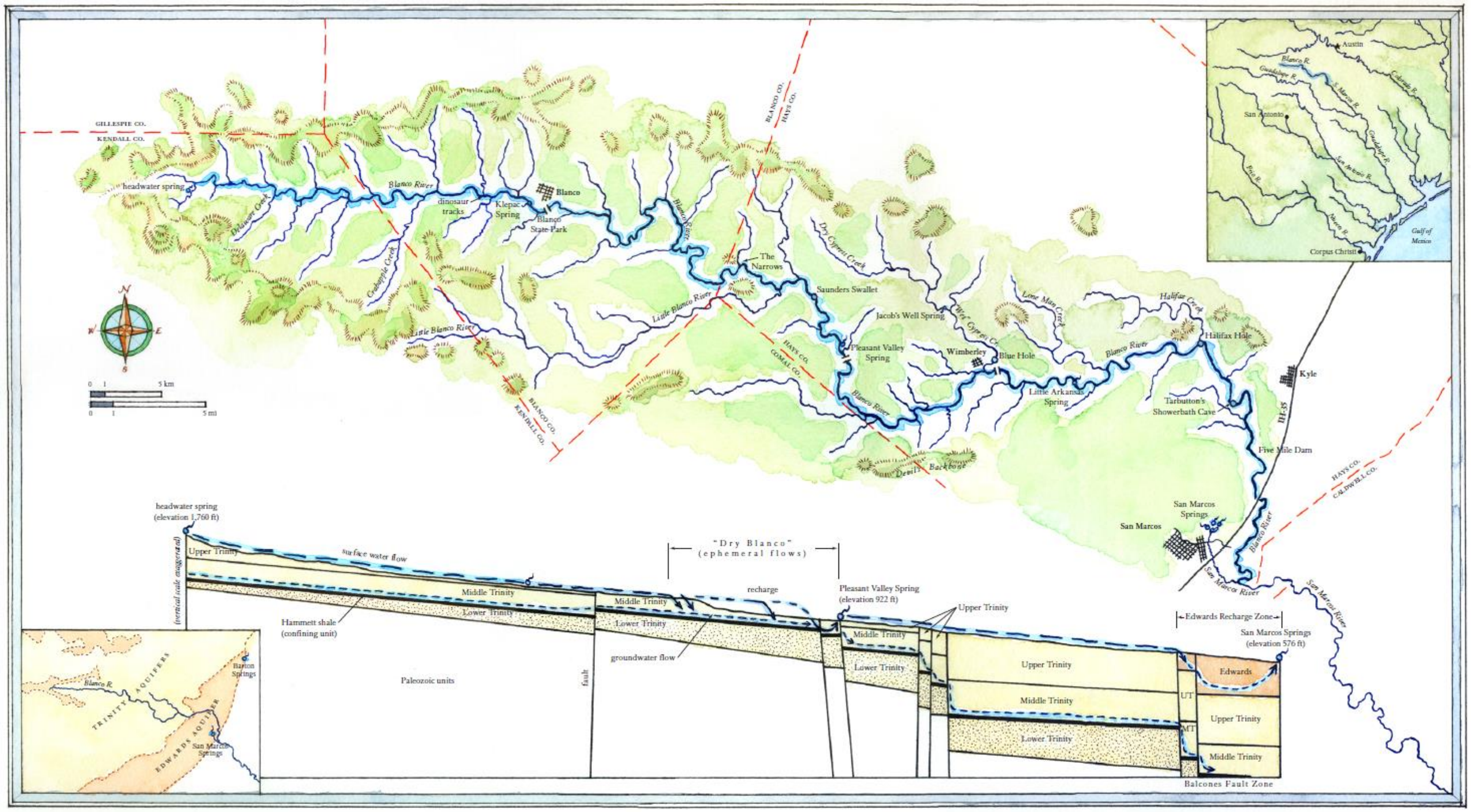


Figure 1: Blanco River watershed with a generalized vertical geologic cross section (drawing by Molly O'Halloran original is in Ferguson (2017))

2 Study area

The Blanco River originates in the northeast corner of Kendall County, TX in the Edwards Plateau (Buckner and Thompson 1963). It flows towards the east and Texas Coastal Plain (Blackland Prairie). Before reaching the Coastal Plain and joining the San Marcos River, it traverses the Balcones Escarpment and BFZ (Smith et al. 2015).

If the sole consideration of this study were surface water runoff and river flow in the Blanco River system, then the Blanco River watershed upstream of the confluence with the San Marcos River would comprise the study area. The Blanco River system includes complex surface water and groundwater interactions, and it interacts with the Trinity and Edwards aquifers. In order to analyze all of the preliminary hypotheses suggested in stakeholder meetings, the study area needs to be extended beyond the surface extent of the Blanco River watershed. The primary rationale for extension is that several important springs located in the Trinity and Edwards aquifers and near the Blanco River system have springsheds that extend beyond the Blanco River watershed boundary.

Figure 2 presents the proposed study area and groundwater model extent. Full details for the selected shape and coverage are provided in Section **6**. The study area, or area of interest (AOI), was extended to enable testing of hypotheses related to Blanco River contributions to the BFZ Edwards Aquifer and associated springs like Barton Springs and San Marcos Springs. This study area encompasses parts of Blanco, Comal, Gillespie, Hays, Kendall, and Travis counties (see **Table 1**).

Table 1: Study area break-out by county

Counties	Area	
	acres	sq. mi.
Blanco	238,275	372.3
Comal	116,064	181.4
Gillespie	51,123	79.9
Hays	370,187	578.4
Kendall	181,003	282.8
Travis	53,911	84.2
Total	1,010,563	1,579

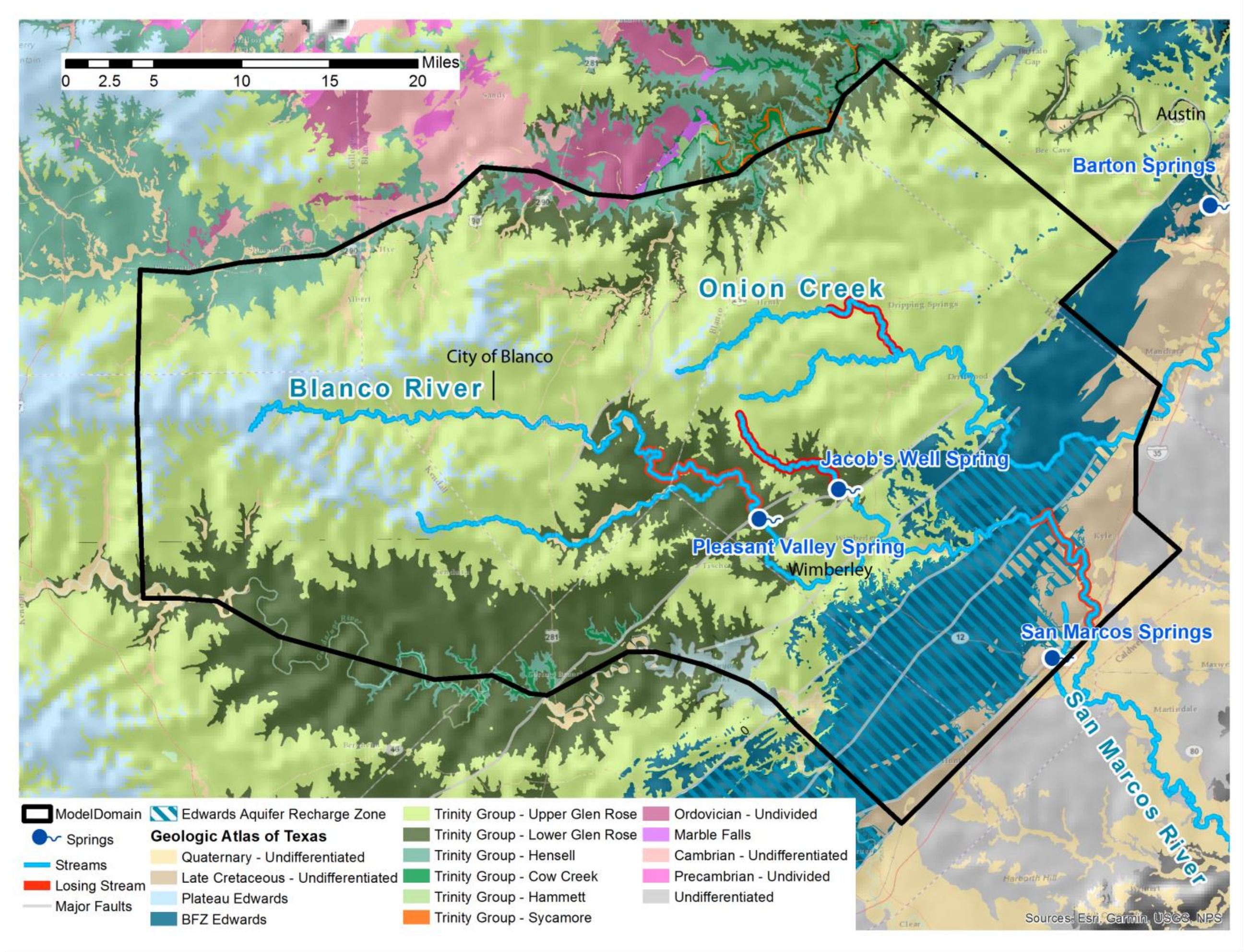


Figure 2: Plan view of the study area

Losing sections of the Blanco River and Onion Creek, or where the rivers are thought to feed into the Trinity and Edwards aquifers, are outlined in red. The Edwards Aquifer recharge zone is indicated by blue hatch markings. Four major springs are also shown.

3 Geology

The eastern margin of the Edwards Plateau is deeply dissected and eroded. This region is known as the Texas Hill Country. The eastern edge of the Hill Country is the Balcones Escarpment and BFZ which provides the transition from the dissected eastern edge of the Plateau to the Texas Coastal Plain and Blackland Prairie. The western boundary of the study area is on the eastern edge of the Edwards Plateau and the eastern boundary is the eastern edge of the BFZ.

3.1 Structural setting

BFZ is a system of mostly southeast-dipping, en echelon, normal faults that provides the transition from the near-horizontal rocks of the Texas craton to the gently dipping sedimentary deposits of the Gulf of Mexico margin (Ferrill et al., 2019). "en echelon" means that the faults are closely spaced, overlapping and subparallel (Smith et al. 2018). The BFZ trend is coincident with the subsurface Ouachita Orogenic Belt and is generally tangent to the Llano Uplift structural zone as shown in **Figure 3**(Wierman et al. 2010, Ferrill et al. 2019). The Ouachita Orogenic Belt and Llano Uplift pre-date the formation of the BFZ, but these structures and the associated San Marcos Arch provide structural control for deposition of the Cretaceous sediments that are the focus of this study, see **Figure 4** and **Figure 5** (Wierman et al. 2010). The BFZ was formed by normal faulting during the early Miocene that displaced and, in some cases, fractured, the carbonate sedimentary structures (Collins and Hovorka 1997; Wierman et al. 2010; Ferrill et al. 2019).

3.2 Stratigraphy

The Early Cretaceous Trinity Group is the primary, stratigraphic focus for this study. The slightly younger, but still Early Cretaceous, Edwards Group provides a secondary stratigraphic focus because of the juxtaposition of these two groups of sediments from deposition and post-depositional offset and deformation in the BFZ. A simplified interpretation of the complex, carbonate stratigraphy of the Trinity and Edwards groups is employed in this study as shown in **Table 2** and **Figure 2**. For detailed stratigraphic interpretation and mapping, the reader is referred to Wierman et al. (2010); Clark et al. (2016a); Clark et al. (2016b); Clark and Morris (2017); and Clark et al. (2018).

3.3 Faults and structure

Numerous faults have been mapped or inferred as part of the BFZ in the study area as shown on **Figure 6** (Collins and Hovorka 1997; Clark et al. 2016a; Clark et al. 2016b; Clark and Morris 2017; Clark et al. 2018; Ferrill et al. 2019). Normal faulting in the BFZ is important because the normal faulting can serve to juxtapose water-bearing units in the Edwards and Trinity groups and thus provide for inter-formational flow and because faulting can provide barriers to flow and force groundwater flow parallel to faults and through gaps between faulted areas (Hunt et al. 2015).

3.3.1 Relay ramps

With the en echelon normal faulting in the BFZ, there are regions of individual faults where the offset is minimal or approximately zero. With minimal offset on an individual fault, offset and extension must occur on an adjacent fault or faults in order to produce the required total offset across the BFZ. This creates the situation where faults in the BFZ may generally provide barriers to perpendicular groundwater flow but may also route flow parallel to faults until zero offset regions where flow can then turn perpendicular to the general strike of the BFZ. The deformation to accommodate the transition from large offset to minimal offset creates relay ramp or transfer structures; these structures provide a zig-zag flow pattern as shown in **Figure 7** and **Figure 8** (Collins and Hovorka 1997; Hunt et al. 2015; Hunt et al. 2017). The parallel-to-fault flow, in regions of large displacement, combined with transverse flow, in regions of small displacement, provide a somewhat circuitous route for flow across the fault blocks in the BFZ.

3.3.2 Fault blocks

The BFZ is 15-31 mi (25-50 km) wide and has a maximum displacement or fault throw of 1200 ft (366 m) (Collins and Hovorka 1997; Ferrill et al. 2019). Mapping of faults in the region suggests that the BFZ contains multiple 2- to 7- mi (3- to 11-km) wide fault blocks bounded by large displacement normal faults with throws ranging from 100 to 850 ft (30 to 265 m) (Collins and Hovorka 1997).

The Tom Creek Fault in Hays County, which becomes the Mount Bonnell Fault in Travis County, provides the western boundary of the BFZ in the study area (Johnson et al. 2012). To the northeast of the study area in Travis County, displacement on the Mount Bonnell Fault is more than 650 ft (200 m) near the Colorado River (Small et al. 1996). This region is adjacent to the Barton Springs segment of the Edwards Aquifer. Tom Creek Fault is of particular importance in this region; it “extends northeast-southwest through Wimberley with throws of as much as 250 ft (76 m) to the east where the fault crosses into Travis County. Yet, about 3 km (2 mi) west of Wimberley, the Tom Creek Fault has throws of about 15 m (50 ft), and close to zero meters another 3 km (2 mi) to the southwest (Smith et al. 2018, p. 21).” In the large displacement sections of Tom Creek Fault (from approximately Cypress Creek in the southwest to Travis County in the northeast), it provides a barrier to flow for the Upper and Lower Glen Rose units of the Trinity Group and hydraulically separates the Trinity Group from the Edwards Group on the eastern side of the fault. In this region, flow is parallel to the Tom Creek Fault and the deformed geologic units provide a relay ramp structure (Smith et al. 2018). Hereafter, the region to the east of the Tom Creek Fault where the Edwards Group crops out is referenced as Tom Creek Fault Block; this region is labeled the Onion Creek Ramp in Smith et al. (2018).

The San Marcos Springs area is the transition between the Barton Springs and San Antonio segments of the Edwards Aquifer. Major faults in the southern segment (i.e. in the transition to the San Antonio segment) in the vicinity of San Marcos Springs include San Marcos Springs (also known as the Hueco Springs Fault outside of Hays County), Comal Springs, Bat Cave, Kyle, Mustang Branch, Hidden Valley, Wimberley, and Tom Creek faults. Displacement of San Marcos Springs and Mustang Branch faults approximately juxtaposes the entire thickness of the Edwards Aquifer against overlying units (Johnson et al. 2012).

In the San Marcos Springs region, the BFZ Edwards Aquifer has been divided into the following four main fault blocks (Johnson and Schindel 2008; Johnson et al. 2012).

- Bat Cave: Has outcrops of the lower members of the Edwards Group. Most wells in this area are likely completed in the Glen Rose Formation of the Trinity Group because the water table is often below the Edwards Group units.
- Hueco Springs: Has outcrops of the middle members of the Edwards Group. Edwards Aquifer yields adequate water to wells in this region.
- Comal Springs: Has outcrops of the upper members of the Edwards Group. Edwards Aquifer yields adequate water to wells in this region.
- Artesian: The top of the Edwards Aquifer is 150 to 600 feet below land surface, is recharged by water flowing northeastward from Bexar County and from Comal Springs Fault block, and contains the southeastern limit of the Edwards Aquifer as defined by the fresh water/saline water interface.

Fault blocks (Tom Creek, Bat Cave, Hueco Springs, and Comal Springs) and associated relay ramps compose the eastern boundary of the study domain as seen in **Figure 10** and **Figure 11**.

3.3.3 Other structures

An eastward plunging anticline, located just west of Wimberley, has been delineated in the Trinity Group (Hunt et al. 2017; Smith et al. 2018); the location of this anticline is shown on **Figure 3**. The limbs of this anticline direct flow in the Trinity Group to the northeast, on the northern limb, and to the southeast, on the southern limb. Also, a horst block has been identified on the northwestern side of the Pleasant Valley Fault, in the Saunders Swallet region, that provides for surface exposure of the Cow Creek Limestone in the Blanco River bed (Smith et al. 2018).

3.4 Surface geology

Surficial geology for the study area, in accordance with the simplified stratigraphic listing in **Figure 2,** is shown on **Figure 2**. The western side of the study area is Hill Country terrain which is dissected Edwards Plateau. In this area, the Edwards Group overlies the Trinity Group but the Edwards has been eroded in the river valleys. Moving eastward in the study domain, normal faulting in the BFZ has moved the stratigraphic section downwards in the down-dropped blocks which places Edwards Group at the surface and at a similar elevation to the Trinity Group in the adjacent, footwall block (Collins and Hovorka 1997; Wierman et al. 2010; Hunt et al. 2015). The schematic section from Wierman et al. (2010), which is reproduced as **Figure 5**, displays the conceptual arrangment from west to east across the study domain.

Table 2: BRATWURST simplified, table listing of stratigraphy

Time Period	Group*	Label		Description	Hydrostratigraphy
Quaternary	NA	🟨	Quaternary - Undifferentiated	Alluvium and colluvium	Relatively unconsolidated, surficial deposits
Late Cretaceous	Taylor, Austin, Eagle Ford, Washita	🟫	Late Cretaceous - Undifferentiated	Marl, mudstone, shale, wackestone, clay	Confining unit - easternmost portion of domain, east of BFZ
Early Cretaceous	Edwards - Fort Terrett, Segovia	🟦	Plateau Edwards	Edwards Limestones on edge of plateau	Unconfined, upland or ridge-top unit in western portion of domain. Is not hydraulically connected to BFZ Edwards units
	Edwards Group	🟦	BFZ Edwards	Balcones Fault Zone, Edwards - undifferentiated	BFZ Edwards, primary aquifer
	Trinity Group	🟩	Upper Glen Rose	Limestones and evaporites	Contains secondary, Upper Trinity aquifer and confining units
		🟩	Lower Glen Rose	Limestones	Contains secondary transmissive units which can be considered part of the Middle Trinity aquifer and confining units
		🟩	Hensell	Sand, siltstone, shale, and dolomite	Transmissive unit in west (part of Middle Trinity aquifer) and confining unit in the east Sands facies in the western part of the domain- facies change to silty shale and dolomite east of the Ouachita deformation front (Wierman et al., 2010)
		🟩	Cow Creek	Limestones	Middle Trinity, primary aquifer
		🟩	Hammett	shale and claystone	Confining unit
		🟧	Sycamore/Hosston	Sandstones and conglomerates	Lower Trinity, secondary aquifer

*Row thickness does NOT denote typical, relative Group thickness

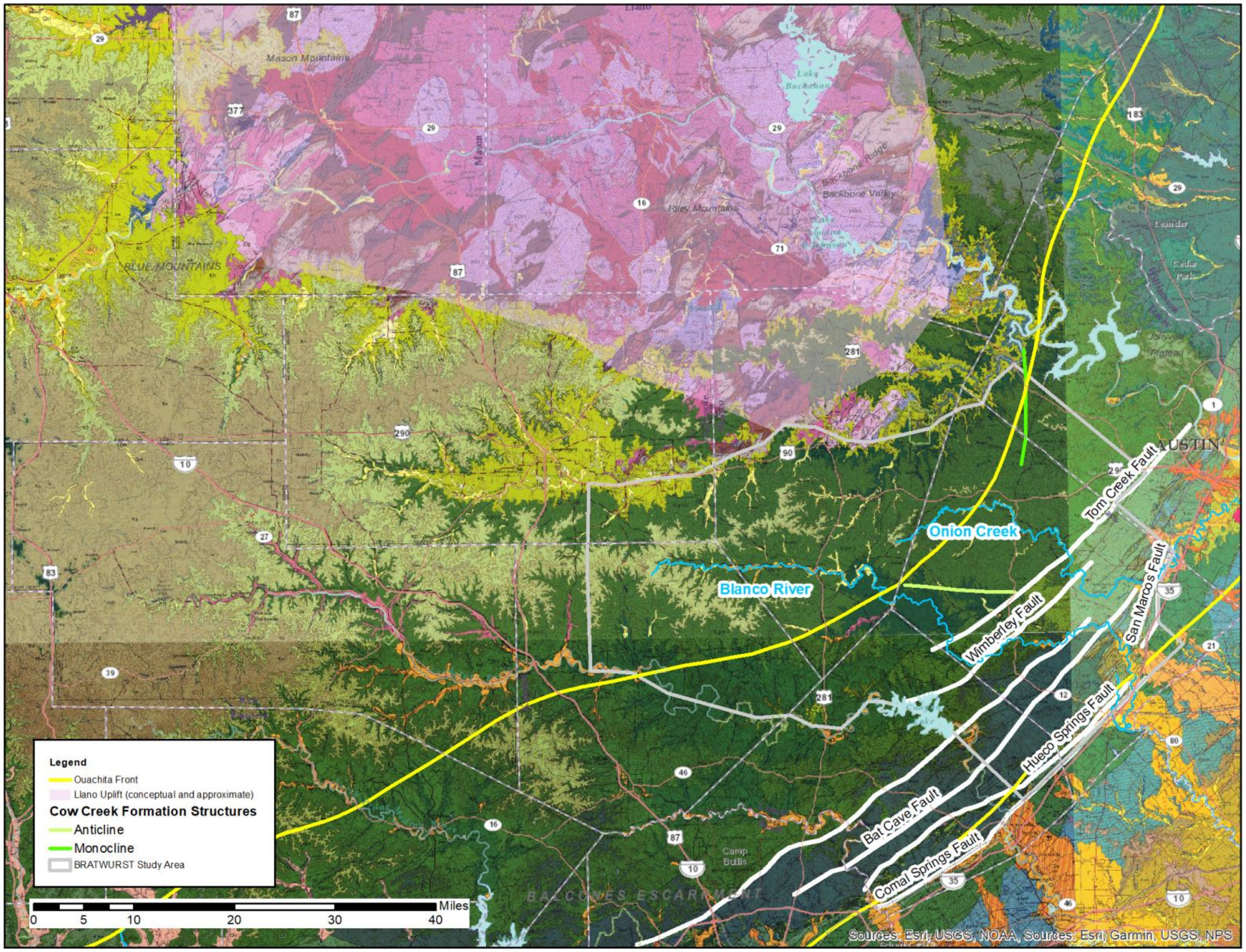
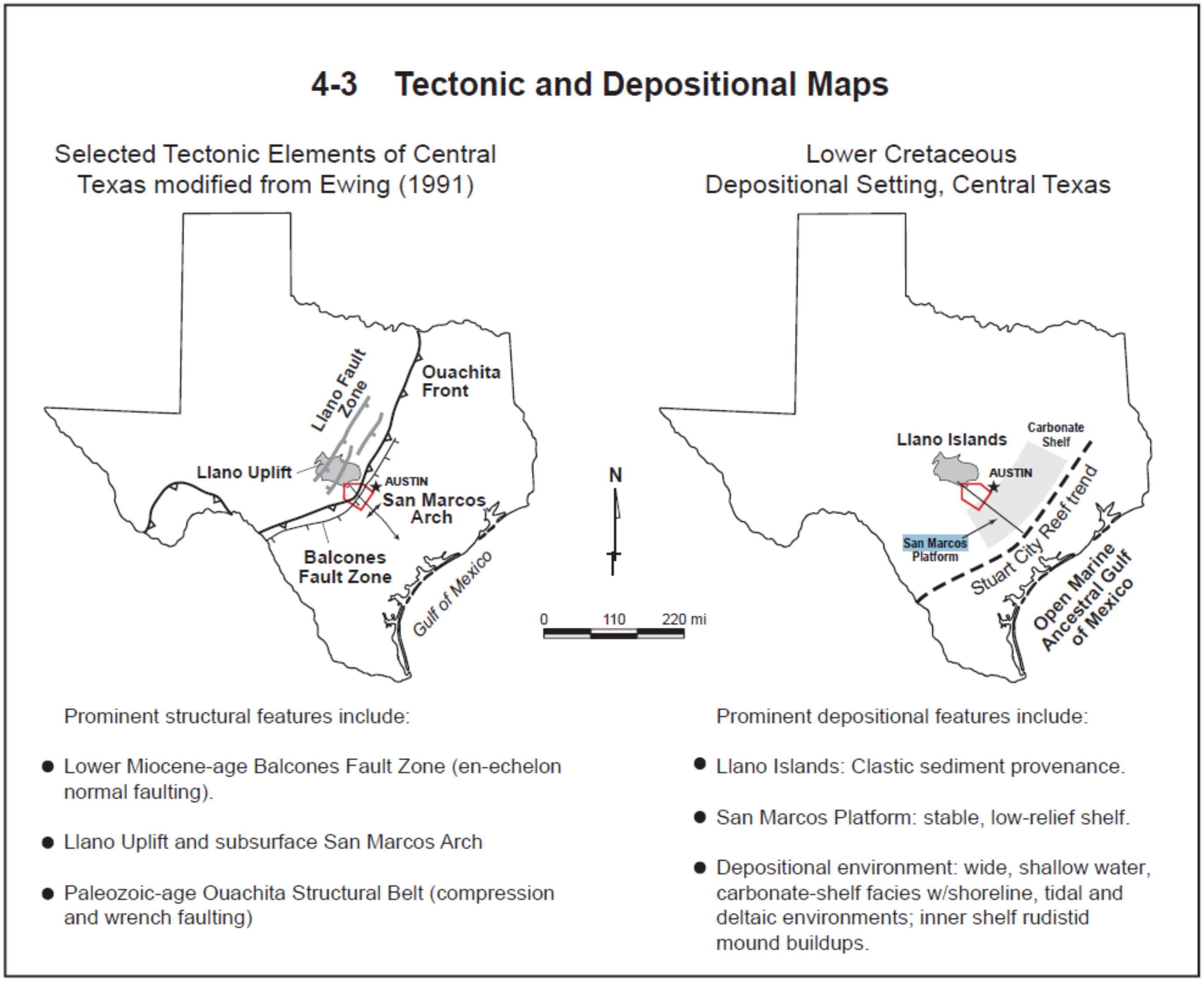


Figure 3: Regional structural overview

Regional structures that are of interest for this study are approximately located for reference. Faults depicted are major faults in the BFZ in and near the study area.



4-3 Tectonic and Depositional Maps

Selected Tectonic Elements of Central Texas modified from Ewing (1991)

Lower Cretaceous Depositional Setting, Central Texas

Prominent structural features include:

- Lower Miocene-age Balcones Fault Zone (en-echelon normal faulting).
- Llano Uplift and subsurface San Marcos Arch
- Paleozoic-age Ouachita Structural Belt (compression and wrench faulting)

Prominent depositional features include:

- Llano Islands: Clastic sediment provenance.
- San Marcos Platform: stable, low-relief shelf.
- Depositional environment: wide, shallow water, carbonate-shelf facies w/shoreline, tidal and deltaic environments; inner shelf rudistid mound buildups.

Figure 4: Structure and depositional maps, Figure 4-3 from Wierman et al. (2010)

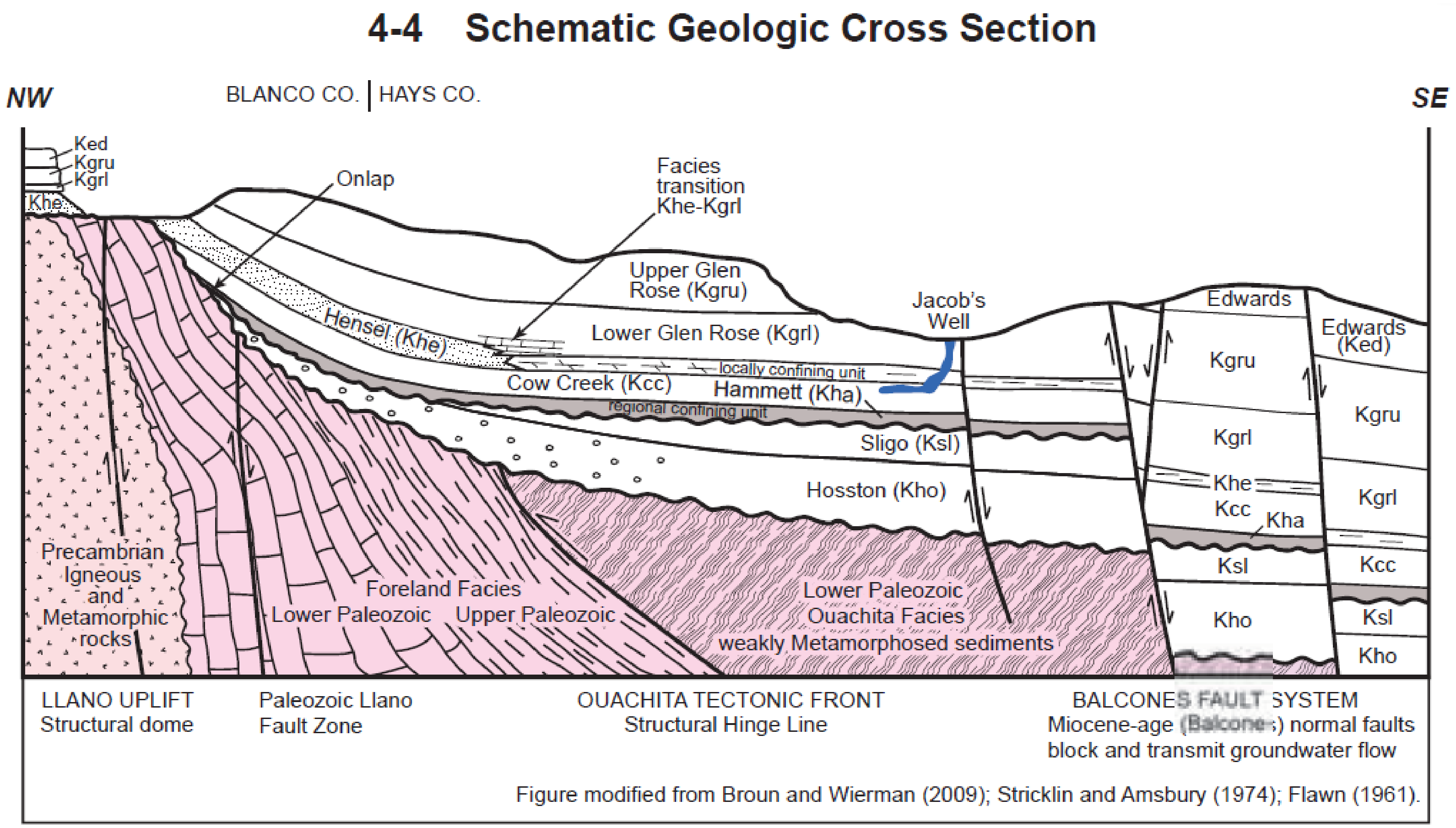


Figure modified from Broun and Wierman (2009); Stricklin and Amsbury (1974); Flawn (1961).

Figure 5: Structural control for Cretaceous (K) sedimentation, Figure 4-4 from Wierman et al. (2010)

Cretaceous sediments were subsequently offset and deformed during Early Miocene as part of BFZ en echelon normal faulting. Note the facies transition called out in the Hensell that is coincident with the Ouachita Front and the hydraulic separation between the BFZ Edwards on the right (SE) and Plateau Edwards on the left (NW).

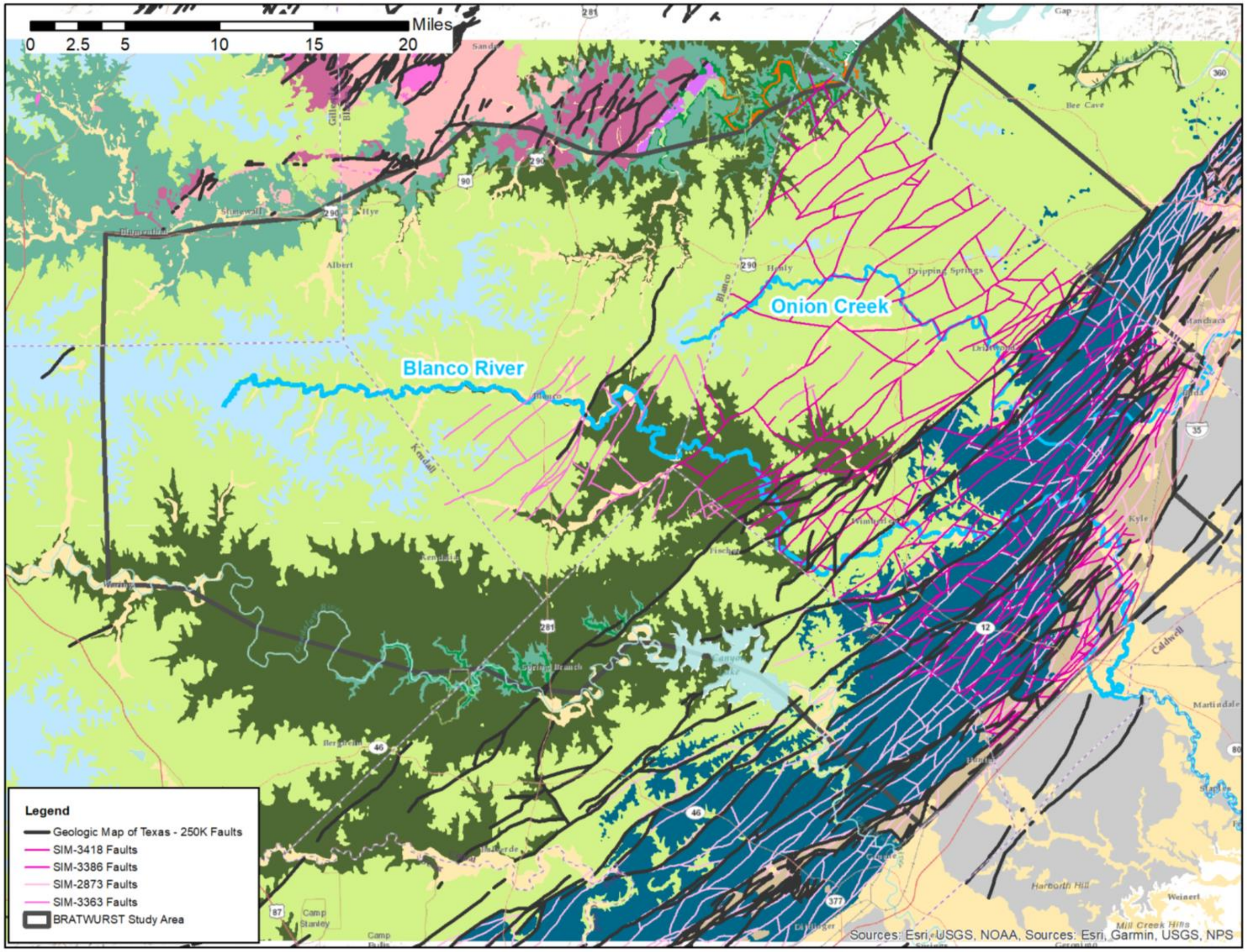


Figure 6: Mapped and inferred faults in the study area

SIM-3418 is Clark et al. (2018); SIM-3386 is Clark and Morris (2017); SIM-2873 is Blome et al. (2005); SIM-3363 is Clark et al. (2016b).

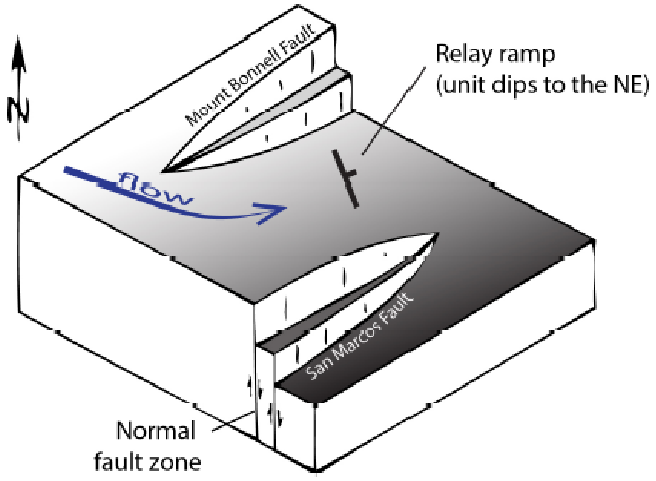


Figure 3. *Schematic diagram of a relay ramp structure and its influence on groundwater flow. Two major faults transfer the displacement from one to the other resulting in folding, fracturing and faulting (not shown) along the ramp structure. These structures were proposed and mapped by Grimshaw and Woodruff (1986) and Collins and Hovorka (1997). Figure modified from Grimshaw and Woodruff (1986).*

Figure 7: Schematic depiction of a relay ramp structure, Figure 3 from Hunt et al. (2015)

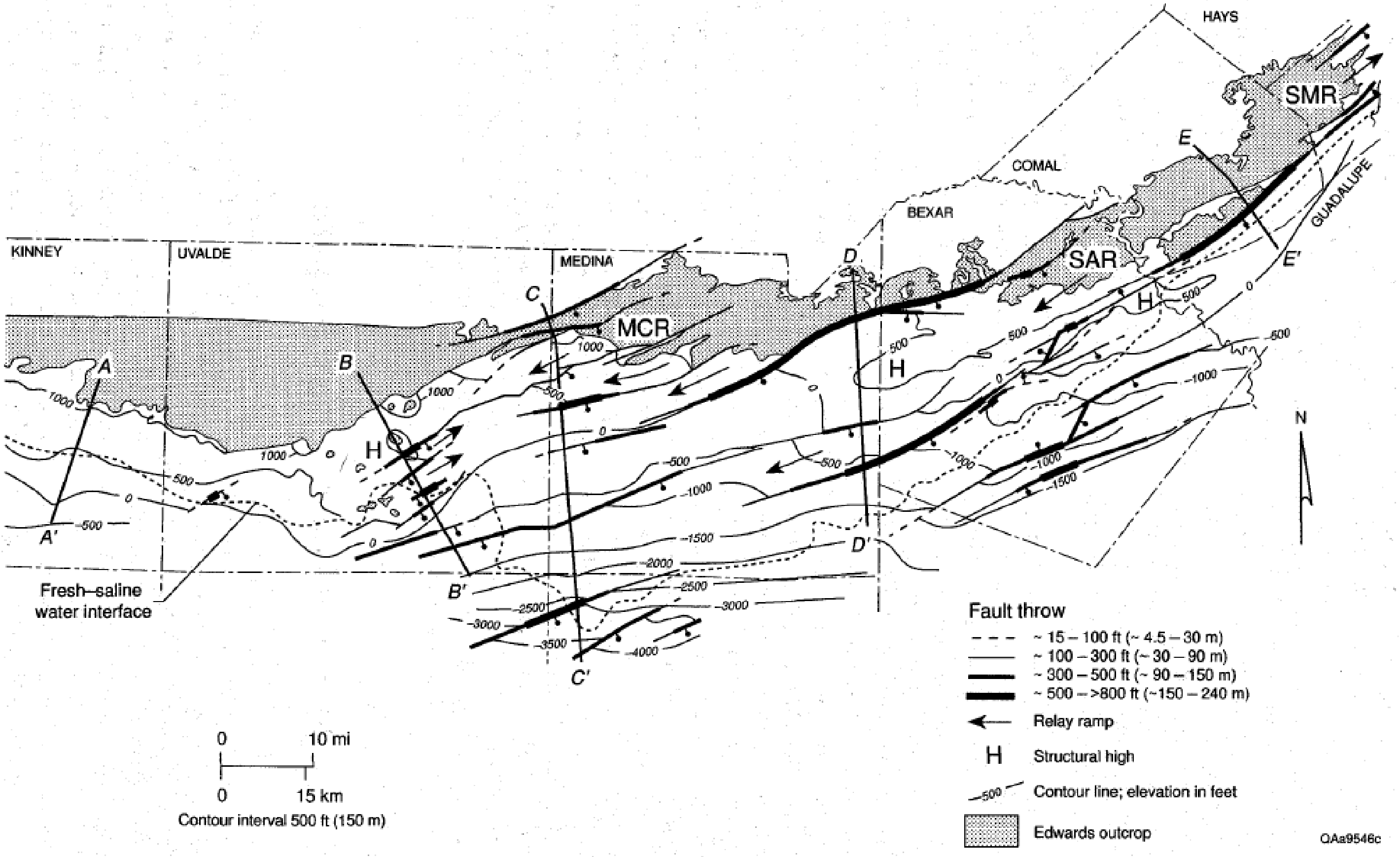


FIGURE 4. Simplified structure of Edwards aquifer strata showing throw of faults. Structural cross sections A–A′ through E–E′ shown in figure 5. MCR = Medina County relay ramp; SAR = San Antonio relay ramp; SMR = San Marcos relay ramp.

Figure 8: Fault blocks and relay ramps in the southern-most portion of the study area, Figure 4 from Collins and Hovorka (1997)

Note the flow divide in Comal County in the vicinity of the E-E′ line and the Guadalupe River - this flow divide suggests that for our study area, flow will be towards the northeast through the San Marcos relay ramp.

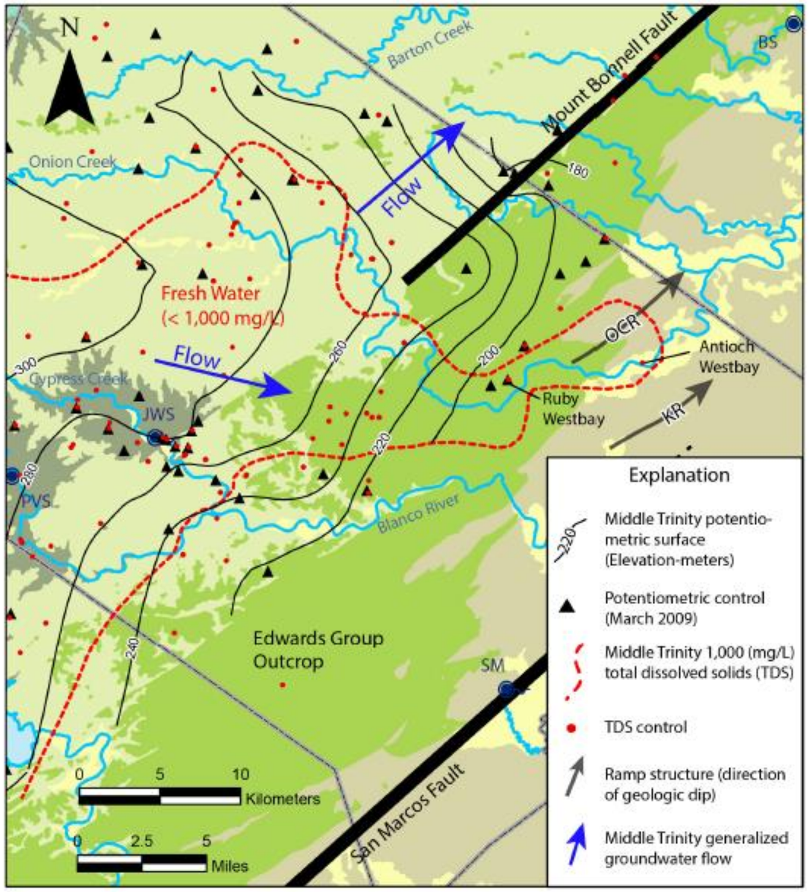


Figure 6. Map showing hydrologic data (potentiometric and geochemistry) relative to the ramp structures and major faults. Flow paths of the Middle Trinity defined by potentiometric heads and the "tongue" of low TDS appear to flow to the east along the Onion Creek ramp. Note the flow to the northeast indicating the fault may be a barrier to flow in that area. Potentiometric data from Hunt and Gary, 2014. TDS data modified from Wierman et al., 2010.

Figure 9: Onion Creek relay ramp and flow patterns, Figure 6 from Hunt et al. (2015)

For BRATWURST study purposes, the Onion Creek relay ramp coincides with the "Tom Creek Fault Block" which is bounded to the north by the Tom Creek/Mt. Bonnell Fault and to the south by the San Marcos/Hueco Springs Fault.

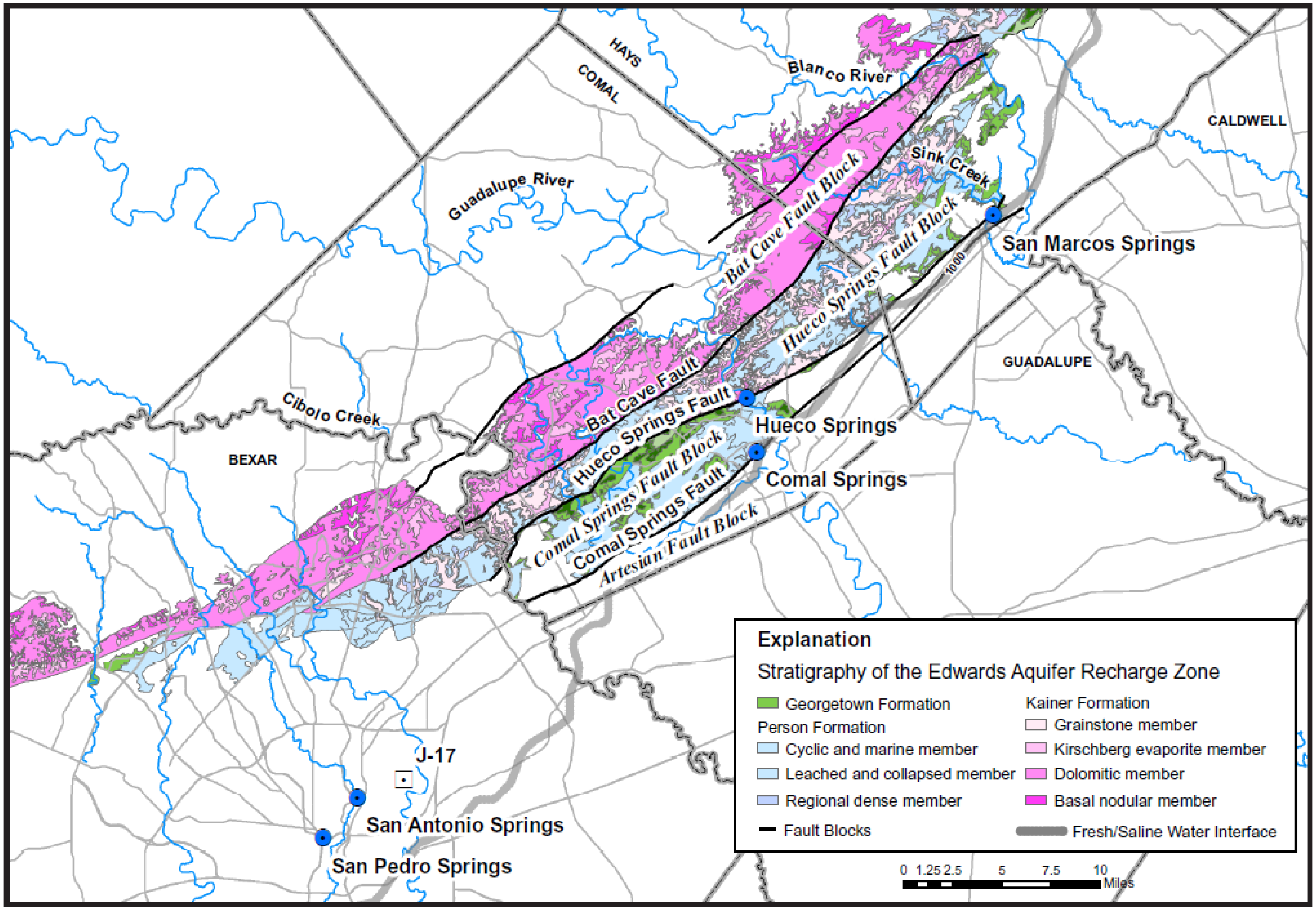


Figure 10: Edwards Group fault blocks identified in the vicinity of San Marcos Springs, Figure 2 from Johnson and Schindel (2008)

Note that this figure shows fault blocks to the south of Figure 9; San Marcos Fault in Figure 9 is the continuation of the Hueco Springs Fault to the northeast beyond San Marcos Springs. The Blanco River provides a reference point between this figure and Figure 9. The Guadalupe River provides a reference point to link this figure to Figure 8.

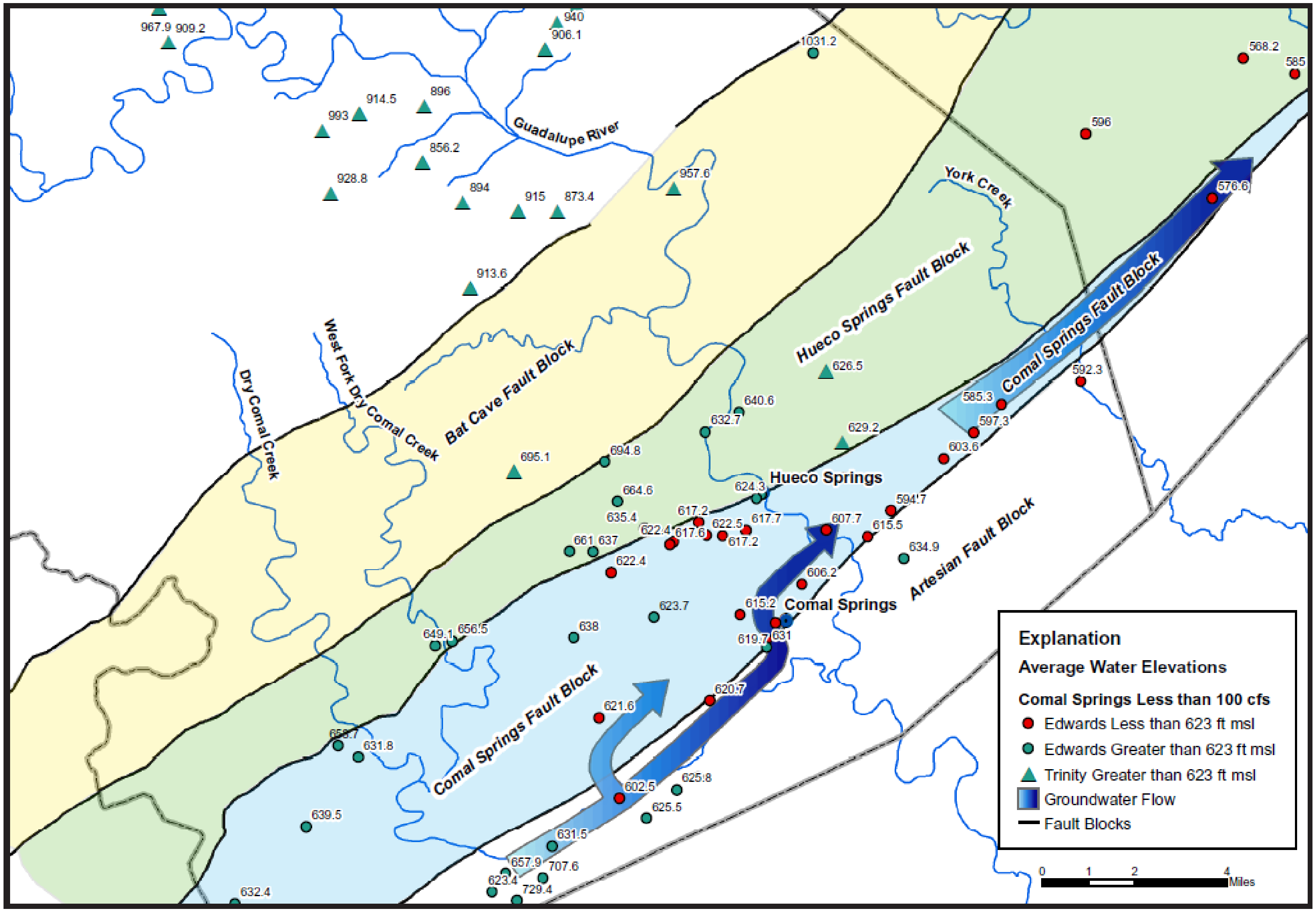


Figure 11: Edwards Group fault block flow paths, Figure 9 from Johnson and Schindel (2008)

Flow directions in the "relay ramp" structures which the interior of the fault blocks agree with Figure 8. Note that the 639.5 point in the lower left of this figure represents the divide portrayed in Figure 8 between flow towards the southwest in the San Antonio relay ramp and towards the northeast in the San Marcos relay ramp.

4 Summary of previous studies

The purpose of this study is to collect and process hydrogeological and hydrological data and information to create a conceptual model as the first step in constructing a numerical model to simulate how the Blanco River interacts with its aquifers. There are no new findings or results from this study. Rather, this study is compilation and synthesis of previous work. Consequently, this entire document provides summaries of previous studies. This section provides summaries of previous studies related to Blanco River and aquifer interaction as well as those related to numerical modeling in the study area.

4.1 Trinity Aquifer hydrostratigraphy and recharge

The Trinity Aquifer is traditionally viewed as composed of three parts: (i) Upper; (ii) Middle, and (iii) Lower. The Upper Trinity Aquifer is associated with the upper member of the Glen Rose Formation of the Trinity Group. The Middle Trinity Aquifer is associated with the lower member of the Glen Rose Formation and the Cow Creek Limestone Member. The Lower Trinity Aquifer consists of the Hosston Formation and overlying Sligo Formation and is separated from the Cow Creek Limestone Member (and the Middle Trinity Aquifer) by the intervening Hammett Shale (Ashworth 1983; Barker et al. 1994; Barker and Ardis 1996; Mace et al. 2000; Wierman et al. 2010; Toll et al. 2018). Although the traditional means of describing hydrogeologic units, like the Trinity Aquifer, is direct correlation with geologic units, like the Trinity Group, hydrogeologic units do not necessarily correlate to geologic units in the study area (Wong et al. 2014; Smith et al. 2018).

The Upper Trinity Aquifer is locally unconfined and discharges into intermittent, wet-weather streams including Onion Creek. It can yield small amounts of water to shallow wells. Recharge is from direct precipitation and inflitration in areas where it is exposed at the surface (Wierman et al. 2010).

The Middle Trinity Aquifer is the primary water source for water supply wells in the study area. It is a karstic and fractured aquifer. Where the Lower Glen Rose Formation is exposed at the surface and is faulted, fractured and contains surficial karst features, direct communication from streams and surface runoff provides focused recharge to the Middle Trinity Aquifer. The Hensell Formation undergoes a facies change approximately associated with the location of the Ouachita Front. To the west of the front, the Hensell Formation is sandy and allows for vertical percolation into the Cow Creek Formation from the Upper Glen Rose Formation. Moving eastward from the Front, the Hensell Formation is finer grained and acts as a semi-confining layer for the Cow Creek Formation (Wierman et al. 2010).

The lithostratigraphic units composing the Lower Trinity Aquifer do not crop out in the vicinity of the Blanco River or Onion Creek. Consequently, there is minimal recharge from precipitation because of limited surface outcrop (Wierman et al. 2010). Primary recharge of the Lower Trinity Aquifer is from leakage in areas to the north and west where the Hammett Shale is thin or absent. If the Hammett Shale is present and faulted, there may be some recharge from Middle Trinity to Lower Trinity aquifers (Ashworth 1983). The Lower Trinity Aquifer is becoming an increasingly important source of water supply as pumping increases in the Middle Trinity Aquifer due to population growth (Wierman et al. 2010).

Hunt et al. (2017) describe two interconnected aquifer zones in the Middle Trinity Aquifer based on physiography, structural setting, degree of karstificaiton, and depth below ground surface.

1. Hill Country Middle Trinity Aquifer located to the west of the BFZ
2. BFZ Middle Trinity Aquifer which is located in the BFZ

Smith et al. (2018) describe the hydrostratigraphy and complex flow systems in the Trinity Aquifers in central Texas. Significant recharge to the Middle Trinity Aquifer occurs from losing streams as discussed in Sections **4.2** and **4.3**. The Trinity Aquifers consist primarily of limestone, dolomite, and marl and exhibit karstification including karst features like caves and sinkholes near the surface. Karstification is also evident below 1,300 ft (400 m) above mean sea level where dissolution along fractures developed conduits. The complex Tom Creek Fault Zone provides the dividing line between the Hill Country Middle Trinity Aquifer and the BFZ Middle Trinity Aquifer. The western Hill Country Middle Trinity Aquifer is a shallow karst system with rapid conduit flow and surface water and groundwater interactions. In this area, the units that comprise the Middle Trinity Aquifer are near the ground surface. To the east of Tom Creek Fault, the BFZ Middle Trinity Aquifer is a confined karst system with relatively limited conduit development and slower groundwater flow. In the confined system, there are no surface and groundwater interactions, and BFZ Middle Trinity units are at depths below ground level of 500 ft (150 m) or greater.

4.2 Blanco River gain/loss and baseflow

Buckner and Thompson (1963) conducted a study to determine the interchange of surface water and groundwater in a reach of the Blanco River above Wimberly, TX that was the proposed site for a reservoir. As part of the investigation, field investigations were performed in February and March of 1963 across about 27 miles of the Blanco River, starting at the river gaging station in Wimberly and extending upstream. Notable findings from this study include:

- Net gain in flow across the 27 miles was 41.1 cubic feet per second (cfs;)
- No flow in the reach from just upstream of the Hays County boundary to just upstream of the confluence with Wanslo Creek; and
- The most significant losses and gains observed during the study were associated with faults including Tom Creek Fault (losing section) and Spring Branch Fault (gaining section).

Although the Buckner and Thompson (1963) study was a baseflow study, the study was conducted in the middle portion (i.e., rather than at the end of the recession) of an approximately one-month hydrograph recession.

Wehmeyer et al. (2013) conducted a streamflow gain and loss study on the lower Guadalupe River Basin and the Blanco River during three selected periods: 1) March 2010; 2) April 2011; and 3) August 2011. Surface water budgets were calculated using available gauging station data. Streamflow gains and losses were identified for reaches (i.e. reach water budgets) where the computed gain or loss was greater than the uncertainty in the computed streamflow in the budget calculation. Notable findings from the study related to the Blanco River include:

- A reach of the Blanco River near Kyle, TX lost 18.7 cfs during the April 2011 analysis period. Much of this loss likely entered the groundwater system through the numerous faults that intersect the stream channel northwest of Kyle (i.e., in the BFZ).
- Two reaches of the Blanco River near Kyle lost 2.20 and 6.60 cfs, respectively, in the August 2011 analysis. Losses were likely from infiltration through numerous faults intersecting the stream channel northwest of Kyle.

- City of Blanco Waste Water Treatment Plant has a permit for discharging treated wastewater (TX0054623) to the Blanco River system.

The water-budget reaches extend between two gauging stations. As a result, the gain/loss analysis coverage area is much larger than provided in other studies and so the results are not focused to a particular fault, karstic feature, or meaningful reach.

Smith et al. (2015) provide analysis and description of the influence of the Blanco River on the Trinity and Edwards aquifers. As part of this work, a thorough description of the varied streamflow regimes in the river is presented from headwaters, in the west, to the San Marcos River confluence, in the east.

- Above the City of Blanco, streamflow is sourced primarily from runoff.
- Near the City of Blanco, springs discharge into the Blanco River.
    - Discharge from the Upper Trinity. Aquifer.
- About 12 mi (20 km) downstream of the City of Blanco, the Blanco River becomes a losing stream as water flows into the subsurface through numerous small recharge features and the Blanco River is generally dry at Saunders Swallet in Hays County.
    - Water lost in this reach of the Blanco River recharges the Middle Trinity Aquifer.
    - Two specific points of focus are 5 mi (8 km) upstream of the Narrows and the Saunders Swallet area.
- Less than 0.6 mi (1 km) downstream of Saunders Swallet, Park Springs discharges and the Blanco River is a flowing stream again.
- Another 1.2 mi (2 km) downstream is Pleasant Valley Springs (PVS) where groundwater discharges at multiple locations through gravels in the stream bed. PVS occurs where a northeast trending fault and associated fractures cross the Blanco River. During drought conditions, PVS becomes the headwaters of the Blanco River. Under average conditions, PVS provides the majority of the water flowing in the river.
    - PVS discharge is attributed to the Cow Creek Limestone in the Middle Trinity Aquifer.
- Blanco River flows for another 24 mi (40 km) to the Edwards Aquifer recharge zone where recharge features like Johnson Swallet divert enough water to cause the river to become dry again under moderate drought conditions.
    - Edwards Aquifer recharge may flow either south to discharge at San Marcos Springs or may flow north to discharge at Barton Springs.
- Blanco River flow that makes it past the Edwards Aquifer recharge zone continues to the San Marcos River.

Hunt et al. (2017) elucidate complex surface water and groundwater interactions between the Blanco River and the Trinity and Edwards aquifers obtained from a suite of studies. Results of gain/loss studies document surface water and groundwater interactions with alternating gaining and losing reaches identified in the Blanco River (and in Onion Creek). Springs and spring-fed tributaries provide for streamflow gains while karst recharge features, like sinkholes, fractures, and caves, provide for streamflow losses. The focused recharge from streamflow contribution directly to the Middle Trinity Aquifer is an important component of the Middle Trinity Aquifer water budget. Blanco River gain/loss study results are summarized by reach in Section **5.4.2**.

Figure 12 provides a summary schematic of the relationships and interactions identified in Smith et al. (2015) and Hunt et al. (2017).

4.3 Onion Creek gain/loss and baseflow

Hunt et al. (2016) identify Onion Creek as an important hydrologic link between the Trinity and Edwards aquifers and present the results of an Onion Creek flow study, which includes Onion Creek tributaries. The flow study revealed complex surface water and groundwater interactions in the Onion Creek watershed. Flow losses were documented along a reach underlain by the Upper Glen Rose Formation in the Trinity Group and these losses contribute focused recharge to the Middle Trinity Aquifer.

Hunt et al. (2017) provide an Onion Creek gain/loss summary discussion along with the Blanco River information. This discussion is presented in Section **4.2**. Section **5.4.2** (including **Table 13** and **Figure 29**) provides a summary of the Onion Creek gain/loss survey results. Onion Creek is an important source of focused recharge for the Middle Trinity Aquifer as well as for the Edwards Aquifer. The upper losing reach (see Section **5.4.2, Figure 29**) contains Burns Swallet and similar karst features that allow surface water to recharge through Upper and Lower Glen Rose Formations to the Cow Creek Formation of the Middle Trinity Aquifer. Recharge of the Middle Trinity Aquifer from Onion Creek may move down dip along a relay ramp to the east or may flow to the northeast towards the Colorado River.

Watson et al. (2018) provide results of subsurface and surface geologic mapping of the Unit 3, a subunit of the Upper Glen Rose Formation. Unit 3 is identified as an important geologic control on focused recharge to the Middle Trinity Aquifer in the Onion Creek watershed. Unit 3 is hypothesized to act as a relatively impermeable boundary which prevents downward migration of water from the watershed into the underlying Middle Trinity Aquifer. In areas where Unit 3 has been removed by erosion from the stream bed or where Unit 3 is absent, prominent fractures observed in the stream bed appear to provide a pathway for recharge to the Middle Trinity Aquifer. The absence of Unit 3 explains the gaining reaches in Onion Creek identified in Hunt et al. (2016).

4.4 Previous numerical modeling and aquifer parameters

Mace et al. (2000) constructed a groundwater availability model to simulate groundwater flow through the Hill Country portion of the Trinity Aquifer system to provide a groundwater resource management tool. The purpose of this model is to provide a tool that can help predict how the aquifer might respond to increased pumping and drought. The model is bounded to the east by the western edge of the BFZ. MODFLOW-96 was employed as the modeling software and a standard porous media formulation was used for simulation calculations. The steady-state model was calibrated for 1975 hydrologic conditions and the transient model was calibrated for 1996-1997.

Jones et al. (2011) updated the Mace et al. (2000) groundwater availability model. The principle updates were to add the Lower Trinity Aquifer as another layer to the model, revise the spatial distribution of recharge and pumping, and calibrate steady-state for 1980 and transient for 1981-1997. Recharge in this updated model is a combination of infiltration of precipitation that falls on aquifer outcrop (diffuse recharge) and infiltration from losing stream reaches (focused recharge). Estimated recharge from infiltration of precipitation was 3.5 to 5 percent of average annual precipitation.

Oliver et al. (19 May 2016) developed a transient analytic element model of the Upper and Middle Trinity aquifers in Hays County to evaluate potential impacts to the Trinity Aquifer from proposed groundwater production at the Electro Purification (EP) well field. This model was subsequently recalibrated to a new series of aquifer tests and then used for additional predictive simulations of potential drawdown from groundwater production (Oliver and Pinkard, 16 April 2018).

Trinity Aquifer parameters have been published in a number of sources. Hydraulic conductivity and storativity were calculated in Toll et al. (2018). **Table 3** and **Table 4** show these parameters in the Trinity Aquifer as compared to values reported in other literature sources. Johnson et al. (2012) reports numerous apparent velocities as calculated from tracers tests performed by the Ewards Aquifer Authority between 2008 and 2010. **Table 5** is modified from this paper to show groundwater velocities along flow paths starting near the Blanco River and traveling toward San Marcos Springs

4.5 Water budgets, Barton Springs Segment of the Edwards Aquifer

Slade (2014) refined the components of the recharge-discharge water budget for the Barton Springs segment of the Edwards Aquifer and quantified recharge that occurs in the main channels of the six major streams that cross the recharge area for the Barton Springs segment. The water-budget calculations cover the period December 1979 through July 1982. One of these six major streams is Onion Creek. Total discharge from the Barton Springs segment is approximately accounted for by discharge from Barton Springs, Cold and Deep Eddy Springs, the lower reach of Barton Creek, and groundwater pumpage. Except during extreme dry conditions, subsurface recharge (i.e. diffuse recharge) and discharge to the aquifer are believed to be minimal. Water-budget calculations indicate that recharge represented 6% of precipitation; runoff represented 9% of precipitation; and evapotranspiration represented 85% of precipitation. The refined recharge-discharge budget calculations suggest that recharge within the main channels of the six major streams accounts for 75% of the total recharge to the Barton Springs segment of the Edwards Aquifer. Long-term recharge, from within the recharge area, that comes from overland flow or tributary streams represents a maximum of 25% of total recharge. Because of the karstic nature of the Edwards Aquifer and because most recharge occurs on the main channels of the streams, substantial porosity has developed under the stream channels and along a major path to the discharge point of Barton Springs. Recent studies calcuate the water budget of the Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer at 68 cfs (Hunt et al. 2019).

Slade (2017) presents a recharge-discharge water budget calculation for the Barton Springs segment of the Edwards Aquifer for the six-year period: November 2003 through October 2009. Impervious cover considerations were included in the water-budget calculation. Only surface sources of recharge and discharge are included in aquifer segment water budget. During some low-flow conditions, subsurface recharge enters the Barton Springs segment of the Edwards Aquifer from south of the segment boundary through discharge from the Blanco River watershed. It is possible that future increases in groundwater withdrawals in the Barton Springs segment will induce additional recharge from the Blanco River due to increased groundwater gradients.

4.6 BFZ Edwards Aquifer

The BFZ Edwards Aquifer consists of the Cretaceous Georgetown Formation and Edwards Group, which is composed mainly of limestone and dolostone. The Edwards Group is composed of Kainer and Person formations in descending order. The aquifer is constrained between an upper confining unit consisting of the Del Rio Clay, Buda Limestone, and Eagle Ford Formation and the underlying upper member of the Glen Rose Formation of the Trinity Group. It is a dissolution modified and faulted karst aquifer (Rose 1972; Maclay and Small 1986; Johnson et al. 2012; Toll et al. 2018).

Johnson and Schindel (2008) and Johnson et al. (2012) identify four fault blocks within the BFZ in the vicinity of the Blanco River that provide the transition for the BFZ Edwards Aquifer through the recharge zone to the artesian zone. The recharge zone is defined by the BFZ; the northwest boundary is the Tom Creek/Mount Bonnell fault and the southeastern boundary is the Comal Springs/Mustang Branch fault. Along the Tom Creek/Mount Bonnell fault, Glen Rose Limestone is in stratigraphic contact with the BFZ Edwards Aquifer across the fault.

Johnson et al. (2012) conducted tracer test experiments and summarize previous tracer test experiments to define the groundwater boundary between San Marcos Springs and Barton Springs and to examine groundwater flowpaths in the San Marcos Springs springshed (**Table 5**). San Marcos Springs is recharged by regional and local sources. The artesian zone of the Edwards Aquifer likely provides the largest part of discharge. The Blanco River is a regional source for San Marcos Spring discharge and the importance of the river as a source increases during dry periods. Local sources for San Marcos Spring discharge include Sink Creek and direct precipitation. During dry periods and low-flow conditions, the groundwater boundary between San Marcos Springs and Barton Springs springsheds is located near the confluence of the Blanco River and Halifax Creek. The Blanco River recharges both springs. The springshed boundary moves towards Barton Springs and Onion Creek during wet conditions when Onion Creek recharge creates a potentiometric surface mound.

Table 3: Hydraulic conductivity values (Toll et al. 2018)

Hydrostratigraphic unit	Hydraulic Conductivity (feet per day)							
	Toll and others (2018)			Literature Values				
	Aquifer Pumping Tests	**Specific Capacity Tests**	**Combined**	**Young and others (2005)**	**LBG-Guyton (2008)**	**Hunt and others (2010)**	**Jones and others (2011)**	**Oliver and Pinkard (2018)**
	median	median	median	calibrated value	calibrated value	median test value	calibrated average	calibrated value
Upper Trinity	0.4*	0.07	0.07	0.5	--	0.08[+]	10.4	0.001
Middle Trinity	0.5	0.2	0.2	1.6[#]	--	5	8.8	0.25 (lower Glen Rose) 4 (Cow Creek)
Lower Trinity	0.5	0.2	0.2	--	0.1 - 15	1.3	4.4	--

*** based on 1 aquifer pumping test**
+ average of 2 field test values
 # calibrated average value over the entire unit

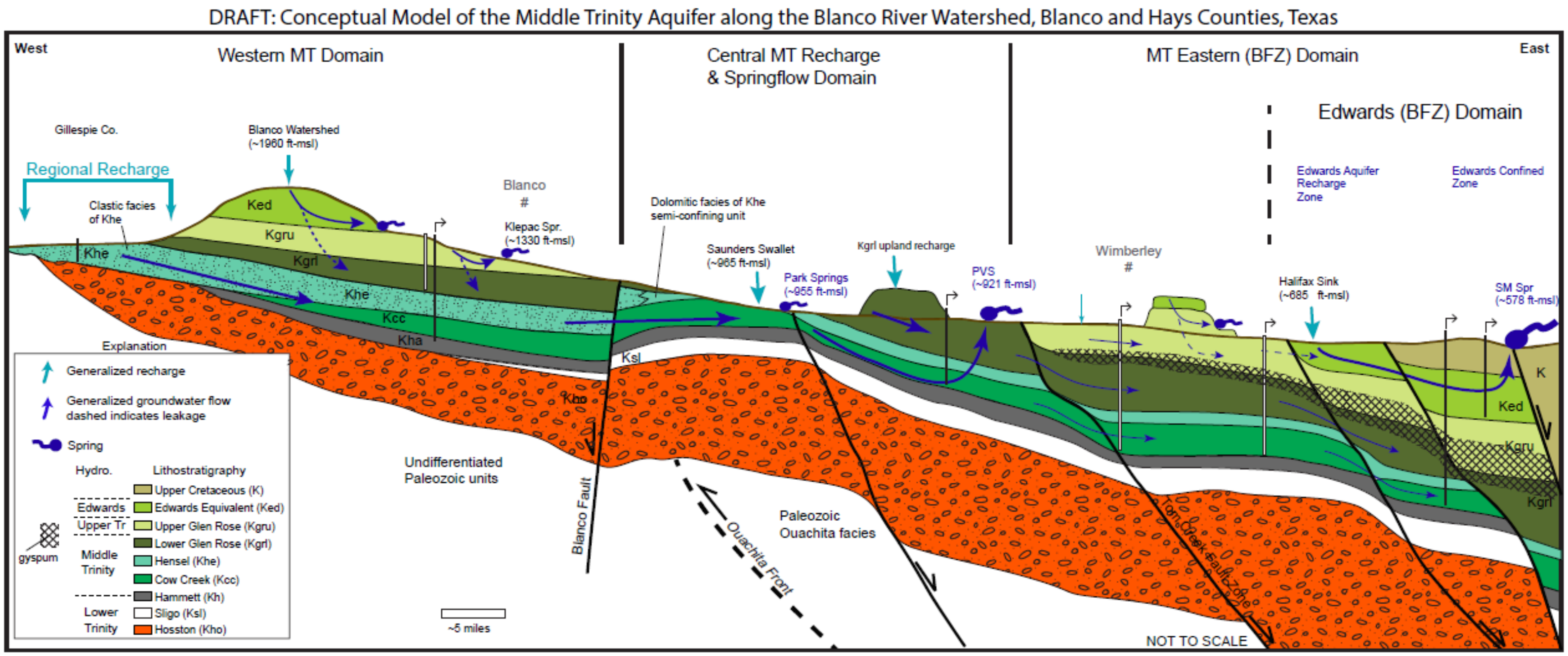
Table 4: Storativity values from Toll et al. (2018)

		Storativity						
Hydrostratigraphic unit	**Count**	**Toll and others (2018)**			**Literature Values**			
		Compiled aquifer pump tests			**Ashworth (1983)**	**Kuniansky and Ardis (2004)**	**LBG-Guyton (2008)**	**Hunt and others (2010)**
		Min	**Median**	**Max**	**average test value**	**calibrated value**	**calibrated value**	**median test value**
Upper Trinity	0	--	--	--	--	--	--	1.2x10^{-5}
Middle Trinity	28	1x10^{-5}	1x10^{-4}	1.5x10^{-1}	7x10^{-5}	--	--	5x10^{-5}
Lower Trinity	6	1x10^{-5}	8x10^{-5}	4.5x10^{-3}	3.8x10^{-5}	1x10^{-5}	5x10^{-6} - 8x10^{-5}	5x10^{-5}
mixed Trinity	13	1x10^{-5}	9x10^{-5}	4x10^{-4}	--	--	--	--
All Trinity	47	1x10^{-5}	2x10^{-4}	1.5x10^{-1}	--	--	--	--

Table 5: Table modified from Johnson et al. (2012) showing results of tracer tests

Injection Point	Injection Date	Recovery Site	Arrival Date	Apparent Velocity
Hallifax Creek Sinkhole	6/10/2008	Weissmuller Spring	8/4/2008	790 ft/d (240 m/d)
		Hotel Spring	8/5/2008	790 ft/d (240 m/d)
Hallifax Creek Sinkhole	9/12/2008	Hotel Spring	10/1/2008	2300 ft/d (700 m/d)
Johnson Swallet	2/26/2009	Weissmuller Spring	5/15/2009	560 ft/d (170 m/d)
		Hotel Spring	4/29/2009	690 ft/d (210 m/d)
		Cabomba Spring	6/5/2009	430 ft/d (130 m/d)
		Deep Hole Spring	12/2/2009	150 ft/d (47 m/d)
		Diversion Spring	5/15/2009	560 ft/d (170 m/d)
		Salt & Pepper 1 Spring	<12/2/2009	>560 ft/d (>170 m/d)
		Salt & Pepper 2 Spring	<12/2/2009	>560 ft/d (>170 m/d)
		Crater Bottom Spring	<12/2/2009	>560 ft/d (>170 m/d)
		Ossified Forest Spring	<12/2/2009	>560 ft/d (>170 m/d)
		Cream of Wheat Spring	<12/2/2009	>560 ft/d (>170 m/d)
		Cypress Point Spring	<12/2/2009	>560 ft/d (>170 m/d)
		Kettleman's Spring	<12/2/2009	>560 ft/d (>170 m/d)
		River Bed Spring	<12/2/2009	>560 ft/d (>170 m/d)

< = arrival prior to the date shown



	Western MT Domain	Central MT Recharge & Springflow Domain	MT Eastern (BFZ) Domain	Edwards (BFZ) Domain
Structure	Depositional dip east (~3 degrees?) off Llano Uplift. Fractures trend BFZ.	BFZ horst block exposes MT rock units. Minor BFZ faults and signficant fractures throughout and associated with springs. Anticline structure north of Cypress. Depositional dip slope in western area from Narrows to Burnett Ranch (Park Springs).	Steep structural gradients from BFZ faults, and relay-ramps. Faulting appears to locally compartmentalize. Highly fractured.	
Hydrostratigraphy	Hensel clastic and thick in west, Cow Creek and Hammett Shale pinch out near headwaters of Blanco River. Middle Trinity relatively thin and thickens to east.	Hensel transitions to thinner confining unit. Lower Glen Rose has localizezd patch reefs with high porosity and is Karstic. Cow Creek is locally exposed within Blanco, is karstic and transmits water to PVS and JWS.	Cow Creek and Lower Glen Rose are primary aquifers. Hensel is locally confining. Lower Kgru and upper Kgrl contain confining units.	Edwards Group is highly karstic, uppermost Kgru are in hydrologic communication with overlying Edwards.
Recharge	Regional inflows from Hensel outcrop in Gillespie County--could be flux boundary? Dominated by diffuse recharge and leakage from overlying units. Recharge as a percentage of rainfall <3-5% (previous modeling studies).	Focused recharge to MT in Blanco River documented up to 10 cfs (Hunt et al., 2017). See new gages between Hwy 281 and Burnett Ranch. Diffuse and discrete recharge to Lower Glen Rose units in uplands--could be represented as a high percentage of rainfall (up to 25%). Kgru is relatively thin and likely provides diffuse and focused recharge to Kgrl.	Lateral inflows of MT along relay ramps from the west. Possible leakage, or induced leakage from overlying Kgru.	Majority of recharge from losing streams. Uplands also provide signicant recharge. Some lateral inflows from Kgru possible. Blanco flow loss ~20 cfs (Hunt et al., 2017).
Groundwater Flow	Middle Trinity dominated by diffuse and locally fracture flow. Middle Trinity relatively old (Klepac and Rhoden wells), while Kgru springs young water. Assume diffuse flow dominates MT with local fracture flow.	Middle Trinity dominated by karstic and fracture flow with some diffuse. Middle Trinity groundwater relatively young. Assume relatively fast flow dominates MT.	Dominated by diffuse and locally fracture (karstic) flow. Compartmentalized system. Middle Trinity groundwater is relatively old. Assume relatively slow flow dominates.	Dominated by karst and fracture flow. Rapid groundwater flow.
Discharge	Discharge from MT from limited pumping (BPGCD data) and lateral outflow. Spring discharge is largely from Ked and Kgru, which sustains Blanco River baseflows (~10 cfs gaining)	Discharge from MT from pumping (HTGCD data), major springs (PVS, JWS) and lateral outflow. Spring discharge is largely from Cow Creek artesian springs. Springflow up to 75 cfs (Hunt et al., 2017), but newer gage data shows more potential sprinflow. HTGCD pumping data....	Discharge from MT from pumping (HTGCD and BSEACD data), and lateral outlfow (unknown).	Discharge from Edwards from pumping (BSEACD, EAA data), and spring discharge at BS and SM.

6/12/2019

Figure 12: Conceptual model of Middle Trinity Aquifer and Blanco River (prepared by B. Hunt as part of the BRATWURST project)

5 Summary of compiled data

This study provides for compilation of existing data and conceptual model interpretation. No new data were collected. Consequently, the primary data sources are project technical stakeholders and Texas Water Development Board (TWDB) groundwater data. TWDB groundwater data includes historical groundwater pumping surveys, groundwater database (GWDB), and the Brackish Resources Aquifer Characterization System (BRACS) database.

Project Technical Stakeholders are:

- Barton Springs Edwards Aquifer Conservation District (BSEACD)
- Blanco-Pedernales Groundwater Conservation District (BPGCD)
- Cow Creek Groundwater Conservation District (CCGCD)
- Edwards Aquifer Authority (EAA)
- Guadalupe-Blanco River Authority (GBRA)
- Hays Trinity Groundwater Conservation District (HTGCD)
- The Meadows Center for Water and the Environment

5.1 Well log data/stratigraphic picks

Well logs with pre-defined, stratigraphic and formational picks were obtained from BSEACD, BPGCD, and TWDB (from both GWDB and BRACS). No stratigraphic interpretations were made as part of this study. Rather, existing interpolations were used when available in well log form or extracted from the literature (Wierman et al. 2010).

Well-log data and stratigraphic picks were used to construct the hydrostratigraphic framework model which is presented in Section **6.1**. A simplified stratigraphic framework was derived for the study that encompasses both the Trinity and Edwards groups (**Table 2**). Within the stratigraphic framework, two primary aquifer units were identified along with three minor aquifer units.

- Primary Aquifers:
    1. Middle Trinity (Cow Creek)
    2. BFZ Edwards
- Minor Water-Bearing Units:
    1. Upper Trinity
        - **Table 6** suggests that the Upper Trinity Aquifer is of limited economic importance in the study area, and the water quality is generally lower than that of the Middle Trinity Aquifer (see Section **5.5**).
    2. Lower Trinity
        - Limited information is available for the Lower Trinity Aquifer. However, it may become economically more important as additional water supply is needed in the Hill Country. Consequently, the goal with the Lower Trinity Aquifer is to include it in BRATWURST but as a placeholder that can be expanded and rigorously defined at a later time, if needed.
    3. Plateau Edwards

- This unit forms ridgetops in the western region of the study area. It is not thought to be economically important in the study area and will be included in BRATWURST but on a secondary level.

5.2 Water-elevation data

Water-elevation data from water wells were obtained from BSEACD, BPGCD, CCGCD, HTGCD, and GWDB. Data were obtained from 6,800 wells and include 140,000 individual water-level measurements. Water-level data are available for wells screened in the Trinity Group and the Edwards Group. Of these 6,800 wells, 2,772 are within the study domain as shown on **Figure 13**. Potentiometric surface plots, based on these water-level data, are provided in Section **6.3**.

5.3 Pumping

Groundwater pumping provides water for municipal, manufacturing, mining, agricultural (irrigation and livestock), and domestic consumption within the study domain. Pumping rate (and thus volume) is metered for some wells within the study area, but many wells are un-metered. In general, data consist of the metered pumping values and permitted annual pumping volumes. Permitted values are what could be pumped and metered values are what was pumped. Exempt wells are not subject to the permitting process and are typically not metered. Estimates are used to project both the number of exempt wells and the annual volume pumped per well.

Pumping data and estimates were obtained from the following sources.

- BSEACD: (BSEACD 2019)
- BPGCD: (BPGCD 2019)
- HTGCD: (HTGCD 2019) and (Broun 2019)
- TWDB: (TWDB 2019)

5.3.1 Data and estimates

Table 6 provides Trinity Aquifer pumping data by groundwater conservation district (GCD). Historical groundwater pumpage by county and aquifer are provided on **Table 7**. Estimated pumping for exempt wells is provided by groundwater conservation district in **Table 8**. A value of 0.5 acre-ft/yr per well is used to estimate exempt well pumpage in the absence of published estimates (BPGCD 2019). **Table 9** shows a list of major pumping wells in the study area, seen in **Figure 14**. These areas will be the focus of hypothesis testing for scenarios of increased pumping due to economic development.

Monitoring wells in the study area are shown in **Figure 71** and listed in **Table B - 1** with select hydrographs in **Figure B - 1**. Calibration points for the groundwater model will be selected from this list upon further review.

Table 6: Permitted pumpage by groundwater conservation district (GCD)

GCD	Aquifer	Number of Wells	Permitted		Reported 2018		Source
			gal/yr	acre-ft/yr	gal/yr	acre-ft/yr	
BSEACD	Upper Trinity	4	12,100,000	37	6,247,287	19	(BSEACD 2019)
BSEACD	Middle Trinity	27	492,481,557	1,511	212,571,252	652	(BSEACD 2019)
BPGCD	Middle Trinity	10	259,690,600	797	198,950,000	611	(BPGCD 2019)
HTGCD	Middle Trinity	74	1,205,443,381	3,699	631,782,570	1,938	(HTGCD 2019)

Table 7: Historical groundwater pumpage by aquifer and county for 2014-2016 (TWDB 2019)

Aquifer	Year	County (acre-ft)						Total
		Blanco	Comal	Gillespie	Hays	Kendall	Travis	acre-ft
EDWARDS-BFZ AQUIFER	2014	-	5,377	-	8,018	-	8,521	21,916
	2015	-	5,288	-	6,960	-	8,319	20,567
	2016	-	5,336	-	8,380	-	9,116	22,832
EDWARDS-TRINITY-PLATEAU AQUIFER	2014	1	5,338	680	5	65	-	6,089
	2015	1	5,053	653	5	61	-	5,773
	2016	1	6,960	665	5	66	-	7,697
TRINITY AQUIFER	2014	2,109	7,844	7,844	3,287	3,805	6,241	31,130
	2015	1,741	6,964	1,847	2,786	3,790	6,407	23,535
	2016	1,638	5,683	1,768	2,862	4,142	7,360	23,453

Table 8: Estimated exempt pumpage by groundwater conservation district (GCD)

GCD	Aquifer	Number of Wells	Estimated Annual Demand		Source
			gal/yr	acre-ft/yr	
BPGCD	Middle Trinity	2000	361,050,000	1,108	(BPGCD 2019)
BSEACD	Middle Trinity	4156	839,627,792	2,577	(BSEACD 2019)
HTGCD	Middle Trinity	9,800	1,193,592,213	3,663	(Broun 2019) (HTGCD 2019)

Table 9: Major pumping centers showing permitted and reported pumpage (see Figure 14 for map view)

Pumping Center	GCD	Aquifer	Permitted		Reported 2018	
			gal/yr	acre-ft/yr	gal/yr	acre-ft/yr
Calitera	HTGCD	Middle Trinity	68,005,193	209	26,188,500	80
Dripping Springs WSC	HTGCD	Middle Trinity	366,582,375	1,125	158,425,300	486
Wimberley Springs Partners	HTGCD	Middle Trinity	162,925,714	500	13,153,000	40
Wimberley WSC	HTGCD	Middle Trinity	210,174,170	645	158,728,000	487
Woodcreek 1	HTGCD	Middle Trinity	104,598,308	321	76,953,900	236
Woodcreek 2	HTGCD	Middle Trinity	107,205,119	329	89,179,600	274
Needmore Ranch	HTGCD	Middle Trinity	289,030,216	887	-	-
Rocking J	BPGCD	Middle Trinity	157,712,091	568	140000000*	430*
EP	BSEACD	Middle Trinity	912383995**	2800**	-	-

* estimated annual production

** proposed, not yet permitted

5.4 Streamflow

Surface water generally refers to water in the hydrologic cycle that moves along the land surface (Viesman and Lewis 2003). The source of water for surface water is precipitation. In this study, surface water within discrete channels in rivers, streams, and springs (as well as lakes and ponds) is referred to as "streamflow." This is to distinguish it from "runoff," water that flows at or just below the land surface outside of such channels, which is treated separately as part of the land-surface process portion of a model. Streamflow is generally a combination of runoff and discharge from groundwater.

Figure 15 displays the rivers and streams, within the study area, that have gauging or measurement stations or are main tributaries of the Blanco River. These streams are candidates for explicit representation in BRATWURST. The seven (7) river and streams, identified on **Figure 15** are listed below.

- Blanco River
- Little Blanco River
- San Marcos River
- Cypress Creek
- Onion Creek
- Bear Creek
- Barton Creek

A spring is a location at the land surface where water discharges from below the surface (Kresic 2010a). For a spring to discharge, the hydraulic head (or potential energy) driving the water in the subsurface must be higher in elevation than the land surface at the discharge point. Mapped springs in the study area are shown on **Figure 15**. In this figure, “Springs (USGS DB)” identifies all mapped springs and “Important Springs” denotes the springs that either: 1) may be explicitly used in future phases, or 2) provide important reference points for conceptual analysis. **Table 10** provides a listing of the “Important Springs”.

Table 10: Listing of "Important Springs" from Figure 15

Name	Aquifer	County	State Well No.	Other Site No.	Aquifer Code
Little Park Spring	Middle Trinity	Hays	5763709	-	218CCRK
Park Spring	Middle Trinity	Hays	5763707	-	218CCRK
Pleasant Valley Spring	Middle Trinity	Hays	5763809	-	218CCRK
Fern Bank Springs	BFZ Edwards	Hays	6808302	295901098005001	218EBFZA
Blanco River Spring	Upper Trinity	Hays	6808105	295933098053101	218GLRSU
Cold Spring	Middle Trinity	Blanco	5761304	300530098241101	218GLRSL
Blanco River Spring	Upper Trinity	Blanco	5761224	300546098251101	110ALVM
Zercher Spring	Upper Trinity	Blanco	5761226	300611098272601	110AVFV
Crabapple Creek Spring	Upper Trinity	Blanco	5760303	300608098304401	218GLRSU
Cypress Creek Spring	Upper Trinity	Hays	6808106	295956098060401	218GLRSU
Jacob’s Well Spring	Middle Trinity	Hays	5763905	300157098073101	218CCRK
C-3 Hays	Middle Trinity	Hays	5755703	300949098182901	-
C-5 Hays	Middle Trinity	Hays	5755704	300930098140201	-

Name	Aquifer	County	State Well No.	Other Site No.	Aquifer Code
A-15 Hays	Middle Trinity	Hays	5755502	301107098122501	-
Barton Springs	BFZ Edwards	Travis	5842914	8155500	218EBFZA
Barton Creek Springs	Upper Trinity	Hays	5748810	301531098043101	218GLRSU
Comal Springs	BFZ Edwards	Comal	6823301	8168710	218EBFZA
Dripping Springs	Upper Trinity	Hays	5756473	301136098053101	218GLRSU
Hueco Springs	BFZ Edwards	Comal	6815901	8168000	218EBFZA
San Marcos Springs*	BFZ Edwards	Hays	6701820	295322097561002	218EBFZA
Upper Barton Springs	BFZ Edwards	Travis	5842920	8155395	218EBFZA

*State Well No. is for Weismuller Spring

5.4.1 Stream/River flow rates

Stream flow rates are measured at gauging stations. The gauging stations in and near the study area are shown on **Figure 16** and listed on **Table 11**. **Table 12** lists a selection of USGS gauging stations which are used in a comparative, graphical analysis and that have discharge measurements in and near the study area. A summary of the lower half of the discharge data, by discharge magnitude, for each station is provided on **Figure 17** through **Figure 25**. The lower half of the discharge magnitude is represented by showing the median, 25th percentile, and minimum discharge value for each day of the year from the period of record for the station. Several stations (08158813, 08170950, and 08171350) only have three to four years of data. Discharge values are provided in cubic feet per second (cfs) – days (cfs – days) which are the total volume in cubic feet measured for each day divided by the number of seconds in a day.

- Each (1) cfs-day represents approximately 2 acre-ft of water volume moving past the station during one day. **Figure 22** shows that the median flow for the first five months of the year exceeds 60 cfs-days. In terms of volume, this is roughly equivalent to 120 acre-feet per day for 151 days or over 18,000 acre-ft of discharge from January through May.

An important characteristic to note in **Figure 17** through **Figure 25** is which rivers and streams show recession in median discharge during July through September (day 181 through day 273) to, or close to, zero. The months of July through September represent the period of greatest cumulative precipitation deficit (see **Figure 40**) and the least likely period during the year for surface water runoff to contribute to stream flow. As a result, the portion of stream flow that is attributable to surface runoff is expected to be small during this time. This suggests that streams with close to zero discharge during July through September are primarily sourced from surface runoff.

The San Marcos River in San Marcos, TX (see **Figure 21**) displays minimal recession, or flow decline, during this period because this portion of the river is adjacent to San Marcos Springs and the majority of the water comes from spring discharge and not directly from surface runoff. Additionally, the Blanco River near Fischer (USGS 08170950 see **Figure 22** and **Figure 27**) and the Blanco River at Wimberley (USGS 08171000 see **Figure 23** and **Figure 28**) also have relatively muted recessions during July through September. This is likely because USGS 08170950 is just downstream of Park Spring and Pleasant Valley Spring, and USGS 0817100 is just downstream of the confluence with Cypress Creek and Jacob's Well Spring in addition to being downstream of USGS 08170950.

Figure 26 provides a comparison of the median discharge during 2016-2018 for each day of the year for the four Blanco River stations in **Table 12**. This relatively short period is dictated by data availability for USGS 08170950. In this figure, median discharge is greater near Fischer, TX and at Wimberley, TX during July through September than it is downstream near Kyle, TX and at San Marcos, TX. For Blanco River water to reach these two downstream-most stations, it must flow across at least part of the Edwards Aquifer recharge zone. The decrease in stream discharge, moving downstream, is likely due in part to focused recharge from the Blanco River to the BFZ Edwards Aquifer in the recharge zone.

Table 11: USGS and Lower Colorado River Authority (LCRA) gauges in and near the study area

Station ID	Name	County	Begin Date	Has Continuous Discharge
08170800	USGS 08170800 Blanco Rv at Crabapple Rd nr Blanco, TX	Blanco	8/12/2016	No
08170890	USGS 08170890 Little Blanco Rv at FM 32 nr Fischer, TX	Blanco	1/14/2016	No
08170905	USGS 08170905 Blanco Rv at Valley View Rd nr Fischer, TX	Hays	8/22/2018	No
08170950	USGS 08170950 Blanco Rv at Fischer Store Rd nr Fischer, TX	Hays	4/19/2016	Yes
08171000	USGS 08171000 Blanco Rv at Wimberley, TX	Hays	12/23/1986	Yes
08170990	USGS 08170990 Jacobs Well Spg nr Wimberley, TX	Hays	4/23/2005	Yes
08158700	USGS 08158700 Onion Ck nr Driftwood, TX	Hays	10/1/1990	Yes
08171290	USGS 08171290 Blanco Rv at Halifax Rch nr Kyle, TX	Hays	12/19/2008	Yes
08171300	USGS 08171300 Blanco Rv nr Kyle, TX	Hays	10/1/1991	Yes
08170500	USGS 08170500 San Marcos Rv at San Marcos, TX	Hays	10/1/1994	Yes
08171350	USGS 08171350 Blanco Rv at San Marcos, TX	Hays	1/22/2015	Yes
08171400	USGS 08171400 San Marcos Rv nr Martindale, TX	Caldwell	5/19/2011	Yes
08155500	USGS 08155500 Barton Spgs at Austin, TX	Travis	4/10/1991	Yes
08158810	USGS 08158810 Bear Ck bl FM 1826 nr Driftwood, TX	Hays	10/1/2007	Yes
08158813	USGS 08158813 Bear Ck at Spillar Ranch Rd nr Manchaca, TX	Hays	10/1/2015	No
08158827	USGS 08158827 Onion Ck at Twin Creeks Rd nr Manchaca, TX	Travis	4/3/2003	Yes
08155200	USGS 08155200 Barton Ck at SH 71 nr Oak Hill, TX	Travis	2/2/1979	Yes
BRBT2	LCRA Blanco River at Blanco	Blanco	3/17/2016	Yes
BDUT2	LCRA Onion Creek at Buda	Hays	2/10/2000	Yes

Table 12: USGS stream gauge measurement locations used in comparative analysis

ID	Name	County	Drainage Area (mi^2)	Data Record (yr)	Figure
08158700	Onion Creek nr Driftwood	Hays	124	29	Figure 17
08158810	Bear Creek nr Driftwood	Hays	12.2	12	Figure 18
08158813	Bear Creek nr Manchaca	Hays		4	Figure 19
08158827	Onion Creek nr Manchaca	Travis	181	16	Figure 20
08170500	San Marcos River at San Marcos	Hays	48.9	25	Figure 21
08170950	Blanco River nr Fischer	Hays	269	3	Figure 22 and Figure 27
08171000	Blanco River at Wimberley	Hays	355	23	Figure 23 and Figure 28
08171300	Blanco River nr Kyle	Hays	412	27	Figure 24
08171350	Blanco River at San Marcos	Hays	436	4	Figure 25

5.4.2 Gain/Loss studies

A number of gain/loss studies have been conducted to document complex surface water and groundwater interactions in the study area. The purpose of the gain/loss studies is to identify the locations of reaches that are gaining water overall and those that are losing water overall. Synoptic flow measurements (i.e. flow measurements collected at the same time) are used to identify which portions of the streams are gaining water and which are losing water. **Figure 29** displays the results of the gain/loss studies summarized in **Table 13** (Hunt et al. 2017).

Table 13: Summary of Onion River and Blanco River gain/loss studies (Hunt et al. 2017)

Reach Name	Stream	Length (mi)	Flow (cfs)
Upper Gaining	Onion Creek	13	+30
	Blanco River	32	+10
Trinity Recharge Zone	Onion Creek	5	-3
	Blanco River	11	-10
Middle Gaining	Onion Creek	17	+85
	Blanco River	27	+75
Edwards Aquifer Recharge Zone	Onion Creek	9	-110
	Blanco River	5	-20
Lower Gaining	Onion Creek	NA	NA
	Blanco River	NA	NA

In **Figure 29** and **Table 13**, there are two losing reaches for the Blanco River and Onion Creek. The downstream-most, or easternmost, losing reach coincides with BFZ and fault blocks where the BFZ Edwards Aquifer is exposed at the surface; this is the Edwards Recharge zone. The other losing reaches are associated with Trinity Aquifer recharge and the reach is labeled “Trinity Recharge Zone” in **Table 13**. On the Blanco River, the “Trinity Recharge Zone” location corresponds to the horst block structure (see **3.3.3**) where the Middle Trinity Aquifer is exposed in the bed of the Blanco River. For Onion Creek, the

Trinity Aquifer recharge area is associated with areas where Unit 3 of the Upper Glen Rose Formation has been eroded and creek water can more easily communicate with the Lower Glen Rose Formation (Watson et al. 2018).

5.4.3 Spring flow rates

Two of the primary springs shown on **Figure 16** are continuously monitored with their own measurement station by the USGS as shown in **Table 14**. San Marcos Springs is a complex of springs that discharges to San Marcos Spring Lake; consequently, San Marcos River station (USGS 08170500) provides a surrogate for San Marcos Springs discharge. **Figure 30** and **Figure 31** display the median and low-flow discharge from Barton Springs and Jacob's Well Spring, respectively. San Marcos River discharge on **Figure 21** provides an equivalent depiction for San Marcos Springs.

Of note in **Figure 21**, **Figure 30** and **Figure 31** is the relatively limited recession during July through September relative to the rest of the gauging stations in **Table 12**. A relatively muted recession during the period of precipitation deficit is expected for spring discharge. **Figure 32** displays the discharge hydrograph for period of record for Jacob's Well Spring.

Table 14: USGS spring discharge gauging stations

ID	Name	County	Data Record (yr)	Figure
08155500	Barton Springs at Austin, TX	Travis	28	Figure 30
08170990	Jacob's Well Spring	Hays	14	Figure 31 and Figure 32

5.4.4 Water rights

Texas Commission on Environmental Quality compiles information on active and inactive (surface) water rights and water-use data (TCEQ 2019). A significant portion of the study area is in the South Texas Watermaster Area. However, most of Blanco, Hays, and Travis counties are in non-Watermaster areas.

Figure 33 shows the locations of the surface water rights diversion points within the region of interest for surface water modeling. **Table 15** provides a listing of right type along with counts. There are 103 different possible extraction points shown on **Figure 33** along with one discharge point.

Table 15: Summary of surface water rights shown on Figure 33

Water Right Type	Count
Diversion Segment	1
Discharge Point	1
Diversion Point	44
Off-channel Reservoir	3
On-channel Reservoir	55

Water Right Type	Count
Total	**104**

5.5 Water chemistry

Total dissolved solids (TDS), major ion chemistry, and isotopic data extracted from the TWDB groundwater database and provided by BSEACD are used to make geochemical interpretations of general water-quality trends. Major ion chemistry indicates that TDS increases with depth in the Trinity Aquifer. Namely, TDS increases at the same rate as sulfate, and generally increases with chloride (Toll et al. 2018). These trends imply that TDS is controlled by the dissolution of gypsum and dolostone in the Glen Rose Limestone and mixing with sodium chloride brines at greater depths, respectively.

As previously described, significant recharge occurs through losing streams to the Middle Trinity Aquifer in the Blanco River watershed. Smith et al. (2018) suggest the up-dip limit of 500 mg/L TDS in Hays County delineates an active recharge zone to the Middle Trinity Aquifer, as Middle Trinity units which crop out coincide with losing river segments on Blanco River and Onion Creek. Younger waters as determined by tritium and carbon-14 (as percent modern carbon) support this notion as they also coincide with plumes of low TDS water. **Figure 9** illustrates TDS contours in mg/L and highlights two distinct groundwater flow paths in the Middle Trinity Aquifer (Hunt et al. 2015; Smith et al. 2018). The presence of low TDS (less than 500 mg/L) water suggests groundwater flows to the east of the Middle Trinity Aquifer recharge zone and to the north parallel to the BFZ Edwards Aquifer, which is consistent with the potentiometric surface in the region. These flow paths are inferred to be conduits that transmit water either deep into the subsurface or as discharge at Pleasant Valley Spring and Jacob's Well to the northeast (Gary et al. 2019).

TDS additionally provides insight of hydraulic interactions between the Trinity and Edwards aquifers (Wong et al. 2014; Smith et al. 2018; Toll et al. 2018). Two multiport wells installed in Hays County provide evidence on the extent of communication between the two aquifers by comparing potentiometric surfaces and TDS concentrations. Higher TDS measurements in the Upper Trinity Aquifer intervals in comparison to the Middle Trinity Aquifer suggest that vertical upward leakage is limited. Wong et al. (2014) conclude that lateral flow transmitted through extensive faulting is the dominating mechanism for communication between the Edwards and Trinity aquifers, as lower permeability units in the evaporate-rich Upper Trinity Aquifer inhibit vertical flow between the Edwards and Middle Trinity aquifers. As such, recharge to both aquifers likely occurs through distinct recharge zones, such as the case in Hay County previously described by Smith et al. (2018).

5.6 Precipitation

Precipitation is water in the atmosphere that falls to the land surface. It has numerous forms including rain, snow, and hail (Viesman and Lewis 2003). For the study area, rain is the primary form of precipitation with occasional hail and infrequent snow. Precipitation is the primary input for the hydrologic cycle (Viesman and Lewis 2003) and provides the water for stream flow and for aquifer storage.

A variety of precipitation data sets are available for the study area. The Parameter-elevation Relationships on Independent Slopes Model (PRISM) gridded precipitation data set (PRISM Climate Group, 2019) was selected for use with BRATWURST. The form of PRISM data obtained was daily precipitation depths on a 4-km grid which covers the continental United States (CONUS). Daily precipitation depth time series, from 1/1/1981 to 5/1/2019, for the 700 grid cells that cover the study area were extracted from the full PRISM data set.

Figure 34 displays contours of annual average precipitation depth from 1981 through 2018 for the study area. **Figure 35** and **Figure 36** represent monthly average values for Blanco, TX and Wimberley, TX respectively. The range of annual precipitation depths in the data set for the study area is 18.4 – 71.1 in. The overall annual precipitation average, for all grid cells in the study area and all years from 1981 through 2018, is 36.6 in.

Gridded precipitation data were also obtained from the Edwards Aquifer Authority (EAA). Precipitation data for the entire study area were only available from the EAA for 2013-2018. EAA gridded precipitation data are compared to the PRISM data on **Figure 37**, **Figure 38**, and **Figure 39**. In terms of average magnitude of precipitation, the EAA and PRISM data sets compare favorably. There are some differences in the patterns of average annual precipitation in **Figure 37**. However, these differences are not significant for use in BRATWURST.

5.7 Evapotranspiration

Evapotranspiration (ET) is total evaporation for a land area and is surface evaporation plus the water consumed by plants, or transpiration (Viesman and Lewis 2003). ET is difficult to directly measure over large areas and, as a result, is typically calculated from weather parameters. Weather parameters required to calculate reference ET, or ET_o, vary somewhat depending on the physical or empirical relationship used in the calculation. Typically, the following four parameters are needed.

1. Air temperature
2. Solar radiation
3. Relative humidity
4. Wind speed

Calculated ET_o is available from the TexasET Network (Texas A&M AgriLife Extension 2019) for the study area. **Table 16** provides typical, historical values of monthly ET_o from the vicinity of the study area. **Figure 40** presents the annual excess precipitation trends for the study area. Excess precipitation is precipitation depth less potential ET (PET) depth. In this case, ET_o is used in place of PET and precipitation depth is taken from **Figure 36**. When excess precipitation is negative in **Figure 40**, it is expected that ET will consume most of the precipitation that falls on the watershed. Brush management in Comal County has been shown to have an effect on the hydrologic budget and water quality (Banta and Slattery 2011).

Note that there is a distinct seasonal trend in excess precipitation in **Figure 40**. Evaporative capacity exceeds precipitation, and excess precipitation is negative, starting in January and continuing through September. July and August are the months with the largest precipitation deficit, or the largest magnitude negative excess precipitation values. From October through December, excess precipitation is positive, suggesting that a fraction of precipitation, on a monthly basis, will be available for surface runoff and infiltration. If a water year were defined based on **Figure 40**, the normal practice would be to start the water year in October at the transition from negative to positive excess precipitation. Conceptually, the end of September should represent the driest soil column conditions during the year as a result of the preceding eight months of precipitation deficit.

The total of (positive) excess precipitation in **Figure 40** is about 0.72 in which represents 2% of the average annual rainfall depth. It would be expected that the actual amount of surface water runoff during the year would be larger than 2% because of differences in characteristic time scales between the monthly calculation in **Figure 40** and surface water runoff processes in the relatively small watersheds in the study area. Surface water runoff processes are expected to have a characteristic time scale of minutes to hours and so will not be accurately captured in the monthly calculation underlying **Figure 40**.

Table 16: Calculated ET$_o$ for the study area (Texas A&M AgriLife Extension 2019)

Location	**Historic ET$_o$ Reference (inches)**												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Austin	2.27	2.72	4.34	5.27	6.39	7.15	7.22	7.25	5.57	4.38	2.74	2.21	57.51
San Antonio	2.42	2.90	4.42	5.47	6.47	6.97	7.31	6.99	5.64	4.44	2.85	2.36	58.24
Average	2.35	2.81	4.38	5.37	6.43	7.06	7.27	7.12	5.61	4.41	2.80	2.29	57.88

5.8 Description of project database

The Arc Hydro Framework is a predefined, data storage schema composed of GIS feature classes and associated data tables that can be implemented in an ESRI geodatabase (Jones et al. 2010). The BRATWURST project database is implemented using the Arc Hydro Groundwater subset of the larger Arc Hydro Framework.

Details of the Arc Hydro Groundwater data framework are available from multiple sources including Jones et al. (2010) and Strassberg et al. (2011). **Appendix A** provides a full description of the project database including summary of framework customizations.

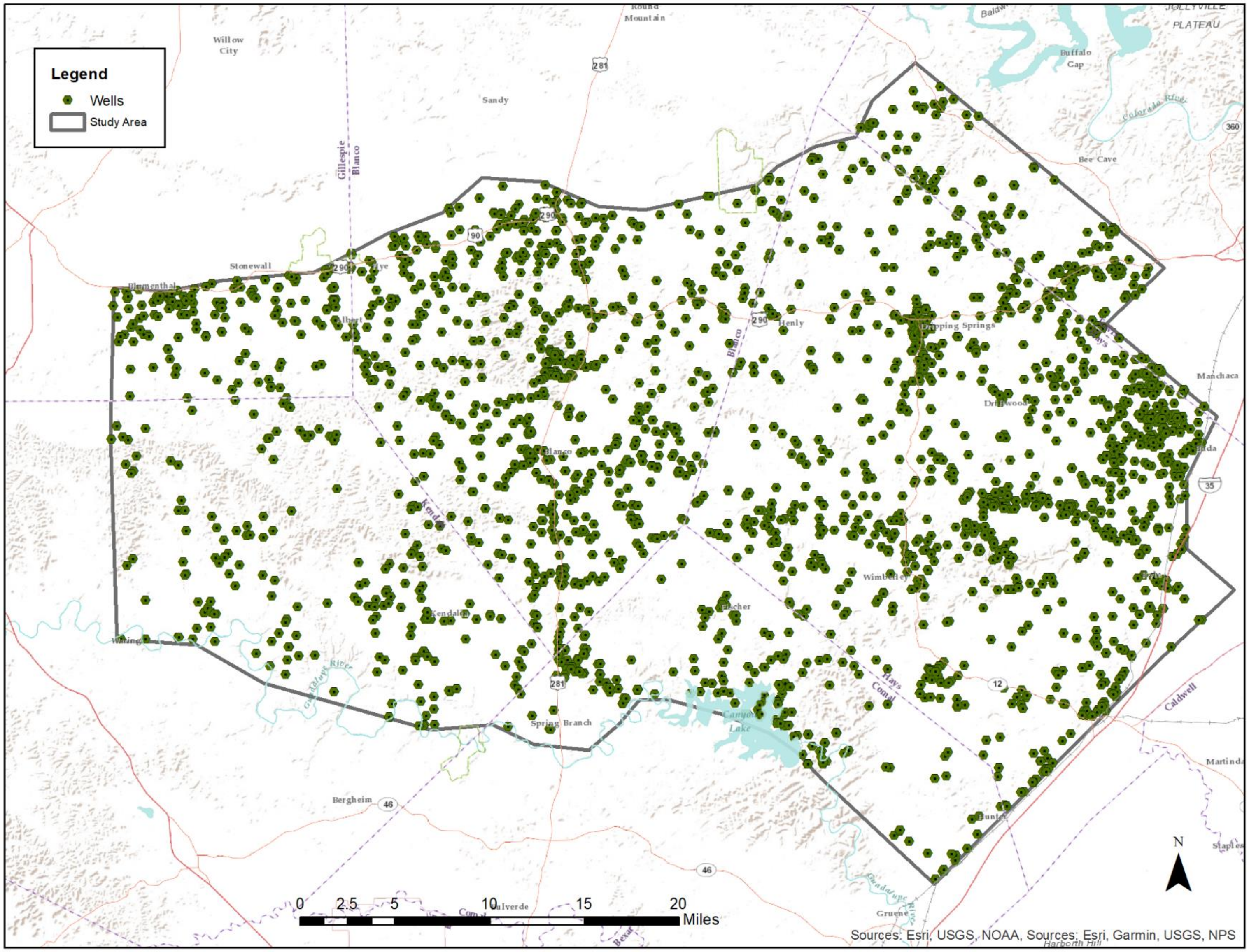


Figure 13: Well locations in the project database that are within the study area

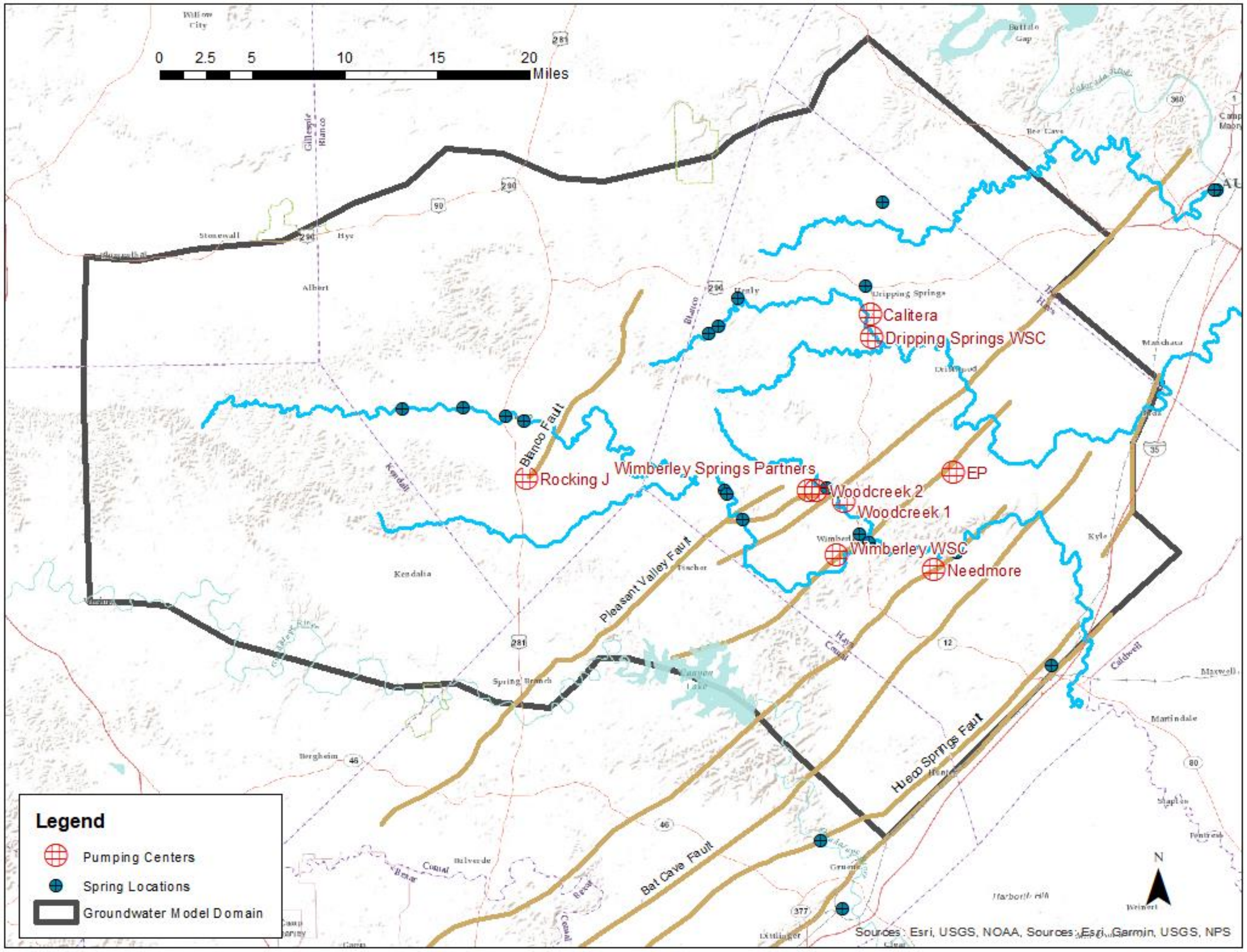


Figure 14: Pumping centers show locations of highest water extraction

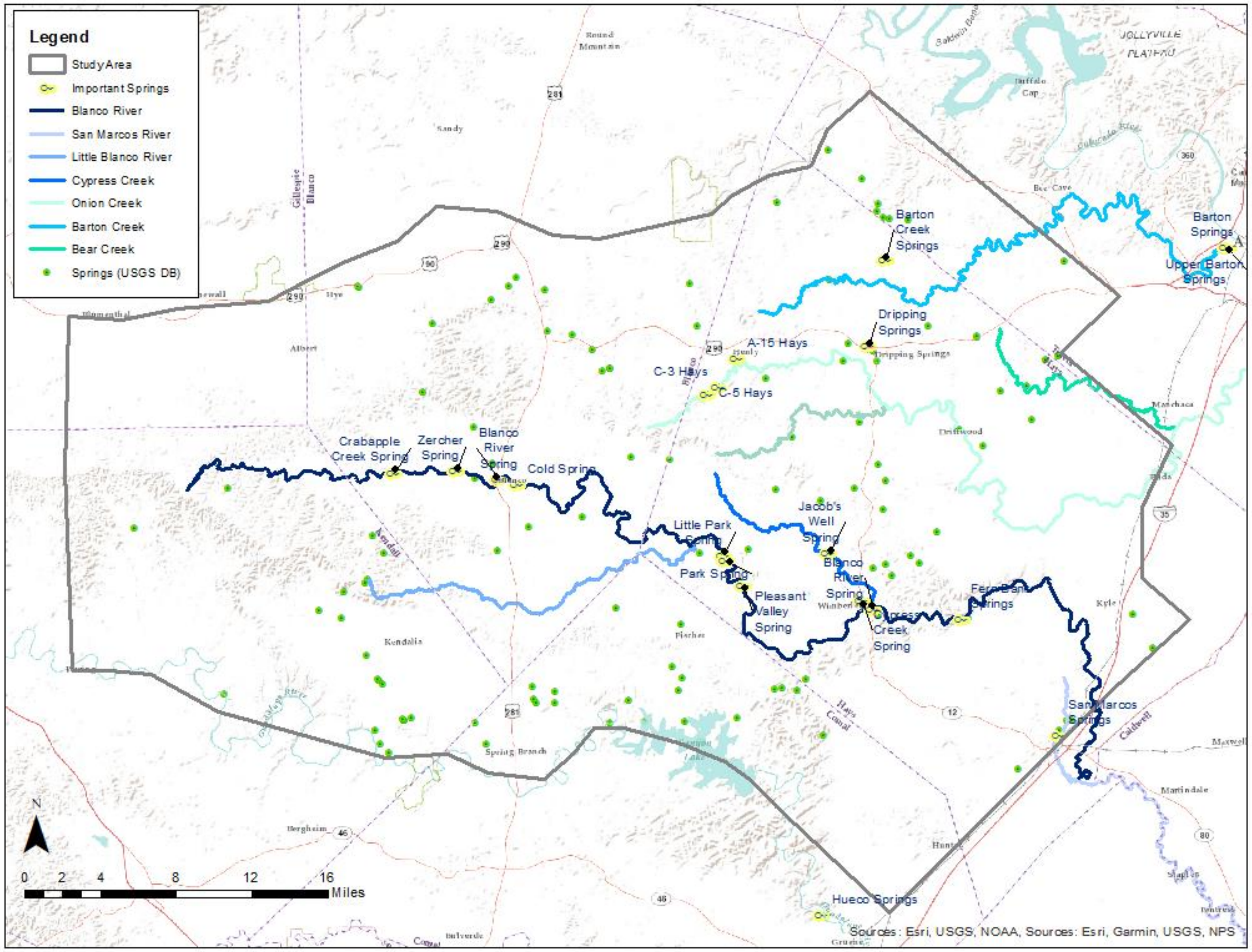


Figure 15: Surface water features in the study area

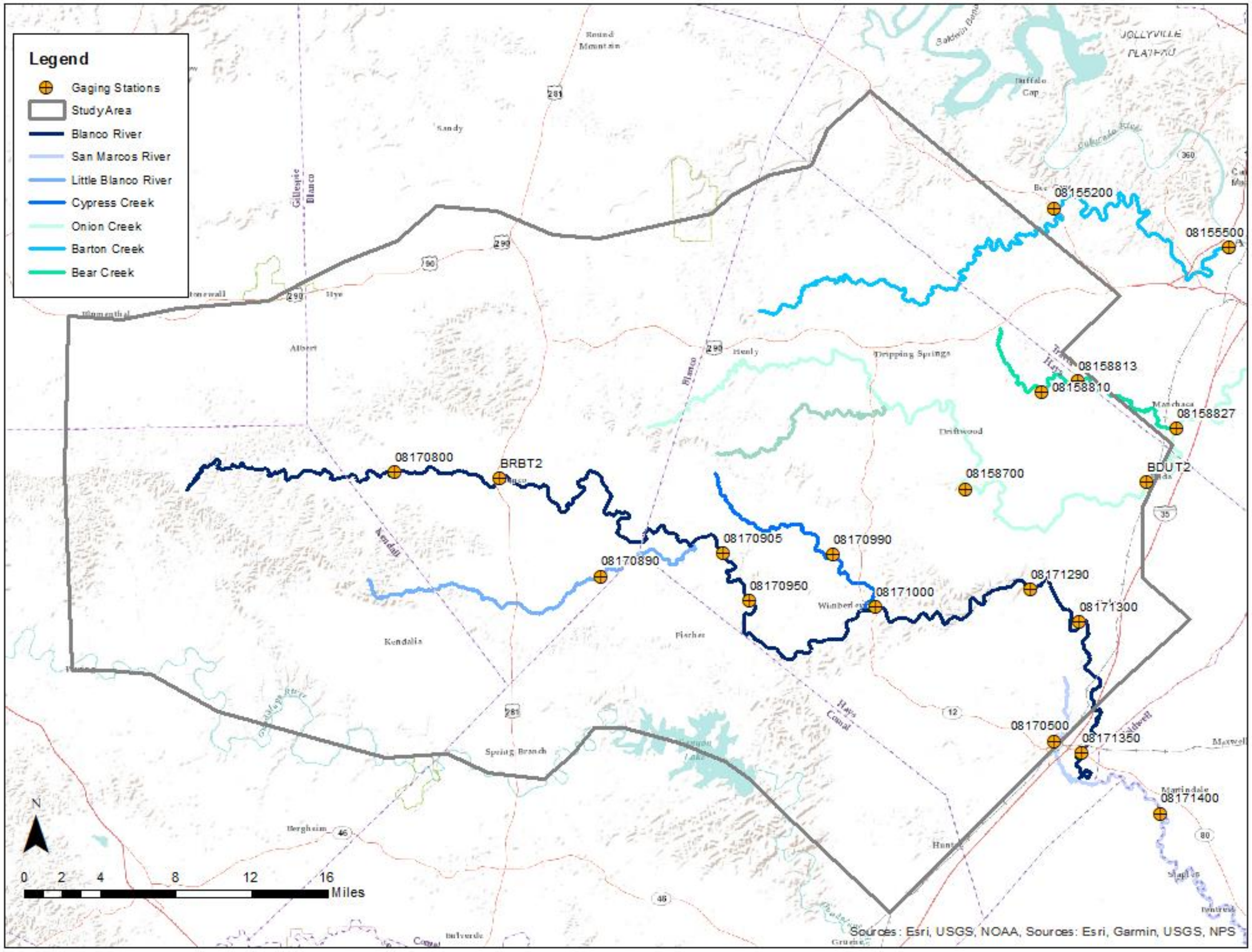


Figure 16: USGS and LCRA gauging stations

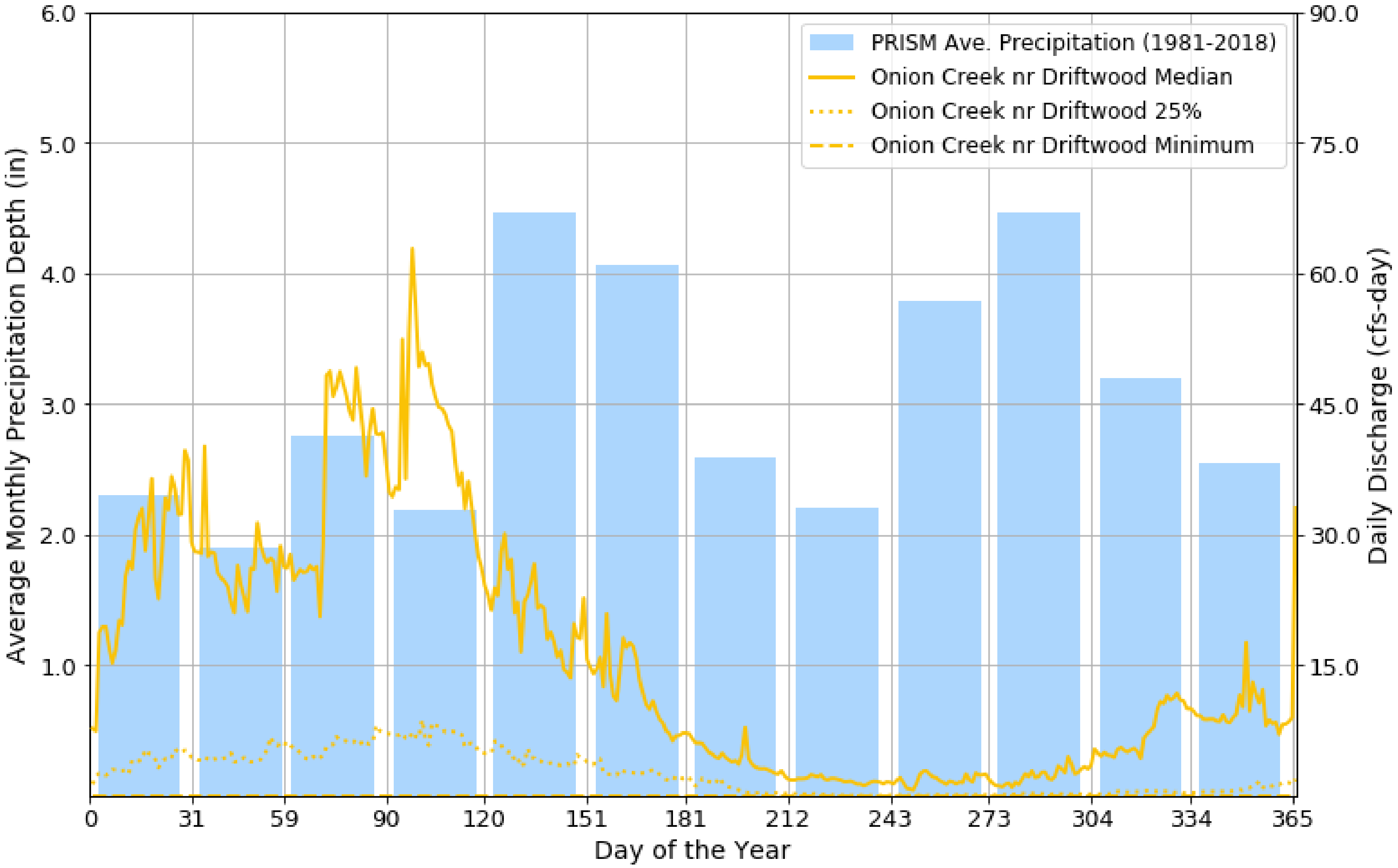


Figure 17: USGS 08158700 Onion Creek near Driftwood, TX - Median and low discharge summary

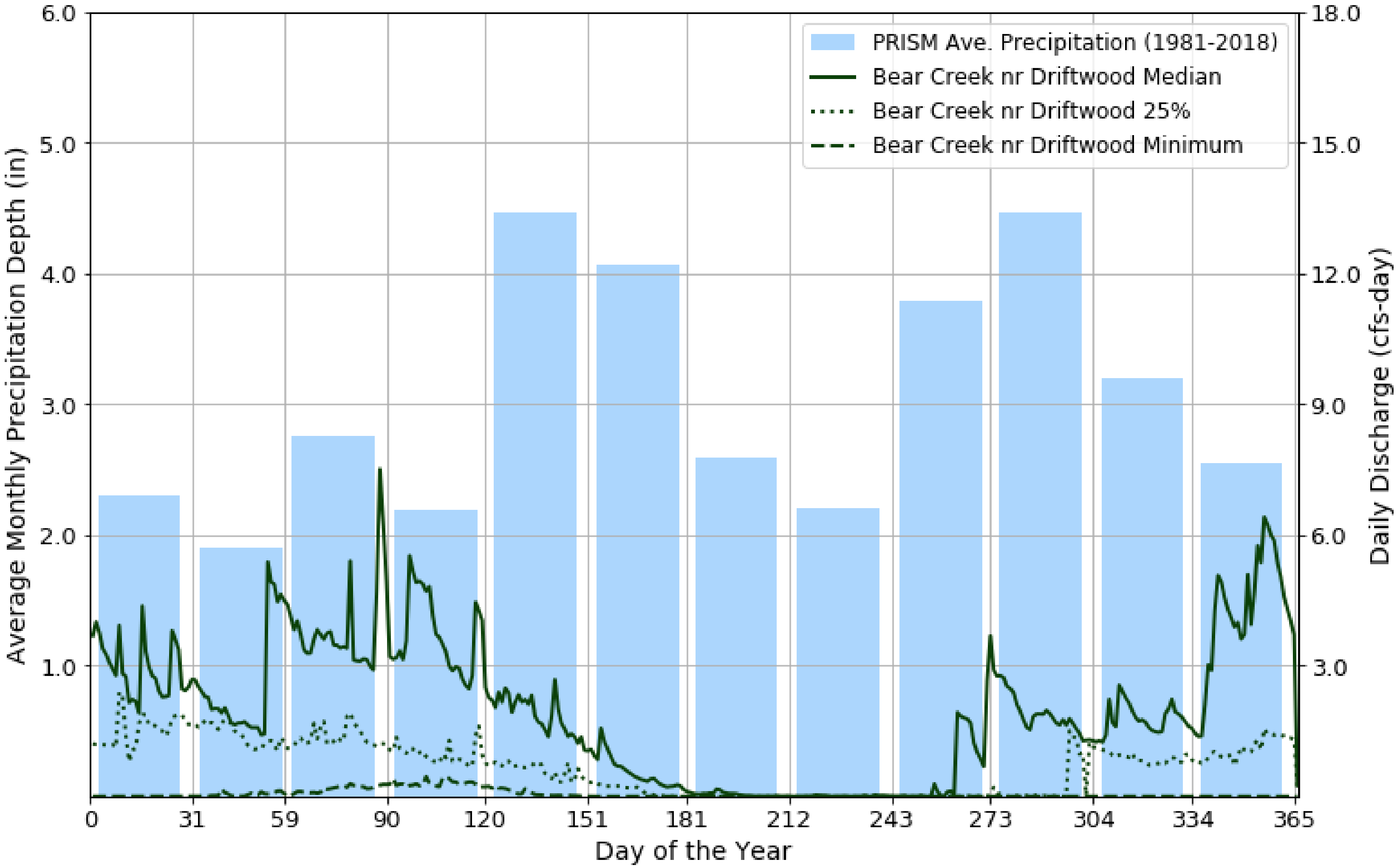


Figure 18: USGS 8158810 Bear Creek near Driftwood, TX - Median and low discharge summary

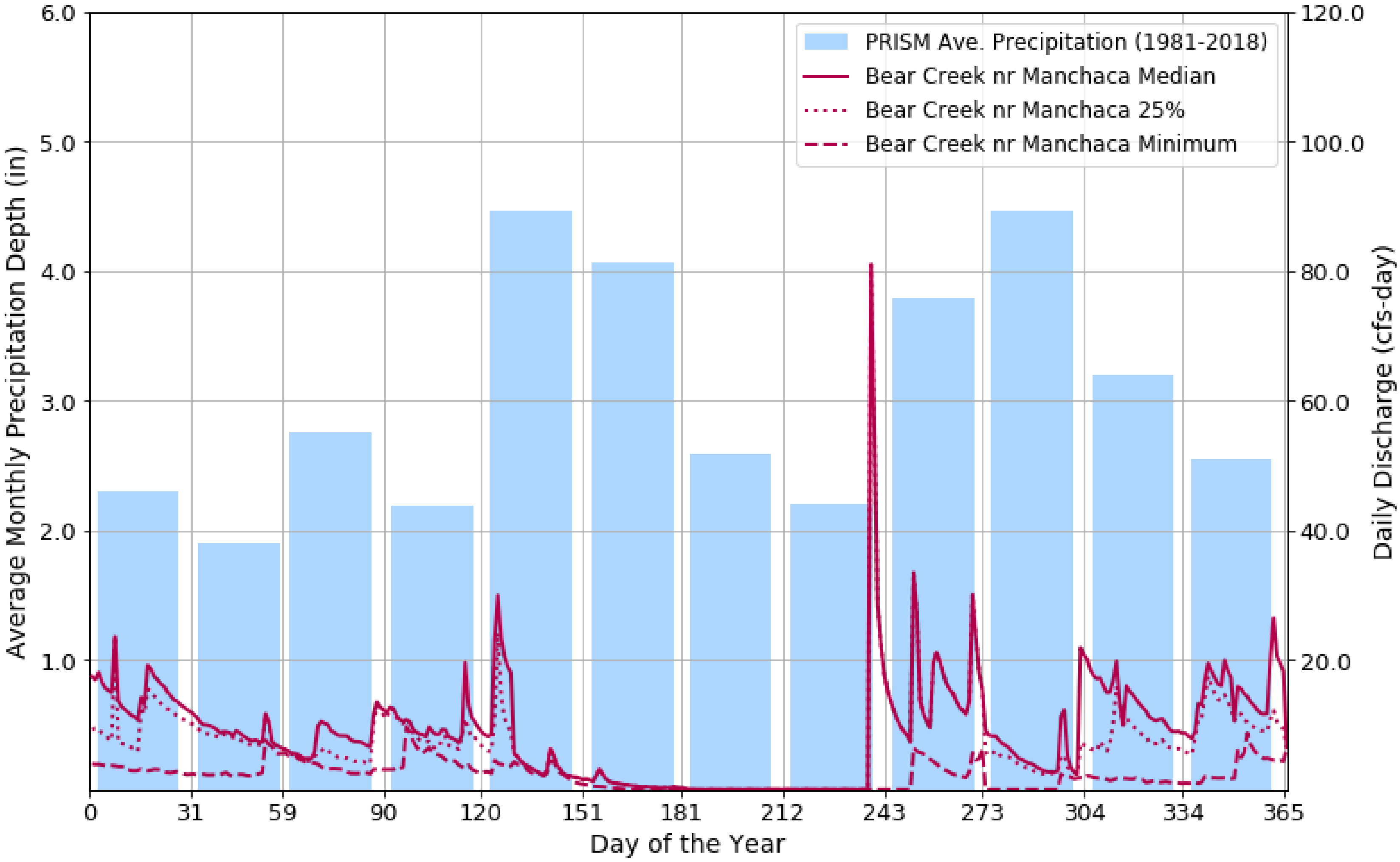


Figure 19: USGS 08158813 Bear Creek near Manchaca, TX - Median and low discharge summary

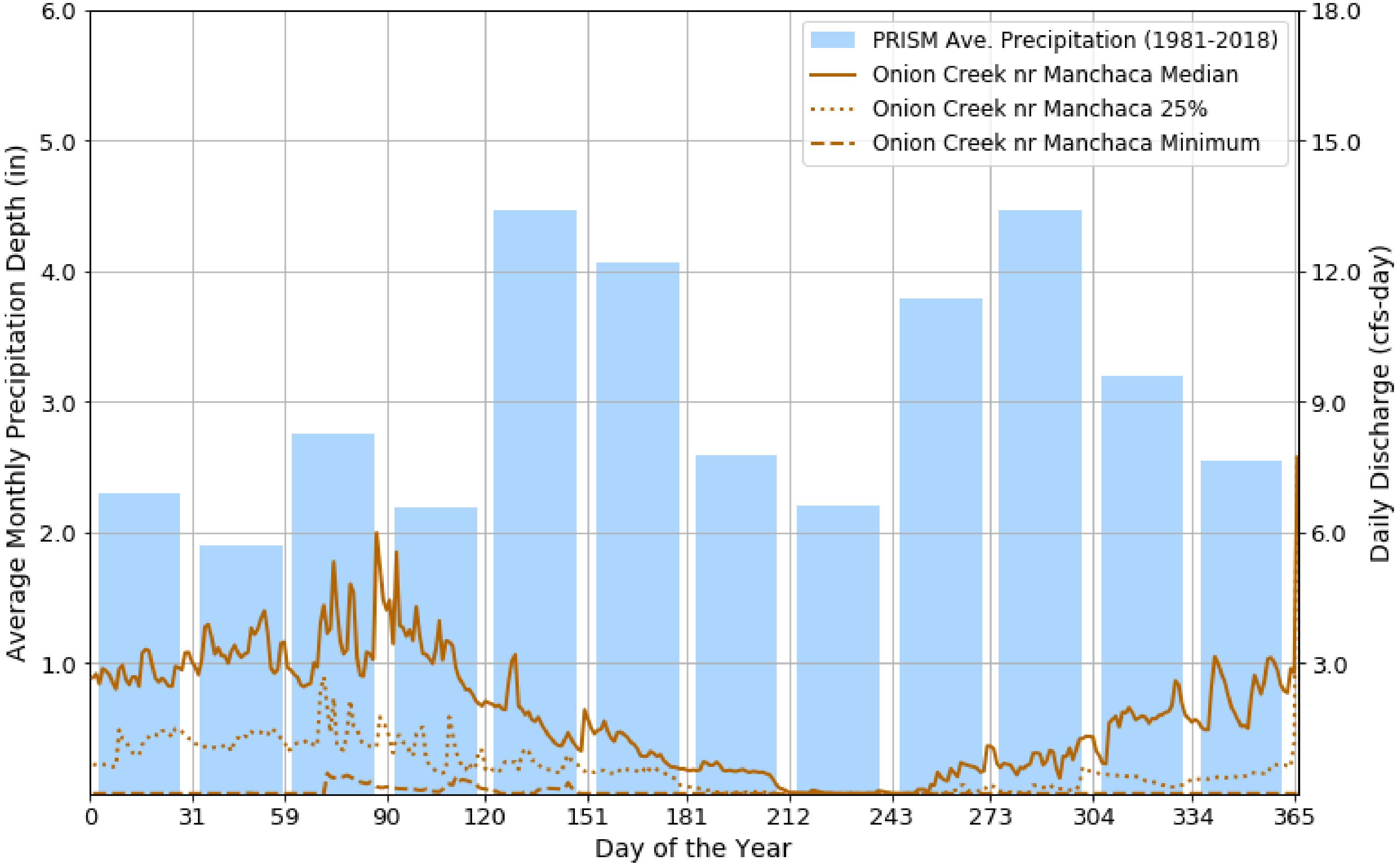


Figure 20: USGS 08158827 Onion Creek near Menchaca, TX - Median and low discharge summary

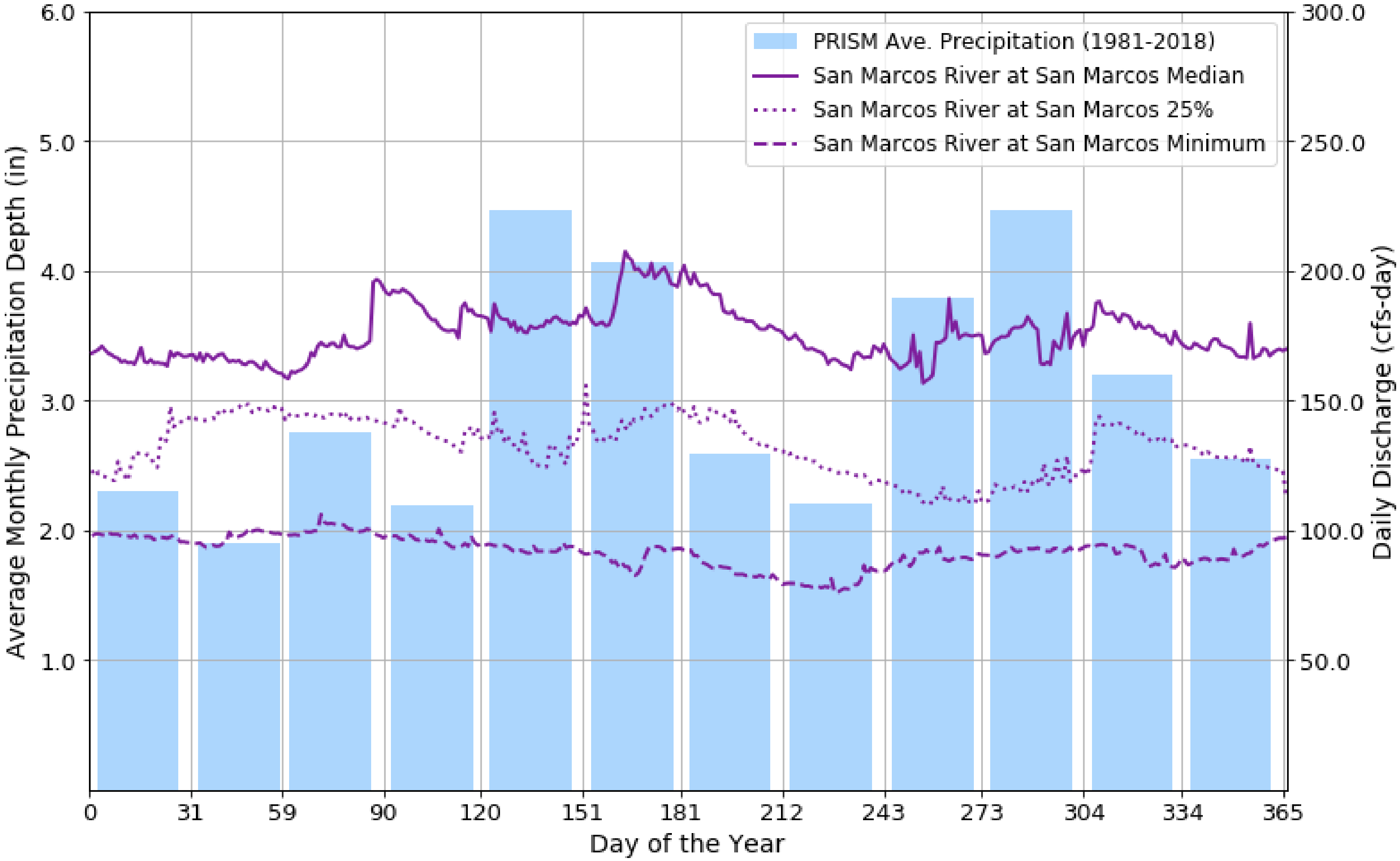


Figure 21: USGS 08170500 San Marcos River at San Marcos - Median and low discharge summary

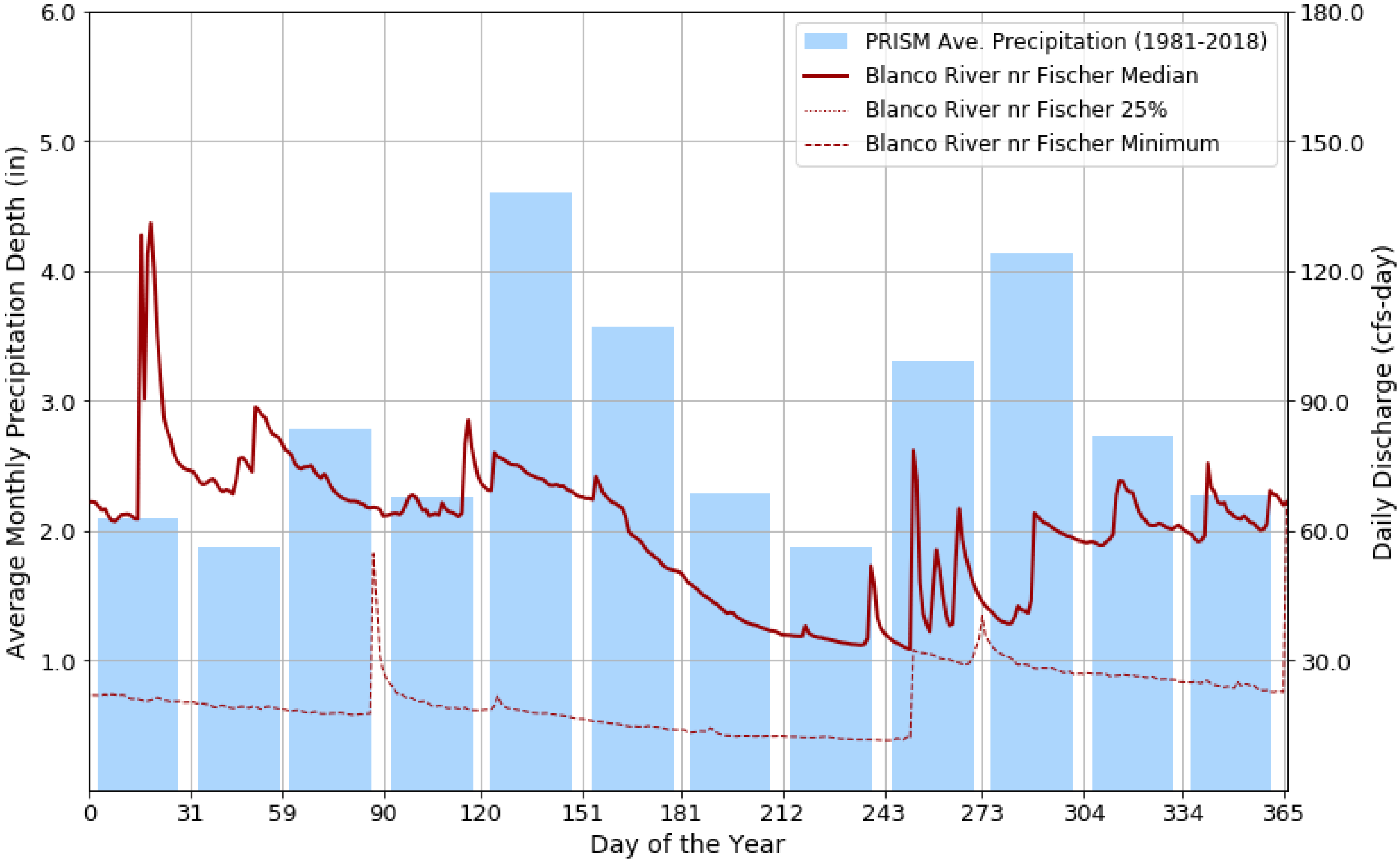


Figure 22: USGS 08170950 Blanco River near Fischer, TX - Median and low discharge summary

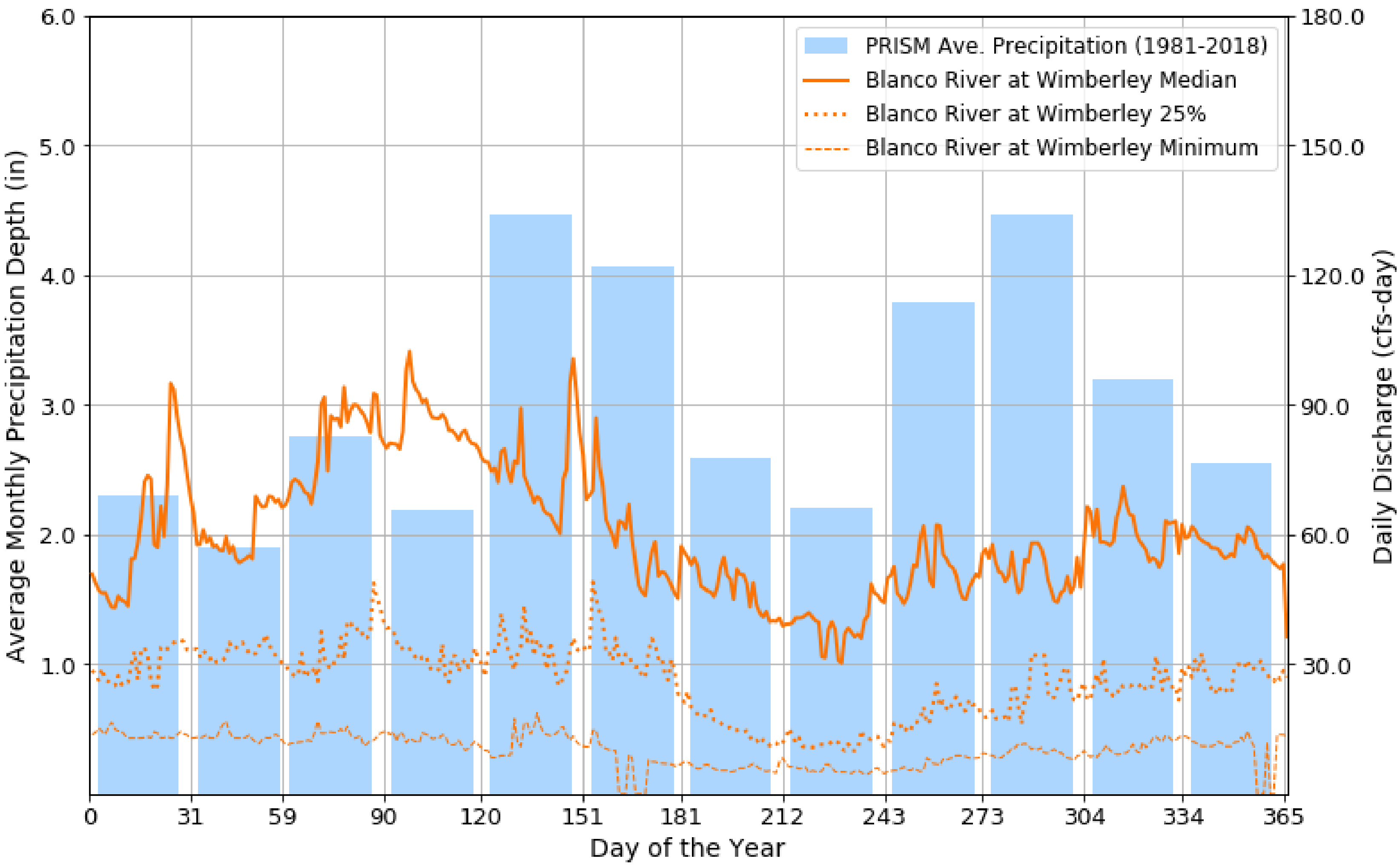


Figure 23: USGS 08171000 Blanco River at Wimberley, TX - Median and low discharge summary

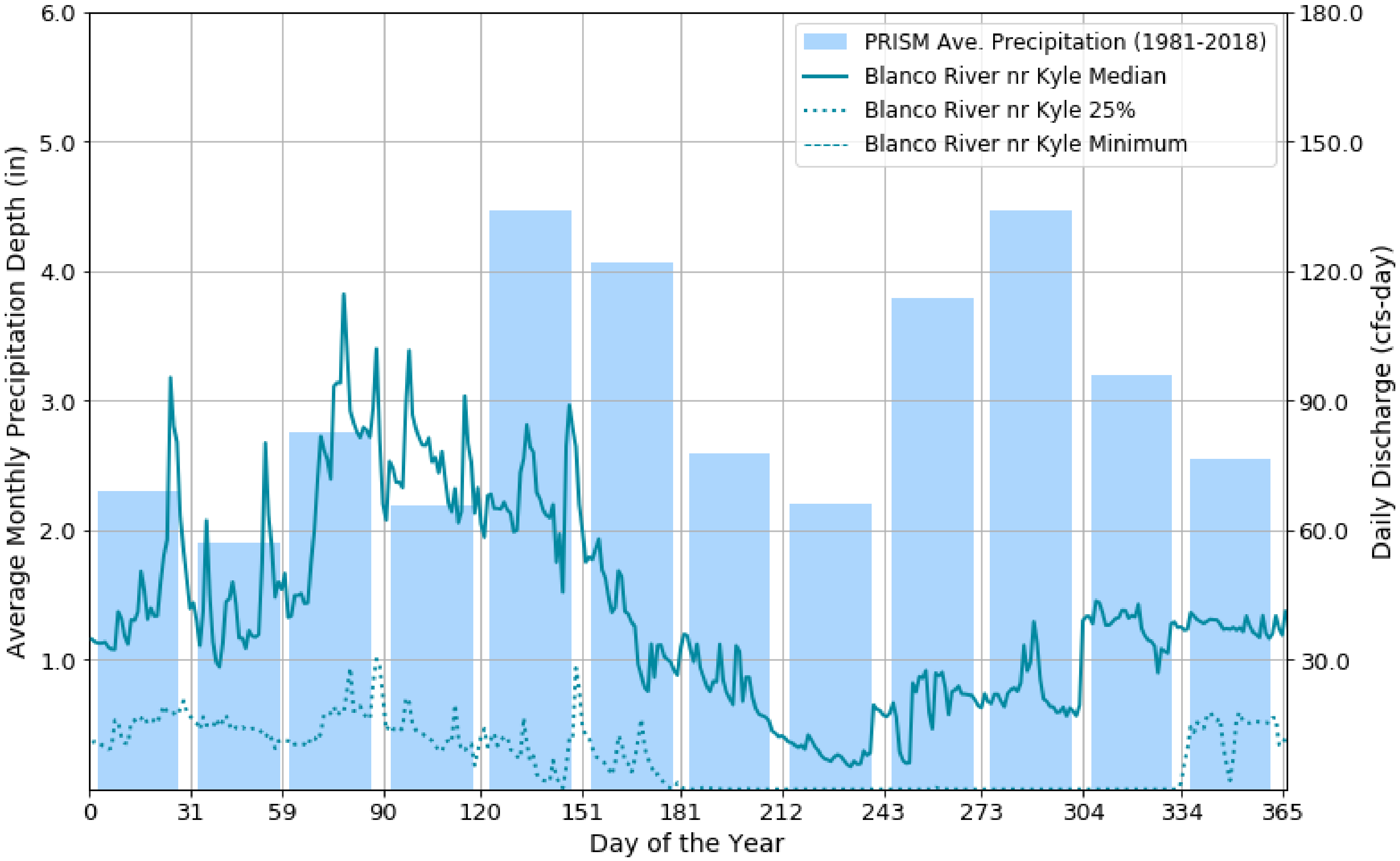


Figure 24: USGS 08171300 Blanco River near Kyle, TX - Median and low discharge summary

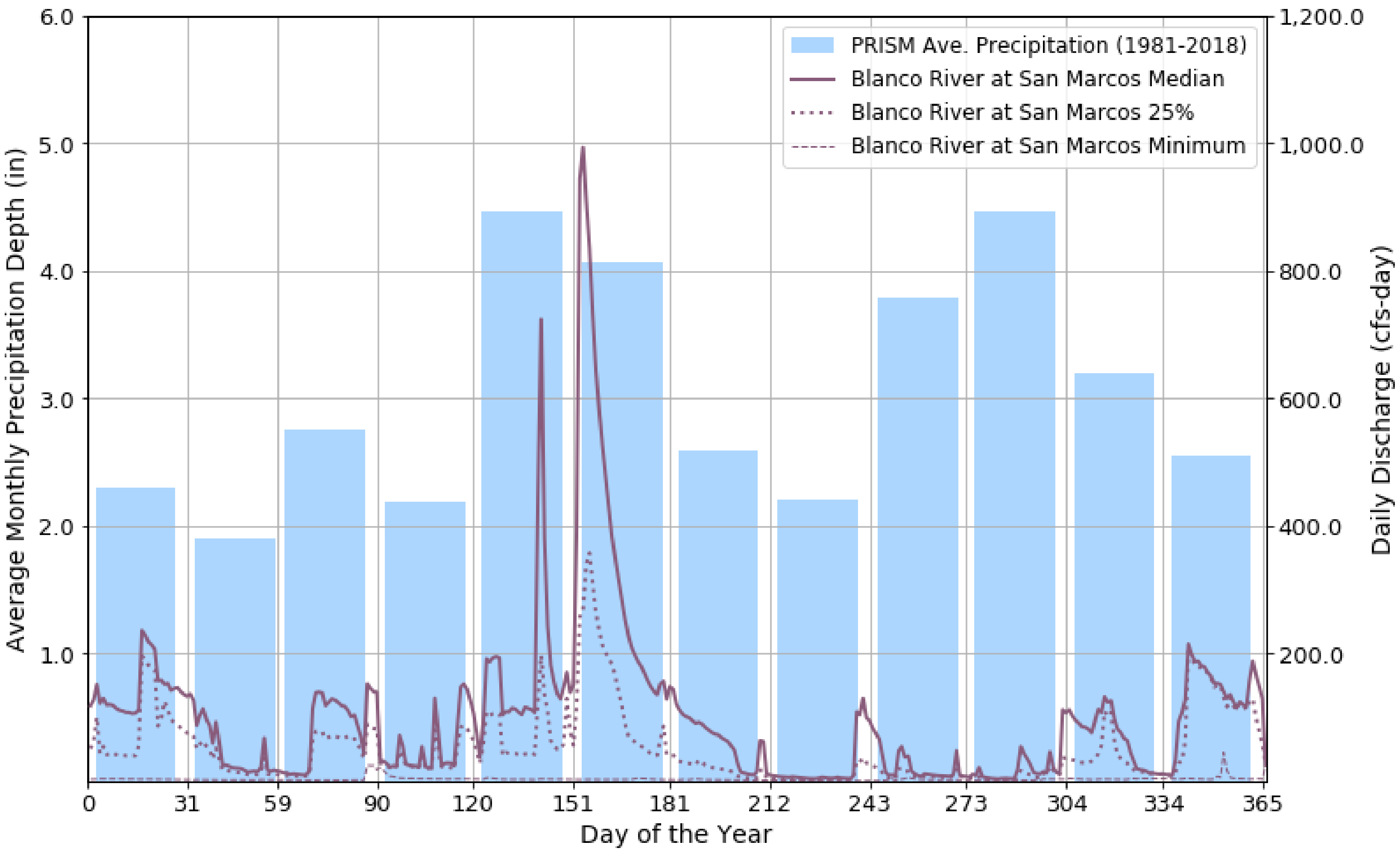


Figure 25: USGS 08171350 Blanco River at San Marcos, TX - Median and low discharge summary

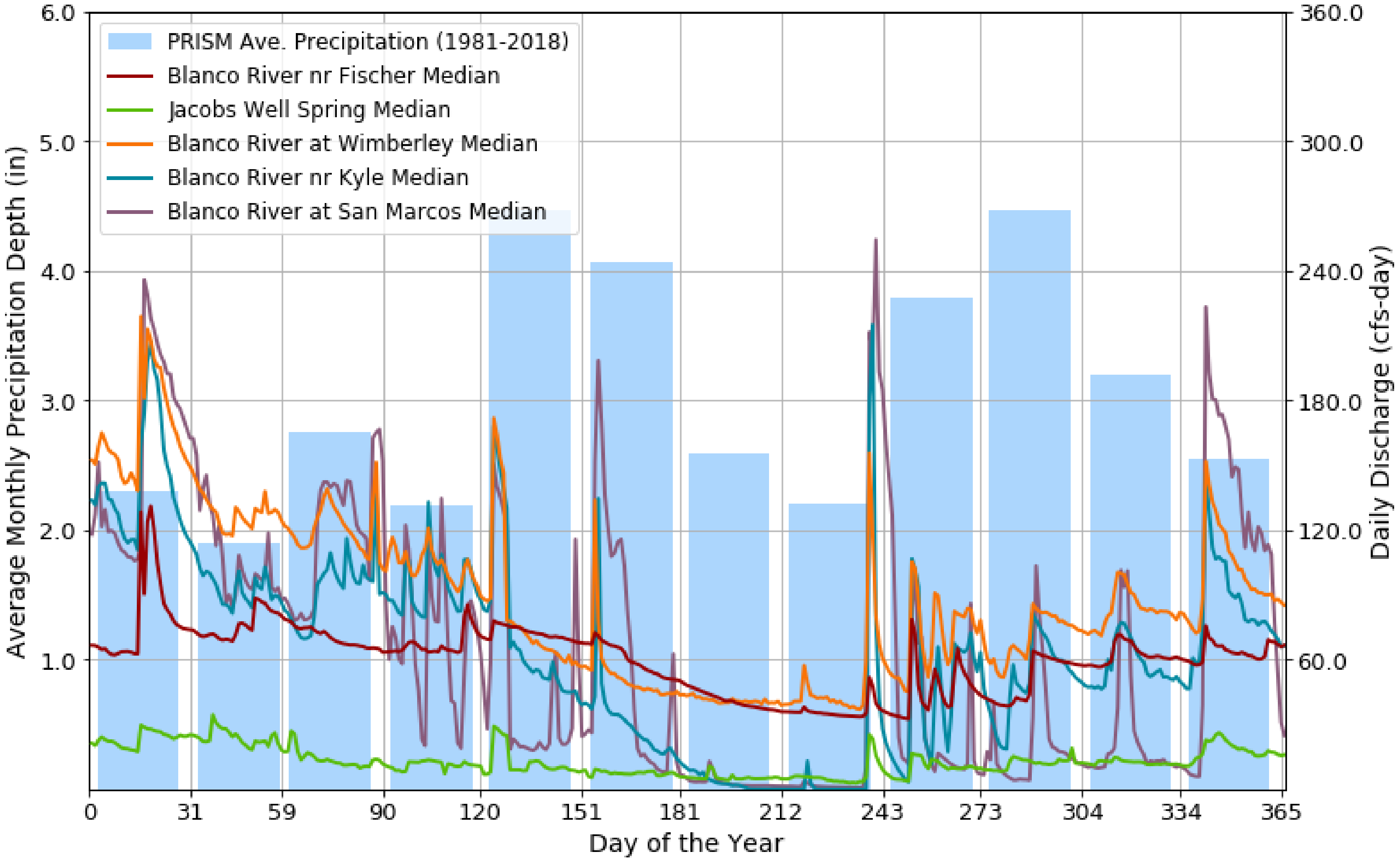


Figure 26: Blanco River system, median flow comparison 2016-2018

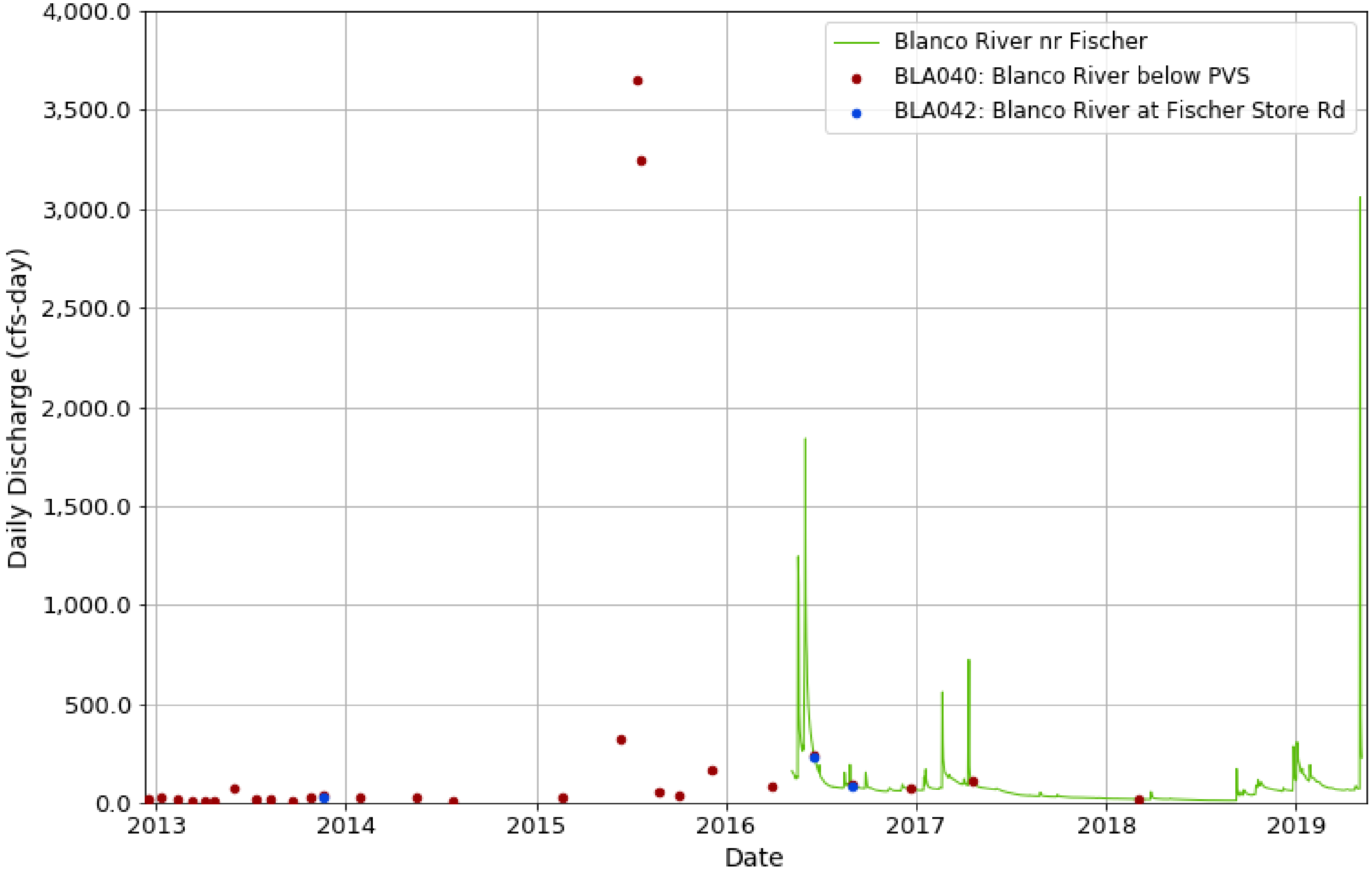


Figure 27: **USGS 08170950 Blanco River near Fischer Store- period of record hydrograph, manual measurements as blue points. Manual measurements at Blanco River below Pleasant Valley Springs as maroon points.**

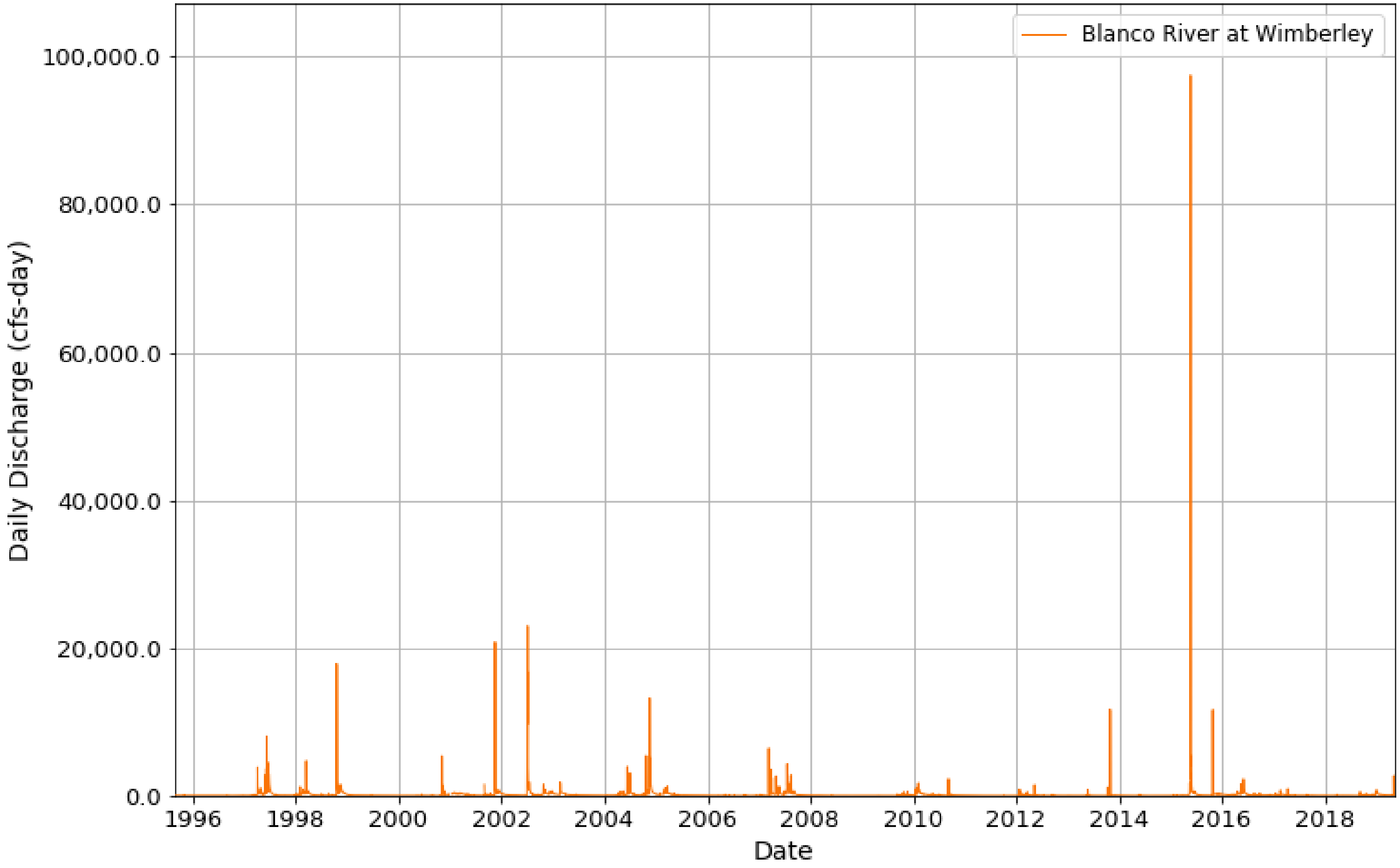
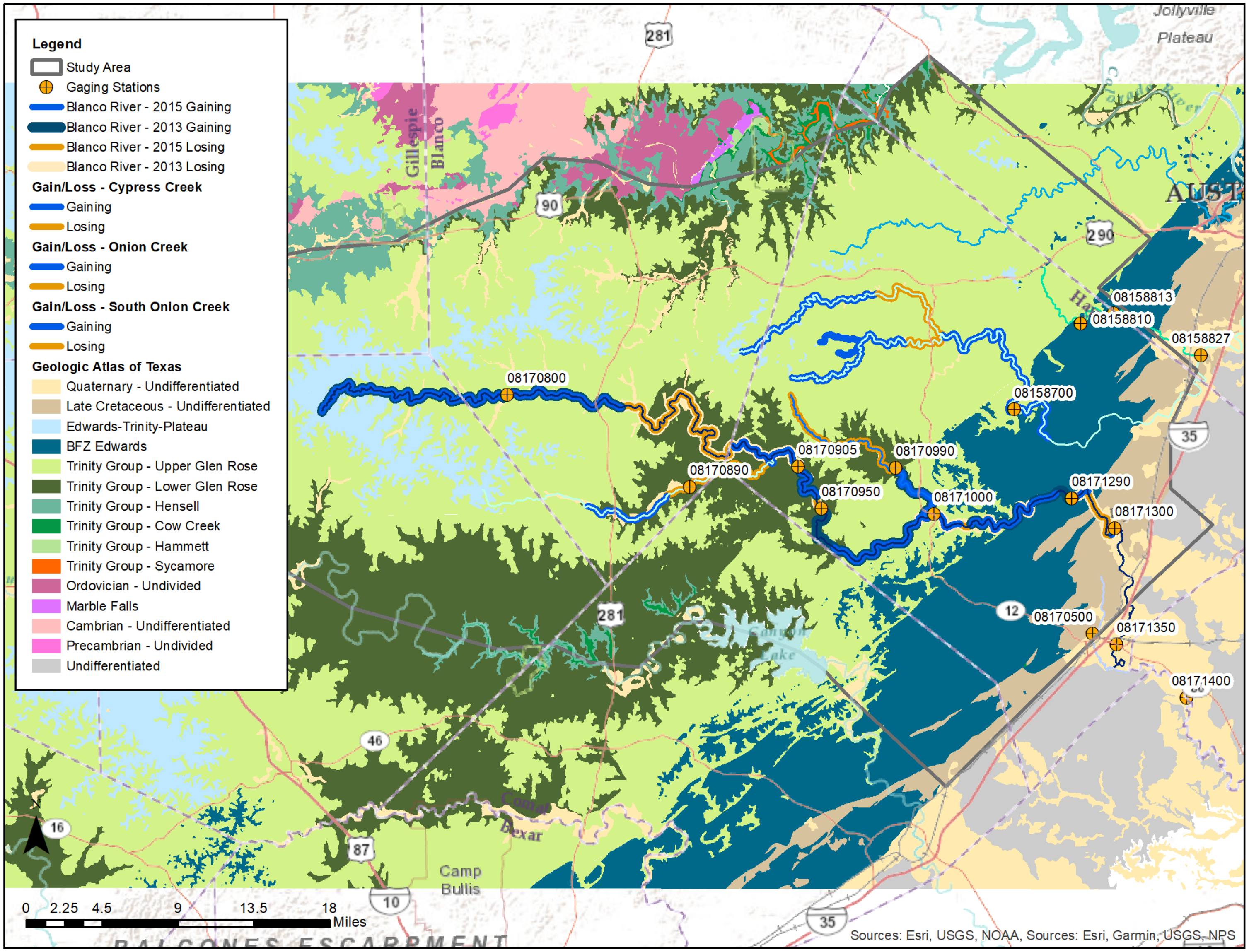


Figure 28: USGS 08171000 Blanco RR12- period of record hydrograph



Sources: Esri, USGS, NOAA, Sources: Esri, Garmin, USGS, NPS

Figure 29: Blanco River and Onion Creek, losing and gaining reaches

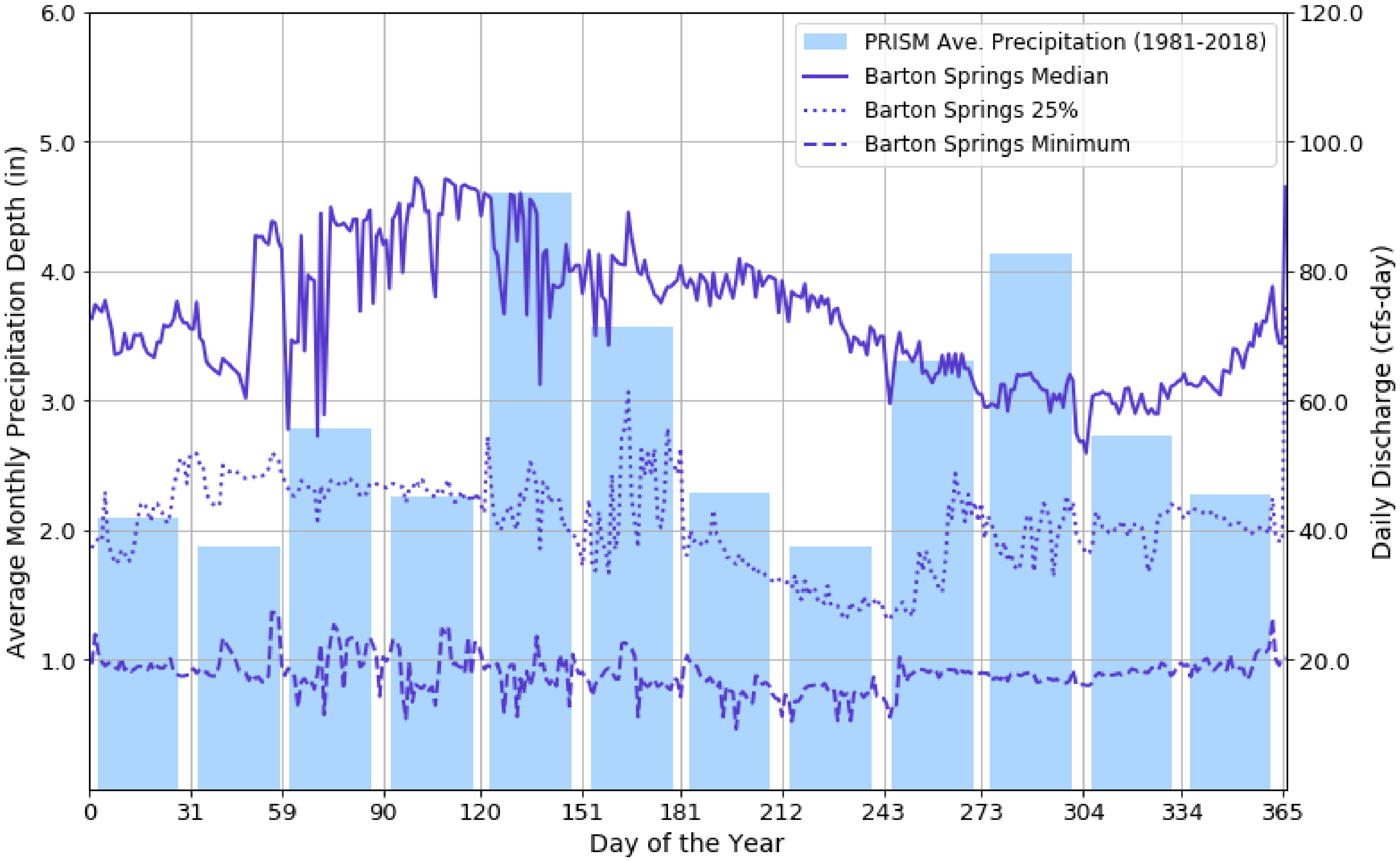


Figure 30: USGS 08155500 Barton Springs at Austin, TX - Median and low discharge summary

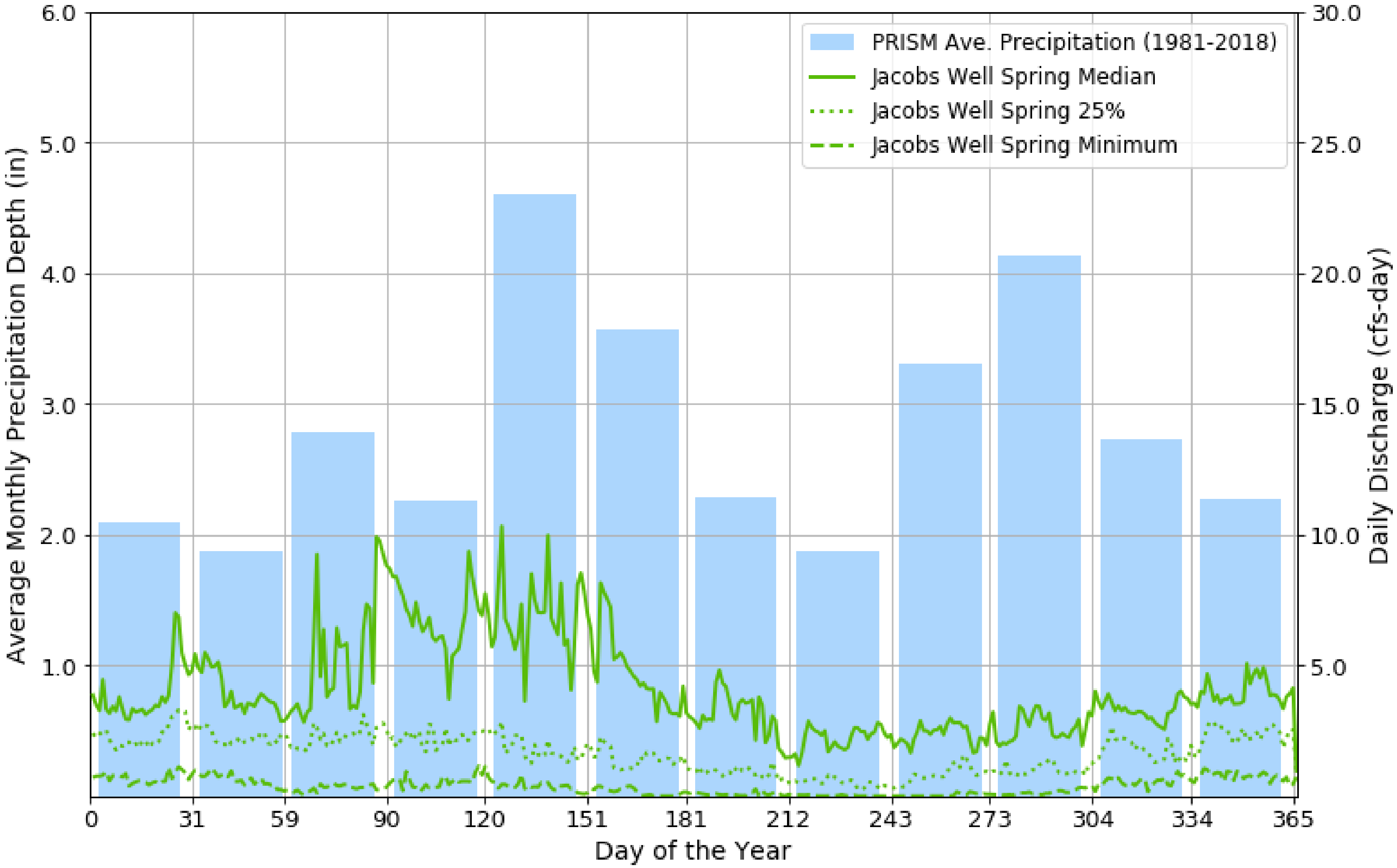


Figure 31: USGS 08170990 Jacob's Well Spring near Wimberley, TX - Median and low discharge summary

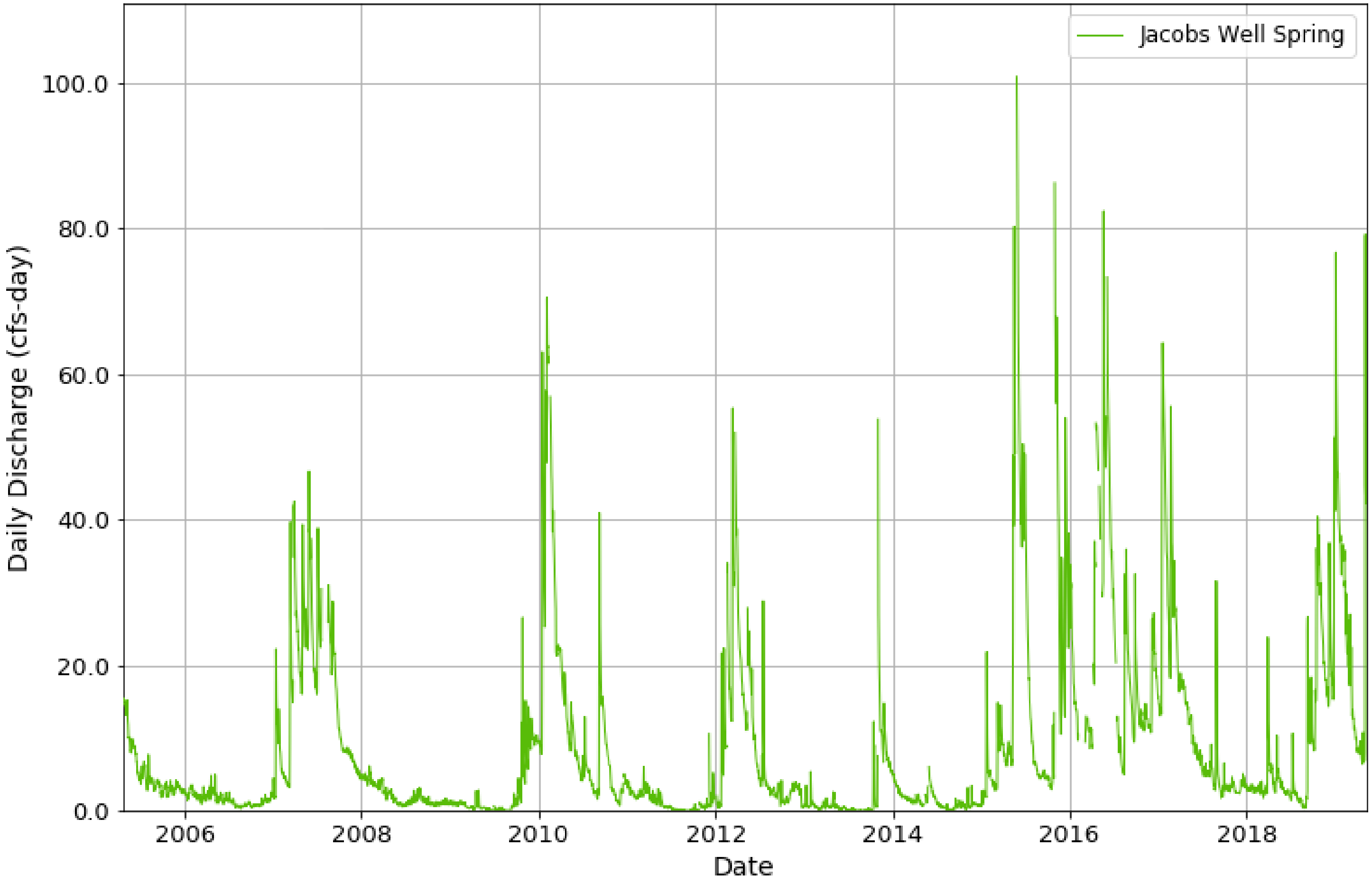


Figure 32: USGS 08170990 Jacob's Well Spring- period of record hydrograph since 2005

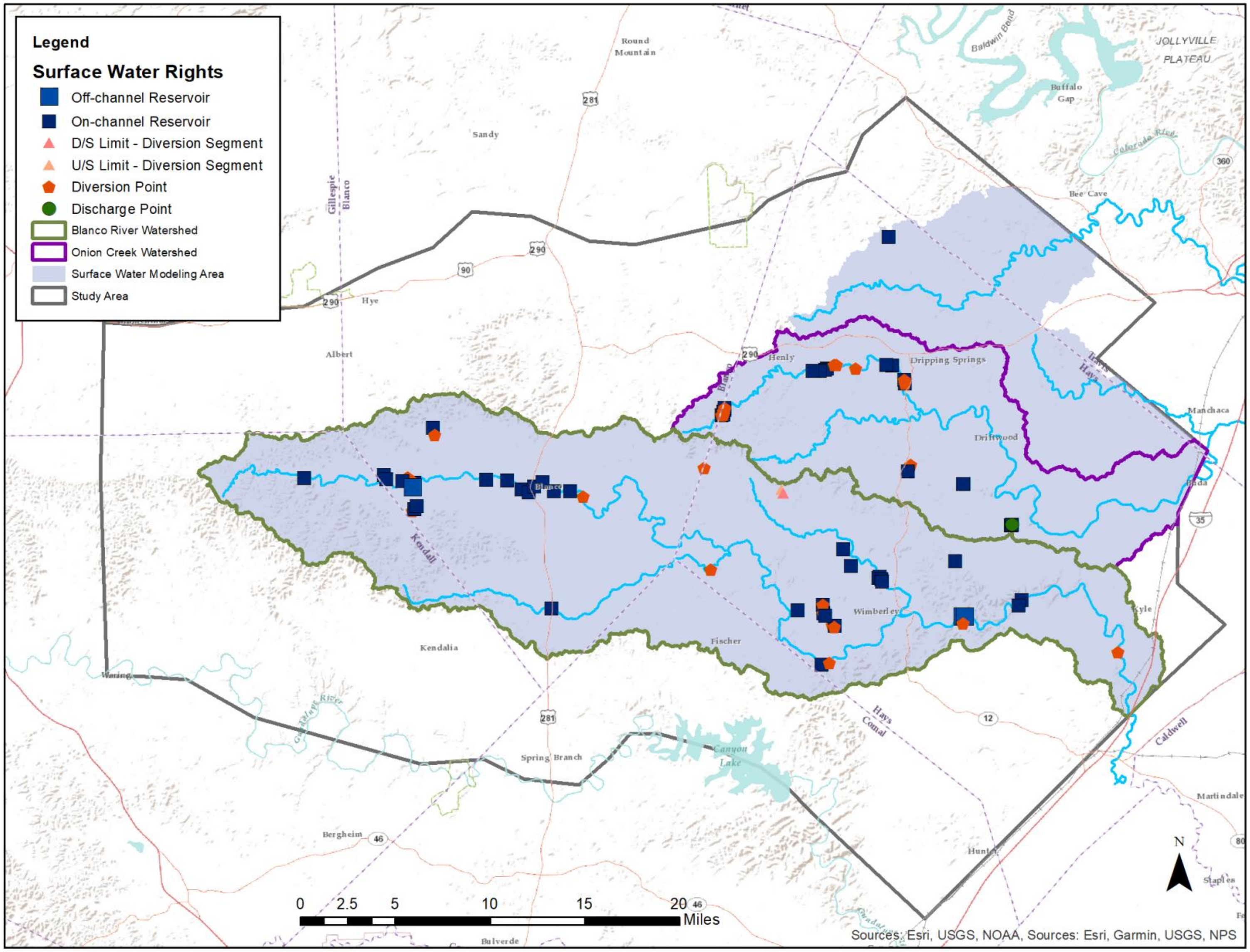
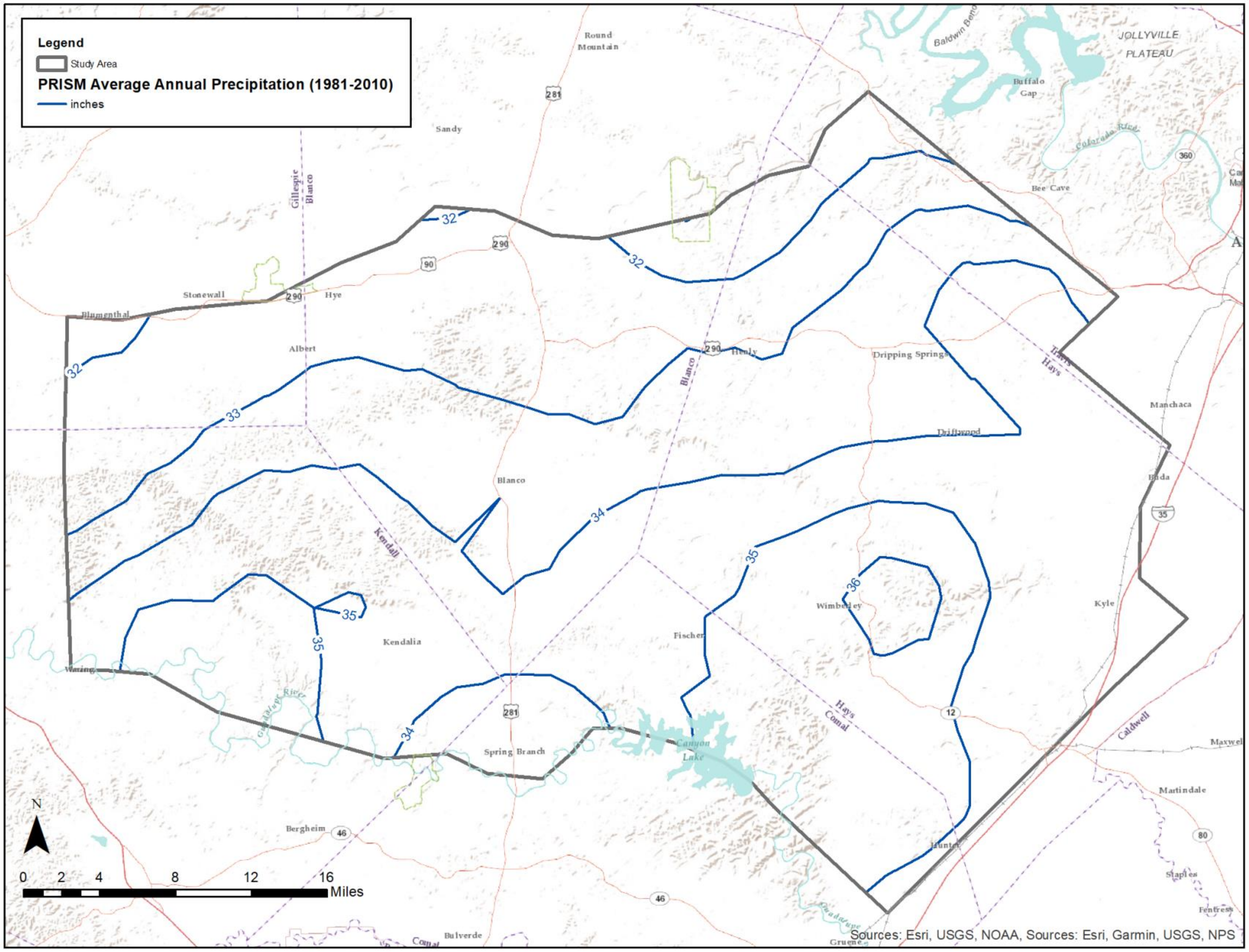


Figure 33: Surface water rights within the surface water areas of the study domain



Sources: Esri, USGS, NOAA, Sources: Esri, Garmin, USGS, NPS

Figure 34: Contours of annual average precipitation, PRISM data set, 1981-2010

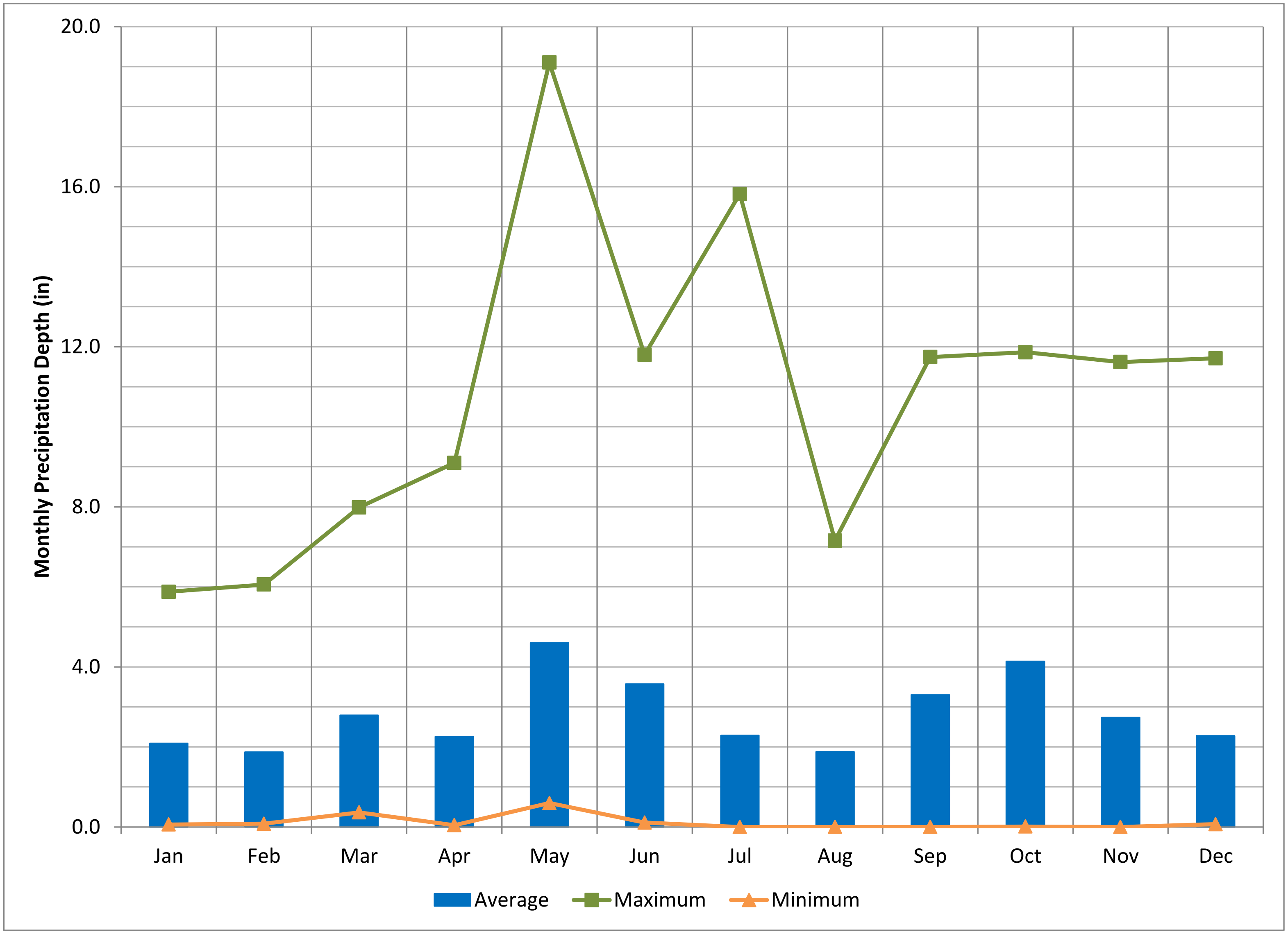


Figure 35: Monthly PRISM precipitation statistics at Blanco, TX, 1981-2018

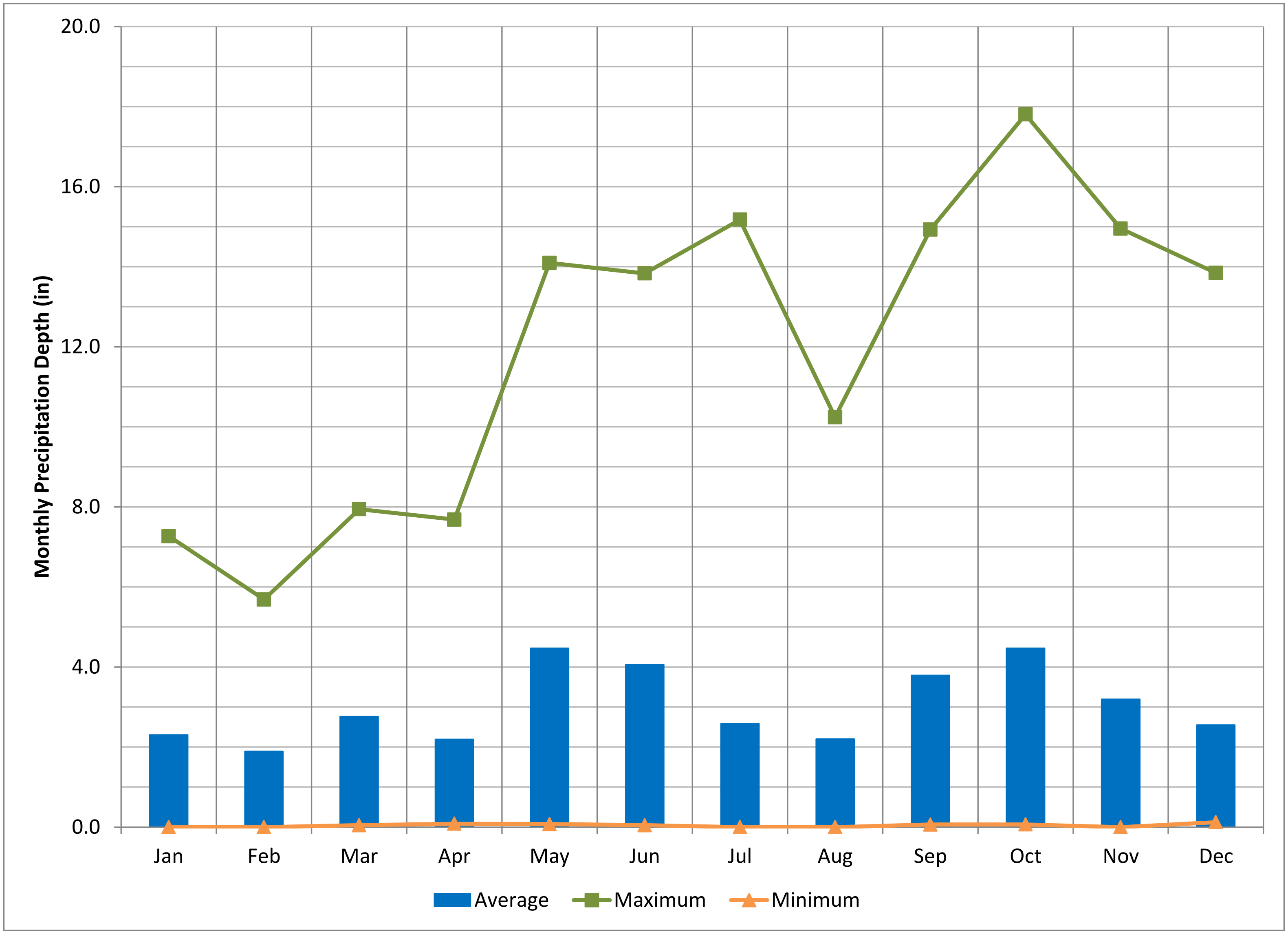
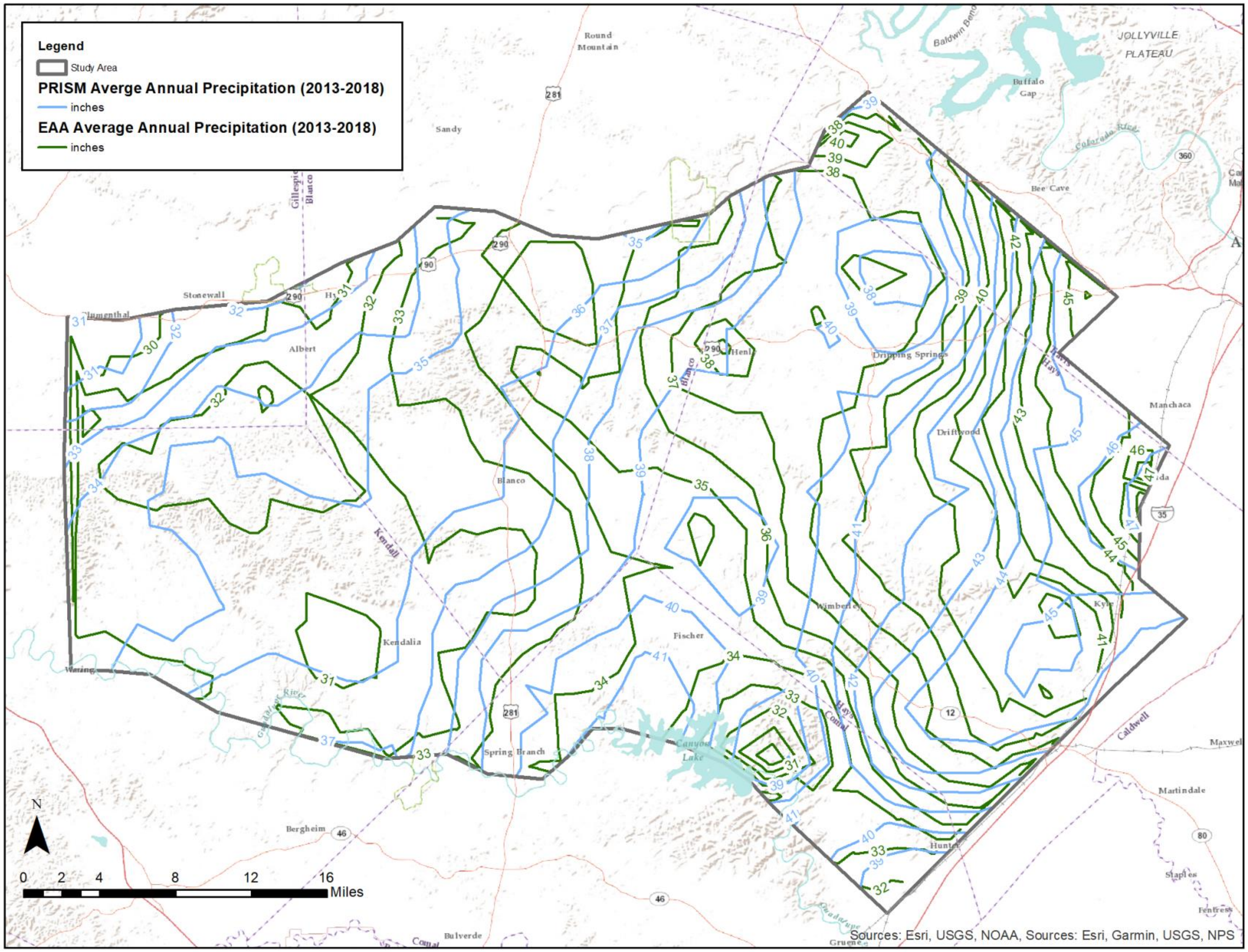


Figure 36: Monthly PRISM precipitation statistics at Wimberley, TX, 1981-2018



Sources: Esri, USGS, NOAA, Sources: Esri, Garmin, USGS, NPS

Figure 37: Comparison contours of annual average precipitation from PRISM and EAA for 2013-2018

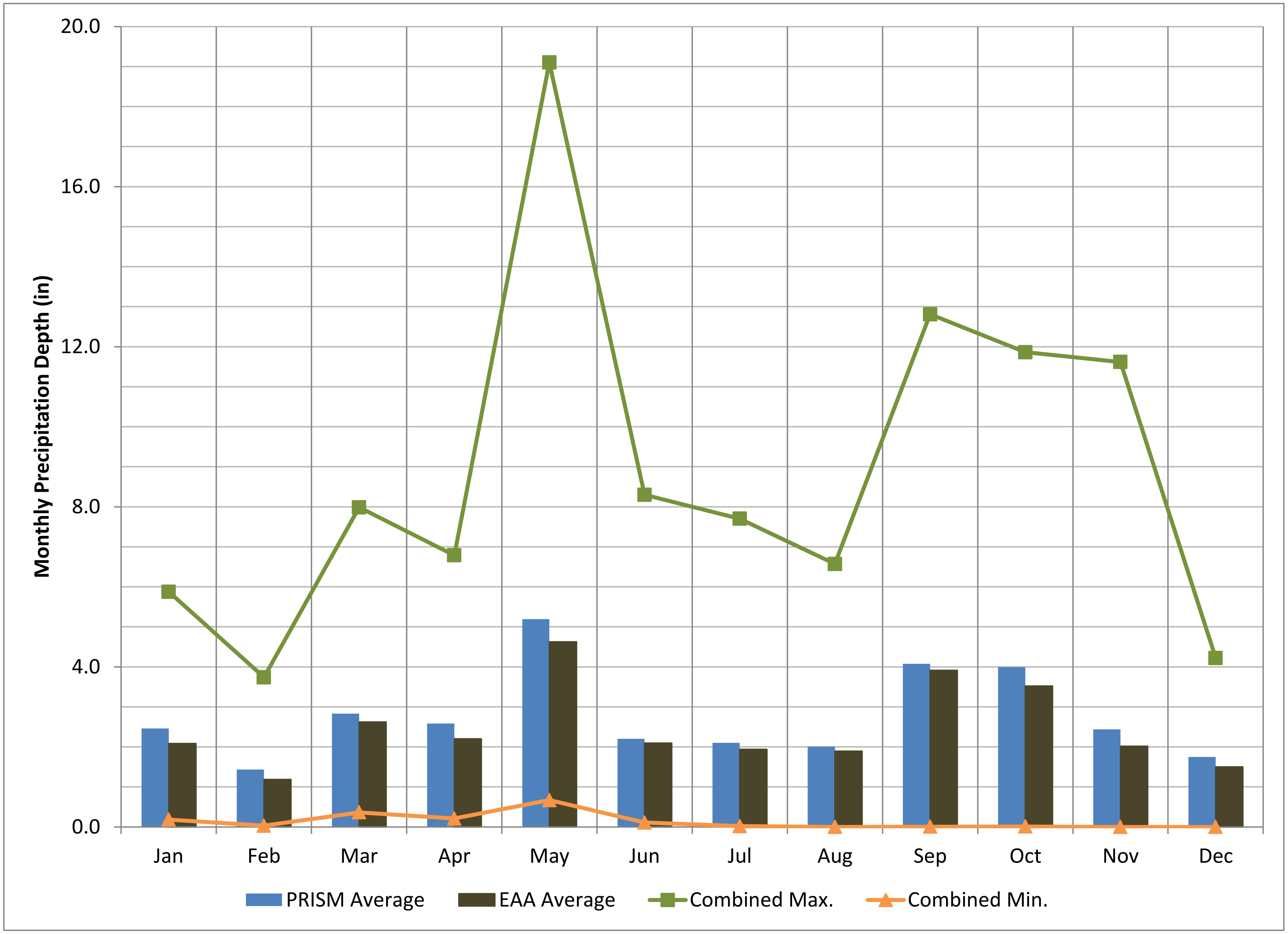


Figure 38: Comparison of monthly statistics at Blanco, TX between PRISM and EAA, 2004-2018

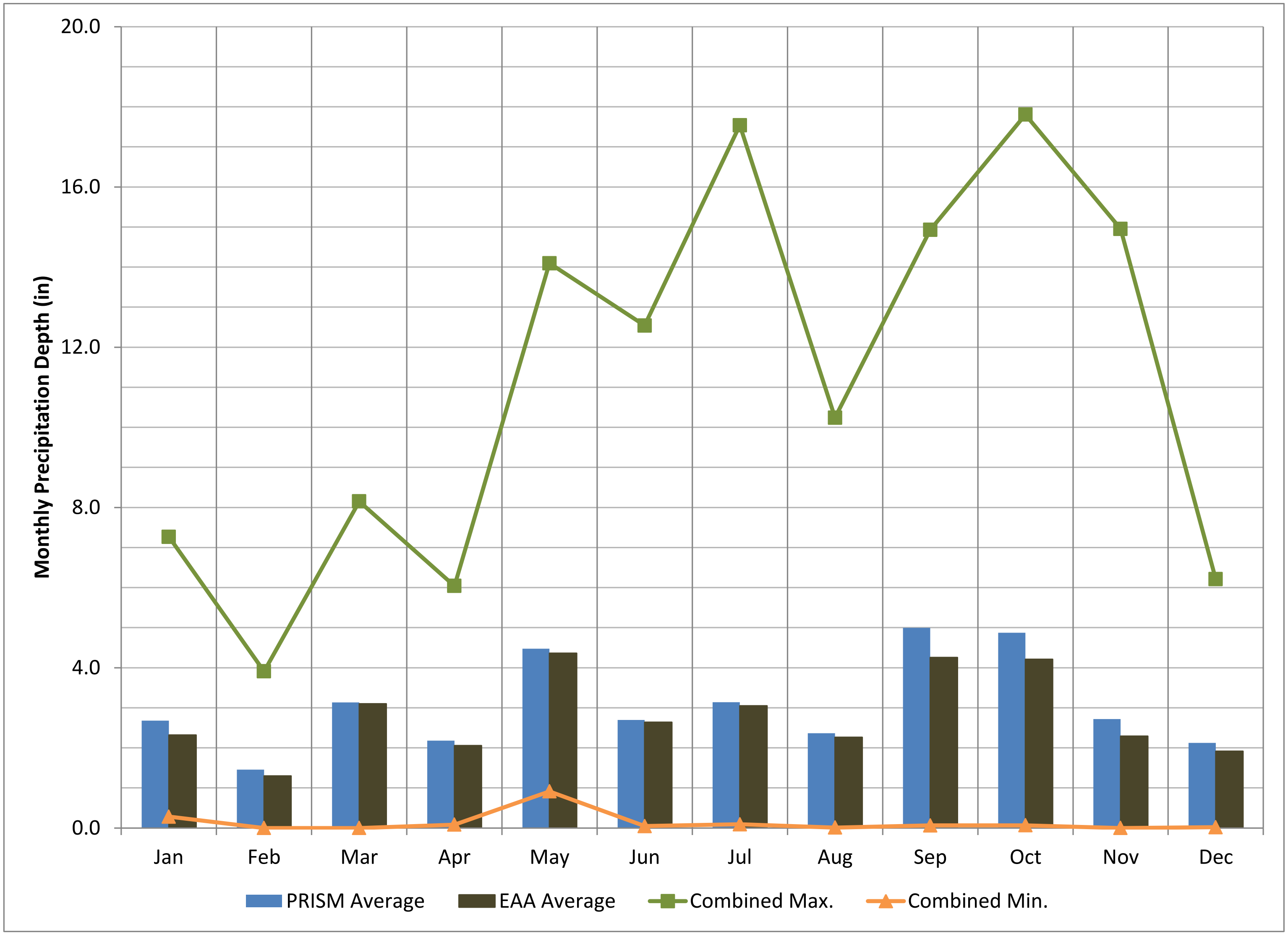


Figure 39: Comparison of monthly statistics at Wimberley, TX between PRISM and EAA, 2004-2018

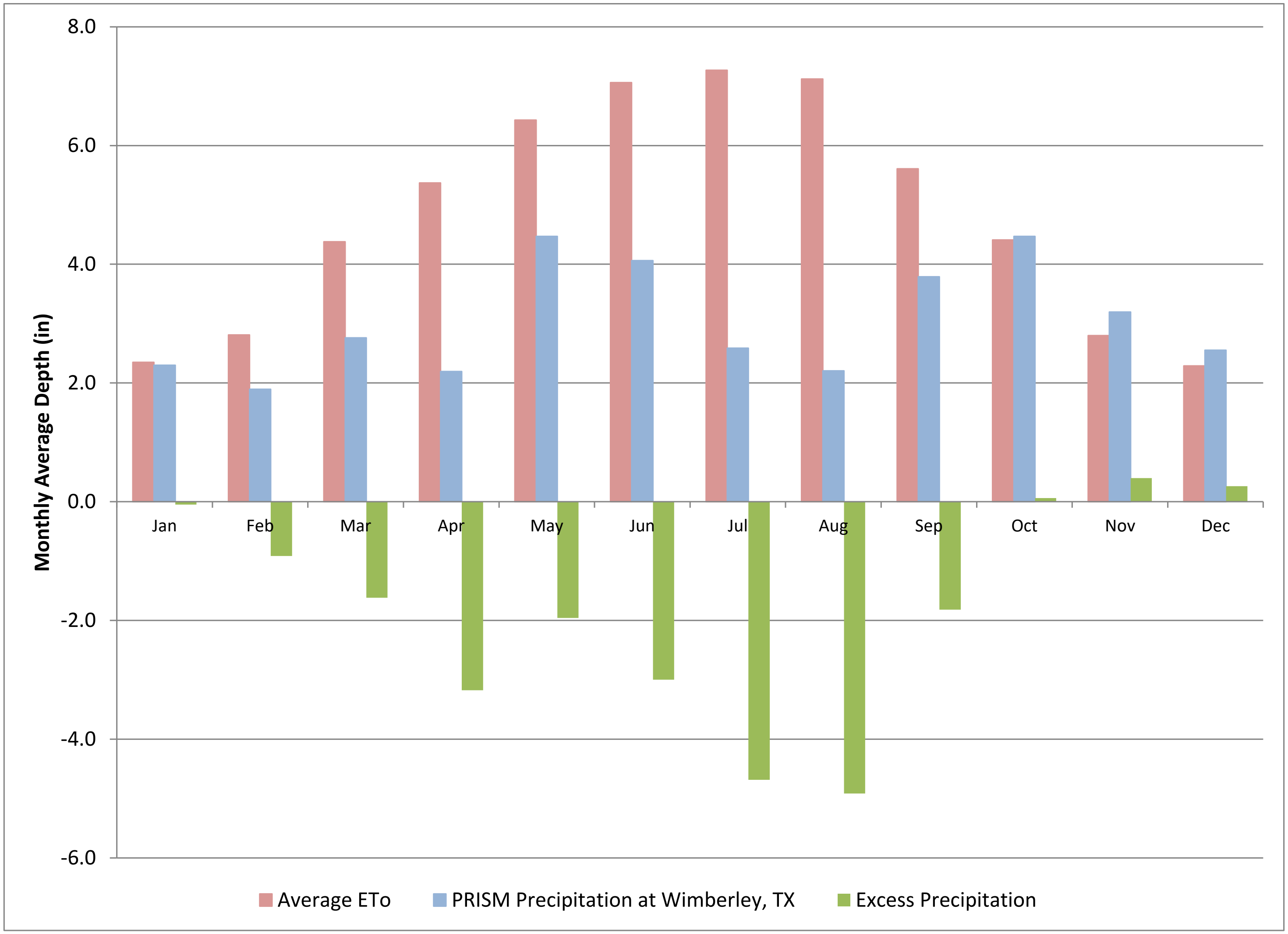


Figure 40: Typical monthly excess precipitation trends for the study area

Excess precipitation is this figure is monthly average rainfall from Figure 36 less monthly average ET$_o$ from Table 16. Period of excess precipitation deficit are those when excess precipitation is negative. Note the change from deficit to surplus from September to October and from surplus to deficit from December to February.

6 Hydrologic Setting

The BRATWURST study area stretches from the edge of the Edwards Plateau in the west to the edge of the Blackland Prairie in the east and traverses the BFZ. The complex structural underpinnings of this region control the hydrologic setting. The Middle Trinity and BFZ Edwards are the two primary aquifers in the study area. Upper and Lower Trinity are secondary aquifers in the study area.

The Blanco River is the main surface water feature in the heart of the study area and is the focus feature for this study. Several Blanco River tributaries, associated streams, and important springs within the study area are important for completing the hydrologic setting. Surface water and groundwater interaction is an important component of the setting.

6.1 Hydrostratigraphic framework

A hydrostratigraphic unit is one or more geologic units that have the same porous media characteristics and act as one hydrodynamic entity (Kresic 2007). While the official definition suggests that hydrostratigraphic units should have the same porous media characteristics, practical implementations often include lumping of geologic units and assignment of lumped characteristics as the spatial variation of porous media characteristics are generally not known in detail.

The hydrostratigraphic framework derived for BRATWURST is shown on **Table 1Table 2**. Given the greater than 1,500 mi^2 project area extent, the main focus of the hydrostratigraphic framework is representation of the controlling structures rather than detailed depiction of porous media characteristics.

Arc Hydro Groundwater (AHGW) software (Jones et al. 2010; Strassberg et al. 2011) was used to develop the framework model from previously published cross sections and structural contour maps. The workflow for framework development is shown on **Figure 43**. It involves creating surfaces for each hydrostratigraphic unit and then extruding between them to create three-dimensional (3-D) hydrostratigraphic units as GeoVolumes. GeoVolumes are ArcGIS multipatch geometries. A multipatch geometry is composed of 3-D rings and triangles and represents objects that occupy a volume (Strassberg et al. 2011).

The framework model was developed using structural elevation contour maps from *Hydrogeologic Atlas of the Hill Country Trinity Aquifer* (Wierman et al., 2010) (seen as a digitized fence diagram in **Figure 44**) and *Stonewall, Texas to San Marcos, Texas Geological Cross Section* (Fieseler and Tybor, 2019) (**Figure 42**) combined with fault-offset values from Smith et al. (2018). **Figure 41** shows the extent of the cross sections and contour maps with respect to the extent of the groundwater model domain. The hydrostratigraphic surfaces were extrapolated west, limitted by published pinchouts and onlap extents. In the southeast section of the domain, Middle and Upper Trinity Aquifer surfaces were extended across the fault blocks in the BFZ, assuming uniform thickness, as seen in Fieseler and Tybor (2019).

Figure 45 shows the full hydrostratigraphic framework model in 3-D. GeoSections are AHGW multipatch objects that are cross sections or cutouts from GeoVolumes. **Figure 46** provides locations and footprints for the GeoSections that are results of the framework model shown on **Figure 47** through **Figure 51**.

6.1.1 Fault blocks and relay ramps

Fault blocks and associated relay ramp structures are important for controlling subsurface flow on the eastern side of the project study area. Four fault blocks were identified in the eastern study area as discussed in Sections **3.3.2**, **4.1**, and **4.6**.

1. Tom Creek
2. Bat Cave
3. Hueco Springs
4. Comal Springs

These fault blocks control flow out of the eastern edge of the study area. Where relatively large offset exists across a fault, groundwater flow is typically parallel to the fault. Where offset is limited or non-existent, groundwater flow can be perpendicular to, or across, the fault.

Figure 47 and **Figure 50** display the framework model across, i.e. perpendicular to, these faults. **Figure 52** displays the flow conceptualization through the fault block representation of the BFZ.

6.1.2 Other structures

Any structural control that results in a transmissive unit at the ground surface, adjacent to a stream or river channel, is important in the hydrostratigraphic framework. The primary locations of this phenomenon are the horst block that exposed the Middle Trinity Aquifer to the west of the Pleasant Valley Fault (see **Figure 52**) and BFZ Edwards Aquifer recharge zone at the eastern side of study area. The BFZ Edwards Aquifer recharge zone corresponds to fault block locations. **Figure 51** shows a section through the horst block area.

Another important structure for the hydrostratigraphic framework is the plunging anticline, delineated in the Trinity Group (see **Figure 52**). The limbs of this anticline may act to direct groundwater flow to the northeast and south away from the axis. **Figure 51** displays a section perpendicular to the anticline axis.

6.2 Watersheds

The primary surface water features for BRATWURST and corresponding watersheds are shown on **Figure 53**. The areas of these watersheds are provided in **Table 17**. Note that the delineated watershed area does not completely overlap with the study area. For surface water considerations, the watershed footprint completely delineates the area of influence.

Table 17: Watershed and surface water simulation area summary

Watershed	Sub-Watershed	Area	
		(acres)	(mi^2)
Bear Creek	Total	29,083	45.4
Onion Creek	South Onion Creek	15,318	23.9
	North Onion Creek	29,814	46.6
	Total	111,305	173.9

Watershed	Sub-Watershed	Area	
		(acres)	(mi^2)
Blanco River	Cypress Creek	24,302	38.0
	Little Blanco River	43,909	68.6
	Total	276,369	431.8
Barton Creek	Total	52,718	82.4
Total Surface Water Area		469,474	733.6

6.3 Water elevation and groundwater flow

The Middle Trinity Aquifer is the focus of the BRATWURST model. Additionally, this is the only aquifer that is present across the majority of the study domain. **Figure 54** shows contours of the Middle Trinity Aquifer potentiometric surface from Hunt et al. (2019). Along the western-side of the study area, flow is generally north to south. A flow divide is located approximately between Cypress and Onion Creeks, which is approximately the location of the plunging anticline (see **Figure 52**). On the southern limb, flow is mostly towards the south and southeast. On the northern limb, flow is mostly to the west and northwest, approximately parallel to the Tom Creek Fault.

The BFZ Edwards Aquifer is present in the fault blocks shown on **Figure 52**. Groundwater flow patterns are largely dictated by fault block structure in this area (see **Figure 11**). **Figure 55** displays contours of the BFZ Edwards Aquifer potentiometric surface within the study domain from the 4th quarter of 2016. Flow directions associated with these contours would be southeast to east.

6.4 Stream flow

The Blanco River is the primary surface water focus of BRATWURST. **Figure 1** provides a map of the Blanco River across the study area. West of the town of Blanco, runoff provides the primary source of Blanco River flow. Springs within the town of Blanco discharge to the river and increase the typical river discharge. Two losing sections of the Blanco River are identified where it crosses outcrops of the Middle Trinity and BFZ Edwards aquifers. In between the two losing sections is perennial Blanco River which is fed by spring flow and by runoff.

Gaining and losing characteristics of the Blanco River are discussed in Section **5.4.2**. There are two identified losing reaches for the Blanco River where it provides water to the Middle Trinity and the BFZ Edwards aquifers. These two reaches are “naturally” losing water to the aquifers located below the stream bed.

Compounding the complexity of stream flow considerations for the Blanco River are stream modifications including restrictions and extractions for surface water rights. These are “anthropogenic” losses. **Figure 33** displays locations of surface water rights extraction points. Numerous on-stream dams and low-water crossings are present along the course of the Blanco River; 4-5 of these are located in the town of Blanco as shown on **Figure 56**. The existence of on-stream dams could complicate the simulation of stream discharge especially during dry periods when these dams could be completely impounding river flow and making this water available for evaporation.

Onion Creek is the other stream of primary interest in the study region because of the importance of conditions in the Onion Creek watershed for influencing the final destination of water that goes from the Blanco River to the Middle Trinity Aquifer. Onion Creek also has two losing reaches; one provides water to the Middle Trinity Aquifer in locations where Unit 3 of the Upper Glen Rose has been eroded, and one provides water to the BFZ Edwards Aquifer in the recharge zone (see **Table 13**).

In addition to the Blanco River and Onion Creek, the following rivers and streams will be explicitly represented in BRATWURST.

- Little Blanco River
- San Marcos River
- Cypress Creek
- Bear Creek
- Barton Creek

6.5 Aquifer recharge mechanisms

BRATWURST deals with two primary aquifers: 1) Middle Trinity and 2) BFZ Edwards. Recharge to the BFZ Edwards Aquifer occurs in the delineated recharge zone, see **Figure 57**. The majority of water recharging the BFZ Edwards Aquifer comes from stream flow and surface runoff that travels directly into the aquifer (Slade 2014). The source of much of the stream flow and runoff is the contributing zone or “Drainage Area”, also shown on **Figure 57.**

Middle Trinity Aquifer recharge also comes from streams and rivers, especially the Blanco River and Onion Creek (Hunt et al. 2017), see **Figure 29**. Some amount of the water that enters the Middle Trinity Aquifer is likely precipitation that percolates downward to reach the saturated regions of the aquifer after falling on the ground surface.

Secondary aquifers that are at or near the surface across the western portion of the study domain, like the Upper Trinity Aquifer and the Edwards Aquifer west of the BFZ, receive some degree of recharge from percolation of precipitation from the ground surface down to saturated groundwater. The secondary aquifers also likely receive recharge from streams and rivers.

6.6 Aquifer discharge mechanisms

Aquifers in the study area discharge to rivers, streams, and focused locations on the ground surface as springs. **Table 10** provides the source aquifer for a listing of the primary springs in the study area; locations of these springs are shown on **Figure 15**.

There is likely some inter-formational flow between the Upper and Middle Trinity and BFZ Edwards aquifers in the BFZ where fault offset has aligned transmissive units from different aquifers. Inter-formational flow is simply flow between two aquifers; consequently, it provides a discharge mechanism from one aquifer and a recharge mechanism for the other aquifer. The magnitude and importance of inter-formational flow are not known at this time.

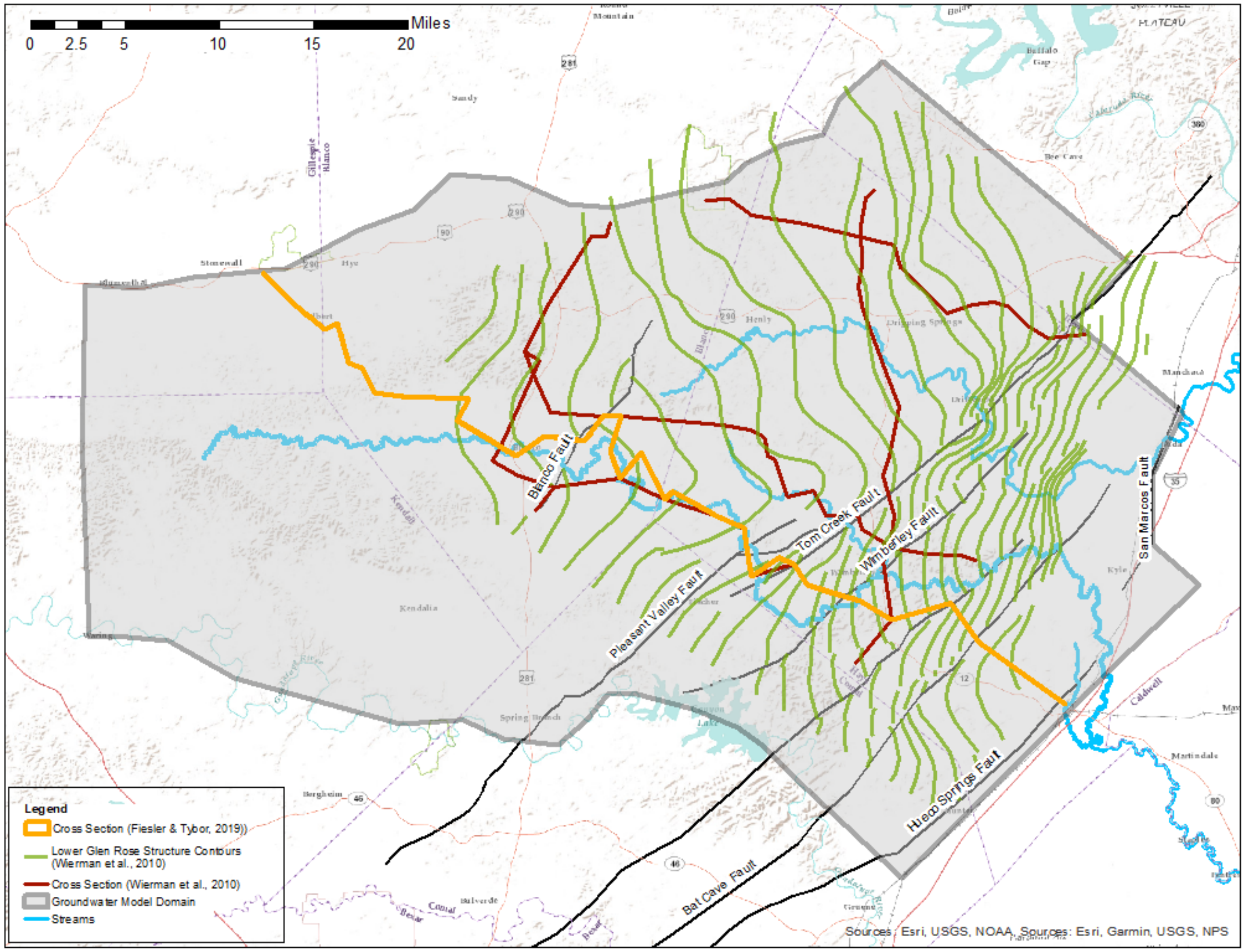


Figure 41: Extent of data inputs to framework model
Orange and red lines delineate the extent of cross sections used as basis for framework model surfaces. Green lines show extent of contoured surfaces that extend into the BFZ.

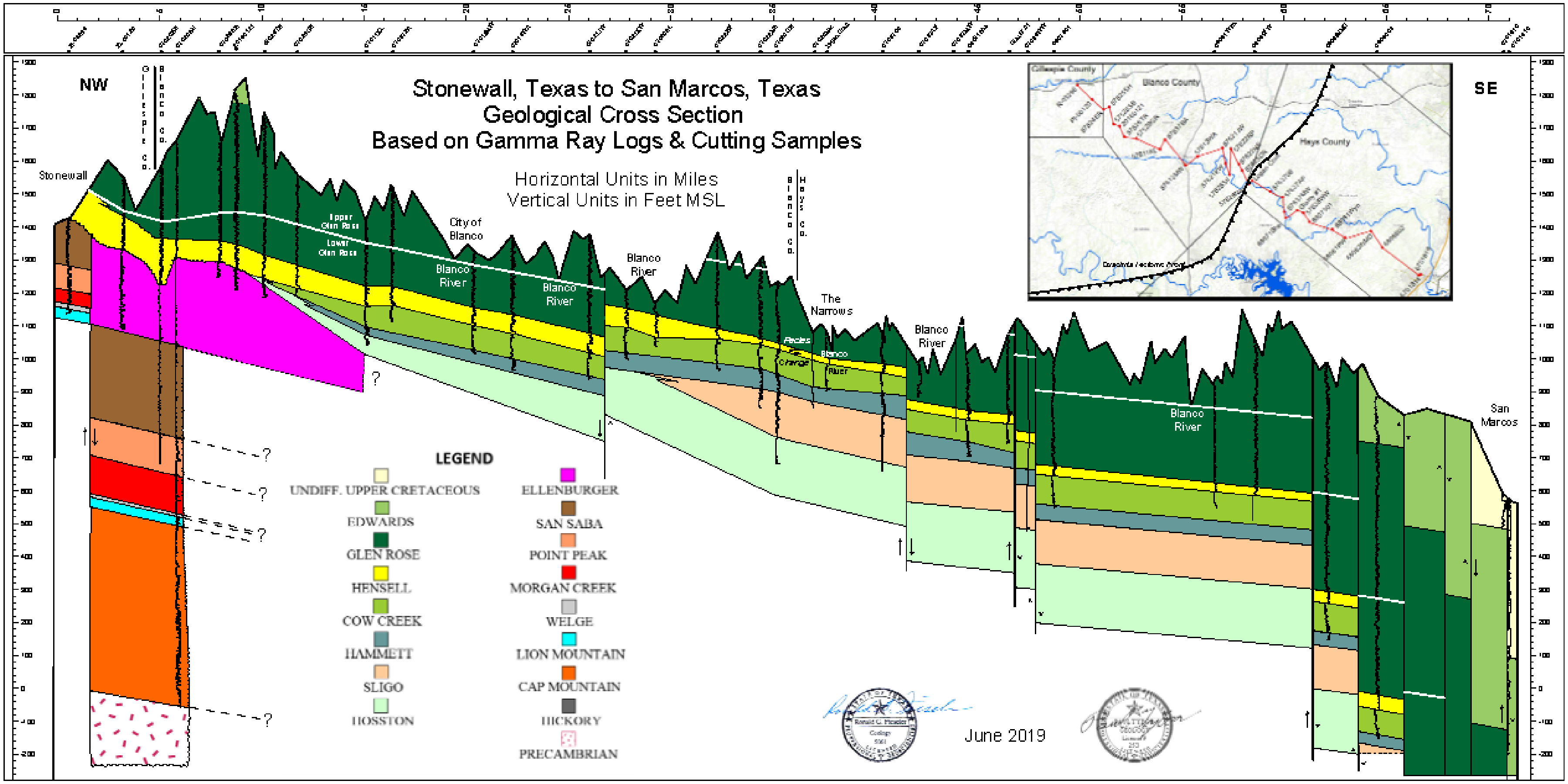
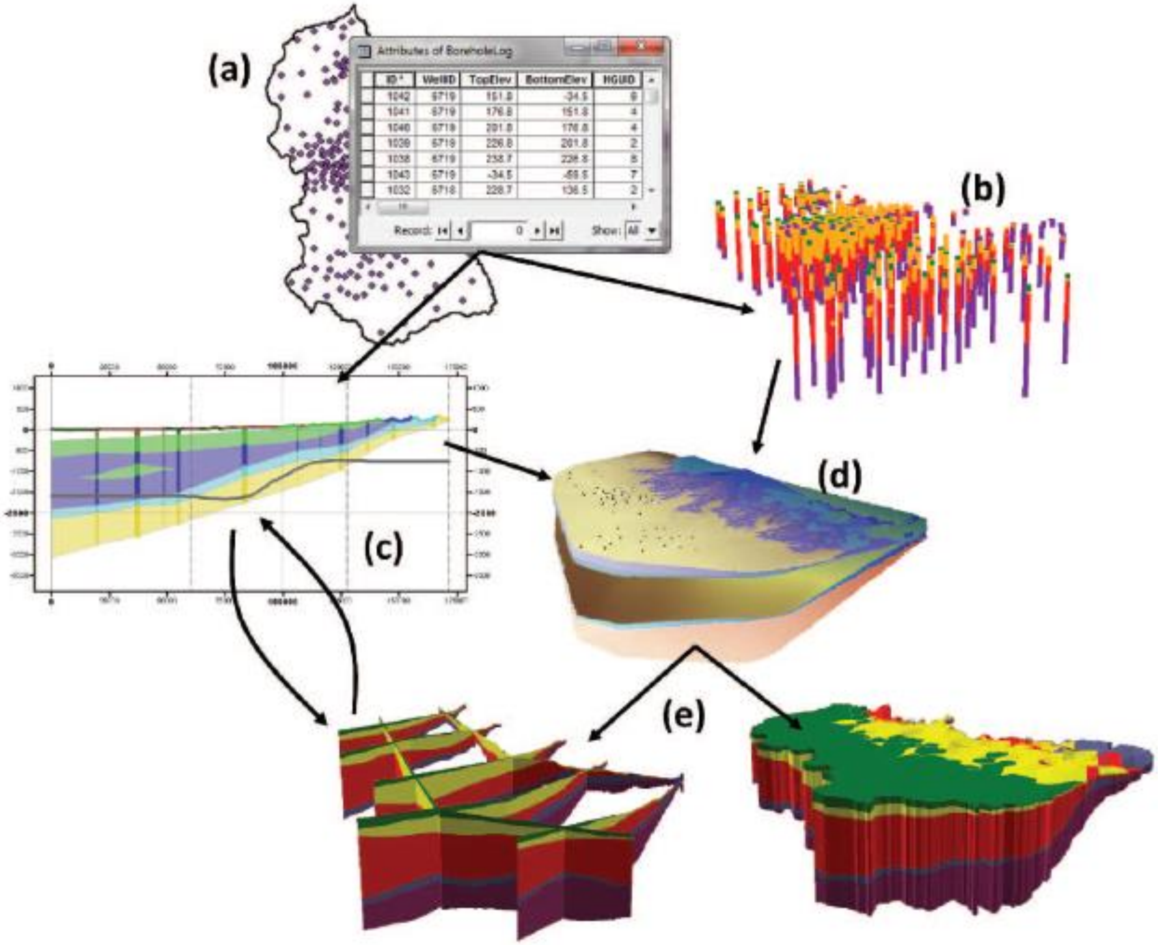


Figure 42: Geological Cross Section from Fieseler and Tybor (2019)
Southeast portion of cross section extends through BFZ and suggest existence of Middle Trinity units across fault blocks.



Attributes of BoreholeLog

ID *	WellID	TopElev	BottomElev	HGUID
1042	6719	151.8	-34.5	6
1041	6719	176.8	151.8	4
1040	6719	201.8	176.8	4
1039	6719	226.8	201.8	2
1038	6719	238.7	226.8	8
1043	6719	-34.5	-69.5	7
1032	6718	228.7	136.5	2

Fig. 7: *Workflow for visualizing subsurface data and building 3D subsurface models. (a) Well features and related borehole stratigraphy, (b) 3D features representing borehole stratigraphy, (c) 2D cross sections, (d) surfaces representing hydrogeologic unit boundaries, (e) 3D fence diagrams and volume objects.*

Figure 43: Workflow for building 3-D framework models with Arc Hydro Groundwater, Figure 7 from Jones et al. (2010)

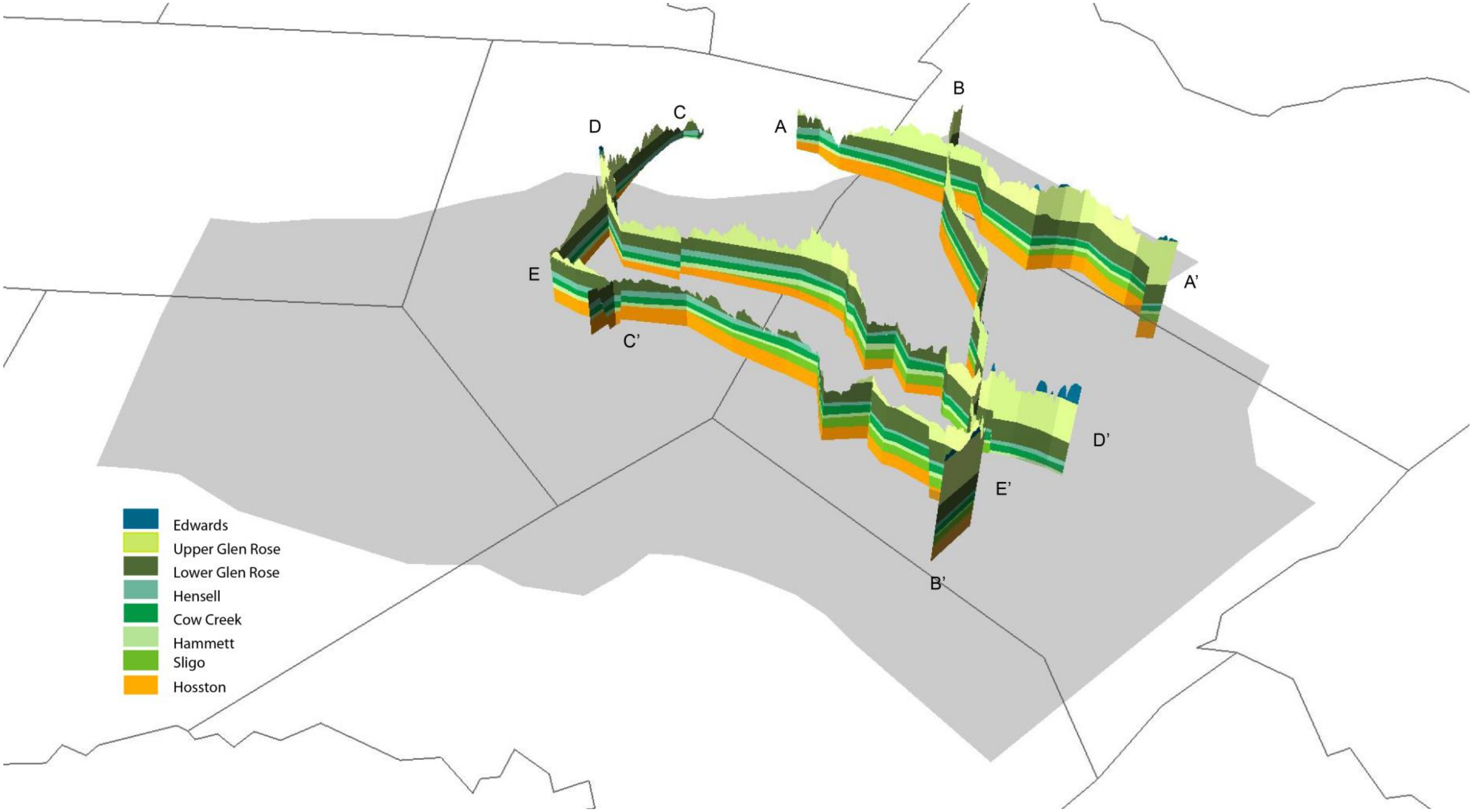


Figure 44: Fence diagram of digitized cross sections from Wierman et al. (2010) incorporated into framework model

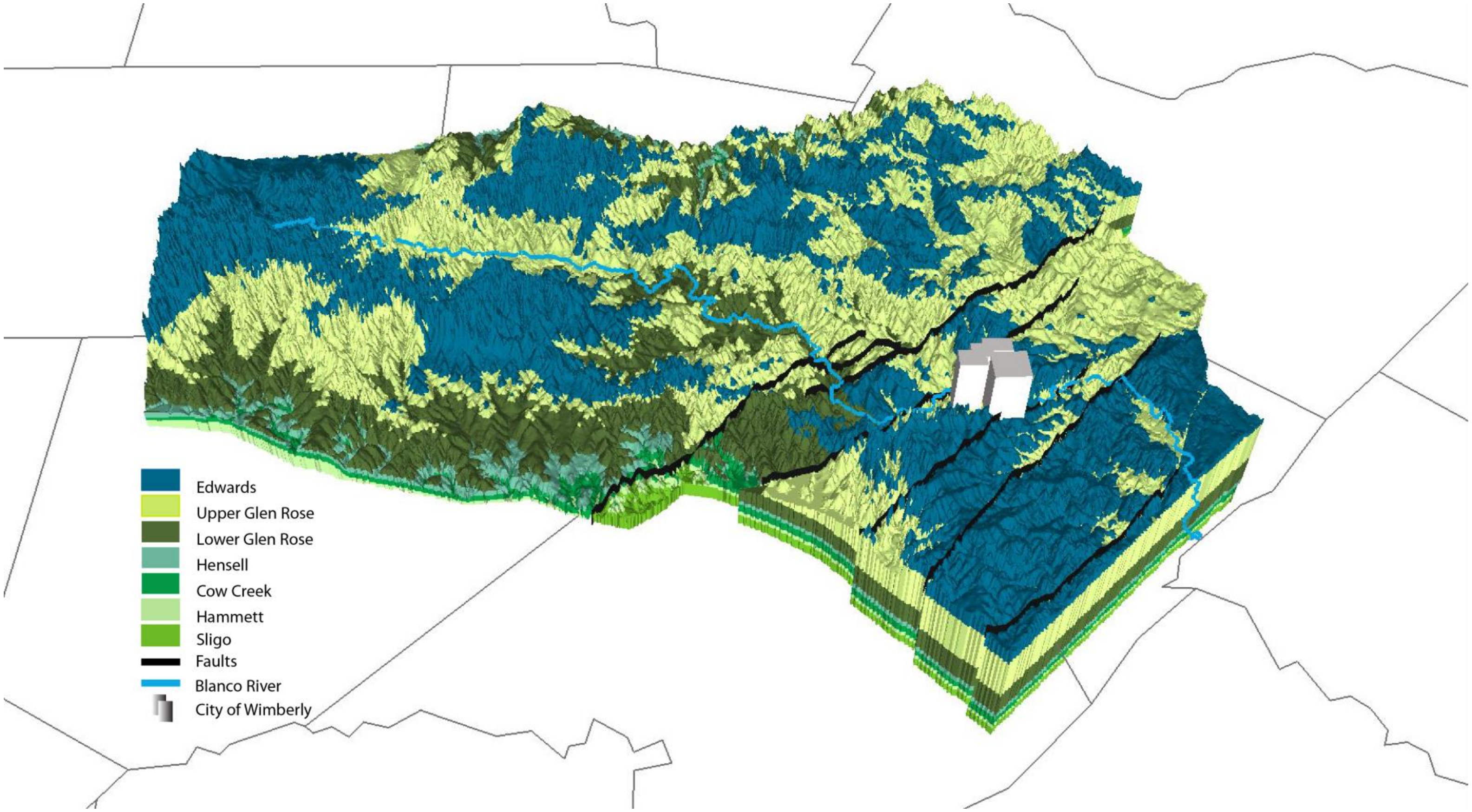


Figure 45: 3-D framework model result

The 3-D framework model is composed of GeoVolumes or multipatch geometries representing each framework unit in Table 2.

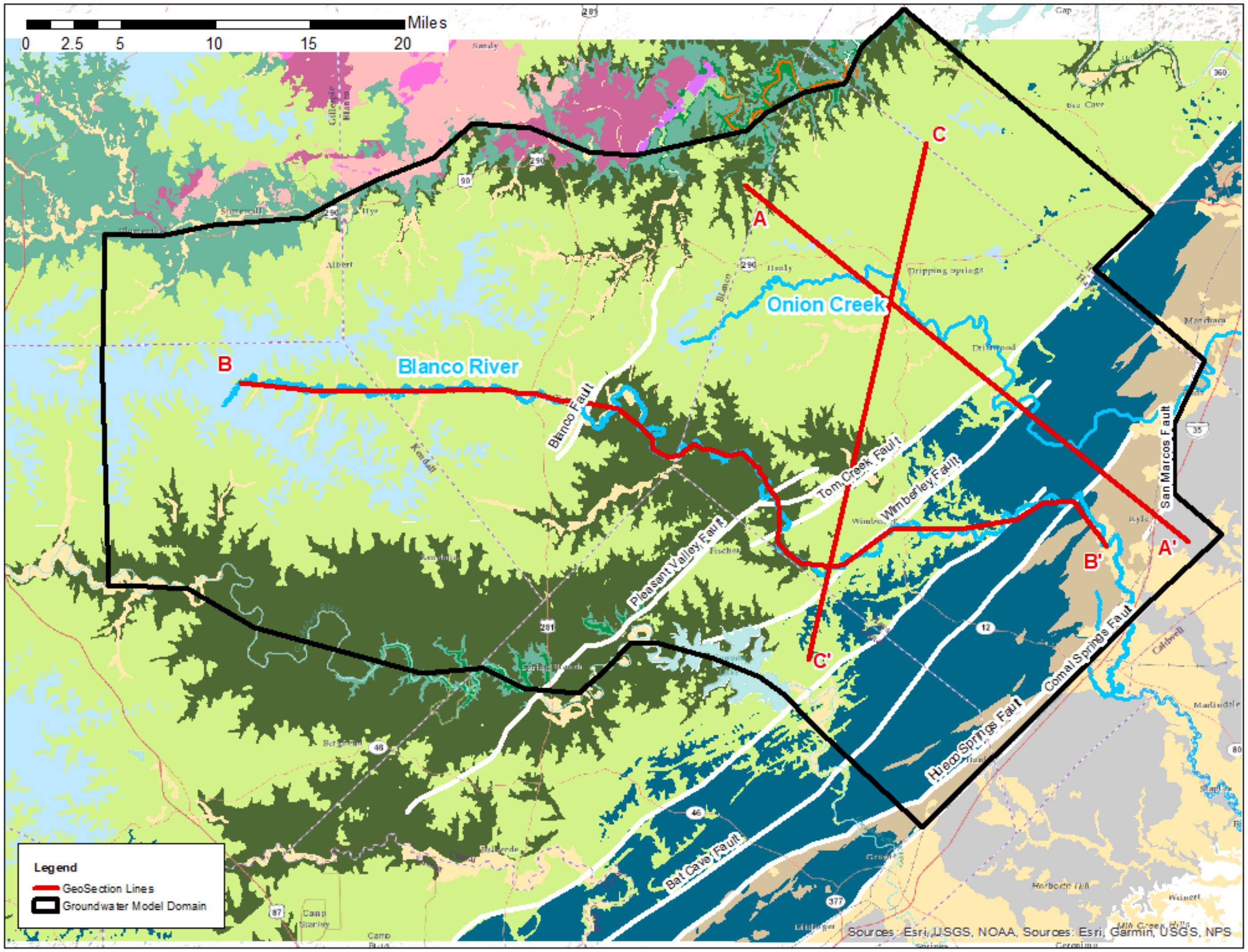


Figure 46: Plan-view layout of GeoSection lines

Section A

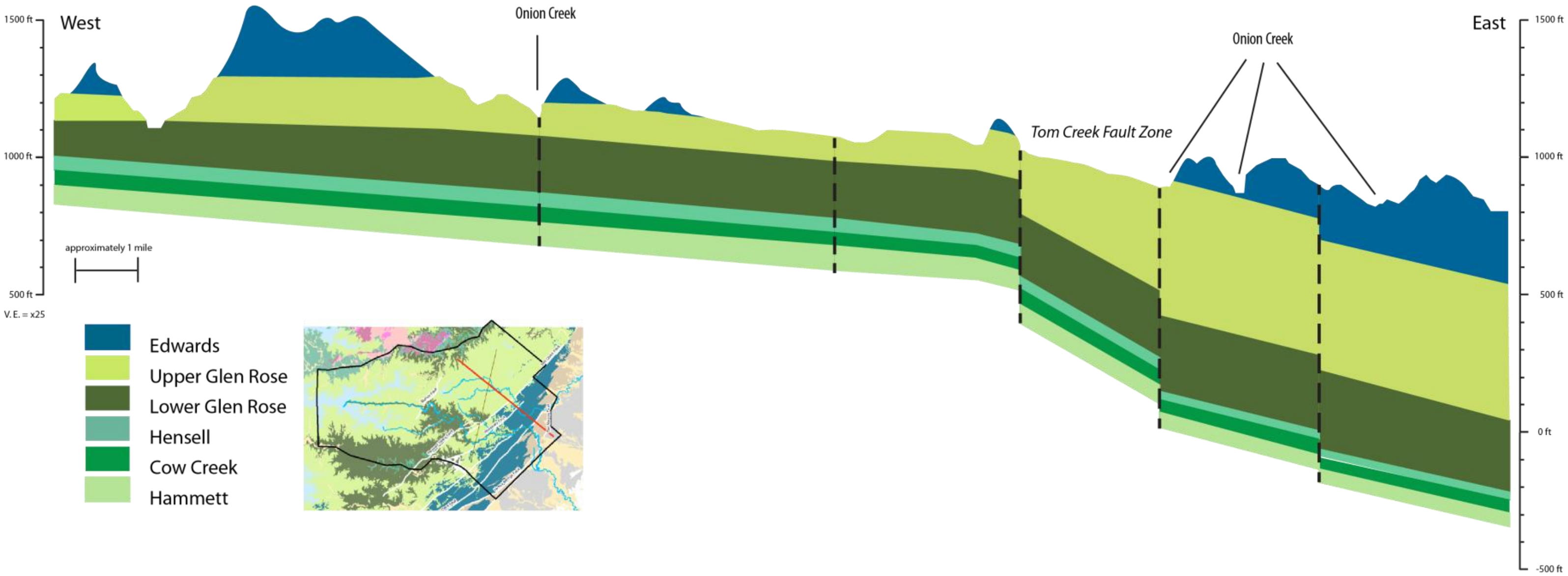


Figure 47: Framework GeoSection A-A'

GeoSection line through the northern part of the study domain: This is region of relatively large offset across the Tom Creek/Mount Bonnell Fault as shown in the section. The Edwards that is shown to the left of the Tom Creek Fault Zone is the Plateau Edwards.

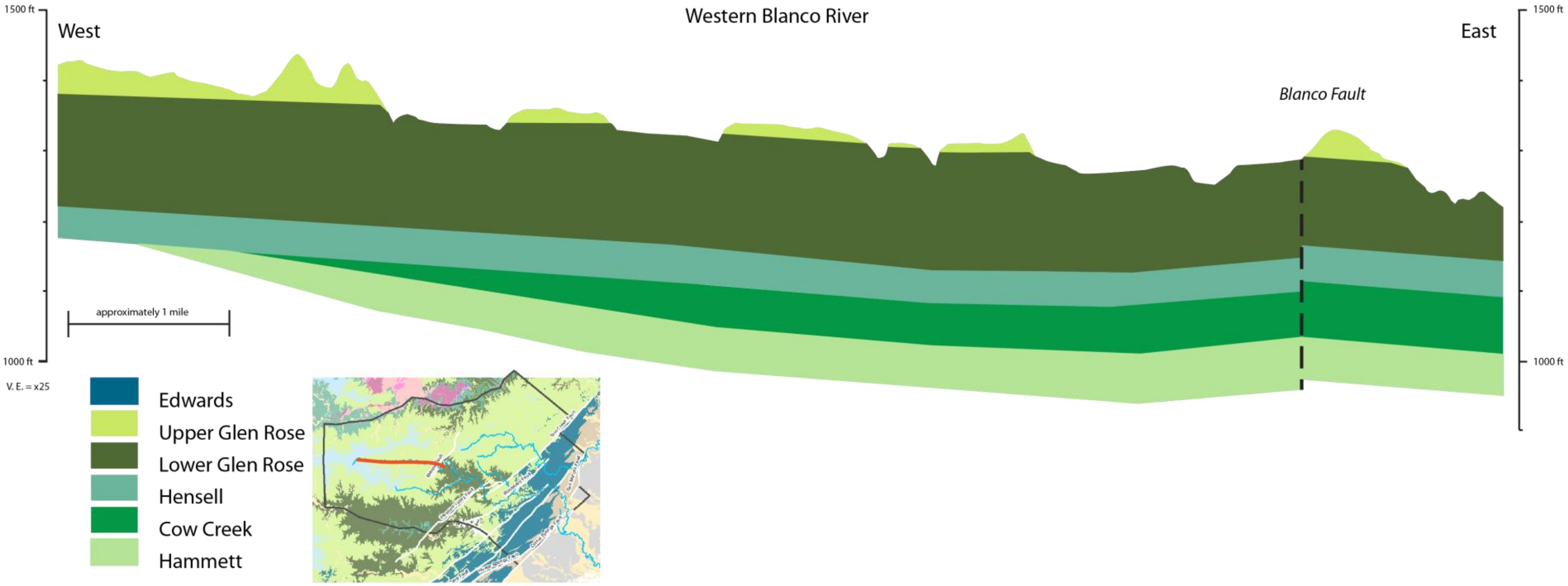


Figure 48: Framework GeoSection B-B', western segment

GeoSection line through the southern part of the study domain: the Tom Creek Fault location represents the western edge of the BFZ. Note that the Edwards on the right-side is the BFZ Edwards and the Edwards on the left side is the Plateau Edwards. Lower Glen Rose and Middle Trinity aquifers are exposed near the surface in the vicinity of the Blanco River. Offset across the Tom Creek Fault is relatively small in this area.

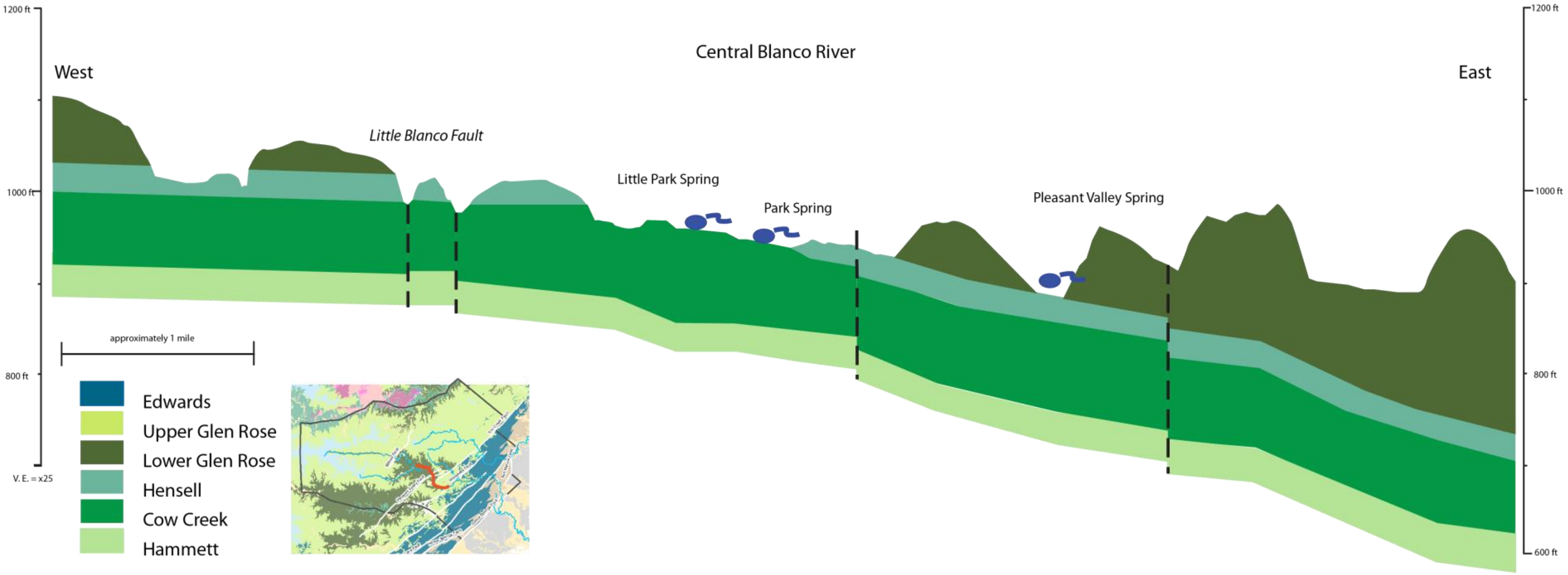


Figure 49: Framework GeoSection B-B', central segment

GeoSection line through the southern part of the study domain: the Tom Creek Fault location represents the western edge of the BFZ. Note that the Edwards on the right-side is the BFZ Edwards and the Edwards on the left side is the Plateau Edwards. Lower Glen Rose and Middle Trinity aquifers are exposed near the surface in the vicinity of the Blanco River. Offset across the Tom Creek Fault is relatively small in this area.

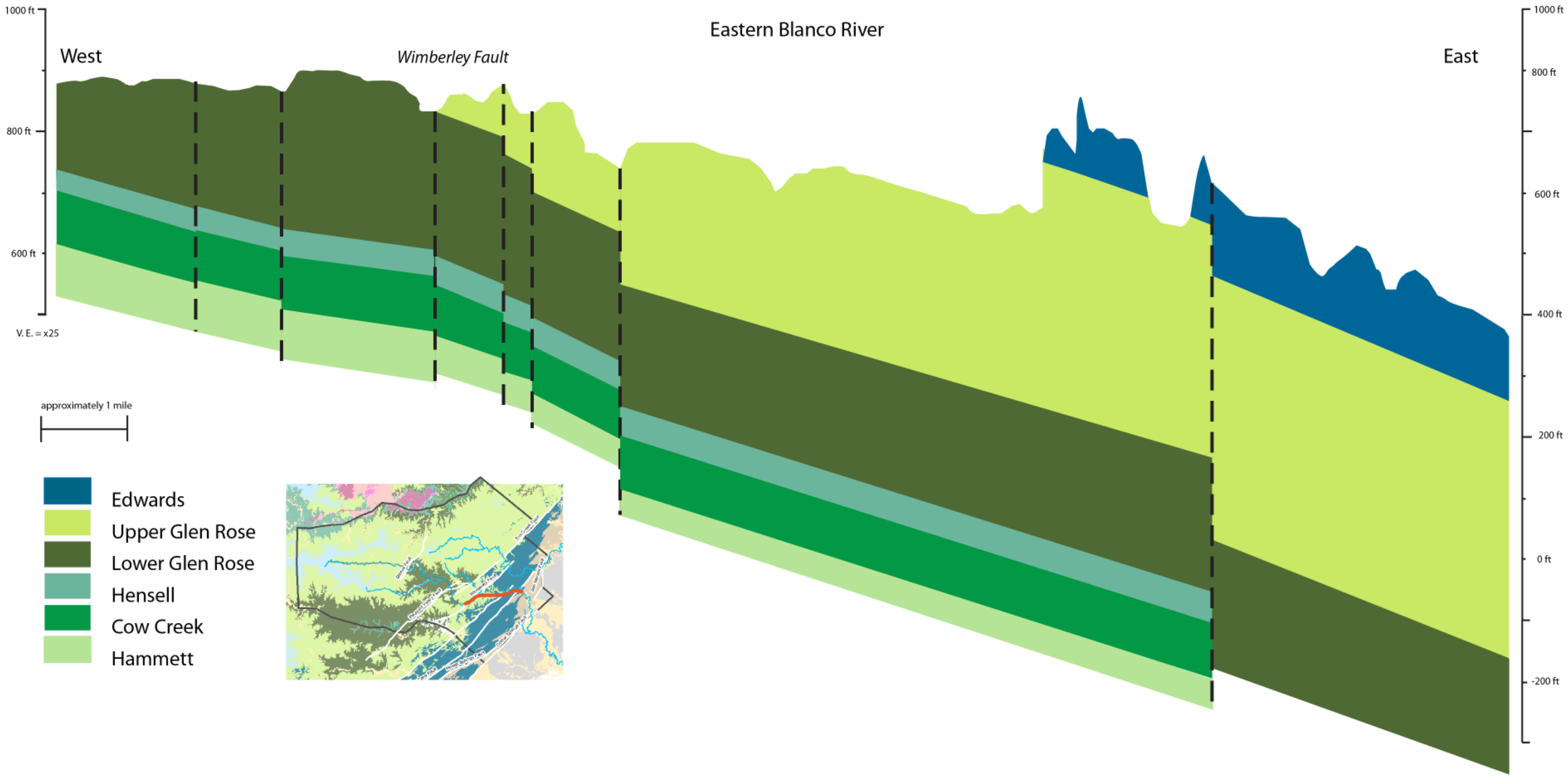


Figure 50: Framework GeoSection B-B', eastern segment

GeoSection line through the southern part of the study domain: the Tom Creek Fault location represents the western edge of the BFZ. Note that the Edwards on the right-side is the BFZ Edwards and the Edwards on the left side is the Plateau Edwards. Lower Glen Rose and Middle Trinity aquifers are exposed near the surface in the vicinity of the Blanco River. Offset across the Tom Creek Fault is relatively small in this area.

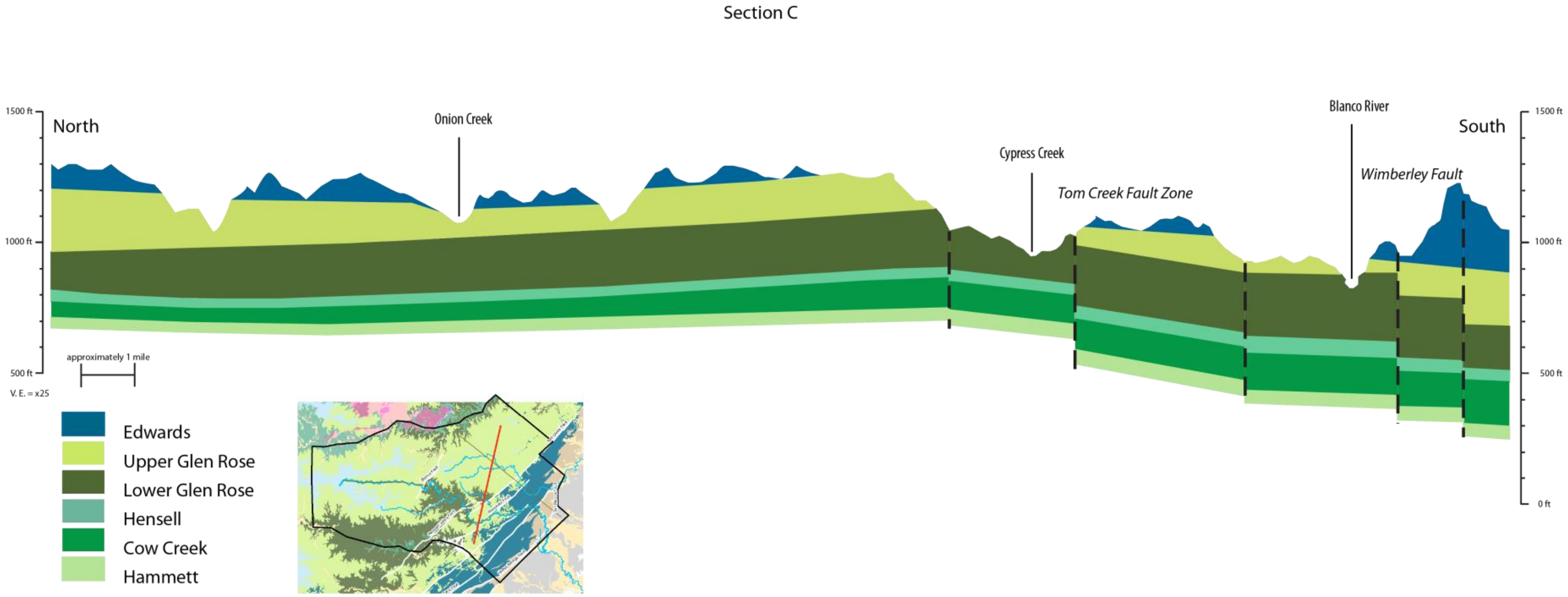


Figure 51: Framework GeoSection C-C'

This section runs from northeast (C) to southwest (C’) in approximately the center of the study domain. The Edwards shown here is Plateau Edwards in upland regions adjacent to Onion Creek. Faults are inferred in the locations shown by the dashed lines.

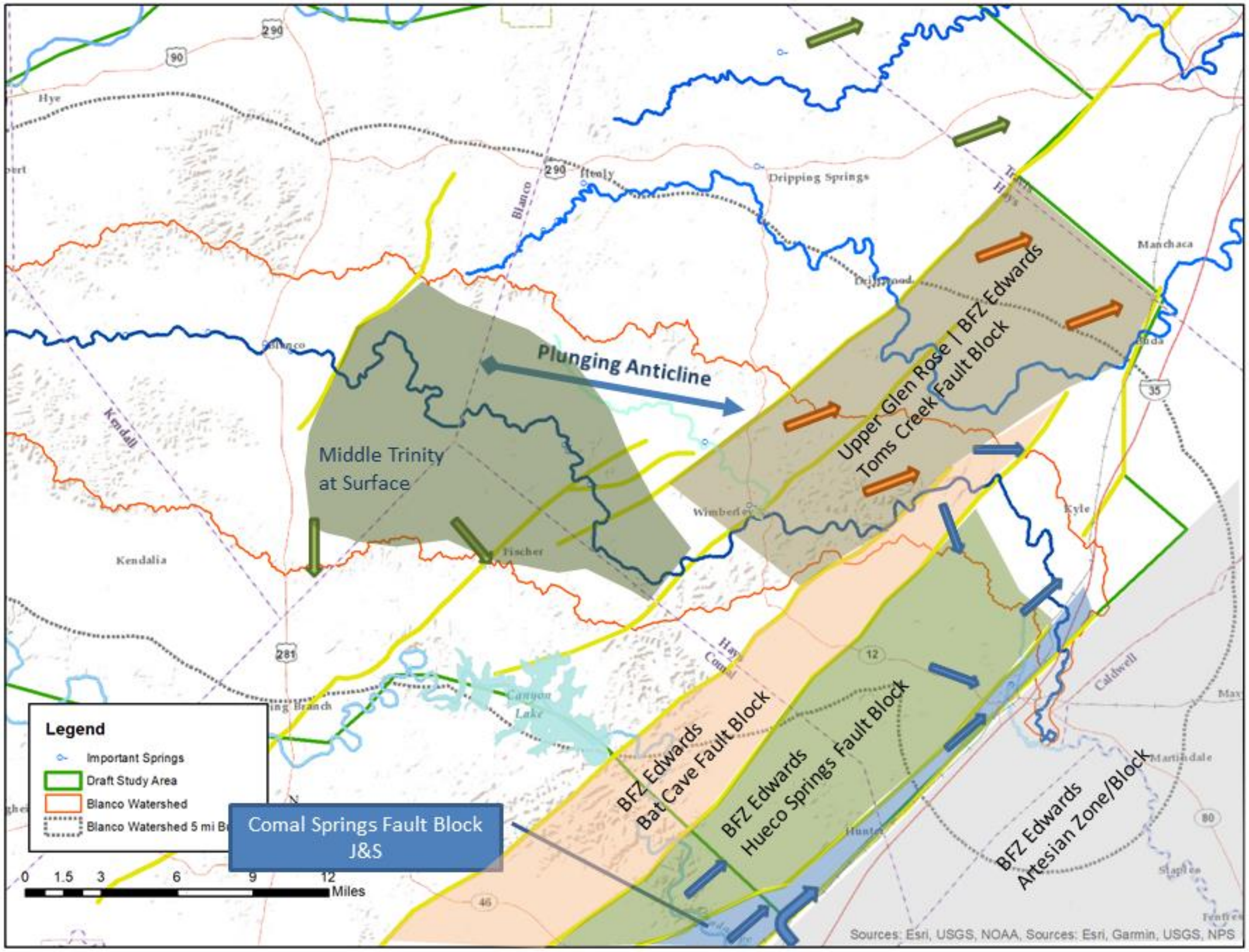


Figure 52: Conceptual fault blocks and structural features and the resultant expected flow directions

Green arrows represent Upper and Middle Trinity Aquifer flow directions; orange arrows represent BFZ Edwards, Upper and Middle Trinity Aquifer flow directions; and, blue arrows represent BFZ Edwards Aquifer flow directions.

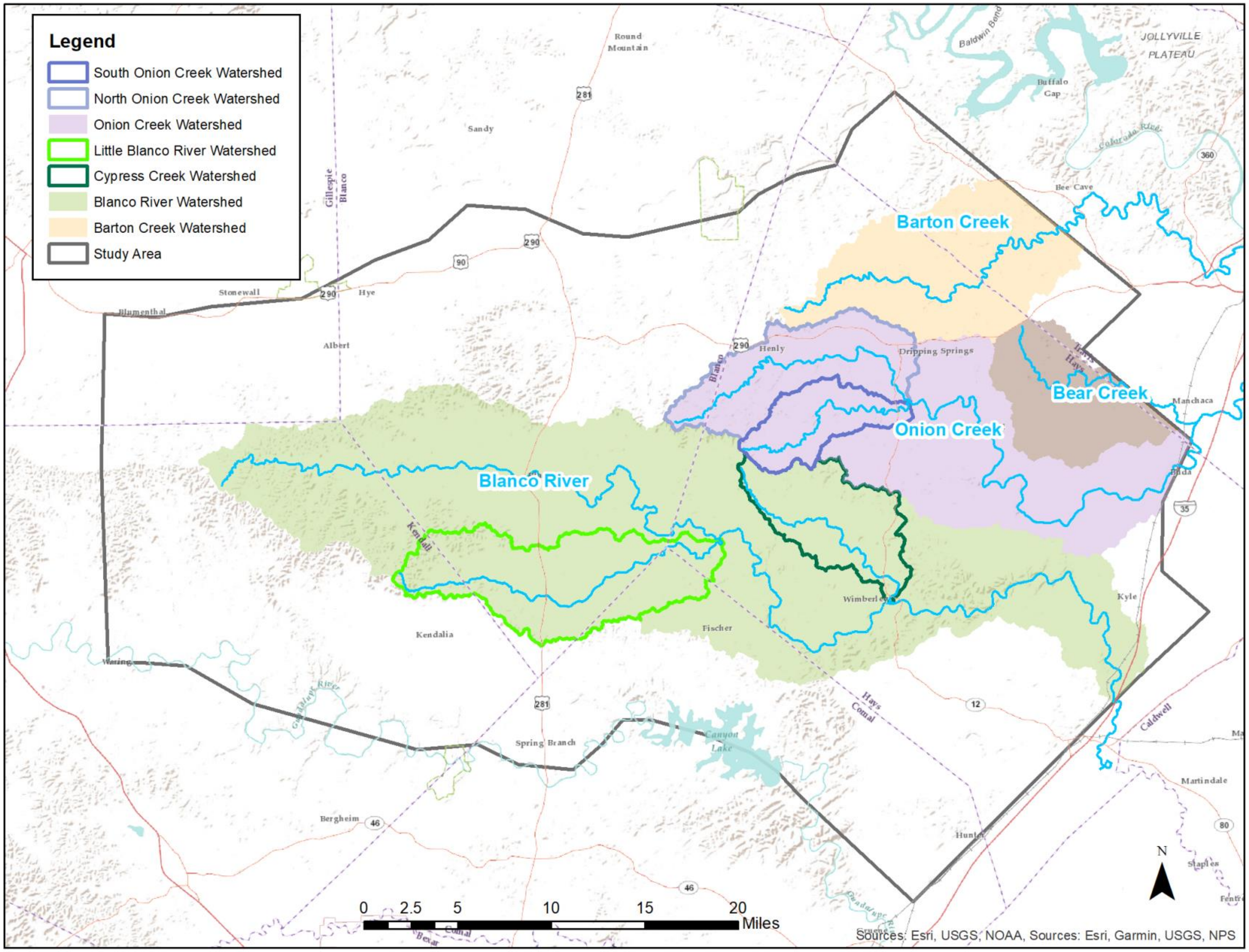


Figure 53: Watersheds and stream segments that will be explicitly simulated in the study area

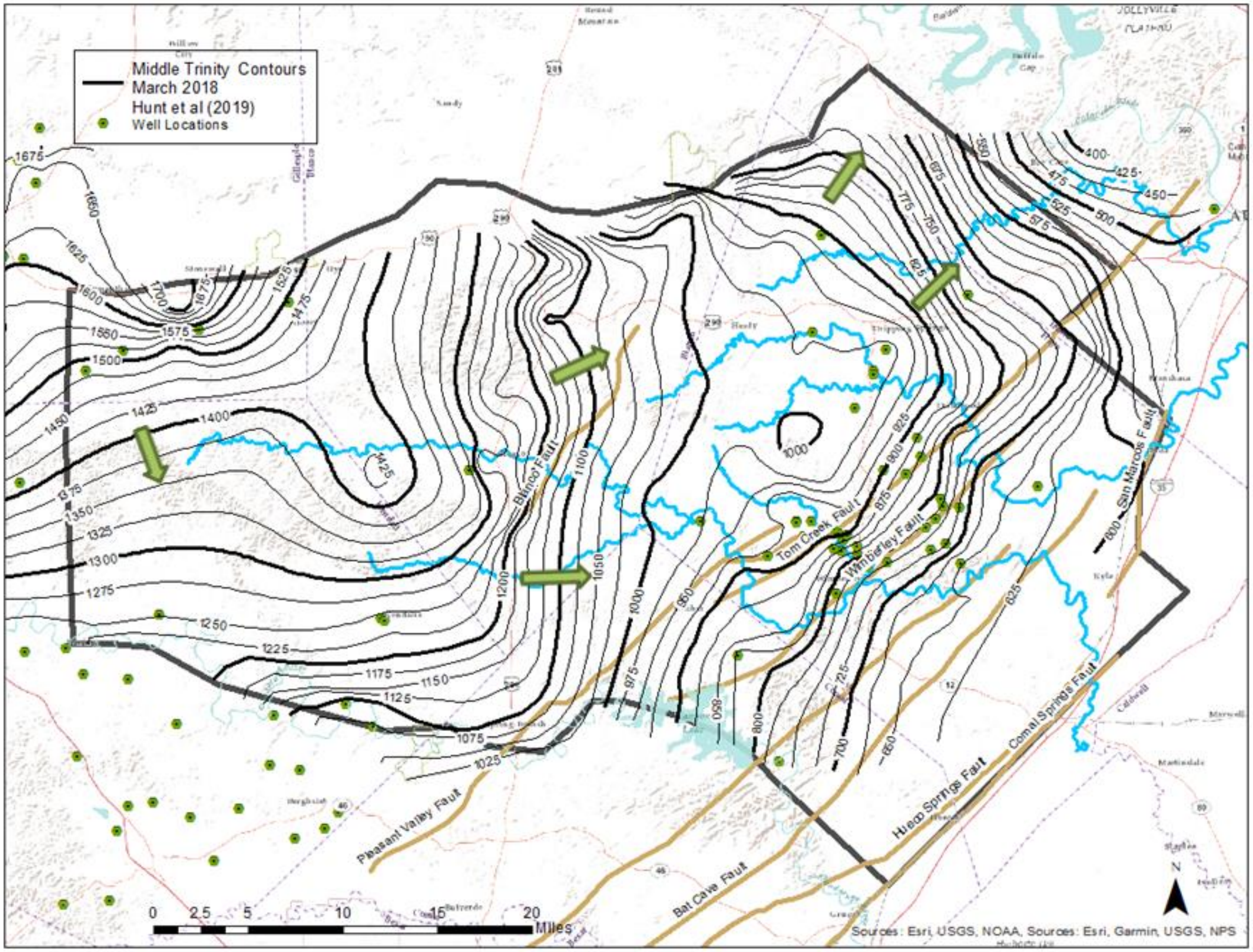
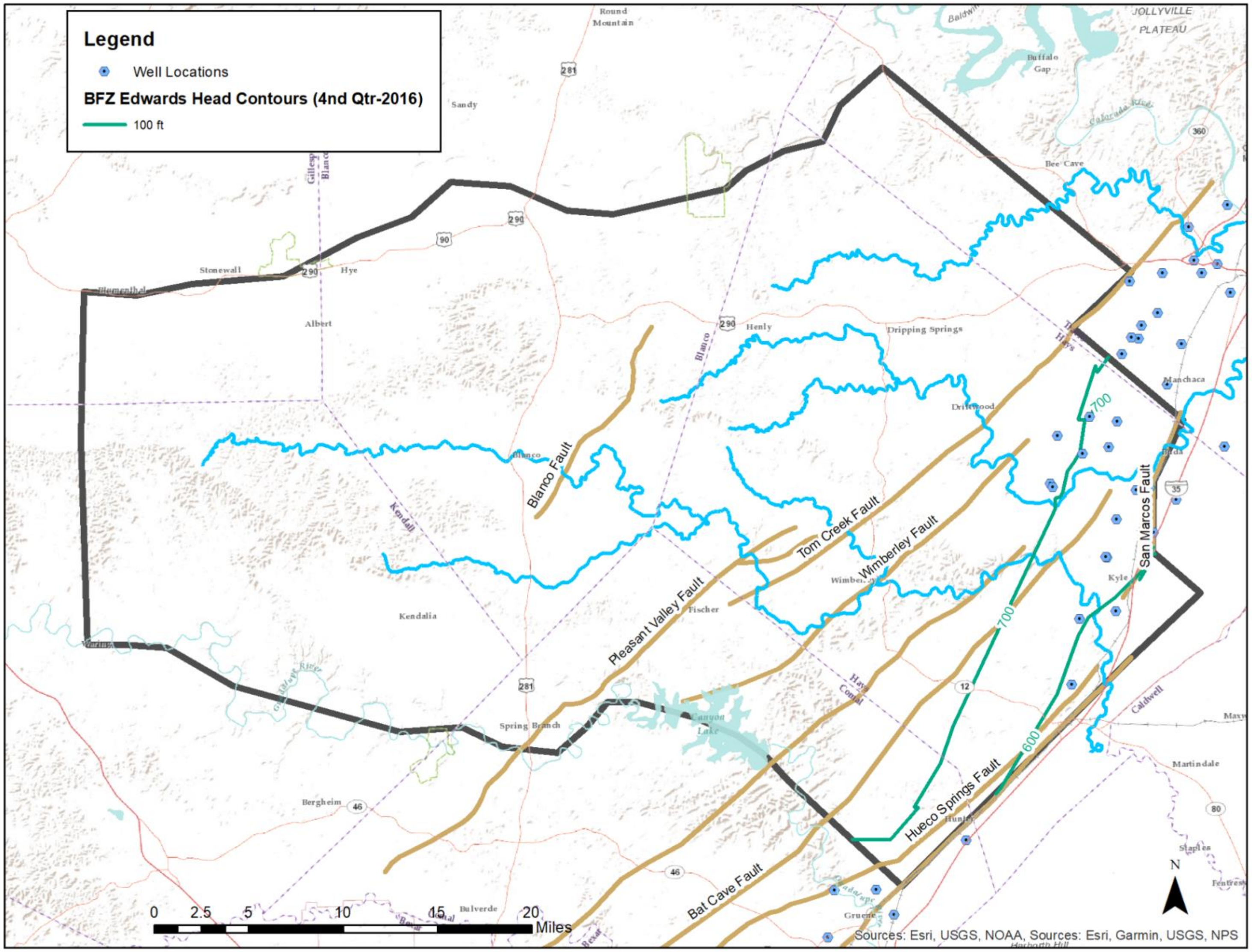


Figure 54: March 2018 Middle Trinity Aquifer Potentiometric Surface from Hunt et al. (2019)

Flow direction arrows are hand drawn to approximate regional patterns.



Sources: Esri, USGS, NOAA, Sources: Esri, Garmin, USGS, NPS

Figure 55: BFZ Edwards Aquifer potentiometric surface contours, 4th quarter 2016

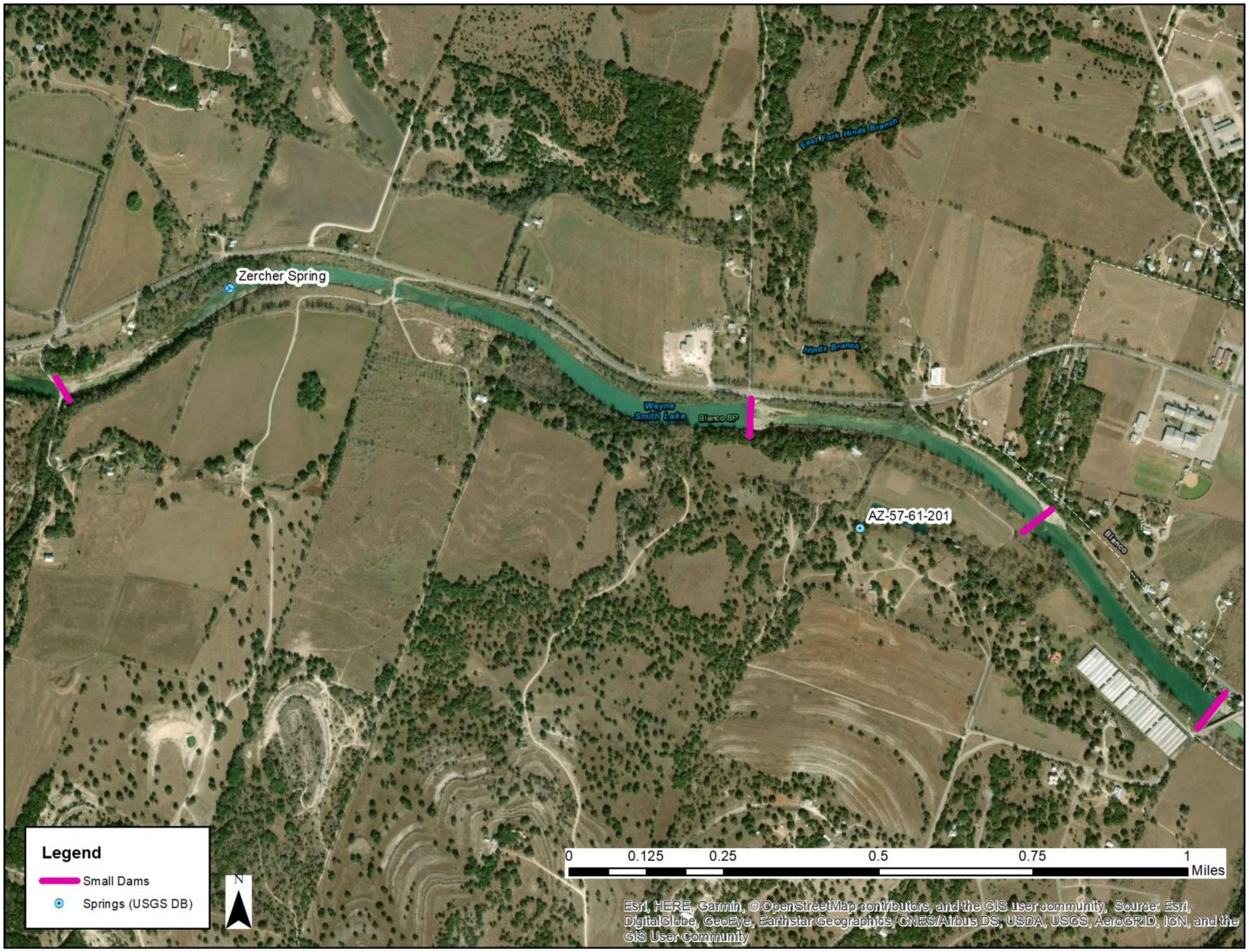


Figure 56: Check dams on the Blanco River, west of Blanco

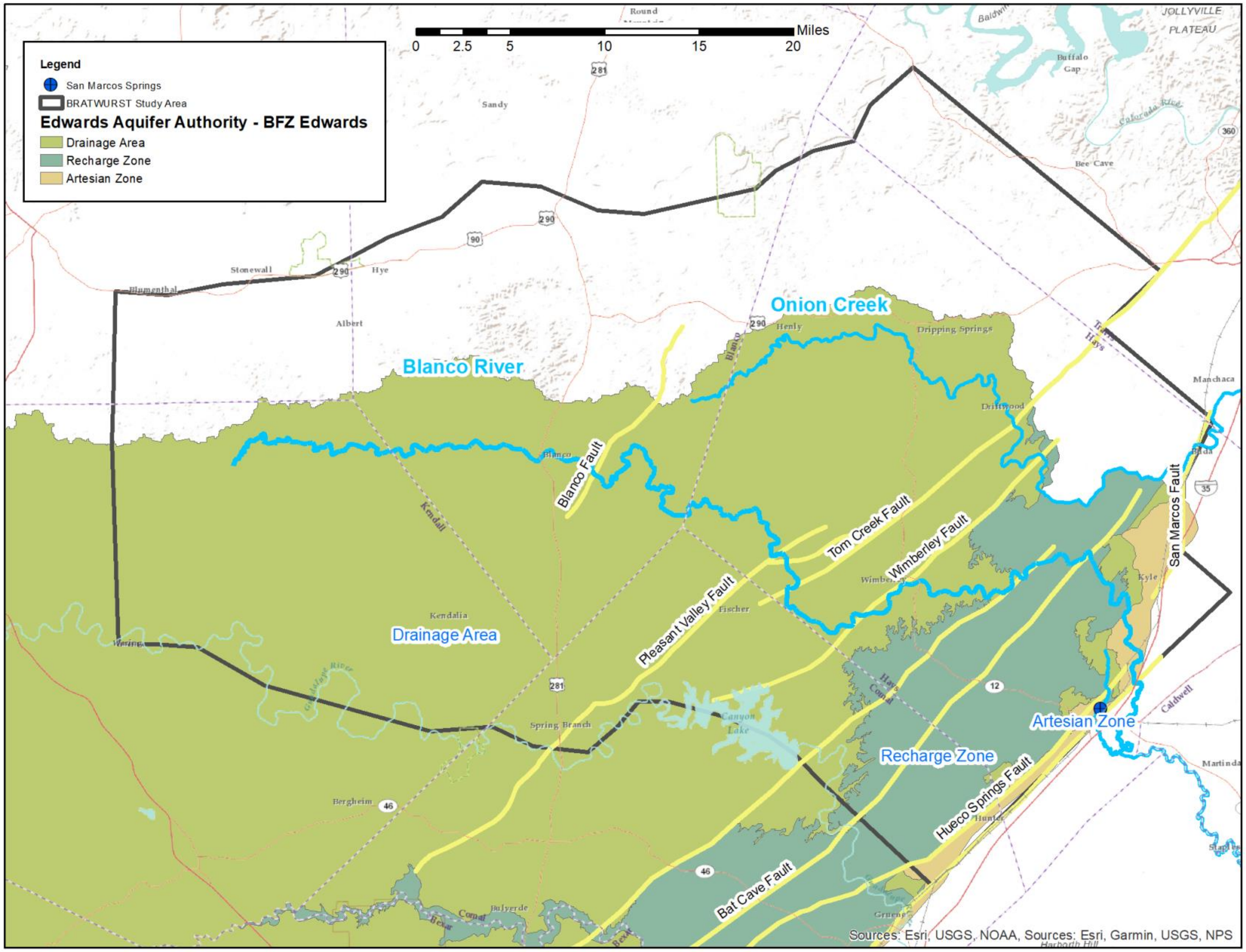


Figure 57: BFZ Edwards Aquifer recharge, artesian, and contributing zones

7 Conceptual Model

The conceptual model represents our understanding of the Blanco River system and how numerical computer models will be implemented to portray this understanding. Interaction between excess precipitation, water flowing in the rivers and streams, and water stored and conveyed in the subsurface is ubiquitous and complex in this system.

- Excess precipitation is precipitation less actual evapotranspiration and so represents the volume of water in the hydrologic cycle that is available for soil moisture content, groundwater recharge, and streamflow (Dunne and Leopold 1978).
- Evapotranspiration is total evaporation for a land area and is surface evaporation plus the water consumed by plants, or transpiration (Viesman and Lewis 2003).
- Evapotranspiration dominates the water balance of the watershed; more than 66% of the precipitation falling on the coterminous United States (CONUS) is lost to evapotranspiration and is not available for groundwater recharge, storage in the near surface, or runoff (Dunne and Leopold 1978).
    - A study area estimate is that evapotranspiration represents 85% of precipitation (Slade 2014).

Because of the importance and complexity of interaction between the water in the Blanco River and the water in the subsurface, conceptual and numerical models of the Blanco River system need to incorporate the full hydrologic cycle for the Blanco River watershed.

7.1 Overview

7.1.1 Integrated Hydrologic Modeling

Integrated hydrologic modeling means simulating the full hydrologic cycle in terrestrial environments where both surface- and subsurface water flow need to be represented. **Figure 58** displays a conceptual water-balance schematic for a watershed. In this schematic, runoff (both overland flow and groundwater runoff) feeds streamflow. Infiltration is the movement of water from the surface into the subsurface, and water that percolates through the unsaturated zone to saturated groundwater is recharge (Dunne and Leopold 1978).

The importance of surface water – groundwater interaction requires the conceptual model to account for both surface water and groundwater in some fashion and thus to treat the full hydrologic cycle in the study area. Computationally, the division or categorization of flow components in the hydrologic cycle into surface water and groundwater flow end members makes sense because the characteristics and driving forces of the two flow types are quite different. The derivation of both the groundwater flow equation and a surface water flow equation, like Reynolds-Averaged Navier Stokes (RANS), begins with the principle of conservation of mass and a representative control volume.

- Groundwater-flow equation: uses the representative elementary volume (REV) which is a control volume filled with geologic, or porous, media and water
- Surface water flow equations: use a control volume that is a homogeneous cube of water

Although the conceptual starting points for representing groundwater and surface water flow are similar, the derivations are completely different as are the media that fill the underlying control volumes. The requirement to link these two disparate flow representations, groundwater and surface water, means that integrated hydrologic modeling is necessarily more complex than dealing with either groundwater or surface water flow in isolation. However, the development of the disparate representations assuming conservation of mass, which just means that a water budget was used to develop the flow representations, provides common footing for integrating the two flow types.

As with all things complex, there are numerous ways to implement integrated hydrologic modeling and “types” of models. Freeze and Harlan (1969) provided a blueprint for fully-distributed, physically-based, numerical models utilizing partial differential equations to represent the full hydrologic cycle on the watershed scale.

- Fully-distributed: grid-based calculation method where each grid cell is assigned a unique collection of parameters to characterize the grid cell for flow calculations. Grid-cell size is dictated by both calculation methods and spatial variability in parameters as observed at the study site. Fully-distributed means that the model accounts directly for spatial variation in inputs or parameters and provides spatial variation in the solution or model responses.
- Physically-based: classical, or Newtonian, physics are used to derive mathematical equations that describe fluid flow from a first principles view point. These mathematical equations are of the differential equation class. Because a grid-based representation is employed, there are multiple spatial dimensions as well as changes over time; consequently, the differential equations are partial differential equations.

One of the original implementations of the Freeze and Harlan (1969) blueprint is the *Systeme Hydrologique Europeen* (SHE) which was commercialized by the Danish Hydraulics Institute as MIKE-SHE (Elizabeth et al. 2011). The Freeze and Harlan (1969) and SHE approach may be categorized as fully – integrated hydrologic modeling (Berg and Sudicky 2019).

A variety of models exist to simulate the full hydrologic cycle at the watershed scale that do not exactly conform to the Freeze and Harlan (1969) blueprint. These models include the USGS’s Precipitation-Runoff Modeling System (PRMS) (Markstrom et al. 2015; USGS 2019) and the Hydrological Simulation Program FORTRAN (HSPF) model (EPA 2018a) which is distributed by both the USGS and the EPA but is more actively developed and maintained as part of EPA’s Center for Exposure Assessment Modeling (CEAM) (EPA 2018b).

PRMS and HSPF do not fully conform to the blueprint because they employ lumped parameters or regionalization in the form of hydrologic response units (HRUs) and use physically-based relationships, which are not in partial differential equation form, in conjunction with empirical relationships. However, PRMS and HSPF still provide integrated hydrologic models in the sense that they simulate the full hydrologic cycle at the watershed scale; they just employ larger-scale grouping and less rigorous physics. Additionally, PRMS and HSPF are usually coupled to a 3-D groundwater flow model to provide enhanced capabilities to represent heterogeneity and complex flow patterns in the subsurface. This slightly less rigorous approach to integrated hydrologic modeling is referred to hereafter as “partially lumped, integrated hydrologic modeling”.

The “partially lumped, integrated hydrologic modeling” approach is recommended in conjunction with a 3-D groundwater flow model for BRATWURST. This slightly less rigorous approach is recommended for the following reasons.

- A relatively large (1,579 mi^2) study area has been selected and the ability to employ some degree of lumping will reduce the parameterization and computational burdens.

- Flood inundation mapping and simulation are <u>not</u> components of this study. Flood inundation mapping and detailed flood-wave simulation require relatively advanced and complex surface water modeling and a refined, 2- or 3-dimensional model grid for surface water simulations.
    - Because this is not a goal of this study, advanced surface water modeling and fully – integrated hydrologic modeling are not required.
    - Surface water flow (i.e. velocity fields) does not need to be simulated and hydrologic routing can be used.
        - Hydrologic routing is the calculation of discharge at points in time for a reach location and does not require a computational grid (Fread 1993).
- A "partially lumped" approach is sufficient for simulating gaining and losing river reaches, sub-watershed scale components of phreatic hydrostratigraphic units, relay ramps and fault block areas, and focused recharge mechanisms.

7.1.2 Recharge

Recharge is the groundwater-centric term for infiltration that percolates down to saturated groundwater. Implicit in this definition is that recharge is water that goes from the ground surface to storage in the aquifer. "Recharge can be defined generally as addition of water to an aquifer or, more strictly, addition of water from the overlying unsaturated zone or surface water body. **Diffuse** (direct) recharge refers to areally distributed recharge, such as from precipitation or irrigation over large areas, whereas **focused**, indirect, or localized recharge refers to concentrated recharge from surface topographic depressions, such as streams, lakes, and playas" (Scanlon et al. 2006, p. 3337). Hereafter, the following definitions are employed.

- **Diffuse** recharge: water from precipitation that infiltrates from the ground surface and percolates downward through the unsaturated zone to saturated groundwater
- **Focused** recharge: water, originally from precipitation but which goes to the overland flow component of the watershed water balance (see **Figure 58**), that reaches saturated groundwater from a focused source like a sink, swallet, fracture, or percolation directly from a stream in a localized area

Inter-formational flow is water that flows from one aquifer to another aquifer. It can be considered a type of recharge. For BRATWURST purposes, inter-formational flow is considered a distinct aquifer inflow category because it is represented solely in the groundwater domain of the hydrologic cycle and does not require direct linkage of, or interaction between, surface water and groundwater processes.

7.1.3 Land-surface processes

Integrated hydrologic modeling is complex. Adding to this complexity is the runoff or overland-flow component of the watershed water balance (see **Figure 58**). Overland-flow processes are typically lumped into the "surface water" category. **Figure 59** shows the three runoff processes that are typically considered.

- **Horton** overland flow: when precipitation intensity exceeds infiltration capacity water accumulates or pools on the surface and runs downhill (Dunne and Leopold 1978).

- **Saturation** overland flow (also called Dunne or Dunnian overland flow): when precipitation falls on already saturated areas, saturation overland flow occurs because the precipitation cannot infiltrate. Saturation can occur when there is groundwater return flow (see **Figure 59**) discharging to the surface and where low permeability horizons exist just below the topsoil (Dunne and Leopold 1978).
- **Interflow**: **Figure 59** displays this mechanism as subsurface stormflow (Dunne and Leopold 1978) which is a somewhat antiquated concept. Interflow is non-vertical flow through the unsaturated zone and is typically divided into “fast” and “slow” interflow (Markstrom et al. 2015).
    - “Slow” interflow is equivalent to diffuse, unsaturated zone flow where flow moves through porous media. It suggests slow transport processes and possibilities for interactions between water and media (Nimmo et al. 2017).
        - “Slow” or diffuse interflow can be associated with non-vertical flow components for diffuse recharge water. Not all interflow water goes to recharge but some fraction may go to recharge (i.e., saturated water storage in an aquifer) and the majority goes to stream flow.
        - “Slow” interflow processes are conceptualized with a REV, or a control volume filled with porous media.
    - “Fast” interflow is equivalent to preferential flow. “Preferential flow moves rapidly through narrow path-ways in disequilibrium with the surrounding matrix material, in contrast to slower diffuse flow, which moves through broad regions of matrix material. It can speed transport of contaminants through the unsaturated zone while exposing them to only a small fraction of the natural subsurface materials, thereby reducing the opportunity for chemical reactions and adsorption. Preferential flow commonly occurs due to elongated pores or fractures, fingering caused by flow instability, or heterogeneities at small or intermediate scales. It becomes more prevalent in situations of stratification, perching, heterogeneity, and geologic complexity {e.g. karst terrain and fractured rock} (Nimmo et. al. 2017, p. 444).” Preferential flow is complex and poorly understood (Pruess 1998; Nimmo et al. 2017).
        - Preferential flow can be associated with focused recharge. Not all preferential flow goes to recharge (i.e., saturated water storage in an aquifer). Some portions go to recharge and other portions to stream flow.
        - “Fast” interflow is conceptualized with control volume that is a homogeneous cube of water.

Examination of **Figure 59** highlights, schematically, that these three runoff processes are not strictly “surface water” processes but rather occur at and below the land surface interface and are associated with a variably saturated zone between the land surface inclusive and the water table, which represents the interface to saturated groundwater. Many land-surface models cover this domain, including climate-related inputs and processes, all the way to the deep soil zone. As noted earlier, an integrated hydrologic modeling approach to the study area requires addressing all three, distinct flow regimes.

1. Surface water
2. Land-surface processes
3. Groundwater

7.2 Conceptualization of regional flow

The combination of the understanding of regional groundwater flow patterns and the what-if questions that drive the need for an analysis tool determine the conceptual model foundation for BRATWURST. Regional flow patterns are controlled by surface water and groundwater interaction and by the two structural domains present in the study area. The structural domains are: 1) the eastern, dissected edge of the Edwards Plateau; and, 2) the BFZ.

An overview of conceptualization of regional flow in the study area is presented schematically in **Figure 60**, **Figure 61**, **Figure 62**, and **Figure 63**. **Figure 60** provides surficial geology and important losing stream reaches associated with the Middle Trinity and BFZ Edwards aquifers. Locations of concern for future groundwater pumping are shown in conjunction with Middle Trinity Aquifer potentiometric surface contours and important spring and surface water locations on **Figure 61**. **Figure 62** displays a conceptualization of surface water and groundwater interaction along the Blanco River similar to that presented on **Figure 1** and **Figure 63** provides hypothesized surface water interactions from the Blanco River in the south to Onion Creek in the north under different flow regimes.

The BFZ forms the eastern side of the study domain. Groundwater flow in this area is controlled by fault block and relay ramp structures (Johnson and Schindel 2008; Johnson et al. 2012; Smith et al. 2018). **Figure 64** displays a simplified conceptualization of the BFZ fault blocks used for BRATWURST along with the flow directions and patterns that will be enforced for these fault blocks using groundwater model boundary conditions. Flow in this area is generally from the southwest towards the northeast, parallel to the major faults in the "BFZ Region" (see **Figure 64**). At the northeastern-facing study area boundaries, groundwater flows from the four labeled fault blocks to the artesian block/zone of the BFZ Edwards Aquifer. Within the BFZ fault blocks, the primary recharge mechanism for the BFZ Edwards Aquifer is focused recharge (see **Figure 57**) including focused recharge from the Blanco River directly to the BFZ Edwards Aquifer in the recharge zone.

The central portion of the study area in **Figure 64**, "Middle Trinity – Focused Recharge Region," represents the transition between the two structural domains. This is the location of the horst block structure, which exposes the Middle Trinity Aquifer in the bed of the Blanco River. This region is identified in **Figure 64** as the area with primarily focused recharge but with secondary contributions from diffuse recharge. This region also hosts the reaches of Blanco River and Onion Creek that provide focused recharge to the Middle Trinity Aquifer. This region is also the part of BRATWURST that will generate insight into contributions of Blanco River water directly to the Middle Trinity Aquifer and indirectly to the San Antonio and Barton Springs segments of the BFZ Edwards Aquifer through inter-formational flow.

The western and northern-most portions of the study area coincide with the eastern, dissected edge of the Edwards Plateau. In these areas, the Upper, Middle, and Lower Trinity are the existent aquifers with the Middle Trinity Aquifer as the primary source of water. Diffuse recharge provides the primary recharge mechanism. The Middle Trinity Aquifer potentiometric surface provides a regional gradient from north to south which is interrupted by the plunging anticline structure which directs flow along the limbs either to the west, north-west, and perhaps the Colorado River, or to the south and the Guadalupe River and unknown points beyond.

Regional surface water flow patterns are equivalent to the stream network in the study area as shown on **Figure 53**. Surface water flow is completely dictated by topography and will follow the boundaries of the watersheds shown on **Figure 53**. The Blanco River, Little Blanco River, Cypress Creek, and Onion Creek are the primary streams of interest in the study area because of the identified groundwater –

surface water interactions associated with these water bodies. Runoff-flow patterns are also bounded by the watershed footprint. These processes depict the transitions and interactions between water on the ground surface and water in the saturated portions of the aquifers.

7.3 Model grid considerations

In the "partially lumped, integrated hydrologic modeling" approach, surface water features are represented with stream segments, reaches, and lakes. Surface and near-surface processes are simulated using Hydrologic Response Units (HRUs) which are lumped regions at the partial watershed scale. The 3-D groundwater model portion of the integrated hydrologic modeling approach is the portion that uses a computational grid.

The plan-view area of the study domain is relatively large (~ 1,580 mi^2) and the intent is to simulate groundwater flow across the entirety of this area. Two common approaches when dealing with large areas in a groundwater model are to vary the grid resolution by stretching the size of grid cells in areas located away from the primary focus area and to use two models. In the two-model approach, a coarse-resolution, regional model is used to provide boundary conditions for a focused area or local area model with a finely resolved grid. The single model stretched grid approach is preferred if feasible because there is generally less overhead with maintaining one model instead of two models. **Figure 65** displays the portion of the study area that was selected for highest resolution, finest grid representation. This is portion of the study area that is most important for obtaining model solutions to what-if questions related to focused recharge from the Blanco River and Onion Creek to the Middle Trinity Aquifer as well as possibilities of inter-formational flow from the Upper and Middle Trinity aquifers to the BFZ Edwards Aquifer.

In terms of vertical grid considerations for groundwater flow modeling, the controlling factor in the study area is the presence of large offset faults (e.g. offsets on the order of 100's of feet). This scale of vertical displacement means that it is not feasible to use hydrostratigraphic layers that are equal to computational grid layers because in the space of a few hundred feet, across fault zones, the elevation of the tops of hydrostratigraphic layers may vary by more than 100 feet. Instead, a vertical computational grid will be created and hydrostratigraphic zone identifiers assigned to model grid cells using the framework model (see Section **6.1**). Grid stretching can be employed in the vertical direction as well as in the horizontal directions.

7.4 Model boundary conditions

The selected modeling approach requires definition of boundary conditions of land-surface processes and for lateral edges of the groundwater flow computational domain. Because integrated hydrologic modeling is to be used, the model framework will inherently calculate groundwater-model, surface-boundary conditions like diffuse and focused recharge.

7.4.1 Land-surface processes

Topography is defined across the model domain as part of model creation and topography generates boundaries at watershed divides which are no-flow boundaries. At locations of surface water outflow from the model domain, water is removed from the model and it naturally flows out. The primary boundaries are then meteorological forcing or weather parameters. Typically, there are three categories of weather parameters that need to be specified in time series format.

1. Precipitation
2. Air temperature
3. Evapotranspiration: ET may also be calculated using one or more weather parameters depending on the calculation method selected.

The main channel of the Blanco River will be represented with stream segments including lake segments, if appropriate, to represent check dams and on-stream reservoirs. Stream segments will also be used to represent the following rivers and streams.

- Little Blanco River
- San Marcos River
- Cypress Creek
- Onion Creek (including South Onion Creek)
- Bear Creek
- Barton Creek

7.4.2 Groundwater flow model

The land-surface process representation in the integrated hydrologic approach will take care of fractioning precipitation into water available for recharge (both diffuse and focused) for the groundwater model within the watershed areas shown on **Figure 53**. Outside of these areas, recharge boundary conditions will be specified, but in these areas regional flow patterns will be enforced with lateral boundary conditions. Consequently, the boundaries of interest are the domain edge or lateral boundaries.

An important concept for groundwater flow model boundary condition definition is the concept of conductance. A specified reference head and conductance control the boundary condition flux for head dependent boundaries. This relationship is represented by Darcy's Law, equation (1), when the reference head is used to calculate the head change from inside the model to outside the boundary (h_{ref}), equation (3).

$$Q = k\frac{\Delta H}{L}A \quad \text{or} \quad Q = C\Delta H \tag{1}$$

Q = discharge or volumetric flow rate
ΔH = change in hydraulic head
A = cross sectional area

k = hydraulic conductivity
L = length or distance
C = conductance, equation (2)

$$C = \frac{k}{L}A \tag{2}$$

$$\Delta H = h_{ref} - h_i \tag{3}$$

h_{ref} = reference head

h_i = hydraulic head at model cell i

Natural hydrologic boundaries (e.g. rivers and relatively impermeable faults) were selected where possible. **Figure 66** provides a schematic depiction of the proposed boundary conditions. Natural boundaries include the following.

- Pedernales River in the north
- Guadalupe River in the south
- A series of faults that in the east that can be represented as barriers to flow

Table 18 provides a full suite of domain-edge, boundary conditions that are proposed for the groundwater model. For the eastern side of the study area, the goal is to reproduce the fault block/relay ramp flow patterns from **Figure 52**. For the western side of the study area, the goal is to reproduce approximately north to south flow that is evident in this area in potentiometric surface maps (e.g. see **Figure 54**).

Table 18: Groundwater model boundary conditions

Location	Layer	Type	Description
North	Top	River	Pedernales River: use approximate location because away from area of interest
	All others	No flow	
South	Top	River	Guadalupe River: use approximate location because away from area of interest
	All others	General Head Boundary (GHB)	Reference head from **Figure 54** to allow water to flow out of the simulation domain
West	All layers	No Flow	Based on typical Middle Trinity Aquifer contours from **Figure 54**
Northeast	All layers	GHB	Set reference head and conductance to easily permit flow out of the domain parallel to the Mount Bonnell/Tom Creek Fault
East	All layers	GHBs – relative barrier	For large offset normal faults that provide block boundary, set low conductance to force flow parallel to the boundary faults (Mount Bonnell/Tom Creek, Hueco Springs/ San Marcos, Comal)
	All layers	GHBs – relatively conductive	Set reference head and conductance to force water out of the domain along "ramps" or blocks.

7.5 Discussion of recharge/discharge mechanisms

Figure 64 and **Figure 59** identify the recharge mechanisms that are important in various regions of the study area. Focused recharge is expected to be dominant for the BFZ Edwards Aquifer. In prior water-budget analysis in the northeastern portion of the study area, Slade (2014) found that focused recharge within the 6 major streams crossing the recharge area for the Barton Springs segment of the Edwards Aquifer accounts for 75% of total recharge. The remaining 25% is attributed to overland flow or tributaries to the major streams and so is also focused recharge. This means that diffuse recharge is negligible in this region. Focused recharge accounted for 6% of average annual precipitation and streamflow/runoff leaving the water-budget area accounts for 9% and evapotranspiration accounts for 85%.

In the “Middle Trinity – Focused Recharge Region” of **Figure 64**, focused recharge is expected to be dominant with diffuse recharge of secondary importance. Moving to the western- and northern-most portions of the study area, diffuse recharge will be the dominant recharge mechanism in BRATWURST. Wierman et al. (2010) describe diffuse recharge mechanisms for the western portion of the study area where the Upper Trinity Aquifer units are exposed at the surface.

7.6 Conduit/diffuse flow

The Middle Trinity and BFZ Edwards aquifers are both karst aquifers. Karst aquifers have three types of porosity:

1) Porosity of rock matrix or primary porosity;
2) Fractures and bedding planes which provide common rock discontinuities provide secondary porosity; and,
3) Solutionally enlarged voids, i.e. channels and conduits, which are developed from the common rock discontinuities (Kresic 2010a).

Many groundwater models traditionally lack the capability of physically-based simulation of triple porosity systems because of the reliance on an equivalent porous media (EPM) approach (Kresic, 2010b). The EPM approach uses a REV control volume filled with porous media and works well for primary porosity and can be adapted to secondary porosity. However, an EPM cannot satisfactorily reproduce conduit flow which is physically similar to pipe network flow and surface water flow, where the control volume is filled with homogeneous fluid rather than geologic media.

Conduit flow is also one of the types or mechanisms of “fast” interflow, or preferential flow, discussed in Section **7.1.3**. Interflow is a near-surface process which occurs in the variably saturated zone. Conduit flow is a more general term in that it applies equally to the variably saturated and saturated zones. In fully saturated regions, conduit flow may be pressurized. The conduit flow process (CFP) module can be used with the MODFLOW-2005, EPM model to satisfactorily simulate conduit flow (Kresic 2010b). Additionally, MODFLOW-USG contains the Connected Linear Network (CLN) Process which is also suitable for simulation of karst conduits (Panday et al. 2013).

Capabilities for representation of conduit-flow processes are required in BRATWURST if the model will be used to test hypotheses with a direct relation to conduit flow. Potential impacts of Middle Trinity Aquifer pumping to spring discharge from Jacob’s Well Spring, which is a known cave and conduit system, provide a target hypothesis that will require the capability to represent conduit flow (Gary et al. 2019).

7.7 Water Budget

A simple watershed water-budget calculation was made for the Blanco River watershed at three USGS gauging stations from **Table 12** using the average annual precipitation depth shown on **Figure 34**. The water-budget calculation uses equation (4) applied across the watershed area for a gauging station.

$$P - AET = RO + Re \qquad (4)$$

P = precipitation
AET = actual evapotranspiration
RO = runoff (streamflow used as an estimate)
Re = recharge to aquifers

In equation (4), there are two unknown quantities, actual evapotranspiration (AET) and recharge (*Re*). If values for AET are assumed, then an estimate for recharge (Re) can be calculated. **Table 19** provides water-balance calculations assuming the following values for AET.

1. 85% of precipitation (Slade, 2014)
2. 75% of precipitation (an arbitrary middle value)
3. 66% of precipitation (Dunne and Leopold, 1978)

For USGS 08170950 “Blanco River nr Fischer”, there are only three years of data. As a result, the “Average Annual Discharge” value for this station is the annual average across 2017-2018, which tend to be a relatively low discharge years at the other two stations. Consequently, the values for USGS 08170950 are shown for reference but there is limited confidence in these values given the short data record.

In equation (4) and **Table 19**, it is assumed that measured streamflow at a point location represents only surface water runoff from precipitation falling on the surface of the watershed. Thus, negative values of net recharge denote net aquifer discharge to the Blanco River. It is possible that springsheds for springs feeding the Blanco River extend beyond the Blanco River watershed boundaries and in this case spring discharge to the Blanco River would represent some amount of transfer of water from outside the watershed to the river.

In actuality, measured streamflow represents all of the following components.

1. Runoff from precipitation falling on the watershed
2. Focused recharge from the stream to underlying aquifers
3. Discharge from groundwater to the stream in gaining reaches
4. Extractions of water from the stream to meet surface water rights
5. Return flows from agricultural, commercial, and industrial consumption

Under the assumption of streamflow equal to surface runoff, only items #1 and #2 above are explicitly accounted for in the water balance. The calculations in **Table 19** provide the following water budget summary for the Blanco River watershed.

- Actual evapotranspiration (AET): 66 to 85% of precipitation
- Surface water runoff (RO): 19 to 21% of precipitation
- Recharge (Re): -6 to 6% of precipitation

Table 19: Watershed water-budget calculations

AET	85%									
Station ID	Area	Annual Precipitation [in]		Annual Excess Precipitation (P - AET)	Average Annual Discharge (RO)			Net Recharge (Re)		
	[acre]	Average (P)	Net (P - AET)	[acre-in]	[acre-in]	[in]	[%]	[acre-ft]	[in]	[%]
08171300	263,680	33.4	5.0	1,320,603	1,810,176	6.9	21%	-40,798	-1.9	-6%
08171000	227,200	33.4	5.0	1,137,898	1,470,546	6.5	19%	-27,721	-1.5	-4%
08170950*	172,160	33.4	5.0	862,238	676,503	3.9	12%	15,478	1.1	3%

AET	75%									
Station ID	Area	Annual Precipitation [in]		Annual Excess Precipitation (P - AET)	Average Annual Discharge (RO)			Net Recharge (Re)		
	[acre]	Average (P)	Net (P - AET)	[acre-in]	[acre-in]	[in]	[%]	[acre-ft]	[in]	[%]
08171300	263,680	33.4	8.3	2,201,005	1,810,176	6.9	21%	32,569	1.5	4%
08171000	227,200	33.4	8.3	1,896,497	1,470,546	6.5	19%	35,496	1.9	6%
08170950*	172,160	33.4	8.3	1,437,064	676,503	3.9	12%	63,380	4.4	13%

AET	66%									
Station ID	Area	Annual Precipitation [in]		Annual Excess Precipitation (P - AET)	Average Annual Discharge (RO)			Net Recharge (Re)		
	[acre]	Average (P)	Net (P - AET)	[acre-in]	[acre-in]	[in]	[%]	[acre-ft]	[in]	[%]
08171300	263,680	33.4	11.4	2,993,367	1,810,176	6.9	21%	98,599	4.5	13%
08171000	227,200	33.4	11.4	2,579,236	1,470,546	6.5	19%	92,391	4.9	15%
08170950*	172,160	33.4	11.4	1,954,407	676,503	3.9	12%	106,492	7.4	22%

*Average annual discharge only for 2017-2018 because of data limitations; these years are relatively low flow at other stations.

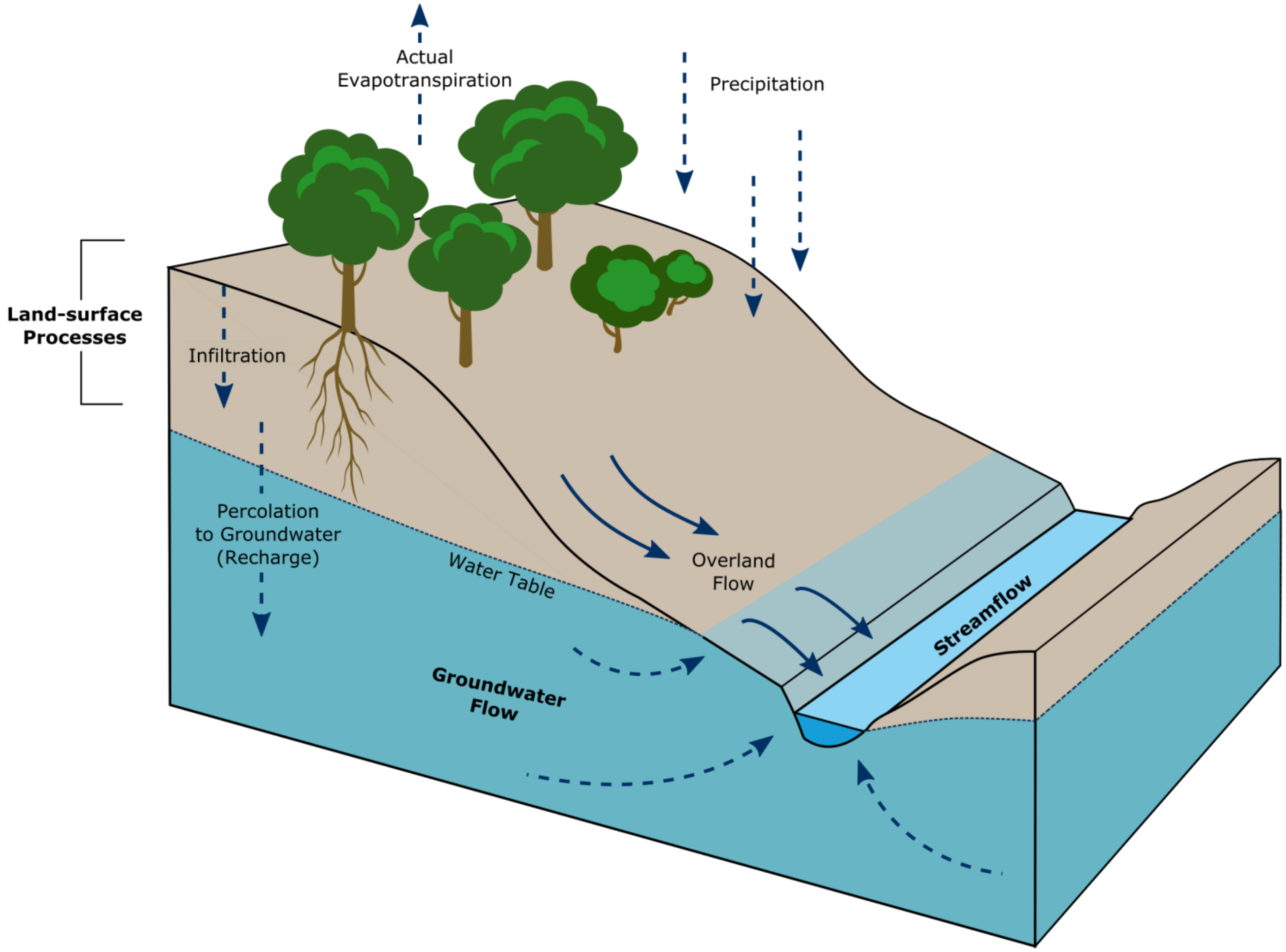


Figure 58: Simplified watershed water balance components after Dunne and Leopold (1978)

Land-surface processes include overland flow and infiltrated water that moves non-vertically as shown in Figure 61. Actual Evapotranspiration (AET), Precipitation (P), Infiltration (I), Overland Flow (OF) = Runoff (RO)

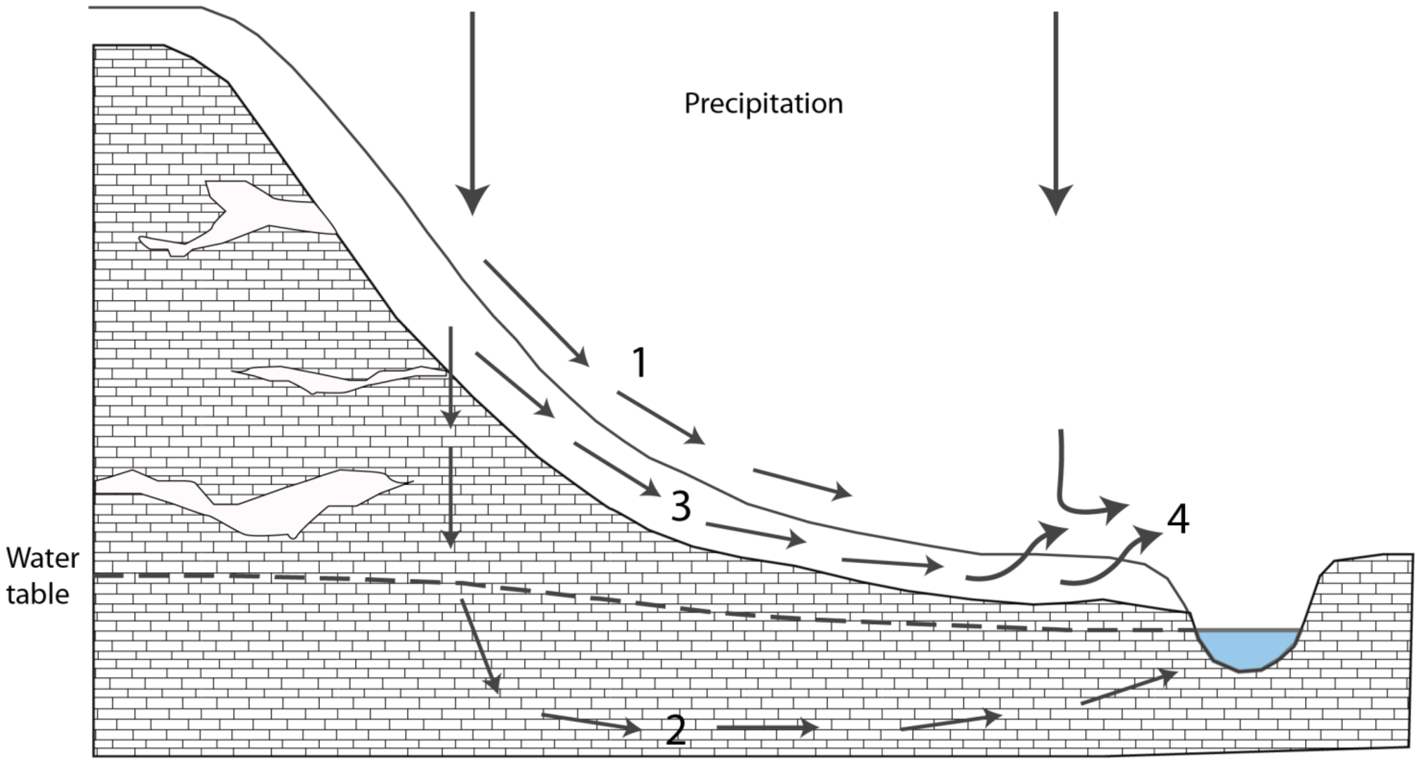


Figure 59: Description of land-surface processes after Dunne and Leopold (1978)

This figure represents the possible paths of water moving downhill in a watershed.

***Path 1*: Horton overland flow**

***Path 2*: Groundwater flow showing groundwater runoff, which is water that infiltrates to groundwater but is discharged to streamflow within the catchment**

***Path 3*: Interflow or shallow subsurface stormflow - this is water that infiltrates and then flows non-vertically and does not become part of saturated groundwater storage**

***Path 4*: Saturation overland flow – composed of direct precipitation on saturated area plus infiltrated water that returns to the ground surface without joining regional saturated groundwater**

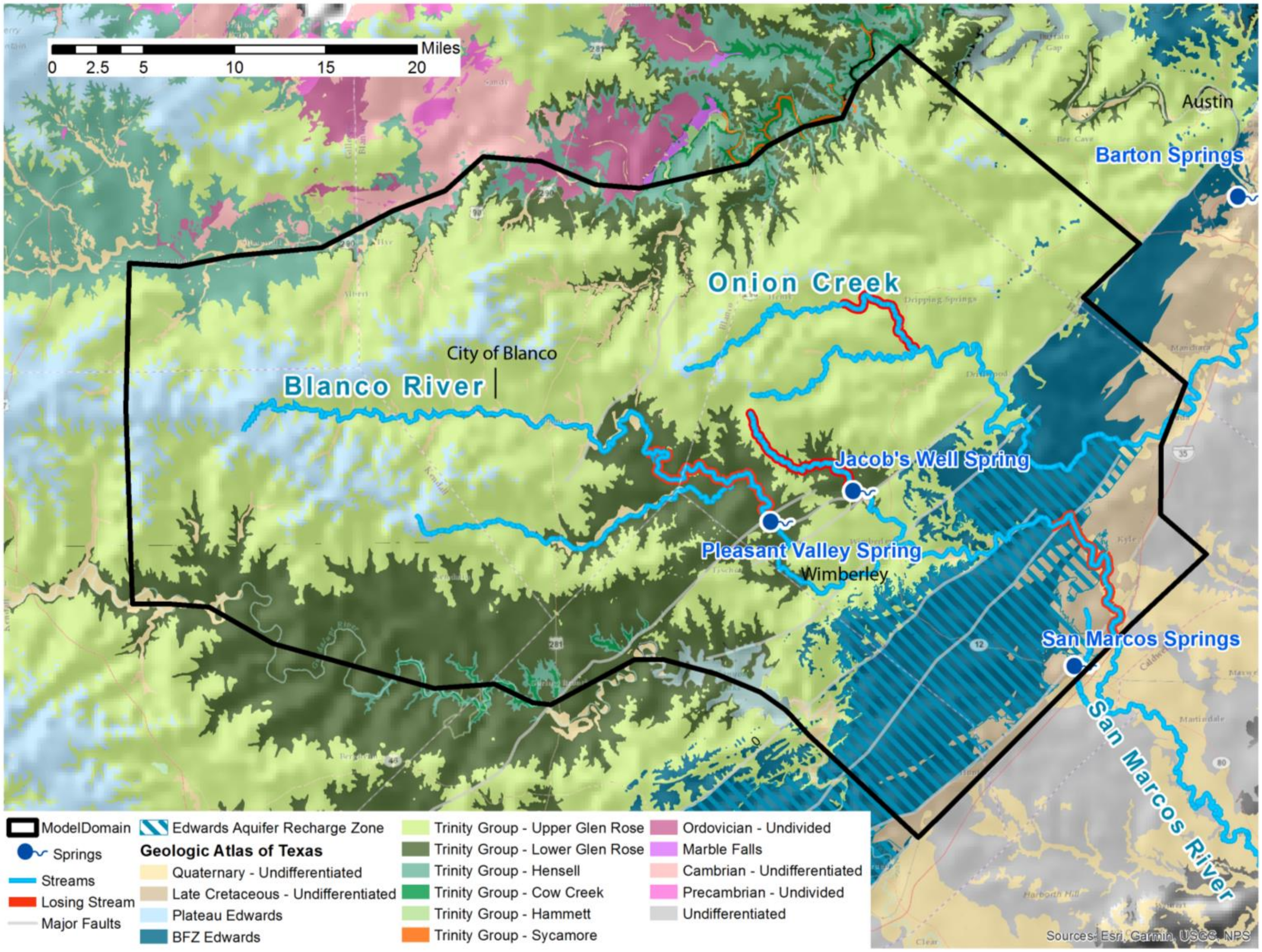


Figure 60: Plan view of the study area highlighting conceptual model considerations

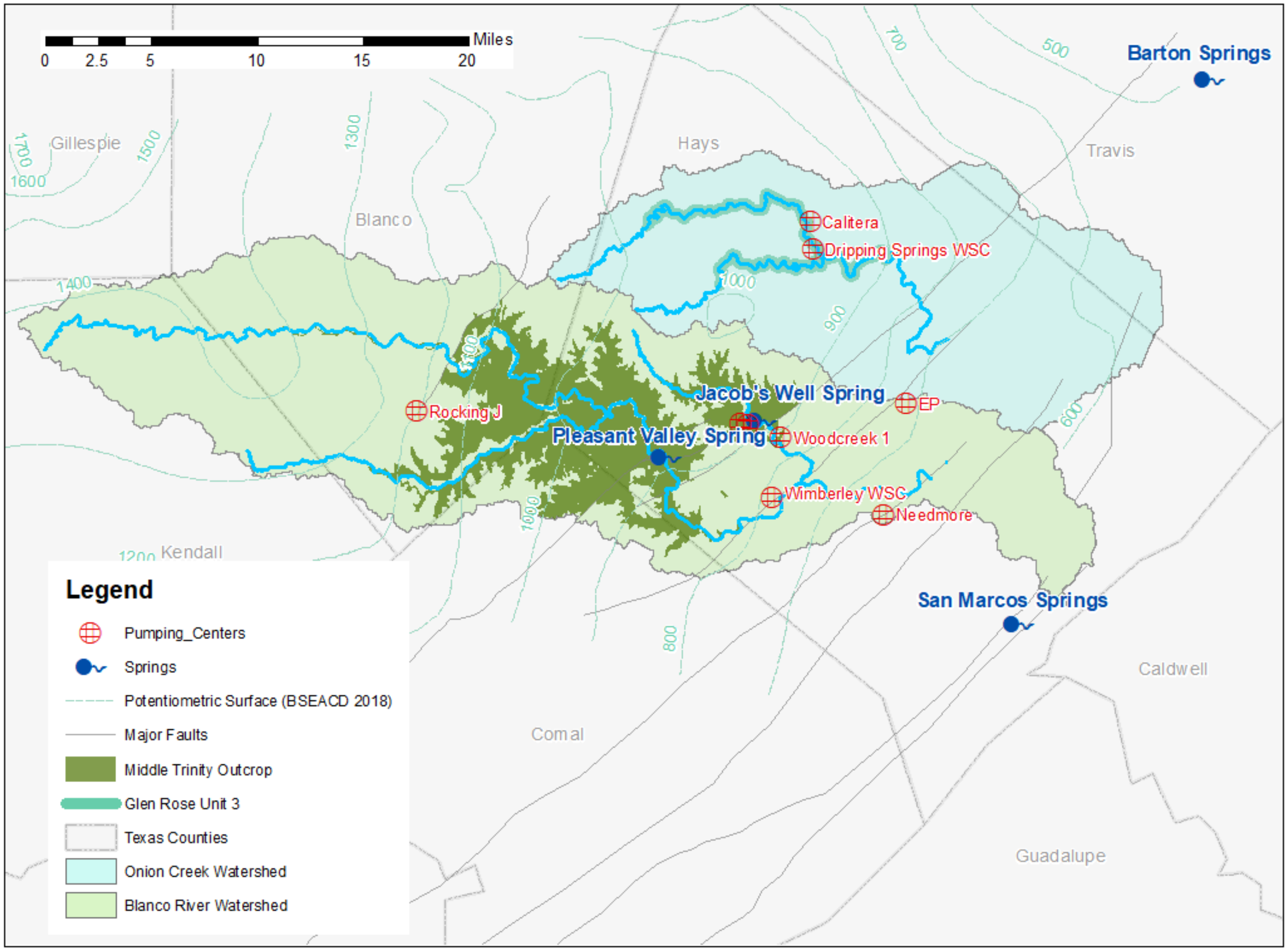


Figure 61: Plan view showing important Middle Trinity Aquifer surface water interaction and potential pumping center locations Barton Springs and San Marcos Springs are Edwards Aquifer springs but shown here for reference. Identified pumping centers are hypothesized future areas of increased groundwater pumping due to economic development.

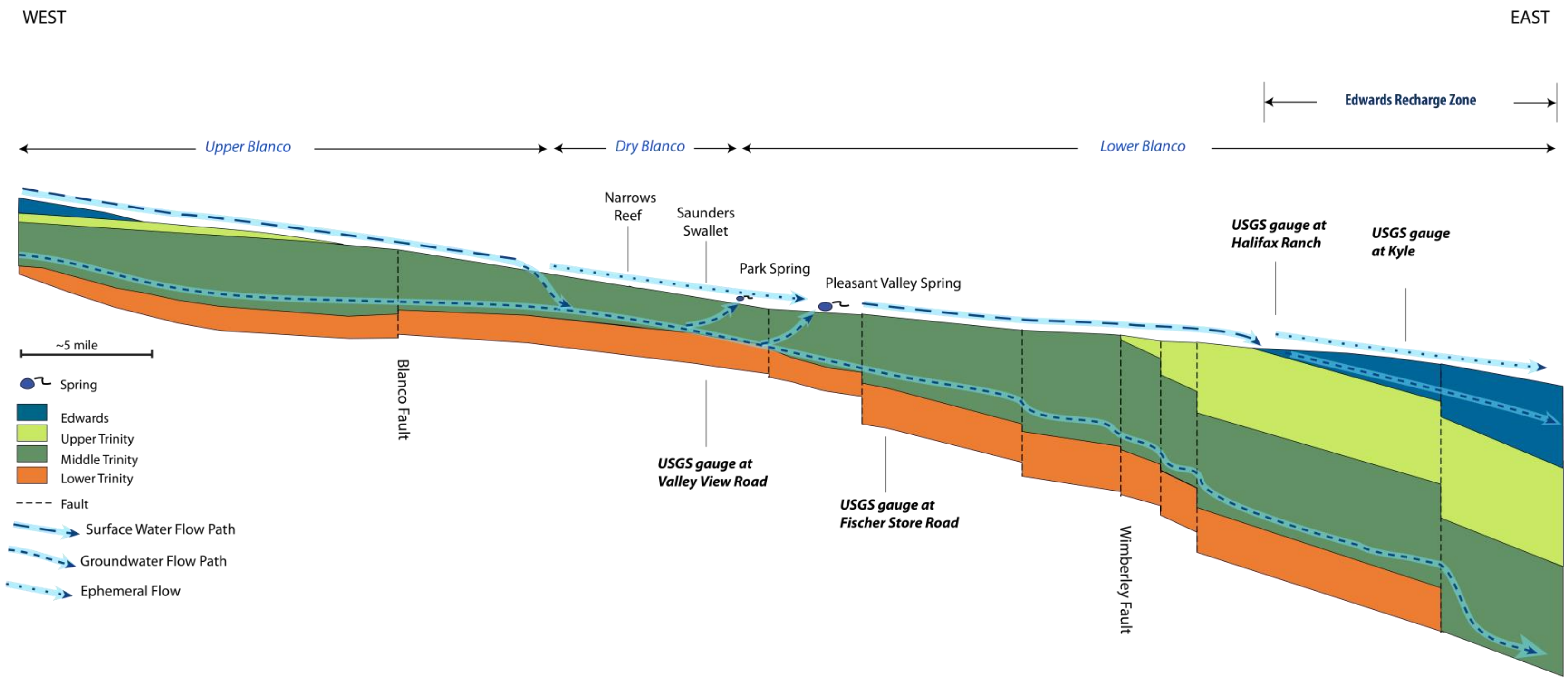


Figure 62: Conceptual section along the Blanco River from west to east

Surface water and groundwater flow paths are shown as they interact in the Trinity and Edwards aquifers.

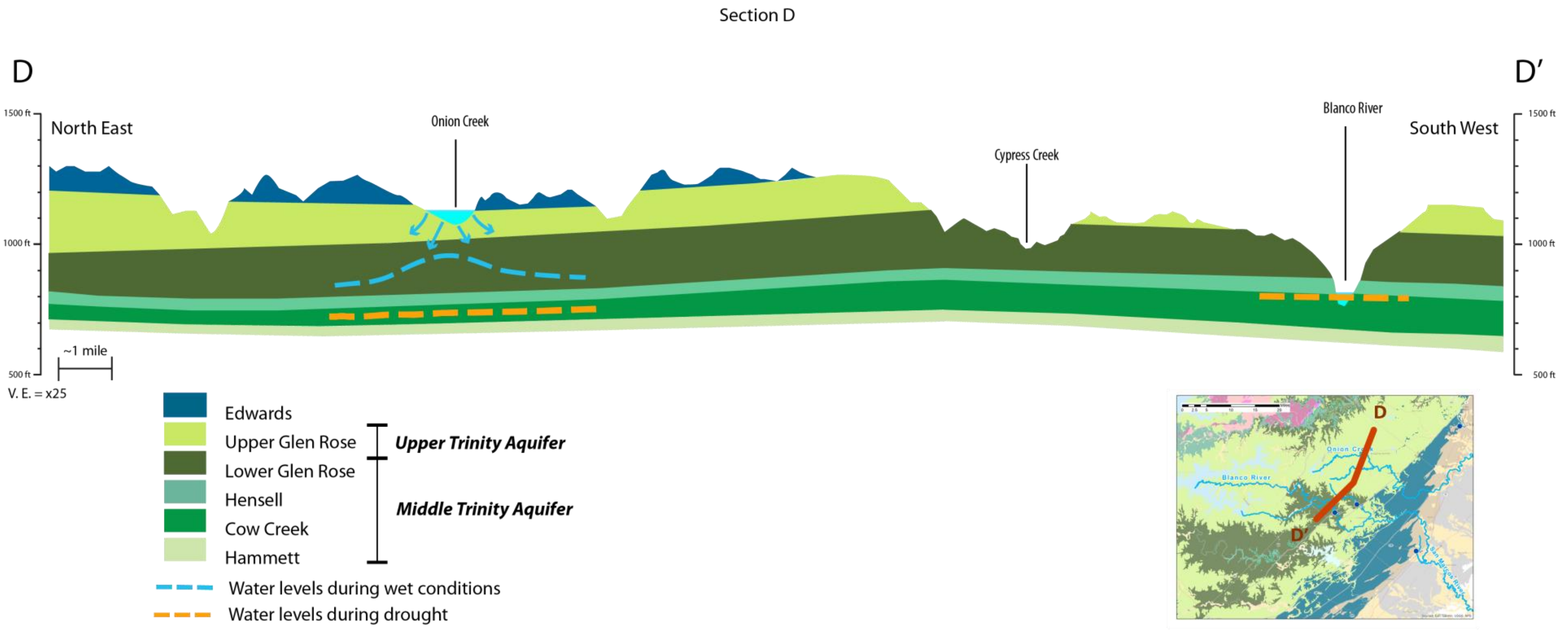


Figure 63: Geosection showing hypothesized, relationships between the Blanco River and Onion Creek under drought conditions

When water is flowing in Onion Creek there is a mounding of groundwater created by recharge from the creek. This mounding enforces a groundwater flow divide that is located between the Blanco River and Onion Creek during normal/wet conditions. During drought periods when Onion Creek is dry, the recharge mound dissipates and allows the groundwater divide to shift. In the drought scenario, some amount of water could flow from the Blanco River past Onion Creek.

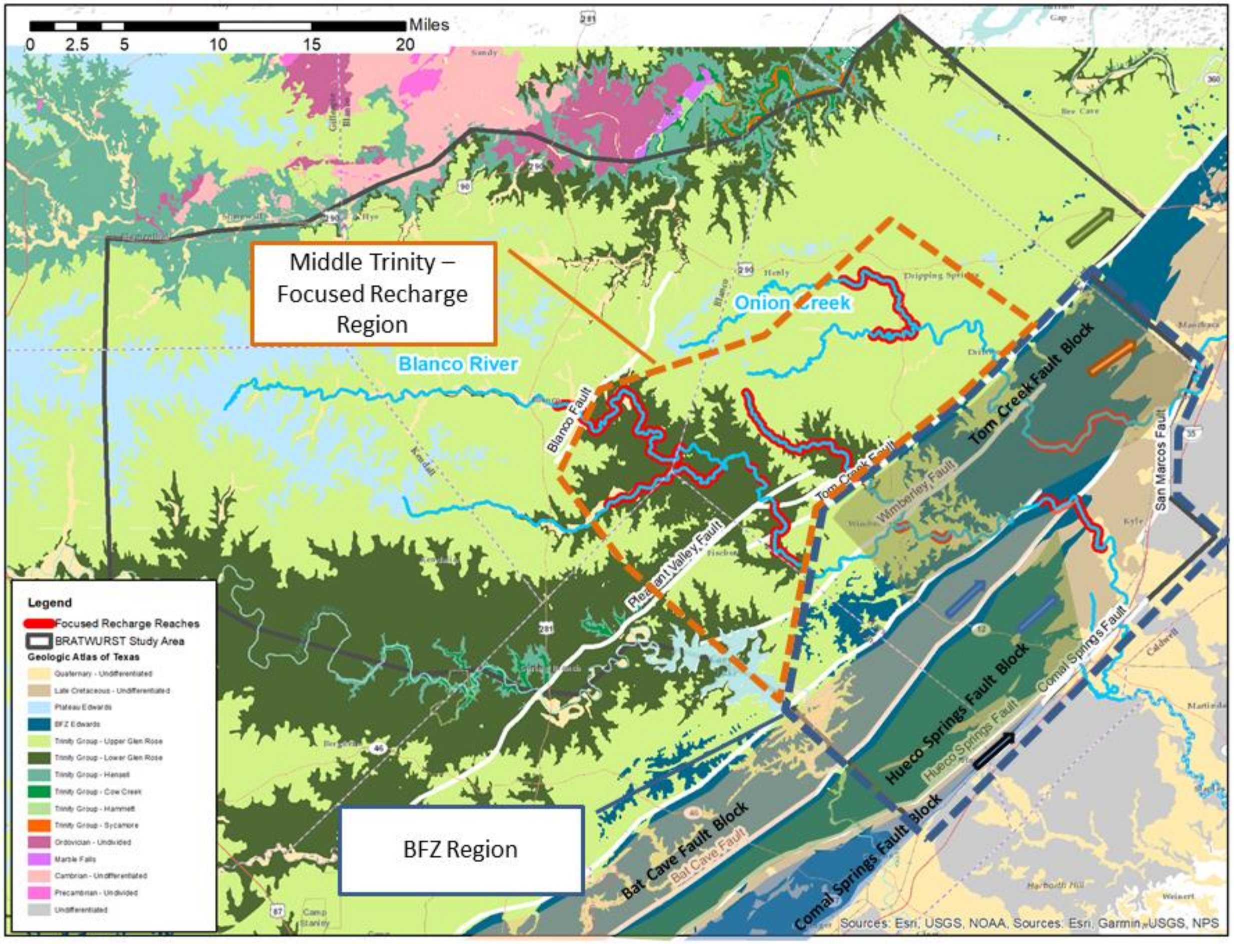


Figure 64: Conceptualization of regional flow

Focused recharge reaches are the identified losing reaches of Blanco River and Onion Creek that feed the Middle Trinity and BFZ Edwards aquifers. Fault blocks in the southeastern portion of the study area provide the relay ramp mechanism to route flow towards the northeast and the artesian block of the BFZ Edwards Aquifer. Arrows represent flow directions obtained from previous studies and represent directions and locations in the study area where simulated flow will be set using boundary conditions. The green arrow represents Upper and Middle Trinity Aquifer flow directions; the orange arrow represents BFZ Edwards, Upper and Middle Trinity Aquifer flow directions; and blue arrows represent BFZ Edwards Aquifer flow directions.

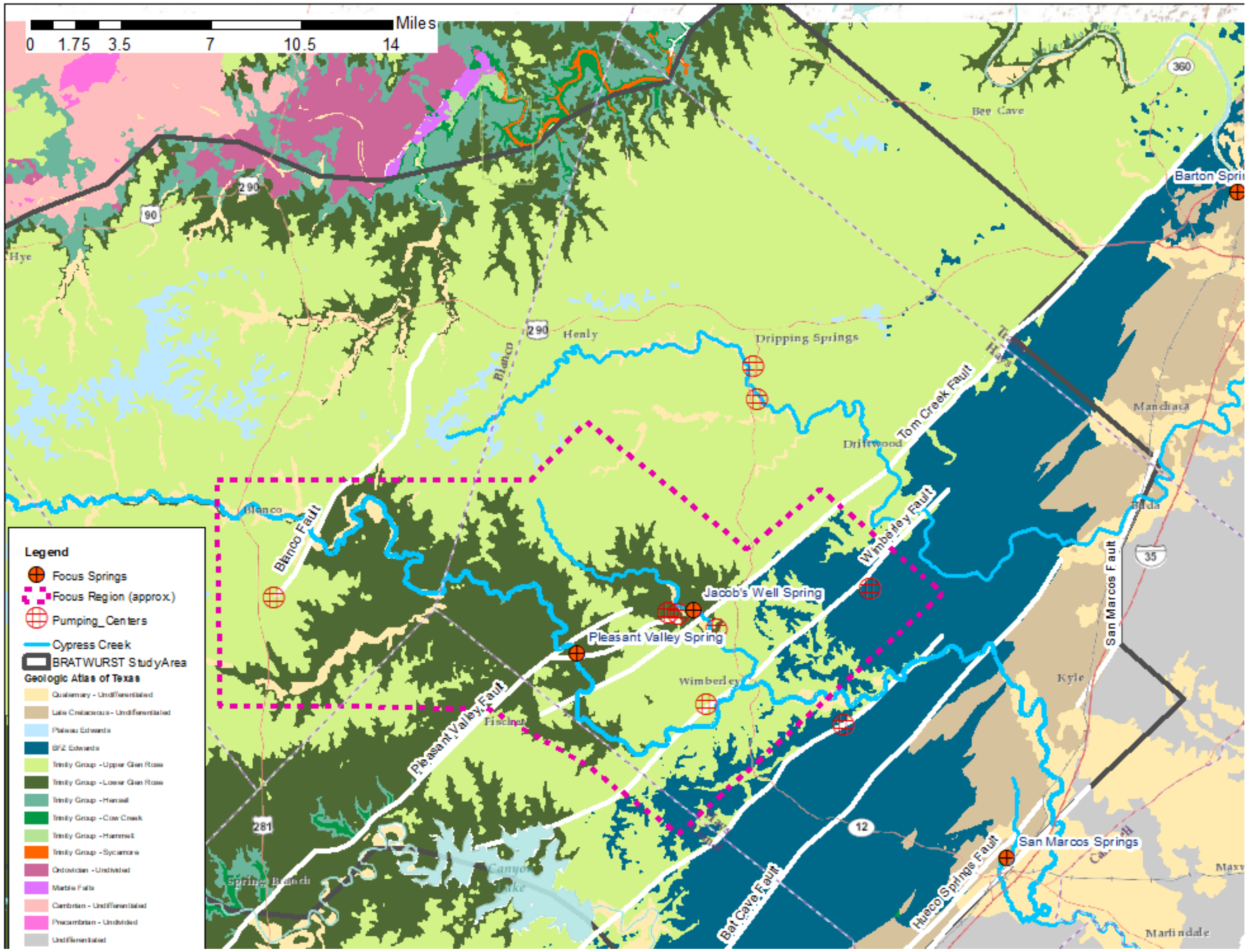


Figure 65: Conceptual flow model of study area

The "Focus Region" represents the area of focused grid refinement assuming that a single model is employed with a stretched grid to represent the entire domain. In this case, the grid will be rotated 44 degrees, counterclockwise from east. Stretching will then occur in all four, rotated directions as it moves from the region of refinement.

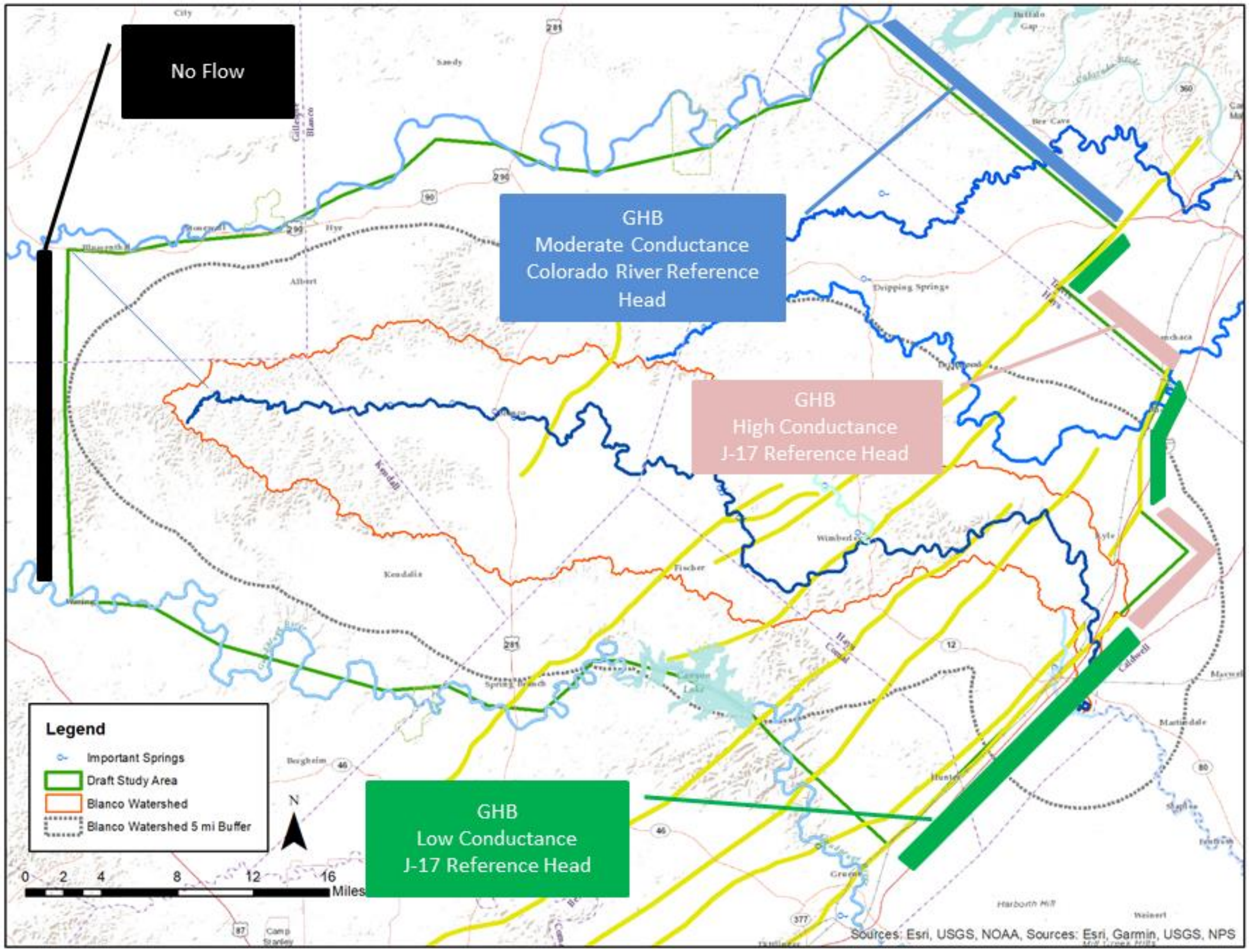


Figure 66: Numerical groundwater flow model boundary conditions

Conductance values will be used to determine or guide directions of flow as part of setting boundary conditions. Hydraulic conductivity and storage will vary spatially throughout the domain. Parallel-to-fault flow can be forced with a relatively large hydraulic conductivity contrast across a fault location (i.e., as a result of offset juxtaposing units of limited and large transmissivity). Perpendicular-to-fault flow can be forced through continuity of transmissive units across fault locations.

8 Discussion and Conclusions

Blanco **R**iver **A**quifers **T**ool for **W**ater and **U**nderstanding **R**esiliency and **S**ustainability **T**rends (BRATWURST) is a proposed tool that will be specific to the Blanco River basin and will explicitly account for surface water in the basin. The purpose of BRATWURST is to allow local landowners, communities, and groundwater conservation districts to better understand and manage groundwater resources in the Hill Country. BRATWURST will be a numerical, computer model designed to examine what-if questions related to groundwater resources and optimal resource management.

The purpose of this Phase I study is to compile pertinent data, research, and what-if questions, and to perform some preliminary analyses to generate a blueprint for BRATWURST construction. This blueprint is a 50%-level design and will have the same degree of fidelity to the final BRATWURST implementation as expected for 50% design drawings relative to “As-Built” drawings.

8.1 Conclusions

The Blanco River has complex interactions with the Middle Trinity and BFZ Edwards aquifers. It has multiple gaining and losing reaches. Additionally, the source of water for gaining reaches varies moving downstream from the headwaters to the confluence with the San Marcos River. The Blanco River also traverses two different structural domains: 1) the dissected, eastern edge of the Edwards Plateau and 2) the BFZ. The structural domains roughly correspond with regions of characteristic economic development. The western half of the Blanco River valley tends to be more rural; the eastern half is rapidly growing in terms of population and economic development.

The following conclusions related to BRATWURST design and future implementation are developed and identified.

- The study area required to capture the driving forces and provide coverage to at least partially address the pertinent what-if questions is shown on **Figure 2**.
- A “partially lumped/integrated hydrologic modeling” approach is recommended for the BRATWURST numerical, computer model to capture the complex surface water and groundwater interactions in the study domain.
    - This approach includes full hydrologic cycle representation at the watershed scale which is composed of an HRU- and stream segment-based representation of land-surface processes and of stream flow and a three-dimensional, groundwater flow model.
    - The 3-D groundwater flow model needs to include capability to represent conduit flow because of the ubiquitous karst terrain in the study area and the desire to examine what-if questions related to mapped conduit systems like Jacob’s Well Spring.
    - Land-surface components of the integrated hydrologic model need to employ a maximum duration time step of one day to represent runoff generation from single-day storms because monthly-averaged calculations will not produce enough excess precipitation.
- Anthropogenic extractions from aquifers via pumpage and from surface water via diversions associated with surface water rights are the primary unknown quantities in the study area water balance.

- A variety of aquifer inflow mechanisms are important for the two primary aquifers in the study domain and importance of inflow mechanisms varies across the study domain.
    - The two primary aquifers are the Middle Trinity and the BFZ Edwards.
    - For the BFZ Edwards Aquifer, focused recharge is the primary inflow in the study domain.
    - For the Middle Trinity Aquifer, focused recharge is of primary importance in the center of the study domain in the vicinity of Wimberley, TX. Moving westward, diffuse recharge becomes dominant.
    - Inter-formational flow may be important at the western boundary of the BFZ in areas where fault offset has juxtaposed transmissive units.

8.2 Discussion

The study domain is identified in Section **7**. Description of the modeling process and calibration points that will be used with this domain are provided in Sections **8.2.1**and **8.2.2**, respectively. The types of numerical, computer models that will be used to create BRATWURST have been identified. However, the specific computer programs and options that will be used is still an open question as detailed in Section **8.2.4**. As part of BRATWURST implementation, land-surface process simulation will likely occur within a portion of the study domain (see **Figure 33** and **Figure 53**). Groundwater-flow simulation will occur across the entire simulation domain (see **Figure 2**). Section **5** summarizes the available data that were compiled for Phase I. A significant amount of data is available for BRATWURST; however, there are multiple sources of uncertainty that need to be specifically addressed as part of BRATWURST implementation.

8.2.1 Description of numerical modeling process

The integrated hydrologic modeling approach proposed for BRATWURST is comprised of two separate models. One component implements land-surface process modeling and one handles groundwater flow modeling. The two components are linked in the unsaturated zone where infiltration leaving the soil zone of the land-surface process model enters the groundwater-flow model as recharge. These two separate components can be created separately and then linked for final, combined model calibration as shown in **Figure 67**.

A flow diagram for land-surface process component implementation is provided on **Figure 68**. The land-surface process model domain should overlap the groundwater-flow model domain so that it provides a solution for the recharge boundary conditions for the groundwater flow model. The two domains do not need to be identical as discussed in Section **8.2.5**. For those regions where the groundwater model domain extends beyond the land-surface process domain, groundwater model recharge is specified using the standard or typical boundary conditions.

The hydrostratigraphic framework model (see Section **6.1**) primarily applies to the groundwater modeling component of BRATWURST. The purpose of the framework is to provide a "formational-level" representation of the subsurface which is geared towards framing groundwater-flow simulations at the "coarsest" resolution. Two additional nested scales of information and heterogeneity will be imposed within the confines of the framework (i.e. scale #1) as shown **Figure 69**.

1. Within formation or framework zonation to approximately identify locations for facies like large reef structures that are regional in extent

2. Geostatistical structure-imitating methods to produce within zone-continuous fields for parameterization (i.e. hydraulic conductivity and storage)

A flow diagram for groundwater-flow component implementation is provided on **Figure 70**. In general, the approach in land-surface process and groundwater-flow model implementation is similar. Both models are highly parameterized models which require more parameter values than there exist data to constrain parameter values.

8.2.2 Calibration, validation, and calibration data sets

The fundamental point of analysis for BRATWURST is developing an understanding of the hydraulic relationships among the Blanco River (and its watershed), the Middle Trinity Aquifer, the BFZ Edwards Aquifer, and the four iconic Hill Country springs.

1. Pleasant Valley Springs (Middle Trinity Aquifer)
2. Jacob’s Well Spring (Middle Trinity Aquifer)
3. San Marcos Springs (Balcones Fault Zone (BFZ) Edwards Aquifer)
4. Barton Springs (Barton Springs Segment of the Edwards Aquifer)

Calibration is the assignment of parameters in the model so that the model reasonably simulates the selected data sets. These selected data sets are the calibration data sets. Validation is then running the calibrated model and reasonably reproducing an independent set of data, which were not included in the calibration process.

Given that a number of stream gauging stations only have data available starting in 2016 (see **Table 11**), the calibration period should start in 2016 to take advantage of increased data availability. Initially proposed calibration and validation periods are listed below.

- Calibration Period: 6/1/2016 through 12/31/2018
- Validation Period I: 1/1/2019 through 12/31/2019
- Validation Period II: 1/1/2008 through 12/31/2008

The proposed integrated hydrologic modeling approach is continuous in both time and space. The goal for calibration data sets is to use continuous measurements (i.e. continuous over time) at a sufficient number of point locations to provide for relatively continuous spatial coverage.

Figure 16 and **Table 11**display the discharge-measurement locations (or gauge locations) that will be used for land-surface processes component calibration. In **Table 11** only the locations with continuous discharge measurements can be used for rigorous calibration. The other locations can, however, be used to provide soft information concerning the amount of water present in the measurement reach. The Barton Springs measurement point is located well outside of the proposed study area. Consequently, Barton Springs and discharge from Barton Springs will not be used as a calibration point. Several other gauge locations in **Figure 16** are outside of the study area. These locations may be needed to interpolate stream-flow discharge to the study area boundaries.

For groundwater-flow modeling, water-level measurements will provide the main calibration targets. Water-level measurements available for dedicated monitoring wells (see **Figure 71** and) are the preferred calibration data sets. **Appendix B** contains an accompanying list of the monitoring wells with select hydrographs. However, water-level measurements obtained from pumping wells (see **Figure 72**) will also be used for calibration data sets.

Figure 15 and **Table 10** provide the "important" springs in the study region. If these springs have discharge measurements, like Jacob's Well Spring and San Marcos Springs, then the discharge time series can be used for calibration of the land-surface processes model and coupling of the land-surface process and groundwater-flow model. "Important" springs without discharge measurements can be used as a "soft" constraint for calibration of the groundwater flow model. At every spring location, it is known that the water level in the aquifer is generally higher than land surface.

8.2.3 Barton Springs

Barton Springs is located outside of the proposed study area and Barton Springs is about 20 miles from the Blanco River. Thus, there is not direct interaction between the Blanco River and Barton Springs. Consequently, Barton Springs and discharge from Barton Springs will not be simulated in BRATWURST. The simulated flow across the northeastern model boundary in the Tom Creek Fault Block (**Figure 73**) will, however, provide insight into the relative magnitude contribution from the Blanco River towards Barton Springs under the scenarios presented in Section **8.2.6**.

8.2.4 Computer models

A "partially lumped, integrated hydrologic modeling" approach is identified in Section **7.1.1** as the preferred implementation for BRATWURST. This approach includes an HRU and stream segment spatial representation for land-surface processes and streamflow combined with a 3-D groundwater flow model. The groundwater-flow model needs to include the capability to represent triple porosity systems (see Section **7.6**). In addition to physical process representation capability, there is another set of criteria for computer program feasibility. Selected computer programs should be open source and freely available so that BRATWURST can be used by multiple groups and can eventually be implemented in a cloud computing environment. Cloud computing environments are the only way to make a tool truly multiple-user and to share the same tool across multiple stakeholder groups.

Table 20 and **Table 21** identify and compare feasible models. MODFLOW-2005 and PRMS have the advantage of being frequently used together and distributed in a form where they are pre-integrated into a single product (i.e. GSFLOW (USGS 2019)). Given this, MODFLOW-2005 and PRMS are the preferred approach. However, there are possible drawbacks with this approach.

- MODFLOW-USG is the "current" version of MODFLOW and is undergoing continued development
- A rectangular grid requires grid rotation and creation of a grid that is larger than the study area which is then customized by setting grid cells that are outside of the simulation domain to be inactive.
- PRMS can use a minimum time step of one day.
- PRMS does not have built-in constituent fate and transport like HSPF.
- Given these drawbacks, it is possible that computer program substitutions will be made during BRATWURST creation.

Table 20: 3-D groundwater-flow simulation computer programs

Computer Program	Grid-type	Conduit flow	Existing integration with watershed model	Nested or refined grid sub-model capability
MODFLOW-2005	Rectangular	Yes, CFP	Yes – PRMS model to make GSFLOW	Yes
MODFLOW-USG	Unstructured	Yes, CLN	No	Yes

Table 21: Watershed-scale, hydrologic cycle simulation computer programs

Computer Program	Grid-type	Interflow	Minimum time step	Constituent transport
PRMS	HRU or rectangular	Yes	1 day	No
HSPF	HRU	Yes	No limitation	Yes

8.2.5 Land-surface process simulation locations

Figure 53 displays the watersheds and stream segments that will be explicitly simulated with a watershed-scale, hydrologic cycle simulation computer program. Areas outside of these identified areas will be included in the groundwater-flow model in order to bound the groundwater model, as much as possible, with hydrologic boundary conditions. The use of delineated watersheds automatically provides hydrologic boundary conditions for the watershed model. For regions that are outside the watershed modeling, the groundwater-flow model can be provided "recharge" boundary conditions to provide a simplified representation of land-surface processes.

8.2.6 What-if questions and scenarios

The fundamental point of analysis for BRATWURST is developing an understanding of the hydraulic relationships among the Blanco River (and its watershed), the Middle Trinity Aquifer, the BFZ Edwards Aquifer, and the four iconic Hill Country springs. The important scenarios to be examined revolve around **what** happens to these hydraulic relationships **if** something important or major changes in study area.

The two primary components of change that are proposed for the initial suite of BRATWURST scenarios are: 1) increased groundwater pumping from the Middle Trinity Aquifer and 2) changes in average weather patterns or changes in climate. The focus of these scenarios will be what these hypothesized changes mean for Blanco River flows (especially dry period flows) from both a water-resource management and an environmental perspective, Middle Trinity Aquifer water level-elevations, and the corresponding amount of water available from the Middle Trinity Aquifer.

The locations of pumping centers to be used in pumping scenarios are shown in **Figure 14**. **Table 22** provides a listing of future pumping scenarios in terms of relative amounts of pumping to be examined in conjunction with the identified pumping centers. Each pumping scenario in **Table 22** will be examined in conjunction with the two climate-change scenarios shown on **Table 23**. Climate scenarios will be represented using Monte Carlo simulation and so there be a selected number (e.g. 100 or 1,000) of synthetic weather time series extracted for each climate scenario and the selected number of Monte

Carlo realizations will be run for each pumping scenario. The simulation period for climate scenarios will be 90 years (i.e. 3, 30-yr climate intervals).

In addition to the climate scenarios in **Table 23**, each pumping scenario will be simulated with a drought of record simulation. The drought of record simulations will use 10 years of "typical" weather from the "Historical" climate scenario followed by a 10-year representation of the drought of record. The total simulation period will be 20 years.

Table 22: Future pumping scenarios

Scenario #	Name	Description
1	Current	Current pumping estimates with EP pumping of 0.5 MGD
2	Increase 1.25	All pumping centers with 1.25 times increase in pumping relative to current conditions estimate except for EP which has pumping of 1.0 MGD
3	Increase 1.5	All pumping centers with 1.5 times increase in pumping relative to current conditions estimate except for EP which has pumping of 1.5 MGD
4	Increase 1.75	All pumping centers with 1.75 times increase in pumping relative to current conditions estimate except for EP which has pumping of 2.0 MGD
5	Increase 2.0	All pumping centers with 2.0 times increase in pumping relative to current conditions estimate except for EP which has pumping of 2.5 MGD

Table 23: Future climate scenarios

Name	Description
Historical	Synthetic weather based on the statistics of historical weather parameter observations
Climate change	Synthetic weather based on global climate model predictions

8.2.7 Uncertainty

The two main sources of uncertainty for BRATWURST are from data limitations and the need to project future conditions. A significant amount of data is available as discussed in Section **5**. The primary source of limited data uncertainty is "anthropogenic" extractions, which includes extraction of groundwater from wells and diversion and extraction of surface waters under existing surface water rights. The actual volume of extractions in both cases is not rigorously measured and so there is a high degree of uncertainty around the volume of extracted water in any particular year. As current and historical volumes of extraction are not really known, it is difficult to develop projections for future extractions, given increased economic development, with any degree of confidence.

Another area of data-related uncertainty involves the requirement for parameterization of the integrated hydrologic models. Parameterization means the assignment of parameter properties, which govern hydrologic and hydraulic movement of water through the water cycle, as a surrogate for changes in soils, vegetation, and geologic materials across the study area. The framework model provides estimates of relatively broad categories of geologic materials by location. However, there is expected to be significant variation of parameter values within and across these broad categories. Because there are two major unknowns, the spatial variation of hydrologic properties and parameters and amount of historical extractions from the study area, there is no way to deterministically calibrate to, or otherwise generate, a unique solution for the hydrologic cycle in the study area at any point in the past or present.

One of the goals for BRATWURST is to provide capabilities to analyze water-resource management scenarios given estimates of future conditions in the study area. Future prognostications are always uncertain. This means that there will not be a deterministic solution for the hydrologic cycle in the watershed in the past, present, or future. The answer is 42 (Adams 1995); but for BRATWURST, the best implementation is to quantify the uncertainty to the degree possible and use probabilistic simulation to propagate the constrained uncertainty of our system knowledge into answers to what-if questions that are paired with likelihoods or probabilities. In addition to creation of numerical computer model of the study area, Phase II of the BRATWURST project will involve casting of the computer model into a probabilistic simulation framework.

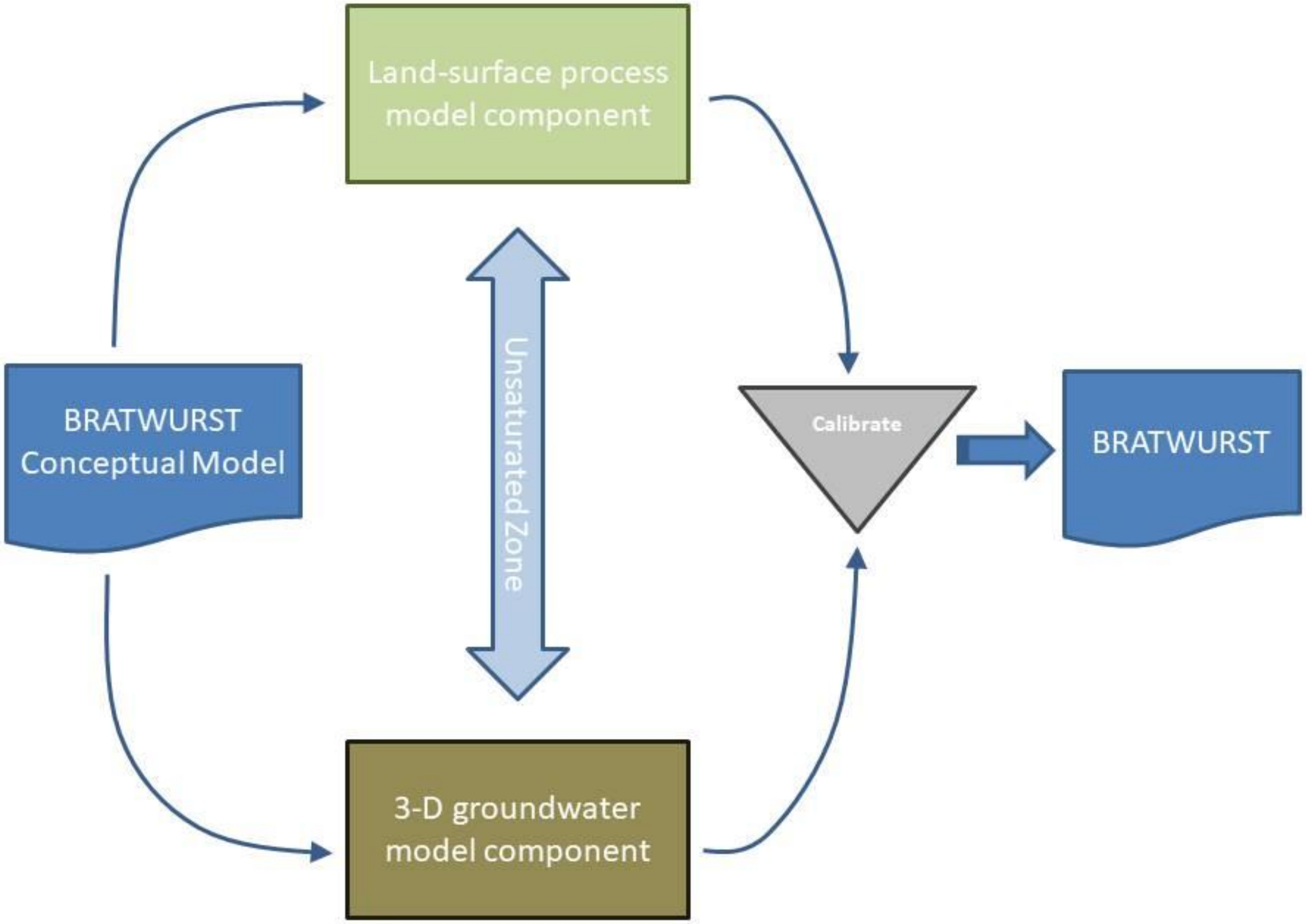


Figure 67: Overview of modeling process and linkage of components

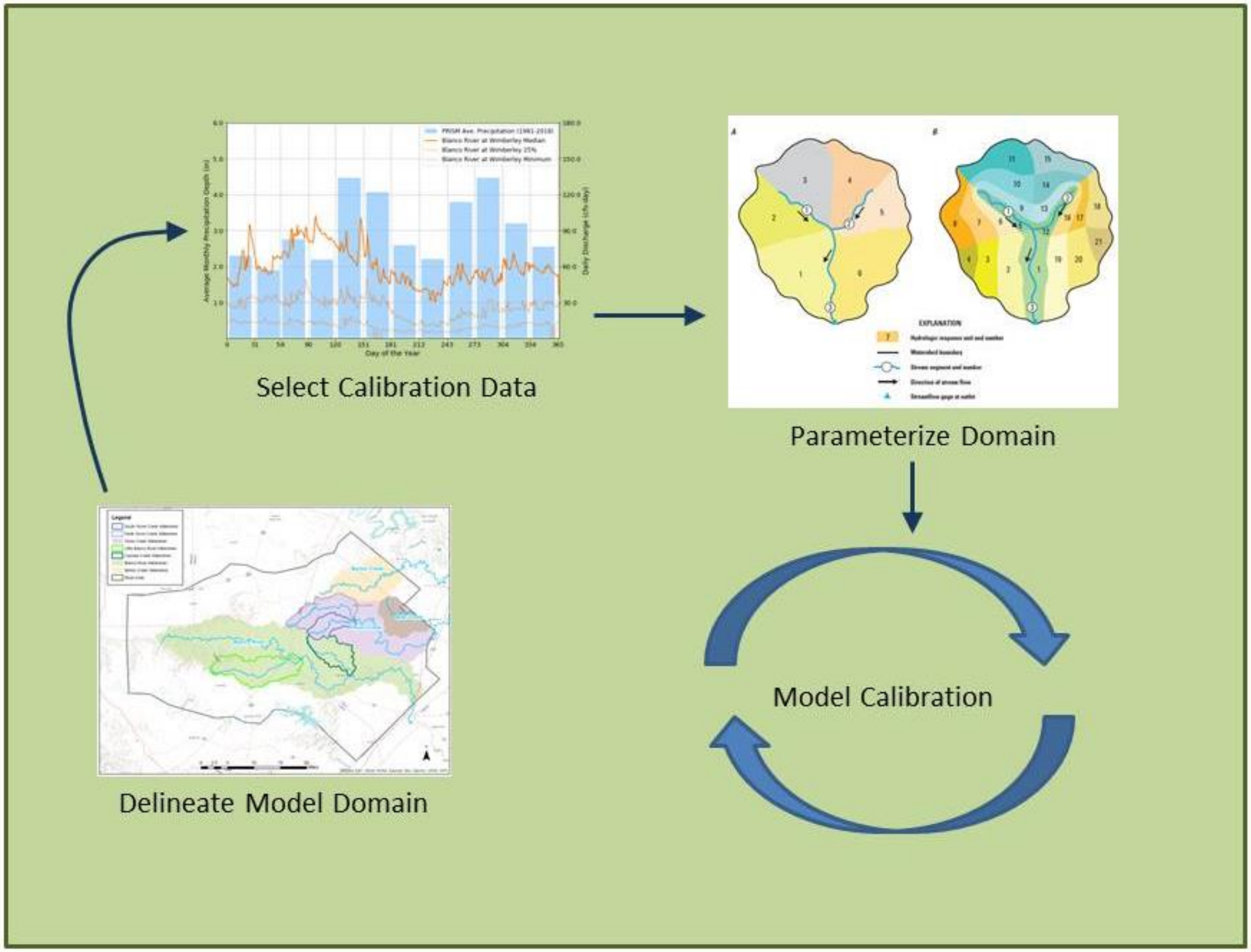
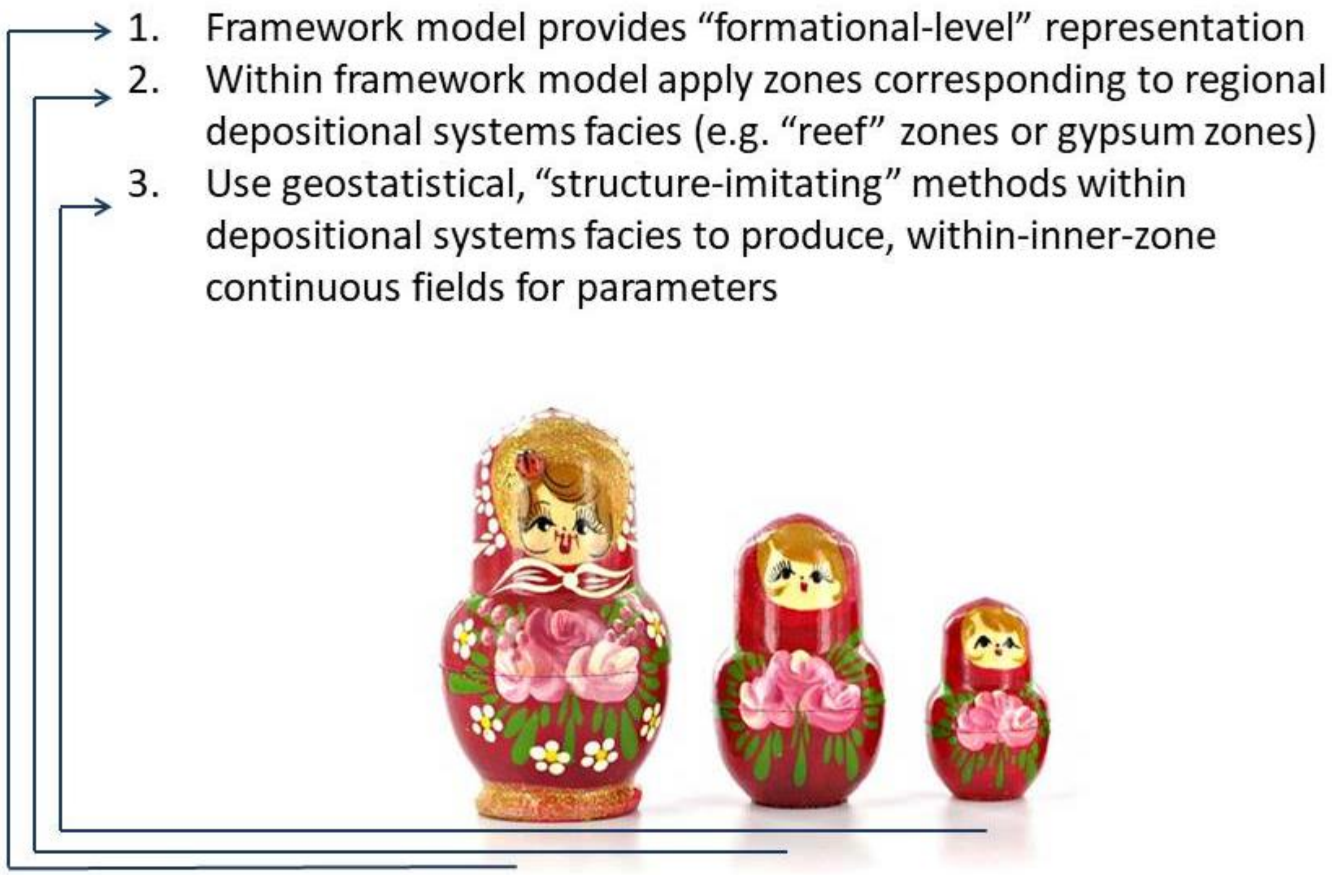


Figure 68: Land-surface process implementation flowchart



1. Framework model provides “formational-level” representation
2. Within framework model apply zones corresponding to regional depositional systems facies (e.g. “reef” zones or gypsum zones)
3. Use geostatistical, “structure-imitating” methods within depositional systems facies to produce, within-inner-zone continuous fields for parameters

Figure 69: Conceptual description of nested groundwater model parameterization using a framework model

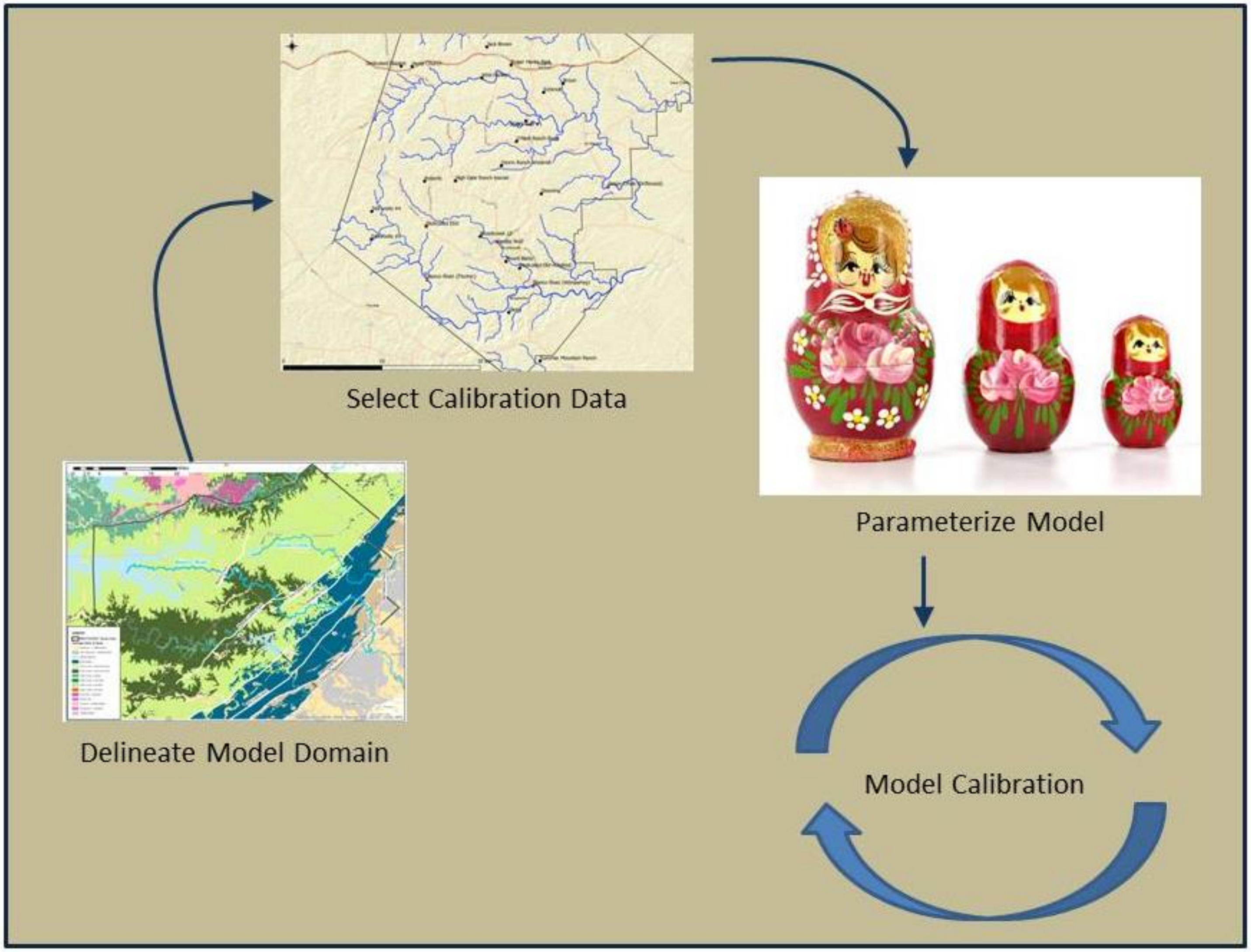


Figure 70: Groundwater model component implementation flow chart

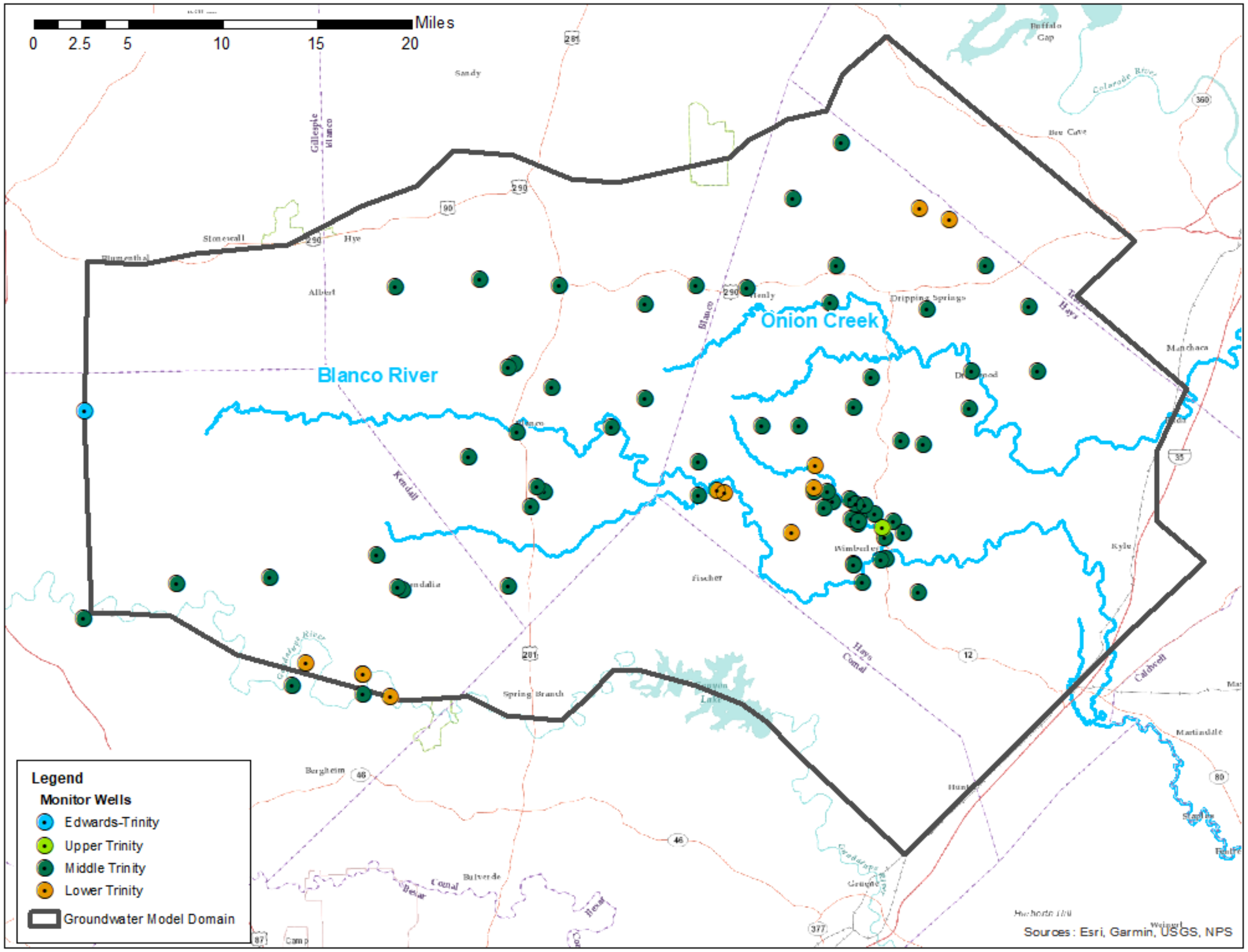


Figure 71: Groundwater model calibration points I – monitoring wells

HTGCD, BSEACD, and BPGWD monitoring well locations. List of wells found in Table B - 1.

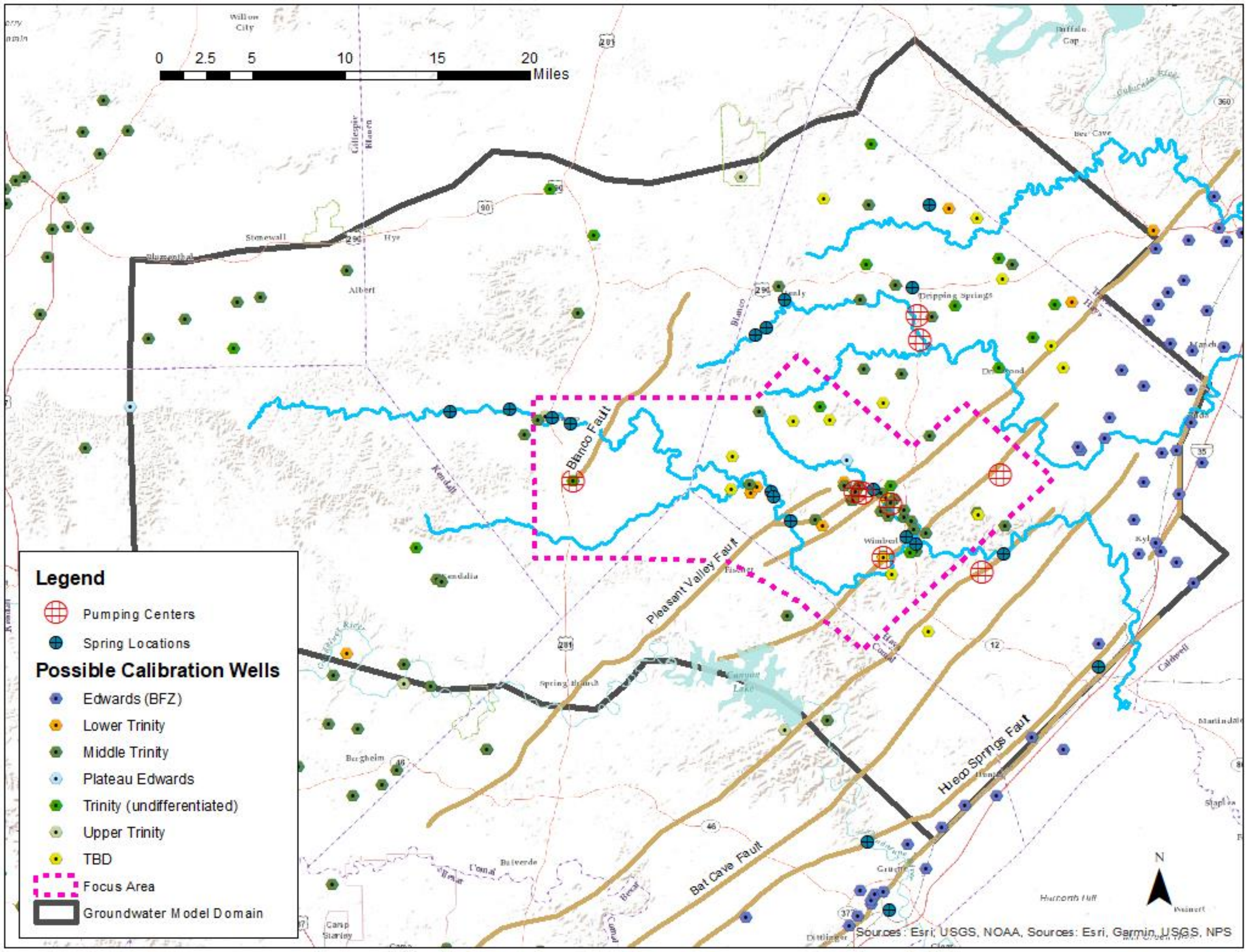


Figure 72: Groundwater model calibration points II - pumping wells with regular water-level measurements

Wells located outside of domain boundaries can be used to make surfaces that completely cover the study area.

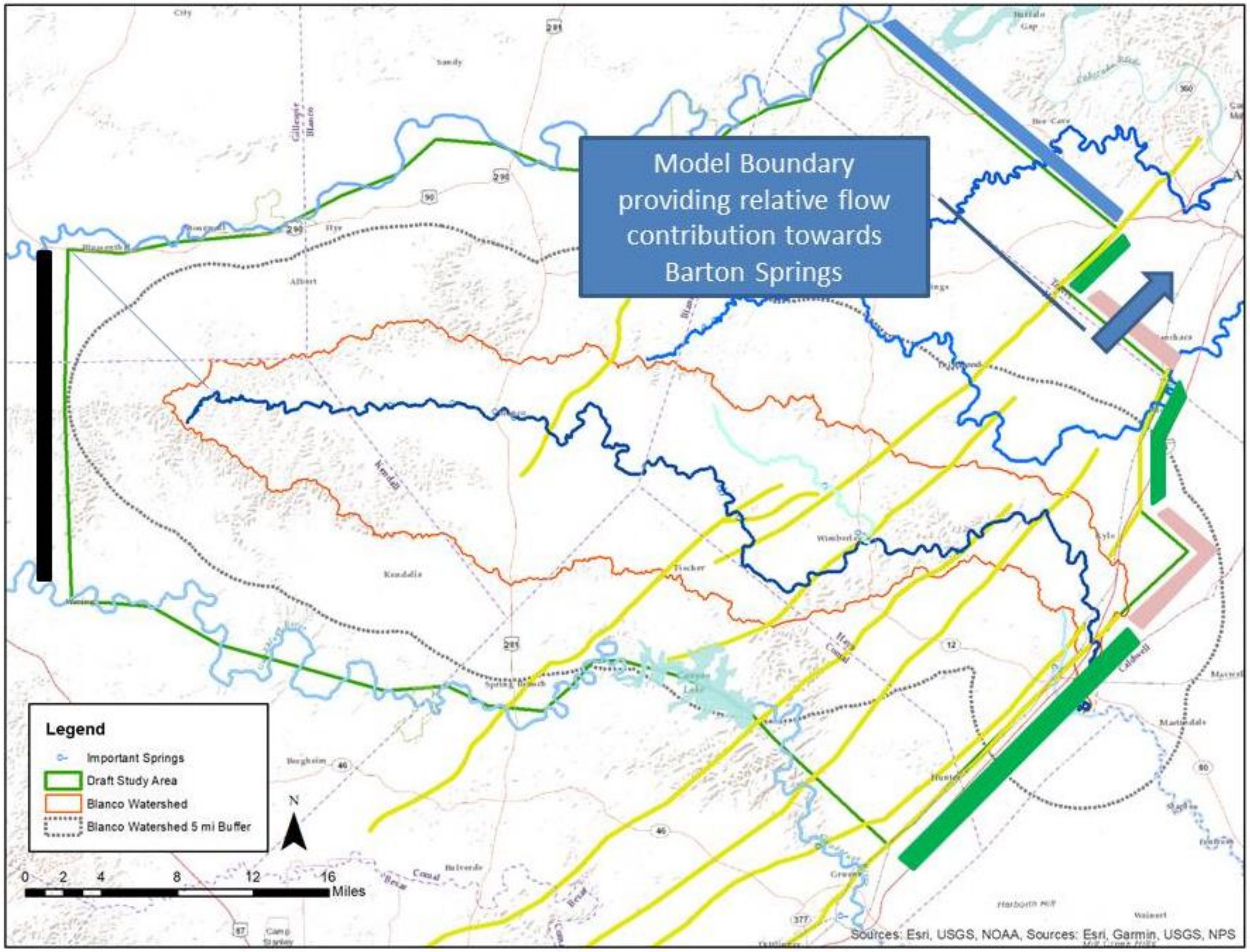


Figure 73: Location on domain boundary used to provide relative flow contributions from study area to Barton Springs

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Appendix A: Project Arc Hydro Groundwater Database

The BRATWURST Geodatabase is and ArcHydro Groundwater Schema file geodatabase. It serves as a repository for geographic information within a relational database system. It provides a common data storage and management framework for storing all the types of datasets supported in ArcGIS and used in the BRATWURST hydrogeologic model. Here, data provided from various sources were cleaned, compiled, and stored in a uniform format. The database also holds the results of geoprocessing and the 3D hydrostratigraphic framework model. Data objects in the BRATWURST database include: wells, boreholes, horizon surfaces, and 3D multipatches that represent volumes. These objects are stored in feature class datasets and raster catalogs. Tables in ArcHydro Groundwater database store time-series data including precipitation, discharge, water-elevations, and water-chemistry measurements.

Unique identifiers are used to relate database objects with other associated objects and/or measurements in the database. For example, wells were assigned a unique identifier called a HydroID. Water-elevation measurements, water-chemistry measurements, and other well-specific measurements are related to respective wells by listing the HydroID of the associated well feature in the FeatureID column of their attribute table. Another identifier, the HGUID, was assigned to each hydrogeologic unit identified in the framework. All framework objects created in the geoprocessing steps were tagged with the HGUID in their attribute table, indicating to which hydrogeologic unit they belong. By tagging database objects and entries with these IDs, they can be easily sorted and searched for future studies.

Table A - 1 lists contents in the geodatabase that were collected as data and used in the creation of the framework model and also the results of the framework model. **Table A - 2** shows the database items that were a result of digitizing cross sections to be incorporated in the framework model. **Table A - 3** is a list of tables included in the database and their contents. Tables in the database store both time series data such as precipitation, discharge, and water levels measurements as well as serving as look up tables. Other tables, such as the Variable definition, provide a lookup table to store the VarID which indicate the type and unit of measurements stored in other tables. The attribute tables of the shapefiles contain the additional information as well as the associated IDs.

Table A - 1: Framework objects

Name	Data type	Description	Notes	Location
Well	2D points	Points indicate locations of wells. Each well is assigned a HydroID and has attributes of land elevation and well depth as well as type of well and source of well information/location	Source: TWDB, BRACS, HTGCD, BSEACD, CCGDC, EAA	Framework Feature Class dataset
Springs	2D points	Name and location of springs in the study area.	Source: USGS	Framework Feature Class dataset

Streams	2D Lines	Major streams in the BRATWURST study area	Source: National Hydrography Dataset	Framework Feature Class dataset
Structure Contours	2D Lines	Feature dataset contains feature classes of structural contours for hydrostratigraphic units	Source: Wierman et al. (2010)	Structure Contours Feature Class Dataset
GeoSection_HCTAtlas	Multipatch	3D representation of 2DXS pannels.	SectionID relates GeoSections to section lines, source of original cross sections: Wierman et al. (2010)	XS2D Feature Class Dataset
GeoVolume	Multipatch	3D representation of hydrogeostratigraphic units as multipatches. Created by extruding between horizons. Multipatches have HGUIDs and HorizonIDs to reference the horizon and the hydrogeographic unit to which it belongs	Framework model result	Subsurface folder
GeoSection_Results	Multipatch	3D representation of 2DXS pannels.	Framework model result	XS2D Feature Class Dataset
BRATWURST_DEM	Raster	Digital elevation model of the study area	Source: TNRIS 30m resoultion	Geodatabase
Top_CowCreek, Top_Hammett, Top_Hensel, Top_LowerGlenRose, Top_SligoHosston, Top_surface, Top_UpperGlenRose	Raster	Extrapolated surface of each hydrostratigraphic unit in the framework model.	Framework model result	Geodatabase

Table A - 2: 2D Cross Section Objects

Name	Data Type	Description	Notes	Location
SectionLine_Wierman_et_al_2010	2D Line	Each polyline feature represents a cross section in map view and has a unique HydroID		Subsurface Feature Class Dataset
Faults	2D polyline	Polylines representsfaults	Fault SectionID links to SectionLine: HydroID	XS2D Feature Class Dataset
XS_HCTAtlas	2D polygons	Each cross section from Hill Country Trinity Atlas (Wierman et al., 2010) digitized in an individual featureclassCross section represented as a panel of polygons	Panel SectionID attribute links to SectionLine: HydroID	XS2D Feature Class Dataset
XS2D_Catalog	Table	Table with list of feature class names, types and SectionID, organizing all 2D cross section objects.		Geodatabase

Table A - 3: List of Tables

Table Name	Contents	Notes
BoreholeLog	Borhole log units with top/bottom depth and elevations are assigned HGUIDs and HGUCodes	WellID is equal to HydroID of associated well feature
HydrogeologicUnit	Hydrogeologic units are given HGUCodes and HGUNames.	HGUCodes are seen throughout database as HGUID

Precipitation_EAA	Table contains daily precipitation measurements in inches. Data from EAA	FeatureID is equal to HydroID of associated well feature
Precipitation_PRISM	Table contains daily precipitation measurements in inches. Data from PRISM	FeatureID is equal to HydroID of associated well feature
SwRIDataCodes	CodeID explains various data flags in database, described in CodeType and Description columns	
TimeSeries	Table contains discharge measurements, indicated by VarID 2.	FeatureID is equal to HydroID of associated well feature
Variable Definition	Variable names indicated by VarID. Describes the type of data found in database tables including chemical constiutents and type of measurements	
WaterChem_plus	VarID indicates chemical constituent and unit of measure, flag indicates CodeID from SwRIDataCodes table. FeatureID's in this table may contain text.	FeatureID is equal to HydroID of associated well feature
WaterChemistry	VarID indicates chemical constituent and unit of measure, flag indicates CodeID from SwRIDataCodes table	FeatureID is equal to HydroID of associated well feature
XS2D_Catalog	Table contains XS2D features and relates them to each section line via SectionID	

Appendix B: Possible Calibration Wells and Hydrographs

Table B - 1: List of monitoring wells in the study area that are possible calibration points (accompanies **Figure 73**)

State Well Number	Monitoring Well Name/Location	Source	Aquifer
5758203	Alamo Springs	CCGCD	Edwards-Trinity
6803109	Sisterdale VFD	CCGCD	Middle Trinity
6804313	Kendalia VFD	CCGCD	Middle Trinity
6802508	Waring VFD	CCGCD	Middle Trinity
6803305	High Point Ranch	CCGCD	Middle Trinity
6804312	BKS Estate Trust	CCGCD	Middle Trinity
6804705	River Mountain Ranch	CCGCD	Middle Trinity
6804809	Waterstone 3351	CCGCD	Middle Trinity
6804804	The Crossing MT	CCGCD	Middle Trinity
6804214	Donop	CCGCD	Middle Trinity
6804806	The Crossing LT	CCGCD	Lower Trinity
6804916	Waterstone Rio Frio	CCGCD	Lower Trinity
6804706	La Cancion	CCGCD	Lower Trinity
57613S1	Anne Wynn Well	BPGCD	Middle Trinity
34776	Arnosky Farms--Blue Barn	BPGCD	Middle Trinity
57612MW	Blanco County Yard Monitor Well	BPGCD	Middle Trinity
57538DC	Dale A. Crenwelge / Tom Blevins Well	BPGCD	Middle Trinity
57538JW	Jason Wheeler New Well 2018	BPGCD	Middle Trinity
57621KW	Karen Wagenfehr Well	BPGCD	Middle Trinity
57536PR	Miller Creek Replacement Well	BPGCD	Middle Trinity
57619QH	Quaid Haack Well	BPGCD	Middle Trinity
57616JA	Rockin J Ranch Monitor Well 2	BPGCD	Middle Trinity
57616J2	Rockin J Ranch Monitor Well 4	BPGCD	Middle Trinity
57619TC	Trey Haack North Pasture Well	BPGCD	Middle Trinity
57535BA	Bamberger Ranch	BPGCD	Middle Trinity
57526BJ	BJ Sultemeier	BPGCD	Middle Trinity
57545EP	Franklin Ranch	BPGCD	Middle Trinity
68052MW	Melissa Weisbrich	BPGCD	Middle Trinity
57546B3	Randy Barton	BPGCD	Middle Trinity
N/A	Amos	HTGCD	Middle Trinity
N/A	Bachardy	HTGCD	Middle Trinity
5764817	Box Canyon	HTGCD	Middle Trinity
5756519	Broun	HTGCD	Middle Trinity
5763603	Byrum	HTGCD	Lower Trinity
5756907	Camp Ben McCulloch	HTGCD	Middle Trinity
5764714	Camp Young Judaea	HTGCD	Middle Trinity
5764502	Downing	HTGCD	Middle Trinity
5756702	DSWS Well #1	HTGCD	Middle Trinity

State Well Number	Well Name/Location	Source	Aquifer
N/A	Fitzhugh Corners	HTGCD	Lower Trinity
6808107	Glenn	HTGCD	Middle Trinity
5756305	Grolnic	HTGCD	Middle Trinity
5764715	Gumbert	HTGCD	Upper Trinity
5755401	Henly Church	HTGCD	Middle Trinity
5764905	Hermosa Paloma	HTGCD	Middle Trinity
5755301	Jack Brown	HTGCD	Middle Trinity
5763702	Lost Springs Ranch	HTGCD	Lower Trinity
N/A	Mandola	HTGCD	Middle Trinity
5763806	McMeans	HTGCD	Lower Trinity
5764705	Mount Baldy	HTGCD	Middle Trinity
5756710	O'Neil Ranch Road	HTGCD	Middle Trinity
5763205	Roberts	HTGCD	Middle Trinity
N/A	Roman	HTGCD	Middle Trinity
N/A	Sabino Ranch	HTGCD	Middle Trinity
N/A	Section 25	HTGCD	Middle Trinity
5849406	Slopes of Nutty Brown	HTGCD	Middle Trinity
5763706	Still # 6 - main	HTGCD	Lower Trinity
5762901	Still White House #1	HTGCD	Middle Trinity
5762902	Still Windmill #4	HTGCD	Middle Trinity
5763203	Storm Ranch Toenail	HTGCD	Middle Trinity
5764105	Storm Ranch WM	HTGCD	Middle Trinity
5849811	Terry Tull	HTGCD	Middle Trinity
N/A	Tom Hegemier	HTGCD	Middle Trinity
N/A	Wanda Graham	HTGCD	Middle Trinity
N/A	WC Arapahoe	HTGCD	Lower Trinity
N/A	WC Maintenance 2	HTGCD	Middle Trinity
5748811	Whisenant & Lyle	HTGCD	Lower Trinity
5755607	Whit Hanks	HTGCD	Middle Trinity
5763908	Woodcreek 23	HTGCD	Middle Trinity
5663615	N/A	TWDB	Lower Trinity
5663616	N/A	TWDB	Middle Trinity
5663617	N/A	TWDB	Middle Trinity
5664403	N/A	TWDB	Lower Trinity
5741903	N/A	TWDB	Middle Trinity
5742702	N/A	TWDB	Middle Trinity
5742706	N/A	TWDB	Middle Trinity
5757907	N/A	TWDB	Middle Trinity
5761220	N/A	TWDB	Middle Trinity

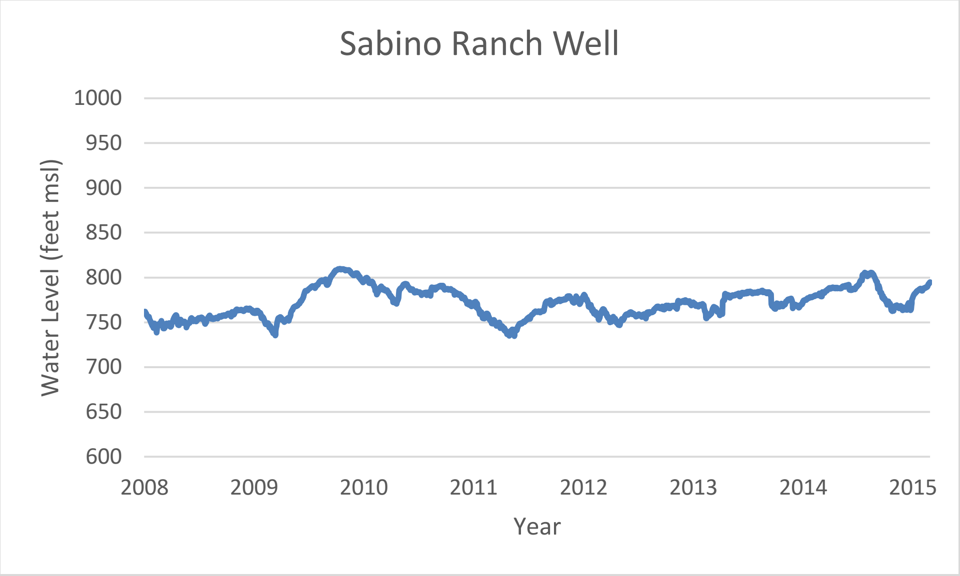

Figure B - 1: Hydrograph for Sabino Ranch Well in Hays County

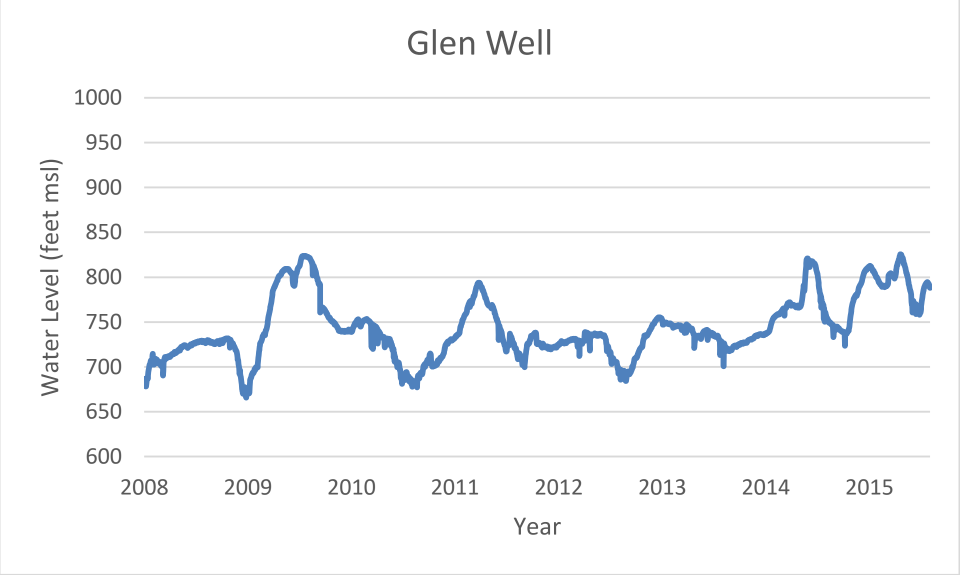

Figure B - 2: Hydrograph for Glen Well in Hays County

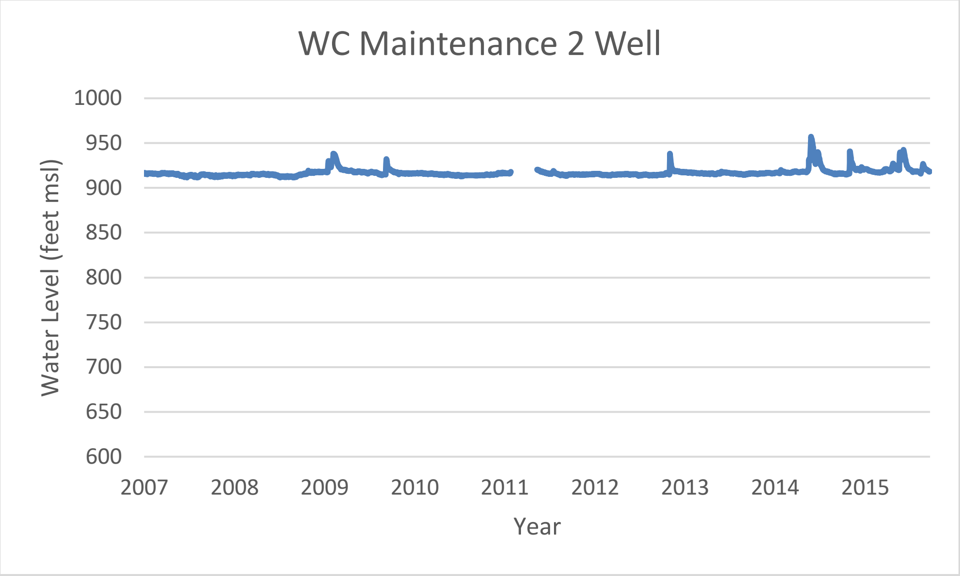

Figure B - 3: Hydrography for WC Maintenance 2 Well in Hays County