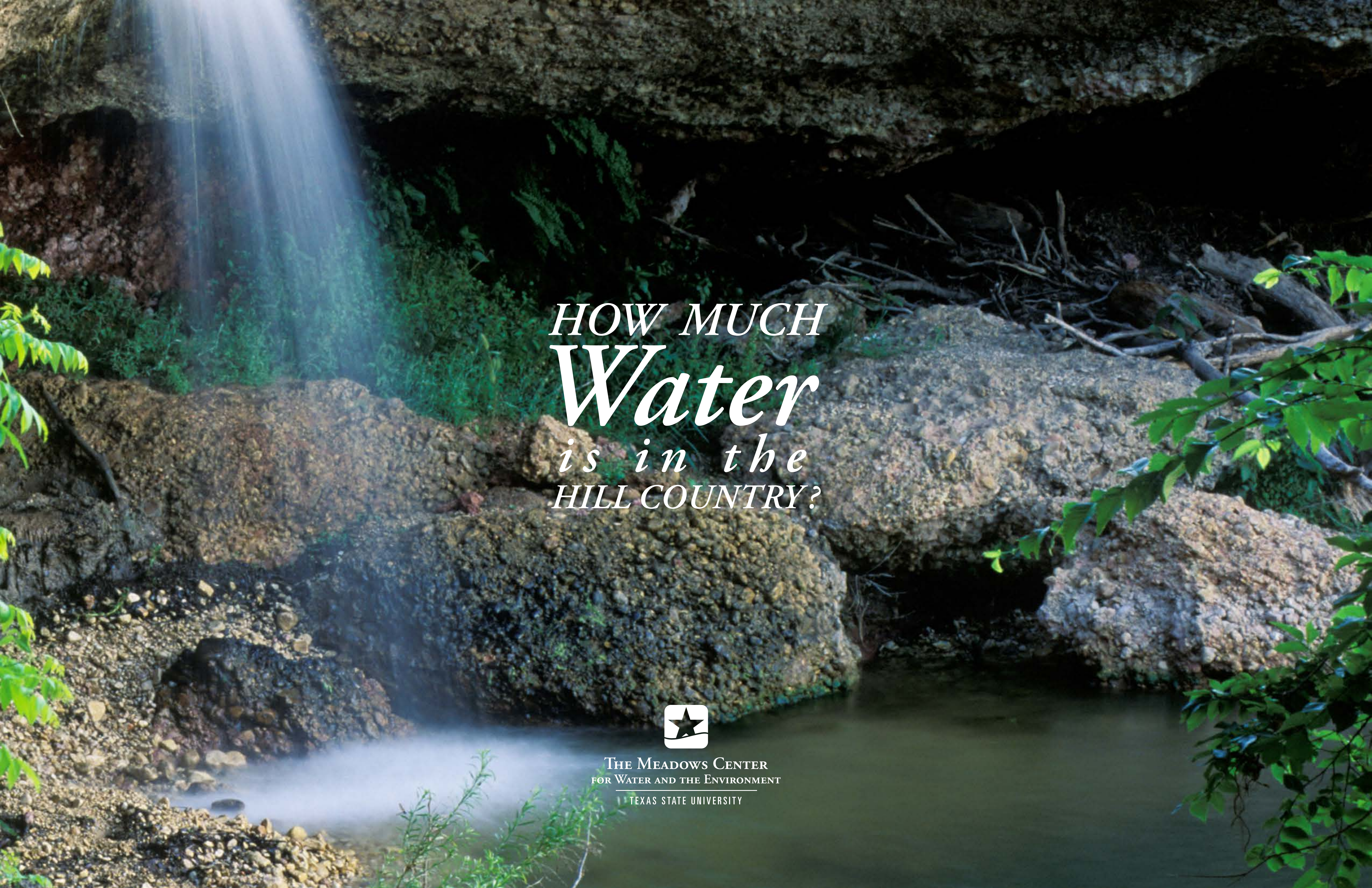

HOW MUCH *Water* is in the HILL COUNTRY?

THE MEADOWS CENTER
FOR WATER AND THE ENVIRONMENT
TEXAS STATE UNIVERSITY

The Meadows Center for Water and the Environment
& Douglas A. Wierman, P.G. present:

HOW MUCH Water is in the HILL COUNTRY?

Contributors: Emily Warren, Kelsey E. Bolfing & Michael Benjamin Haggerty. Maps by Mary Van Zant and Laura Parchman. Design by Barrett Pierce.

Special thanks to:
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The Meadows Center
for Water and the Environment
Texas State University

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ACRONYMS

BCRAGD - Bandera County River Authority Groundwater District

BFZ - Balcones Fault Zone

BPGCD - Blanco Pedernales Groundwater Conservation District

CTGCD - Central Texas Groundwater Conservation District

EAA - Edwards Aquifer Authority

GAM - Groundwater Availability Model

GAT - Geologic Atlas of Texas

GCD - Groundwater Conservation District

GMA - Groundwater Management Area

HCUWCD - Hill Country Underground Water Conservation District

HTGCD - Hays Trinity Groundwater Conservation District

SWR - State Well Reports

TBWE - Texas Board of Water Engineers

TDLR - Texas Department for Licensing and Registration

TWC - Texas Water Commission

TWDB - Texas Water Development Board

USGS - United States Geological Survey

WIID - Water Information Integration and Dissemination

EXECUTIVE SUMMARY

The Hill Country is a unique region of Texas where rivers rise out of the limestone, spilling the means for life onto what would be an otherwise dry and difficult place to survive. The conservation of the Hill Country's hydrologic systems is not only important to protecting the diverse wildlife indigenous to this area but also to the growing population moving into the expanding urban corridor between Austin and San Antonio and west into the Hill Country. The current period of prolonged drought has depleted many reservoir levels to historic lows and created a growing reliance on groundwater to support the escalating population of Central Texas. Since there are few regulations that can be placed on aquifer pumping, there is a very real possibility that unsustainable groundwater development and drought could endanger major springs that are instrumental to the base flow of the major rivers in the Hill Country region. There is still much to learn about the interconnected nature of these aquifers, rivers and lakes.

The purpose of this this project was to develop a methodology for hydrogeologic research that will help scientists, decision-makers, and stakeholders better understand how the aquifers, springs, and rivers in the Hill Country interact.

APPROACH

This project focused on the Blanco River, the Pedernales River, the Medina River, and Onion Creek. These basins were chosen as representative watersheds because each is underlain by aquifers that are being increasingly developed and each present opportunities for a suite of hydrogeologic studies. Through an extensive literature review and informal interviews, researchers identified common data gaps and methodologies for further research.

FINDINGS

1. The methodology of study described in this report has proven effective in helping to understand groundwater/surface water interactions and their impact on the overall question "How much Water is in Hill Country".

2. While Groundwater Conservation Districts are the most active organizations currently researching and monitoring surface-groundwater interactions in the Hill Country, they need extensive support in expanding, compiling and distributing their work.

3. Additional work is necessary on the four stream segments identified so that significant data gaps can be filled, interpreted and related to land management activities. The best opportunities to fill existing data gaps are to complete contemporary gain-loss studies, geologic surveying, and groundwater monitoring that can be related directly to the baseflow of a river.

- Gain-loss studies can help identify the most hydrologically valuable stretches of a river deserving of further research. Pleasant Valley Spring was "discovered" through detailed gain/loss studies. Detailed gain/loss studies performed on the Blanco River and its main tributary, Cypress Creek, have identified areas warranting further study. Gain-loss studies have not been recently performed on Onion Creek, on approximately 85 miles of the Pedernales River, and on tributaries of the Pedernales.

- Geologic and geophysical surveys help map hydrologically significant structural geologies underlying the rivers and their surrounding landscape. Surveys can identify the source of springs, the destination of sinkholes, and the paths of conduits between them. Surveys can be used to profile regions instrumental to recharge and springflow that should be managed conscientiously.

- All GCDs in the study area have ongoing groundwater level monitoring programs, however they are not focused near the major streams. Implementation of enhanced groundwater level monitoring programs along all of the study area streams is necessary to fully understand groundwater/surface water interactions.

4. As the hydrogeologic framework of the rivers become more defined, it is possible to more accurately evaluate and recommend potential land management techniques to compliment the regions that are most important to those hydrogeologic systems, including:

- Minimize impervious cover
- Enhanced Recharge Stormwater Structures
- Enhanced Recharge Dams
- Rainwater Harvesting
- Management of Groundwater Pumping
- Specify Well Construction Standards
- Brush management

INTRODUCTION

Determining how much surface water is in the Hill Country is a relatively simple proposition.The amount of surface water in storage in our reservoirs is closely monitored by various governmental authorities. Storage changes based on managed releases and inflows. Inflows generally consist of storm flow and base flow from our streams and rivers. Storm flow is typically a short duration event based of rainfall. Base flow in our streams is the result of groundwater/surface interactions, with base flow originating from the underlying aquifers. The hydrogeologic origins of base flow can only be determined through rigorous scientific research.

The goal of this project is to document a scientific methodology that can be applied to Hill Country streams to determine groundwater/surface water interactions. Further understanding these interactions will facilitate informed decision-making for sustainable water management strategies. Detailed stream gain and loss delineations can provide insight into appropriate and scaled on-the-ground practices that can effectively conserve and maintain Hill Country water resources.

Project researchers initially used the Blanco River as a case study to identify the types of detailed hydrogeologic data and analyses that are necessary to understand groundwater/surface water interactions. Recent studies and research in the Blanco River basin have demonstrated that detailed hydrogeologic studies are necessary to understand groundwater/surface water interactions with confidence (Wierman, 2010, Kocis, 2014, and Smith, 2014). Researchers also conducted extensive research, interviews, and literature reviews to determine the types of data currently available and what data gaps exist in our understanding of Hill Country groundwater/surface water interactions.

Researchers then focused the study area to include four creek and river basins generally underlain by the Hill Country Trinity and Edwards Aquifers in Hays, Blanco, Gillespie, Kendall, Travis and Bandera Counties. In general, the stream reach segments studied started at the headwaters and extended to where they cross the Balcones Fault Zone. These reaches are thought to be the most active with regard to groundwater/surface water interactions. A terrain map of the area is shown on Figure 1A with the individual stream segments shown on Figures 2A, 3A, 4A and 5A.

Figure 1B. Study Area Counties and Watersheds

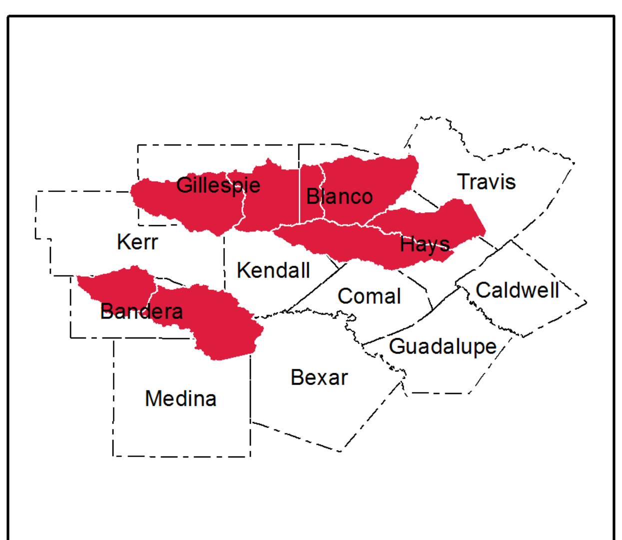
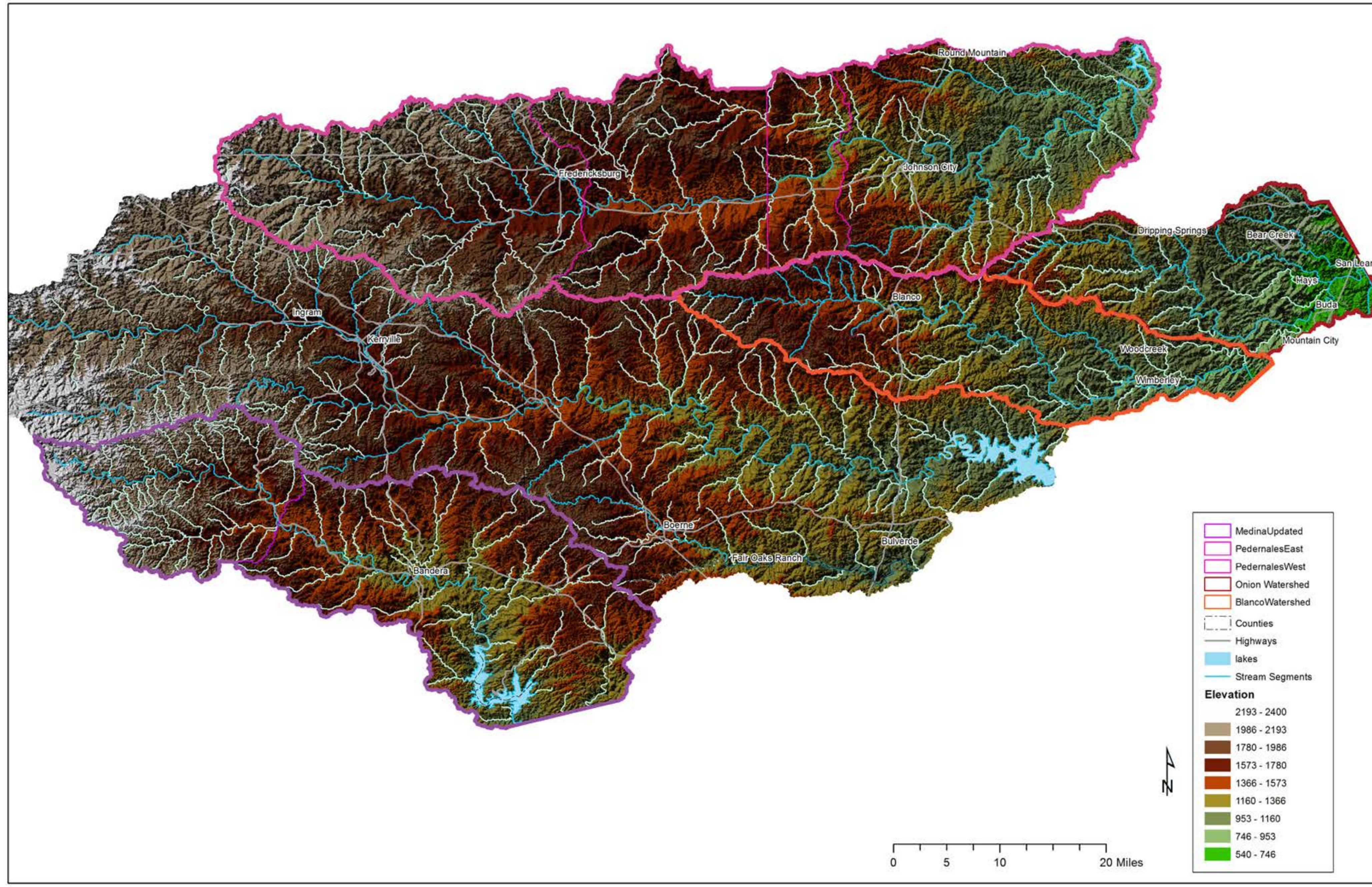
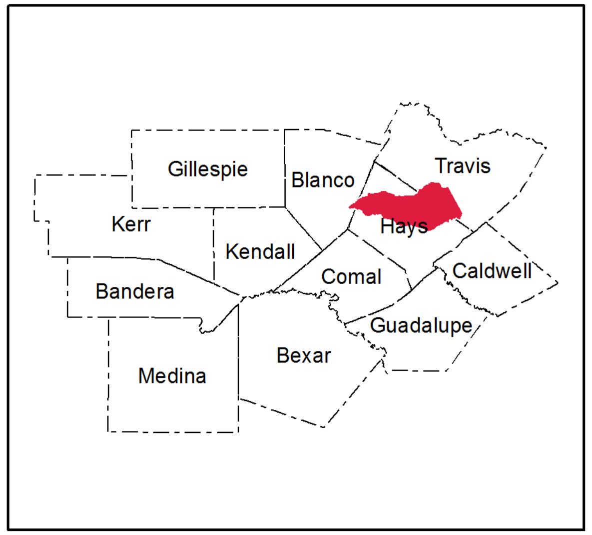


Figure 1A. General location map of study area showing ground terrain



- Onion Creek: This project focused on the geographic area including the headwaters in Blanco County to the Balcones Fault Zone. This reach of Onion Creek has undergone significant development and the resulting increases in groundwater usage are potentially causing a long-term reduction in flow. There are no comprehensive recent studies in this area.

Figure 2B. Onion Creek



- Blanco River: This project focused on the geographic area including the headwaters in Kendall County to the Balcones Fault Zone. This reach of the river has undergone a series of recent studies to define the interaction of groundwater and surface water and serves as an example of the product of a rigorous study methodology.

Figure 3B. Medina River Watershed

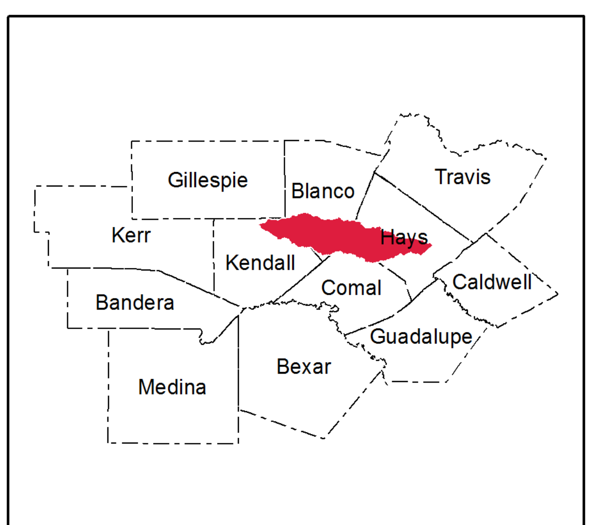


Figure 2A. Terrain Map of the Onion Creek Watershed

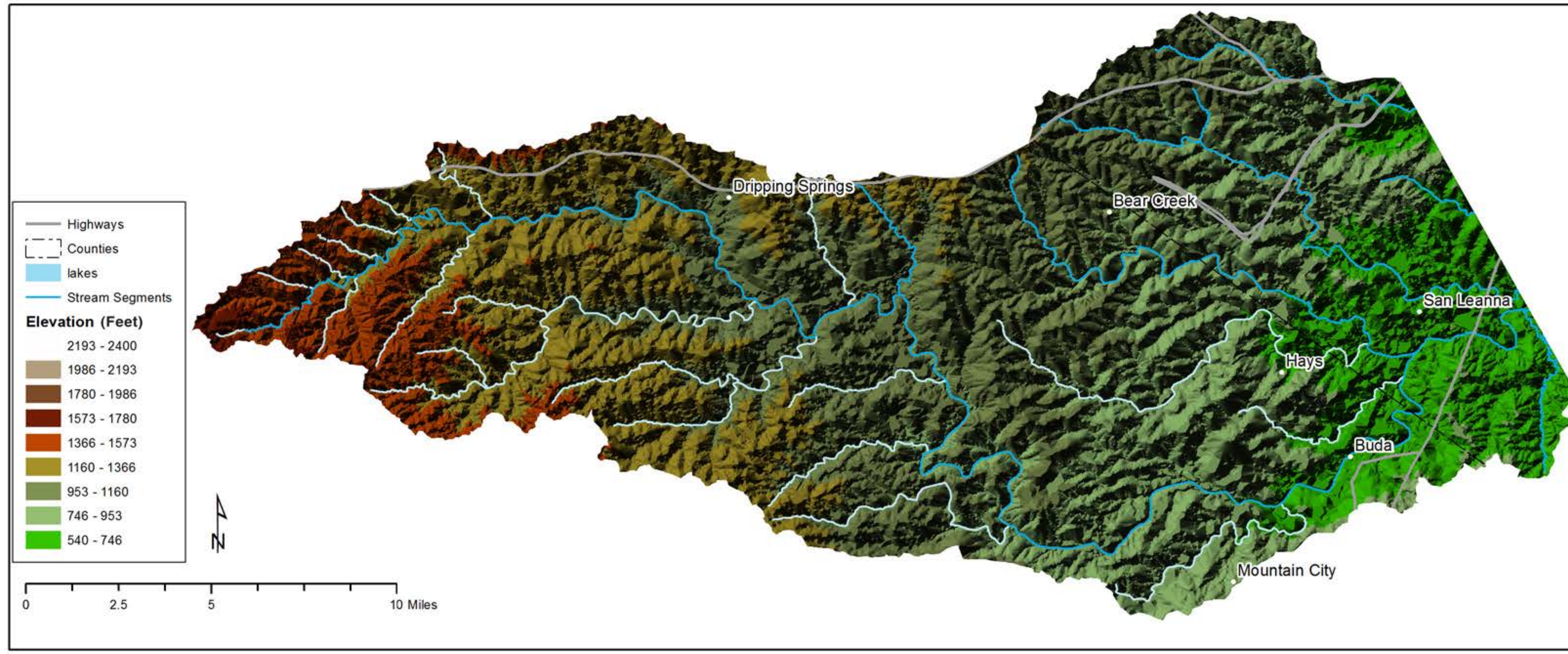
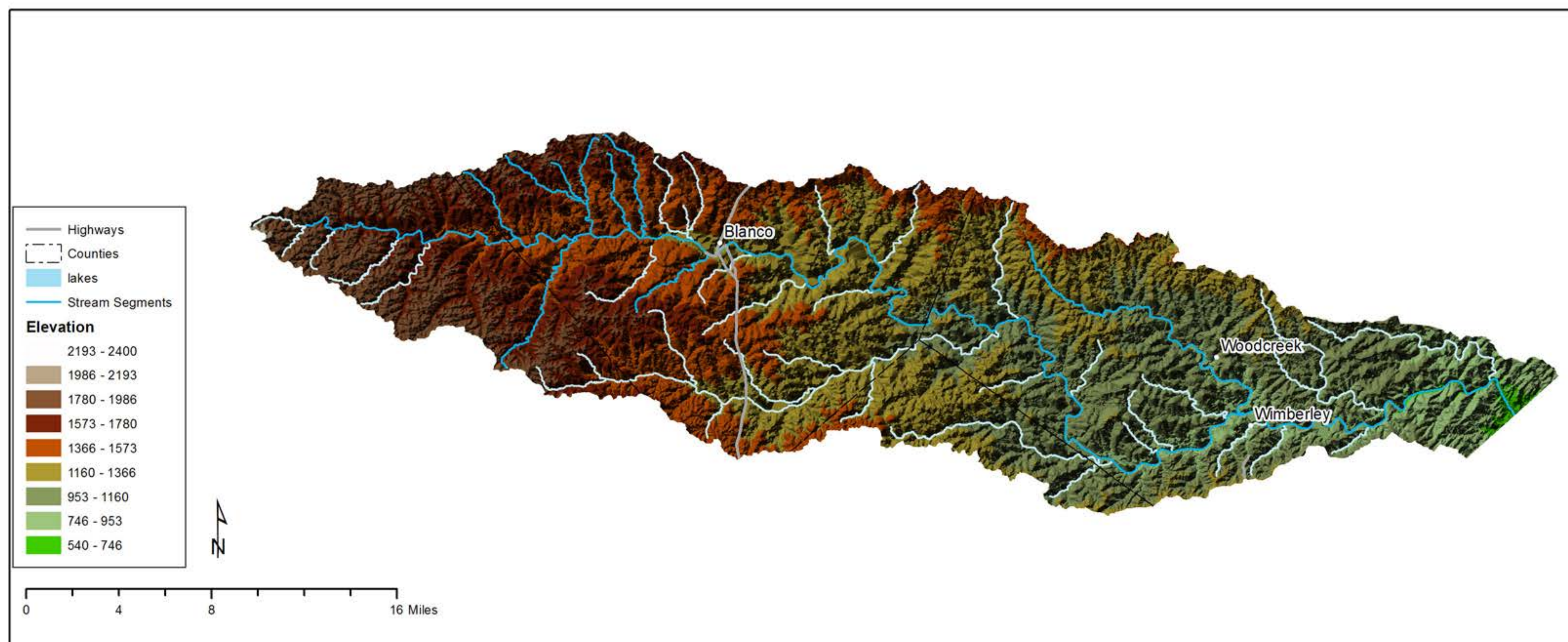


Figure 3A. Terrain Map of the Blanco River Watershed



- Pedernales River: This project focused on the geographic range including the headwaters near Harper, TX to the confluence with Colorado River at Lake Travis. The sources of gains and losses in the river have not been well studied since the 1960's. Groundwater usage for agriculture (vineyards) and development are increasing and their potential impact on gains and losses from the main channel and tributaries is not well documented.

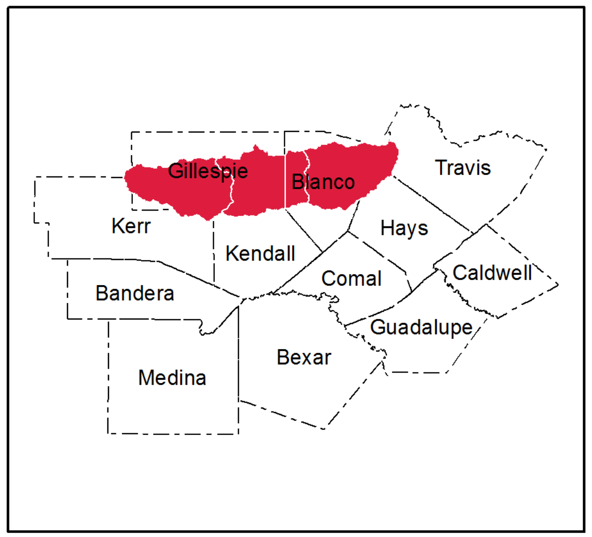


Figure 4B. Pedernales River Watershed

- Medina River: This project focused on the geographic range including upstream of Medina to Bandera upstream of Medina Lake. The groundwater/surface water interactions for this stretch of the river have not been fully identified.

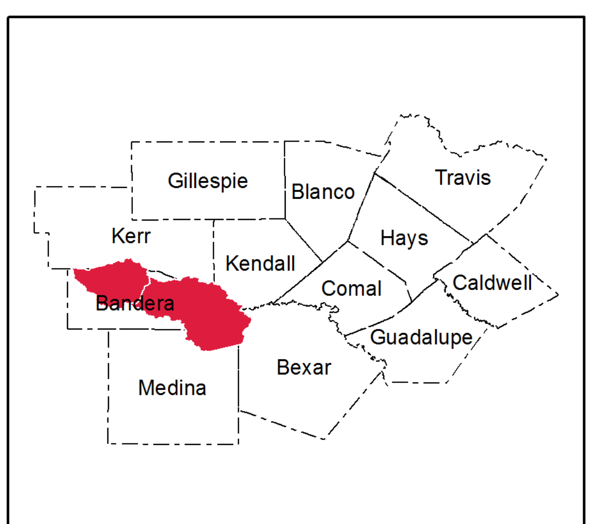


Figure 5B. Medina River Watershed

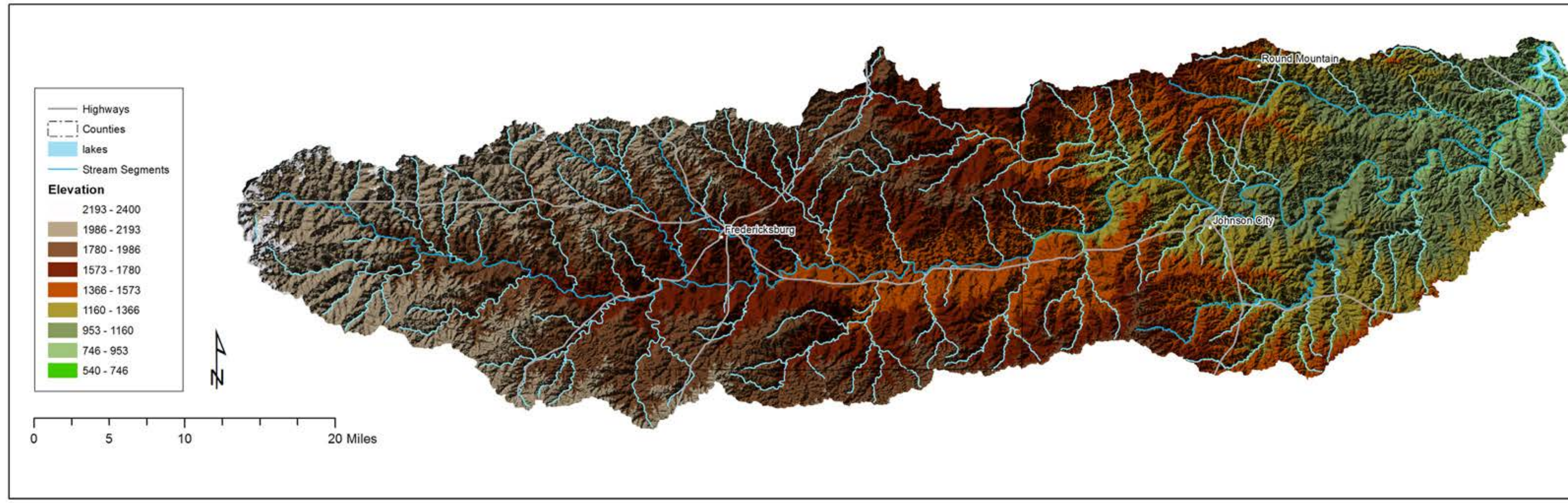


Figure 4A. Terrain map of the Pedernales River Watershed

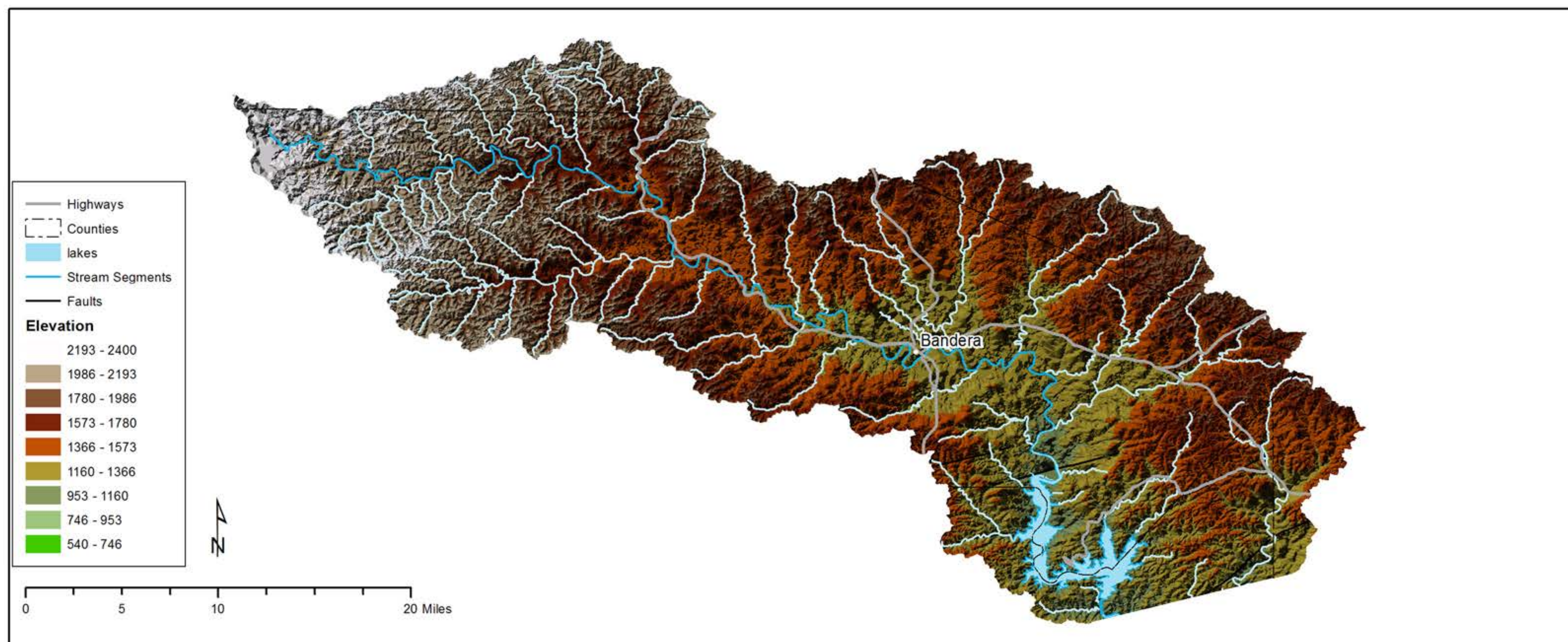


Figure 5A. Terrain map of the Medina River Watershed

INFORMAL INTERVIEWS AND SURVEYS

Project researchers conducted informal interviews and surveys to provide information and augment the concurrent research assessing how much is known about regional surface and groundwater sources (See Appendix). Initially, researchers interviewed seven water resource scientists and policy makers representing organizations including several Groundwater Conservation Districts, the Texas Water Development Board, and the Lower Colorado River Authority. These informal and information-gathering interviews helped outline the current state of:

- groundwater and surface-water management;
- monitoring;
- supply estimation; and
- research in the Hill Country.

Based on these interviews, project researchers issued two informal surveys to collect opinions from citizens interested in, or involved in, regional water issues. While these surveys and interviews were not designed to be representative of the general public, they allowed for both professional and public input on their concerns regarding the Hill Country's water supply. The interviews and surveys also collected recommendations for potential research and solutions. The results, in turn, helped affirm the scientific research, methodology, and land management strategies that this project recommends.

HYDROGEOLOGY OF THE HILL COUNTRY TRINITY AQUIFER

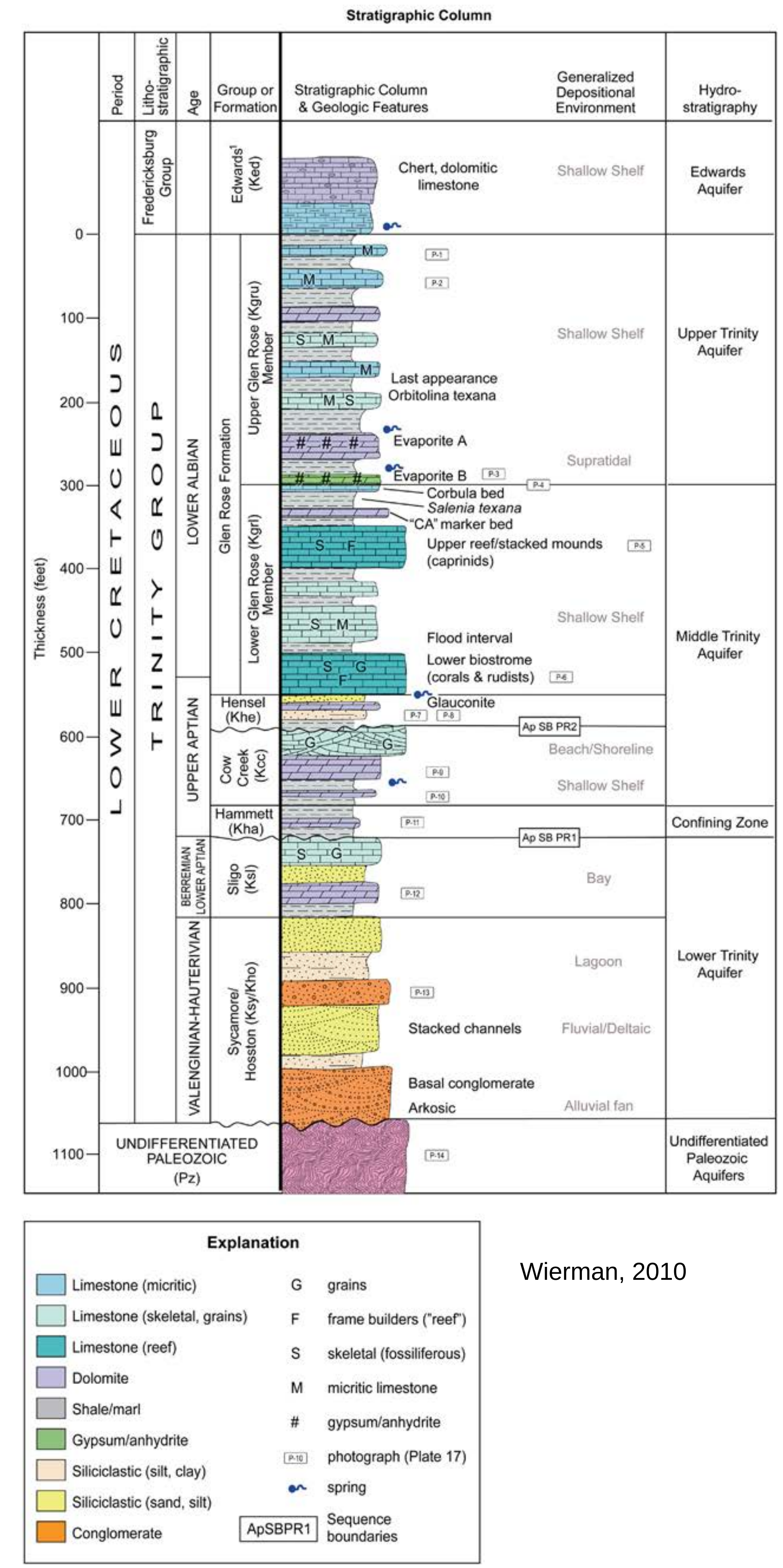
The streams included in this study generally originate from the Trinity Aquifer in the Hill Country. The Trinity Aquifer is composed of Cretaceous sediments of the Trinity Group and is divided into lower, middle, and upper aquifers based on the hydraulic characteristics of the sediments (Barker, 1994) (See Figure 6 for a Stratigraphic Column of the Trinity Group).

The Lower Trinity Aquifer consists of the Hosston and Sligo formations in the subsurface and Sycamore Sand in outcrop. The Middle Trinity Aquifer consists of the Cow Creek, the Hensel and the Lower Member of the Glen Rose limestone. The Upper Trinity Aquifer consists of the Upper Member of the Glen Rose Limestone. Low permeability sediments in the middle and upper parts of the Glen Rose limestone separate the Middle and Upper Trinity Aquifers. The Lower and Middle Trinity Aquifers are separated by the low permeability Hammett Shale except where it pinches out in the northern part of the study area (Mace, 2000).

The study area is completely underlain by the Middle Trinity Aquifer. (See Figure 7 for a Geologic Map of the Study Area and Figure 8 for a Key to the Geologic Units). The Upper Trinity aquifer exists in most of the study area except where it has been eroded away along the lower reaches of the Pedernales, Blanco, Guadalupe, Cibolo, and Medina rivers.

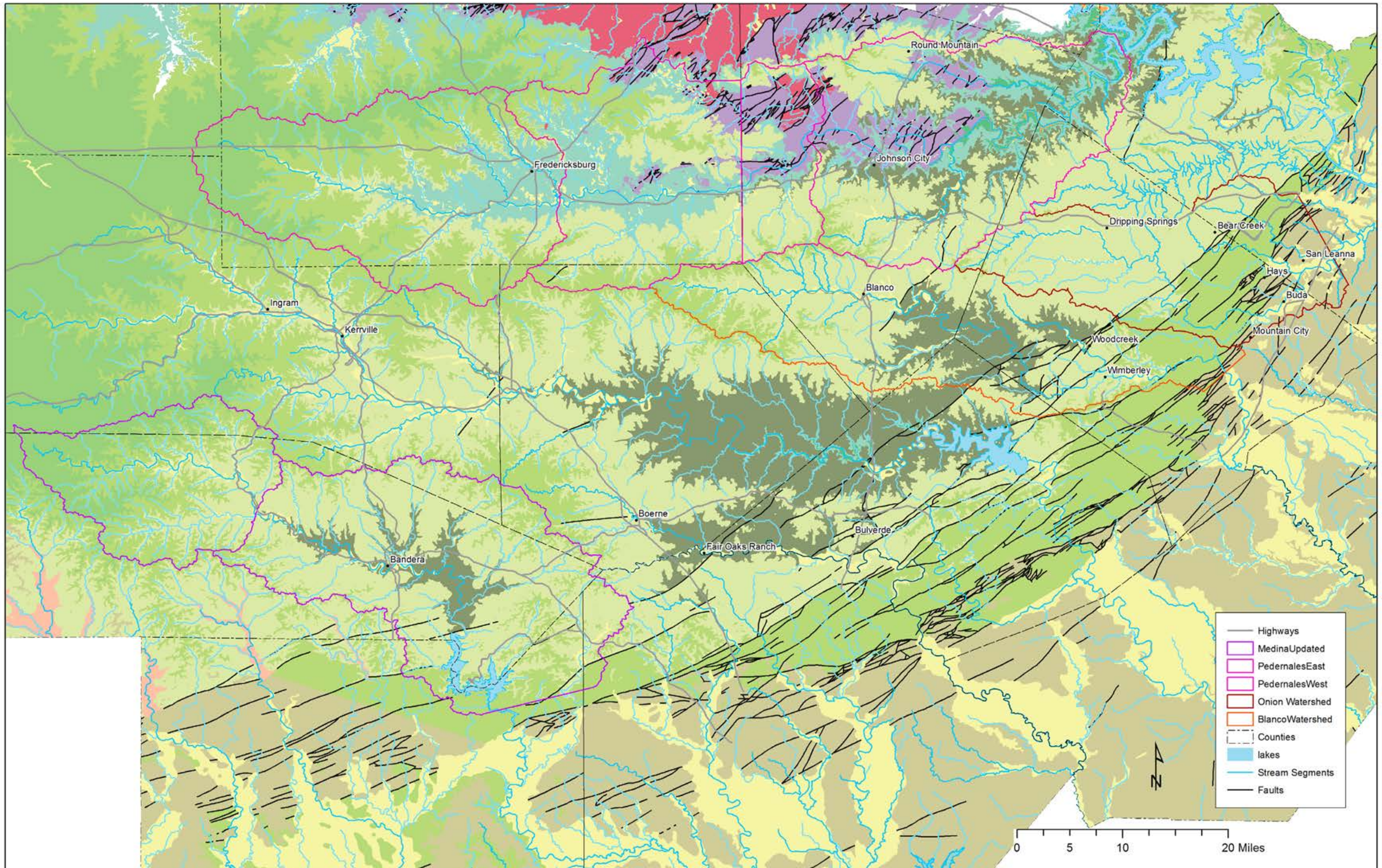
In the western part of the study area, the Edwards Group cap the Trinity Aquifer sediments and form the Edwards Plateau. (Mace, 2000) The Pedernales River also flows over Cambrian and Ordovician Age strata along the flanks of the Precambrian Llano Uplift in western and central Blanco County.

Figure 6. Stratigraphic Column of the Trinity Group.



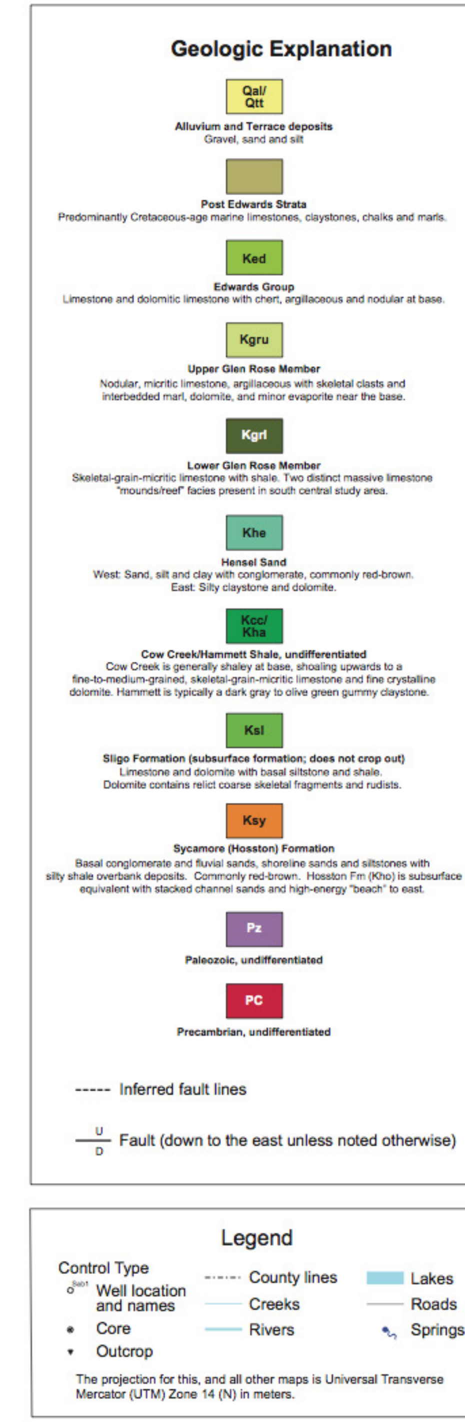
Wierman, 2010

Figure 7. Geologic Map of the Study Area



Source: Geologic Atlas of Texas

Figure 8. Geologic Units Key



The Balcones Fault Zone (BFZ) traverses the eastern edge of the study area. Along the fault zone, the Trinity and Edwards Group sediments have been down faulted through a series of normal faults such that the Edwards Group are adjacent to Trinity sediments as shown on Figure 9.

Many of the rivers and streams in the area arise along the eastern margins of the Edwards Plateau, such as the Medina, Pedernales, Guadalupe, and Blanco rivers. The streams generally traverse from west to southeast. In gaining streams, groundwater seeps out contributing to streamflow. In losing streams, stream water moves into groundwater systems. Most of the Hill Country streams have a net gain of water from the Trinity Aquifer system where groundwater seeps from shallow gravity springs into the streams along shallow impermeable bedding plans. Streams in the study area also gain significant flow where structure features such as fractures, faults, and karst penetrate confining units and create artesian springs such as Jacob's Well and Pleasant Valley Spring in the Blanco River basin. Significant stream losses can also occur when streams flow over karst features, fractures, and faults in areas where groundwater levels are below the level of the stream.

To understand the relationship of groundwater and surface water, an understanding of spring flow is important. Below is a summary of spring features from Springs of Texas (Brune, 2002).

> "*Springs may be classified as gravity or artesian. Artesian springs issue under pressure, generally through some fissure or other opening in the confining bed which overlies the aquifer. Most of the large springs in the Balcones Fault Zone are of this type. ……On the other hand, gravity springs drain from aquifers with no additional pressure.areas where groundwater levels are below the level of the stream.*"

The origin of most gravity springs is generally shallow and relatively local to the spring. The recharge areas for these shallow gravity springs are generally proximal to the spring and result of direct precipitation falling in the immediate area. Artesian springs are generally the result of a larger, regional hydrogeologic system with recharge contribution originating from areas often located far away from the springs.

Figure 10 is a schematic geologic cross section indicating general groundwater recharge and discharge in the Hill Country Trinity Aquifer. Shallow gravity springs tend to originate in the Edwards and Upper Glen Rose as the result of local infiltration from precipitation migrating downward until a relatively impermeable layer is encountered. Flow is then redirected laterally, typically along a bedding plane, until the bedding plane is exposed and the water flows out onto the surface. Regional recharge and groundwater flow result in Jacob's Well, a large artesian spring originating from the Cow Creek. The major source of recharge to the Cow Creek is through the Upper and Lower Glen Rose and Hensel formations, where exposed at the surface, many miles to the west of the spring. Infiltration moves downward into the Cow Creek and moves down gradient to the southeast. The Hensel becomes a confining layer overlying the Cow Creek creating artesian pressure.

Figure 9. Shematic Cross Section

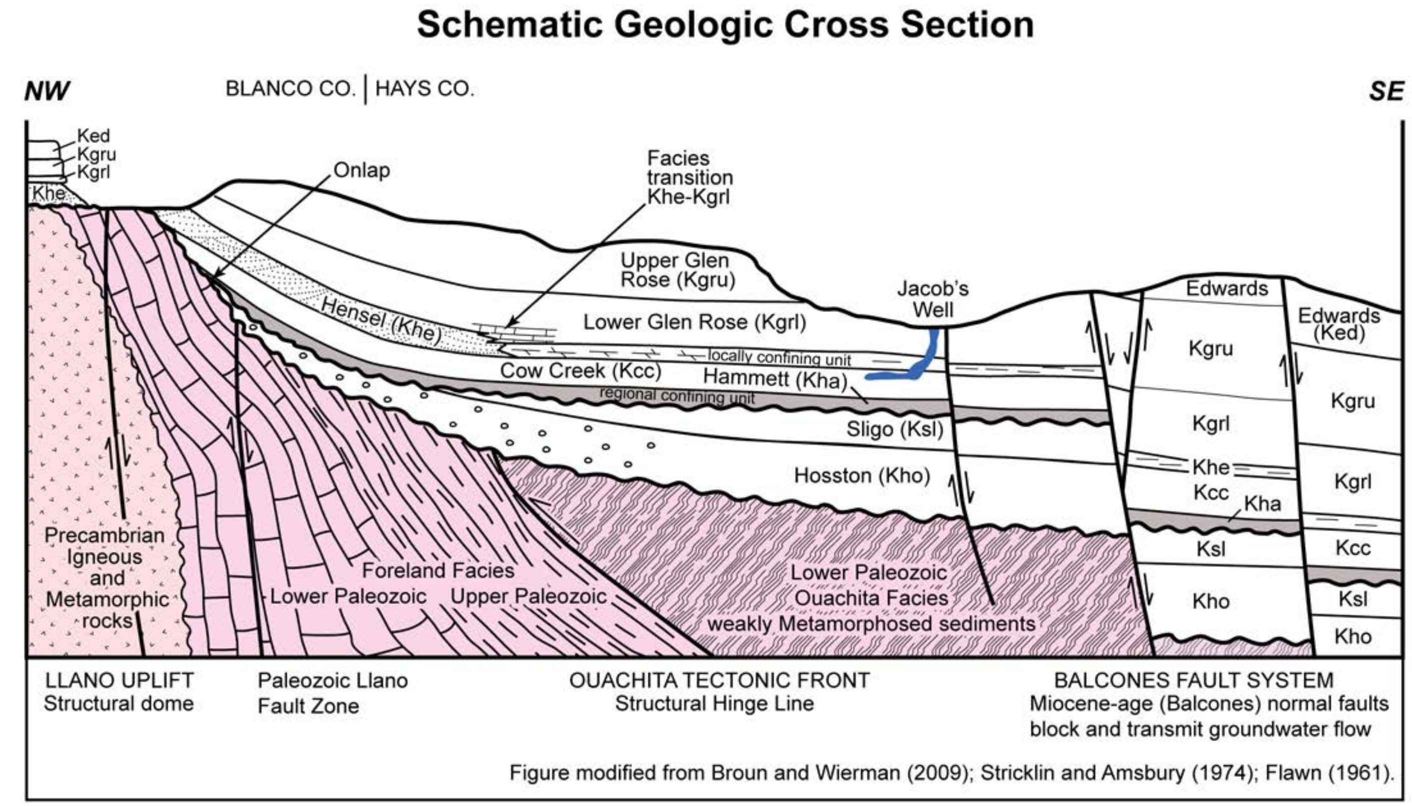
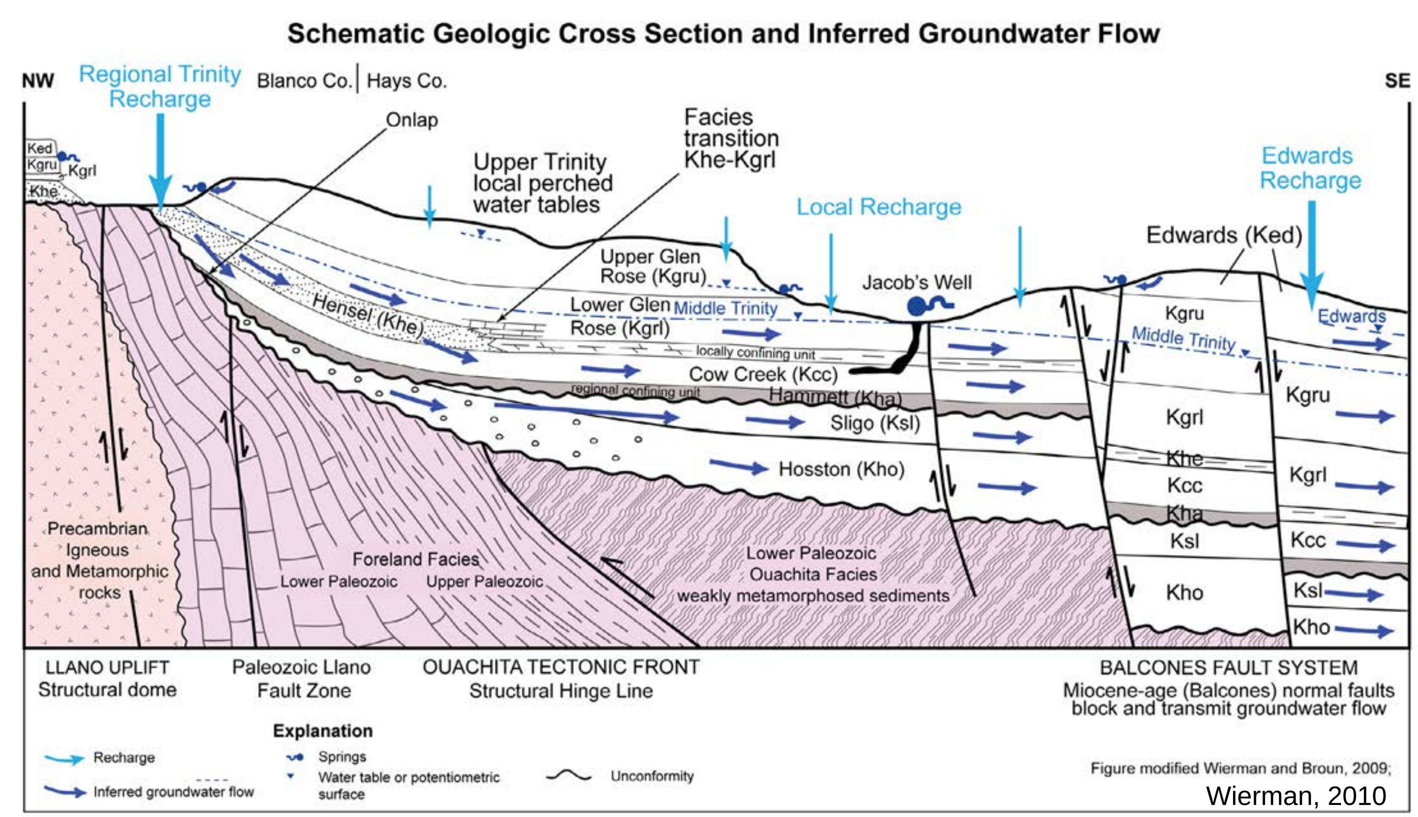
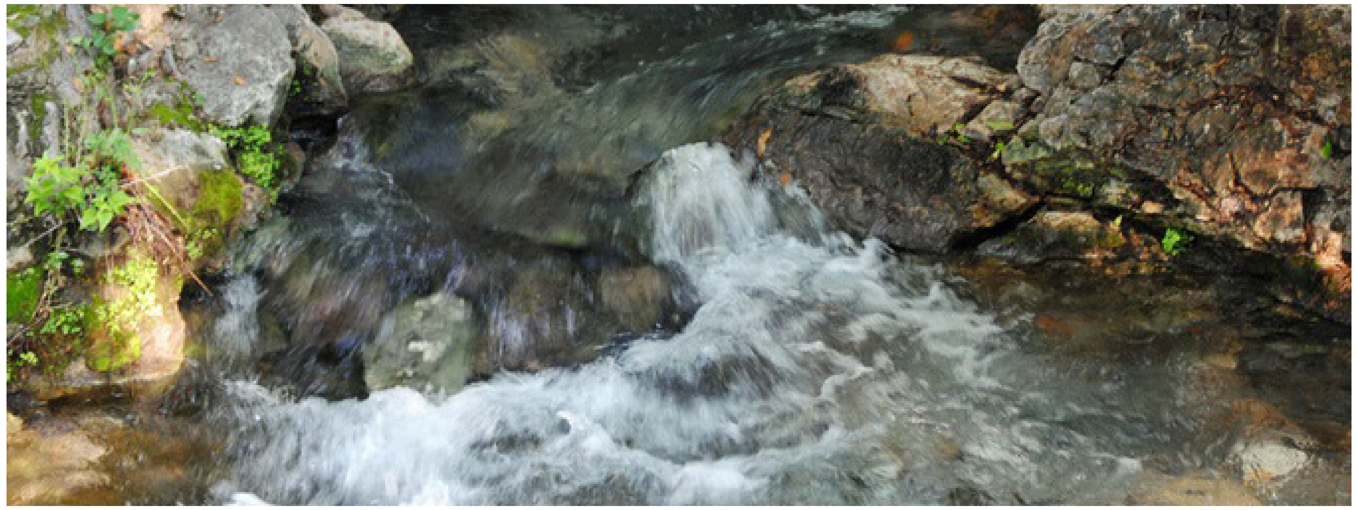


Figure 10. Schematic Cross Section and Inferred Water Flow





METHODOLOGY FOR THE STUDY OF HILL COUNTRY STREAMS

The goal of any hydrogeologic study is to understand the geologic setting and how groundwater and surface water interact with the local geology. Based on literature review, interviews and experience in the Hill Country, the hydrogeologic tools that are generally effective in understanding the hydrogeologic setting of the Hill Country Trinity Aquifers include:

1. State Well Reports;
2. Classification of drill cuttings;
3. Downhole geophysical logs;
4. Geologic mapping;
5. Water level monitoring;
6. Water quality monitoring;
7. Stream gain/loss studies; and
8. Dye tracing studies.

These tools and their effectiveness and limitations are summarized below.

1. State Well Reports

The State of Texas requires that well drillers prepare and submit State Well Reports (SWR) to the Texas Department for Licensing and Registration (TDLR) and the local groundwater conservation district (GCD). The Texas Water Development Board (TWDB) posts logs for the entire state on the Water Information Integration & Dissemination (WIID), which is an online viewer of groundwater data (http://wiid.twdb.texas.gov/). The TDLR also maintains an electronic database of well logs. Most GCDs maintain paper copies of logs drilled within their jurisdiction. Thousands of wells have been drilled in the area of interest. The databases only contain a fraction of the number of wells that have been drilled. For example, the Hays Trinity Groundwater Conservation District, which covers approximately 54% of Hays County, estimates there are over 5,000 exempt residential wells in the district (HTGCD, 2005). The TWDB database only includes approximately 2,500 wells for all of Hays County.

The reports include information on well construction, such as well location, depth, well diameter, casing type. A lithologic log is also required indicating the geologic units encountered while drilling. There are several problems that are common when attempting to use state well reports for hydrogeologic interpretation. Many of the older logs are difficult to locate, particularly wells drilled before GPS instrumentation was widely available. Similarly, the accuracy of the well elevation is generally poor. The lithologic log on most well reports is very general and difficult to correlate with accepted geologic terminology. The reports do provide insight into what depths and aquifers are penetrated in a given area and ranges of well yields.

2. Classification of Drill Cuttings

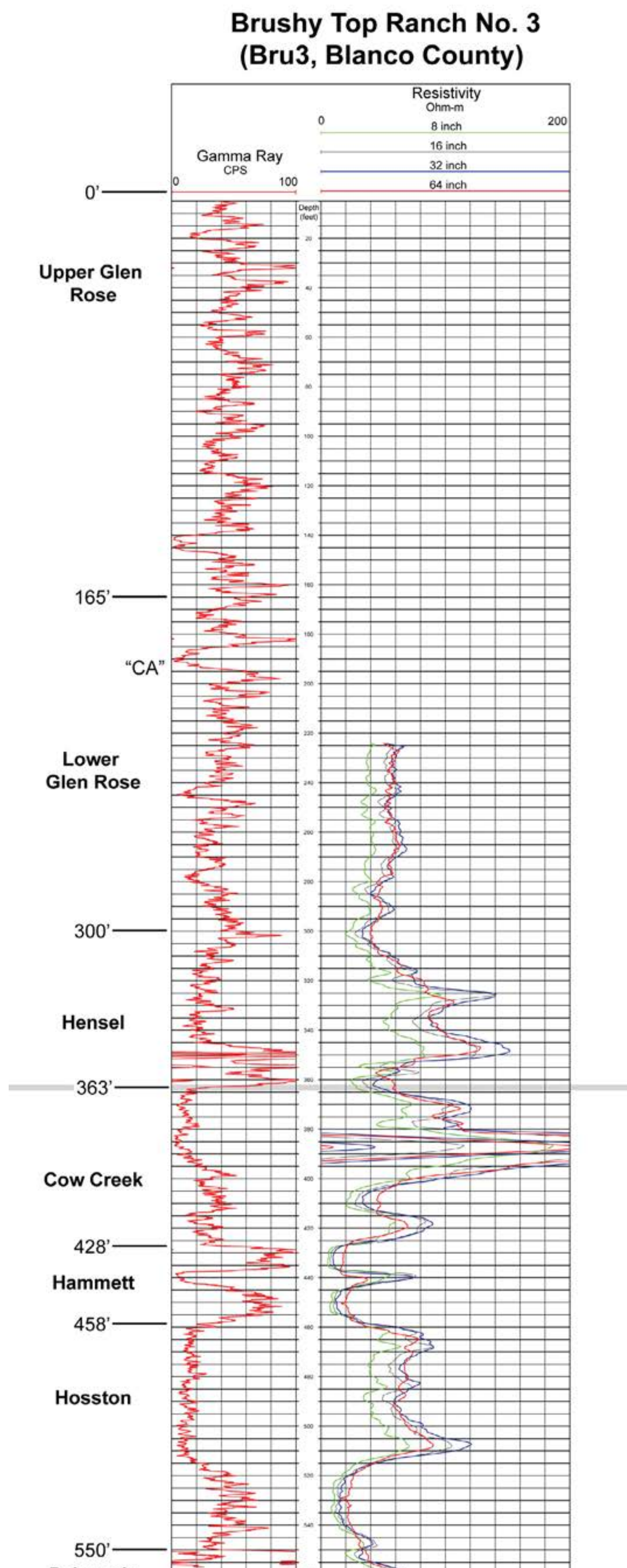
During the drilling of a water well, rock cuttings, or chips, representative of the formations being penetrated are bought to the surface. The cuttings can be collected at regular intervals while drilling. The cuttings can be visually examined, classified as to rock type and compared to surface outcrops to interpret from which formations they originated. Classification of drill cuttings is the more direct way to interpret subsurface geology from wells, but is infrequently performed. The classification process is quite time consuming and sample collection requires extra effort from drillers over what is required by law.

3. Downhole Geophysical Logs

Given the information constraints in the state well reports to interpret local geology, many of the Hill Country GCDs are using downhole geophysical logging techniques to aid in delineating their local stratigraphy. Geophysical logs are often run immediately after drilling a new well, prior to installing a well pump. Most GCDs do not require a log to be run, therefore most new wells do not have geophysical logs. The Blanco Pedernales Groundwater Conservation District (BPGCD), Hill Country Underground Water Conservation District (HCUWCD), Bandera County River Authority and Groundwater District (BCRAGD) and Central Texas Groundwater Conservation District (CTGCD) have recently jointly purchased a downhole geophysical logging unit and have since logged over 240 wells. The GDCs will log wells at the well owner's request for no charge as along as the pump is not in the well.

The natural gamma log is the most commonly used geophysical tool. The natural gamma log measures natural gamma radiation emitted from geologic materials. Generally, geologic units containing abundant clay particles will produce high gamma counts. The method is very good for differentiating impermeable layers (clay-rich shales) from transmissive geologies (carbonate limestones and dolomites). Unlike many other geophysical techniques, natural gamma logs can be run in existing, cased wells. Generally, GCDs will look for opportunities to log private water supply wells, either when being drilled or when the well pump is pulled for maintenance to avoid the cost of pulling and reinstalling the well pump. Other common logs such as electrical resistance and SP cannot be run in cased wells, only open boreholes. Induced conductivity logs can be run in PVC cased wells because unlike metal casings, PVC does not interfere with the induced conductivity equipment. The geophysical log is compared to other data, such as drill cuttings and outcrop data, to derive an interpretation of the subsurface geology. It requires reviewing many geophysical logs to develop an interpretation of an area. Figure 11 is a typical geophysical log complete with interpreted geology.

Figure 11. Typical Geophysical Log



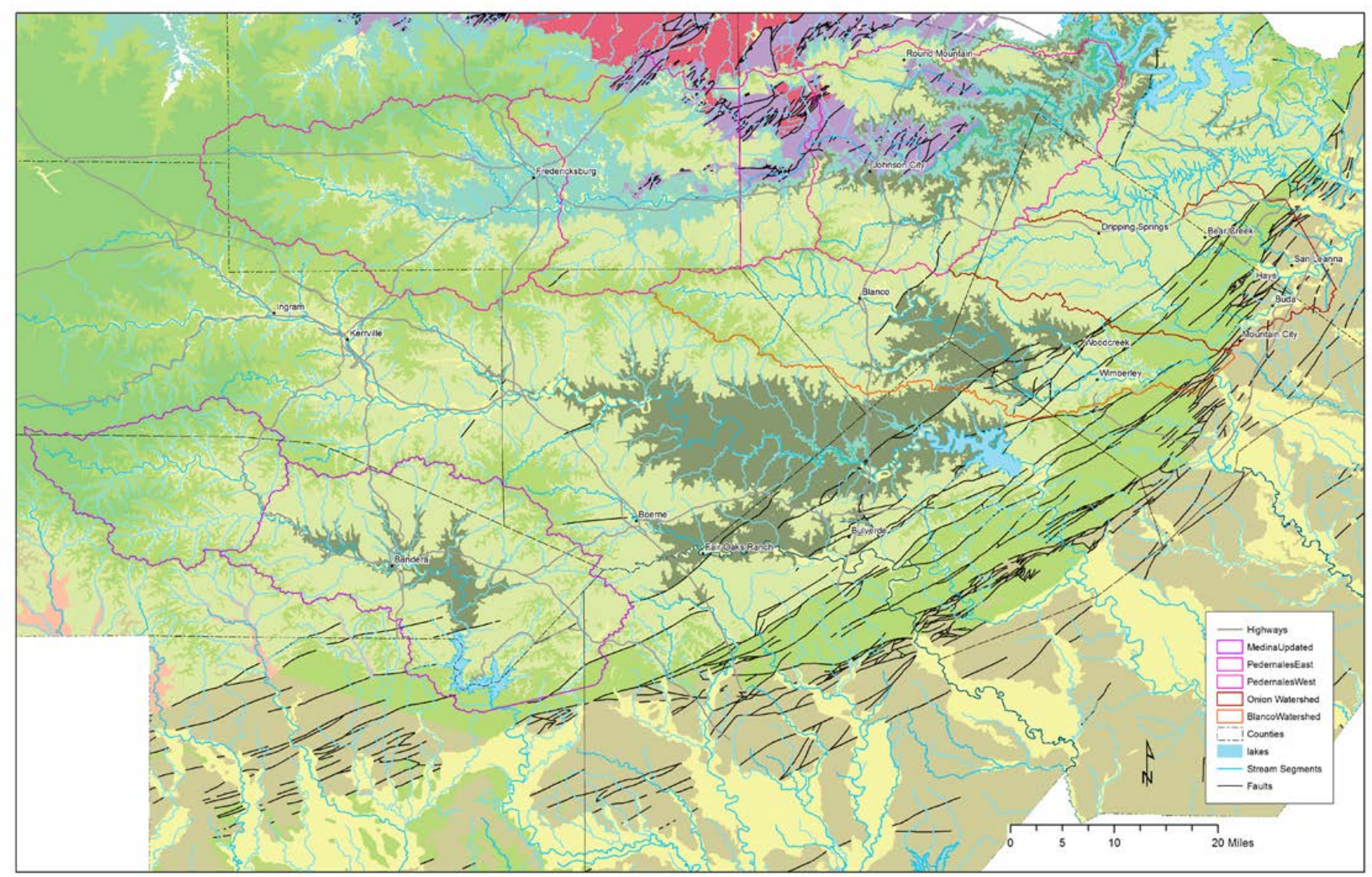
From Wierman et al 2010

4. Geologic Mapping

There are numerous publications describing the geology and geologic maps of the basins of interest. Figure 12 shows the general geology of the study area watersheds using the Geologic Atlas of Texas (GAT) as the source of the geologic maps (http://www.twdb.state.tx.us/groundwater/aquifer/gat/). Geologic references such as the GAT are too large in scale to aid in identifying local features related to groundwater/surface interactions such as faults, geologic structures, springs, and karst features. Detailed field mapping can be used to supplement larger scale geologic maps to identify the relationship between local geologic structure, springs and regional geology. Field work should include both the main stream channel and major tributaries. For example, work on the Blanco River has illustrated the value of detailed, field mapping in identifying the relationship between faults, fractures, and karst features and the occurrence of springs and sinks in both the main channel and major tributary, Cypress Creek. Figure 13 is an example of detailed geologic descriptions of an outcrop along the Blanco River.

The compilation and analysis of State Well Reports, geophysical logs and detailed mapping enables the preparation of geologic structure maps showing the elevation of the top of a geologic unit, isopach maps showing unit thickness and geologic cross sections. The tools are useful in interpreting local geologic conditions. For example, if the depth of a well is known, one can determine which aquifer is being used by referencing a structure contour map and determining the elevation of the top of well using commonly available online tools, such as Google Earth®. An example of a structure contour map showing the elevation of the top of the Cow Creek and isopach map showing the thickness of the Cow Creek are shown on Figures 14 and 15.

Figure 12. Geologic Map of the Study Area



Source: Geologic Atlas of Texas

Figure 13. Measured Geologic Section – Upper and Lower Glen Rose Contact, Blanco River, Blanco County.
From Wierman, 2010

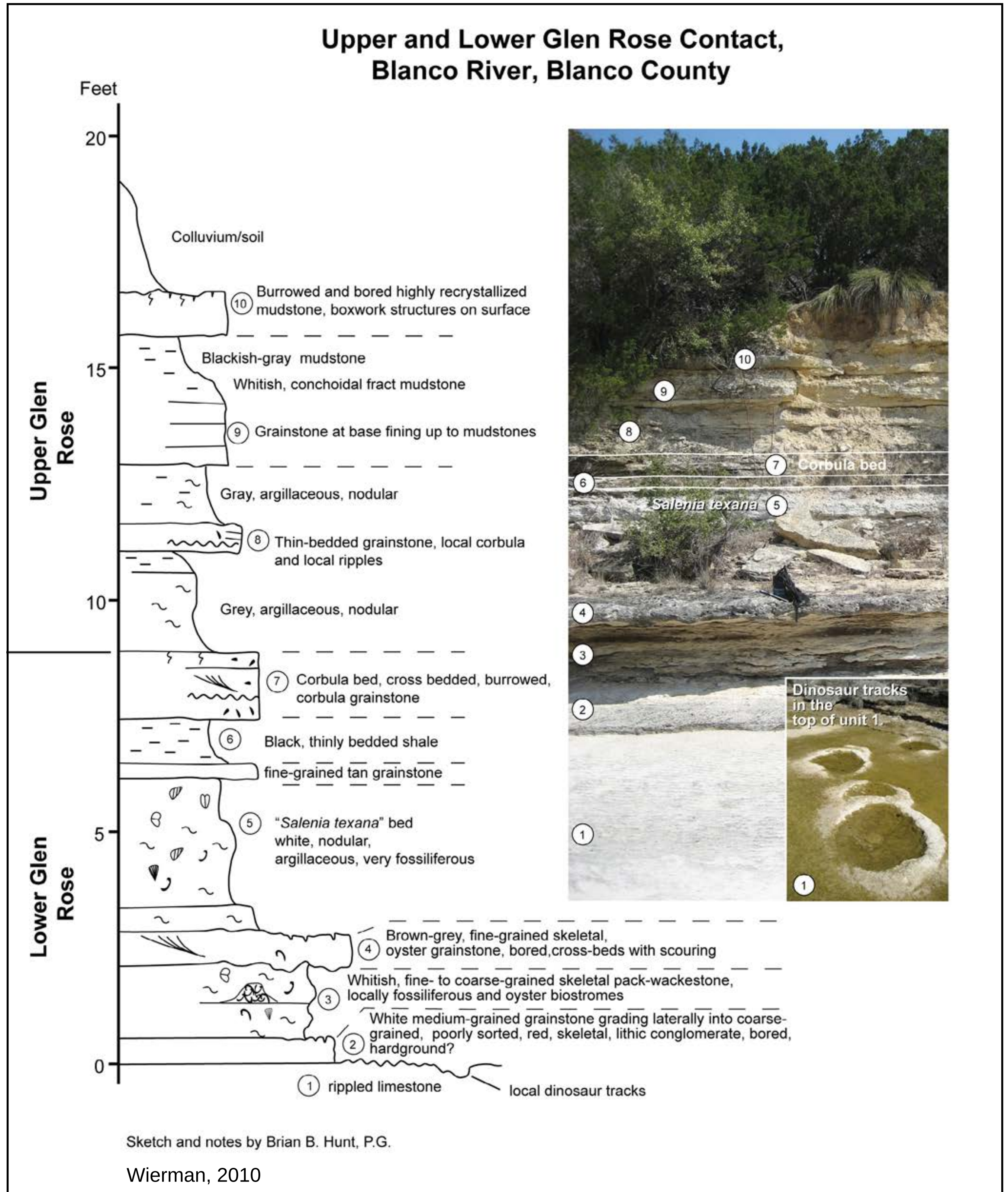


Figure 14. Isopaph Map - Cow Creek

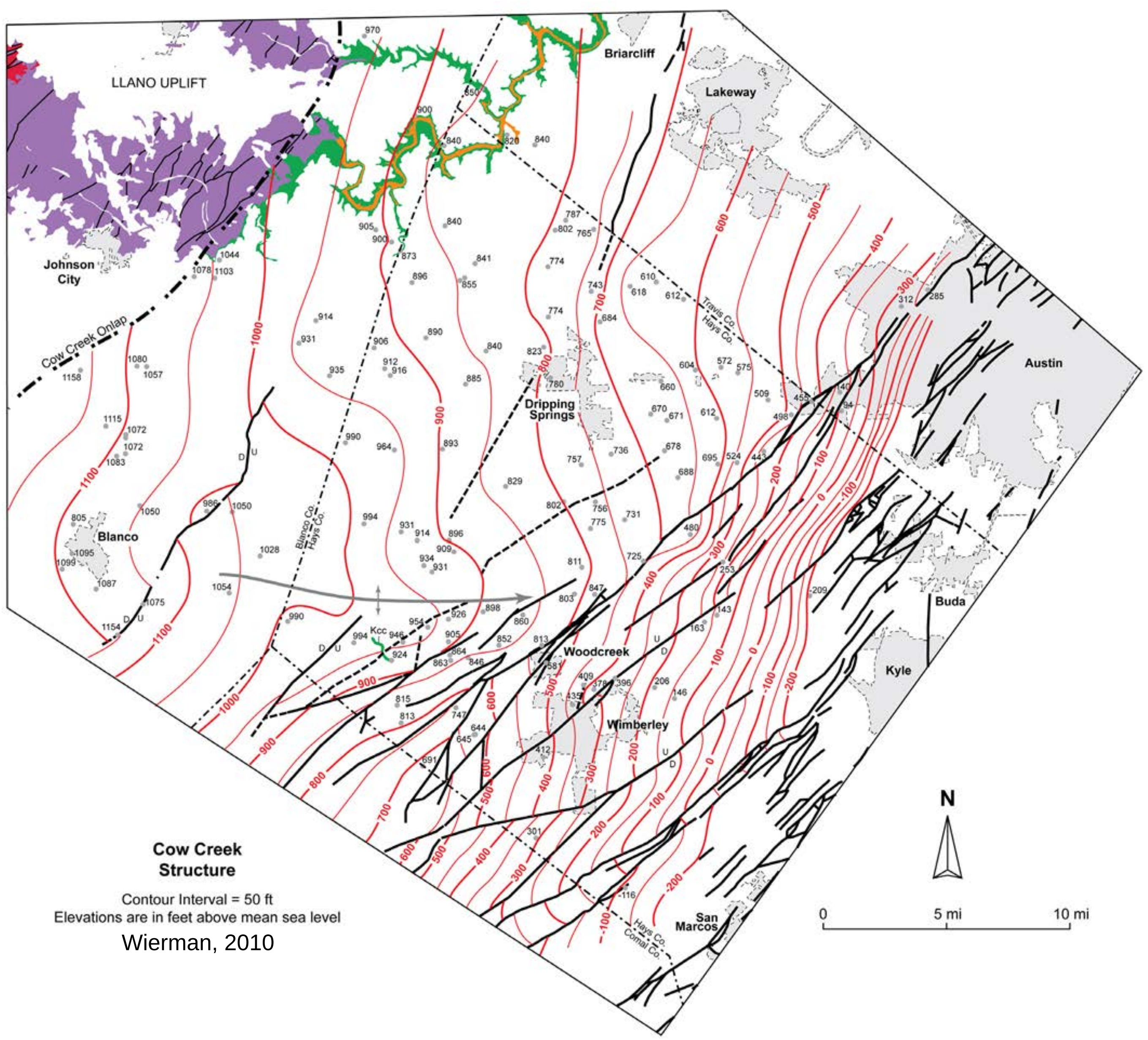
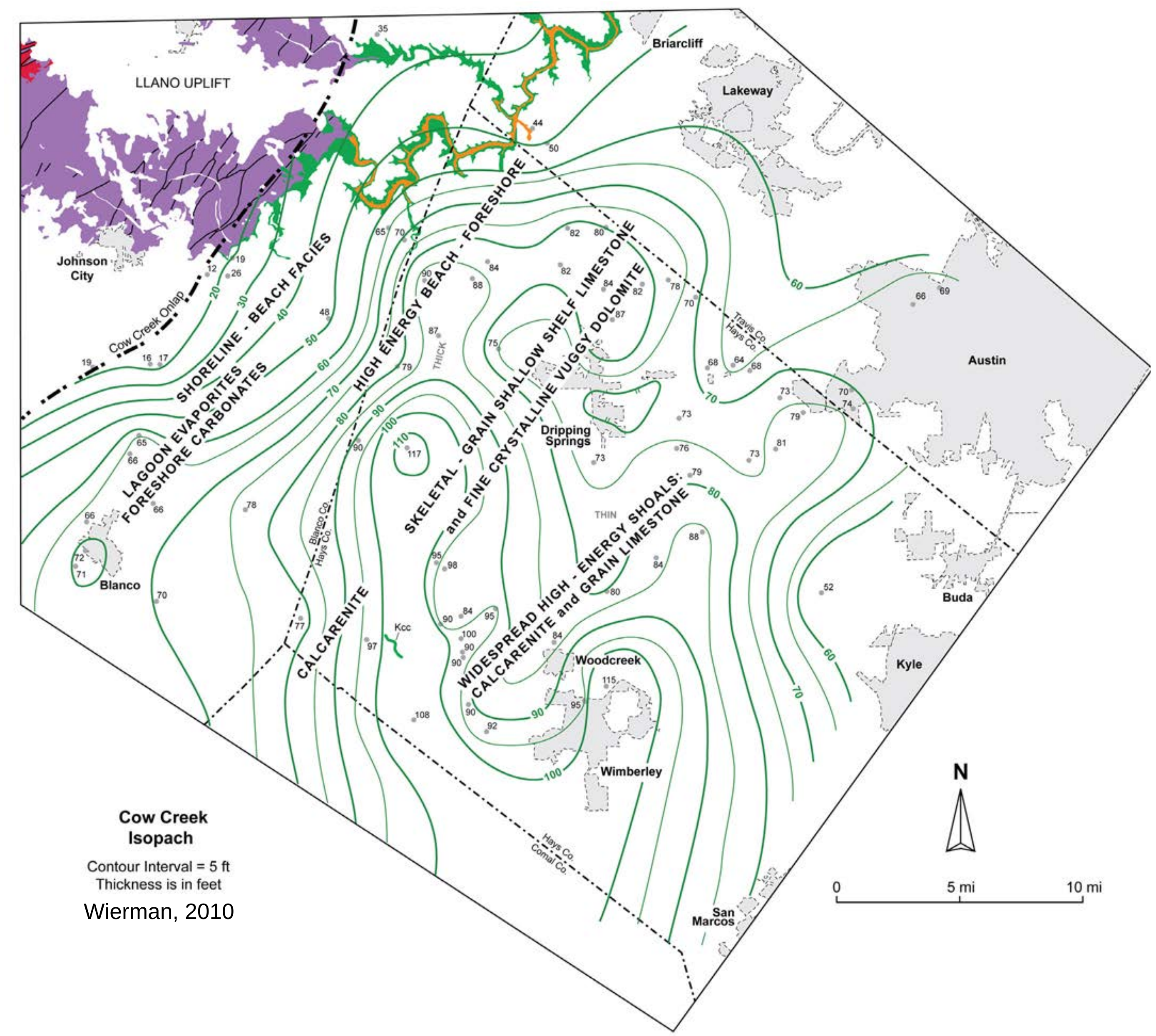


Figure 15. Structure Map - Cow Creek



5. Groundwater Water Level Monitoring

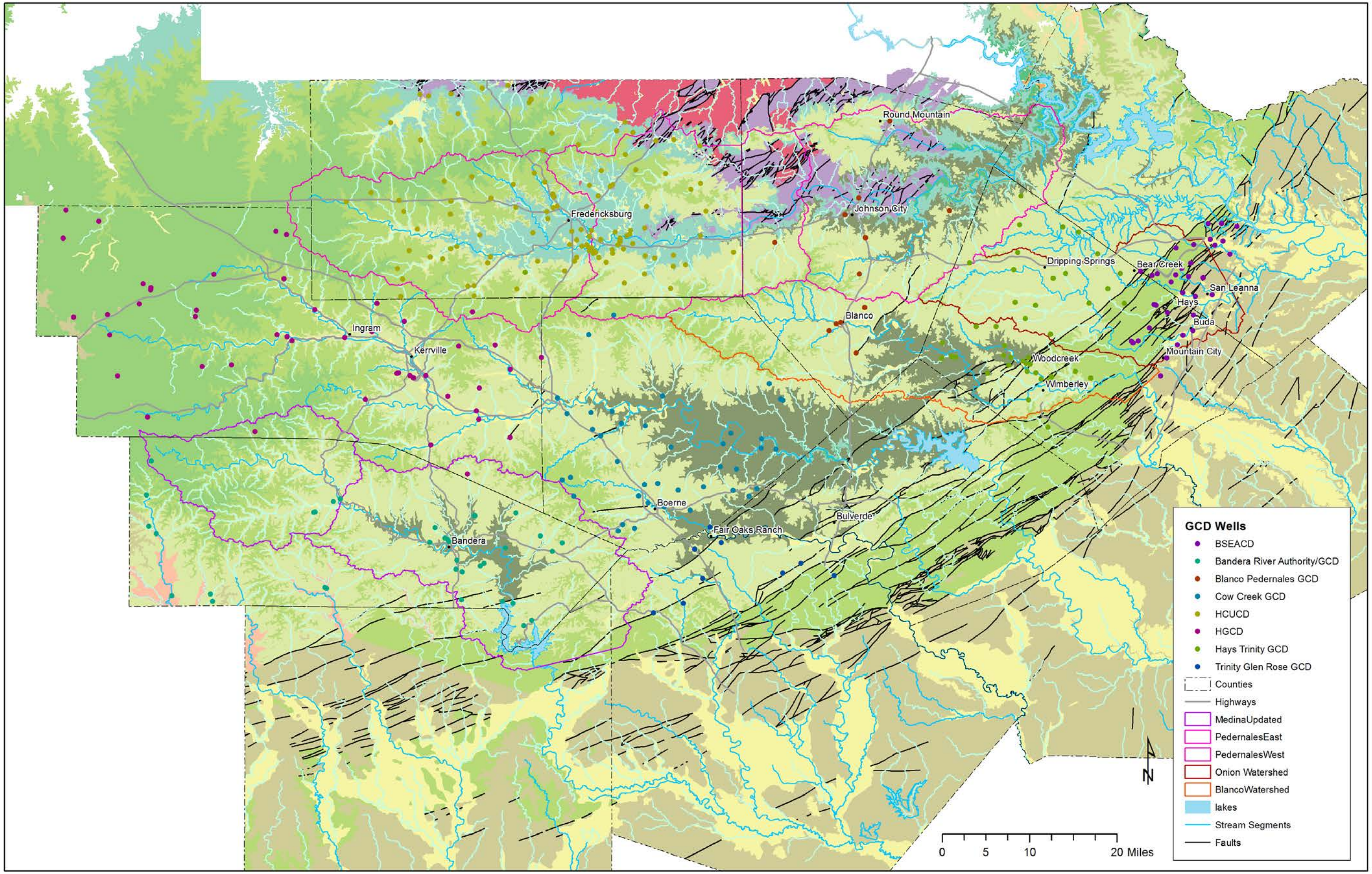
Monitoring groundwater levels in the vicinity of streams is a valuable tool to aid in understanding groundwater/surface water interactions. In areas where water levels (potentiometric surface) in the uppermost aquifer are below the base of a stream bed, there is the potential for stream loss into the aquifer depending on the permeability of the stream bed geology. If the potentiometric surface is above the elevation of the stream bed across a reach of stream, there is the potential for groundwater to flow into the stream (via spring) and contribute to base flow. The general practice in the Hill Country is measuring water levels in existing residential water wells by the local GCD. The TWDB has a statewide water level monitoring program as well and provide real-time data on line (http://waterdatafortexas.org/groundwater/). As there can be multiple aquifers at a single well location, it is important to understand the construction of the well and which aquifer the well is open to. State well reports, geophysical logs, or other local data are key to understanding which aquifer is being measured.

All of the GCDs in the Hill Country study area have routine groundwater level monitoring programs. The data is typically posted on their web pages. A summary of the number of wells being monitored is presented in Table 1. All of the wells monitored in the study area are shown on Figure 16. The frequency of monitoring programs varies from continuous to quarterly depending on the GCD.

Table1. Summary of Groundwater Conservation District Water Level Monitoring Programs

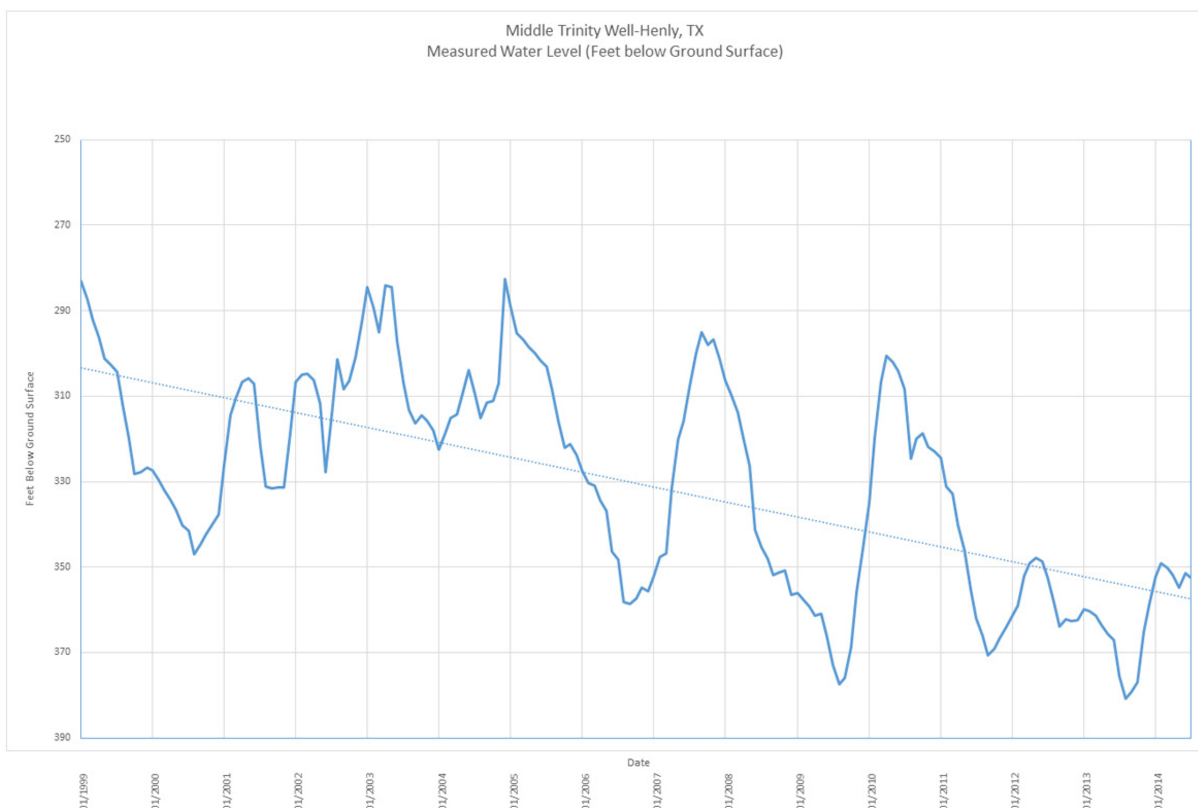
Groundwater Conservation District	**County**	**Number of Wells Monitored**
Hays Trinity GCD www.haysgroundwater.com	Hays	**44**
Barton Springs Edwards Aquifer CD www.BSEAD.org	Hays	**38**
Blanco Pedernales GCD www.blancogroundwater.org	Blanco	**12**
Hill Country Underground Water CD www.HCUWCD.com	Gillespie	**~122**
Cow Creek GCD www.ccgcd.org	Kendall	**42**
Bandera River Authority and Groundwater District www.bcragd.org	Medina	**37**

Figure 16. Groundwater Level Monitoring Wells



Groundwater levels can be used to develop hydrographs showing water level trends over time as well as potentiometric surface maps indicating groundwater elevations and groundwater flow directions. Unfortunately in the Hill Country, there are very few wells with a long period of record (over 20 years) making it difficult to determine long term water level trends. Figure 17 is a hydrograph from a Middle Trinity well in Hays County with a relatively long period of record, dating from 1999. This hydrograph illustrates the effect of wet and dry cycles on groundwater levels and an overall decline in water levels over the period of record.

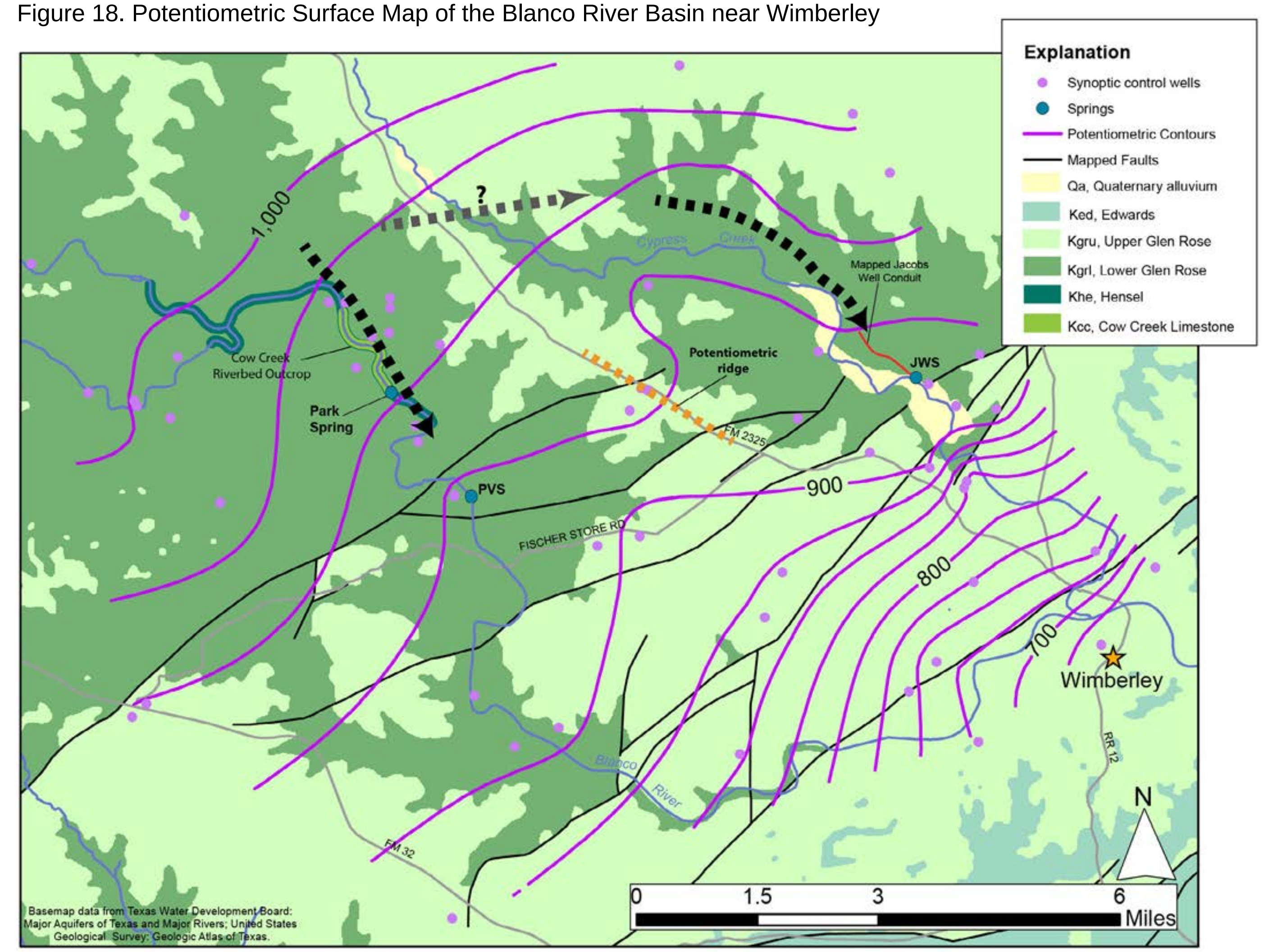
Figure 17. Hydrograph from a Middle Trinity Well



Source: HTGCD

Figure 18 is a potentiometric surface map of the Blanco River basin near Wimberley. The map was created by measuring a large number of wells within a short time frame and then plotting and contouring the groundwater elevation. The map indicates groundwater flow is generally to the southeast in the particular area of study. In addition, springs are likely to occur in areas where groundwater elevations intersect with ground surface elevations.

Figure 18. Potentiometric Surface Map of the Blanco River Basin near Wimberley



Source: Watson, 2014

6. Groundwater Quality

Comparison of surface water quality (chemistry) and groundwater quality can be a useful tool is determining groundwater/surface water interactions. Groundwater quality generally reflects the composition of the aquifer. Typically, inorganic anions and cations are measured. Cations include calcium, magnesium, sodium and potassium. Anions included chloride, sulfate, carbonate and alkalinity. Water quality results can be presented on a Piper Diagram such as in Figure 19, which illustrates water quality results from cations and anions from water samples collected from the Upper, Middle and Lower trinity aquifers and several Hill Country streams. It appears the stream ore closely resemble water quality in the Upper and Middle Trinity Aquifers, and not the Lower Trinity Aquifer.

C14, a radioactive isotope of carbon, can be useful in measuring the age of groundwater if the groundwater is less than 50,000 years old. C14 is often expressed as a percentage of modern carbon. Generally, waters recharging aquifers from the surface have the same concentration of C14 as the atmosphere, which is relatively constant. Over time, the C14 decays and concentrations decrease. C14 is a good indicator of relative age, but there are other factors that affect the C14 concentration in groundwater. Inorganic carbon dissolved from carbonate rocks such as the Hill Country Trinity Aquifers can affect C14 values.

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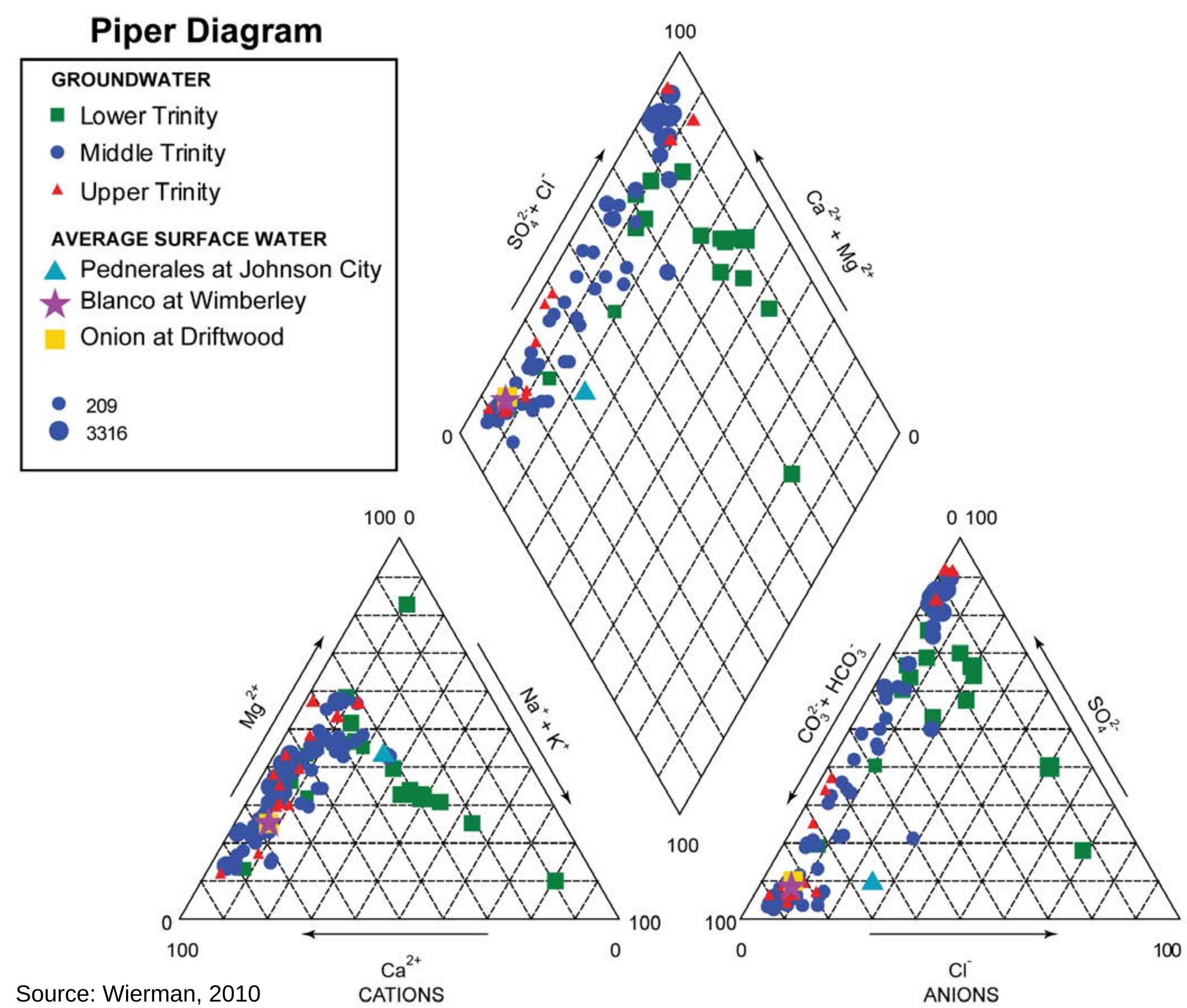
Tritium (a radioactive isotope of hydrogen) is an element that exists in very small concentrations naturally within the earth's environment as a product of the lithium decay. Large concentrations of Tritium were deposited into the atmosphere anthropogenically during the nuclear testing of the mid-20th Century. Prior to nuclear testing Tritium concentrations ranged only from 2-8 Tritium units. After the testing, it is estimated that $1.12x10^{9}$ Tritium units were added to the atmosphere in the northern hemisphere. Since nuclear testing has ceased, Tritium concentrations have decayed to approximately 13-14 Tritium units. By measuring the amount of Tritium in a water sample, you can determine when the water was last in the atmosphere, and subsequently how long ago the water was precipitated on the earth. Using tritium data collected directly from springs we can determine how long the water has been underground during its recharge path is from recharge zone to spring (Motzer, 2007).

The relative dating ranges are as follows:

- <0.8 TU indicates submodern water (prior to 1950s)
- 0.8 to 4 TU indicates a mix of submodern and modern water
- 5 to 15 TU indicates modern water (<5 to 10 years)
- 15 to 30 TU indicates some bomb tritium
- >30 TU: recharge occurred in the 1960s to 1970s

In the area of interest, some C14 data have been collected over the last few years (Wierman, 2010). Additional C14 data and tritium data is currently being collected by the TWBD through BSEACD for the study area.

Figure 19. Piper Diagram of Trinity Aquifer and Select Stream Samples



Source: Wierman, 2010

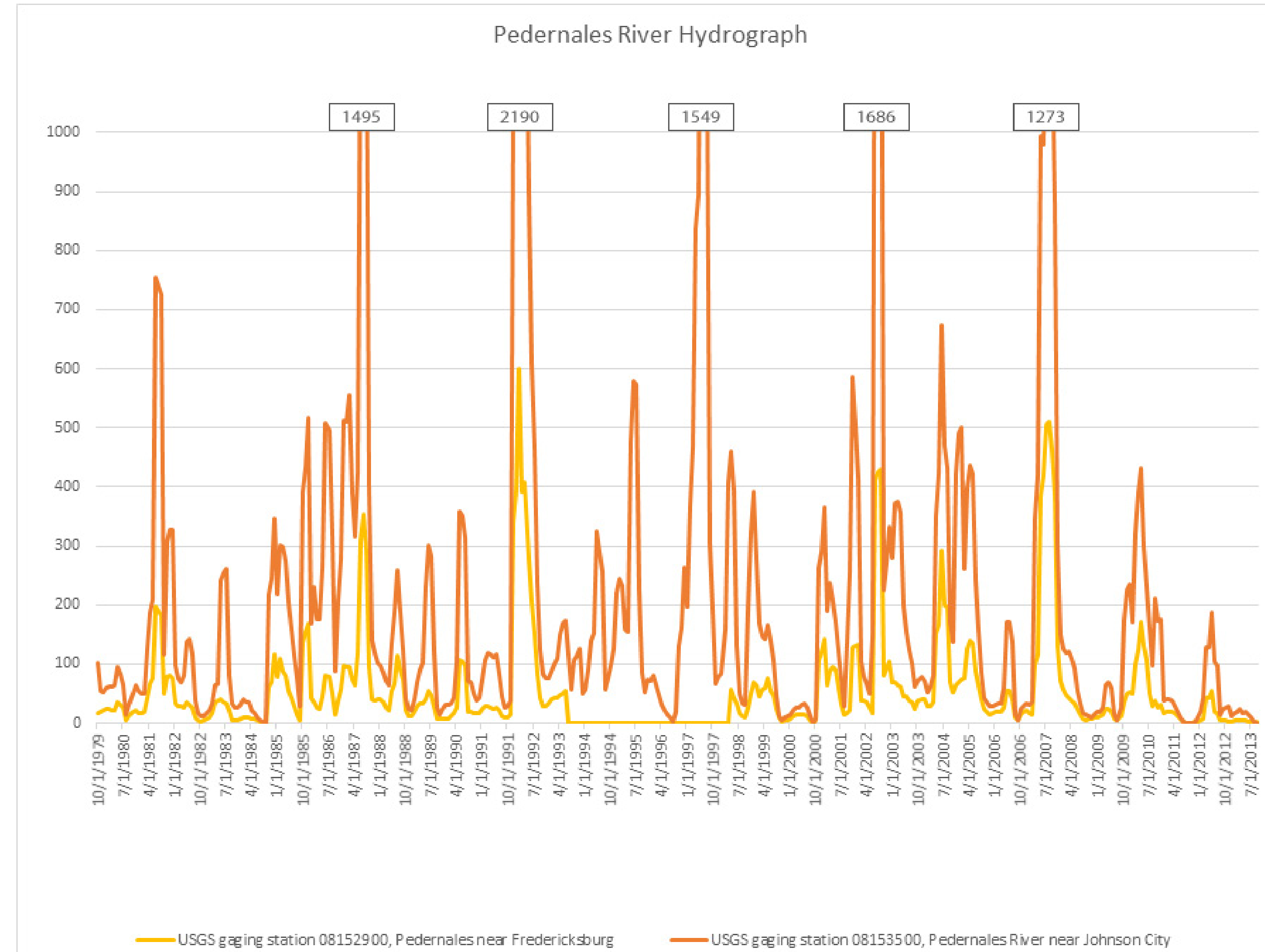
7. Stream Gain/Loss Studies

The interconnectivity of groundwater and surface water can be quantified through gain/loss studies, sometimes referred to as base flow studies. In the Trinity Aquifer, where streams flow across areas of exposed rock (outcrops), stream flow gains and losses are indicative of aquifer discharge and recharge. Stream flow gains indicate groundwater discharge and stream losses indicate aquifer recharge. Gain/loss studies are conducted by measuring stream flow at two points, one upstream and one downstream, and comparing the difference. If the downstream point has more flow, then the stream is gaining (aquifer discharge). Conversely, if the downstream flow is lower, the stream is losing (aquifer recharge). Gain/loss studies are typically performed during base flow conditions to minimize any effect from short term stormwater runoff (Wierman, 2010).

As stated previously, most Hill Country streams gain flow from northwest to southeast. For example, review of long term stream gaging data from USGS gaging stations (www.usgs.gov) on the Pedernales River (See Figure 20 for gages near Fredericksburg and Johnson City) indicates relatively consistent gains over time. While comparison of discharge at USGS gages is useful in documenting gains or losses over a long reach of river, this type of analysis is not of sufficient detail to determine specific areas of gain and loss and their potential relationship to local land practices and water use.

A review of the literature for gain/loss studies on the streams of interest indicate many of the detailed studies were performed in the 1920s, 1950s, and 1960s. A summary of the major gain/loss studies performed on study area rivers is presented in Table 2. It is important to note that this table is not inclusive of all studies performed. The studies conducted in the 1950s and 1960s were as a result of the drought of the 1950s and documenting the impact of drought on flow in Hill Country streams. The studies in conducted 1960s documented flow conditions during more "normal" flow conditions during non-drought conditions.

Figure 20. Hydrograph from two Gaging Stations on the Pedernales River



Areas of gain and loss can change over time. For example, it has been documented that groundwater pumping from the Middle Trinity Aquifer in the vicinity of Jacob's Well spring causes a reduction in its flow (Wierman, 2008). If a stream derives much of its flow from shallow gravity springs originating in close proximity and the area is subsequently developed with a large amount of impervious cover, then stream flow gain will be reduced.

Computer modeling by the TWDB for Groundwater Management Area #9 (GMA 9) provides some insights into the effects of groundwater pumpage over time on river and spring flow using the Groundwater Availability Model (GAM) for the Hill Country Trinity aquifer. In GAM run 08-70 (Chowdury, 2008), a non-pumping scenario (likely reflecting Hill Country water use in the 1940s and 1950s) was compared to pumping in 2008. The results of GAM run 08-70, summarized below, illustrate that pumping has significantly decrease stream and spring flow.

> *"The steady-state model results with no pumping and average recharge conditions indicate considerable rise in water levels in the aquifers and an increase in groundwater discharges into the rivers and springs. For example, discharges to the rivers increased by up to about 9 percent in the Edwards Group Aquifer, up to 13 percent in the Upper Trinity Aquifer, and up to 22 percent in the Middle Trinity Aquifer compared to discharges during 2008. Spring discharges also locally increased by up to 9 percent in the Edwards Group, up to about 83 percent in the Upper Trinity Aquifer, and more than 180 percent in the Middle Trinity aquifers." (Chowdury, 2008)*

Due to the development in Hill Country over the last five decades, most of the older gain/loss studies of the 1950s and 1960s likely reflect groundwater/surface water interactions closer to the non-pumping scenario than the 2008 scenario.

Table 2. Summary of the Major Gain-Loss Studies Performed on Study Area

Stream Name	Date of study	Reference for data	Research Identification	Reach length (river mi)	Total gain or loss (-) in reach (ft /s)
Pedernales River	1/9 - 17/1956	TWBE (1960)	Below Harper to near Johnson City	70	3.3
Pedernales River	4/3 - 4/1963	USGS (1963)	Harper to Hamilton Pool	18.2	0.46
Pedernales River	4/15 - 21/1963	USGS (1963)	Harper to Hamilton Pool	88.7	12.31
Pedernales River	1994 - ongoing	HCUCD	Approximate 15 mile reach near Fredericksburg	15	
Medina River	9/6 - 7/1955	TBWE (1960)	5.8 mi above Medina to Turks Head Mountain in Medina Lake	45.7	-4.84
Medina River	6/3 - 5/1925	TBWE (1960)	5 mi above Lima to 4 mi below Pipe Cr	43.8	2.2
Medina River	1/3 - 7/1955	TBWE (1960)	8.3 mi above Medina to 1.5 mi below Bandera-Medina Co line	47.1	-0.67
Medina River	2/17 - 18/1955	TBWE (1960)	Bandera to Turks Head Mountain in Medina Lake	20.4	-4.62
Medina River	12/9/1924	TBWE (1960)	Main Dam to near Riomedina	10.9	6.6
Medina River	5/26 - 28/1925	TBWE (1960)	Medina Co Irrigation Co. diversion dam to Losoya	55.1	-3.2
Medina River	2009-2011	USGS (-)	Upstream of Medina to downstream of Bandera	~45	
Onion Creek	4/23 - 24/1958	TBWE (1960)	FM 12 to mouth	59.2	-24.9
Onion Creek	5/28/1980	Slade and others (1982)	FM 150 (08158700) to US 183 (08159000)	35.4	-82.7
Blanco River	3/15 - 16/1955	TBWE (1960)	10 mi upstream of Wimberly to northeast of San Marcos	33.3	-10.3
Blanco River	2/25 - 3/4/1963	USGS (1964)	9 mi below Blanco to Wimberly (08171000)	27.1	25.9
Blanco River	7/22/1924	TBWE (1960)	above Halifax Cr to near Kyle	4.2	-13.1
Blanco River	1/24 - 28/1955	TBWE (1960)	upstream from Little Blanco R to northeast of San Marcos	49.6	-2.65
Blanco River	7/10-14/1957	TBWE (1960)	Wimberley (08171000) to Kyle (08171300)	16.2	-13.9
Blanco River	6/12/1924	TBWE (1960)	Wimberley to Kyle	19.4	14.0
Blanco River	7/15 - 16/1924	TBWE (1960)	Wimberley to Kyle	19.4	-12.8
Blanco River	11/20/2013	Kocis (2014)	Just downstream of Blanco to northeast of San Marcos	52.52	34.9

8. Dye Tracing Studies

Dye tracing has been used in the Edwards and Trinity Aquifers to document surface water and groundwater flow paths. Due to the karstic and fractured nature of the aquifers in the Hill Country, groundwater flow can be sufficiently rapid to allow for successful dye tracing. Dye is injected into a point source, such as a well or sink hole, and downgradient points are monitored for the arrival of the dye. Monitoring points are typically well or springs. In the Hill Country, travel times can range from hours to days to a few weeks.

Non-toxic fluorescent dyes are often used as they are easy to detect. Common dyes include fluorescein, rhodamine and pyranine.

Dye tracing studies have been important in understanding the groundwater/surface water interactions within the Trinity and Edwards aquifers along the Balcones Fault Zone. The relationship between flow in Onion Creek and subsequent discharge into Barton Springs was established using dye tracing studies (Hunt, 2006).

While dye tracing studies have been valuable in delineating groundwater/surface water interactions along the Balcones Fault Zone, there are limitations in their use. The areas to be studied need to be characterized by rapid groundwater movement such that studies can be carried out in a reasonable amount of time. Dye tracing studies require a large of amount of up front planning and logistics. Suitable injection locations must be identified. Private residential wells are often used as monitoring points and well owner permission must be obtained at numerous locations. The wells need to be instrumented with dye detectors (often carbon canisters) and periodically monitored resulting in a large commitment of manpower.

CASE HISTORY OF STUDY METHODOLOGY – BLANCO RIVER

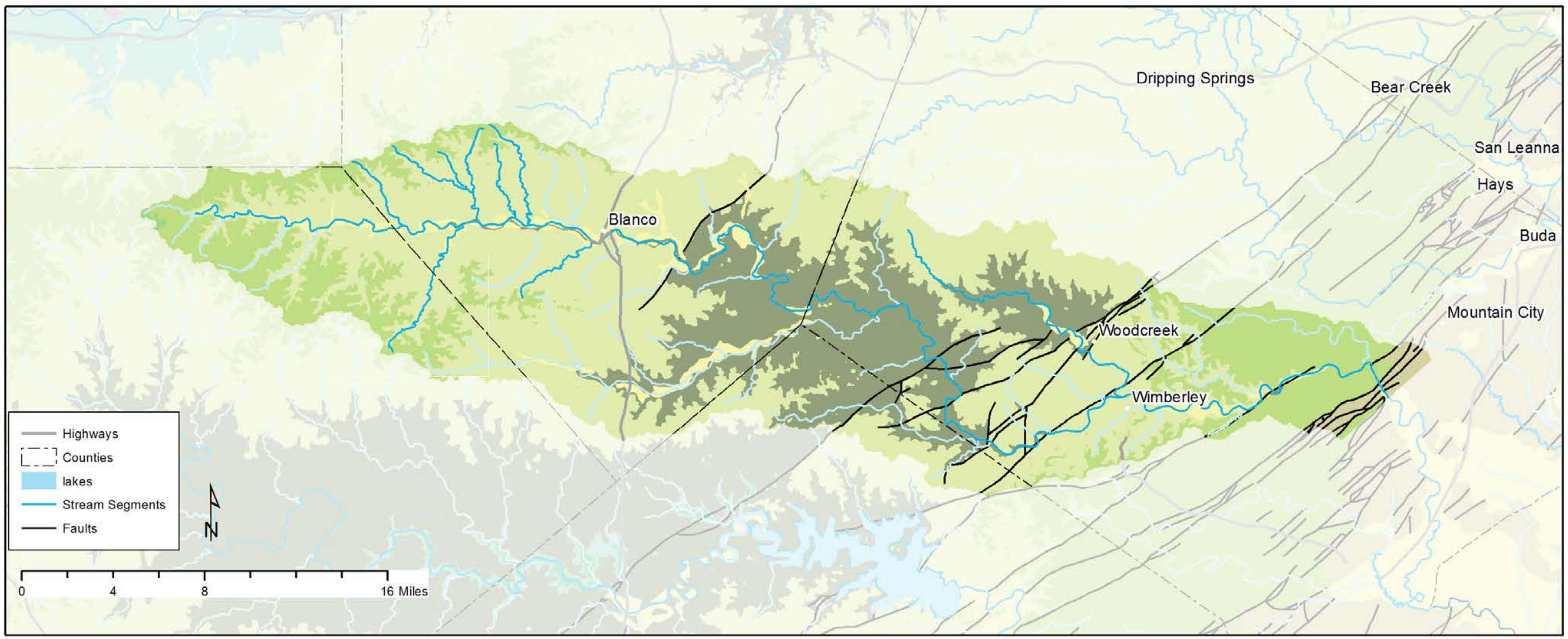
Recent studies by various groups including GCDs, local universities and independents illustrate the value of developing comprehensive study methodologies in documenting groundwater and surface water interactions. A summary of key findings and their significance to understanding the Blanco River are summarized below. This summary is intended to provide an overview of key findings, not a detailed review of all the studies performed.

The Blanco River originates in Kendall County and flows from west to east across Blanco and Hays Counties (Figure 21). The Blanco stream flow originates from springs that have their source at the base of the Edward's Plateau. The river transverses the Upper Glen Rose formation (upper Trinity Aquifer) across western Blanco County.

The river cuts down through the Upper Glen Rose in eastern Blanco and western Hays County into the Middle Trinity Aquifer. The Lower Glen Rose is the primary Middle Trinity unit exposed, though Hensel and Cow Creek crop out along the river in the vicinity of the confluence of the Little Blanco river and downstream. The river continues to flow across the Trinity Aquifer to the Balcones Fault Zone. The fault zone is a series of normal faults with older Trinity units juxtaposed against young Edwards units (Figure 9).

During wet periods, flow occurs along the entire reach of the river. During normal and drier periods, flow ceases in the initial reach of lower Glen Rose. Flow resumes through a series of small springs associated with small throw normal faults near Burnett Ranches. These small springs are believed to be the headwaters of the "lower" Blanco River.

Figure 21. Geologic Map of the Blanco River Watershed



DATA GAP ANALYSIS

Inventory of Information Relating the Study Methodology

To gain an understanding of the state of the science relating to area streams, researchers reviewed published literature and conducted interviews with key water individuals currently involved in studying and managing the Hill Country water resources. Within the Hill Country, the groundwater conservation districts (GCDs) are actively involved studying the resource and collecting data. Interviews were held with the general managers/staff of the GCDs to gain an understanding of the types of data that are on file and on-going studies and monitoring programs. The following GCDs were interviewed:

- Barton Spring Edwards Aquifer Conservation District
- Hays Trinity Groundwater Conservation District
- Blanco Pedernales Groundwater Conservation District
- Hill Country Underground Water Conservation District
- Cow Creek Groundwater Conservation District
- Bandera County River Authority and Groundwater Conservation District

In general, all of the GCDs interviewed stated that they have active groundwater monitoring programs, track water use, collect SWR's and have performed some interpretive studies. Some of these studies are mentioned in this report. A common data gap is the inability of the GCDs to fully assimilate all of the data being collected and prepare comprehensive documents for public use.

Other ongoing programs include the USGS stream gaging program on many of the streams (www.USGS.gov) and TWDB's (www.twdb.texas.gov) groundwater level monitoring program. The Edwards Aquifer Authority is conducting a five-year long study of the interactions of the Trinity and Edwards Aquifers. The Edwards Aquifer-Trinity Aquifer Inter-Formational Flow Study is looking at four study areas: Guadalupe/Blanco, Cibolo, Medina and Nueces. The studies are focusing on groundwater/surface water interactions along the interface of the Trinity and Edwards Aquifers (Gary, 2013). The BSEACD and HTGCD are collaborating with the EAA on the Blanco River Studies.

Available Data and Data Gaps

Through literature review and interviews, the following discussion summarizes the available data and identifies data and study gaps.

Blanco River

As previously described, the study methodology outlined in this project has been in large part, executed on the Blanco River and a significant data base exists. The compilation of The Hydrogeologic Atlas of the Hill Country Trinity Aquifer (Wierman, 2010) synthesized geologic information across Blanco and Hays County. Previous and recent gain/loss studies and detailed geologic mapping have contributed greatly to our understanding of the river (Hunt, 2013, Kocis 2014, Smith 2014). Some detailed information on geologic structure (the occurrence of faults and fracture) is lacking, though basic interactions of ground and surface are generally known. Cooperative studies between Edwards Aquifer Authority (Gary, 2013), the Barton Springs Edwards Aquifer Conservation District (Hunt, 2014 personal communication), Hays Trinity Groundwater Conservation District and others are ongoing. The major data gap is long term groundwater level monitoring throughout the basin and correlating groundwater levels with major spring flow. Coordinating the ongoing monitoring programs of the Blanco Pedernales GCD and the HTGCD and expanding the programs with additional monitoring locations along the Blanco River is necessary. Additional water level monitoring will provide data to help predict the impact of additional groundwater pumpage in the Middle Trinity Aquifer on streamflow in the Blanco River.

During wet periods, flow occurs along the entire reach of the river. During normal and drier periods, flow ceases in the initial reach of lower Glen Rose. Flow resumes through a series of small springs associated with small throw normal faults near Burnett Ranches. These small springs are believed to be the headwaters of the "lower" Blanco River.

A review of gain/loss studies from 1955, 1963, and 2013 indicates significant gains in the main channel downstream of Burnett Ranches (Figure 22). Detailed field mapping and flow measurements documented a major spring system in the bed of the main channel, subsequently named Pleasant Valley Spring (Hunt, 2013). In Wimberley, Cypress Creek contributes a significant gain to the Blanco River. Previous studies have shown the majority of flow in Cypress Creek originates from Jacob's Well. Jacob's Well is an artesian spring that originates in the Middle Trinity Cow Creek Aquifer. Recent mapping and log interpretation indicate that the source of water from Pleasant Valley Spring is also the Cow Creek Aquifer. Gain/loss studies indicate Pleasant Valley Spring and to a lesser extent, Jacob's Well, provide the majority of base flow the Lower Blanco River.

Water from the Blanco River enters the Edwards Aquifer through the Balcones Fault Zone. Dye tracing studies have shown water can discharge into San Marcos Springs or Barton Springs, depending on climatic conditions. When other contributing streams are dry, such as Onion Creek, the Blanco River can help maintain flow to Barton Springs as well as San Marcos Spring (Johnson, 2012).

As a result of these studies on the Blanco River, the implications of the groundwater/surface water interactions are better understood: *During drought conditions, base flow in the Lower Blanco River is very important to maintaining flow at Barton Springs and San Marcos Springs (Figure 23).*

Base flow is dependent on artesian spring flow (Pleasant Valley Spring and Jacob's Well from the Middle Trinity (Cow Creek) Aquifer. The Middle Trinity is the sole source of municipal water supply and the majority of private residential wells in the Wimberley Valley. Previous studies have shown municipal pumpage from the Middle Trinity directly impacts flow from Jacob's Well (Wierman, 2008). A similar situation likely exists with Pleasant Valley Spring. With increased development and water use in the Wimberley Valley, management of groundwater pumpage is the most effective technique to manage base flow in the Blanco River and downstream effects.

Figure 22. Blanco River Gains and Losses

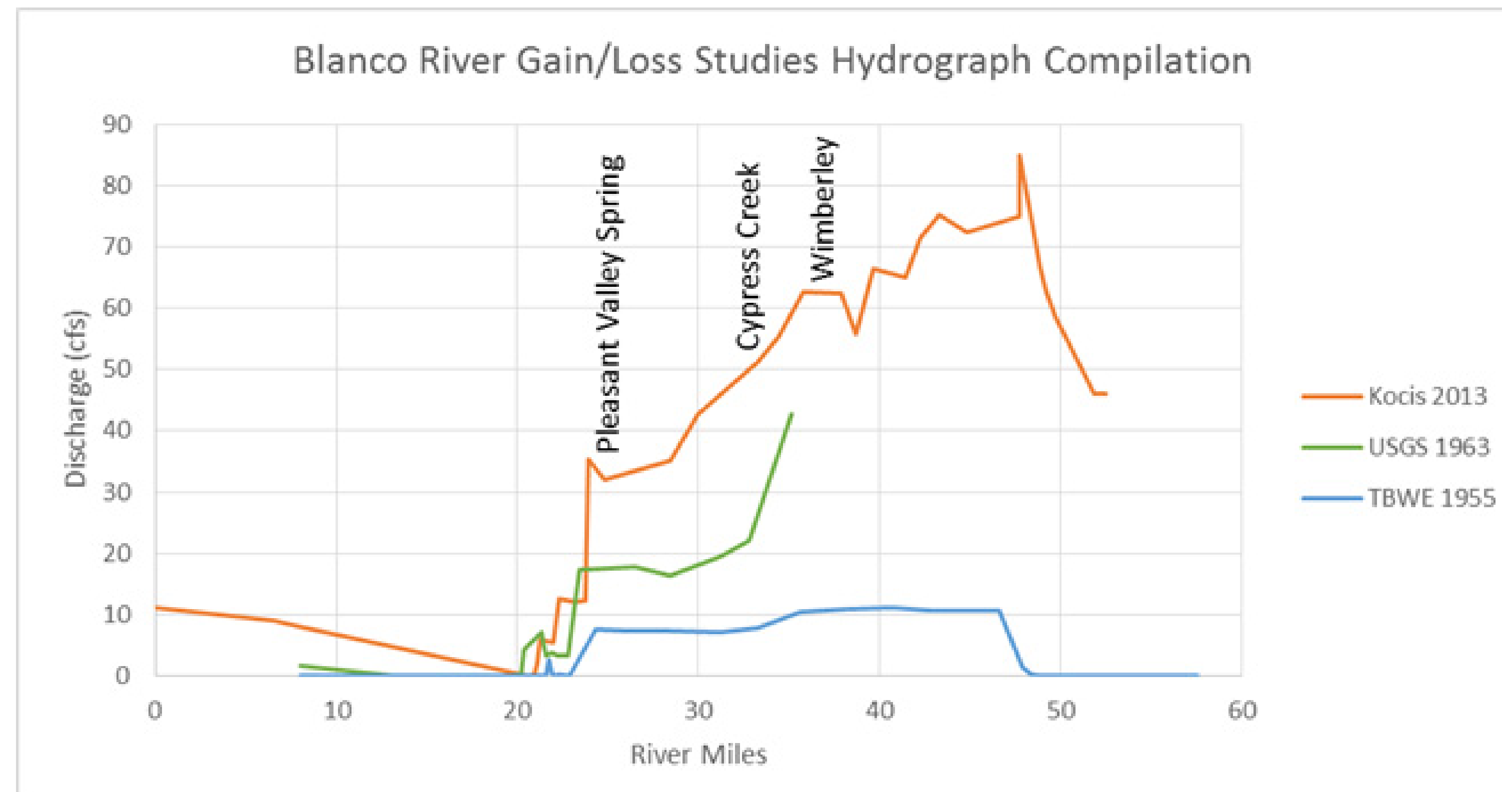
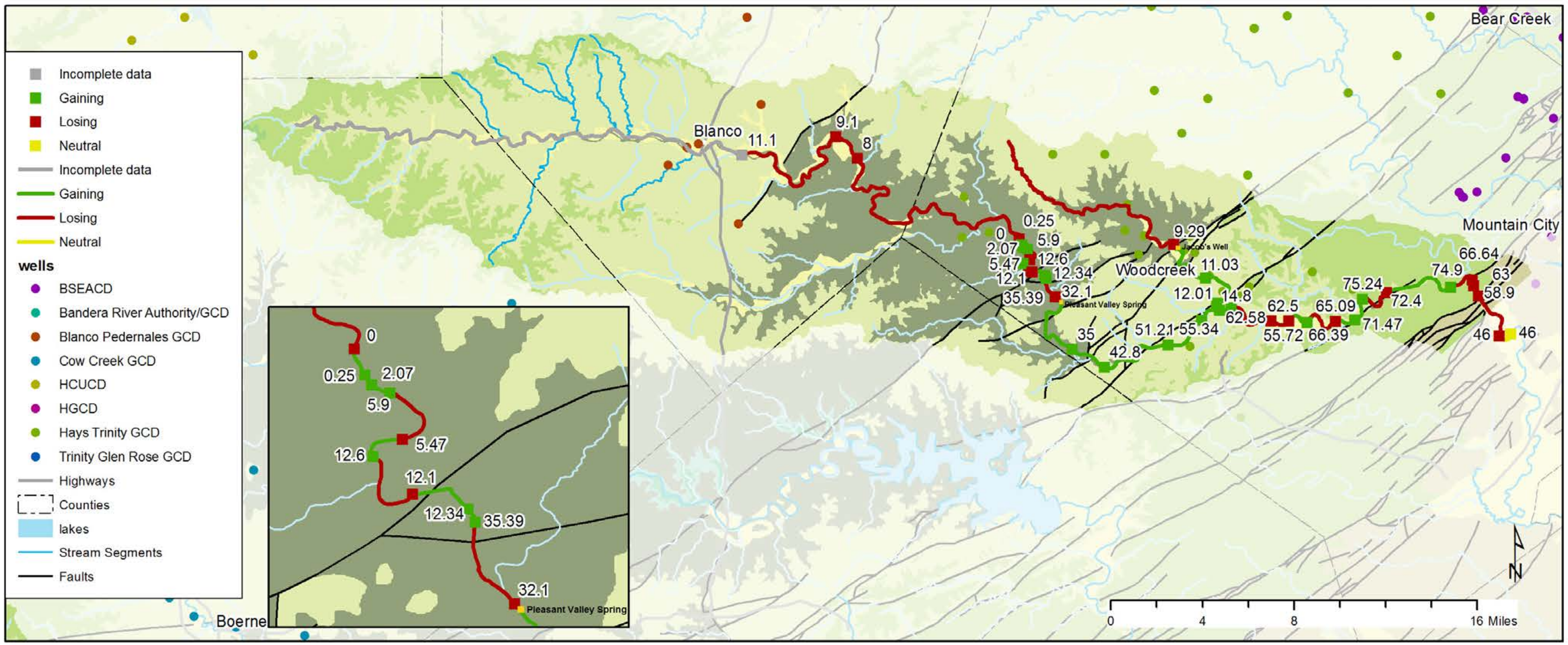


Figure 23. Gain/Loss Study Results from Blanco River, 2013



* Values are stream flow in cfs

Onion Creek

The general geology of Onion Creek from its origin in Blanco/western Hays County to the Balcones fault zone is well established. See Figure 24 for a geologic map of the watershed. The creek originates in the upper Glen Rose (Upper Trinity Aquifer) and flows to the east where it crosses the Balcones Fault Zone on top of the Edwards Aquifer. Significant work has been done documenting groundwater/surface water interactions between Onion Creek, the Edwards Aquifer and Barton Springs at the eastern end of our study area. Dye tracing studies have shown that water in Onion Creek enters the Edwards Aquifer through karst features and discharges into Barton Springs and into San Marcos Spring during periods of relatively high flow (Hunt, 2006). A gain/loss study performed in 1958 (Slade, 2002) indicated significant gains (43 cfs) between Highway 12 in Dripping Springs and a location near the intersection of Highway 150 and Highway 967 (Figure 25). This gain may be attributable to discharge of shallow groundwater to springs originating from the Upper Glen Rose beneath the City of Dripping Springs. Muller (1990) described the occurrence of shallow groundwater discharge to Onion Creek. In contrast, review of aerial photography from 2013 indicates water in most of Onion Creek except for the reach that had a significant gain during the 1958 study. Wet and dry reaches are shown on Figure 26.

Figure 24. Geologic Map of the Onion Creek Watershed

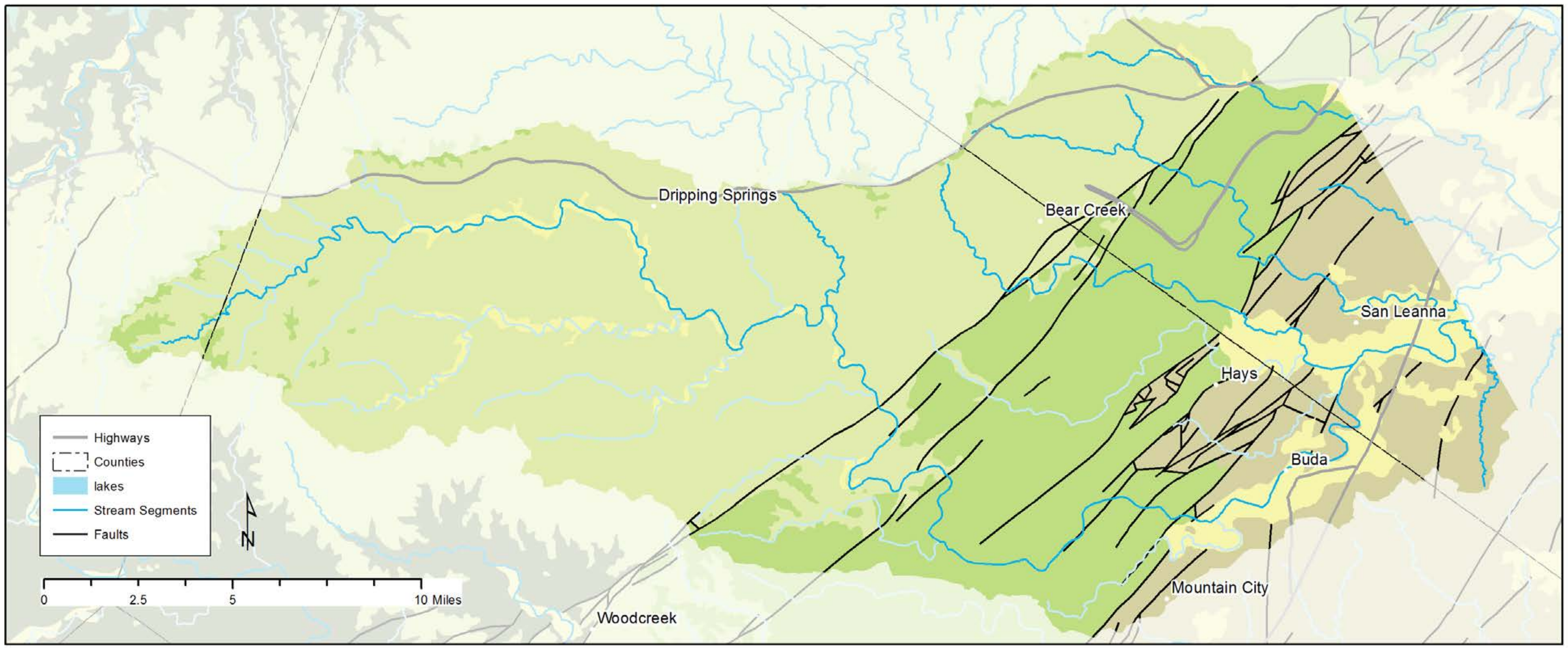
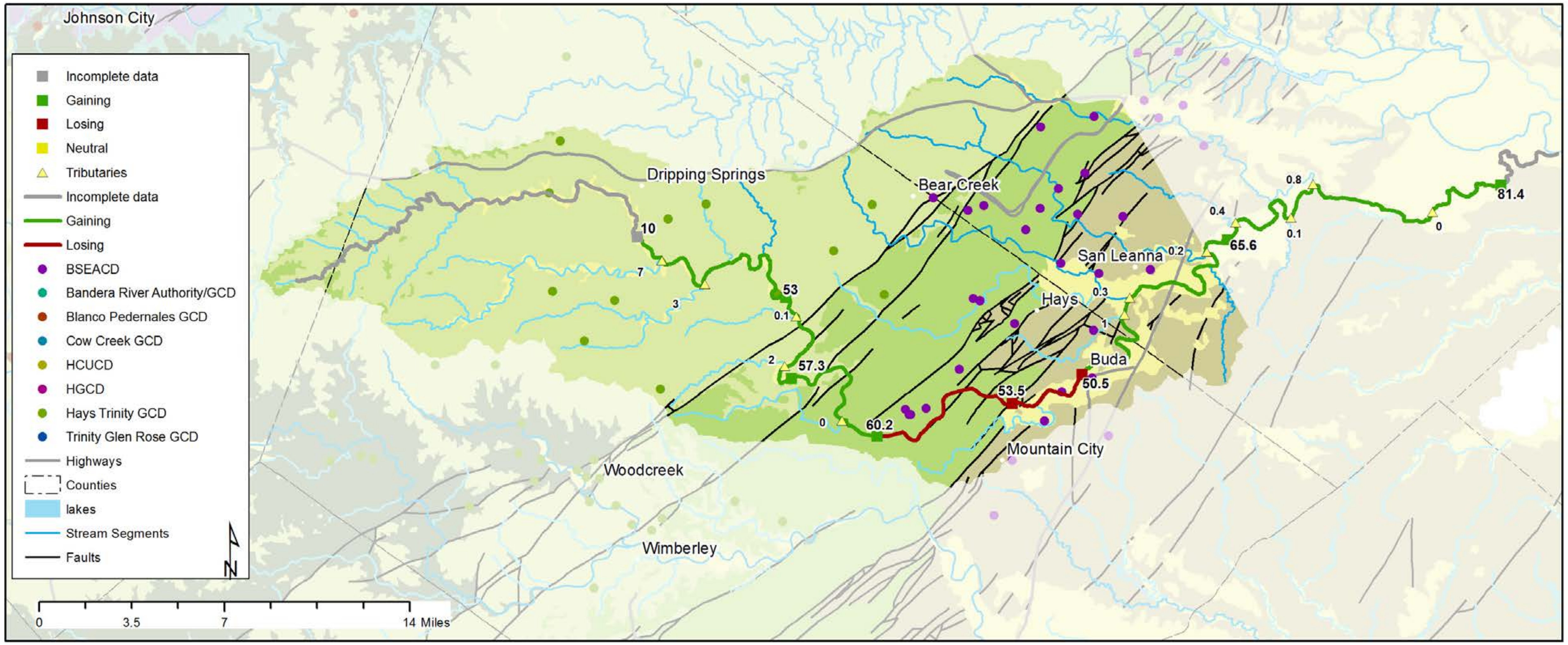


Figure 25. Gain/Loss Study Results from Onion Creek, 1958



* Values are stream flow in cfs

Historic streamflow gain-loss studies collected on Onion Creek document that Onion Creek base flow was sustained by gains in the stream channel from the Trinity Aquifer (Slade, 2002). However,………Slade (2007) notes that the streamflow of Onion Creek has diminished in recent years. Slade (2007) attributes this decrease in Onion River flow to recent substantial increases in groundwater pumpage in northern Hays County (in the Onion Creek basin). "Because of the increased withdrawals in the area, it is expected that Onion Creek will experience no flow conditions for all but storm water runoff periods in the future."

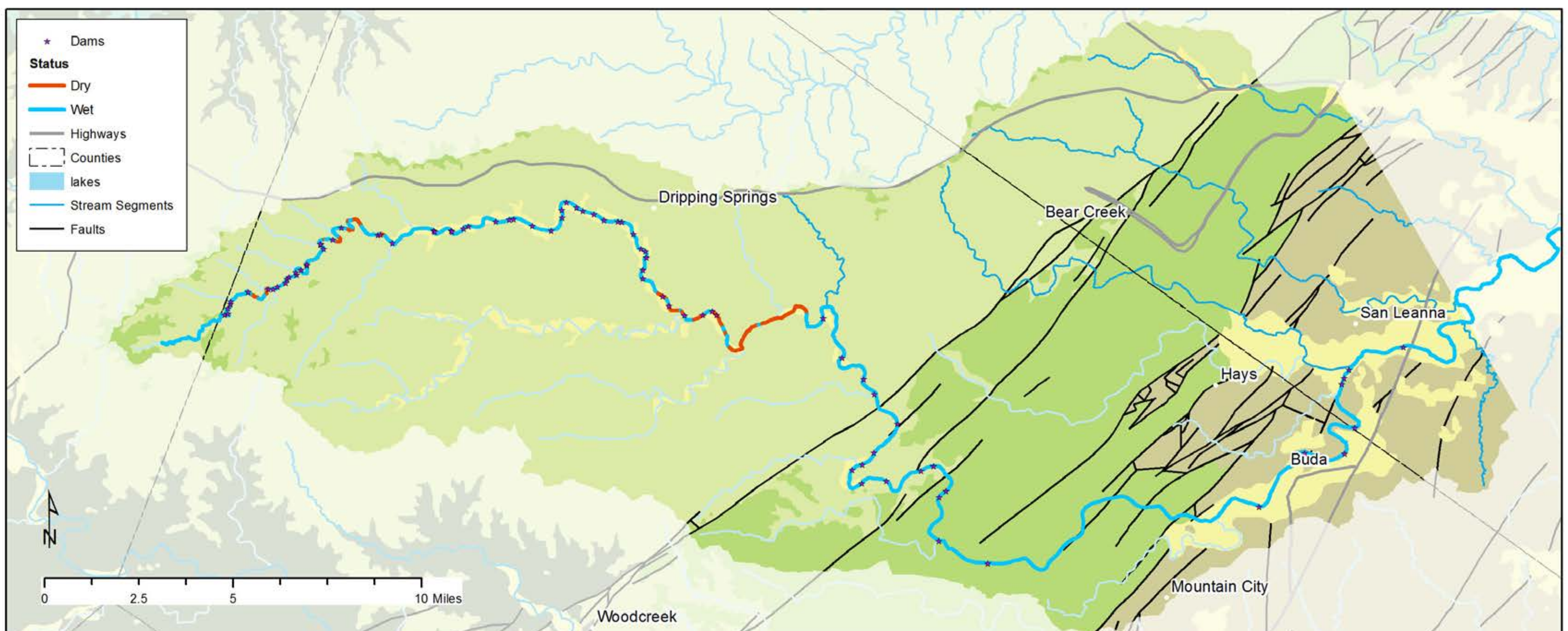
Based on this information, it appears there have been significant changes in the groundwater/surface water interactions since the 1958 study along the reach downstream of Dripping Springs. No gain/loss studies have been performed upstream of Dripping Springs to the headwaters in Blanco County. There have been significant changes in the basin due to rapid residential development resulting in a large increase of groundwater pumping and impervious cover. A review of groundwater level monitoring data collected by the HTGCD and TWDB from wells located along Onion Creek indicated the potentiometric surface of the Middle Trinity aquifer is significantly lower than Onion Creek, indicating there can no gain from the Middle Trinity. Figure 17 is a hydrograph from a Middle Trinity Well located approximately 1 mile from the Onion River. Water levels in the well have been generally greater than 300 feet below land surface.

The elevation difference between the well and the creek is approximately 100', thus putting the potentiometric surface at 200' or more below the creek. In addition, there are currently over 40 impoundments/dams in the main channel of the creek from the headwaters to Interstate 35 (Figure 26). The impoundments/dams will tend to restrict flow and may interfere with gain/loss studies.

Based on the methodology presented in this study, additional groundwater level monitoring and gain/loss studies are necessary to understand current conditions in Onion Creek. Presently, there are no water level monitoring in the shallow groundwater zone beneath the City of Dripping Springs as described by Muller (1990) and only a few deeper wells being monitored in the Middle Trinity Aquifer by the HTGCD. A more robust groundwater level monitoring program along the creek is a significant data gap. A detailed geologic cross section traversing the length of the creek has not been developed. Detailed field mapping and a compilation of existing wells logs are necessary sets to create the cross-section.

The lack of current gain/loss studies reflecting current conditions are a significant data gap. Historical gain/loss studies do not appear to coincide with more current conditions. Performing updated gain/loss studies along the entire reach from the headwaters to the Balcones Fault Zone will document current conditions and may identify areas which warrant additional detailed study.

Figure 26. Onion Creek: Wet and Dry Reaches - 2013 and In-Channel Impoundments



Wierman, 2010

Pedernales River

The Pedernales River originates in the eastern edge of Kimble and Kerr Counties. It transects all of Gillespie and Blanco Counties before crossing the northern tip of Hays County and the western edge of Travis County where it flows into Lake Travis (Colorado River). The HCUWCD, BPGCD and the HTGCD have been active in hydrogeologic data collection in their respective counties.

Flow originates in near the Edwards/Upper Glen Rose contact near Harper (Figure 27). Over a relatively short distance, the river cuts down through the upper and Lower Glen Rose and into the Hensel Sand. The river flows across the Hensel Sand through the city of Fredericksburg to the western edge of Blanco County. The river flows through outcrops of Ordovician and Cambrian strata that flank the southern edge of the Llano Uplift. The remaining portion of the river in Blanco. Hays and Travis Counties flows through the Lower Cretaceous formations to the confluence with Lake Travis (Colorado River).

Figure 27. Geologic Map of the Pedernales River Watershed

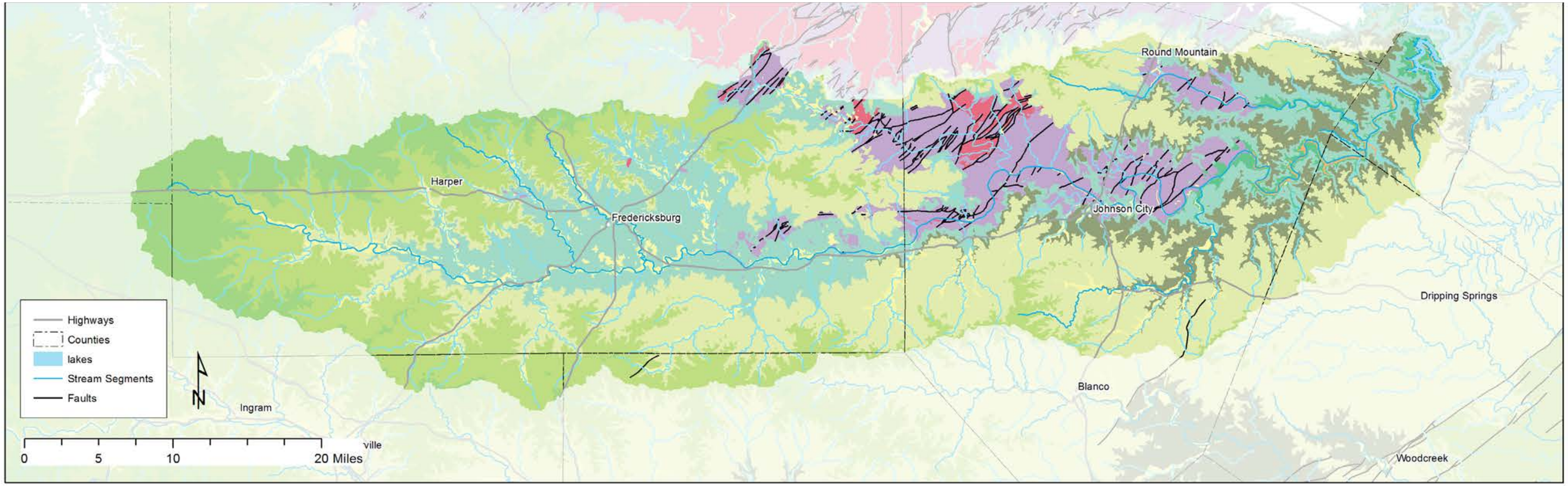
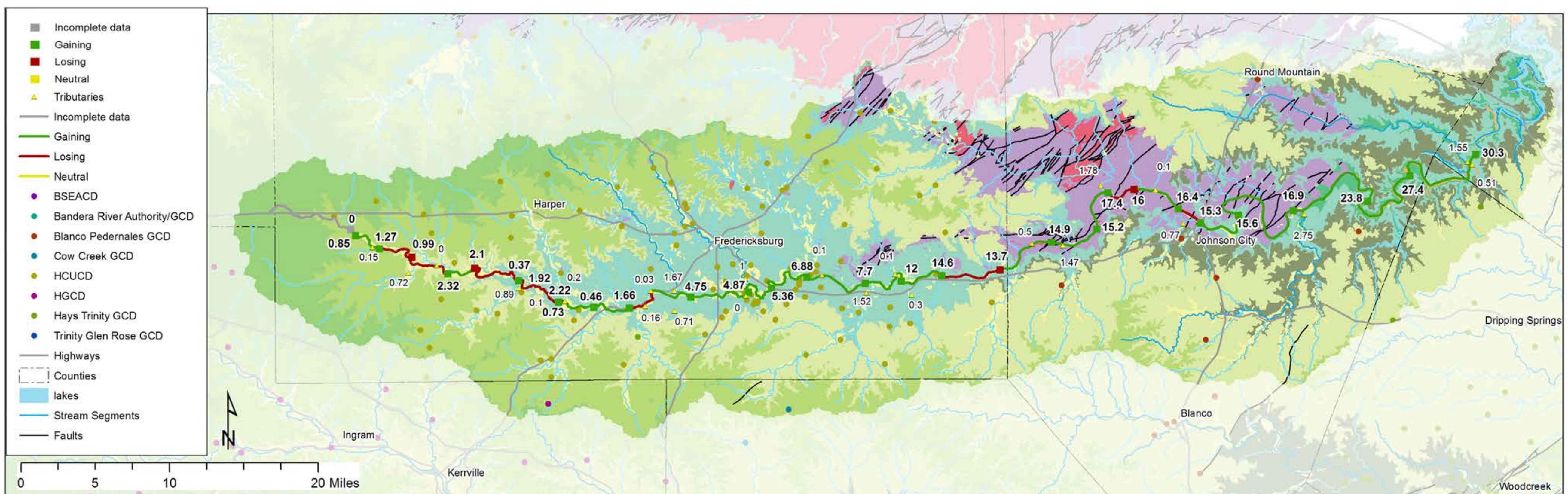


Figure 28. Gain/Loss Study Results from Pedernales River, 1962



Much of the available information for Hays and eastern Blanco Counties was summarized in the Hydrogeologic Atlas (Wierman, 2010). Updated geologic cross sections and structure contours map(s) of the aquifers are currently being updated on a cooperative basis by the BSEACD, BPGCD and HTGCD. All three districts have active groundwater level monitoring programs. There is no district in western Travis County.

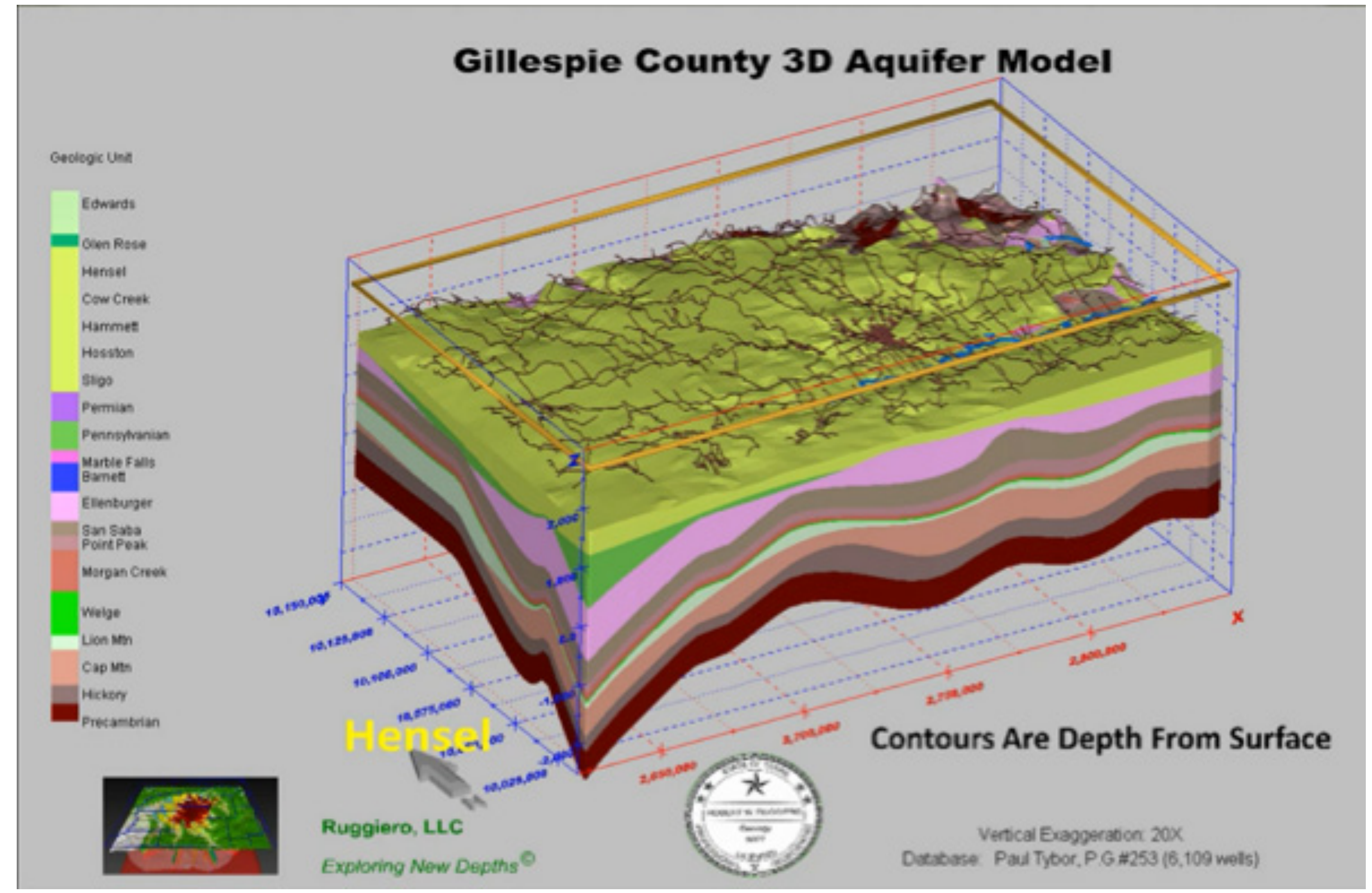
The HCUWCD has been very active in collecting and interpreting well logs. A 3D geologic model of the subsurface has been developed for the geologic units/aquifer which underlie Gillespie County and is available on the district's webpage (www.HCUWCD.com). A screen shot from the model is presented in Figure 29.

Detailed gain/loss studies were performed on the Pedernales River in 1955 and 1963. The 1955 Study was performed during the drought of record, while the 1963 study was performed during a more "normal" rainfall period. The results of these studies are reported in TWC Bulletin 6407. These studies were performed when the population and water use was considerable less than at present (Figure 28).

Discharge in the main channel was measured along with the contribution of tributary streams. During the 1962 study, approximately 33% of the total discharge throughout the study reach was attributable to gains in the main channel or a net gain of 10 cfs at the terminus of the river at Lake Travis. Main channel losses were noted between river miles 50 and 70, the reach between Stonewall and Johnson City. The remaining 66% of the total discharge originated from tributaries. The large percentage of tributary contribution indicates that an understanding of the hydrogeology of the tributaries is important to sustainable management of the river. See figures 30A and 30B for graphic displays of the 1962 study data. Source water in the tributaries of the Pedernales, which contribute significant base flow, have not been inventoried or evaluated.

The HCUWCD conducts routine stream gaging in the Pedernales River along an approximate 15-mile reach south of Fredericksburg. The purpose of the program is the determine if there are losses in the Pedernales River due to groundwater withdrawal from the City of Fredericksburg well field. Flow is measured in the Pedernales main channel at eleven locations and at two tributaries, Barons Creek and Live Oak Creek, near their respective confluence with the Pedernales. The locations are measured at multiple times during the year and the program has been in place since 1994. The program indicates there is generally a loss in the main channel despite consistent contributions from the Barons and Live Oak Creeks (Tybor, personal communication).

Figure 29. Gillespie County 3D Aquifer Model Image source: www.HCUWCD.org



Identification of significant gains or losses over relatively short subreaches can be an indication of areas requiring additional study, such as detailed field mapping, groundwater level measurements or well logging to determine the specific source of the gain or destination for the loss. Based on the results of the 1962 study on the Pedernales River, the source of the discharge in the tributaries at river miles 27, 43, 84 and 94 (Live Oak, South Grape, Miller and Flat Creeks, respectively) warrant additional detailed investigation.

There are data gaps relating to our further understanding of the groundwater/surface water interactions of the Pedernales River. The geologic data collections of the HCUWCD, BP-GCD and the HTGCD should be combined into one comprehensive document focusing on the river. This could be a compilation of the various databases and creating a series of graphics or 3D model. A detailed geologic cross section traversing the entire length of the creek has not been developed. Detailed field mapping and a compilation of existing wells logs are necessary sets to create the cross-section.

There has been considerable development in Gillespie County since the last comprehensive gain/loss study was performed in 1963. The city of Fredericksburg has grown and agricultural irrigation has increased, primarily due to the establishment of vineyards/winery industry. Northern Hays and southwest Travis Counties have also experienced significant growth and use of groundwater. An updated gain/loss study should be performed along the entire reach of the river, with efforts to duplicate the gaging points (main channel and tributary) of the 1963 study.

The sources of the previously mentioned tributary gains need to be further investigated. Detailed field reconnaissance and mapping of the major tributaries could determine the location and geologic origins of the source springs.

Figure 30A. Pedernales River Gain/Loss Hydrograph Compilation - 1956 and 1963

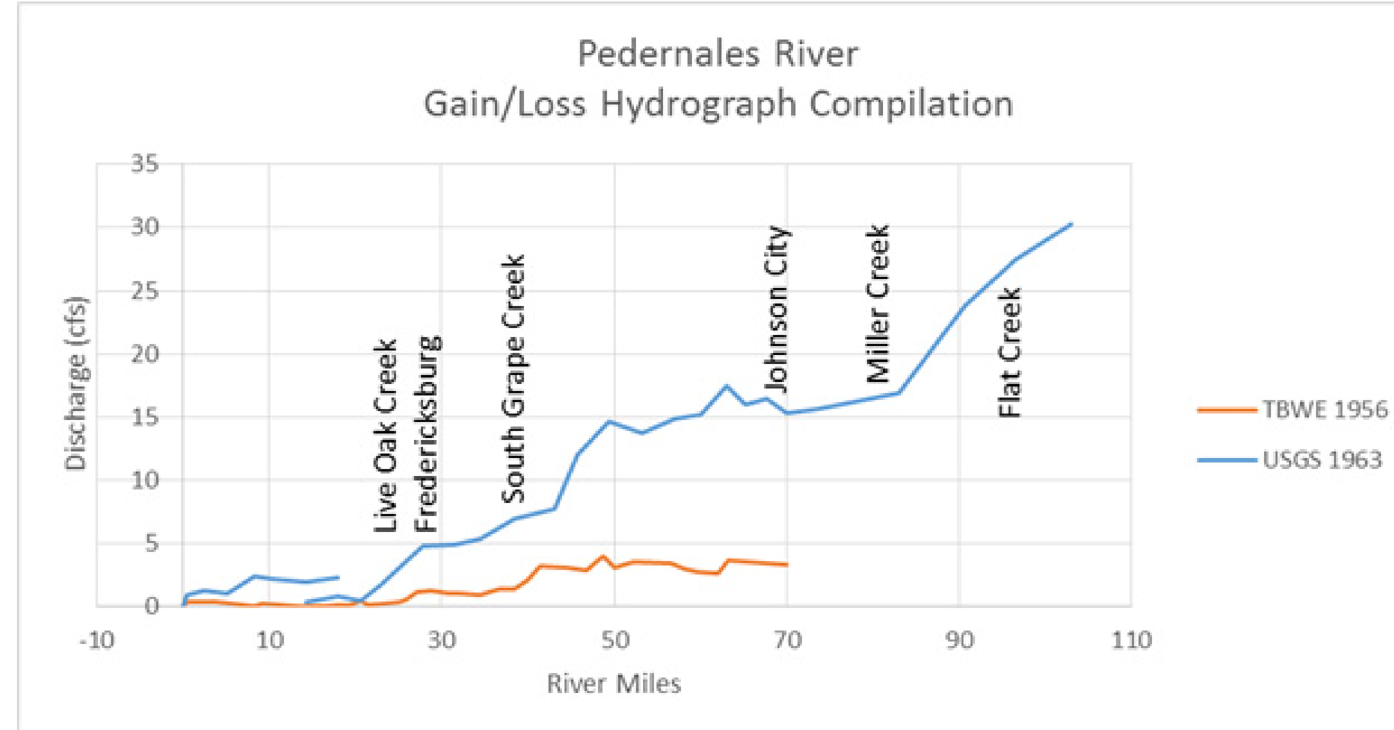
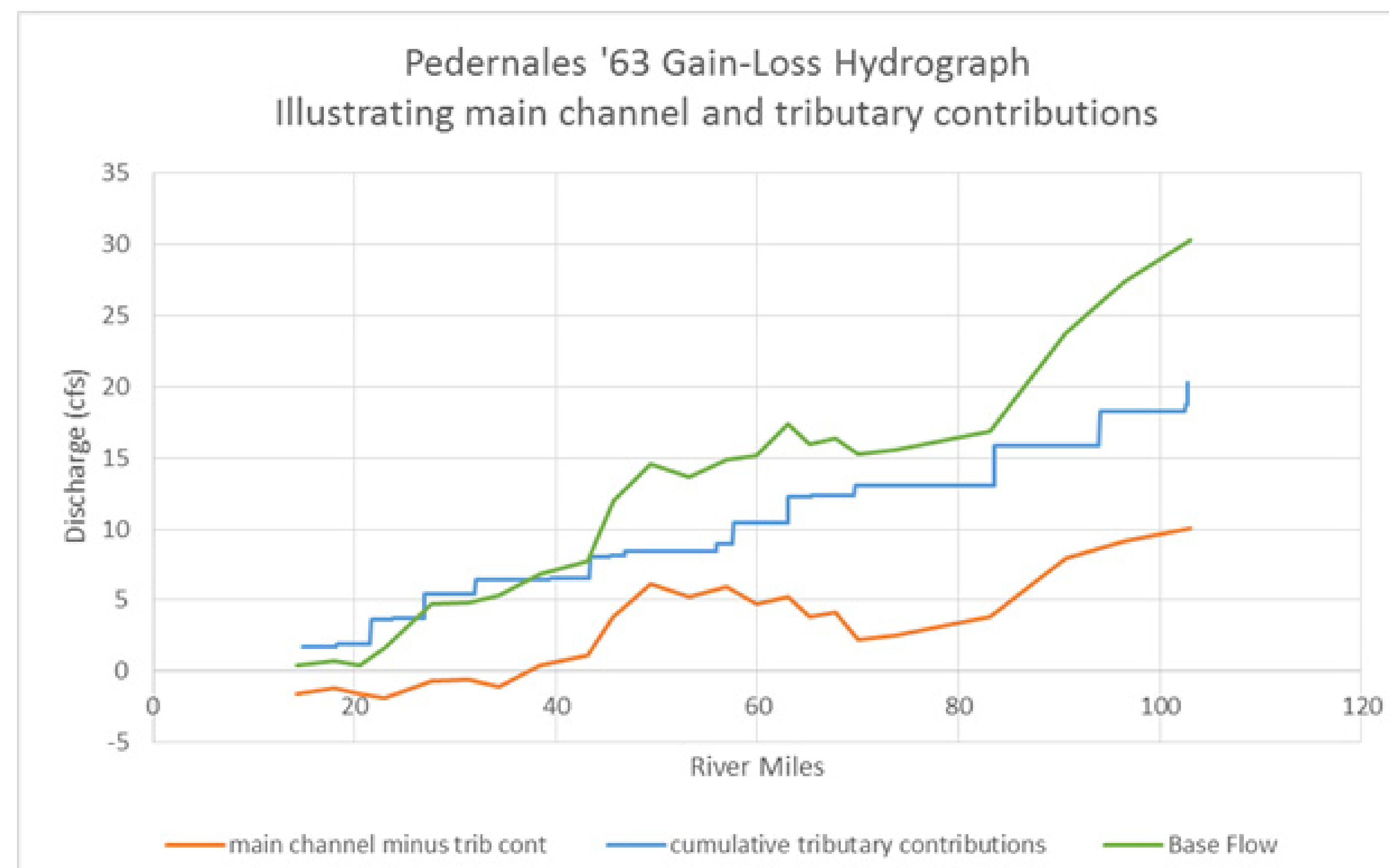


Figure 30B. Pedernales River 1963 Gain/Loss Hydrograph with Main Channel and Tributary Contributions

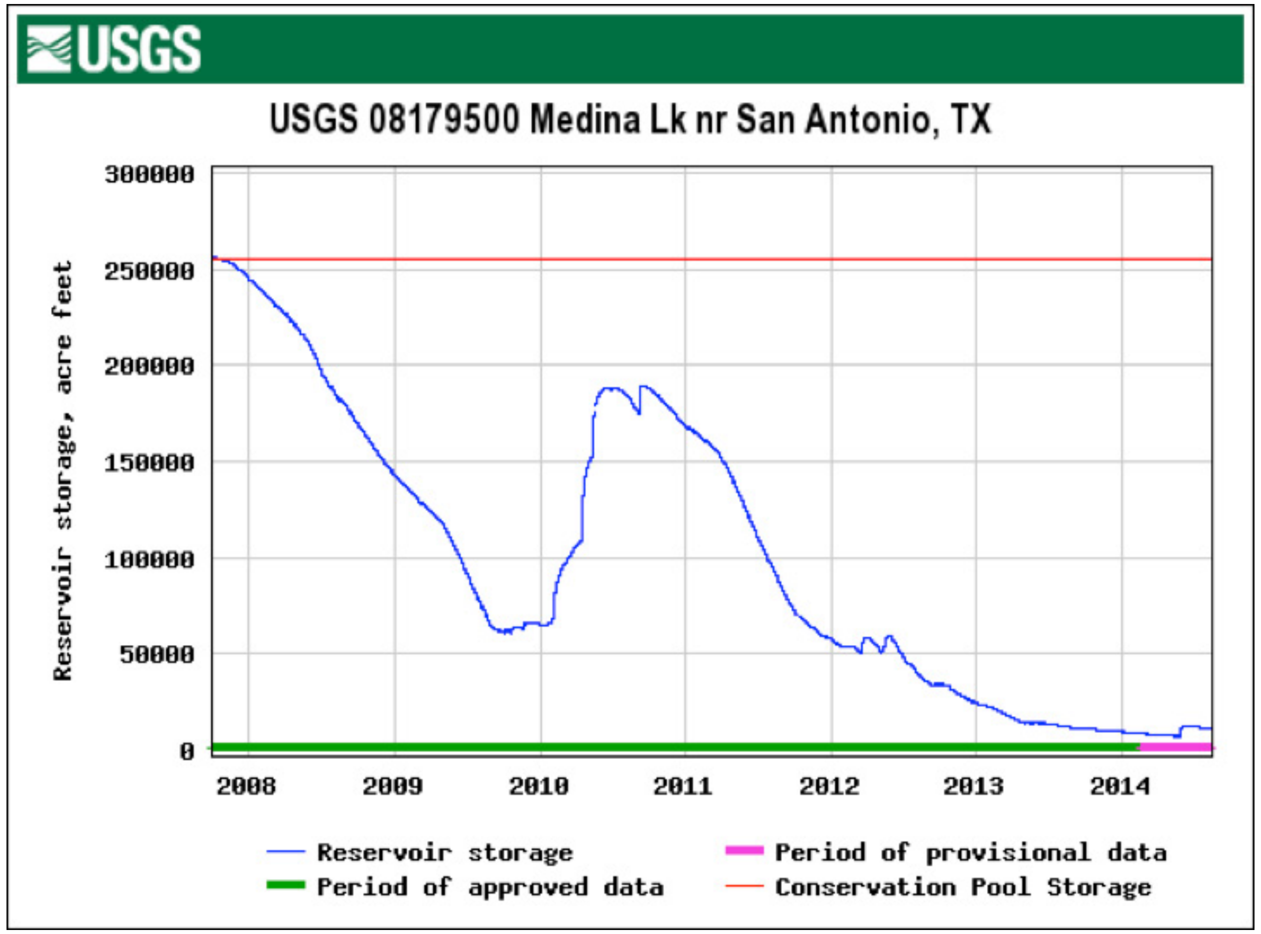


Medina River

Similar to other Hill Country streams, the Medina River originates near the contact of the Edwards Plateau and the Upper Glen Rose Formation. See Figure 31 for a geologic map of the Medina River Watershed Flow originates at or near the base of the Edward sand and in the upper portions of the Upper Glen Rose. The river flows over the Upper Glen Rose through the city of Medina. A few miles downstream of Medina, the river cuts into the Lower Glen rose. The river is incised into the Lower Glen Rose through the city of Bandera to the mouth of Medina Lake. Medina Lake is situated over Upper Glen Rose and Edwards Aquifer strata.

Water Levels and lake storage in Medina Lake have been significantly reduced since the lake was last full in 2008 (Figure 31). The storage in 2008 was at the Conservation Pool Storage level of approximately 250,000 acre/ft. In July, 2008, lake storage was 12,000 acre-ft. Large water losses from the lake to the Edwards Aquifer have been the subject of many past and ongoing studies by USGS, San Antonio River Authority and EAA. Lambert (2000) estimated recharge to the Edwards Aquifer from the Medina Lake system to range between 115 and 135 acre-ft/day depending on lake stage. Slattery (2004) estimates and average of 3083 acre-ft/month (103 acre-ft/day) was lost from the lake to the Edwards Aquifer.

Figure 31. Reservoir Storage in Medina Lake - 2008-2014 . Source:USGS



Most of the previous study efforts on the Medina River have focused on the reach downstream of Bandera, relating the large losses from the lake to the Edwards Aquifer. Gain/loss studies performed on the reach between Medina and Medina Lake and beyond were performed in the 1955 during drought conditions. Only one or two measurements were made in the reach between Medina and Bandera This reach of the river is generally a gaining reach based on long term monitoring from at USGS stream gages located at Medina and Bandera. The record of measurement is relatively short for the two gages (2007 for Bandera and 2011 for Medina) and it appears major precipitation events may make interpretation difficult. Generally the gain is in the range of several cfs.

During the period 2009-2011, the USGS (unpublished) performed a series of gain/loss studies starting from upstream of Medina and continuing to several miles downstream of Bandera. The study was performed in cooperation with the BCRACD. The gains and losses are well documented, but the actual source of the gains and losses were not mapped as part of the study. The potential interaction of the Lower Glen Rose and the river has not been documented.

To determine the groundwater/surface water interactions in the Medina to Bandera reach, groundwater level elevations along the river should be determined. BRAGCD has an active groundwater level monitoring program with several of the wells located along the river (See Figure 16). Additional wells are needed to supplement the existing program. Concurrent with groundwater level monitoring, a gain/loss study should be performed from Medina to Bandera. The study should be conducted when flows are at base flow conditions and not reflecting flood conditions. Based on the results of the water monitoring programs, detailed geologic mapping along the river should be performed to attempt to relate local geologic conditions to the gaining and losing reaches. A detailed geologic cross section traversing the length of the creek has not been developed. Detailed field mapping and a compilation of existing wells logs are necessary components to create the cross-section.

SUMMARY AND CONCLUSIONS OF DATA GAP ANALYSIS

The methodology of study described in this report has proven effective in helping to understand groundwater/surface water interactions and their impact on the overall question "How much Water is in Hill Country". The research has indicated that additional work is necessary on the four stream segments identified so that significant data gaps can be filled, interpreted and related to land management activities.

In general, GCDs are the most active in collecting hydrogeologic data such as well logs, water levels and water quality. While many of the GCDs are actively collecting data, there is a lack of data interpretation and evaluation, primarily due to budget constraints.

Detailed gain/loss studies performed on the Blanco River and its main tributary, Cypress Creek, have identified areas warranting further study such as detailed geologic mapping, water level and water quality monitoring. Pleasant Valley Spring was "discovered" through details gain/loss studies.

Recent gain/loss studies have been performed on the Blanco and Medina Rivers, but not on Onion Creek. A reach of the Pedernales River near Fredericksburg is routinely measured (~15 miles) but the remaining ±85 miles have not been studied in detail since the early 1960s. Source water in the tributaries of the Pedernales, which contribute significant base flow to the main channel, have not been inventories or evaluated.

While all of the GCDs in the study area have ongoing groundwater level monitoring programs, the programs are generally district wide and not focused near the major streams. Implementation of enhanced groundwater level monitoring programs along all of the study area streams is necessary to fully understand groundwater/surface water interactions.

LAND MANAGEMENT TECHNIQUES TO BENEFIT WATER

Greater understanding of the groundwater/surface water interactions via the methodology developed in the report will assist in the effective planning and implementation of land management techniques that benefit groundwater and surface water supplies. Since 97% of land in Texas is privately owned, to preserve the water that sustains our rivers, streams and aquifers, it is essential that landowners are provided the scientific information necessary to enable sustainable land stewardship implement land management and conservation strategies. Land management strategies can be tailored to a particular watershed (or sub-watershed) once the complex hydrogeologic setting and environmental needs of an area are researched and defined.

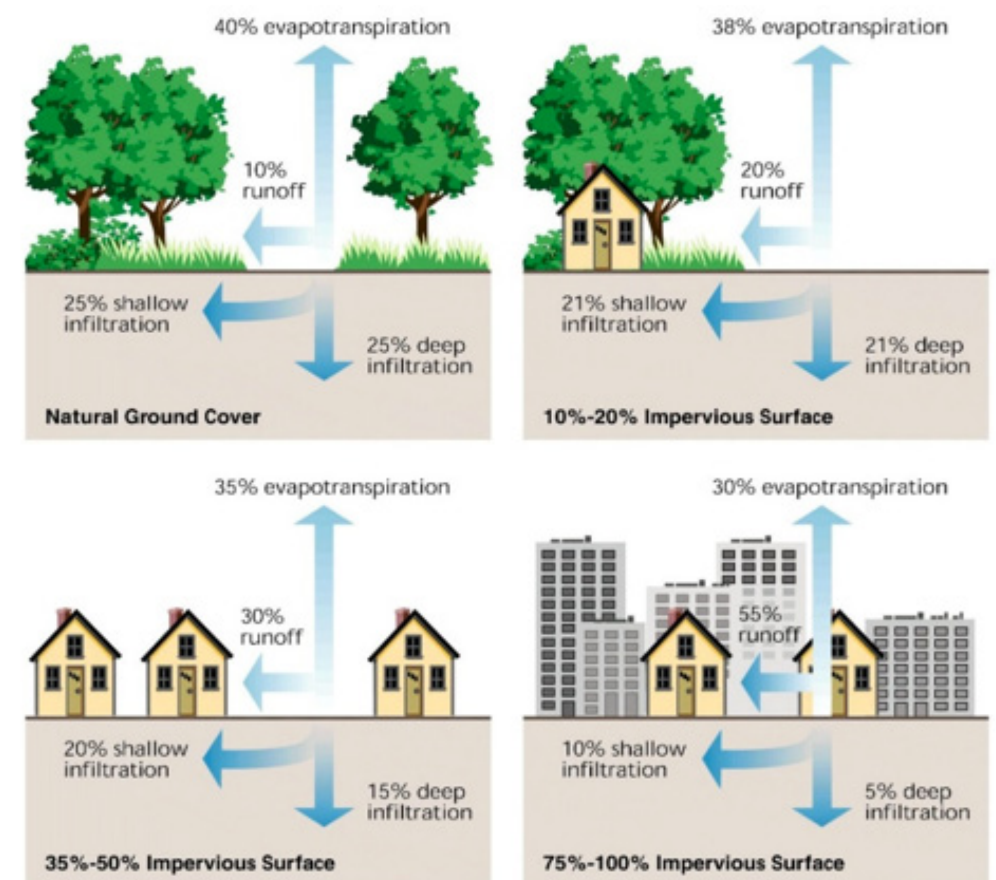
As the land in the Hill Country continues to be fragmented, there are more and more first-time landowners on smaller and smaller pieces of land. This can be looked at as either an unfortunate change in the landscape dynamic or as an opportunity to affect the change for the better. Ecologically conscious land management is possible by understanding the science of the aquifer, and in turn educating and empowering these new landowners with land/water stewardship management strategies. The land management strategies discussed herein do not constitute a complete list of all possible strategies, but is intended to describe some of the most common techniques used in the Texas Hill Country.

Minimize Impervious Cover

The spread of impervious cover is one of the simplest detriments to groundwater recharge to understand. The construction of buildings, sidewalks, roads etc. creates a physical barrier that prevents rainwater from entering the soil, thus reducing or eliminating infiltration into the subsurface. The reduced infiltration can impact both shallow and deep aquifer recharge (see Figure 27). In streams that are fed by shallow gravity springs in rapidly developing areas, such as Onion Creek, increased impervious cover has the potential to reduce base flow in the creek.

Runoff from impervious cover is often simply diverted to the nearest stream causing an increase in peak flood flows. Increase flood flow can cause increased erosion and sediment loading in the creek, impairing ecosystem stability and degrading water quality. The Center for Watershed Protection developed an impervious cover model (ICM). The ICM predicts that most stream quality indicators decline when watershed impervious cover exceeds 10%, with severe degradation expected beyond 25% impervious cover.(http://clear.uconn.edu/projects/TMDL/library/papers/Schueler_2003.pdf). Therefore in areas where streams are sourced from shallow groundwater contribution impervious cover should be maintained at the minimal level possible (~10%) to reduce the impacts on groundwater recharge and base flow of streams.

Figure 32. Impact of impervious Cover on Runoff and Infiltration.



Schueler, 2003

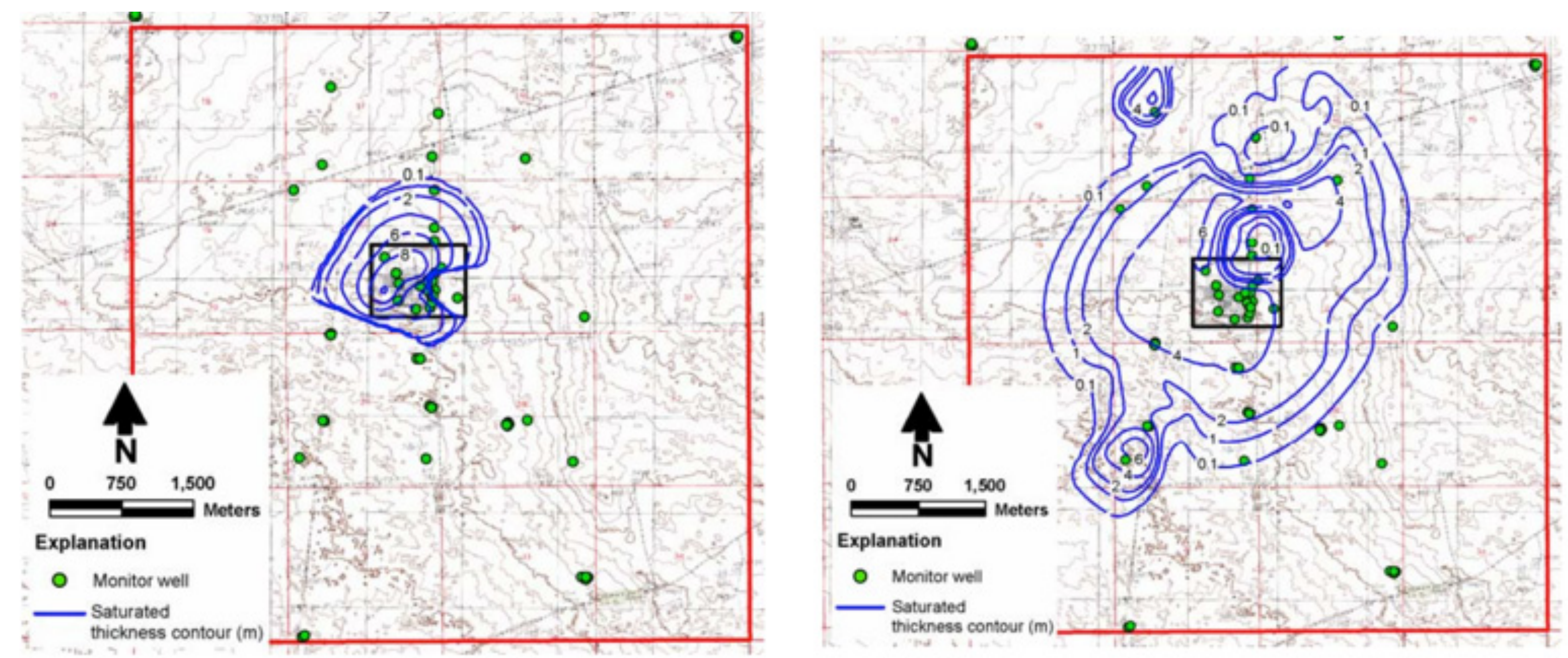
Enhanced Recharge Stormwater Structures

In most urban/developed areas, stormwater best management practices (BMP's) are often designed to mitigate the excess runoff caused by impervious surfaces by directing it off-site. This style of management contributes to peak storm flows and flooding in urban streams, creating instability for stream and riparian ecosystems. Enhanced Recharge Stormwater Structures retain stormwater runoff in infiltration basins on-site allowing the water to recharge into the underlying aquifers. The effectiveness of this type of BMP is dependent on local hydrogeologic conditions. For example, in areas of thick impermeable soil/rock such as clay or shale, this management technique would not be as effective as areas of shallow permeable soil/rock.

If the accelerating urban growth of the Hill Country applied enhanced recharge stormwater structures to mitigate the construction of impervious surfaces, they could not only offset the increase in runoff caused by these impervious surfaces, but also potentially increase the groundwater recharge for their area as compared to natural recharge. The karstic nature of the Hill Country Trinity Aquifer and the Edwards Aquifer make these areas prime candidates for the application of this kind of BMP.

The effectiveness of enhanced recharge stormwater structures scales from small-scale private well benefits to a larger regional groundwater supply increases with the spread of its use. Scaling just affects the magnitude and distribution of the increase in the perched groundwater lens created by the structures. The figures below show the increase in extent and magnitude of a perched groundwater lens through the construction of multiple retention ponds that recharge the stormwater runoff of a 70 acre property in Arizona. In this same study it was estimated that the net groundwater consumption of a housing development (600 homes) could be reduced by 26% by implementing enhanced recharge stormwater structures on-site to mitigate impervious cover (Miller, 2006).

Figure 33. Measured Increase in Groundwater Lens Thickness due to Capture from Site Development (Miller, 2006)



Perched Lens Saturated Thickness in 2002

Increase to Regional Aquifer Saturated Thickness in 2012

Enhanced Recharge Stormwater Structures

Recharge dams are effective management tools for boosting groundwater levels or securing spring flows downstream of recharge zones. They are similar to Enhanced Recharge Stormwater Structures in the fact that they retain stormwater for the purpose of aquifer recharge. But they're different in the fact that they are built on tributary drainages to take advantage of naturally occurring stormwater runoff, instead of built alongside impervious cover to mitigate anthropogenic runoff. Recharge dams are built perpendicular to stream channels located in areas of particularly high recharge geology to take advantage of the naturally high rates of infiltration. These types of dams are constructed with drainages that impede stormflow excess, inundating low lying drainages after periods of heavy rains.

By understanding the local hydrogeology and the occurrence of recharge zones, small recharge ponds can be constructed in these recharge areas to take advantage of their high rates of infiltration. Additionally, detention basins could be built upstream of these recharge ponds to effectively slow stormwater runoff to the downstream basin's rate of infiltration, thus maximizing the duration of recharge. Therefore, these structures not only enhance recharge but also provide flood control, reducing dangerous peak flows in downstream streams and rivers.

Rainwater Harvesting

Rainwater harvesting is a pragmatic, sometimes cost-efficient way to acquire water for rural landowners who cannot hook up to a municipal water system, have insufficient or depleted groundwater resources or would like to develop a redundant water supply system. Rainwater harvesting systems can collect and store non-potable water, or employ simple water treatment technologies to generate potable water. By conserving groundwater through rainwater collection, aquifer depletion can be lessened which in turn benefits streams fed by groundwater contribution.

Urban dwellers often install small rainwater collection systems (rain barrels) for landscape water use. Even if the landowner is hooked into a municipal or private water supplier, rainwater harvesting can greatly reduce their reliance on the public supply and/or groundwater supply. Additionally, having a metric of which to gauge and conserve your water use can be the biggest impact that rainwater harvesting can have. Being able to physically see where your water comes from and how much of it you use on a daily basis can have a lasting effect on a person's perspective towards water use.

Rainwater collection systems from rooftops also help mitigate the negative aspects of impervious cover. Collecting and storing the water for beneficial use eliminates roof contribution to impervious cover.

The BCRAGD is promoting a new concept in rainwater collection/enhanced groundwater recharge. The concept is to collect rainwater off of a residential rooftop, then instead of routing the water the storage tanks, the water is run or injected into an onsite water well. The water then recharges the aquifer and be available for later use. There are some regulatory issues surrounding this approach such as will treatment of the water be necessary prior to injection and if so, to what degree. If the regulatory issues can be resolved, this technique has widespread potential applications for all of Hill County (Jeffery, personal communication).

Management of Groundwater Pumpage

As previously described, there are generally two types of springs: gravity and artesian. Gravity springs are generally shallow, low yielding springs and do not arise from our major aquifers tapped with water supply wells. Artesian springs typically have their origin in deeper regional aquifers. These aquifers, such as the Cow Creek where confined by the Hensel formation, are usually the main sources of groundwater. As these aquifers continue to be developed, pumping can have a direct impact on artesian spring flow. For example, flow from Jacob's Well is being reduced from municipal pumping from the Cow Creek Aquifer (Wierman, 2008). Understanding of the groundwater/surface water interactions can result in developing pumping scenarios that minimize impacts from pumping to spring and stream flow. In the case of Jacob's Well, it may be possible to relocate the pumping center to the down thrown side of the Tom Creek Fault Zone during periods of drought and low flow from Jacob's Well.

In the case of streams fed by shallow gravity springs and groundwater pumpage in the area is from deeper aquifers, management of groundwater pumpage will have little or no impact on spring/stream flow. In the case of Onion Creek, the creek is fed from shallow springs originating in the Upper Glen Rose (Upper Trinity Aquifer). Groundwater useage in the area is primarily from the Lower Glen Rose and Cow Creek (Middle Trinity Aquifer). Figure x is a hydrograph of a well directly alongside Onion Creek in western Hays County. Water levels in the well have been generally greater than 300 feet below land surface. The elevation difference between the well and the creek is approximately 100 feet, thus putting the potentiometric surface at 200 feet or more below the creek.

Well Construction Standards

As previously mentioned, the TDLR well surface casing sealing requirement (16 TAC Chapter 76) only require the upper 10 feet of the well be sealed. The remaining well borehole does not have to be sealed unless waters of differing water quality are allowed to comingle. The shallow sealing requirement can allow for shallow groundwater zones that may be the source water for shallow gravity springs be drained down into deeper aquifers thus depleting spring and stream flow. The reduction in stream flow in Onion Creek over time may be, in part, due to these well construction standards. In Hays County, the HTGCD has increased to the TDLR sealing requirement to fifty feet (HTGCD Rules 2013) below ground surface. Fifty feet is not adequate to full seal off the upper water bearing units. In addition, the HTGCD rules were first promulgated in 2005 indicating all of the pre-2005 wells were likely drilled under the less stringent TDLR rules.

Brush Management

> “*With poor grazing practices and repression of naturally occurring wildfires during the past century, invasive brush species such as mesquite and ashe juniper have inundated vast areas of land that once thrived with a rich diversity of native woody plants, grasses and forbs. Consequently, much of the rainfall that would have otherwise infiltrated deep into the soil providing subsurface flow and aquifer recharge is now either caught up in the heavy brush canopy and evaporated, taken up through the roots and transpired, or it runs off the land, taking valuable soil with it. Land stewardship planning that includes selective brush management benefits soil, water and wildlife by stabilizing the soil, improving water quality, and increasing surface water and groundwater availability.” (LCRA, 2012)*

While predictive modeling of brush management calculates a substantial positive effect on groundwater recharge and subsequent streamflow, there is a lack of scientific research to either confirm or deny the assumption that brush removal increases infiltration rates. In a study conducted in 2000 (Bednarz, 2000) the calibrated SWAT models that were run calculated an average annual water yield increase of 13,000 gallons-172,000 gallons per treated acre. While that range represents an incredible potential for brush management’s effect on Texas’ water supply, it is only a simulated estimate.

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This land management technique would have great potential to be scaled to a watershed magnitude as there are cost-share and incentive programs already designed and in effect in certain areas. In addition to the potential benefits to Texas’ water supply, landowners can personally benefit from an increase in production value if they are running an agricultural or wildlife operation (Conner et al, 2000).

A new state water supply enhancement program with an annual budget of approximately $4 million is incentivizing landowners in the Hill Country to clear brush on their land. Individual landowners may be eligible for up to $600,000 per project. There is criticism coming from some scientists and environmentalists across the State who claim that brush removal alone will increase runoff and sediment loading, and reduce groundwater recharge. The planting of deep-rooted native grasses might be necessary to see a beneficial effect from the removal of brush. Planting native grasses can also mitigate the impacts of historical overgrazing. Overgrazing affects the natural hydrologic quality of land through the reduction of ground cover and root stability, soil compaction, decreased recharge potential, increased runoff and decreased water quality due to larger sediment and nutrient loadings.

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APPENDIX A - INFORMAL OPINIONS ON THE STATE OF GROUNDWATER AND SURFACE WATER MANAGEMENT IN THE HILL COUNTRY: SUMMER 2014

Introduction

The interviews and surveys detailed in this report were conducted by the Meadows Center for Water and the Environment in concordance with the research project How Much Water is in the Hill Country. Multiple water resource scientists and policy makers were interviewed in the initial stages of this project to offer several professional perspectives that would help outline the current state of: Groundwater/surface-water management, monitoring, supply estimation and research in the Hill Country. These expert interviews allowed us to learn more about what is being done in the above stated fields by various state organizations like Groundwater Conservation Districts, the Texas Water Development Board, and the Lower Colorado River Authority. After these preliminary interviews, two sets of surveys were then issued to gauge the publics' knowledge and perception of these water management topics in the Hill Country. The surveys were distributed to two separate regional groups of citizens interested and/or involved in regional water issues. While these surveys and interviews were not designed to be representative of the general public, they allowed for both professional and public input on the current concerns regarding the Hill Country's water supply and also recommendations for potential research and solutions. The results in turn helped affirm the scientific research, methodology and land management strategies that the "How Much Water is in the Hill Country" project recommends.

Expert Interviews

Most questions in the interviews were directed at finding out what was being done to accurately estimate the amount of water in the Hill Country. We also asked what they thought could be done to improve the ability to quantify the water Hill Country streams and aquifers and manage it accordingly. While we had a set list of primary questions to ask in every interview we also asked questions pertaining to the particular organization they worked for. What was maybe more valuable than ascertaining what was being done to monitor and manage our groundwater, was learning about what wasn't being done and what should be done.

The participants in the preliminary interviews were: Bill Hutchison, a private consultant and previous Texas Water Development Board groundwater modeler, Brian Hunt and John Dupnik, the Senior Hydrologist and General Manager of Barton Springs Edwards Aquifer Groundwater Conservation District, Rick Broun General Manager of Hays Trinity Groundwater Conservation District, Rene Barker, Hyrdrogeologist for Edwards Aquifer Research and Data Center, Ron Anderson, Chief Engineer for the LCRA, and Alex Broun, a Professional Geologist. The results of the in-depth interviews were very common across the board. All stated that although Texas is using state of the art technology to model our water supply, we still need more extensive data collection in a multitude of forms: more data collection points, data on private wells, more real time data, more geophysical data and more gain-loss studies along rivers and creeks. The responses of the interviews all point to the conclusion that there is a large opportunity for hydrogeologic research in the Hill Country. While there is data being collected and made available, it is not enough to understand the area or its rivers as completely as we should in order to manage and conserve them confidently. The development of additional hydrogeologic research in the Hill Country can provide regional decision makers with accurate data to interface with future land development, potential conservation easements/efforts and sustainable water management, among other things. It is important that more data starts getting collected sooner than later because at the rate that the Hill Country is growing and developing, its streams and rivers will only deviate more from their original state. It's important to know what the baseline data is for any research study, without it you can only guess at what conditions were prior to changes. Additionally, data collected during the current drought we are experiencing, which is flirting with the drought of record, would serve as incredibly important data in planning for future drought.

The information taken from the interviews advised the development of two separate surveys which were distributed to approximately 3000 people.

FIRST SURVEY

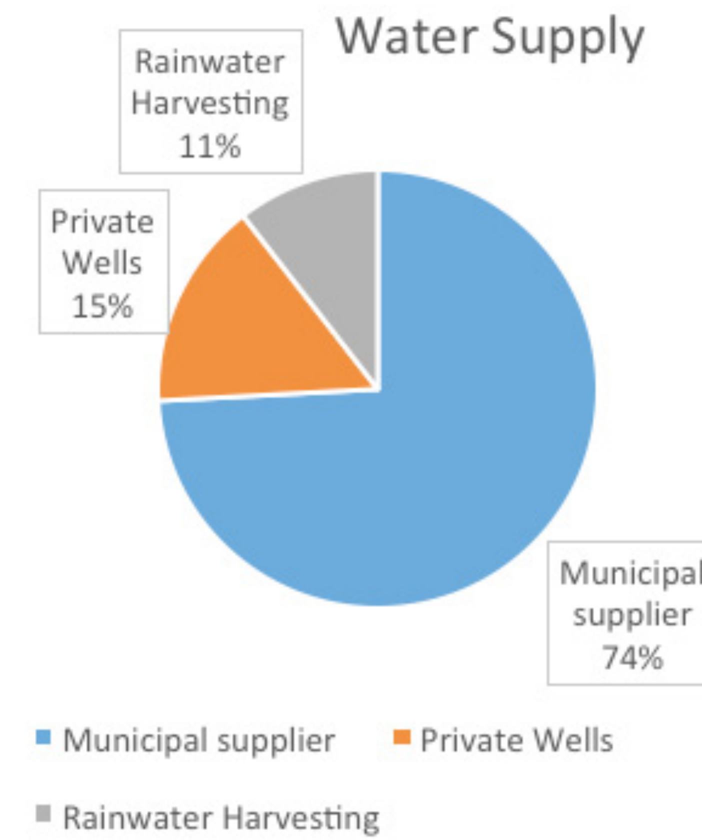
The first survey was sent to the Hill Country Alliance Technical Committee, a group of local and regional water experts, conservationists, that provide discourse and comment on conservation issues for the "the Hill Country Alliance". This survey would serve as a first trial, to be reviewed and edited by suggestion before being sent out to a larger audience. The Hill Country Alliance "is a nonprofit organization whose purpose is to raise public awareness and build community support around the need to preserve the natural resources and heritage of the Central Texas Hill Country." Forty-three people received the survey and twenty-two people responded, leading to a response rate of 51.2%. Over 90% of the respondents considered themselves knowledgeable about water policy in TX and over 70% considered themselves a leader in water planning. About 91% thought of themselves as knowledgeable about Groundwater Conservation Districts and nearly 80% thought of themselves as knowledgeable about Desired Future Conditions. This survey was distributed by hand after a Technical Committee meeting and then it was analyzed using the "Statistical Package for the Social Sciences" (SPSS). After the closed ended questions were evaluated, the open ended questions were analyzed using an open-coding technique. Data was analyzed for frequencies, descriptive statistics, and basic inferential statistics(?).For the answers to this preliminary survey in their entirety, please review "Appendix A" located at the end of the document.

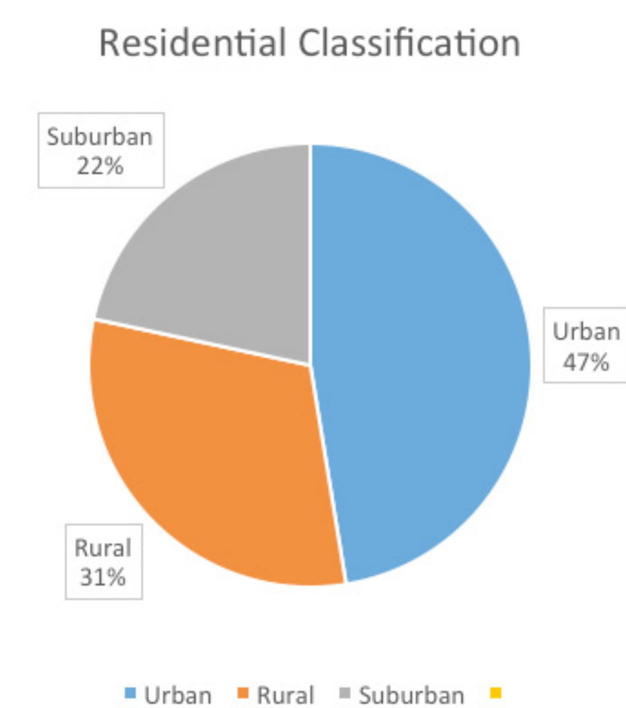
SECOND SURVEY

After the results of the first survey were analyzed, it was re-written and proofed by multiple experts including environmental researchers and survey research professors at Texas State University. The survey was then entered into Constant Contact, an online survey generator, and distributed to 2,992 people by means of an email database provided by the Meadows Center for Water and the Environment and Texas Stream Team. The Texas Stream Team is a "program which is a network of trained citizen scientists and supportive partners working together to gather information about their most important natural resource - water." This audience is not expected to represent the views of the general public, but rather to gain opinion from water-educated and interested stakeholders. The results of this survey were analyzed using Constant Contact.

43.3% of the respondents were 56-75 years old, 52% female, 46% lived in urban area, 30% rural and 21% suburban. 82% acquire their water from a municipal supplier, 17% from private wells and 11.6% from rainwater harvesting.

Most of the audience for the second survey should be considered conscious of water issues. Over three quarters of respondents considered themselves knowledgeable about hydrology as well as the unique geology of the Texas Hill Country. Twenty-five percent said that they participate in the local or state water planning process.





Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.	**strongly disagree**	**somewhat disagree**	**neutral**	**somewhat agree**	**strongly agree**
I am knowledgeable about water policy in Texas.					
	2%	8%	13%	56%	21%
I am knowledgeable about hydrology.					
	6%	5%	12%	53%	24%
I am knowledgeable about the unique geology of the Texas Hill Country.					
	5%	8%	10%	50%	27%
I am knowledgeable about Groundwater Conservation Districts (GCD).					
	4%	12%	21%	42%	21%
I am knowledgeable about Desired Future Conditions (DFC).					
	19%	18%	25%	26%	13%
I am confident that I could explain water policy to others.					
	15%	18%	25%	27%	16%
Texas manages its water effectively for regional use, like the Hill Country.					
	23%	35%	31%	10%	2%
I support clear flowing water in streams, creeks, and rivers in the Texas Hill Country.					
	1%	1%	5%	10%	83%

Only 12% of the survey respondents believed that Texas manages its water effectively for regional use, like the Hill Country. 93% support clear flowing water in streams, creeks and rivers in the Hill Country.

In general, the survey respondents were educated about water conservation management techniques with more than 99% being knowledgeable about at least one of the listed management techniques that could conserve water. 86.5% of respondents were actively involved in some form of voluntary water conservation land/property management themselves. The top three conservation strategies being implemented by survey respondents were: Xeriscaping-58.2%, Use of native grasses-46.4%, Rainwater Harvesting 44.2%

Only 45% of respondents said that they were aware of any current water conservation educational outreach programs. (Considering that the audience is a fairly conservation educated group,) This tells us that Texas' educational outreach programs can become much more extensive.

When the second survey audience was asked for the top 3 areas that Texas' water supply estimation techniques could be improved, this is how they responded.

Out of the following water supply estimation techniques, check the top three areas improvements are needed	**Number of Response(s)**	**Response Ratio**
Increase the number of places groundwater data, such as aquifer levels, are measured.	64	26.4%
Increase the number of places surface water flow is measured (data points)	43	17.7%
3. Provide state funding to the Groundwater Conservation Districts	88	36.3%
Create more detailed groundwater models to address local issues	68	28.0%
2. Interconnect groundwater and surface water models to more accurately predict/simulate groundwater-surface water interactions.	128	52.8%
Increase metering of groundwater use	69	28.5%
Increased metering of surface water use	38	15.7%
1. More closely coordinate surface and groundwater planning efforts	146	60.3%
Increase groundwater monitoring of water levels and quality	60	24.7%
Base Desired Future Conditions on stream/spring flow instead of aquifer levels.	55	22.7%
Other	12	4.9%
Total	242	100%

When looking at the cost/benefit of management techniques, the majority opinion for 10 out of 16 management techniques was a low cost; high benefit. High cost; high benefit often came in as the second most popular choice for many of the questions.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.	high cost; low benefit	high cost; high benefit	low cost; low benefit	low cost; high benefit	don't know/not applicable
Enhanced recharge features	9%	24%	2%	23%	41%
Xeriscaping	3%	10%	10%	66%	11%
Revised Well Construction Rules that increase surface casing depths	9%	21%	3%	8%	59%
Voluntary reduction in groundwater pumping	3%	6%	26%	48%	17%
Land development rules	4%	22%	8%	38%	27%
Limit livestock to sustainable levels	9%	19%	11%	29%	32%
Voluntary conservation easements	1%	14%	19%	44%	23%
Tax exemptions	10%	17%	11%	22%	40%
Rainwater collections	9%	18%	22%	40%	11%
Brush management	9%	18%	11%	39%	23%
Proliferation of native grasses	3%	13%	10%	60%	15%
Minimize impervious cover	2%	25%	4%	54%	16%
Improving education of geology and hydrology	7%	18%	11%	46%	19%
Improving education of water policy	4%	19%	10%	52%	14%
Improving education of the above listed water management techniques	4%	21%	7%	54%	15%
Better understanding of water supply estimations	3%	21%	8%	44%	24%

Concluding Remarks

These data are not supposed to represent the views of the general public but rather the views and opinions of water-conscious and interested individuals. The survey questions were intended to create a third party opinion on potential research opportunities for hydrogeology and land management in the future. The results largely coincide with the conversations and recommendations made by the water resource professionals in the preliminary interviews. The most prevalent response from both the expert interviews and the surveys to what should be done to more efficiently manage our groundwater supply was to increase our data points. While Texas has one of the more extensive and complex water management and monitoring networks in the nation, there are still very large data gaps, even in areas of particular importance and vulnerability like the Hill Country.

Central Texas is experiencing the environmental strain of explosive growth coupled with a period of prolonged drought. This persistent rise in population and urban growth will only continue to stress our natural resources more and more as time passes. Therefore, we need to monitor the effects of this growth on our environment if we want to manage this limited water supply appropriately. Without extensive hydrogeologic research, there might not be enough representatively significant data to indicate the negative effects of growth on the area until it is too late and the damage has already been done. The existence of a fully realized data bank allows management entities like Groundwater Conservation Districts to set their rules and regulations grounded in scientific basis. These management entities cannot set appropriate limits on the amount of water development in their area without having a scientifically accurate reason for doing so. Developing a base line of data during the current drought, which has tested the historic drought of record, could prove as the most important tool in helping prepare for future droughts. With the current dichotomous way that water is managed in Texas (surface water vs. groundwater), one of the most powerful ways to understand the nature of water is to fully characterize the relationship between surface and groundwater through hydrogeologic research.

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