HOW MUCH *Water* is in the PEDERNALES?

Occurrence of Flowing Water and Water Quality during Base Flow Conditions in the Pedernales River Basin

The Meadows Center for Water and the Environment
Texas State University

Hamilton Pool by Marcus Calderon

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TABLE OF CONTENTS

Appendices available at Pedernales.MeadowsWater.org

LIST OF FIGURES AND TABLES

Figures

Tables

LIST OF ACRONYMS

BPGCD: Blanco-Pedernales Groundwater Conservation District

BSEAGD: Barton Springs Edwards Aquifer Conservation District

GAT: Geological Atlas of Texas

GIS: Geographic Information Systems

HCUWCD: Hill Country Underground Water Conservation District

LCRA: Lower Colorado River Authority

MCWE: The Meadows Center for Water and the Environment

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NLCD: National Land Cover Database

NHD: National Hydrological Database

STH: State Highway

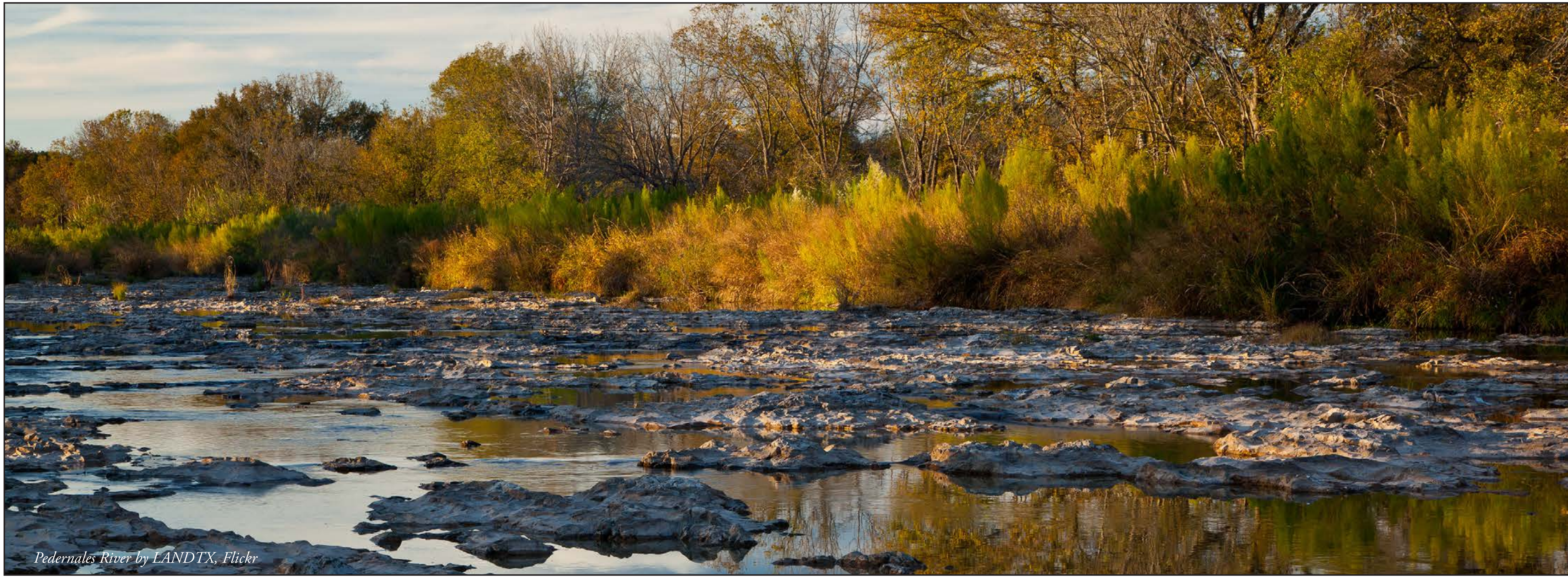
TNC: The Nature Conservancy

TPWD: Texas Parks and Wildlife Department

TWC: Texas Water Commission

USH: United States Highway

USGS: United States Geological Survery


Pedernales River by LANDTX, Flickr

EXECUTIVE SUMMARY

The Pedernales River is in relatively good condition with respect to base flow conditions and base flow water quality. The Pedernales River and its tributaries traverse parts of eight counties in the Hill Country of Central Texas and are an important contributor of water to Lake Travis, the source of water for the City of Austin. Multiple aquifers contribute to base flow in the Pedernales River. Springs and streams originating in the Edwards and Glen Rose Aquifers appear to provide the majority of the main channel base flow in the western part of the Pedernales Basin. The Paleozoic and Trinity Aquifers contribute to base flow in the eastern basin area.

Changes in land cover from 2001 to 2011 indicate land cover did not significantly change over the ten year period, and the basin is generally scrubland and forest. However the amount of developed land increased in the Fredericksburg and Johnson City areas. Increasing impervious cover in developed areas may have implications for storm water quality. Due to the sandy nature of the Hensel (red sands) versus the carbonate characteristics of the majority of the other geologic units in the basin, areas underlain by Hensel are more buildable and amenable to agricultural and urban development and therefore more susceptible to water quality impacts.

Overall, the Pedernales River is a gaining river, meaning flow generally increases moving downstream, though there are losing reaches where surface water recharges the underlying aquifers. Common gaining and losing reaches were observed in the 1962 and 2016 gain/loss studies. Gaining and losing reaches are generally attributable to the underlying geology, though groundwater pumpage may be influencing Pedernales River base flow near the City of Fredericksburg. A significant gaining reach occurs between Johnson City and the confluence with Lake Travis. The occurrence of multiple droughts over the last decade and a half have caused a significant decrease in base flow of the river.

In general, water quality in the river under base flow conditions is good. While there have been changes in water quality, at least partly due to human impact, there have not been significant changes since a comparable study in the 1960s was performed. Analysis of several water chemistry parameters indicate water chemistry is primarily influenced by geology and land cover.

Now is the time to gain a more solid understanding of natural systems and the interconnectedness between surface and groundwater for water planning, wise water policy and the health of Hill Country springs, streams and rivers in the future.

Pedernales River by Jason Kaechler, Flickr

INTRODUCTION

The Pedernales River watershed is an ecologically and economically diverse region that spans 1,281 square miles that are primarily situated within the Texas counties of Gillespie and Blanco, with small portions being contained in Kimble, Kerr, Kendall, Hays, Travis, and Burnet counties. Human activity within the Pedernales River watershed is primarily rural and/or agricultural, as the largest population centers are the Cities of Fredericksburg (pop. 10,829), the seat of Gillespie County, and Johnson City (pop. 1,785), the seat of Blanco County. Also contained within the watershed are the towns of Round Mountain in the northern end of the watershed on United States Highway (USH) 281 (pop. 181), Stonewall (pop. 469) and Hye (unincorporated) on USH 290 between Fredericksburg and Johnson City, the town of Harper (pop. 1,006) on US 290 west of Fredericksburg, and the Austin exurb of Briarcliff (pop. 1,438) at the northeast end of the watershed.

The hydrology and hydrogeology of the Central Texas Hill Country define the occurrence of flowing, or “live” water in rivers and streams. The interaction of groundwater and surface water in this part of Texas is complex and not fully understood. A more complete understanding of these complexities will facilitate more effective water resource utilization and land management from both a water quality and quantity perspective. Thanks to the generous support of the Cynthia and George Mitchell Foundation, this report is the third in a continuing series of reports prepared by The Meadows Center for Water and the Environment (MCWE) entitled *How Much Water is in the Hill Country?*

The first report, *How Much Water is in the Hill Country?,* prepared in 2014, developed an effective hydrogeologic methodology for understanding groundwater/surface water interactions in Texas hill country streams. Tools that can be used for this purpose include:

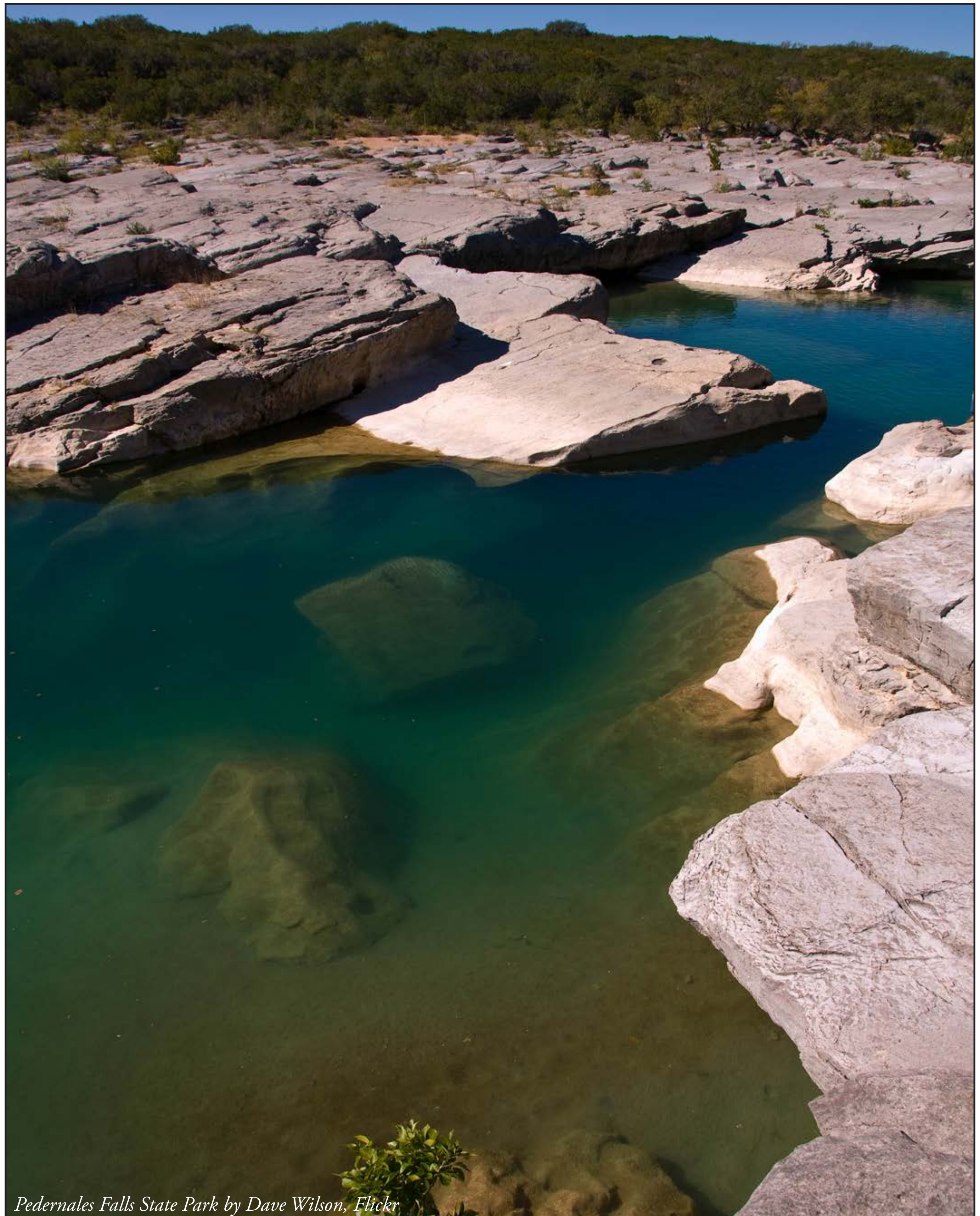
- Reviewing state well reports
- Classification of drill cuttings
- Downhole geophysical logging
- Geologic mapping
- Water level monitoring
- Water quality monitoring
- Stream gain/loss studies
- Dye tracing studies

The report examined four watersheds from a hydrogeologic perspective, identifying data gaps regarding groundwater-surface water interactions. The watersheds studied included the Blanco River, Onion Creek, Medina River and Pedernales River. Based on local stakeholder interest, this study focuses on the Pedernales River.

Based on the data gaps identified in the first report, the second report, *How Much Water is in the Hill Country? Conservation Strategies, Management Approached and Action Plan - 2015*, focused on documenting the occurrence of surface water in tributaries and the main channel of the Pedernales River during base flow conditions. The report presented a preliminary summary of the technical work performed during 2015. Based on preliminary data, recent studies, and input from stakeholders across the watershed, the report focused on the highest priority and regionally appropriate actions to improve and sustain surface water and groundwater resources.

The second report specifically:

- Summarized recent studies and reports
- Identified water supply and water quality threats
- Suggested approaches to manage and mitigate threats and/or enhance the river
- Identified existing programs and activities to stretch resources
- Compiled information to guide the allocation of future resources



Pedernales Falls State Park by Dave Wilson, Flickr

This third report, *How Much Water is in the Hill Country? Occurrence of Flowing Water During Base flow Conditions in the Pedernales River Basin,* presents data and analysis of information collected during 2015-16 focused on identifying the origin of flowing waters during base flow, or low flow conditions. A companion report, *The Pedernales Subwatershed Atlas,* provides an inventory of relevant physical data from the watershed for assessing groundwater-surface water interactions and potential human development impacts. The data collected during this third study also forms a significant baseline for comparison with past and future data, and for assessing the effectiveness of future mitigation and land management efforts.

A base flow (gain/loss) study was performed in August, 2016. The only basin-wide gain/loss study performed on the Pedernales River occurred in 1962, and published in 1964 (Holland and Hughes 1964). Completing an updated study helps quantify the amount of water flowing in the main channel and tributary contributions and allow a comparison of river conditions in 1962 and 2016.

The work performed is included in the Scope of Study section of this report. As part of the ongoing study, Sarah J. Zappitello, a graduate student from Texas State University's Department of Biology and The Meadows Center for Water and the Environment, prepared a Master of Science thesis utilizing data collected during the current study and presented an in-depth analysis of surface water quality data. The thesis, completed in May 2016, complements the data and analyses in this report (Appendix A).

INTRODUCTION TO THE PEDERNALES RIVER BASIN

The Pedernales River flows 106 miles through Texas Hill Country, being an important tributary of the Colorado River. The headwaters of the Pedernales are spring-fed and originate in southeastern Kimble County. The river flows in an easterly direction through Gillespie County, into Blanco County and ultimately into the Colorado River in Travis County. Overall, the main channel of the river passes through four counties with a drainage area of more than 819,200 acres. The Pedernales catchment area extends into eight counties, with the river having a number of important tributaries along its reach (Figure 1). Most of the tributaries are highly intermittent, but there are several perennial streams that provide important surface water to the main stem (TNC 2007).

The Pedernales is valued as a relatively pristine river in Central Texas, with important intact habitats providing shelter for a number of threatened and endangered species. There are 19 rare plant species found in the watershed, 34 fish species, at least six species of salamander and numerous other insects and larvae residing in and around the river (LCRA 2012). The region is home to a wide array of plant and wildlife species, including 118 species found nowhere else in the world (TNC 2007). The river consists of a mixture of riffles, pools and runs, providing an important variety of habitats for aquatic species.

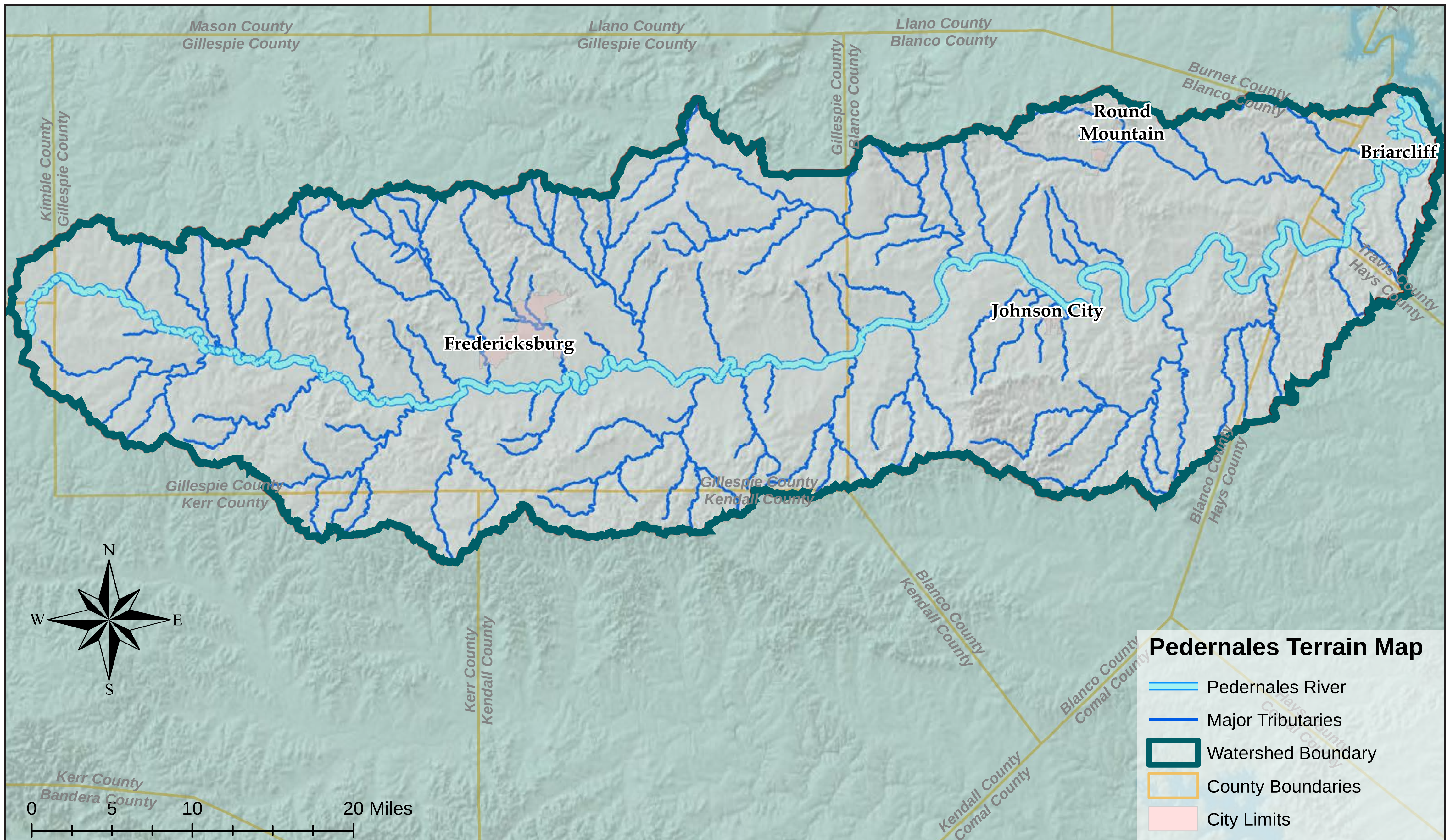


Figure 1. Pedernales Terrain Map

Physiography and Topography (after LCRA, 2000)

The Edwards Plateau is a physiographic region occupying about 35,900 square miles of Central and West-Central Texas. Combined with the High Plains to the northwest, it makes up the southernmost extent of the Great Plains physiographic province of the United States The central and western portions of the Edwards Plateau exhibit little relief, except along major stream valleys, and the plateau merges almost imperceptibly into the High Plains region to the northwest. The prominent Balcones Escarpment, which rises several hundred feet above the West Gulf Coastal Plain, forms the arc-shaped southeastern margin of the Edwards Plateau. Headward erosion of the streams flowing across the Edwards Plateau toward the Balcones Escarpment has dissected the southeastern part of the plateau, forming the subregion known as the Balcones Canyonlands. The resulting terrain is generally known as the Texas Hill Country, being characterized by steep canyons, narrow divides, and high gradient streams. The Pedernales River valley is the northernmost watershed of the Balcones Canyonlands, being bounded on the north by the Llano Uplift region. Plateau elevations in the study area increase from about 900 feet msl (above mean sea level) at the southeast end of the Pedernales River valley to about 2,200 feet msl at the west end. Valley bottom elevations increase from about 700 feet msl at the Pedernales River's confluence with the Colorado River to about 2,100 feet msl at the river's headwaters.

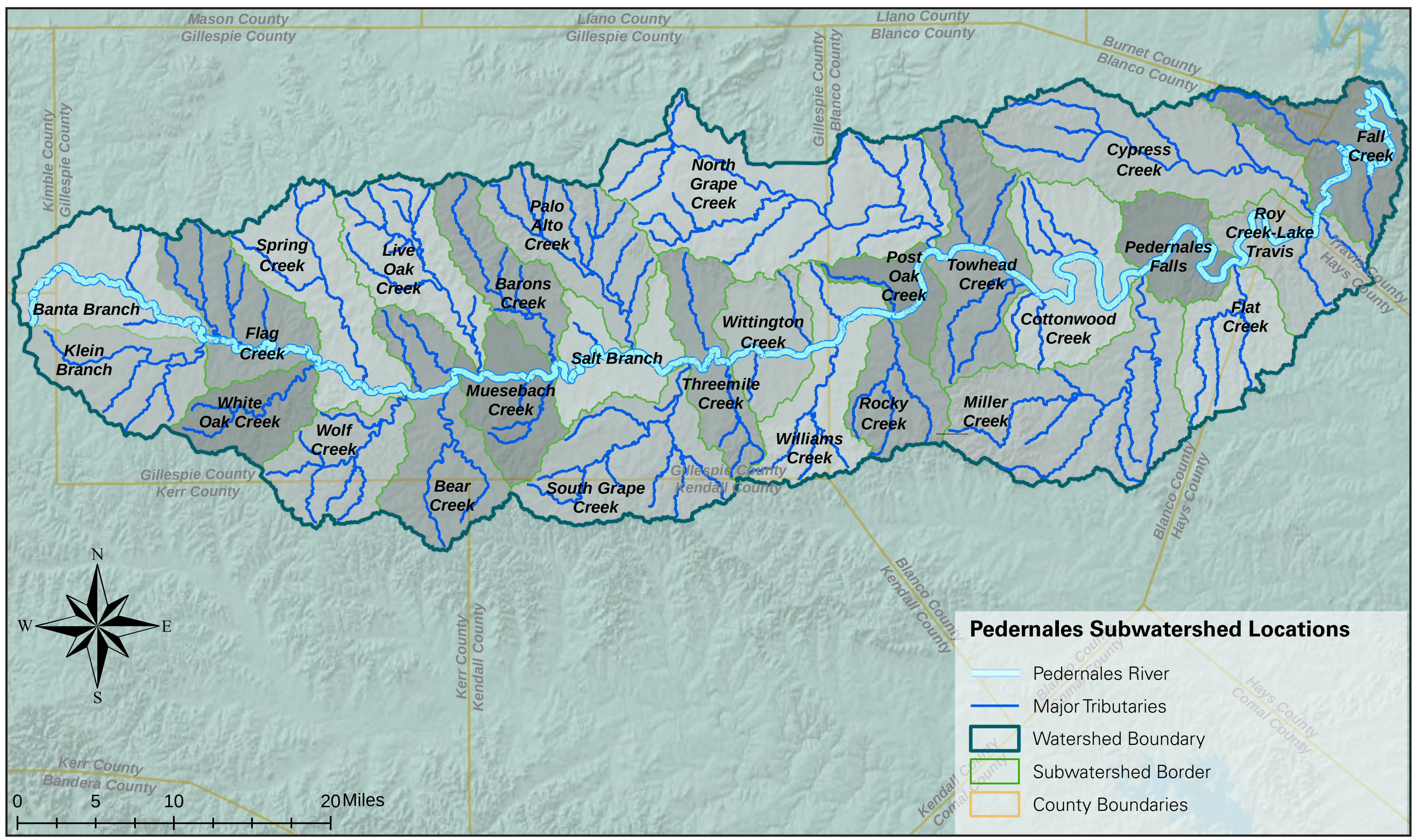


Figure 2. Pedernales Subwatershed Locations (Source: National Hydrological Database)

Subwatersheds

Land surface elevations range from approximately 2,300 feet msl west of Harper, to approximately 680 feet msl at Lake Travis. As defined by the United States Geological Survey (USGS) Watershed Boundary Dataset, the basin is dissected into 27 subwatersheds (Figure 2). Subwatershed Map A, listing subwatershed area from smallest to largest, is included on Table 1. A fact sheet of each subwatershed includes a detailed map, important facts, percentage of land area by land cover and surficial geology (Appendix C).

Subwatershed	Area (miles^2)
Post Oak Creek	18.9
White Oak Creek	27.7
Pedernales Falls	28.2
Rocky Creek	28.3
Wittington Creek	31.0
Barons Creek	32.4
Salt Branch	33.5
Three Mile Creek	34.3
Muesebach Creek	34.3
Flat Creek	37.1
Roy Creek	37.2
Wolf Creek	38.7
Klein Branch	41.4
Flag Creek	44.6
Live Oak	45.6
Williams Creek	46.6
Fall Creek	48.5
Banta Branch	48.8
Palo Alto Creek	51.3
Bear Creek	53.2
Toehead Creek	55.6
Spring Creek	56.3
Cottonwood Creek	58.5
South Grape Creek	63.1
Cypress Creek	81.6
Miller Creek	88.4
North Grape Creek	115.6

Table 1. Subwatershed Areas

SCOPE OF STUDY

The study consisted of several primary efforts: GIS data collection and mapping, literature review, water quality sampling and water quality laboratory analysis, base flow study and preliminary data analysis and interpretation. The study area included the Pedernales River basin from the headwaters springs just east of Harper to the Hamilton Pool Road at Hammett's Crossing where the river enters into backwaters of Lake Travis.

GIS Data Collection, Mapping and Database – Literature Review

GIS is a versatile tool that can be used for a variety of functions, including mapping physical and hydrological features of a certain area, housing and centralizing multiple forms of environmental data, and performing spatial and data analysis using various tools offered within the program. The study used the ESRI suite of GIS products, specifically ArcMap and ArcCatalog version 10.1.

Land cover data was collected and analyzed for patterns using National Land Cover Database (NLCD) shapefiles, along with shapefiles of watershed and subwatershed boundaries, tributaries and flowlines from the National Hydrological Database (NHD). A geologic map from the Geological Atlas of Texas was added for analysis of geology. The team was then able to synthesize these data and calculate land cover types by subwatershed as well as percentage of surficial geology by subwatershed. Groundwater quality data was extracted from the Texas Water Development Board online database and sorted by aquifer. Additionally, surface water flow information obtained from the Hill Country Underground Water Conservation District (HCUWCD) was analyzed for possible long term gains and losses along a reach of the Pedernales River near Fredericksburg.

Water Chemistry Mapping and Analysis

Chemical analysis of surface water and groundwater is used to evaluate water quality, examine human impacts, and understand water pathways of groundwater to the surface and vice versa. Major ion chemistry is a standard tool used to decipher hydrogeochemical patterns as well as impacts of human activity (Dunne and Leopold 1978). Spatial patterns in water chemistry were evaluated as related to both man-made and natural sources by utilizing spatial analysis in ArcGIS. The field data points provide spatial locations for the water samples. Two sets of water quality samples were obtained during the study.

Pedernales Falls State Park - Twin Falls by Texas Parks and Wildlife Department

Flowing Water Inventory Sampling - 2015

During the summer of 2015, a flowing water inventory was performed by The Meadows Center and other stakeholders. The purpose of the inventory was to identify sites that contained flowing water, standing water, or no water at all (dry sites) and to help determine the origin of water during base flow conditions. Sites were identified as those with public access for observation by locating where public roads intersect a National Hydrography Dataset flowline. Nine hundred and thirty-two sites were identified. On August 10 – 11, 2015, a team of Texas State University staff and volunteers observed flow conditions at the 932 sites and developed a database of the observations. From the inventory observations, sites were selected for follow-up water chemistry sampling.

The flowing water inventory was staged such that flow conditions would be similar to the conditions during the 1962 base flow study conducted by the United States Geological Survey (USGS) (Holland and Hughes, Bulletin 6407 (1964). During the 1962 study and during the flowing water inventory in 2015, flow measurements were made downstream of the confluence of the Pedernales River and Cypress Creek near Reimer's Ranch. A comparison of the discharges from 1962 and 2014 at USH 87 (USH 87), USH 281 (USH 281) and near Reimer's Ranch are shown on Table 2 along with the increase in flow along the river.

Measurement Location	May 1962	August 2015	2016 Base Flow Study
Fredericksburg @ USH 87	4.8 cfs	2.0 cfs	8 cfs
Johnson City @ USH 281	15.3 cfs	18.0 cfs	24 cfs
Reimer's Ranch, downstream of Cypress Creek (1962 &2015) and Hammett's Crossing (2016)	30.3 cfs	27.8 cfs	52.8 cfs

Table 2. Flow Measurements – Main Channel of Pedernales River

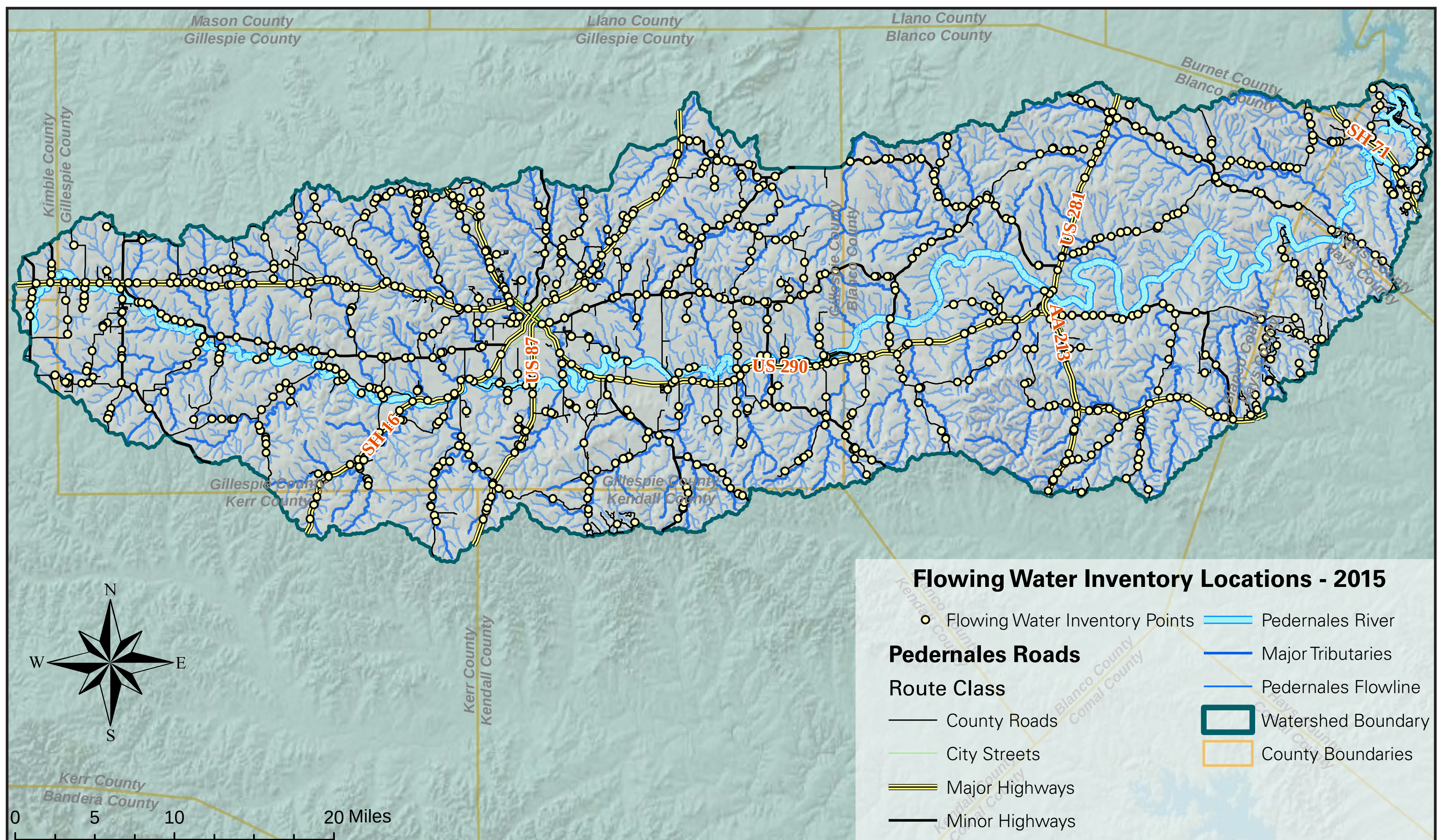


Figure 3. Flowing Water Inventory Locations – 2015

A complete description of the flowing water inventory and preliminary observations were included in the How Much Water is in the Hill Country? Conservation Strategies, Management Approached and Action Plan – 2015 report. The synoptic water sampling event was designed to capture a “snapshot in time” of the water chemistry based on the 2015 flowing water inventory. Water sample locations were chosen from intersections of publicly accessible road crossings of the Pedernales River and tributaries with flowing water based on the flowing water inventory. Out of the 932 locations, 117 sites had water during the sampling event two weeks later. Of the 117 sites with flowing water, 79 sites were chosen to collect water samples plus nine springs and three wells for a total of 91 sample sites. Sites are located on Figure 6. The synoptic sampling event occurred over the course of two weeks, from 27 August to 10 September 2015, and during this time period no precipitation events occurred.

The following parameters were analyzed:

Calcium, magnesium, sodium, potassium, chloride, fluoride, sulfate, nitrate, bromide, total nitrogen, ammonium, total phosphorus, particulate phosphorus, solube reactive phosphorus, dissolved organic carbon, particulate nitrogen, particulate carbon, delta 2Hydrogen, delta 18Oxygen, total suspended solids and nonvolitale suspended solids.

Refer to Appendix A for additional details of the water quality sampling event.

Figure 4. Example of a Flowing Water Inventory Site

Figure 5. Sampling at the Headwaters of the Pedernales River

Base Flow Study Sampling 2016

To enable flow weighted comparison with water quality data collected during the 1962 study (Figure 12), samples were collected during the 2016 base flow study. Samples were collected at 11 main channel locations during the base flow study in August 2016 as shown on Figure 8. A limited set of parameters were analyzed as a similar set of parameters were analyzed in 1962. Parameters analyzed in 2016 included chloride, nitrate-nitrogen, sodium, potassium, magnesium, calcium, silica, alkalinity and hardness. A summary of the results are contained in Table 12.

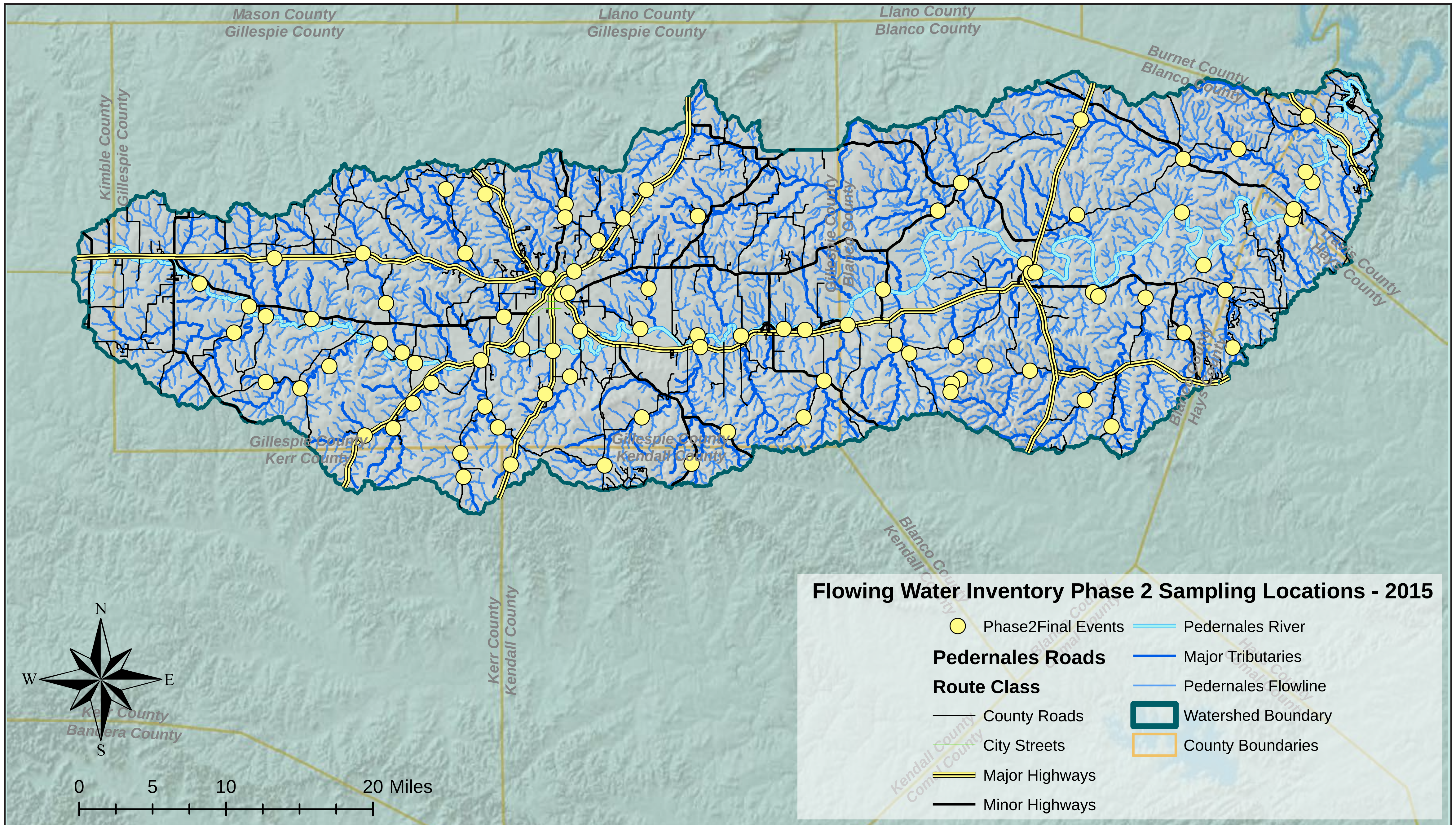


Figure 6. Flowing Water Inventory Phase 2 Sampling Locations – 2015

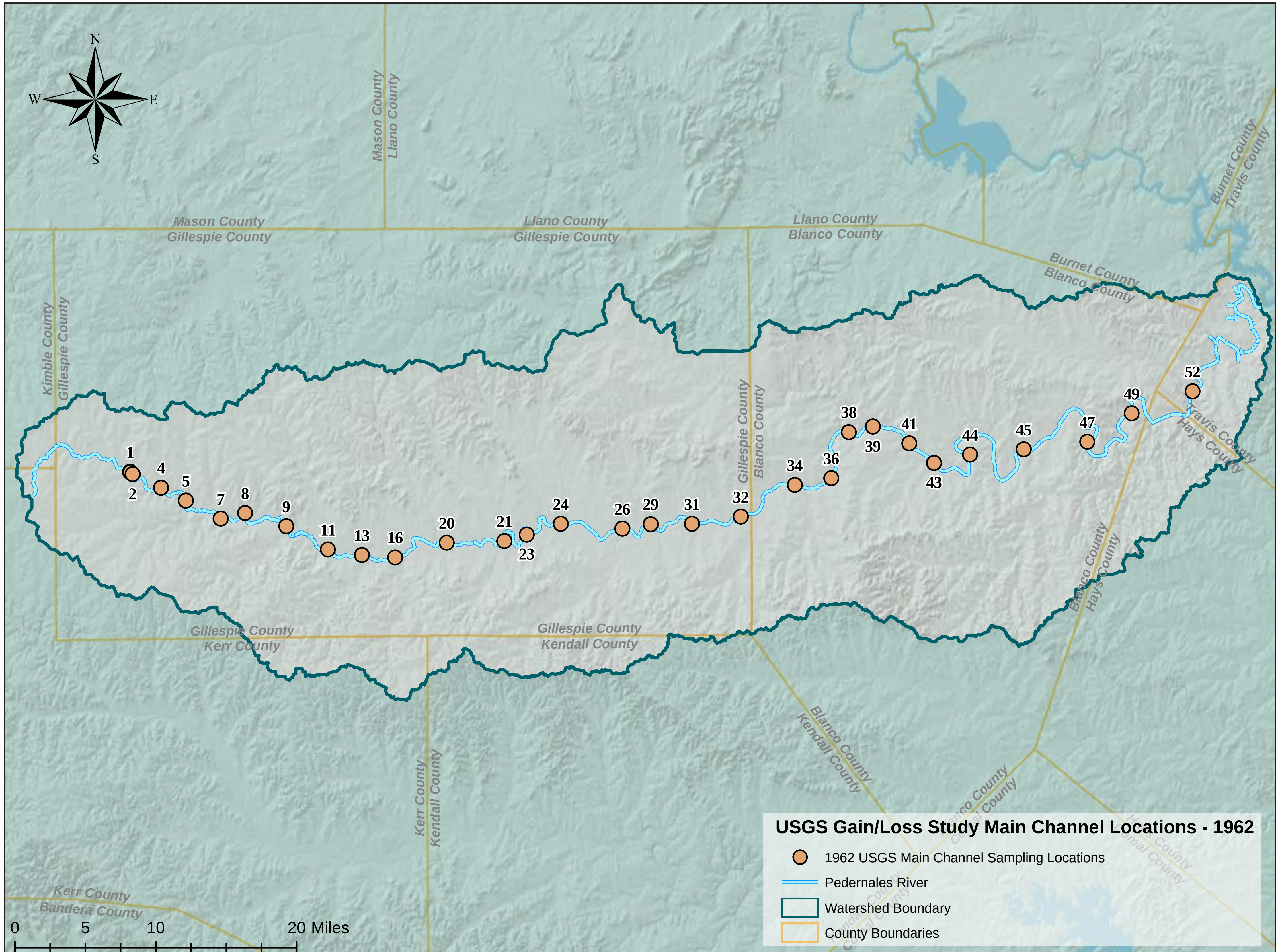


Figure 7. USGS Gain/Loss Study Main Channel Locations – 1962

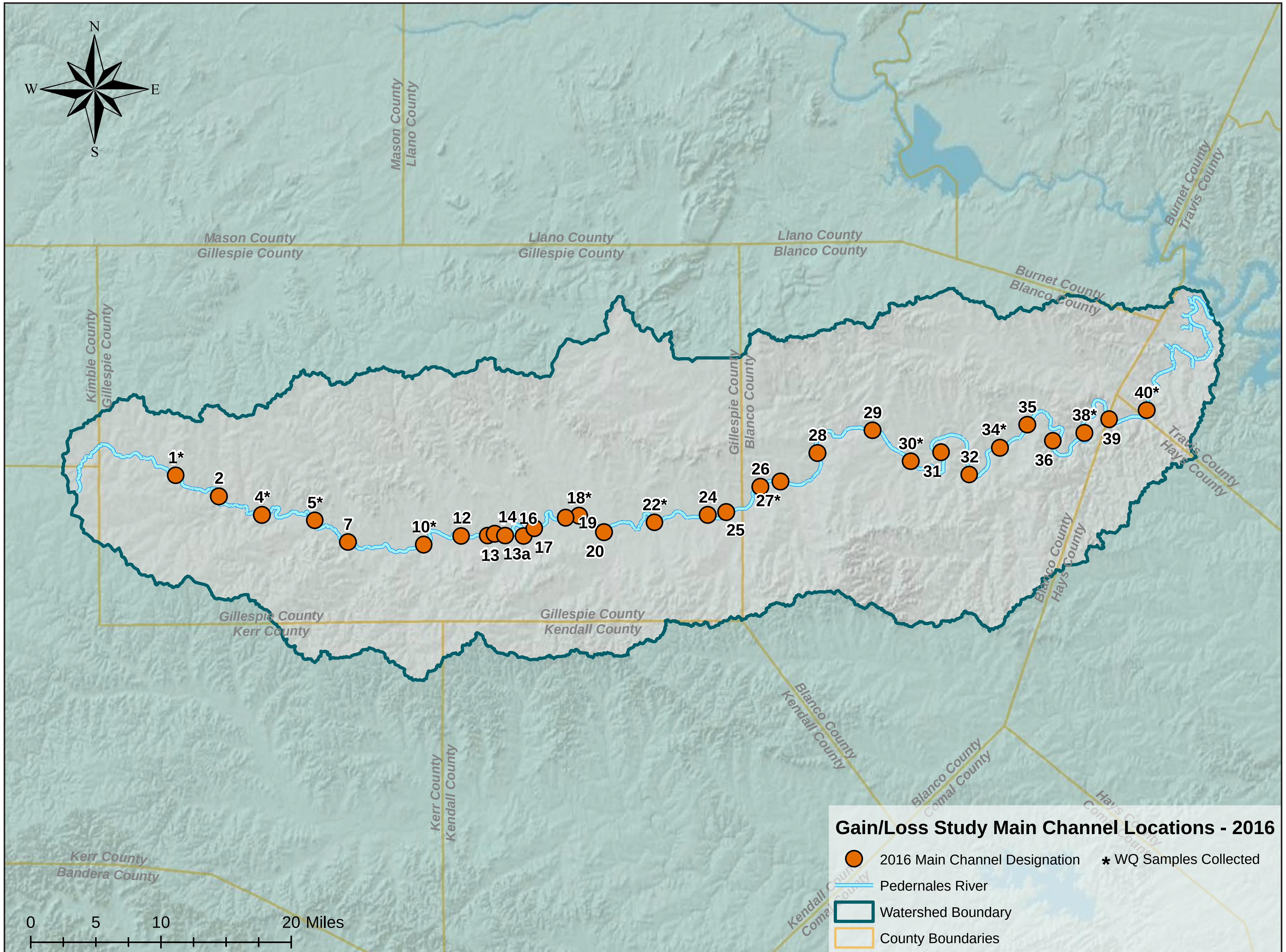


Figure 8. Gain/Loss Study Main Channel Locations – 2016

Geology of the Pedernales Basin

There are many publications available describing the geology of all or part of the Pedernales Basin. A representative listing of geologic references used in this report is included in the appendices. Differing terminology for the various rock units is common among the various references. For consistency throughout this report, the stratigraphic nomenclature and geologic map contained in the Geologic Atlas of Texas (GAT)-Llano Sheet (1981 version), Virgil E. Barnes, and published by the Bureau of Economic Geology at the University of Texas-Austin are used. Report 273 "Groundwater Availability of the Lower Cretaceous Formations in the Hill Country of South-Central Texas" (Ashworth, 1983) and Report 339 "Evaluation of the Groundwater Resources of the Paleozoic and Cretaceous Aquifers in the Hill Country of Central Texas" (Bluntzer, 1992) were the key resources used to develop the following geologic descriptions. A geologic map of the basin and generalized stratigraphic column is included as Figures 9 and 10. Maps showing the surficial extent of the various formations are shown on Figures 12-17.

Period	Group	Formation	Member	Aquifer
Cretaceous	Fredericksburg	Edwards	Segovia	Edwards-Trinity Plateau
			Fort Terrett	
	Trinity	Glen Rose	Upper Glen Rose	Upper Trinity
			Lower Glen Rose	Middle Trinity
		Hensel		
		Cow Creek		
		Hammett		
		Sligo		Lower Trinity
		Sycamore		
Pennsylvanian	Canyon	Undivided rocks		
		Smithwick		
	Bend	Marble Falls		Marble Falls
Ordovician	Ellenburger	Honeycut		Ellenburger
		Gorman		
		Tanyard		
Cambrian	Moore Hollow	Wilberns	San Saba	
			Point Peak	
			Morgan Creek	
			Welge	Welge-Lion Mountain
		Riley	Lion Mountain	
			Cap Mountain	
			Hickory	Hickory
Precambrian		Undivided rocks		

Figure 9. Stratigraphic Column from Zappetello (2016) adapted from Wierman et al. (2010) and Standen and Ruggiero (2007)

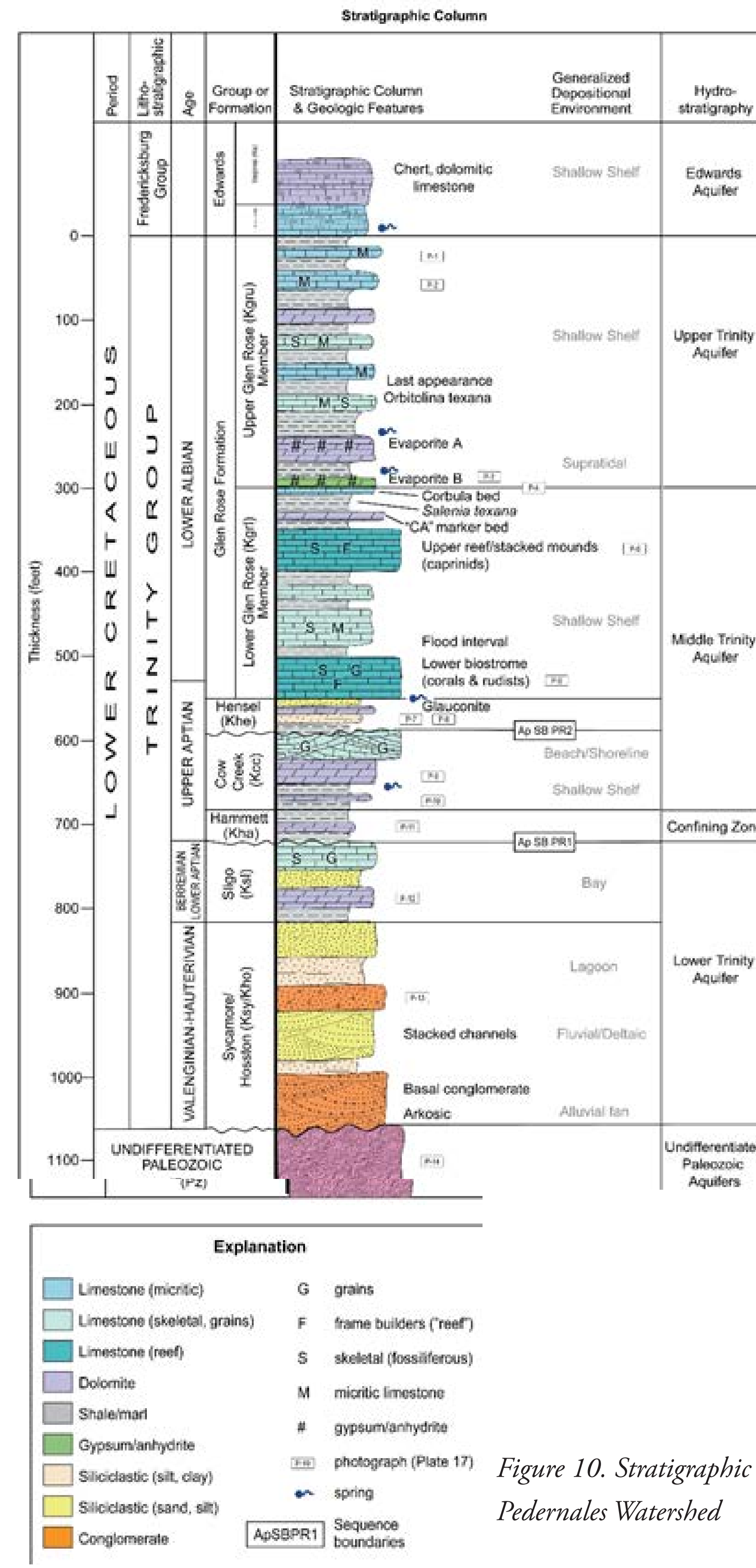


Figure 10. Stratigraphic Column of Pedernales Watershed

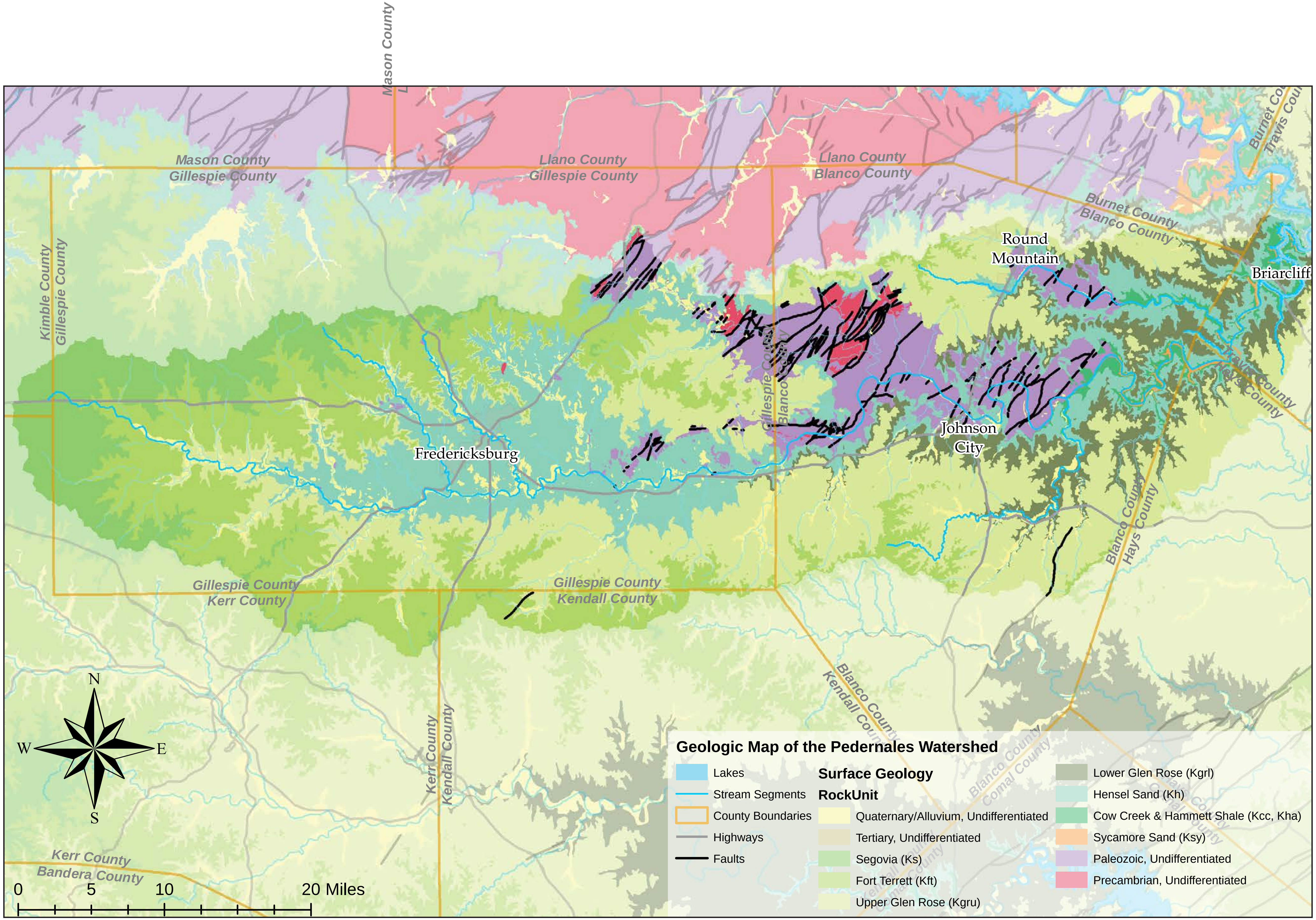


Figure 11. Geologic Map of the Pedernales Watershed

Pre-Cretaceous Rocks

The Pre-Cretaceous rocks consist primarily of Precambrian, Cambrian, Ordovician and Pennsylvanian strata, being exposed in north western Blanco County and north eastern Gillespie County along the Pedernales River. The Precambrian rocks are generally granitic, being part of the Llano Uplift. These granites are expressed as upward protruding knobs which protrude through the Paleozoic and Cretaceous strata. The Paleozoic rocks are primarily sandstones, dolomites and limestones. Structurally, the units are highly faulted, fractured, and folded. They are mapped and referred to as undifferentiated Paleozoic rocks. Unless locally fractured, the Precambrian rocks are not considered to be a significant aquifer. Several Paleozoic strata yield moderate to high amounts of water to wells (Bluntzer), including:

- Cambrian Hickory (Crh) Aquifer (sandstone);
- Ordovician Ellenburger Group (Ob, Oh, Og, Ot)-Cambrian San Saba (Cws) Aquifer (fractured limestone and dolomite);
- Marble Falls Aquifer (IPmf) (fractured limestone).

Lower Cretaceous rocks are relatively flat lying strata dipping slightly to the south and east and make up the majority of the surficial strata and shallow aquifers.

The Sycamore Sand (Hosston Member in the subsurface) is a sandstone, siltstone and conglomerate and makes up the Lower Trinity Aquifer in the Pedernales Basin. It crops out as the lowest Cretaceous unit in the deeply incised stream and river valley in western Blanco, northern Hays and Travis Counties. To the east of the Pedernales basin in Hays County, the Lower Trinity Aquifer is under confined conditions, being confined by the overlying Hammett Shale and the rest of the lower Cretaceous section.

The Hammett Shale and Cow Creek Limestone are mapped by Barnes as a single unit on the Geologic Atlas of Texas, although most researchers currently consider them as two separate units. Both can be considered as part of the Middle Trinity Aquifer. The Hammett Shale is a calcareous and dolomitic shale, acting as a confining layer separating the Lower and Middle Trinity Aquifers. The Cow Creek Limestone is a massive, locally cross-bedded dolomitic limestone and can be a very productive aquifer. The unit thins to the west, onlapping Paleozoic rocks. Both the Hammett Shale and Cow Creek Limestone crop out and overlay the Sycamore Sand in the deeply incised Pedernales River valley in Northern Hays County.

The Hensel Sand is the uppermost lower Cretaceous rock unit in the flat, broad river valley of central Gillespie County and the dominant Middle Trinity Aquifer member throughout most of the river valley. The Hensel Sand is composed of sand, sandstone, conglomerate and thin limestone units. The thickest sandstone is present around the Llano Uplift. The relatively flat central plain of Gillespie County is directly underlain by the Hensel Sand. The Hensel can produce moderate to large quantities of water. Due to the sandy nature of the Hensel, the recharge rates are generally higher than the overlaying carbonate units.

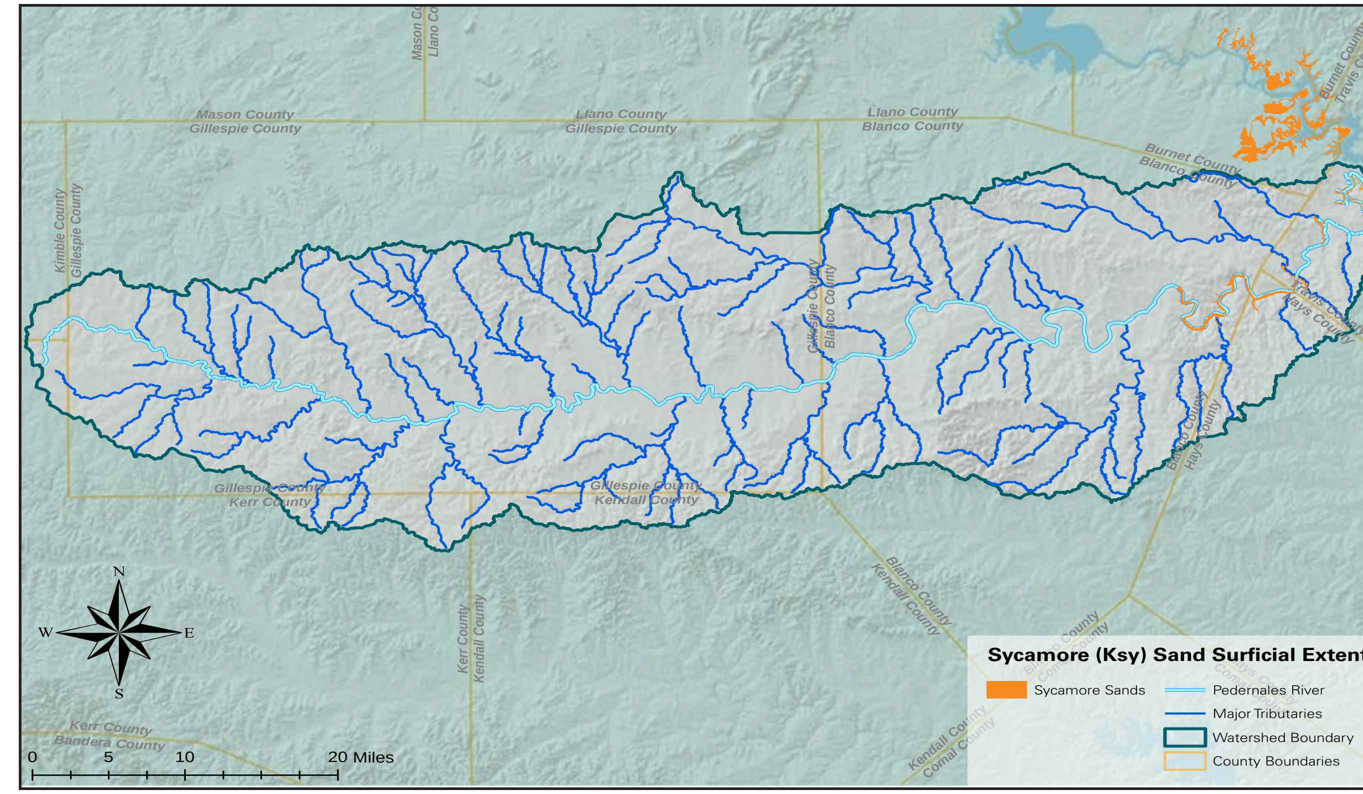


Figure 12. Sycamore (Ksy) Sand Surficial Extent

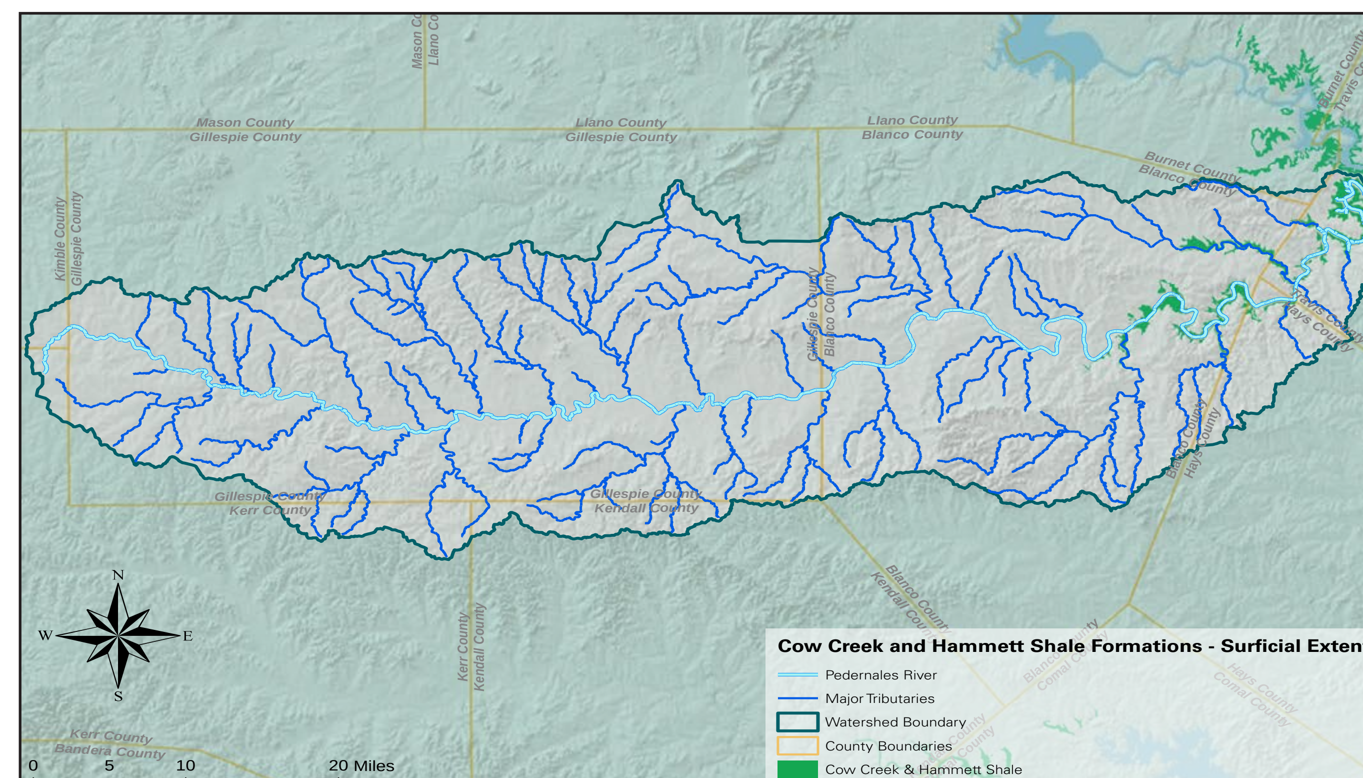


Figure 13. Cow Creek and Hammett Shale Formations – Surficial Extent

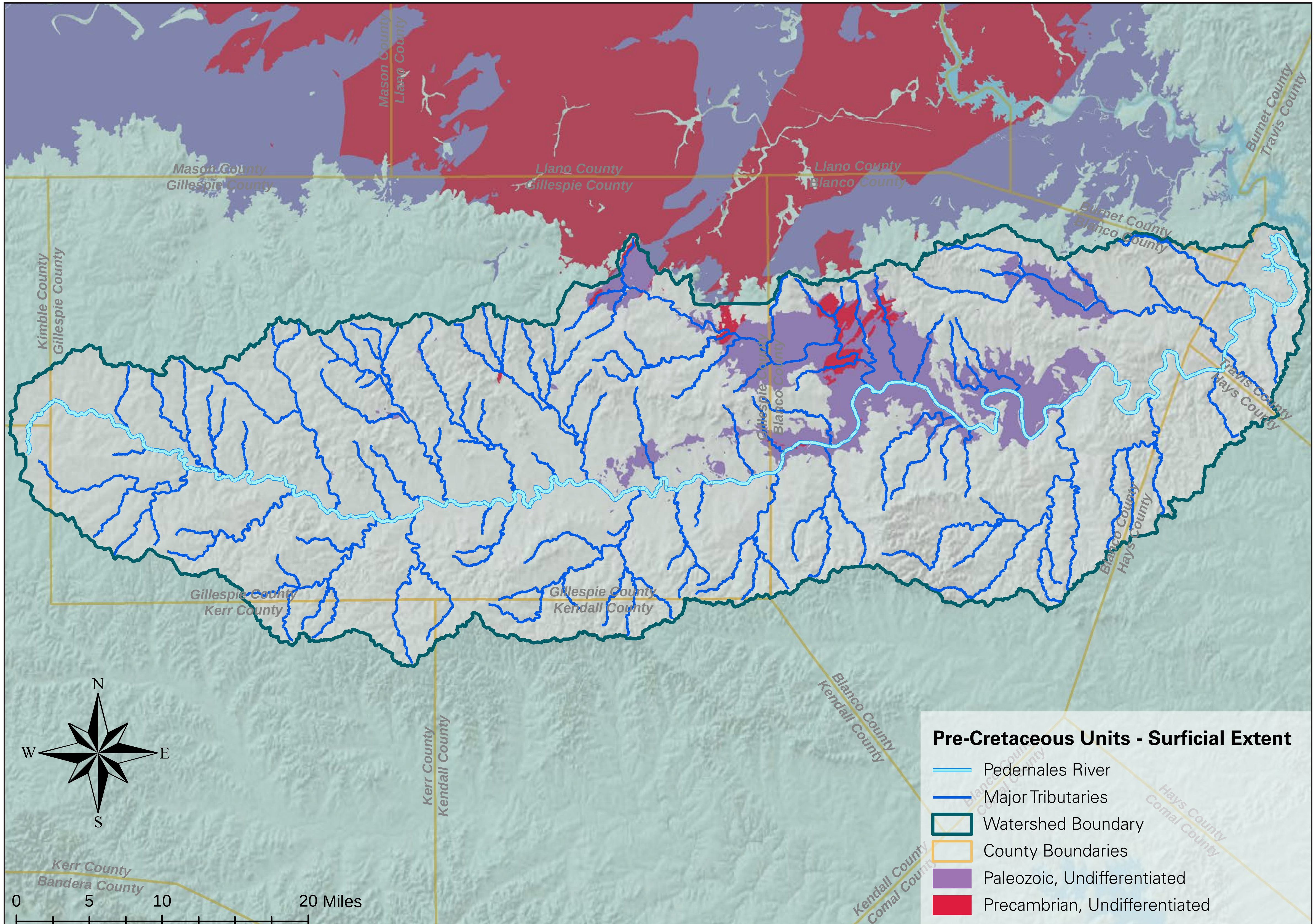


Figure 14. Pre-Cretaceous Units – Surficial Extent

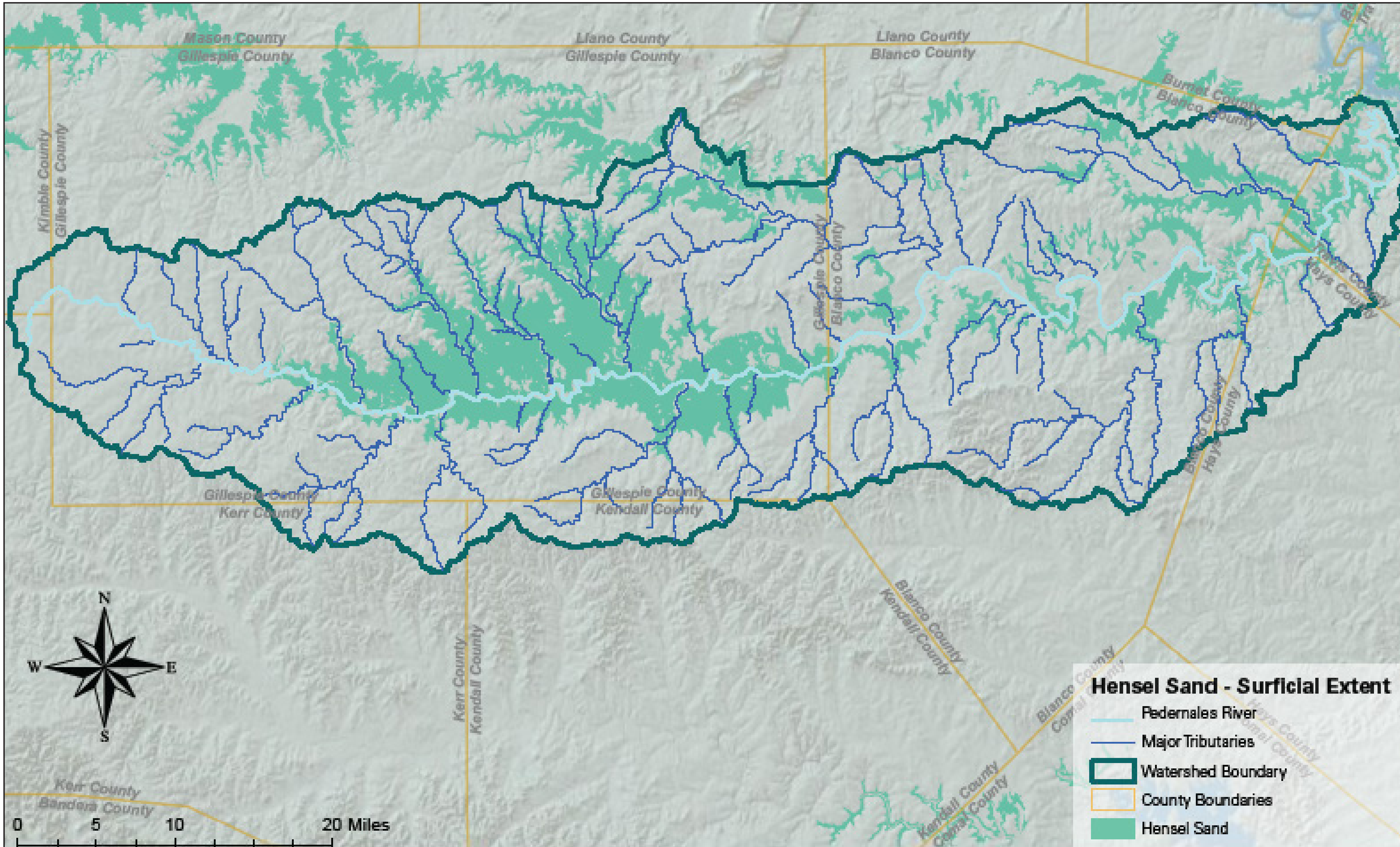


Figure 15. Hensel Sand – Surficial Extent

The Glen Rose Formation consists of two members:, the Upper Glen Rose and Lower Glen Rose. These resistant limestone and dolomitic units form steep topography that rings much of the central part of the watershed. The Lower Glen rose pinches out in eastern Blanco County. The Lower Glen Rose is the uppermost member of the Middle Trinity Aquifer, while the Upper Glen Rose makes up the Upper Trinity Aquifer. Two distinct evaporate zones of anhydrite and gypsum occur in the Upper Glen Rose near the contact of the two units, where the Lower Glen Rose is present. Where exposed at the surface, the Upper Glen Rose is under unconfined conditions, generally not being a major producer of groundwater to wells. Where present and in conjunction with the other underlying members of the Trinity Aquifer, the Lower Glen Rose can yield moderate to large quantities of water to wells.

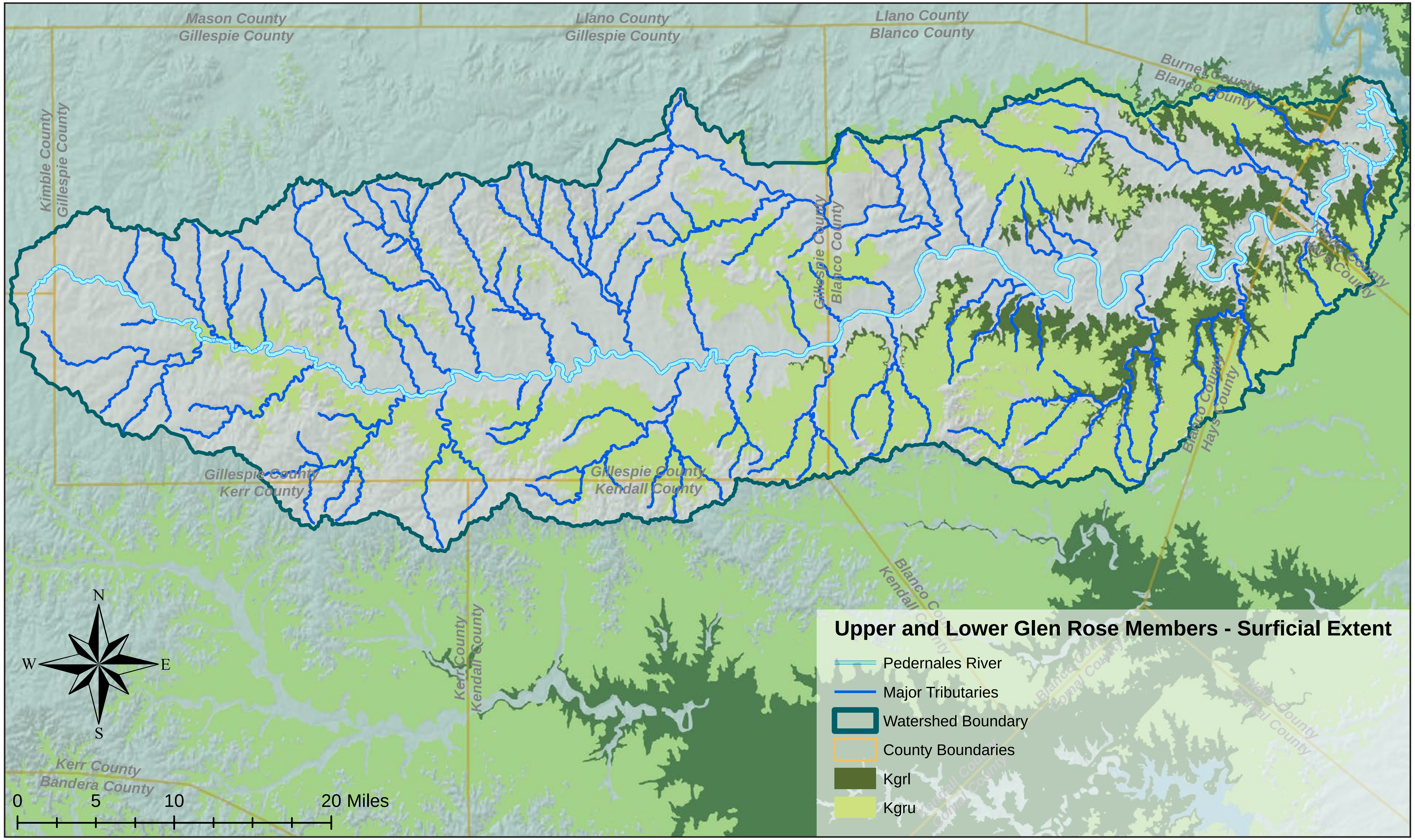


Figure 16. Upper and Lower Glen Rose Members – Surficial Extent

The Edwards Formation forms the Edwards Plateau around the western end of the watershed and consists of the Fort Terrett and Segovia Members. The upper part of the Fort Terrett is a cherty fossiliferous limestone and dolomite. The lower section of the Fort Terrett is a nodular limestone and clay, acting as a confining unit on top of the Upper Glen Rose. The Segovia Member is a cherty limestone and dolomite, with marly layers in the lower section of the unit. The Segovia yields small to moderate quantities of water to wells. Many springs originate from the Fort Terrett and Segovia, mainly on top of the marly and/or clayey layers.

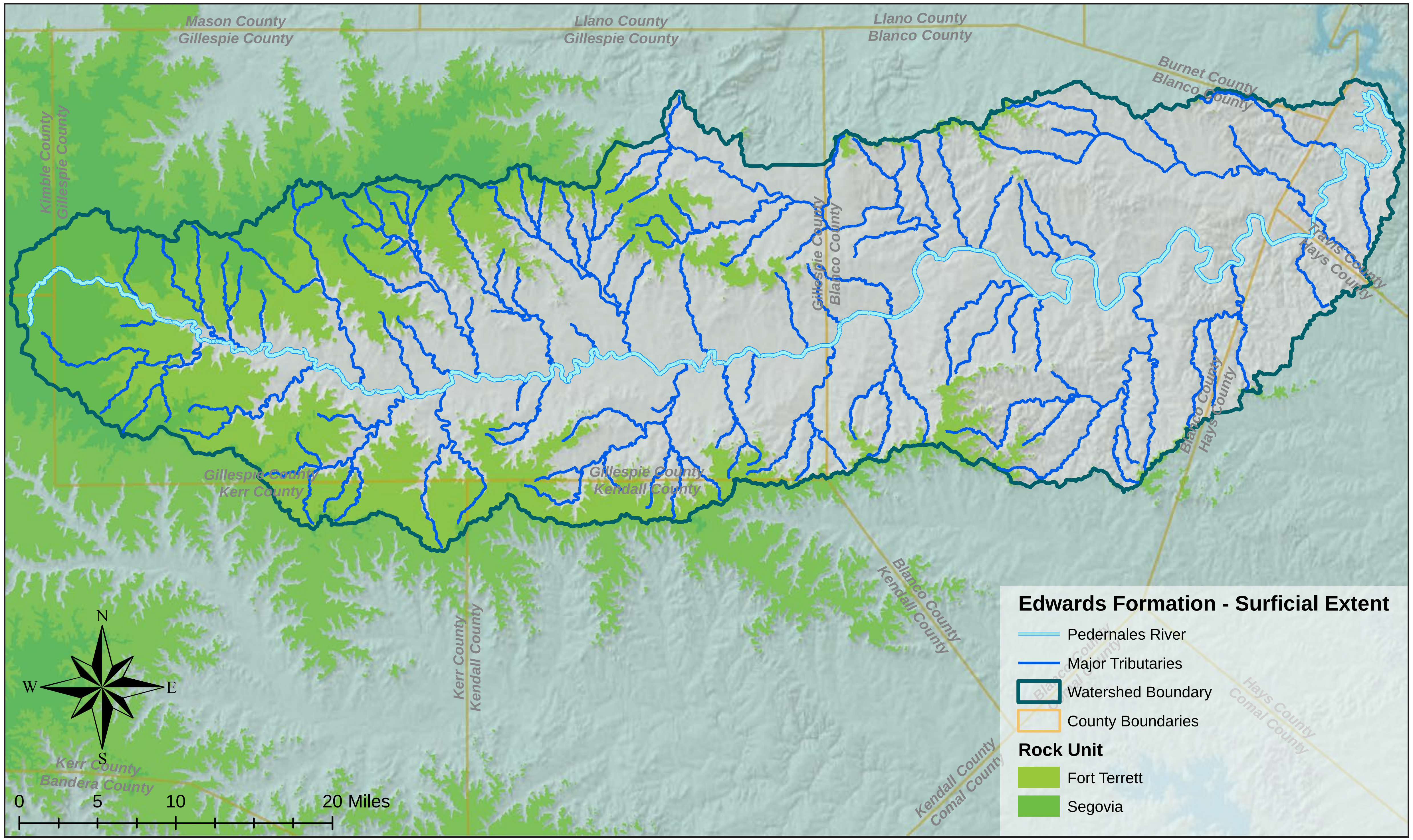


Figure 17. Edwards Formation – Surficial Extent

Recent Deposits

Alluvial deposits, including flood plain deposits, river terraces and unconsolidated stream deposits are typically found around stream channels. The deposits are gravels, sand silt clay and/or organic materials, generally locally derived from the bedrock or soils near the streams. In larger rivers subject to large flooding events, these materials can be transported many miles downstream from the place of origin. Significant stream underflow can occur through these deposits in the more permeable, thicker materials.

Rock Unit	Rock Unit Symbol	% of Total Land Area	Square Miles
Quaternary Alluvium	Qal, Qc, Qt	2.6%	33.5
Edwards (Fort Terrett, Segovia)	Kft, Ks	15.6%	199.1
Glen Rose, Upper	Kgru	22.8%	291.8
Glen Rose, Lower	Kgrl	10.6%	136.3
Hensel Sand	Kh	31.0%	397.3
Cow Creek	Kcc, Kch	1.9%	24.6
Hammett Shale	Kha	0.2%	2.2
Sycamore	Ksy	0.4%	5.6
Undifferentiated Paleozoic and Precambrian	Ipmf, Oh, Og, Ot, Cws,Cwp, Crc, Chr, pCtm, pCvs, pCy)	14.8%	189.6
		100%	1280

Table 3. Surficial Geology of the Pedernales Basin by Rock Unit

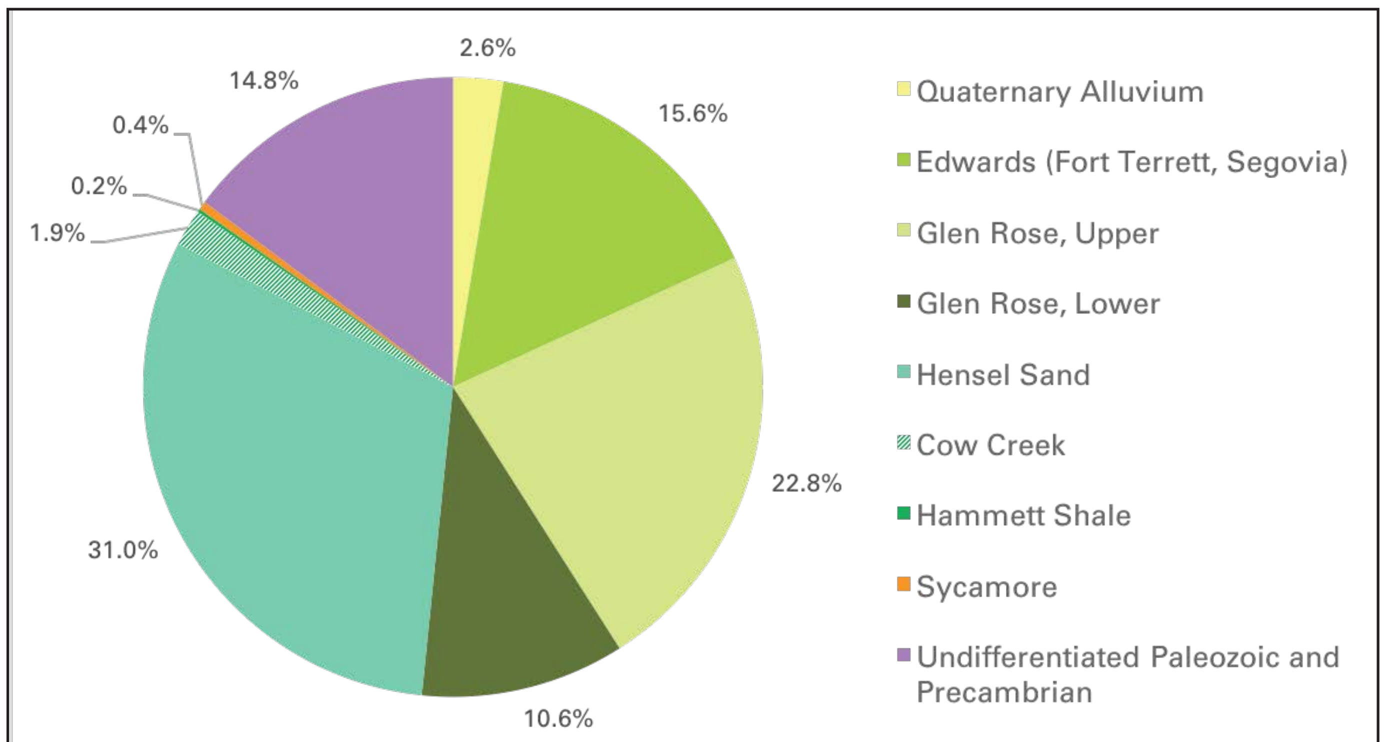


Figure 18. Surficial Geology as a Percent of Total Land Area

Surficial Geology

The percentage of the surficial geology of the total land area is shown on Figure 18 and Table 3. The Hensel Sand, Glen Rose (upper and lower) and Edwards comprise over 80 percent of the surficial geology. The Glen Rose and Edwards formations, and to a lesser extent the Hensel Sand, are carbonate formations. Shallow groundwater and springs originating from these formations should reflect the composition of the carbonate rocks; namely high dissolved solids, calcium, magnesium and hardness.

Water quality, land cover and topography is influenced by surficial geology. The large broad valley in the center of the basin running from west of Fredericksburg eastward to Stonewall (Palo Alto, Salt Branch, Baron's sub-watersheds) and a smaller area in the North Grape Creek sub-watershed are the main area of cultivated cropland in the Pedernales River basin. These areas are underlain by the Hensel Sand, which is easily eroded and forms relatively flat, cultivatable land. Being relatively flat, the area underlain by the Hensel Sand is generally the most developed.

Conversely, areas of surficial Edwards and Glen Rose are characterized by higher topography, steeper valleys and incised creeks and streams. Deeply incised creeks dominate the eastern end of the basin in sub-watersheds such as Miller, Flat, Cottonwood, Roy and Fall. The rivers and their tributary streams in these subwatersheds have eroded down through the Upper Glen Rose down to the Sycamore in some areas. The shallow limestones and dolomites are not suitable for cultivated agriculture, but are generally used for open grazing. Shrub/scrub and evergreen (juniper) are the dominant land covers in areas of surficial carbonates.

The surficial geology of the basin by rock unit, as well as the dominant surficial geology in each sub-watershed, are presented in the Pedernales River Atlas.

Pedernales Falls State Park by Texas Parks and Wildlife Department

Edwards (Fort Terrett, Segovia)	Glen Rose, Upper	Glen Rose, Lower	Hensel Sand	Undifferentiated Paleozoic and Precambrian
Greater than 50% of Watershed				
Banta	Flat		Palo Alto	
Klein	Miller		Salt Branch	
Spring	Rocky			
White Oak	South Grape			
Wolf	Williams			
Flag				
Greater than 40% of Watershed				
Live Oak	Roy		Barons	North Grape
Bear	Threemile		Muesebach	Toehead
			Wittington	
Greater than 30% of Watershed				
South Grape	Muesebach		Ped Falls	Post Oak
	Post Oak		Threemile	Cottonwood
	Towhead			
	Wittington			
Greater than 20% of Watershed				
Barons	Cottonwood	Cottonwood	Cypress	Pedernales Falls
Palo Alto	Cypress	Fall	Fall	
	Fall	Flat	Live Oak	
	North Grape	Roy	Roy	
	Salt Branch		Bear	
	Wolf			
	Bear			

Table 4. Dominant Surficial Geologic Units by Subwatershed

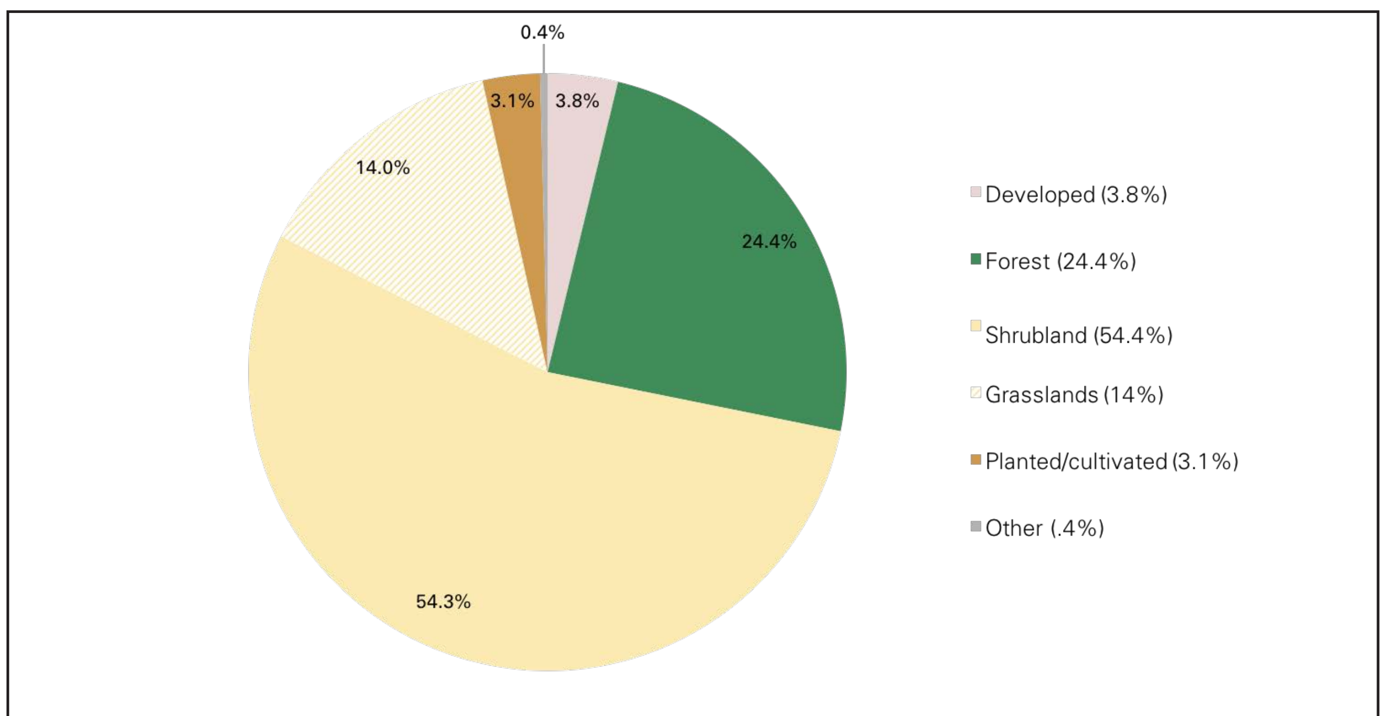


Figure 19. Land Cover - Percent Coverage of Basin – 2011

Land Cover

Land cover, particularly developed land use, plays a role in determining water quality, and both storm flow and base flow. Increased impervious cover, septic systems, organized sewage treatment, and non-point source pollution can impact water quality. GIS files of basin land cover data from 2001 and 2011 were obtained from the National Land Cover Database (NLCD) provided by the Multi-Resolution Land Characteristics (MRLC) Consortium (MRLC 2011). Although the data sets contained a detailed breakdown of many land cover types, many similar land uses were combined for the purpose of this report and consolidated into six categories.

The basin was primarily forest and shrub land in 2011, with a lesser amount of grassland. Only 3.82 percent of the land surface is developed, with the cities of Fredericksburg and Johnson City being the main population centers. The most developed sub-watersheds were Barons (21 percent), Muesebach (10 percent), Wittington (8 percent) and Salt (7 percent). The Pedernales Subwatershed Atlas contains pie charts of each individual sub-watershed indicating the percentages of various land uses.

The land cover data sets from 2001 and 2011 were compared in order to determine land cover changes over the ten year period. Additionally, MRLC provided a land cover change index from 2001 to 2011 which provided a detailed breakdown of the previous land cover type at a certain location as well as its current land cover designation. The specific gain or loss in acreage for each land cover type throughout the watershed was extracted from the index's GIS data. One caveat to the accuracy of these numbers is that the overall combined change rate within the index file was lower than the combined change rate between the 2001 and 2011 land cover GIS files because changes in land cover types occasionally occurred more than once within some pixels. Detailed information on specific land cover types from 2001 to 2011 is in Appendix C. Figures 19, 20 and 21 indicate the land cover and land cover changes from 2001 to 2011.

The watershed has seen a 2.02 percent increase in developed land from 2001 to 2011, with most of the increases occurring within the city limits of Fredericksburg, Johnson City, and to a lesser extent, Stonewall, Harper, Briarcliff, and Stone Mountain. Indeed, the land cover classification with the highest increase in acreage from 2001 to 2011 was "Developed, Open Space," or land that is identified as having an impervious cover of 20 percent or less. Most land use within the Open Space category is classified as "commonly includ(ing) large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes" (MRLC 2011). However, despite having the highest rate of increase in acreage from 2001 to 2011, the Open Space category still comprises only 3.32 percent of all land within the Pedernales watershed.

Primary Land Cover	Square Miles	% Coverage of Basin	Secondary Land Cover Category
Developed	49	3.8	Developed open space, low, medium and high density development
Forest	312	24.4	Deciduous, evergreen and mixed forest
Shrubland	696	54.4	Shrub and scrub land
Grasslands	179	14.0	Grasslands/herbaceous
Planted/cultivated	40	3.1	Pasture, hay and cultivated crops
Other	4	0.4	Open water, bare rock and woody wetlands

Table 5. General Land Cover of the Pedernales Basin – 2011

As stated in the Regional Water Quality Plan (2005), "various published and unpublished reports and in unpublished data compilations, the City of Austin has indicated that physical and biological degradation of streams begins to occur at between five and eighteen percent (5-18 percent) impervious cover". Therefore it is expected that there is some degradation occurring from the "Developed, Open Space" land use areas, but these areas make up a small portion of the watershed.

Land use and surficial geology are closely linked in the watershed. Developed and cultivated crops areas closely mirror the areas of surficial Hensel Sand. The sandy nature of the soils developed on the Hensel are tillable and suitable for crops. The large areas of surficial carbonate rocks (Edwards and Glen Rose) contain very shallow rocky soils unsuitable for most cultivated crops and are generally left in shrub and forest lands.

Secondary Land Cover Categories	2001 Land Cover (miles^2)	2011 Land Cover (miles^2)	Change in Land Cover (miles^2)
Open Water	3.5	3.6	0.1
Developed, Open Space	18.4	42.5	24.2
Developed, Low Intensity	3.1	4.0	0.9
Developed, Medium Intensity	1.2	1.8	0.6
Developed, High Intensity	0.4	0.6	0.2
Barren Land (Rock/Sand/Clay)	0.1	0.5	0.4
Deciduous Forest	83.7	74.4	-9.3
Evergreen Forest	262.9	237.9	-25
Mixed Forest	0.3	0.2	-0.2
Shrub/Scrub	691.5	695.6	4.1
Grassland/Herbaceous	176	178.7	2.7
Pasture/Hay	9.9	9.6	-0.3
Cultivated Crops	29	30.6	1.5
Woody Wetlands	0.6	0.6	<0.1
Emergent Herbaceous Wetlands	<0.1	<0.1	<0.1

Table 6. Changes in Land Cover – 2001-2011

Pedernales River by Don J Schulte, Flickr

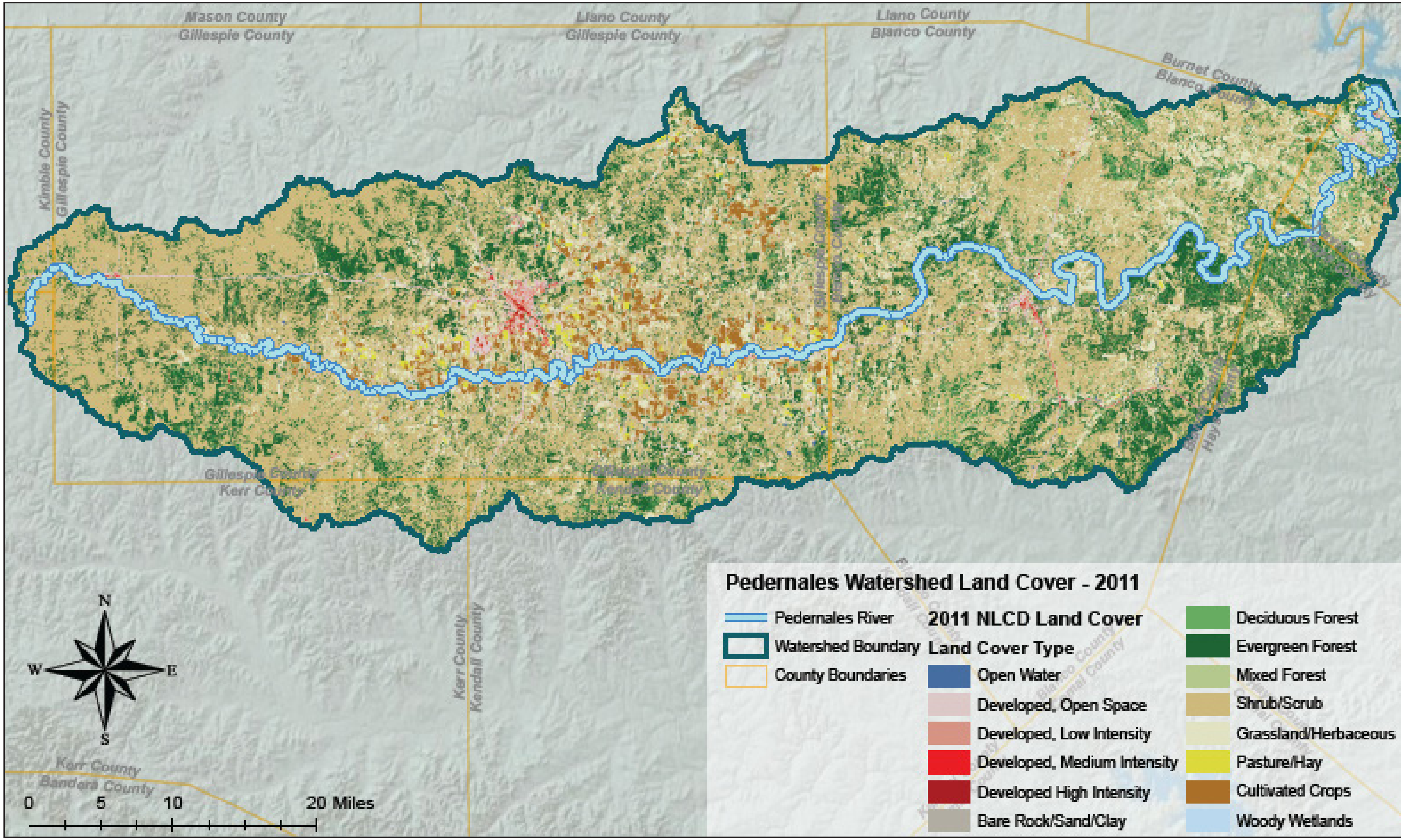


Figure 20. Pedernales Watershed Land Cover – 2011

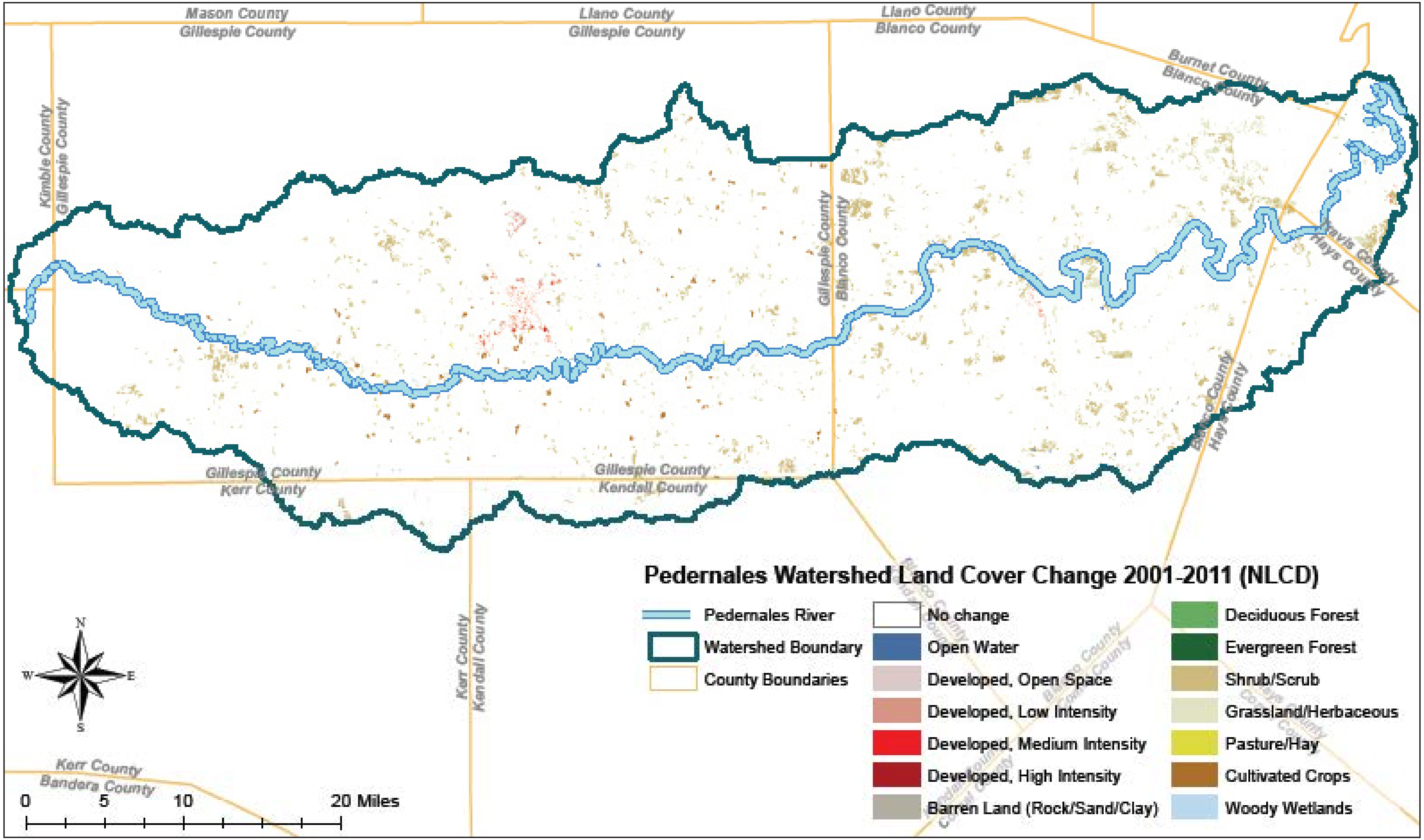


Figure 21. Pedernales Watershed Land Cover Change – 2001-2011 (NLCD)

Setting Milky Way Over Pedernales River by Christopher V. Sherman, Flickr

GROUNDWATER-SURFACE WATER INTERACTIONS

This section discusses groundwater-surface water interactions based on historic data collected by the Hill Country Underground Water Conservation District (HCUWCD), flowing water inventory, and the 2015 synoptic water chemistry sampling event.

What is base flow?

Discussion of the hydrology of the Pedernales River and its tributaries focuses primarily on base flow conditions, not storm runoff events. The base flow of a river is determined by its interface with groundwater. Base flow, also often referred to as base run-off or groundwater runoff, has many definitions in the literature. Base runoff is defined by the USGS as sustained flow of a stream in the absence of direct runoff. It includes natural and human-induced stream flows. Natural base flow is sustained largely by groundwater discharges (http://water.usgs.gov/edu/dictionary.html).

Base flow is important because the water contribution from groundwater keeps our rivers flowing, thereby providing a relatively constant water source for environmental, ecologic and human needs, particularly during periods of little or no precipitation. Identifying a specific quantitative discharge value at a given point in a stream, and defining it as base flow, can be difficult because hydrology conditions in various parts of a watershed can vary. If there has been recent precipitation in the upper part of a watershed, but none at the point of interest, for example, surface runoff will likely influence the downstream flow. Another common example in the Hill Country occurs after there has been a significant wet period, raising groundwater levels and supporting relatively strong spring discharges even after the wet period has passed and there has been no recent precipitation. Any flow that occurs 25 percent of the time or less (25th percentile) can generally be considered base flow.

Occurrence of Springs

There are many sources of data regarding the occurrence of springs in the Central Texas Hill Country and the Pedernales River basin. The Texas State Board of Water Engineers assembled county by county summaries of wells and springs during the 1930s and 1940s, and USGS topographic maps of various vintages illustrate spring locations. Other USGS publications include Open-File Report 2003-315 and the compilation of springs by Brune (1981).

The reality is that we don't know how many springs or seeps are present in the Pedernales River basin and the number is constantly changing. Although the strong perennial springs are easily identified and quantified, the smaller springs are often temporary or intermittent in nature and dependent on local groundwater levels that fluctuate on the basis of wet or drought periods. Springs may occur in stream beds with flowing waters, also making detection difficult. As an example, Pleasant Valley Spring, the largest documented spring in the Hill Country Trinity, wasn't "discovered" until a few years ago since it is in the Blanco River channel bed with detailed stream measurements being required to locate the spring. Streams may lose flow to the sub-surface within a short distance downstream from their origin, also making it difficult to locate some springs. Finally, the sheer size of, and limited access to, private property makes it difficult to accurately inventory all of the springs. In fact, the flowing water inventory was an attempt to locate general areas of springs by inventorying flowing waters during a low flow period.

USGS Gauging Stations

The USGS maintains two gauging stations along the main channel of the river. The furthest upstream gauge is located at USH 87 (USGS 08152900) south of Fredericksburg, while the most downstream gauge is located at USH 281 (USGS 08153500) at Johnson City. The period of record for the USH 87 and USH 281 gauges is 27 years (1979) and 77 years (1939), respectively. Figure 22 illustrates the mean monthly discharges for the overlapping period of records (since 1979), with the discharge percentiles also being shown. The flow at the USH 281 gauge is consistently greater than that at the USH 87 site, indicating the river is generally gaining flow between the two stations.

Unfortunately, the USGS gauge does not maintain a gauging station downstream of USH 281, creating a major data gap when attempting to analyze water flows throughout the entire basin. As previously shown on Table 1, the flow was measured downstream of the USH 281 gauge during the period between the 1962 study and the flowing water inventory. The measuring point was located at Reimer's Ranch, just downstream of the Cypress Creek confluence. Based on these two measurement sets, the river tends to gain 35-50 percent of its flow downstream from the USH 281 gauge and the confluence of Cypress Creek.

The Lower Colorado River Authority (LCRA) tracks Pedernales River inflows into Lake Travis. The LCRA uses an inflow runoff factor (drainage area ratio) of 2.030 times the measured discharge at the USH 281 USGS gauge, which is consistent for the measurements made during this study (LCRA unpublished data, 2016).

Data spanning the period of record for both gages were used to calculate flow percentiles based on daily mean flows. The total period of record for each site, as well as for five year increments, were used to identify any long-term trends. The percentile data is illustrated in Tables 7 and 8, with the data graphically presented in Figures 22, 23, and 24.

The linear trend of data for all percentiles at the Johnson City gauge is increasing over the period of record, although periodic droughts over the last five to ten years also are reflected in the data. Data from the 2010-2015 increment, compared to the 1950-1955 increment (generally considered the drought of record), indicate the 10th percentile is lower than in the 1950-1955 increment. The 25th percentile is generally the same between the two periods, although the 50th, 75th, and 90th percentiles are generally higher in 2010-2015 than 1950-1955. This finding suggests flow extremes during drought conditions, such as in the 1950s and 2010s, may be becoming more severe. The droughts are drier, and the heavy rain events are becoming larger in eastern Gillespie County and western Blanco County. This same phenomenon was previously noted by Hunt (2012) and Wierman (2010).

Calculated percentile data from the USH 87 station near Fredericksburg for the period of record indicate decreasing trends over the period of record. The rate of decline is greater for the larger percentiles and less for the lower percentiles. Comparing similar periods of record for the USH 281and USH 87 stations indicate similar declining trends since 1980, although the rates of decline for the various percentiles are greater for the USH 281 station.

Though climatic influence was not the focus of this ongoing study, the decreasing flows measured at several gaging stations on the river have been occurring over the last ten years, and could be attributed to climatic effects. An analysis of the flow characteristics indicate the flow percentiles at two USGS gauging stations have been decreasing over the last ten years and are approaching, or are currently at, the levels observed during the drought of the 1950s.

Time Jun-May	Min.	10th Percentile	25th Percentile	50th Percentile	75th Percentile	90th Percentile	Max.
1940-1945	2.7	11	26.5	50	151.5	352	24,500
1945-1950	0.9	8.9	13	28	82	174	8,560
1950-1955	0.1	0.2	3	8.3	24	71.5	129,000
1955-1960	0.1	0.5	5.8	64	157	294	48,800
1960-1965	0.1	2.7	12	29	59.5	184	8,760
1965-1970	0.1	6.2	18	53	124.75	254	13,900
1970-1975	0.1	16	29.25	67	149	327.5	29,300
1975-1980	0.5	36	51	80	161	386.8	36,400
1980-1985	0.1	3.7	19	45	97	211.5	14,000
1985-1990	0.35	21	38	87	164.75	388	29,100
1990-1995	2	21	40	88	142.75	395.5	50,200
1995-2000	0.1	4.32	19	64	146.5	373.4	40,100
2000-2005	0.1	15.5	53	107	224	415	49,100
2005-2010	0.1	5.65	19	35	130.75	325	39,700
2010-2015	0.1	0.1	4.325	20	35	69.5	9,690

Table 7. Discharge Percentiles – USGS Gauge near Johnson City at USH 281

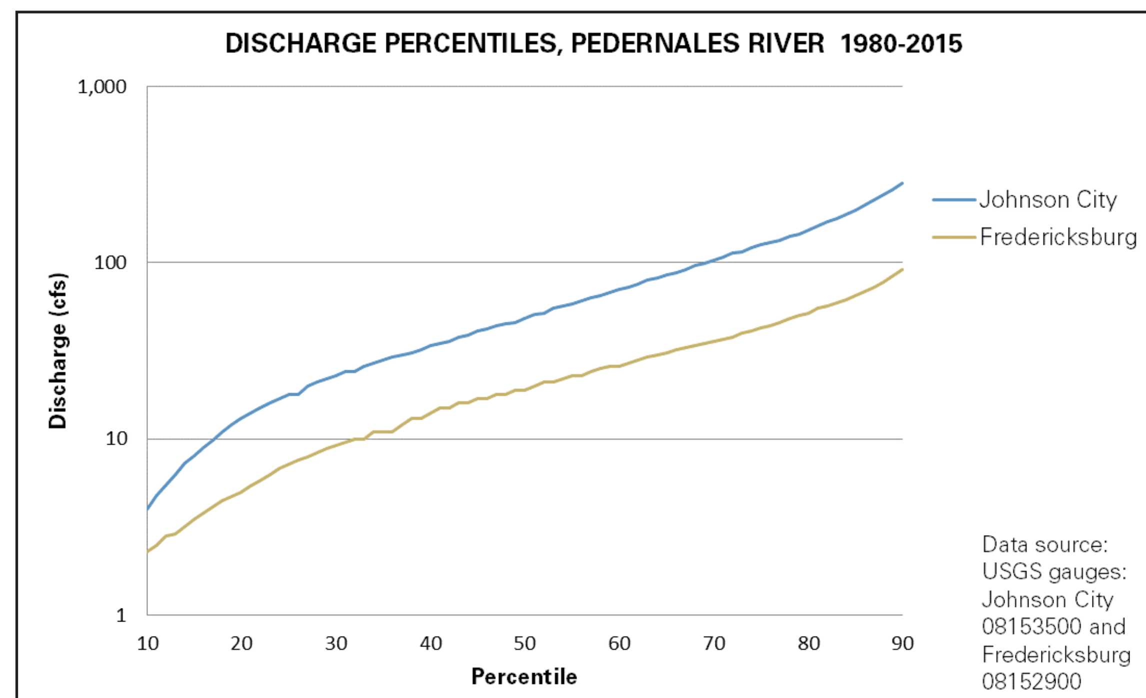


Figure 22. Pedernales River Discharge Percentiles – 1980-2015

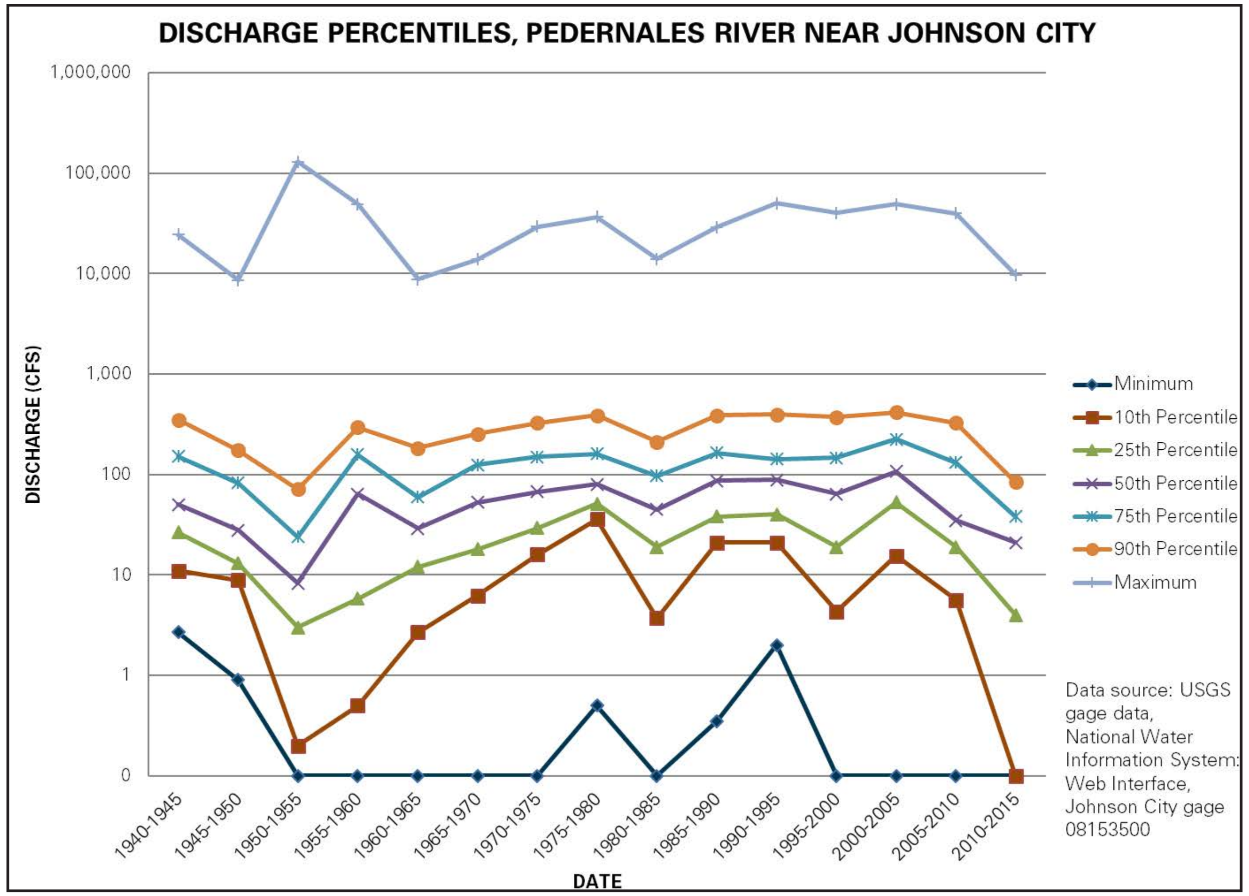


Figure 23. Pedernales River Discharge Percentiles near Johnson City – 1940-2015

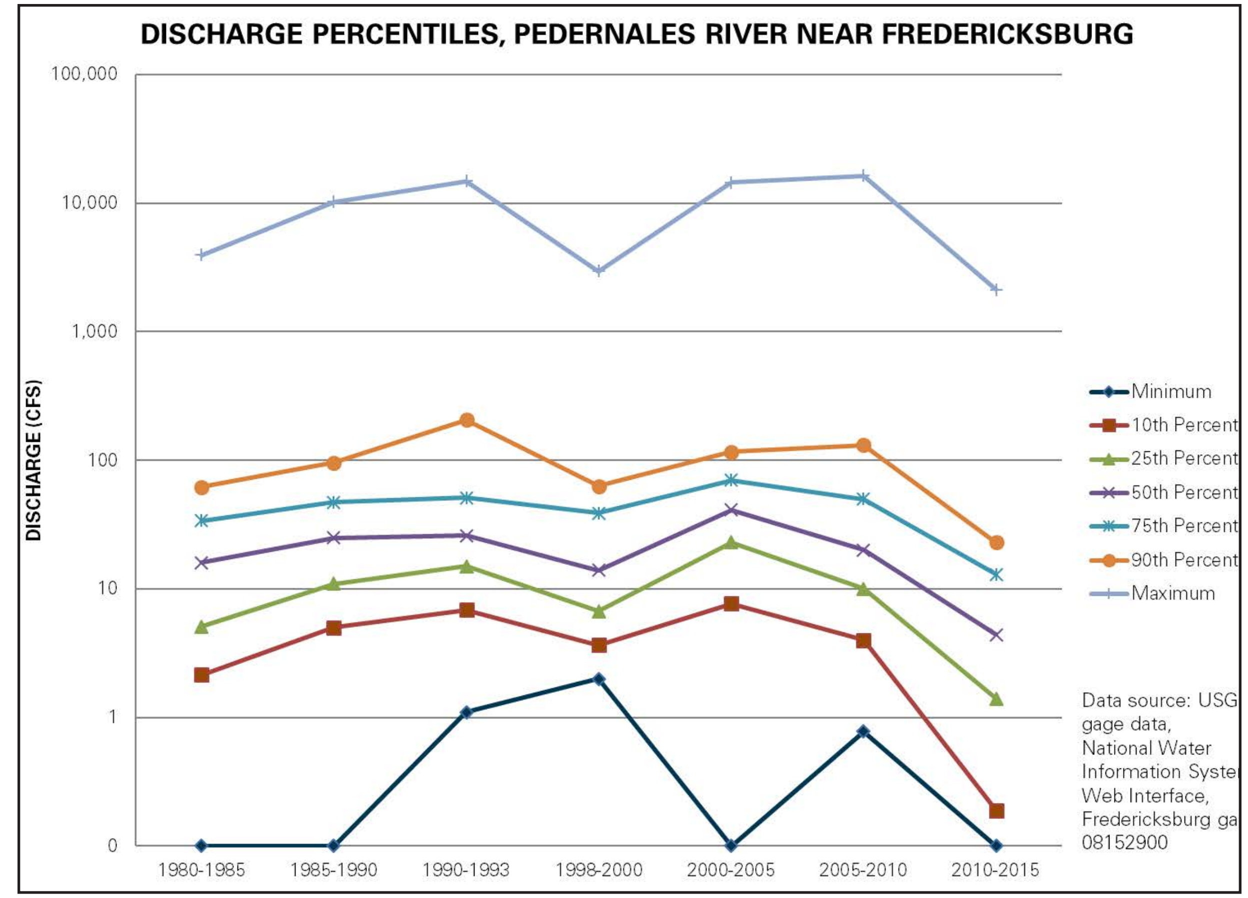


Figure 24. Pedernales River Discharge Percentiles near Fredericksburg – 1980-2015

Fredericksburg Percentiles Based on Daily Means for 5 Year Increments							
Time Jun-May	**Min.**	**10th Percentile**	**25th Percentile**	**50th Percentile**	**75th Percentile**	**90th Percentile**	**Max.**
1980-1985	0.1	2.15	5.1	16	34	62	3,940
1985-1990	0.1	5	11	25	47	96	10,200
1990-1993	1.1	6.87	15	26	51	206.6	14,800
1998-2000	2	3.67	6.7	14	39	63.3	2,960
2000-2005	0.1	7.7	23	41	70	116.5	14,500
2005-2010	0.78	4	10	20	50	131.5	16,300
2010-2015	0.1	0.1	1.4	4.3	12	20	2,130

Table 8. Discharge Percentiles – USGS Gauge near Fredericksburg at USH 87

Pedernales River Inflow Contribution to Lake Travis

The Pedernales River is one of four major inflows/tributaries to the Highland Lakes and an important source of inflow to Lake Travis, being the major water source for the City of Austin, surrounding area and downstream users on the Colorado River. The four major inflows monitored by LCRA include the Llano River, Colorado River, Sandy Creek and the Pedernales River. From 1942 to 2015, the average annual inflow to the Highland Lakes from the four inflows was 1,213,098 ac-ft. Figure 25 illustrates the average annual contribution from the Pedernales River was 281,059 ac-ft, or approximately 23 percent of the total inflow (LCRA unpublished data, 2016). The City of Austin typically uses about 150,000 acre-feet a year.

Base Flow Studies on the Pedernales River

Several base flow studies, often referred to as gain/loss studies, have been performed on the Pedernales River. The following major base flow studies have been conducted:

- Detailed gain/loss studies were performed in 1956 and 1962 by the USGS and published by the TWC (Holland and Hughes, 1964). Both studies originated several miles east of Harper at the headwaters of the main channel. The 1956 study terminated at Johnson City due to heavy rainfall. The 1962 study terminated just downstream of Cypress Creek near Lake Travis. Flow measurements and water quality samples were collected in the 1962 study. These data are used as a baseline to compare present day flow and water quality. During the 1962 study, flow was measured at main channel and tributary sites. The sites are shown on Figure 26.
- As part of the current study, a base flow study was conducted during the period of August 8 – 9, 2016 by the Meadows Center and partners. Partners included City of Austin, Blanco-Pedernales Groundwater Conservation District (BPGCD), Barton Springs Edwards Aquifer Conservation District (BSEAGD), Hill Country Underground Water Conservation District (HCUWCD), Texas Parks and Wildlife Department (TPWD) and numerous local landowners. The study started near the headwaters springs near Harper and terminated at Hamilton Pool Road (Hammett's Crossing). Due to the high lake levels in Lake Travis (approximately 14 feet higher in 2016 versus 1962), water was backed up in the river to just north of Hamilton Pool Road and the study could not proceed to the confluence of Cypress Creek as in the 1962 study. Thirty-one main channel sites, nine tributary sites and one spring were measured in 2016. Qualitative flow observations were made at an additional 36 tributary sites. The measured sites are shown on Figure 26, qualitative observations are shown on Figure 27, and data is summarized on Table 10. Methods for discharge measurements were consistent withTurnipseed and Sauer (2010).
- The HCUWCD has been performing detailed base flow studies from 1996 to the present on a reach of the river to the south of the City of Fredericksburg, near the Fredericksburg municipal well field. Approximately 13 sites are measured several times a year (HCUWCD unpublished data, 2015). The sites are shown on Figure 29 and results shown on Figure 30.

In concept, gain/loss studies are fairly straight forward. A series of flow discharge measurements are made along the river, and the discharge at each end of a reach are compared. If the downstream measurement is larger than the upstream measurement, this indicates a gaining reach. If the downstream measurement is less than the upstream measurement, this indicates a losing reach. During base flow conditions, gains are due to groundwater discharging into the river, either through discrete springs or through more non-point seep/infiltration. Tributary flow also contributes to gains if not separately accounted. Losses can be attributable to geologic, or sometimes man-induced conditions. Stream losses can also occur due to transpiration and evaporation. The 1962 study did not attempt to quantify transpiration or evaporation, but considered them to be small losses (Holland and Hughes, 1964). To maintain consistency for comparison, these factors were considered to be small loses in the 2016 study. There was no precipitation during the 2016 study.

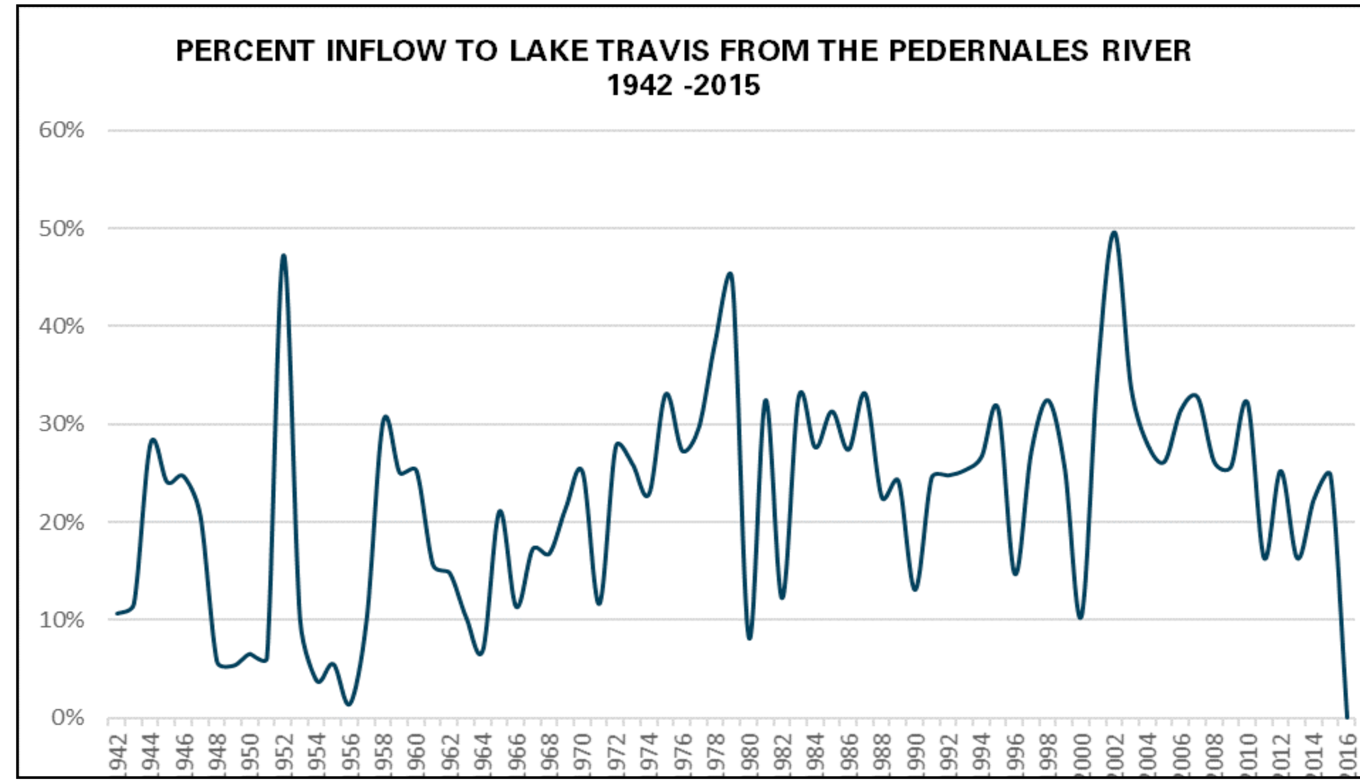
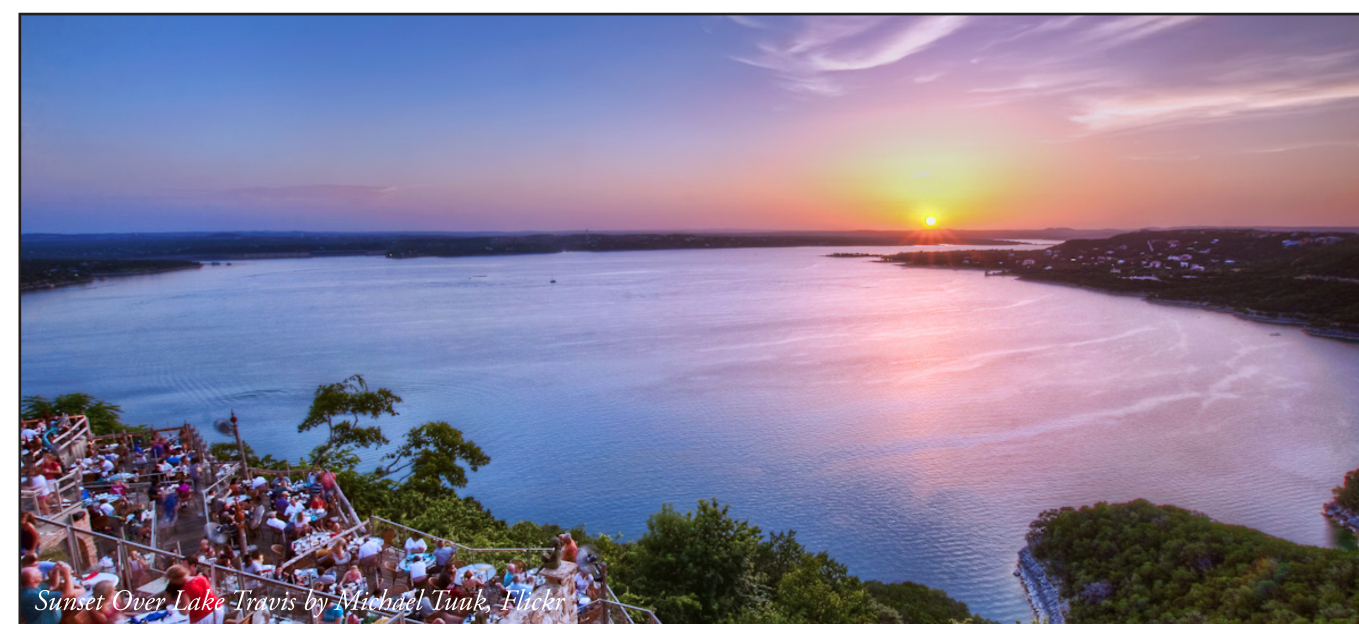


Figure 25. Percent Inflow to Lake Travis from the Pedernales River – 1942-2015



Sunset Over Lake Travis by Michael Tuuk, Flickr

GL ID	Site Name	River Mile	Lat	Long	Main Channel Discharge	Tributary Discharge	Gain/Loss	Date	
1*	Pedernales River at FM 2093 (MUSKA)	1.3	30.27776	-99.21619	0.5*			8/10/2016	TSU 1
2	Pedernales River at Fielder Road	4.8	30.25798	-99.16868	1.2		0.7	8/10/2016	TSU 1
3	Klein Branch at Fielder Road		30.23549	-99.18385		2.4*		8/10/2016	TSU 1
4*	Pedernales River at Pump Station Road	9.4	30.24011	-99.12061	3.2		2	8/10/2016	TSU 1
5*	Pedernales River at White Oak Road (SECHRIST)	14.5	30.23450	-99.06206	3.7		0.5	8/10/2016	TSU 2
6	White Oak Creek near White Oak Road		30.14400	-99.34100		0.7		8/10/2016	TSU 2
7	Pedernales River at GBPGCDa-Shandua Road	17.8	30.21374	-99.02543	3.3		-0.4	8/10/2016	TSU 2
8	Spring Creek FM 2093 Crossing/Usener Road		30.24365	-99.02469		0		8/10/2016	TSU 2
9	Wolf Creek at Kott Road off HWY 16		30.19270	-98.98992		1.3		8/10/2016	TSU 2
10*	Pedernales River (Tybor PR-1616)	24	30.21139	-98.94114	5.5		2.2	8/10/2016	HCUWCD
11	Live Oak Creek (LO-1652)		30.25000	-98.91564		0.7		8/10/2016	HCUWCD
12	Pedernales River Boos Road (PR-1588)	27.7	30.21975	-98.89933	6.8		1.3	8/10/2016	HCUWCD
13	Pedernales River at Hwy 87 USGS GAUGE	29.2	30.22018	-98.87000	8		1.2	8/10/2016	USGS
13a	Pedernales River (PR-1563)	29.9	30.22203	-98.86258	7.1		-0.9	8/10/2016	HCUWCD
14	Pedernales River (PR-1556.5)	30.7	30.21994	-98.85100	5.8		-1.3	8/10/2016	HCUWCD
15	Barons Creek (BR-1570)		30.23706	-98.84356		1.5		8/10/2016	HCUWCD
16	Pedernales River (PR-1544)	33.1	30.21950	-98.83050	4.7		-1.1	8/10/2016	HCUWCD
17	Pedernales River at US 290 (PR-1535)	34.4	30.22731	-98.81847	6.2		1.5	8/10/2016	HCUWCD
18*	Pedernales River at Goehman Lane (PR-1508)	38.4	30.23928	-98.76906	4.1		-2.1	8/10/2016	HCUWCD
19	Pedernales River/Palo Alto Creek (PR-1501)	39.4	30.23731	-98.78361	9		4.9	8/10/2016	HCUWCD
20	Pedernales River at Jung Lane	41.5	30.22358	-98.74105	11.5		2.5	8/9/2016	BPGCD
21	South Grape Creek at Jellystone Park		30.22582	-98.72058		2		8/9/2016	BPGCD
22*	Pedernales River at Gellerman Road	46.4	30.23272	-98.68509	15		3.5	8/9/2016	BPGCD
23	Three Mile Creek at US 290		30.22761	-98.68148		0		8/9/2016	BPGCD
24	Pedernales River at LCRA Gauge	50.8	30.23998	-98.62613	14		-1	8/10/2016	LCRA
25	Pedernales River at Klein Road	52.8	30.24265	-98.60567	18.2		4.2	8/9/2016	BPGCD
26	Pedernales River (Cockshutt)	55.4	30.26689	-98.56772	20.3		2.4	8/9/2016	BPGCD
27*	Pedernales River at RM 1320	56.7	30.27208	-98.54549	16.1		-4.2	8/10/2016	TPWD
28	Pedernales River (Favrot)	61.6	30.29939	-98.50434	21.4		5.3	8/10/2016	TPWD
29	Pedernales River at Pedernales Ranch Estates POA Park	66	30.32097	-98.44319	18.3		-3.1	8/10/2016	TPWD
30*	Pedernales River at Johnson City USGS gauge	70	30.29120	-98.40080	24		5.7	8/10/2016	USGS
31	Pedernales River (Fielding)	73.9	30.30026	-98.36680	23.6		-0.4	8/10/2016	TPWD
32	Pedernales River at Pedernales Hills Road	80	30.27844	-98.33549	36.7		13.1	8/9/2016	BPGCD
33	Miller Creek at Dam (Caven)		30.30136	-98.30012		0.3		8/9/2016	BSEACD
34*	Pedernales River After Miller Creek (Caven)	83.8	30.30457	-98.30167	32.7		-4.1	8/9/2016	COA
35	Pedernales River Downstream of Miller Creek (Hendrix)	86.2	30.32643	-98.27119	24.9		-7.7	8/9/2016	BSEACD
36	Pedernales River at PFSP	90.7	30.31083	-98.24280	42.2		17.2	8/9/2016	COA
36a	PFSP Spring		30.33671	-98.24998		14.9		8/12/2016	BSEACD
37	Flat Creek (Reese)		30.30181	-98.21038		1.5		8/9/2016	BSEACD
38*	Pedernales River (Reese)	94.8	30.31852	-98.20792	44.6		2.4	8/9/2016	BCOA
39	Pedernales River at Pedernales Place	99.3	30.33179	-98.18036	45.1		-0.1	8/9/2016	COA
40*	Pedernales River at Hammett's Crossing	102	30.34027	-98.13900	52.8		7.8	8/10/2016	COA

* estimated flow

Table 9. Pedernales River Base Flow Study Results, 2016

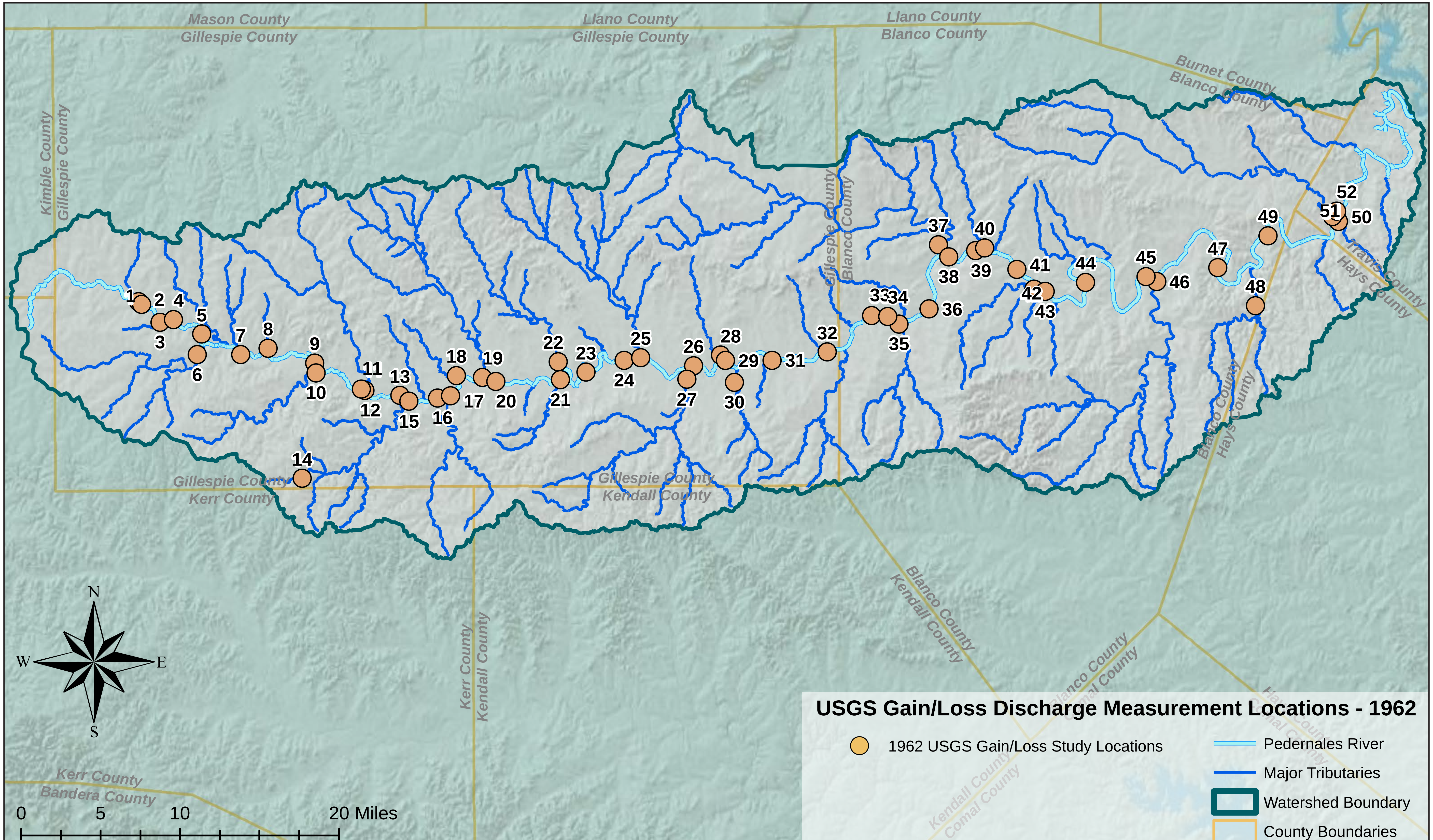


Figure 26. USGS Gain/Loss Discharge Measurement Locations - 1962

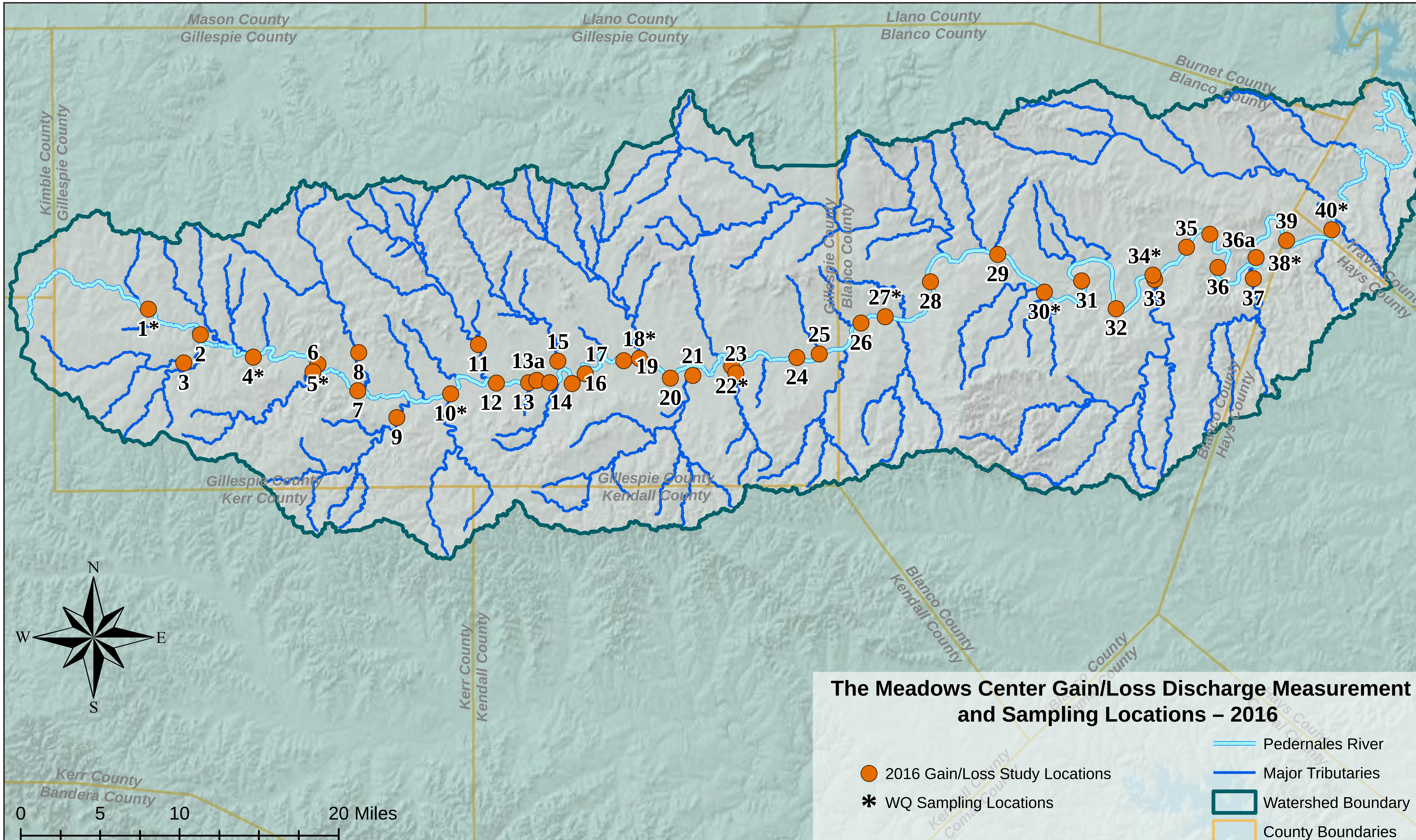


Figure 27. The Meadows Center Gain/Loss Discharge Measurement and Sampling Locations - 2016

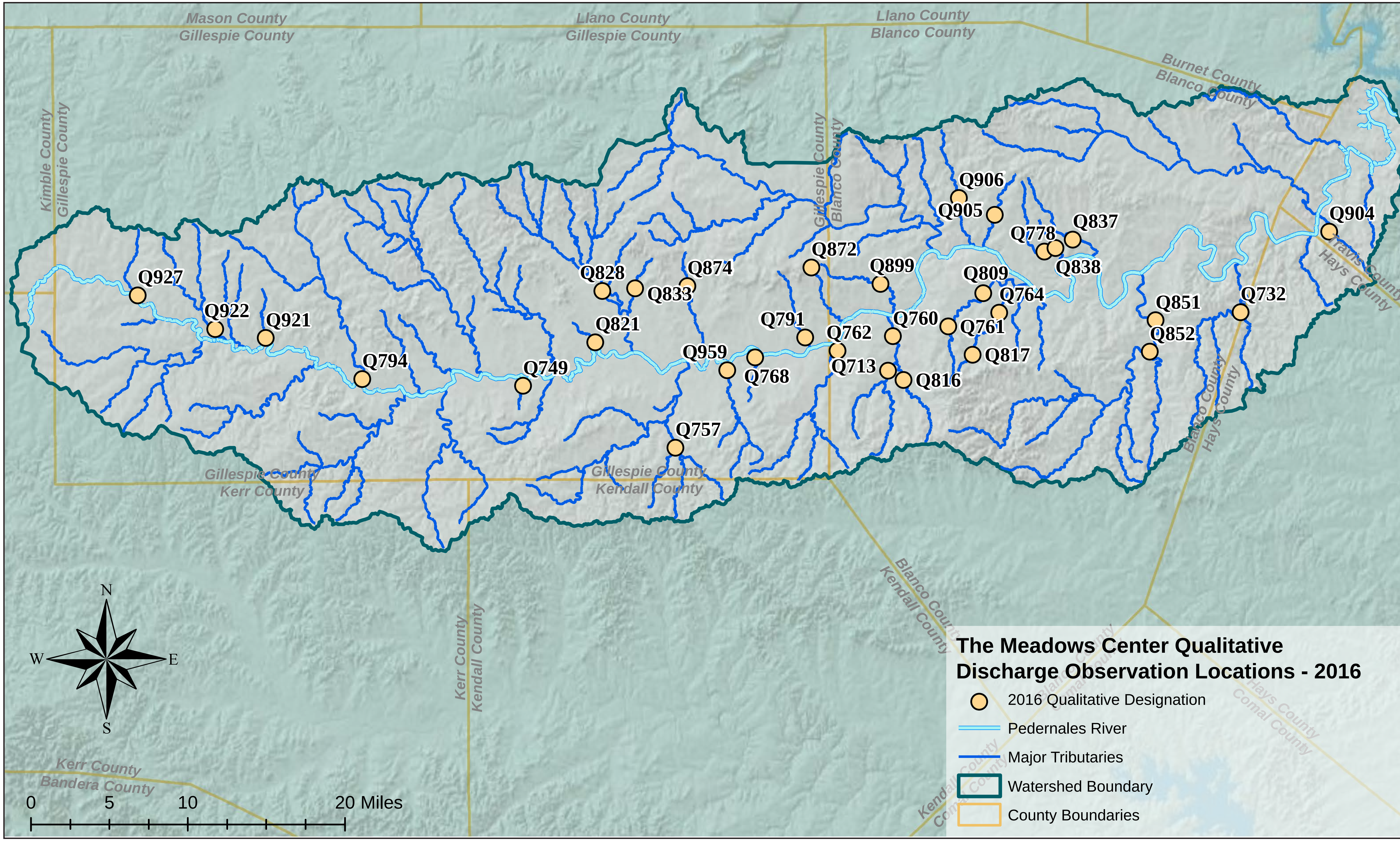


Figure 28. The Meadows Center Qualitative Discharge Observation Locations – 2016

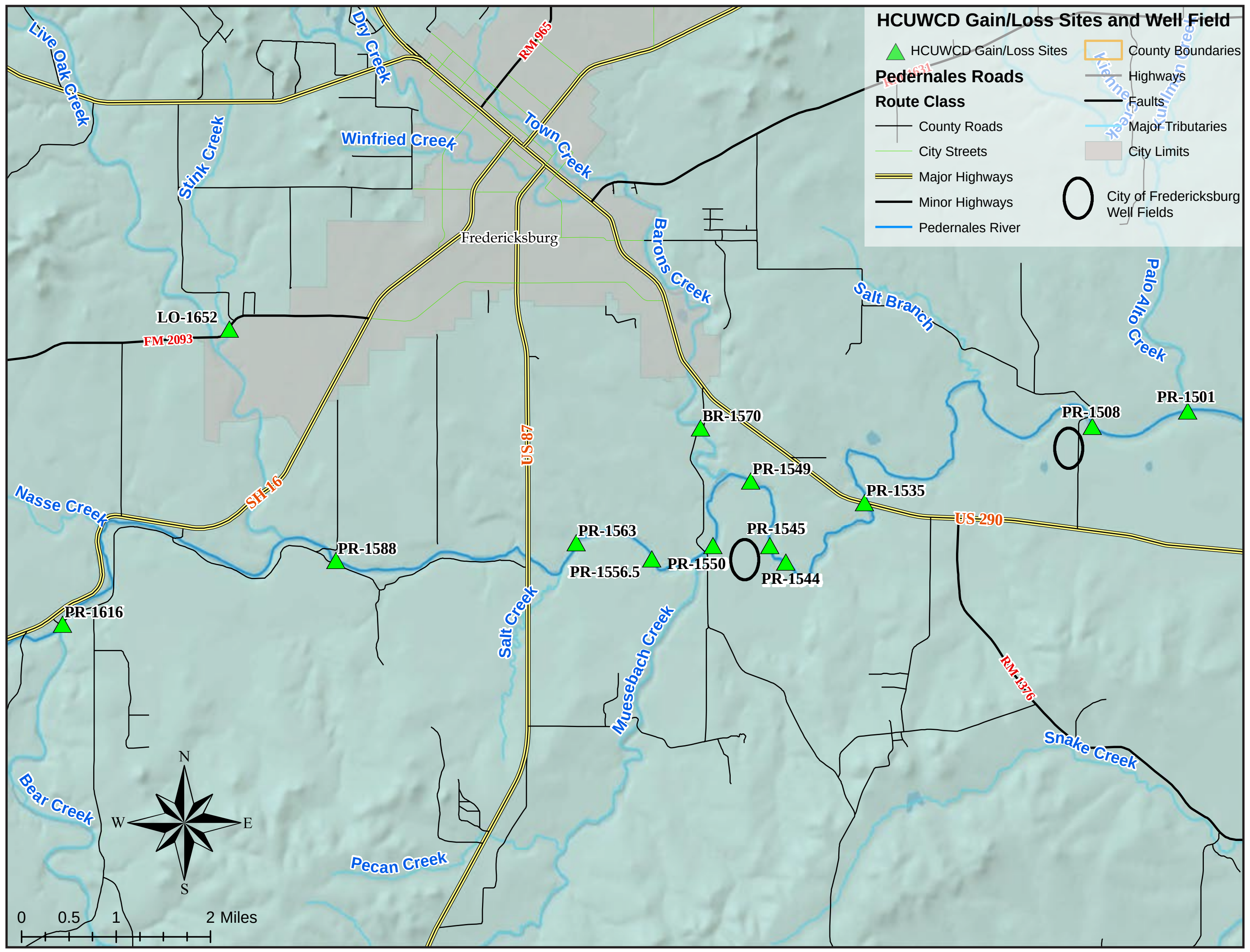


Figure 29. HCUWCD Surface Water Gauging Locations and City of Fredericksburg Municipal Well Field

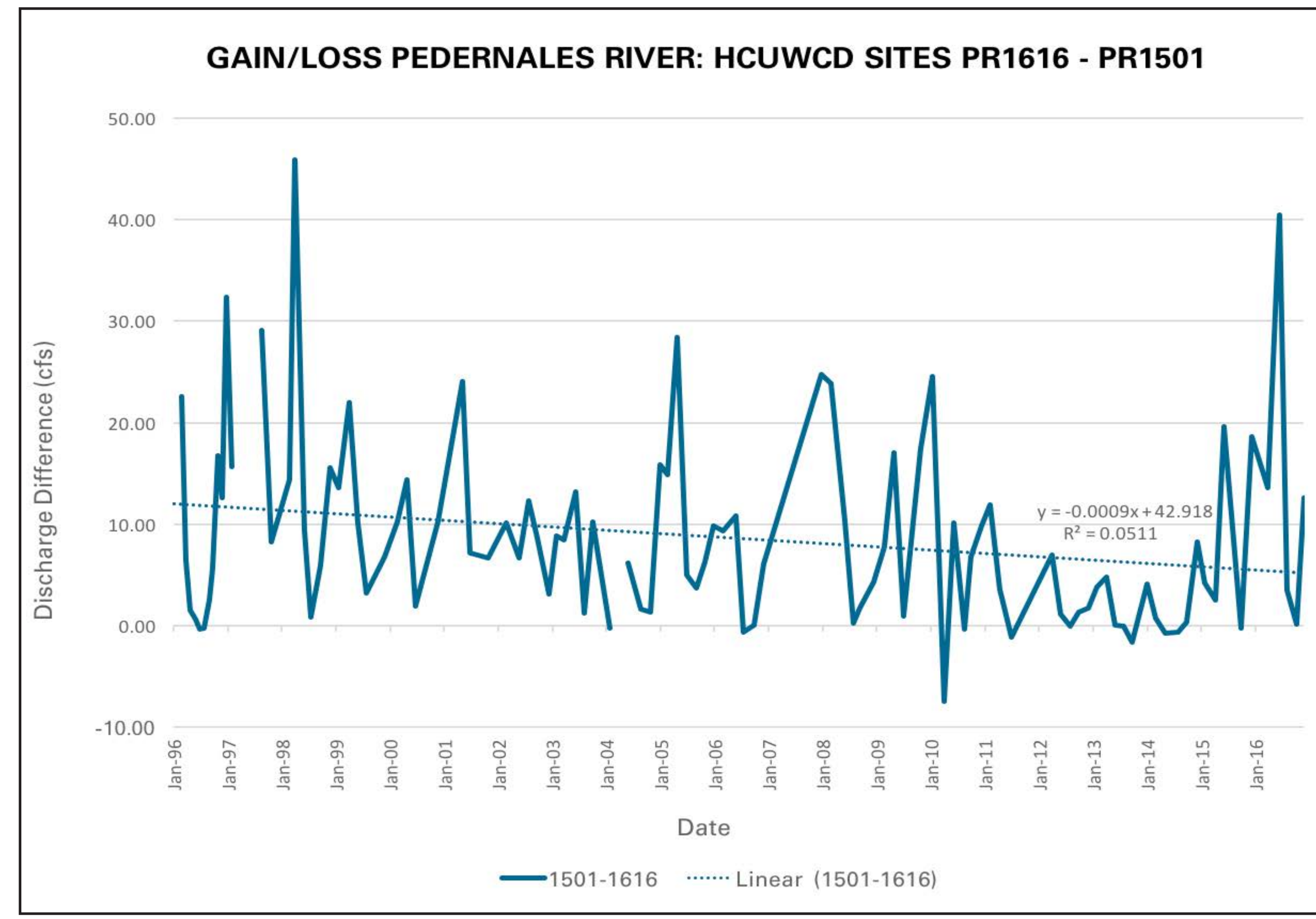


Figure 30. Gain/Loss Pedernales River: HCUWCD Sites PR-1616 to PR-1501

1962 Base Flow Study

Although the overall river discharge has exhibited declining trends, at least since 1980, the river is an overall gaining river. There are losing reaches of the main channel where surface water is recharging groundwater. Both studies indicated the river was an overall gaining river. It is noted that the TWC studies measured sampling locations by river mile, starting at the headwaters near Harper with River Mile 1 and working downstream, versus the common method of starting at the end of the river and working upstream.

During the 1962 study, the main channel discharge (flow) was measured along with the contribution of tributary streams. Approximately 40 percent of the total flow throughout the study reach was attributable to gains in the main channel, or a net gain of 13 cubic feet per second (cfs) at the terminus of the river at Lake Travis over the tributary gains. The main channel gains are the result of groundwater discharge into the channel (Figures 31 and 32). There also may have been minor contributions from small streams that were not measured during the study.

The remaining 60 percent of the total discharge originated from tributaries (approximately 20 cfs), as measured in the 1962 study. The large percentage of tributary contribution indicates an understanding of the hydrogeology of the tributaries is important to achieving sustainable management of the river. Although tributary source water in the tributaries of the Pedernales was visually documented in the flowing water inventory, it has not been quantitatively inventoried or evaluated since the 1962 study. Miller and Flat Creeks discharge were above 2 cfs, with Live Oak, South Grape, North Grape, and Rocky Creeks contributing 1 cfs each.

Pedernales Falls State Park by John Nixon, Flickr

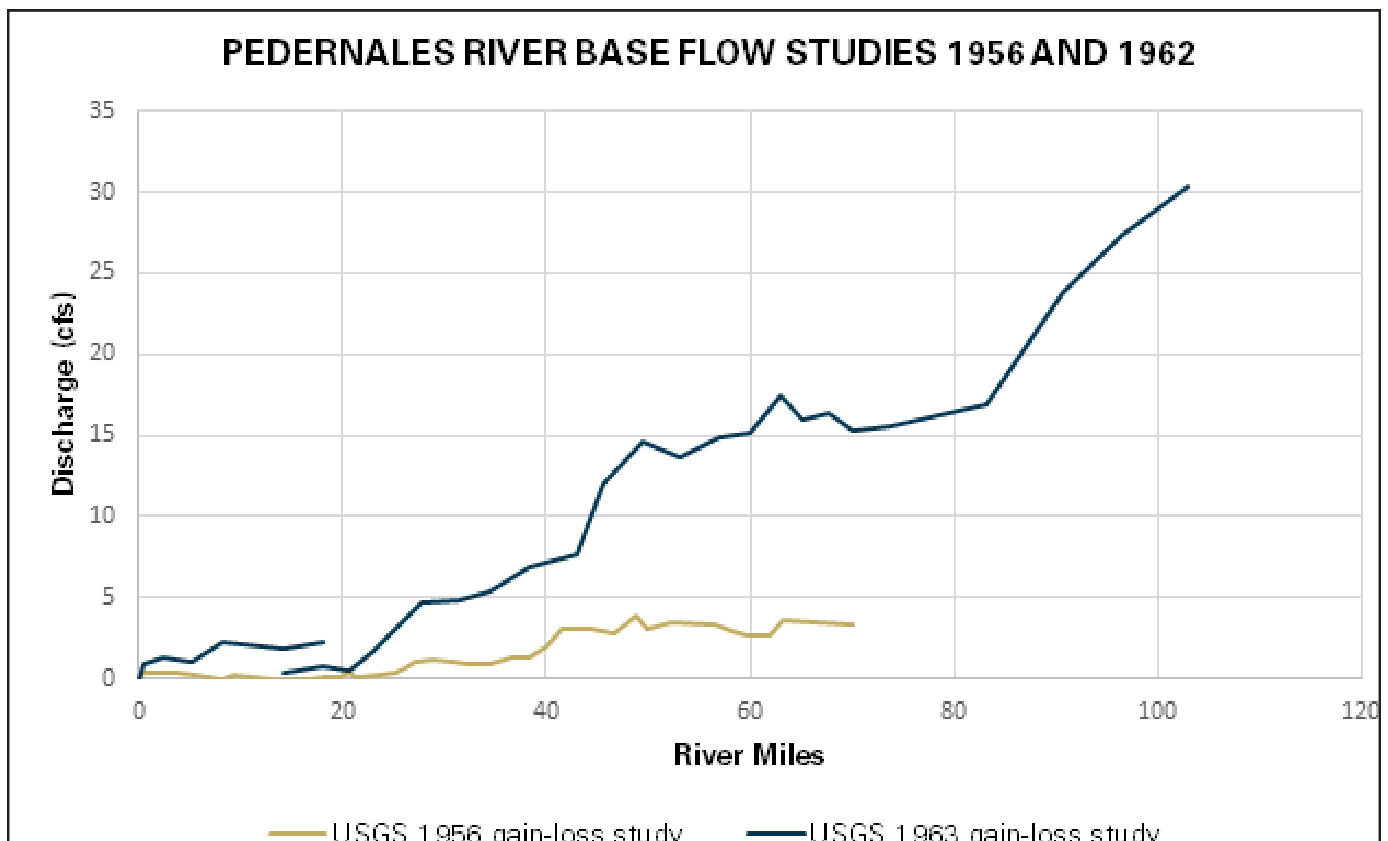


Figure 31. Pedernales River Base Flow Studies – 1956 and 1962

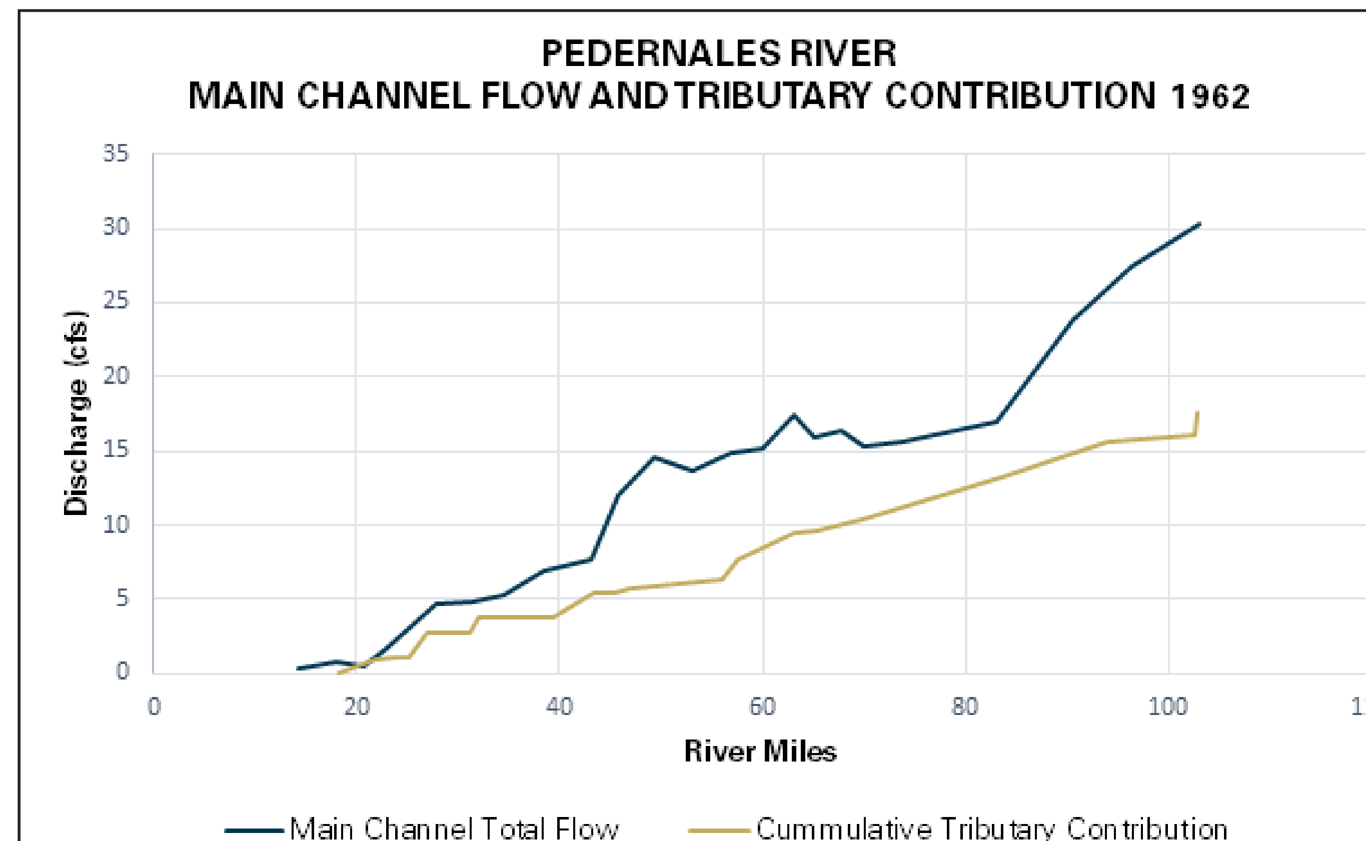


Figure 32. Pedernales River Main Channel Flow and Tributary Contribution – 1962

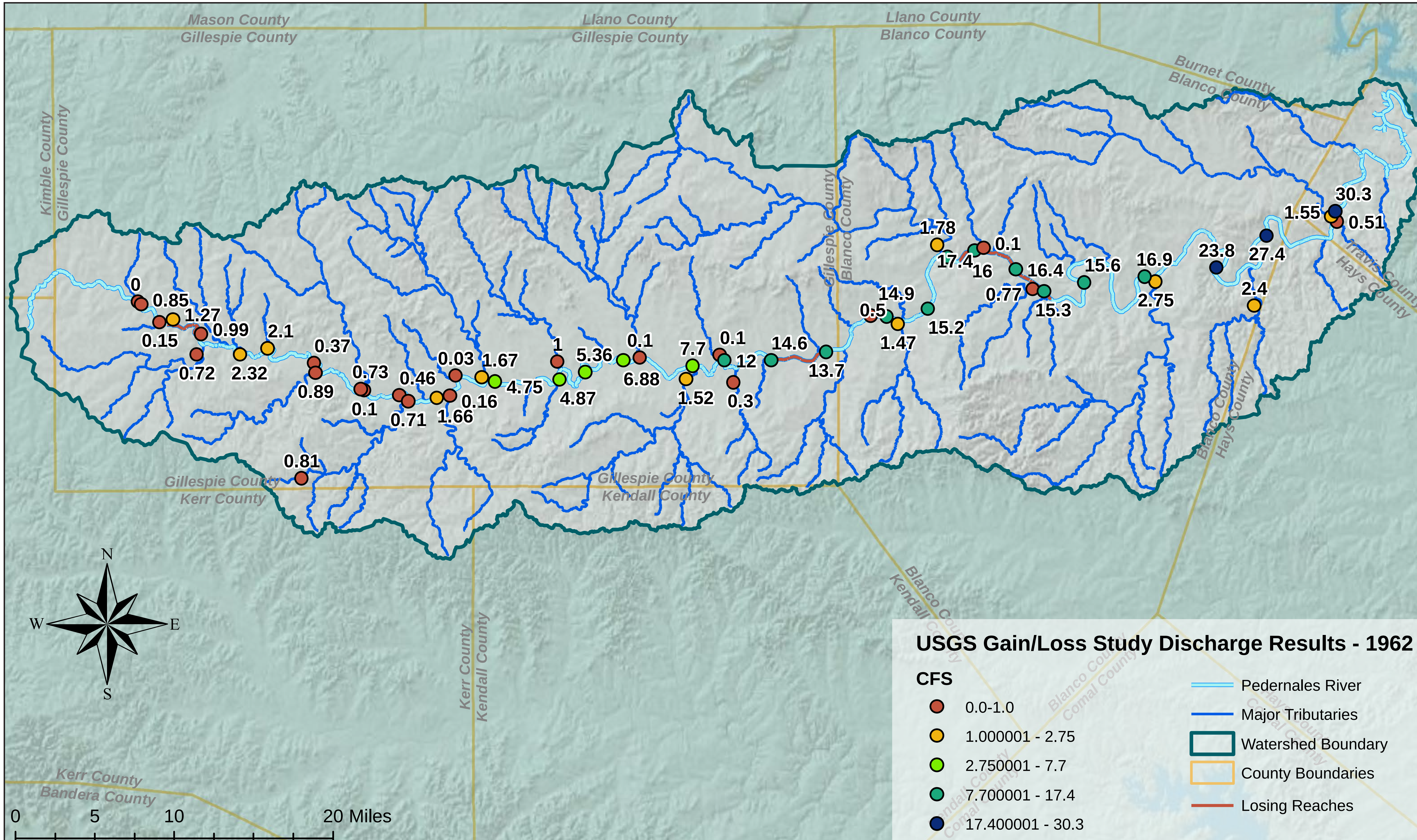


Figure 33. USGS Gain/Loss Study Discharge Results – 1962

Gaining Reaches - 1962

Based on the 1962 study, there appear to be significant main channel gains between river miles 40 and 50 and between river miles 85 and 100. Main channel losses were noted between river miles 65 and 70, the reach between Stonewall and Johnson City.

The gaining reach between river miles 40 and 50 (near Stonewall and eastward into Blanco County) occurs where there is primarily Hensel geology at the surface, underlain by undifferentiated Paleozoic aquifers. Bluntzer (1992) stated the following regarding this area:

> *"water in those aquifers (Paleozoic) probably moves southward and southeasterly along the dip of the aquifers. In some areas of Gillespie and Blanco Counties, a significant portion of the recharge probably moves into the Middle Trinity Aquifer (Hensel) and discharges into the Pedernales River and its tributaries.... This condition is particularly apparent for the Ellenburger-San Saba aquifer in the Pedernales River Valley of eastern Gillespie County and Northern Blanco County."*

The gains measured in the 1962 study may reflect the down dip movement and subsequent discharge of groundwater to the river in this area.

The gaining reach along river miles 85 and 100 occurs in the area where the Pedernales River has incised sufficiently deep to expose the base of the Middle Trinity Aquifer and top of the Lower Trinity from the confluence of Miller Creek downstream to approximately Flat Creek in the main channel of the river and up into some of the tributaries. The river valley is incised down though the Upper and Lower Glen Rose units, Hensel, Cow Creek, Hammett, Sligo, and Sycamore (Hosston). Down cutting through the Upper and Lower Glen Rose has likely created shallow gravity springs that feed the tributaries. This deeply incised valley also may allow for the semi-confined Cow Creek member of the Middle Trinity aquifer and confined Sycamore member of the Lower Trinity to discharge into tributaries and the main channel. Over 40 percent of the flow gain measured in the 1962 study and in the flowing water inventory occurred over this reach of the river.

Losing Reaches - 1962

The main losing reach of the river interpreted from the 1962 study between approximate river miles 65 and 70 occurs between the Gillespie-Blanco County line and Johnson City where the river flows over undifferentiated Paleozoic strata. The Paleozoic strata is quite deformed and fractured at the confluence of North Grape Creek, at approximately river mile 63 (Figure 34). Such structure features in the bedrock such as faults, fractures, and folded bedding planes may allow the surface water to enter the aquifer (losing reach). It is not clear whether the water is recharging the underlying Paleozoic aquifers or contributing to river flow downstream.

Pedernales River by Jim Nix, Flickr

Figure 34. Pedernales River at the Confluence of North Grape Creek. (Note structure and fracturing in the Paleozoic Bedrock in the riverbed, potentially a losing reach in the main channel of the Pedernales.)

Base Flow Study – 2016

The results of the 2016 study were similar to the previous studies. Several areas of gain and loss were noted. Overall flow was somewhat higher in 2016 versus 1962, but both studies represented base flow conditions. A comparison of flow at the USGS gauging stations near Fredericksburg (USH 87) and Johnson City (USH 281) for the 1962 and 2016 studies is shown on Table 10.

Discharge in the river during the 2016 study at the USGS gauges at Fredericksburg and Johnson City was slightly above the median flow, but the flow appeared to reflect base flow conditions and was not influenced by recent rainfall events. There was a significant rainfall event several days after the study concluded.

Location	1962 Base Flow Study	2015 Water Quality Study	2016 Base Flow Study
USGS Gauge at USH 87	4.8 cfs	2.0 cfs	8 cfs
USGS Gauge @ USH 281	15.3 cfs	18.0 cfs	24 cfs
Near Riemers Ranch or Hammett's Crossing	30.3 cfs	27.8 cfs	52.8 cfs

Table 10. Pedernales River Discharge Comparison

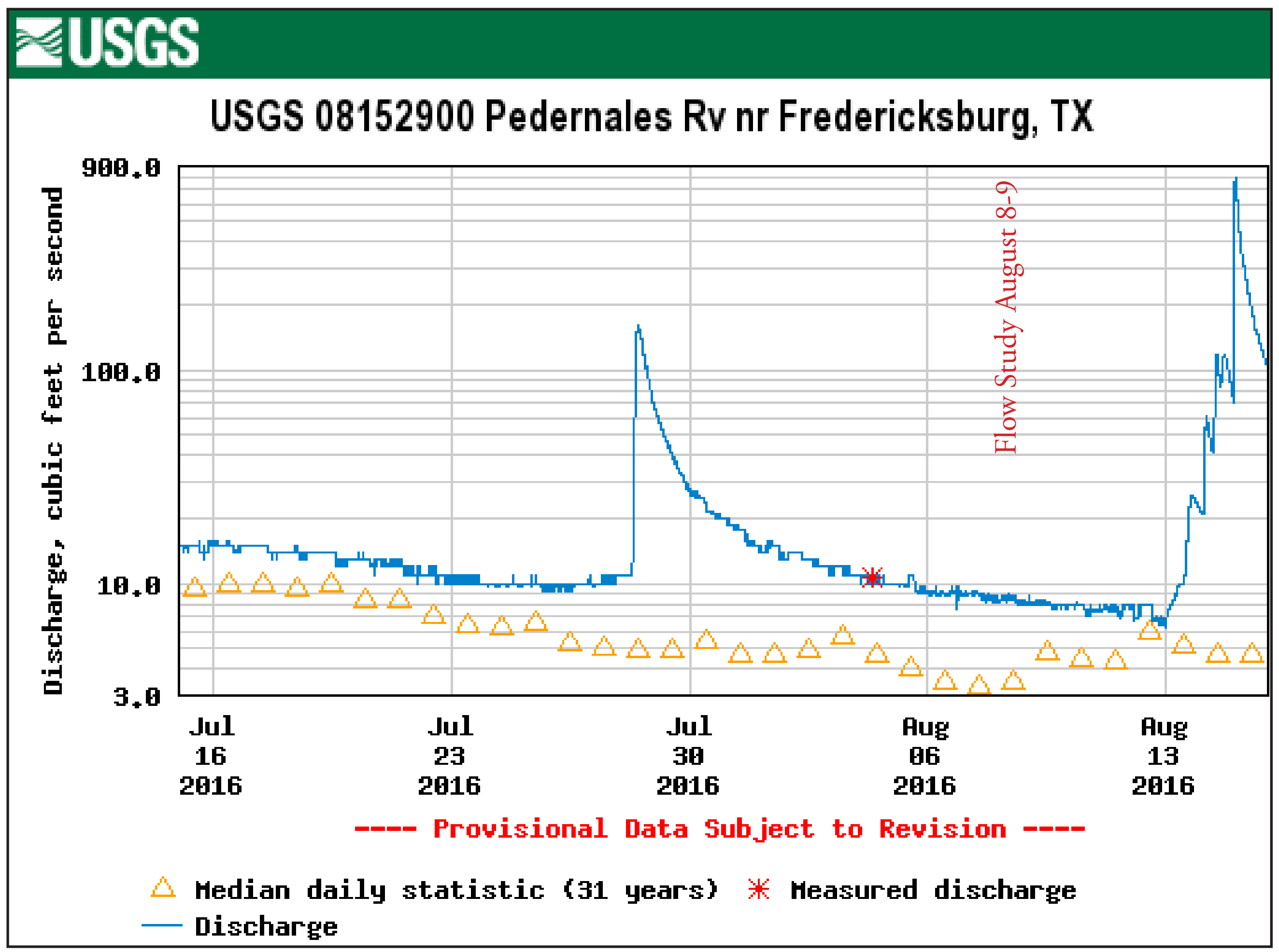


Figure 35. Pedernales River discharge at Fredericksburg (USH 87) – 2016

Source: http://nwis.waterdata.usgs.gov

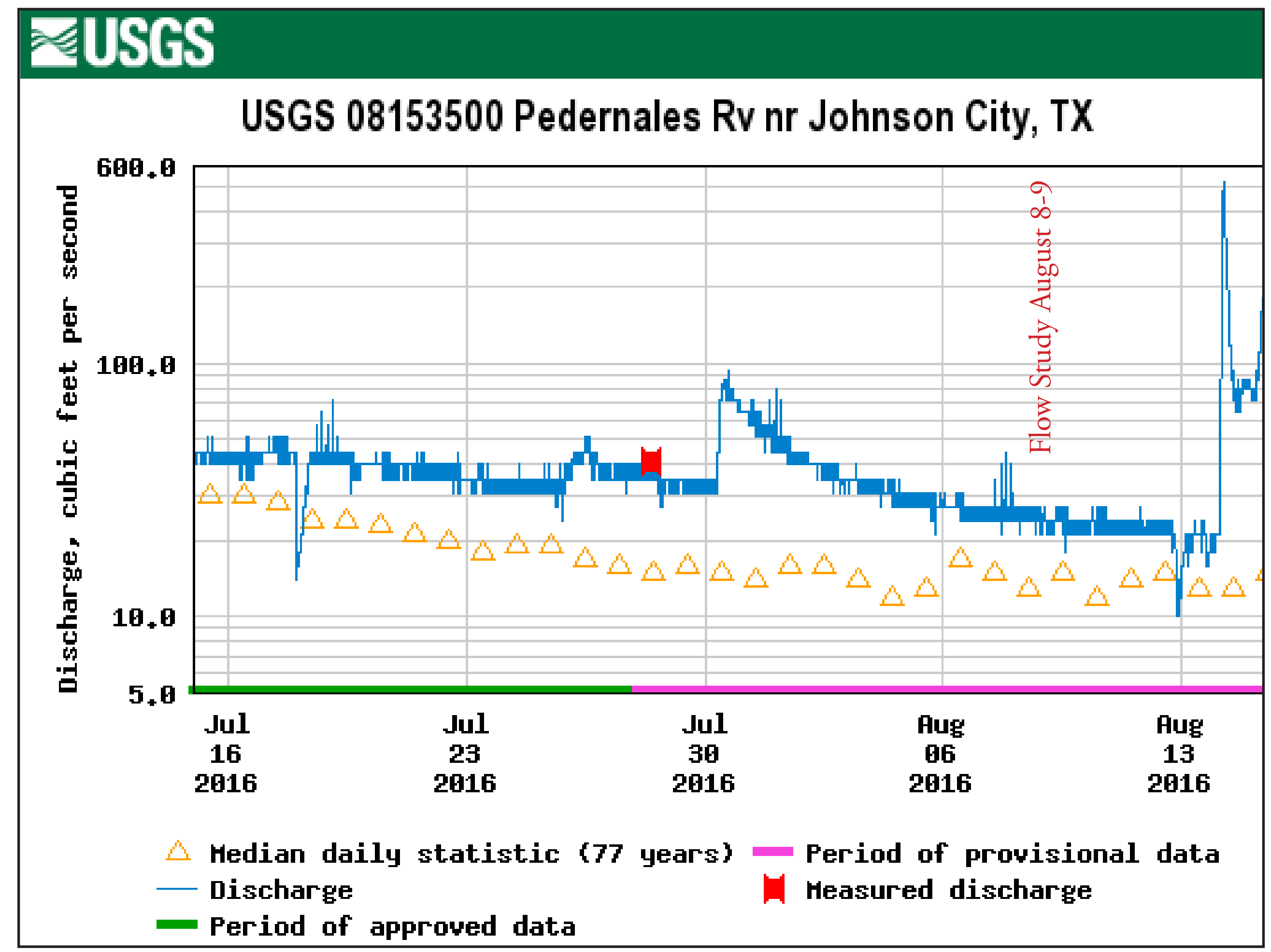


Figure 36. Pedernales River discharge at Johnson City (STH 281) – 2016

Source: http://nwis.waterdata.usgs.gov/

Gaining Reaches – 2016

Overall, the river continues to be a gaining river. There appear to be significant main channel gains between river miles 40 and 50, and between river miles 75 and 100, similar to the 1962 study. As previously discussed, both of these gaining reaches appear to be influenced by the local geology.

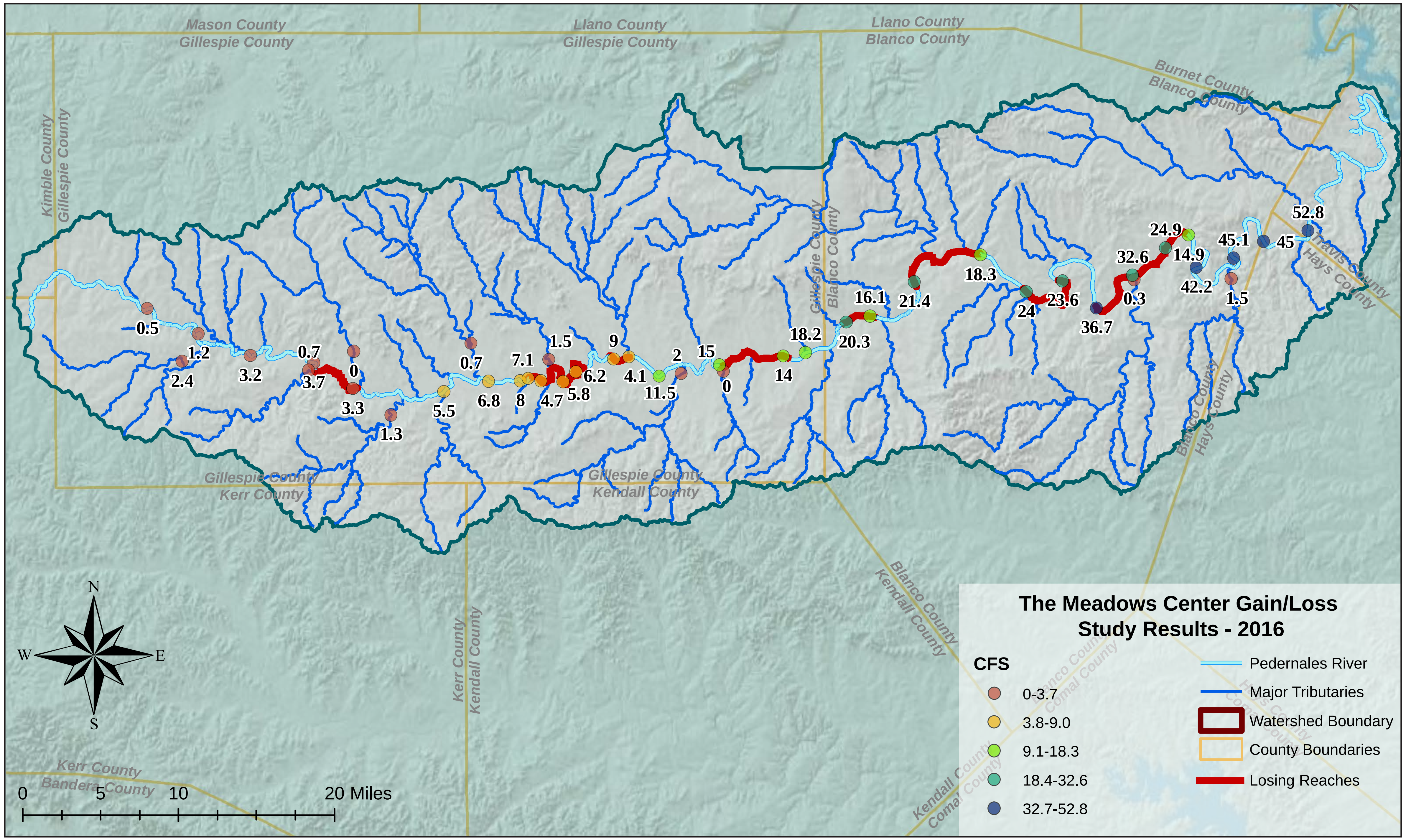


Figure 37. The Meadows Center Gain/Loss Study Discharge Results – 2016

FWI ID #	Road/Water Body Intersection	Estimated Flow	Lat	Long
713	Middle Fork Rocky Creek at Hazy Hills Road	1	30.225101	-98.53387
732	Flat Creek at Fitzhugh	3	30.27158	-98.2086
760	Rocky Creek at Triple Creek Road	2	30.252375	-98.52905
761	Towhead Creek at US 290	S	30.260453	-98.47835
762	Williams Creek at McCall Creek Road	S	30.240866	-98.5803
764	Flat Creek at US 290	1	30.271213	-98.4312
794	Spring Creek at Morris Ranch Road	D	30.218483	-99.01833
816	East Fork Rocky Creek at Old #9 Highway	S	30.21775	-98.51936
828	Palo Alto Creek at US 290	1	30.288436	-98.79687
837	Cottonwood Creek at Cypress Mill	1	30.329339	-98.36348
851	Miller Creek at Zenner Ahrens Road	2	30.265093	-98.28707
852	Miller Creek at Yeager Creek Road	2	30.240076	-98.29237
904	Hamilton Creek at Hamilton Pool Road	2	30.335868	-98.12726
906	Hickory Creek RM 1323	1	30.362547	-98.46845
749	Salt Creek at US 87	S	30.212918	-98.86997
757	West Fork Hunters Creek at Country Creek Road	3	30.163767	-98.7294
768	Salt Branch at Lower Crabapple Road	D	30.235555	-98.65613
778	Hardin Russell Creek at Wahrmund Arens Road	D	30.320018	-98.38945
791	Wittington Creek at Klein Road	D	30.25154	-98.60985
809	Towhead Creek at Grape Creek Road	S	30.286724	-98.44584
817	Flat Creek at Friedrich Road	D	30.237686	-98.45566
821	Salt Branch at US 290	D	30.247535	-98.80364
833	Kuhlman Creek at FM 1323	D	30.290594	-98.76671
838	Salter Spring Creek at Cypress Mill	1	30.322676	-98.37956
872	Iron Rock Creek at RM 1323	D	30.307293	-98.60414
874	Cave Creek at RM 1323	D	30.292352	-98.71886
899	Post Oak Creek at Wahrmund Arens	D	30.294288	-98.54075
905	Buffalo Creek at FM 1323	S	30.349049	-98.43535
921	Devils Creek at PFM 2093	D	30.250987	-99.10727
922	Flag Creek at US 290	D	30.258098	-99.15395
927	Barta Branch at FM 2093	S	30.28501	-99.22516
959	Threemile Creek at Old Austin Highway	D	30.225458	-98.68203
	North Creek at US 290	D		
	North Grape at RM 1323	3		
Flow Estimate D = dry 0 = Standing water, no flow 1 = <0.1 cfs 2 = 0.1 - 0.5 cfs 3 = 0.5 - 1.0 cfs 4 = >1.0 cfs				
FWI ID = Flowing Water Inventory ID number				

Table 11. Qualitative Flow Observations – 2016

Losing Reaches – 2016

There are three significant losing reaches measured during the 2016 study as shown on Figure 37.

The losing reach south of Fredericksburg is near the Fredericksburg municipal well field. Beginning in late-1995, the HCUWCD began gauging discharge at a number of the locations along a reach of the Pedernales River, starting at a site along STH 16 south of the Gillespie County airport and ending near the Wild Flower Seed Farm on the north side of USH 290. Gauging locations were also established on Live Oak Creek and Barons Creek. Gauging stations are generally located along the reach of river that traverses just south of the City of Fredericksburg, which operates two municipal well fields located along this reach. The reach has been monitored to determine if groundwater withdrawals via the well field may be affecting flow. The measuring sites and well fields are shown on Figure 29.

Figure 26 shows the total discharge between HCUWCD stations PR-1616 and PR-1501, which are the most upstream and downstream extent of the study area. Both Live Oak and Barons Creeks contribute flow to the main channel, also being the largest tributaries along the reach. Although Muesebach Creek, a lesser tributary, also contributes to the reach, it is not routinely measured. Figure 26 also provides a linear trend analysis of the data. Although the reach has consistently been a gaining reach, the gain has been reduced approximately 8 cfs, or roughly by two thirds over time. This reach was actually a losing reach in the 2016 study, losing approximately 4 cfs between stations PR-1616 and PR-1501. Additional studies are necessary to further investigate potential losses due to the Fredericksburg wellfields.

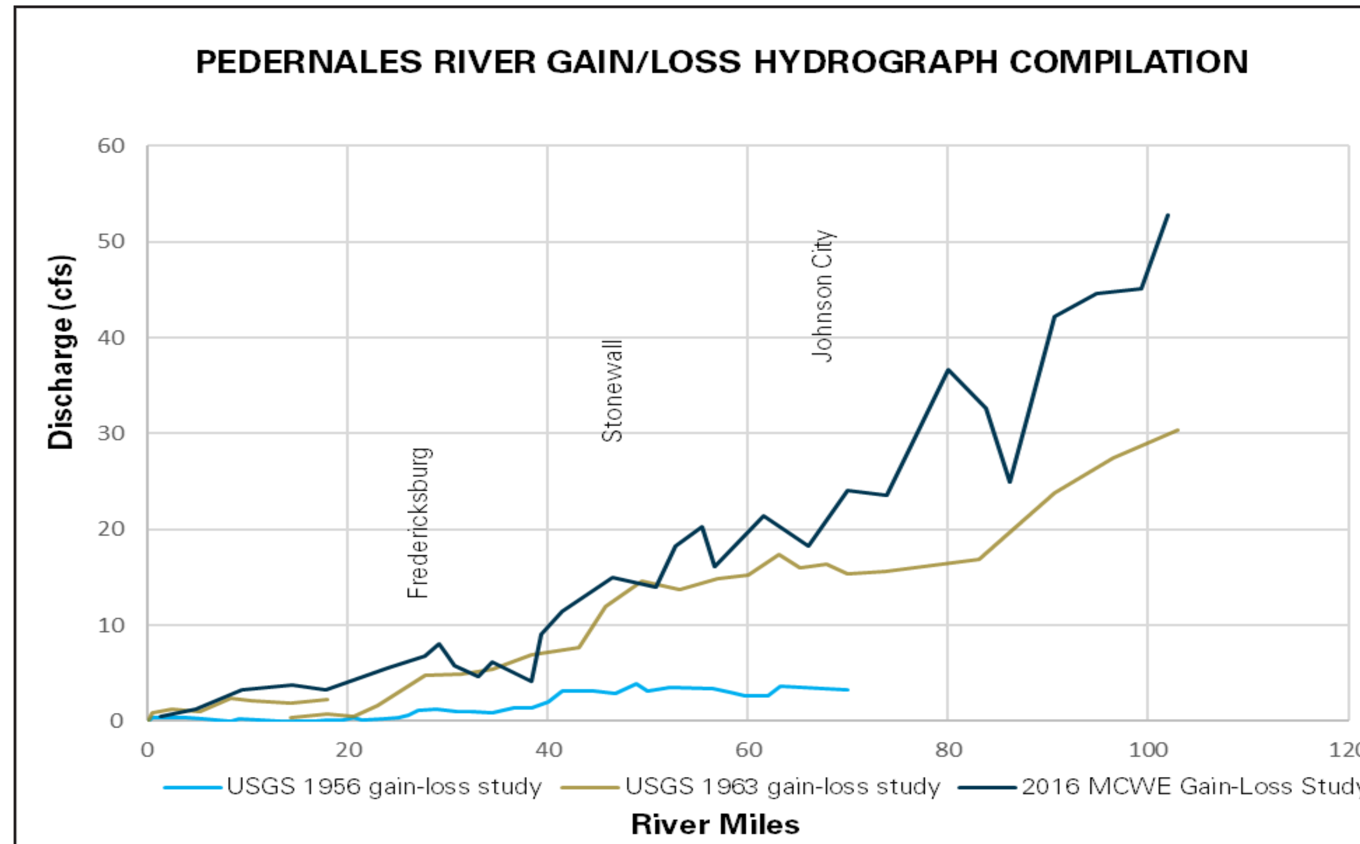


Figure 38. Pedernales River Gain/Loss Hydrograph Compilation

Flow at Live Oak and Barons creeks have been measured since 1996. These creeks have also exhibited decreased flow trends since 1996. Both initially had discharges of approximately 6 cfs, but are currently discharging approximately 2 to 4 cfs for Barons and Live Oak, respectively (Figure 39).

The large loss upstream of Pedernales State Park near river mile 90 is likely the source water area for the large spring near the falls in the state park.

In Brune's "Streams of Texas",

> *"Pedernales Falls emerges at 249 meters above sea level at the foot of the fall in Pedernales Falls SP, 18 km east of Johnson City. It issues under artesian pressure from the Marble Falls limestone.....Water which flows from this spring originates as surface water flowing from various streams into the Pedernales River in Blanco and Gillespie Counties....Dye studies have shown that the water which feds the springs enters the Marble Falls Limestone in the Pedernales River bed about 4 km upstream, near the R.W. Robinson ranch house."*

The loss upstream of the spring was approximately 12 cfs. The discharge at the spring was approximately 15 cfs, which accounts for most of the upstream loss. This large loss was not noted in the 1962 study, likely due to the more limited number of measurement locations in this reach of the river compared to the 2016 study.

The third losing reach occurred near the Blanco-Gillespie County line where the river flows over faulted and folded Paleozoic strata, similar to flow conditions noted in the 1962 study.

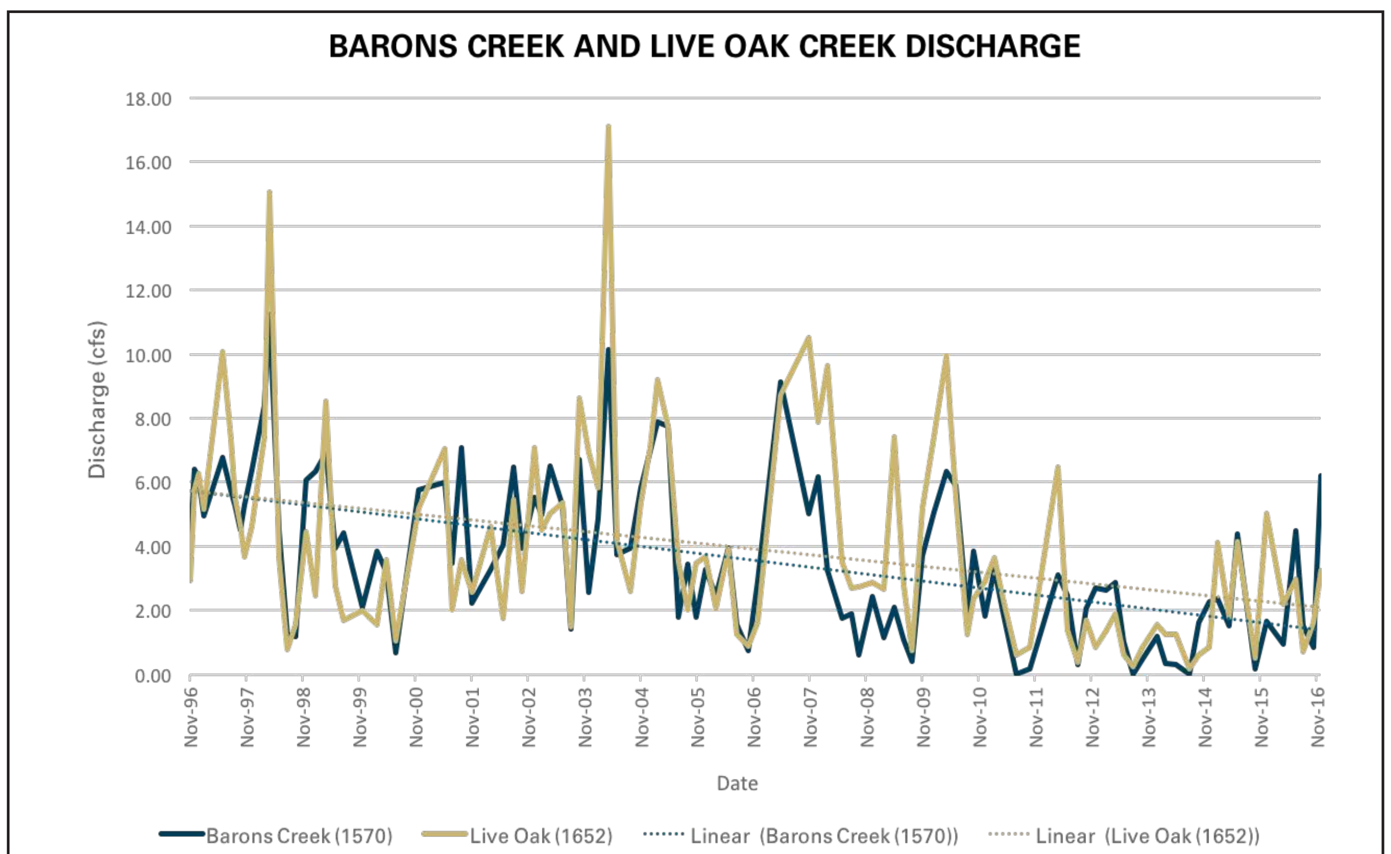


Figure 39. Hydrographs for Barons and Live Oak Creeks (HCUWCD unpublished data, 2015)

Pedernales Falls State Park by mlhradio, Flickr

General Observations – River Discharge

As a general observation for both the 1962 and 2016 studies, the rate of gain in flow is somewhat slower from Harper to Stonewall than from Stonewall to the terminus of the studies. There is a significant amount of alluvium in the channel west of Stonewall. As the main channel becomes more alluvial (thick sand and gravel in the stream river channel) in nature, subsurface underflow may be occurring, resulting in less stream flow being measured than is actually occurring along this reach of the river (Figure 39). The river channel to the east of Stonewall is generally underlain by harder, most resistant Paleozoic and Cretaceous strata with little or no alluvium in the main channel.

Hamilton Creek Hamilton Pool Nature Preserve by rulbradio, Flickr

Groundwater is the primary potable water source throughout the watershed. Increased groundwater use from population growth over time may be resulting in decreasing discharge into the Pedernales River over the last 35 years. The population of Gillespie County has increased from 10,048 in 1960 (Texas Association of Counties) to 25,570 in 2014 (US Census Bureau), a 240 percent increase in population, with much of this growth is occurring in Fredericksburg and the surrounding area.

There has been a large expansion in the acreage of vineyards and wineries in the county. The HCUWCD permits groundwater pumpage for vinyards at one arce-foot a year for each acre of grapes. Due to the relatively small amout of acres planted in grapes, water usage from vineyards is relatively small. This study did not address potential water quality issues from stormwater events. Similarly, the population of Blanco County has increased from 3,657 in 1960 (Texas Association of Counties) to 10,812 in 2014 (US Census Bureau), a 290 percent increase in population.

Based on the flowing water inventory and gain/loss studies, upstream sub-watersheds originating in the Edwards Plateau, including Banta Branch, Flag Creek, Klein Branch, and White Oak Creek, receive source water at the contact between the Segovia and Fort Terrett members of the Edwards Limestone. Similar observations were reported by Bluntzer (1992).

Spring, Live Oak, Barons and Palo Alto Creeks exhibit similar geological and hydrological characteristics. The headwaters originate in the Edwards Limestone. The tributaries are incised down through the Upper Glen Rose, subsequently flowing onto the lower lying Hensel Sand towards the main channel of the Pedernales River. Groundwater likely discharges from the Hensel into the creeks and main river channel. The area underlain by the Hensel Sand generally contains more human development since the Hensel is more favorable for agricultural activities, compared to the steeper topography and carbonates of the Edwards and Glen Rose. The Hensel areas are also generally flatter and more likely to be developed.

Due to the lack of public access and large tracts of land, areas underlain by surficial undifferentiated Paleozoic and Precambrian strata were not accessible. Large areas of North Grape Creek, Pedernales Falls, Post Oak, Threemile, and Towhead subwatersheds are not traversed by public roads, and significant landowner outreach for possible access to these areas was not within the scope of the present study.

As previously mentioned, the gaining reach along river miles 85 and 100 during the 1962 and 2016 study is located in the area where the Pedernales River and tributaries have incised sufficiently deep to expose the base of the Middle Trinity Aquifer and the top of the Lower Trinity from the confluence of Miller Creek downstream to approximately Flat Creek. Sub-watersheds in this area include Roy Creek and Miller Creek (including McCall, Yaeger, Turkey and Middle Creeks). Flow during the inventory was noted in these tributaries, and appears to originate from the Upper and Lower Glen Rose formations. Because the flow was not actually measured, however, it is difficult to determine if the large increases in flow in the main channel are the result of tributary inflow or springs in the main river channel. Groundwater inflow directly into the main channel could originate from the lower members of the Middle Trinity aquifer, such as the Hensel or Cow Creek, and/or the Lower Trinity aquifer (Sligo and Sycamore) exposed in the river valley. In addition, shallow groundwater flow inputs to the river from the Paleozoic strata on the north side of the river, mainly Ellenberger and Marble Falls, may be contributing significant inlow to the river. This reach of the river is targeted for additional study in 2017.

WATER QUALITY ANALYSIS

2015 Sampling Event

The purpose of the synoptic basinwide sampling event in 2015 was to obtain a snapshot of water quality during base flow conditions in the main channel and flowing tributaries. A detailed description and interpretation of the data is presented in the Zappetello thesis in Appendix A. Comparisons of water quality by sub-watershed and the main channel were made. Groundwater quality of the underlying aquifers was compared to surface water to determine source aquifers of base flow. The conclusions of the thesis are as follows:

> *The water quality in the Pedernales River is generally good. Although total dissolved solids at a few sites are above EPA drinking water limits of 500 mg/L (approximately 781 µS SC), all other ion and nutrient concentrations meet drinking water limits. Headwater springs are the source of the Pedernales River during baseflow conditions and are very important to the health of the river. Water in the springs originates from several geologic units with similar carbonate geochemistry. Due to somewhat homogeneous aquifer chemistry, interpreting the groundwater source is dependent on the geologic location of springs. The geochemical groundwater signature indicates surface locations that are near springs and allows enhanced spatial analysis of spring locations when exact spring access is limited due to restricted private property. By overlaying the spring locations with surface geology, and therefore identifying host geologic unit and source aquifer, groundwater in the Pedernales River was determined to originate from the Edwards-Trinity Plateau Aquifer, the Trinity Aquifer, the Marble Falls Aquifer, and the Ellenburger-San Saba Aquifer.*
>
> *Combining naturally occurring geochemical tracers like major ions and stable isotopes with principal component analysis is a powerful tool for evaluating geochemical trends. Groundwater has a distinct regional signature with respect to stable hydrogen and oxygen ratios. The isotopic gradient from groundwater to river water follows an evaporitic trend and indicates a strong evaporation control on water chemistry within the watershed. Some of the major ion concentrations are elevated near cities and may reflect human impacts from treated wastewater discharge. When the overall geochemical dataset for the 2015 synoptic watershed sampling is analyzed for statistically relevant patterns using PCA, human impact and proximity to springs seem to be the dominant factors controlling water chemistry. This information will be useful for water conservation and planning because Pedernales River and tributary flows have been decreasing since the 1980's, severe drought has affected the region, and population in central Texas is increasing.*

Comparison of 1962 and 2016 Water Quality

The water quality sampling of major cations and anions was conducted in the 1962 (Holland and Hughes, 1964), 2015 and 2016 studies. Detailed comparisons of water quality concentrations between the 1962 and 2015 were discussed in Zappetello's study (2016). Flow discharge measurements were made in 1962 and 2016, but not in 2015. Therefore, loading comparisons can be made between the 1962 and 2016 data, but not the 2015 data. The 2016 water quality results are shown on Table 12. Water quality results from a sample of the Pedernales State Park Spring taken by the Texas Water Development Board are also included.

Comparison of loading data can provide an indication of potential changes in river water quality over time. Loading calculations are based on concentration and discharge. The discharge in the river during the 2016 study was slightly higher than during the 1962 study, therefore one might expect slightly higher loading rates given similar concentrations. For discussion purposes, concentration and loading results for one major cation and two major anions (calcium, chloride and sulfate are compared). Calcium and sulfate are generally naturally occurring in the geology of the the basin. The source of chloride is more likely the result of human activity such as human and animal wastes and water treatment equipment such as water softeners or reverse osmosis units.

Site Description	River Mile	Sample Date	Chloride (mg/L)	Nitrate (mg/L)	Sulfate (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Magnesium (mg/L)	Calcium (mg/L)	Silica (mg/L)	Fluoride (mg/L)	Total Alkalinity (mg/L)	Total Hardness (mg/L)
G/L 1	1.3	8/9/2016	40.33	6.25	19.86	28.27	1.25	23.90	71.54	1.74	0.23	272	300
G/L 4	9.4	8/9/2016	28.25	0.39	20.19	20.96	2.24	28.12	41.16	N/A	0.32	202	166
G/L 5	14.5	8/9/2016	29.27	0.00	19.98	21.63	2.09	28.70	43.43	N/A	0.32	220	240
G/L 10	24	8/9/2016	36.83	0.47	19.06	23.47	2.92	30.89	39.92	1.65	0.32	216	240
G/L 18	38.4	8/9/2016	52.72	0.57	28.88	34.20	3.44	34.33	36.22	1.65	0.36	210	242
G/L 18 dup	38.4	8/9/2016	53.18	0.56	29.21	34.69	3.55	35.04	37.04	1.65	0.36	212	240
G/L 22	39.4	8/9/2016	54.51	1.53	31.37	36.69	3.41	37.52	39.58	1.70	0.38	226	262
G/L 27	56.7	8/9/2016	53.72	0.46	36.50	36.62	3.28	38.99	32.53	1.69	0.42	212	244
G/L 30	70	8/9/2016	50.94	0.00	35.90	35.05	3.20	39.28	34.50	1.70	0.37	196	224
G/L 34	83.8	8/9/2016	38.92	0.00	32.84	26.89	2.58	35.52	37.41	1.62	0.38	210	244
G/L 38	94.8	8/9/2016	33.41	0.35	30.69	23.11	2.33	32.25	36.99	1.58	0.31	200	234
G/L 40	102	8/9/2016	32.69	0.00	30.29	22.59	2.29	31.90	35.92	1.61	0.32	194	224
Pedernales State Park Spring*	88	8/28/2015	31.6	0.56	29.2	17.9	n/a	28.9	46.6	n/a	0.26	212	240
Samples Analzed by XXXXXXXXXXX													
* TWDB Data: http://www2.twdb.texas.gov/apps/waterdatainteractive//GetReports.aspx?Num=5746317&Type=GWDB													

Table 12. Pedernales River Water Quality Sampling Results – 2016

Pedernales Falls State Park by cool.as.a.cucumber, Flickr

Calcium concentrations generally ranged from 30 to 40 mg/l. The results from the samples from 1962 and 2016 obtained near the headwaters springs near Harper were significantly higher, 72 mg/l and 82 mg/l, respectively (Figure 40). The higher concentrations likely reflect the geochemistry of the Edwards and Glen Rose carbonates. Concentrations decrease as the river flows out of the carbonates and onto the more silica-rich Hensel Sand formation. Concentrations remain fairly constistent, ranging from 30 to 40 mg/l throughout the remainder of the run of the river. Despite consistent concentrations, calcium loading increases to over 10,000 lbs/day (2016) along the entire length of the river reflecting increasing discharge (Figure 46).

Chloride concentrations ranged from 28 mg/l to 119 mg/l (Figure 41). Chloride concentrations were significantly higher in 1962 as compared to 2016. In both sample sets, chloride concentrations were relatively low from the headwaters to near Fredericksburg where concentrations are significantly higher. Concentrations tend to remain elevated downstream to Johnson City. Sulfate concentrations tend to follow the the same trend (Figure 42). Increasing concentrations of chloride near Fredericksburg and continuing to Johnson City are likely a combination of natural conditions and human impact.

Zappetello (2016) discusses potential sources of chloride in the river samples

> *Cl- (chloride) is a conservative ion and does not react with the natural system. For this reason, it is sometimes used as a tracer in water flow studies. Cl- can originate in natural or manmade sources. Cl- is added to drinking water in water softeners and then ends up in human wastewater. It is also found in fertilizer and livestock feed and supplements. Cl- accumulates by evapotranspiration in groundwater irrigated fields, even if the groundwater is not particularly high in chloride. This is an active agricultural area and fields in the region are irrigated from groundwater.*

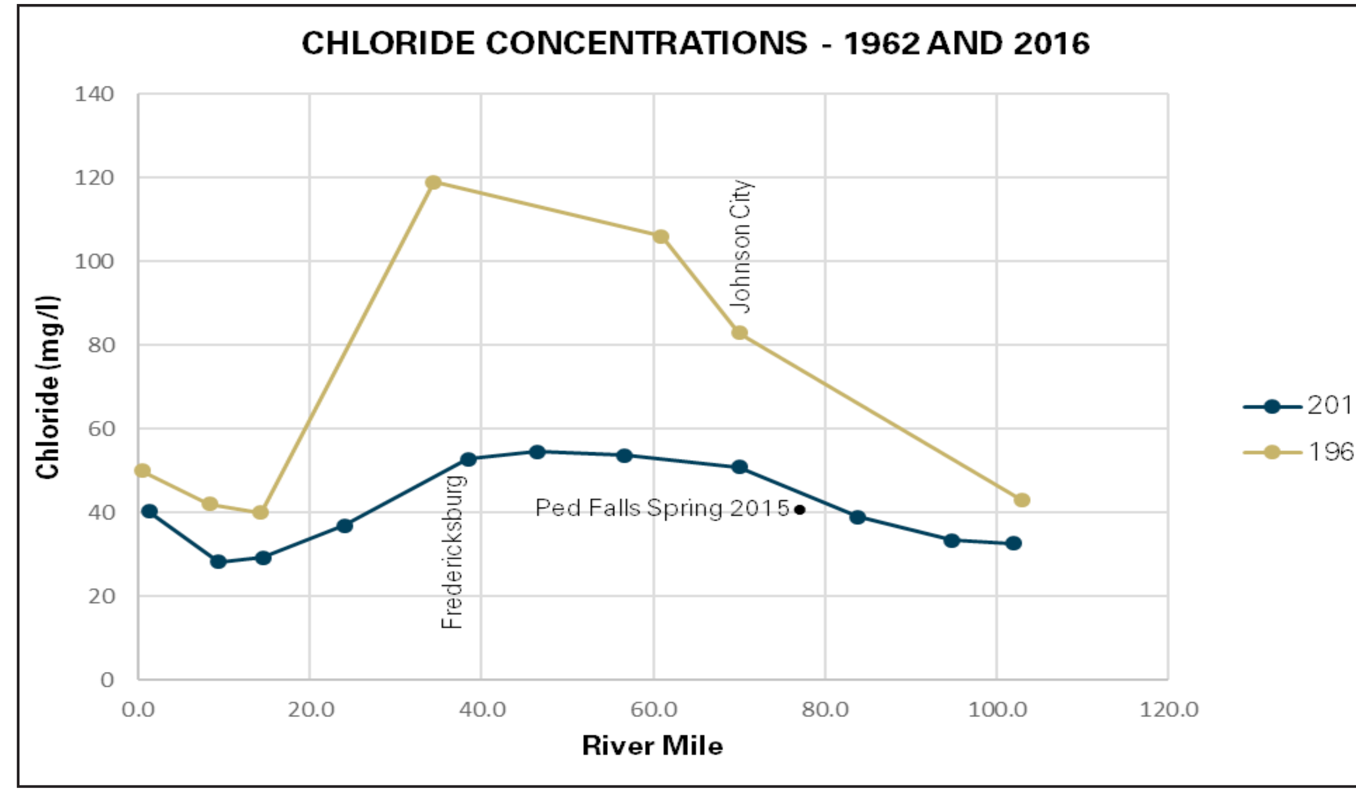


Figure 41. Chloride Concentrations – 1962 and 2016

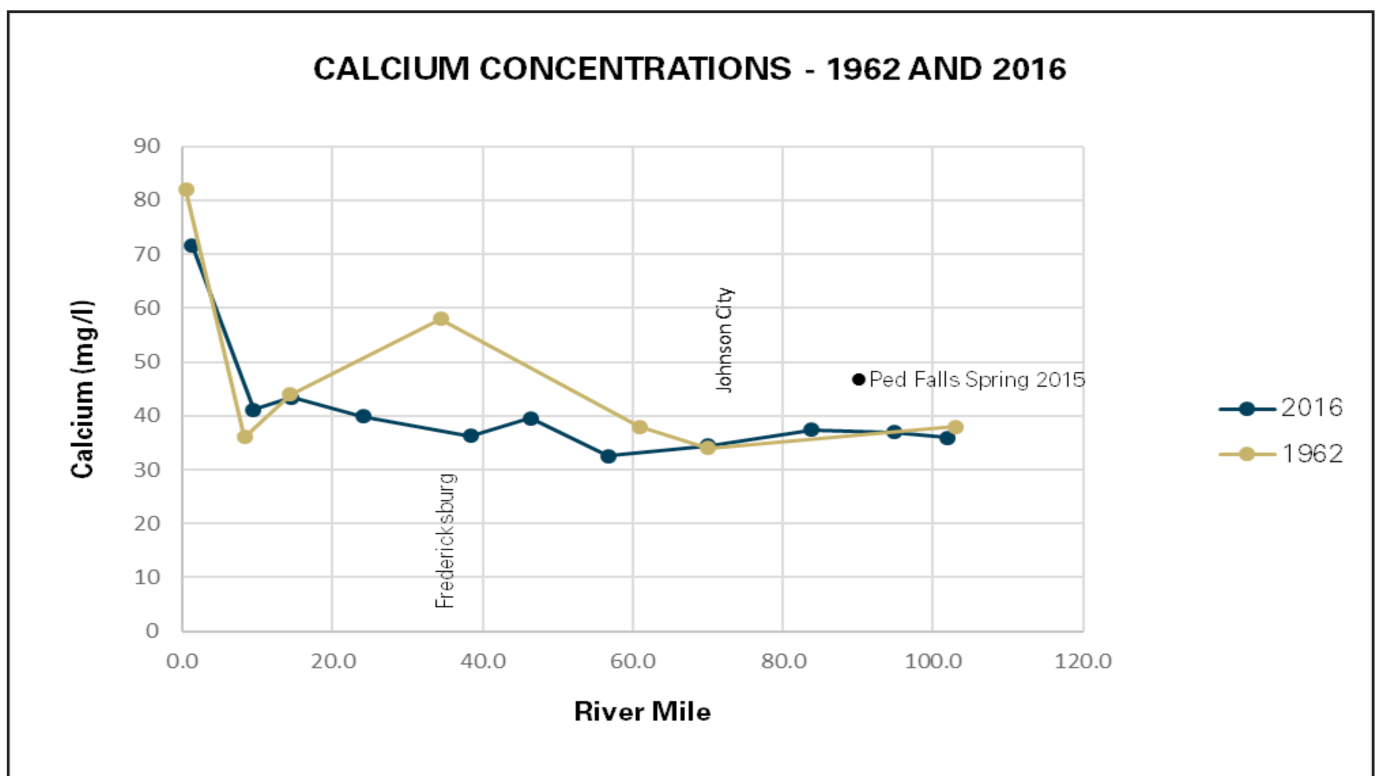


Figure 40. Calcium Concentrations – 1962 and 2016

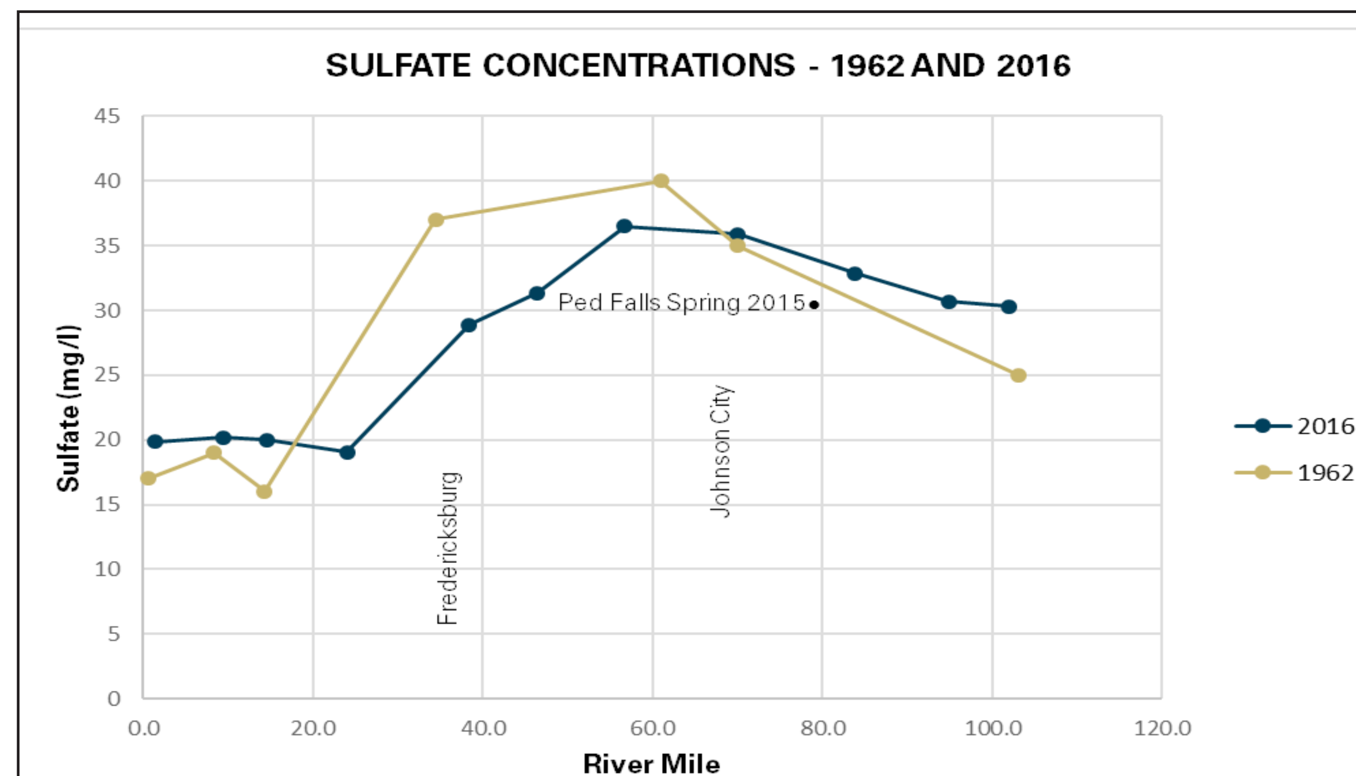


Figure 42. Sulfate Concentrations – 1962 and 2016

Chloride is also naturally occurring in groundwater in the watershed. Groundwater quality sampling results collected by the Texas Water Development Board indicate chloride concentrations are generally higher in groundwater than surface water as shown on Figure 45.

The Cities of Fredericksburg and Johnson City both source their municipal water supplies from the Ellenburger Aquifer. Chloride concentrations in the river originate in the aquifer, but are brought to the surface and distributed into the environment through human activities. Both Johnson City and Fredericksburg discharge treated wastewater effluent into tributaries of the Pedernales River. The lower chloride concentrations observed in 2016 may be the results of changed wastewater discharge practices in Fredericksburg.

From Zappetello (2016):

> *The wastewater discharge practices have changed in Fredericksburg since 1995 (personal communication with J. Horry, City of Fredericksburg Water/Wastewater Superintendent, 24 Nov 2015). The city wastewater treatment plant is located adjacent to Barons Creek, and all treated effluent was previously discharged into the creek. In 1995, some reclaimed effluent began to be used to water a golf course in the Live Oak Creek subwatershed (Laby Bird Golf Course) and an additional golf course in the Palo Alto subwatershed (Boot Camp) since 2009. Some treated wastewater continues to be discharged into Barons Creek, and volumes vary depending on time of year and weather.*

Chloride, sulfate, and calcium loading trends tend to reflect the overall gaining nature of the river, with loading increasing with increasing flow as shown on Figures 43 ,44 and 46.

Nitrate concentrations are often used as an indicator of man-made impact to water quality. Municipal wastewater effluent, animal waste and fertilizers are common sources. Lower concentrations of nitrates can create algal blooms in creek and rivers. Nitrate concentrations are generally less than 1 mg/l and in some cases below laboratory detection limits. The exception is the most upstream samples in both the 1962 and 2016 which indicated elevated nitrate concentrations (Figure 47). The source of elevated nitrates near the headwaters springs is not known.

Pedernales Falls State Park by Karola, Flickr

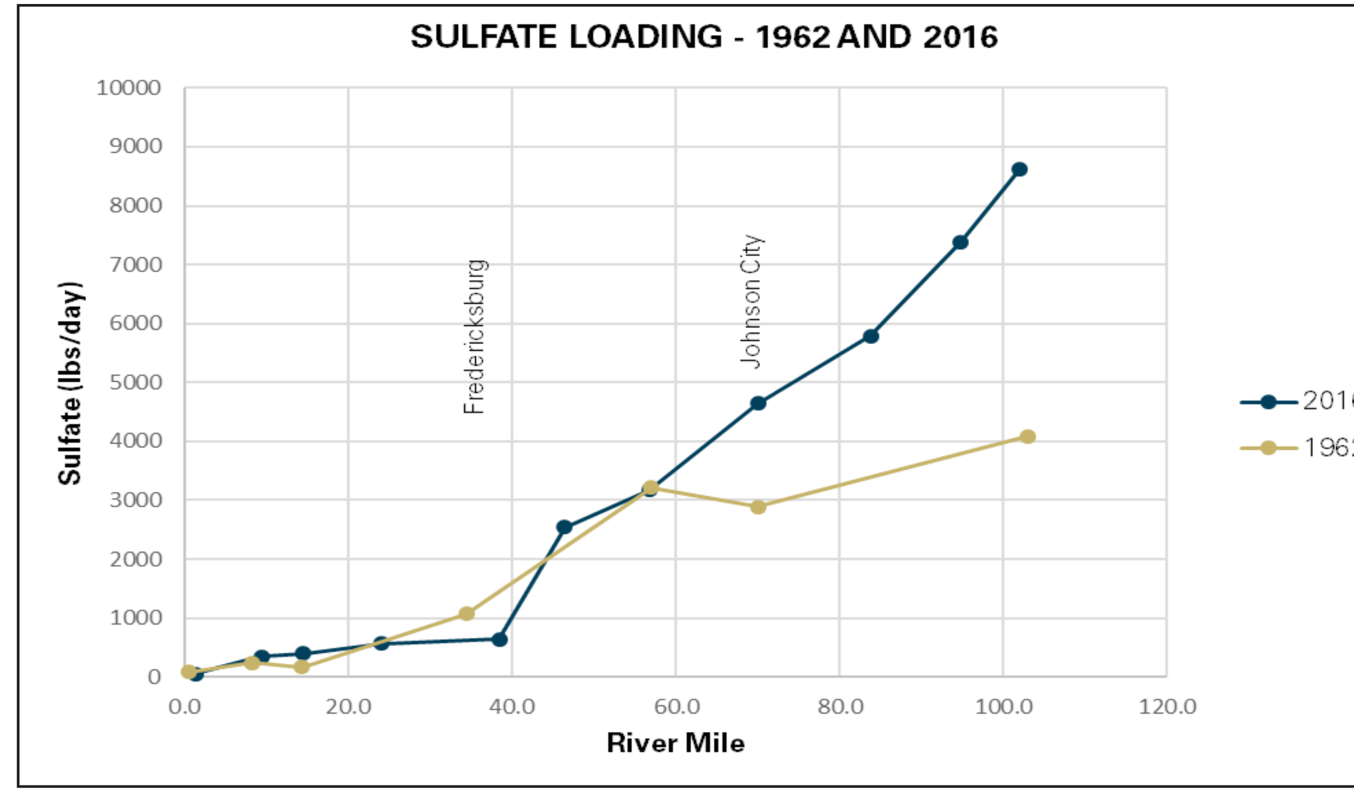


Figure 43. Sulfate Loading – 1962 and 2016

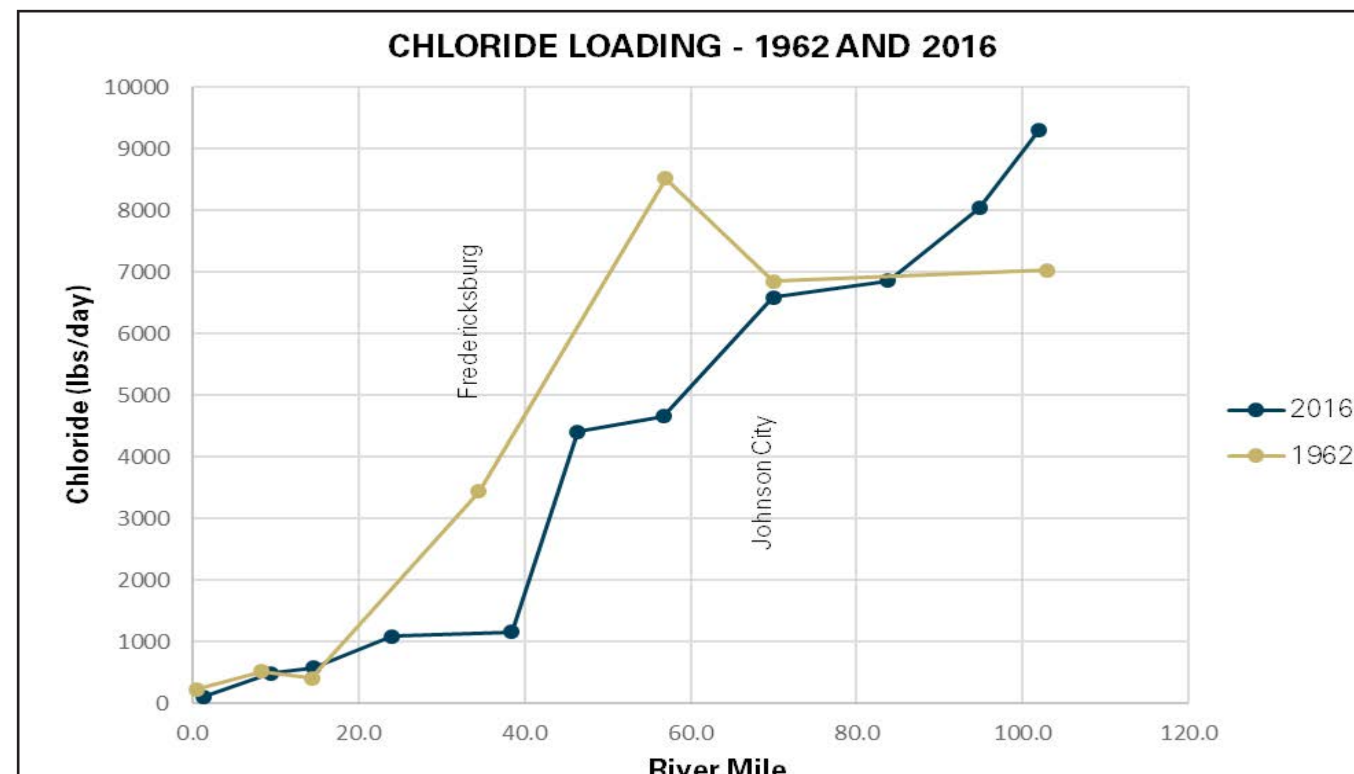


Figure 44. Chloride Loading – 1962 and 2016

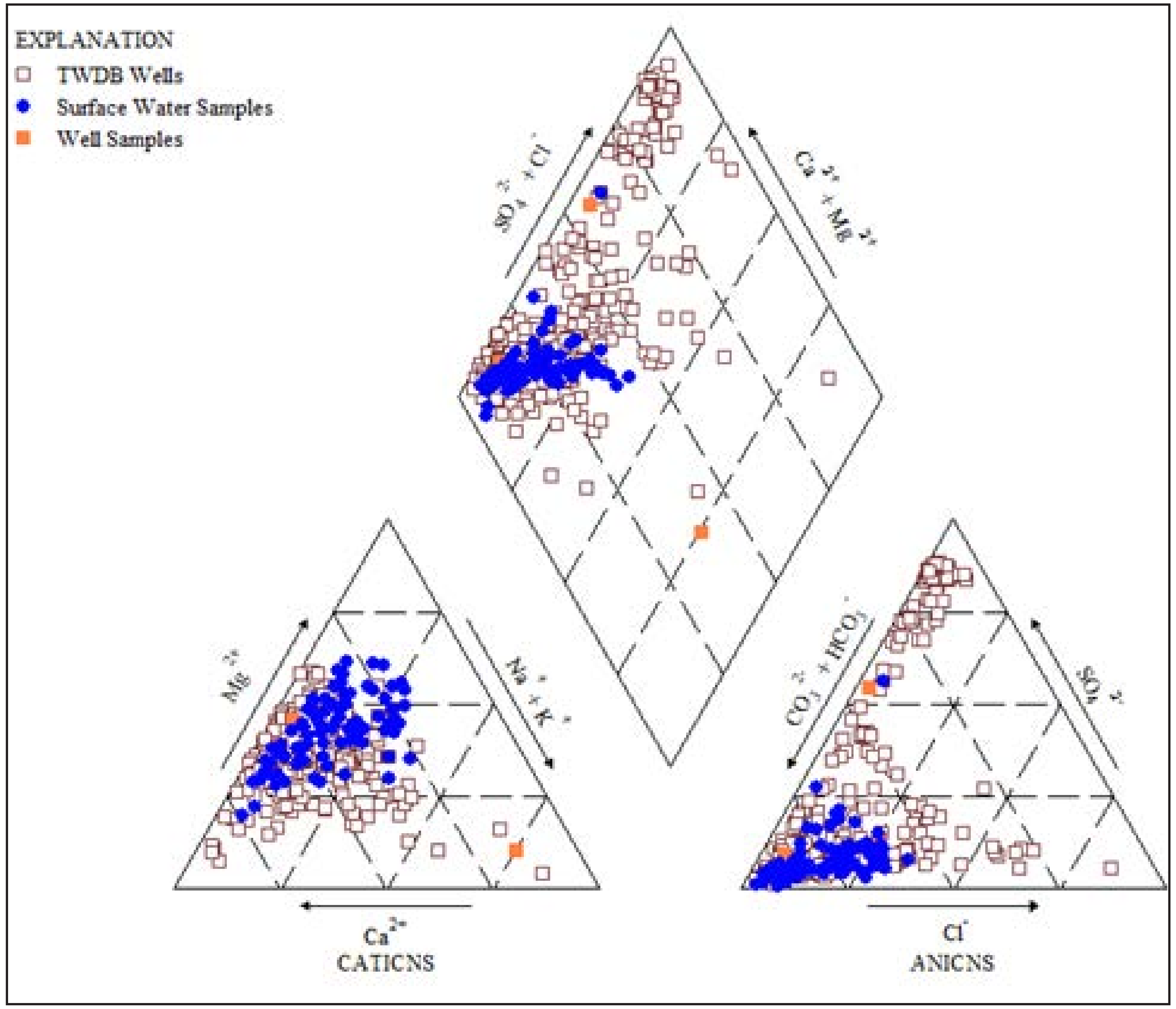


Figure 45. Piper Diagram of Synoptic Water Sample Chemistry from 2015 with TWDB Well Chemistry (Zappetello 2016)

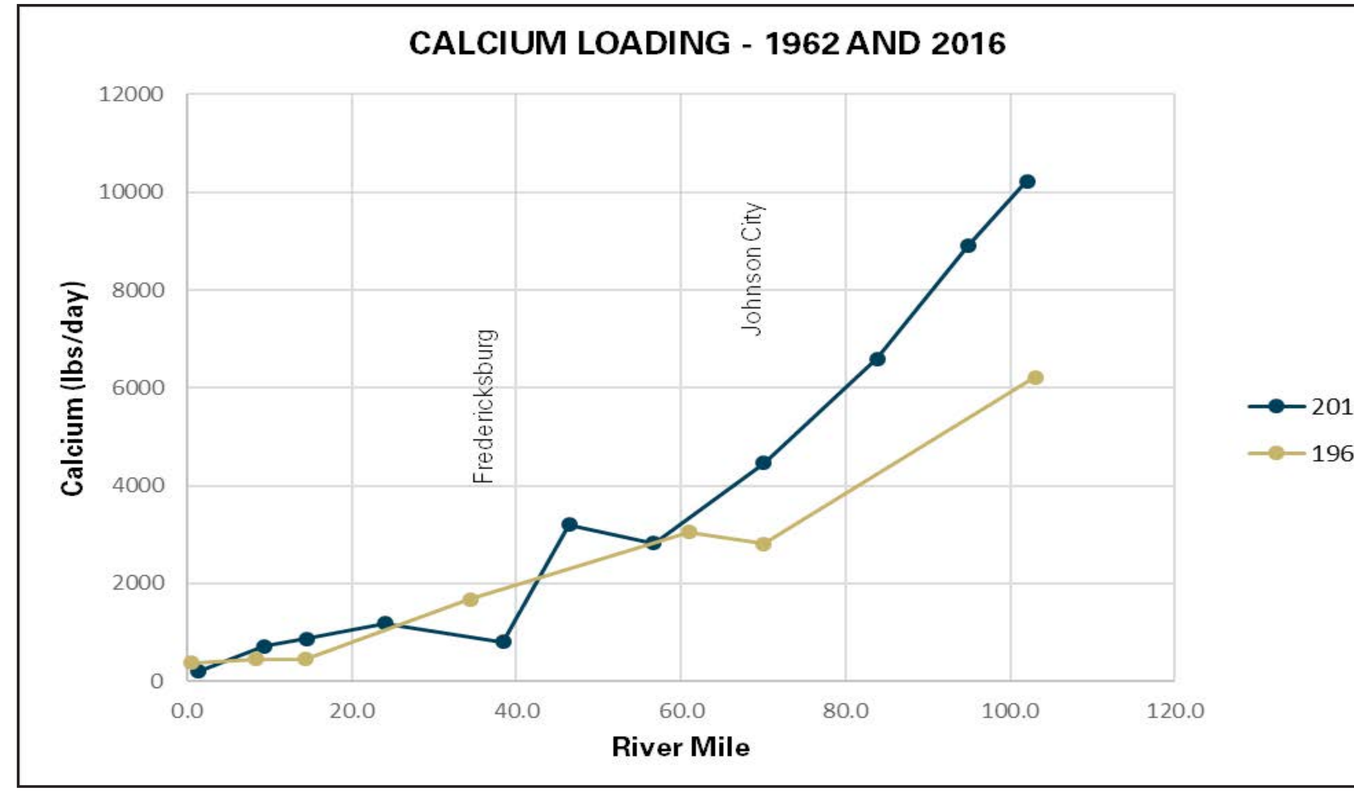


Figure 46. Calcium Loading – 1962 and 2016

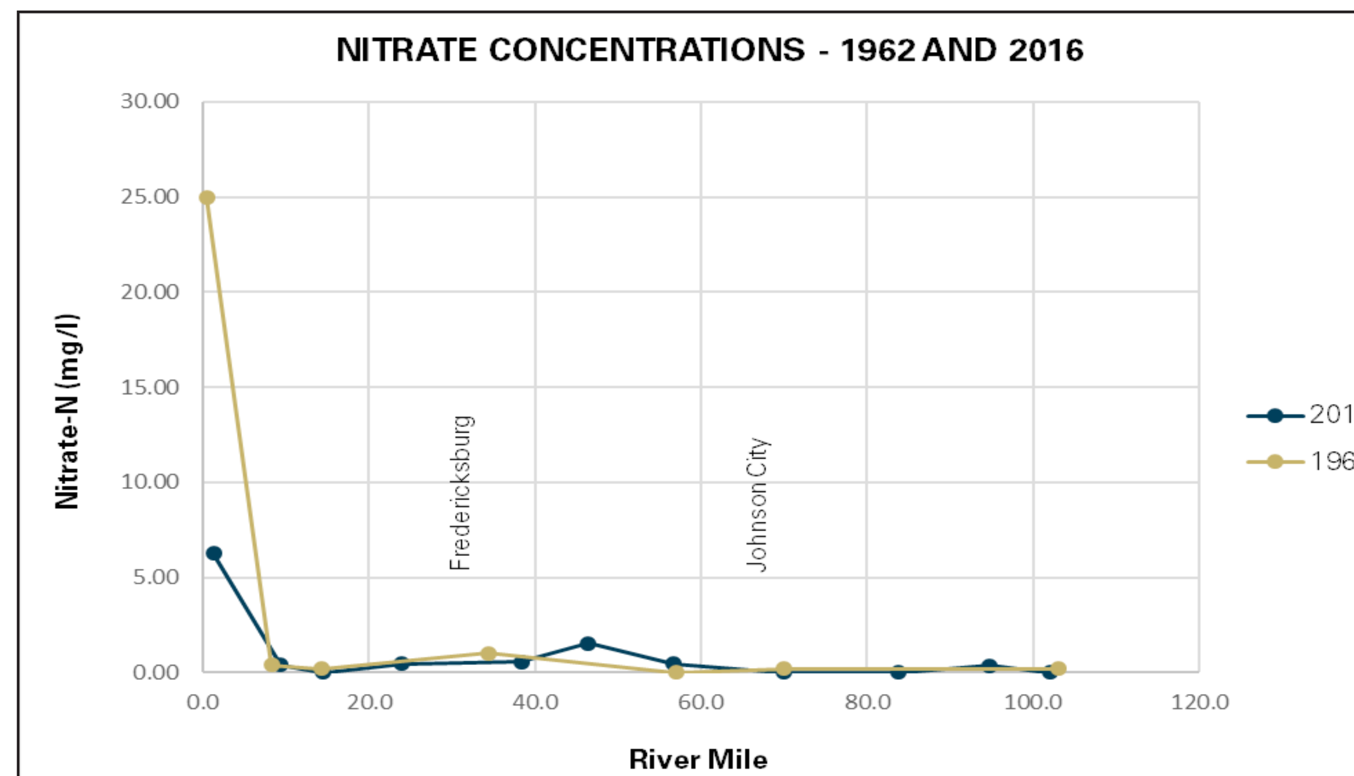


Figure 47. Nitrate Concentrations – 1962 and 2016

SUMMARY OF RESULTS

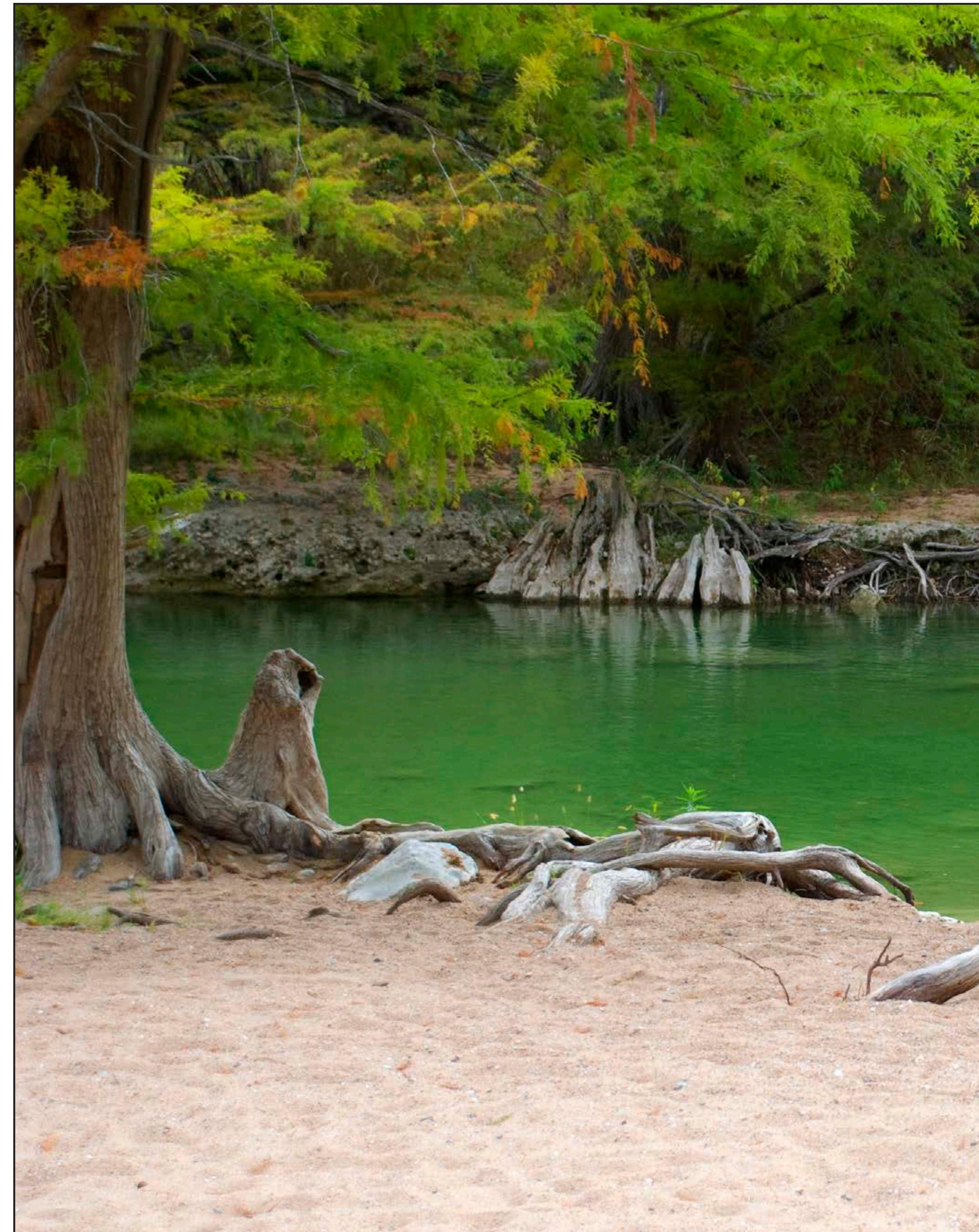
Based on the observations during the flowing water inventory, water quality analyses and GIS analysis of the occurrence of surficial geologic units, multiple aquifers contribute to base flow in the Pedernales River. Springs and streams originating in the Edwards and Glen Rose Formations appear to provide the majority of the main channel base flow in the western part of the Pedernales Basin. The Paleozoic and Trinity Aquifers contribute to base flow in the eastern basin area. The central basin area is directly underlain by the Hensel Formation. Due to the sandy nature of the Hensel versus the carbonate characteristics of the majority of the other geologic unit in the basin, areas underlain by Hensel are more buildable and amenable to agricultural and urban development.

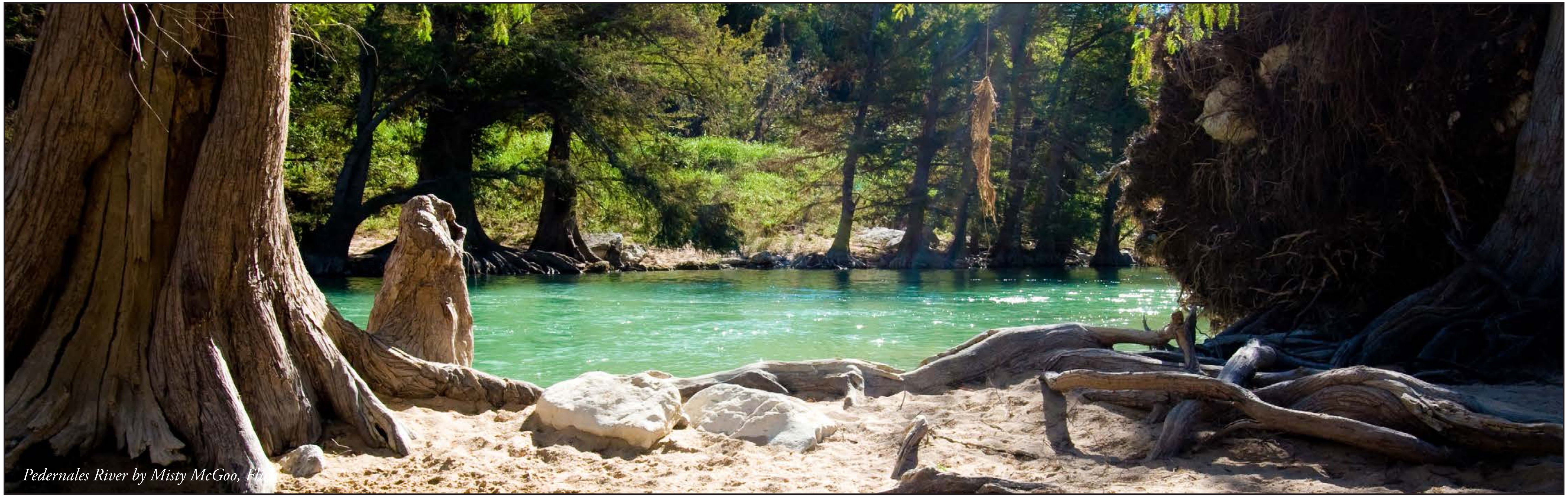
GIS analysis of changes in land cover from 2001 to 2011 indicate land cover did not significantly change over the ten-year period, and the basin is generally scrubland and forest. However, the amount of developed land increased in the Fredericksburg and Johnson City areas. Increasing impervious cover in developed areas may have implications for storm water quality, which was not measured in this study.

Overall, the Pedernales River is a gaining river, meaning flow generally increases moving downstream, though there are losing reaches where surface water recharges the underlying aquifers. Common gaining and losing reaches were observed in the 1962 and 2016 gain/loss studies. Gaining and losing reaches are attributable to the underlying geology. Losing reaches were observed in areas underlain by folded and faulted Paleozoic strata. A major losing reach upstream of Pedernales Falls State Park was not noted in the 1962 study, due to the locations of measuring points available in 1962. This losing reach is believed to be the source area for the major spring located in the park near Pedernales Falls which flows directly back into the river. Gains were typically noted in areas of flat lying carbonate aquifers, such as the Edwards and Glen Rose formations. One losing area observed in 2016 that was not observed in 1962 is the reach south of the City of Fredericksburg. Losses in this area have been increasing over the last two decades and may be attributable to groundwater withdrawal from the City of Fredericksburg well field. Additional study is needed in this area.

Analysis of surface water flow discharge indicates the period 2010-2015 closely resembled flow conditions during the drought of the 1950s. While it is clear the lower flows are the result of recent droughts experienced in Central Texas, it is not clear if these droughts are the results of short term or long term climate change.

In general, water quality in the river under base flow conditions is good. While there have been changes in water quality, at least partly due to human impact, there have not been significant changes since the original 1962 study was performed. Analysis of several water chemistry parameters indicate water chemistry is influenced by geology and land cover. Concentrations of inorganic cations and anions increase from the headwaters area of the Edwards Formation to the central plain area, the latter underlain by Hensel Sand, the most developed area of the basin. Groundwater in the aquifer and the resultant headwater springs/tributaries emanating from the Edwards are relatively low in dissolved constituents. The increase in constituent concentrations in the area of the Hensel is likely attributable, in part, to human development and in part to naturally-occurring water chemistry in the underlying aquifers. These conditions may be different during storm flows.





Pedernales River by Misty McGoo, Fl

NEXT STEPS

A solid understanding of natural systems and the interconnectedness between surface and groundwater will become increasingly important for water planning, wise water policy and the health of Hill Country rivers, streams and springs in the future. This will require further scientific research, along with strengthened partnerships and increased engagement between water resource managers, landowners and policy makers. Below are recommended next steps:

1. The river gains substantial amounts of water from tributaries and the main channel near Johnson City to the confluence with Lake Travis. To understand which geologic unit/aquifers are contributing to this gain, a synoptic groundwater level measurement event is planned for 2017. As part of this study, detailed water level monitoring of wells along the river via pressure transducers may be included in the study. Understanding which areas have greatest influence on groundwater recharge and discharge could allow targeted efforts for land management activities, land conservation and education.
2. Discharge data collected by the HCUWCD along a reach of the Pedernales River near the City of Fredericksburg municipal well field indicates increasing river losses over time. It is unclear if the losses are the result of groundwater pumpage or other factors. A detailed analysis of available surface and groundwater data should be performed.
3. Groundwater users can fall into two broad categories: well-owners and non-well-owners. The long-term abundance and quality of groundwater largely depends on the perceptions and knowledge of, and actions taken by, these groundwater users. A study to assess groundwater users and general public's understanding and perception of the value of groundwater, and of local management of groundwater, in the Pedernales Watershed is planned for late 2016. Ultimately, the results of the survey will complement the scientific analysis of groundwater hydrogeology. Together, this information will allow the project partners to better target education and outreach activities in the watershed, as well as to determine which educational and landowner management strategies will be most effective.
4. The influence of the Pedernales River, particularly the large area of the river basin underlain by the Hensel Sand, on regional groundwater flow in the Middle Trinity Aquifer has not been adequately studied. This area is likely the regional recharge zone for the Middle Trinity Aquifer in southern Blanco and Hays Counties, including major springs such as Jacob's Well and Pleasant Valley Springs. Understanding regional flow and the potential groundwater/surface water interactions across river basins will facilitate input into ongoing regional modeling efforts relating to groundwater management.
5. Storm water quality can differ greatly from baseflow water quality. A synoptic storm water sampling event should be performed during a basin wide percipitation event. Understanding storm water quality will provide insights into the need for active storm water management in the basin.

REFERENCES

Ashworth, J.B., (1983), Report 273 Groundwater Availability of the Lower Cretaceous Formations in the Hill Country of South-Central Texas, Texas Water Development Board

Barnes, V.E. Project Director (1981 version), Geologic Atlas of Texas (GAT)-Llano Sheet, Bureau of Economic Geology at the University of Texas-Austin

Bluntzer, R.L., (1992), Report 339 evaluation of the Groundwater Resources of the Paleozoic and Cretaceous Aquifers in the Hill Country of Central Texas, Texas Water Development Board

Brune, G., (1981), Springs of Texas – Volume 1. Texas A7M University Press, 566p.

Dunne, T. and Leopold, L.B. (1978). Water in Environmental Planning. W.H. Freeman and Company. San Fancisco, USA.

Heitmuller, F.T. and Reece, B.D. (2003) Database of Historically Documented Springs and Spring Flow Measurements in Texas, USGS Open File Report 03-315.

Hill Country Underground Water Conservation District, unpublished data, (2015)

Holland, P.H. and Hughes, L.S.,(1964) Bulletin 6407 Base-Flow Studies Pedernales River, Texas, Texas Water Commission

Hunt, B. B., B. A. Smith, R. Slade, Jr., R. H. Gary, and W. F. K. Holland, (2012), Temporal trends in precipitation and hydrologic responses affecting the Barton Springs segment of the Edwards Aquifer, Central Texas: Gulf Coast Association of Geological Societies Transactions, v. 62, p. 205–226.

Lower Colorado River Authority, unpublished data, (2016)

Lower Colorado River Authority, (2000), Pedernales River Watershed Brush Control Assessment and Feasibility Study. Accessed from http://www.tsswcb.texas.gov/files/docs/brush/feasibilitystudies/FS_LCRA_2000.pdf

Lower Colorado River Authority. (2012), Pedernales River Watershed poster. Accessed from http://maps.lcra.org/default.aspx?MapType=Watershedpercent20Posters

Meadows Center for Water and the Environment (2014), How Much Water is in the Hill Country?

Meadows Center for Water and the Environment (2015), How Much Water is in the Hill Country? Conservation Strategies, Management Approached and Action Plan

Multi-Resolution Land Characteristics Consortium (2011), National Land Cover Database.

Regional Water Quality Protection Plan for the Barton Springs Segment of the Edwards Aquifer and Its Contributing Zone (2005), Naismith Engineering, Inc.

Romans, K., (2014) The Pedernales River: A Literature Review and Characterization, Hill Country Alliance

Rose, P., 1972, Edwards Group, Surface and Subsurface, Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 74, 198 p. 35 figs, 19 plates.

Scott, R. W. (ed.), 2007, Cretaceous Rudistids and Carbonate Platforms: Environmental Feedback, SEPM Special Publication No. 87. Tulsa, Oklahoma

Scott, R.W., A.M. Molineux, H. Loser, and E.A. Mancini, 2007, Lower Albian Sequence Stratigrphy and Coral Buildups: Glen Rose Formation, Texas, USA. In R.W. Scott (ed.), Cretaceous Rudists and Carbonate Platforms: Environmental Feedback, SEPM Pub no. 87, Tulsa, Oklahoma, p.181-191

Standard Methods for the Examination of Water & Wastewater 21st Edition, (2005), American Public Health Association, American Water Works Association, Water Environment Federation, Baltimore, Maryland, USA.

Standen, A. and Ruggiero, (2007), Llano Uplift Aquifers: Structure and Stratigraphy. Prepared for the Texas Water Development Board.

Stricklin, F. L., Jr., C. I. Smith, and F. E. Lozo, 1971, Stratigraphy of Lower Cretaceous Trinity deposits of Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 71, 63 p.

Texas Association of Counties, http://www.county.org

The Nature Conservancy, (2007), Conservation Plan for the Pedernales River Watershed.

Turnipseed, D.P., and Sauer, V.B., (2010), Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods book 3, chap. A8, 87 p.)

Wierman, D. A., Broun, A. S., Hunt, B. B., (2010), Hydrogeologic Atlas of the Hill Country Trinity Aquifer, Blanco, Hays, and Travis Counties, Central Texas. Hays-Trinity Groundwater Conservation District, United States.

US Census Bureau, www.census.gov

F.T. Heitmuller, F.T. and Reece, B.D.,2003, USGS Open-File Report 03-315: Database of historically documented springs and spring flow measurements in Texas.

Zappetello, S. J., (2016), Geochemical Clues to Groundwater Sources of the Pedernales River, Texas. Master's thesis, Texas State University Department of Biology, San Marcos, Texas.

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Hays Trinity Groundwater Conservation District

Hill Country Alliance

Hill Country Underground Water Conservation District

Texas Parks & Wildlife Department

Texas State University Biology Department

Texas State University students

Travis County

West Cave Preserve

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Pedernales Sunset by Christopher V. Sherman