A Tale of Two Rivers

The Llano River of Central Texas

Llano River Watershed Alliance - 2022

Llano River Watershed in Kimble County and in Mason County

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Introduction

The Llano River is one of the iconic rivers of the Hill Country of Texas. Similar to its neighboring rivers - the Nueces, Sabinal, Frio, Medina, Guadalupe, Pedernales, and San Saba - the Llano River originates from springs emanating from the Early or Lower Cretaceous (about 100 million years) sedimentary limestones and dolomites of the Edwards Plateau geologic region. Unlike its neighbors, the Llano River also flows across Precambrian (over 1 billion years) igneous and metamorphic rocks (granite, schist, gneiss) of the Llano Uplift geologic region, resulting in two river segments with distinctly different characteristics and management requirements.

Due to the pristine nature and constant flow of springs, the Llano River, along with the other Hill Country rivers, is a valuable resource to the Hill Country and much of the rest of Texas. It provides habitat for unique plant and animal communities, recreational opportunities for a growing state population, and critical water supplies to local and downstream communities and ecosystems, especially during drought. Subtle changes in spring flow due to shifts in climate and increased aquifer pumping, along with changes due to land fragmentation, loss of riparian habitat, and encroachment of woody species on upland habitats, have the potential to decrease the water quality and quantity of the river. More immediate changes such as increased urban stormwater runoff, wildfire, and sand and gravel mining also affect water supply.

The proactive protection and preservation of the Llano River is an environmental, economic, and cultural concern. Effective methods for protecting the quantity and quality of the river need to result from coordinated actions between informed local, state and federal natural resource agencies, the scientific community, funding partners, and non-governmental organizations such as the Llano River Watershed Alliance (LRWA). To facilitate these efforts, the LRWA (formerly the South Llano Watershed Alliance) has prepared this report to characterize the Llano River from its upper elevations on the Edwards Plateau to its confluence with the Colorado River over the Llano Uplift in the community of Kingsland. The report complies new information for the Llano River and incorporates and updates information presented in previous reports prepared by or for the Alliance: *"Land of the Living Waters"*[1]*; "The Unknown River of Central Texas"*[2]*; "Headwaters of the Llano River"*[3]*;* and *Floods on the Llano River, Texas - Fall 2018* [4]. The report also incorporates, in noted places, anecdotal

[1] Environmental Defense Fund. "Land of the living waters: a characterization of the South Llano River, its springs, and its watershed", 2008.

[2] Environmental Defense Fund. "The unknown river of Central Texas: a characterization of the James River, its springs and its watershed", 2010.

[3] South Llano Watershed Alliance. "Headwaters of the Llano River : a characterization and comparison of the rivers, springs and watersheds of the North Llano and South Llano rivers", 2012.

[4] Llano River Watershed Alliance. "Floods on the Llano River, Texas - Fall 2018", 2019

information that while not in the published literature, may be helpful in understanding the characteristics of the watershed. All reports are available on the LRWA website, www.llanoriver.org.

General Description

Owing to its geographic setting, the Llano River is one of the most unique rivers in Texas, if not the nation. Situated at the convergence of the Chihuahuan Desert to the west and south, Great Plains to the north, and humid Gulf Coast plains to the east, the Llano can transform from a mere trickle to a raging torrent in only a matter of hours. Combine to this climatic mix with distinct geologies and a rapidly changing demographic and the results are a diverse array of challenges unique only to the Llano. Understanding these challenges is key to understanding the river.

Figure 1 - Location of Llano River Watershed.

The Llano River, including its main tributaries the North and South Llano, is 163 or 160 miles in total length, depending on which main tributary is followed (Figure 1). The Llano watershed [5] drains an area of 4,466 square miles, approximately the size of Jamaica. There is over 1,600 feet elevation difference in the watershed. The highest point in the watershed, at 2,487 feet above mean sea level, is above the North Llano River in eastern Sutton County. The lowest point is 825 feet above sea level at the confluence of the Llano River with the Colorado River at Lyndon B. Johnson (LBJ) Reservoir near the community of Kingsland.

The Llano River originates on the Edwards Plateau, a 30,000 square-mile upland ecoregion roughly extending from the Pecos River on the west to the Balcones Escarpment (stretching from Austin to San Antonio to Del Rio) on the east and south. Capping the Edwards Plateau is thick limestone rock that dissolved over time to form what is considered the largest continuous karst [6] area in the United States. [7] On average, approximately 22 to 29 inches of precipitation falls on the eastern portion of the Edwards Plateau where the Llano watershed is located. As most of the Plateau consists of thin soil atop limestone bedrock, the majority of this precipitation runs off quickly. However, some of the precipitation finds its way through the sinkholes, conduits, caves, rock fractures, and root zones to recharge the vast, underlying aquifer.

The majority of the flows of the Llano River are derived from springflow. The US Geological Survey (USGS) estimates that 81% of the flow past the river gage below the city of Junction is from base flow (that part of streamflow that is not direct surface runoff), or spring flow. [8] Downstream of Junction, where fewer springs exist and more tributaries enter the river, the percentage of base flow decreases to 72% near the city of Mason and 62% at the city of Llano.

The North Llano River and South Llano River are the headwaters of the Llano. These headwaters lie just to the west of the 100th meridian, where explorer and geologist John Wesley Powell noted that the arid west begins [9]. From its headwaters, the North Llano River flows intermittently across the Edwards Plateau for its first 31 miles - and the South Llano River 35 miles - slowly notching canyons into the underlying 100-million-year-old rock.

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[5] John Wesley Powell, defined a watershed as “that area of land, a bounded hydrologic system, within which all living things are inextricably linked by their common water course and where, as humans settled, simple logic demanded that they become part of the community.”

[6] Karst areas include features such as caves, sinkholes, and subsurface drainage networks, or conduits.

[7] Roberto Anaya, “Conceptual model for the Edwards-Trinity (Plateau) Aquifer System, Texas”. In: *Aquifers of the Edwards Plateau* (eds. Robert E. Mace, Edward S. Angle, and William F. Mullican, III). Texas Water Development Board Report 360, February 2004.

[8] E.L. Kuniansky, “Precipitation, streamflow, and base flow, in West-Central Texas, December 1974 through March 1977”. U.S. Geological Survey Water-Resources Investigations Report 89-4208, 1989.

[9] Wallace Stegner, *Beyond the Hundredth Meridian: John Wesley Powell and the Second Opening of the West.* New York: Penguin Press, 1954.

Where the canyons erode deeply enough to expose the water stored in the underlying karst aquifer, springs emerge along the canyon walls and in the river beds. These springs, located at an approximate elevation of 1,900 feet on the South Llano and 2,000 feet on the North Llano, have historically supplied constant flow for the South Llano River's final 20 miles to Junction and relatively constant flow for the North Llano River's final 27 miles. At Junction, appropriately known as the "Land of Living Waters", the South Llano joins the North Llano, becoming the Llano River for the final 105-mile journey to Lake LBJ in the chain of water-supply reservoirs known as the Highland Lakes.

Downstream from Junction, the Llano River leaves the confining canyons of the Edwards Plateau but continues to flow over Cretaceous limestones. The Llano River from Junction to the Kimble and Mason county line maintains the general character of the North and South Llano rivers, but becomes wider, with more meanders.

Near the Kimble and Mason county line, the character of the Llano River changes significantly. The Llano leaves the more easily eroded sedimentary limestone rocks of its Edwards Plateau origin and begins to cross older, more resistant Paleozoic (about 500 million years) sedimentary rocks forming the upper layers of the Llano Uplift. The Llano Uplift is the remnant of an ancient mountain range uplifted over one billion years ago but eroded over time and later covered and then uncovered by the Edwards Plateau. As the river crosses onto the uplift, the predominantly bedrock river channel becomes more resistant to erosion and straightens, except where bedrock joints or fractures cause bends in the channel.[10] The riparian zone becomes narrower and steeper and mid-channel bedrock islands become more common.

Just above the US Highway 87 bridge in southern Mason County, the Llano River begins to cross even more resistant Precambrian igneous and metamorphic rock, over one billion years old. Very few springs exist here and the river channel is confined and relatively straight. The composition of the river sediment contains considerably more sand and fewer gravels than the limestone segments of river. This is the result of in-situ (in place) weathering of the granites and metamorphic rocks. [11] The Llano continues across the Precambrian rocks of the Llano Uplift to its mouth in Kingsland at the confluence with the Colorado River.

The Llano watershed is located in what is considered "Flash Flood Alley", an area with the highest flood runoff per unit of area in the country. Here, warm, moist air from the Gulf of Mexico colliding with cool air masses from the Great Plains to the north are forced to rise up the Balcones Escarpment (the eastern and southern edge of the Edwards Plateau) and can

[10] Franklin Thomas Heitmuller, "Downstream trends of alluvial sediment composition and channel adjustment in the Llano River watershed, Central Texas, USA : The roles of a highly variable flow regime and complex lithology", PhD diss., University of Texas, Austin, 2009.

[11] Heitmuller, 2009

produce intense rainfall events. In 1935, for example 22 inches of rain fell in Uvalde (south of Junction) in less than 3 hours.[12]

Conversely, the Llano watershed is also subject to extreme drought. Globally, the 30th parallel, which transects the basin, lies along a climatic transition zone where rising air heated at the surface along the Equator begin to descend back to earth, in a phenomenon referred to as Hadley Cells. As the air descends, it warms and expands, making condensation and precipitation more difficult. The majority of deserts of the world, including the nearby Chihuahuan Desert, are found along 30 degrees north or south latitude. During the Drought of the Fifties (1950-1957) below average precipitation occurred in all years, and for three years, annual rainfall was 10 inches or more below normal.[13]

In addition to the geological and climatic influences on the river, anthropogenic activities also impact hydrologic responses in the watershed. Pioneers coming to the area in the mid-1800s found a woodland and grassland savanna mosaic maintained by migrating bison herds and wildfires. Increased settlements brought livestock and fences and a reduction in wildfire, resulting in overgrazing and an increase in woody plant species. Significant loss of soil (anecdotally estimated to be 6-10 inches) and the increase in woody plant species brought changes to recharge and runoff rates across the watershed, especially on the Edwards Plateau.

The population of the watershed is estimated to be about 20,000 (Appendix A), with the majority of population located in the lower portion of the basin around the Highland Lakes. Llano and Mason counties, in the lower portion of the watershed have seen a population increase (17 and 11 percent respectively) over the last ten years, while population in the upper portions of the watershed have actually decreased (Kimble County decreased 7%; Edwards County decreased 5%.) The statewide population growth since 2010 is about 15%.

Population figures alone, however, do not provide a clear picture of the demographics in these counties. For example, of the 9,000 parcels in Kimble County, non-Kimble county residents own 55 percent, and non-Texas residents own an additional 5 percent.[14] As populations along the I-35 corridor continue to grow at some of the fastest rates in the country (Austin grew 30% in the last decade and San Antonio grew 20%), residents from these and other urban areas seek to purchase parcels in the Hill Country as places to recreate.

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[12] Leslie Lee, “Do you live in Flash Flood Alley : Experts explain the Central Texas phenomenon and what residents should know”, Texas Water Resources Institute, txH20, Fall 2016.

[13] “Drought History for Texas’ 10 Regions”, prepared by South Central Climate Science Center, Norman, Oklahoma, May 28. 2013, updated January 12, 2018.

[14] Verbal communication, Judge Delbert Roberts, Kimble County, 2008

Such demand results in once large family ranches being divided into smaller tracts in a process called fragmentation.

Fragmentation across the Llano and other Hill Country watersheds results in: increases in the number of water wells and septic systems; increases in the construction of stream crossings and small dams; increases in impermeable cover; and the introduction of exotic plant and animal species, resulting in degraded riparian habitats, increased streambank erosion and decreases in water quality and streamflows.

Fortunately, the Llano watershed still remains a healthy watershed with no major impairments.[15] Yet, with future changes likely resulting from increased fragmentation and a changing climate, it will be necessary for landowners and stakeholders alike to offset the impacts of these threats through proper land and water stewardship via education, outreach, and community participation. This report identifies the threats and offers solutions for the community to preserve and protect the Llano River watershed now and into the future.

Geologic Influences

The geologic setting of the Llano River results in the river having two very distinctive characters. The upper portion of the river, referenced in this report as the Edwards Plateau or Plateau portion of the river, is influenced by spring flow, gravel sediments, stream meanders, and wide, gently sloping riparian zones, often dominated by native pecan trees. The lower portion of the river, referenced here as the Llano Uplift or Uplift portion of the river, is dominated by fractured bedrock channels (which may result is stream loss), sandy sediments, straight stream channels, and narrow and steep riparian zones (Figure 2).

Edwards Plateau

The limestones of the Edwards Plateau began to be formed over 100 million years ago when a vast inland sea, the Western Interior Seaway, extended from present-day Guatemala to the north slope of Alaska, covering all of Texas. Deposition and compaction of shells from marine organisms formed the limestone, burying rocks from previous geologic periods, including the Llano Uplift (see below). Ancient meanders in the landscape today suggest that by about 70 million years before the present day, streams that would later become the Llano and other Hill Country streams were already in place.[16]

[15] A waterbody is considered impaired if it fails to meet one or more water quality standards for its designated use.

[16] Peter R. Rose, “Late Cretaceous and Tertiary burial history, Central Texas”, Gulf Coast Association of Geological Societies Journal, v. 5 (2016), p. 141-179.

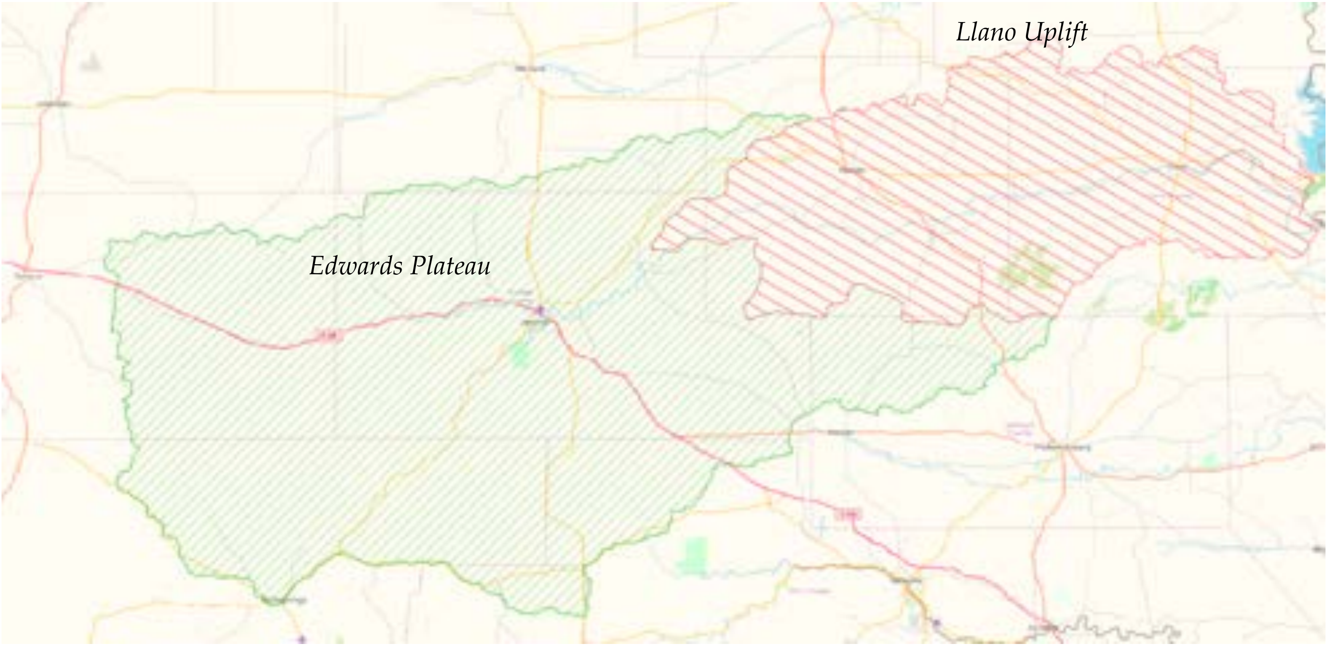

Figure 2 - Geologic Regions of Llano Watershed.

About 23 million years ago, during the Miocene, tectonic stress due to the downwarping of the present-day Gulf of Mexico thrust the Edwards limestone upward as much as 1,600 feet along the Balcones Fault Zone, which roughly follows the present day I-35 corridor, turning west at San Antonio towards Del Rio. The Balcones Fault Zone is an ancient zone of instability in the Earth's crust and is an extension of the Appalachian Mountains.

Following this upthrust event, the ancient streams that flowed across the Edwards limestone began eroding and weathering into the margins of the newly formed Edwards Plateau. Geologist Pete Rose estimates that following the creation of the Edwards Plateau, over 8,000 cubic miles of material were eroded or weathered from the Plateau, exposing the underlying basement of Precambrian rocks of the Llano Uplift.

Llano Uplift

The Llano Uplift is the result of two continental shelfs colliding over 1 billion years ago. When the two shelves collided, one of the shelfs was forced under the other in a process known as subduction. A similar process occurs today off the coast of the Pacific Northwest. As the subducted plate is forced beneath the overlying plate, the material is melted, forming magma.[17] In the Pacific Northwest, this magma moves to the surface as a volcano (Mount St.

[17] Mosher, S. Levine, J.S.F. and Carlson, W.D., "Mesoproterozoic plate tectonics: A collisional model for the Grenville-aged orogenic belt in the Llano uplift, central Texas." The Geological Society of America v 36 #1:55-58, 2008.

Helens, for example). Other times, as in the case of the Llano Uplift, the magma cools slowly beneath the surface, forming a dense granitic dome and other metamorphosed rocks. Tectonic activity, again likely along the Balcones Fault Zone, pushed this granitic dome upwards where it was exposed and then eroded over a billion years to nearly level ground, then buried by Edwards Limestone before again being exposed in the Llano watershed when the overlying limestone was removed.

Climatic Influences

Epochal climatic variations in the Llano watershed have resulted primarily from advances and retreats of continental glaciers. Although debate surrounds what vegetative communities existed during various glacial periods, pollen analysis from caves on the Edwards Plateau suggest that during maximum periods of glaciation (~12,000 - 22,000 years ago), cooler conditions resulted in an open savannah landscape with a mixed to tall grass (unlike grass species seen today) understory and trees confined to canyons and along riparian corridors.[18] Soils during this period were also three feet thicker than during post-glacial times. As the glaciers retreated, conditions warmed and more open woodlands resulted, including an increase in the abundance of juniper. The transformation of grasslands into woodland likely led to the disappearance of many grazers (early deer, antelope, camel) who maintained the grassland vegetation.[19]

Despite major continental glaciation ceasing, smaller-scale glaciation (Little Ice Ages) continued to affect the climate on the Edwards Plateau, with grasslands and woodlands exchanging predominance the Plateau's surface. Pollen data note a peak in woodlands around 1,800 years ago, followed by an advancement of grasslands with cooler and drier conditions beginning 1,000 years ago.[20]

Present day climatic conditions on the Edwards Plateau and in the Llano watershed are influenced by the El Niño/Southern Oscillation, driven by surface water temperatures in the eastern Pacific. When Pacific waters are warmer, an El Niño results, generally producing wetter than average conditions. Conversely, cooler surface-water conditions during a La Niña

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[18] Hall, S., & Valastro, S. "Grassland Vegetation in the Southern Great Plains during the Last Glacial Maximum." *Quaternary Research, 44* (2), 237-245. 1995. doi:10.1006/qres.1995.1068

[19] Seersholm FV, Werndly DJ, Grealy A, et al. "Rapid range shifts and megafaunal extinctions associated with late Pleistocene climate change". *Nat Commun.* 2020;11(1):2770. Published 2020 Jun 2. doi:10.1038/s41467-020-16502-3

[20] Carpenter, Stephen M.; Miller, Kevin A.; Frederick, Charles D.; Cecil, Leslie G.; Cody, Mercedes C.; and Peyton, Abby (2012) "The Little Paint Site: A Classic Toyah Camp on the South Llano River, Kimble County, Texas," Index of Texas Archaeology: Open Access Gray Literature from the Lone Star State: Vol. 2012, Article 3. https://doi.org/10.21112/ita.2012.1.3

generally bring dryer conditions to the watershed. The drought of the fifties and the recent severe drought in 2011 occurred during La Niña episodes.

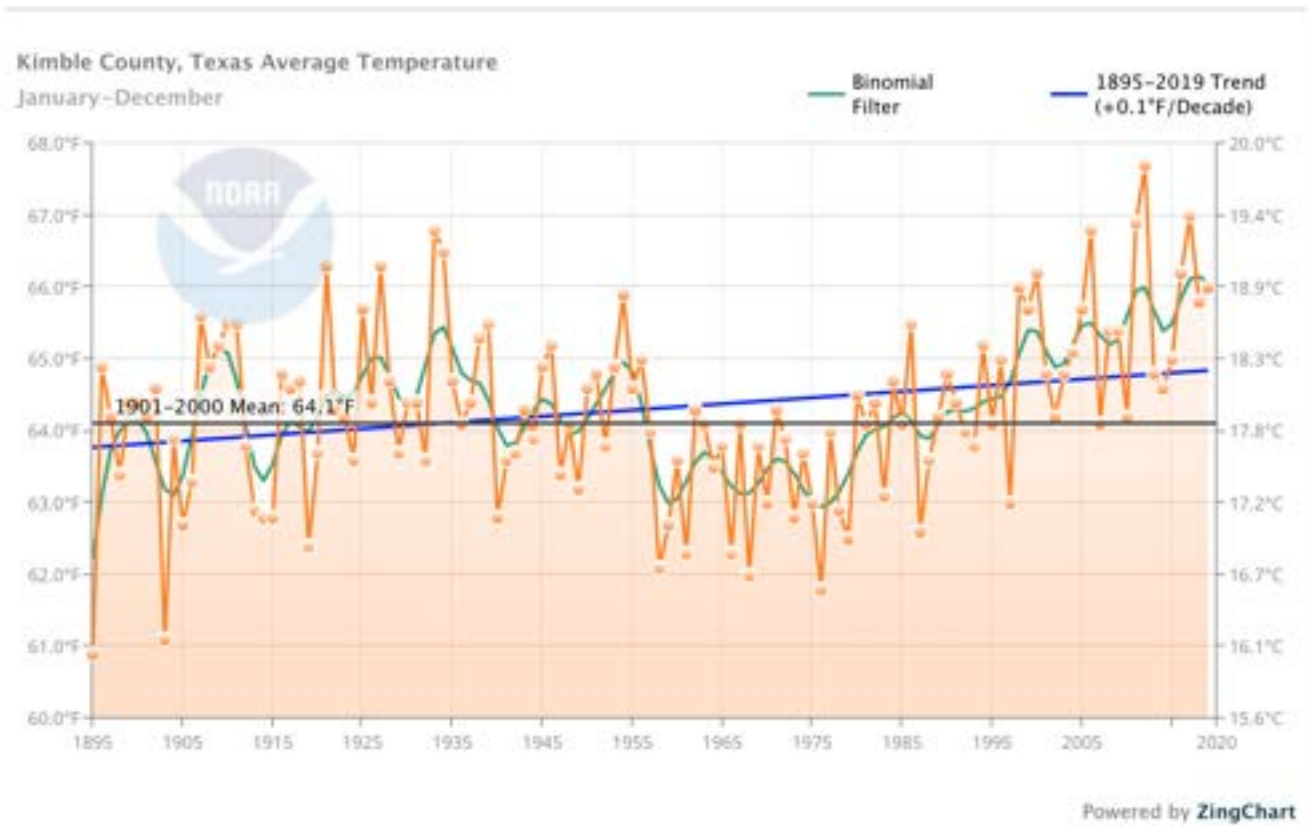

Figure 3 - Trends in Average Temperature for Kimble County 1895-2019.

Added to these climate variations is the steady increase in temperature since measurements began in the late 1800s (Figure 3), coupled with the projected increases in temperature over the next century due to increased levels of carbon dioxide in the atmosphere. The annual average temperature at Junction is 64.1°F and has increased 0.1° F every decade so that the average temperature is now 1.2 °F warmer since records began.[21] Climate models predict that temperatures for Central Texas will continue to increase during the next century with summer average high temperatures projected to increase 4 to 6 °F by the middle of the 21st century. [22]

[21] NOAA National Centers for Environmental information, “Climate at a Glance: County Time Series”, published September 2020, retrieved on September 18, 2020 from https://www.ncdc.noaa.gov/cag/

[22] Hayhoe, Katherine, “Climate Change Projections for the City of Austin”, ATMOS Research & Consulting, April 2014.

Conversely, the average annual precipitation for Junction is 25.7 inches, but this amount has been diminishing at a rate of 0.1 inches per decade so that the average is now 1.2 inches less than at the turn of the 20th century (Figure 4). Annual average precipitation for the rest of the 21st century is predicted to remain about the same, however, droughts as well as floods are

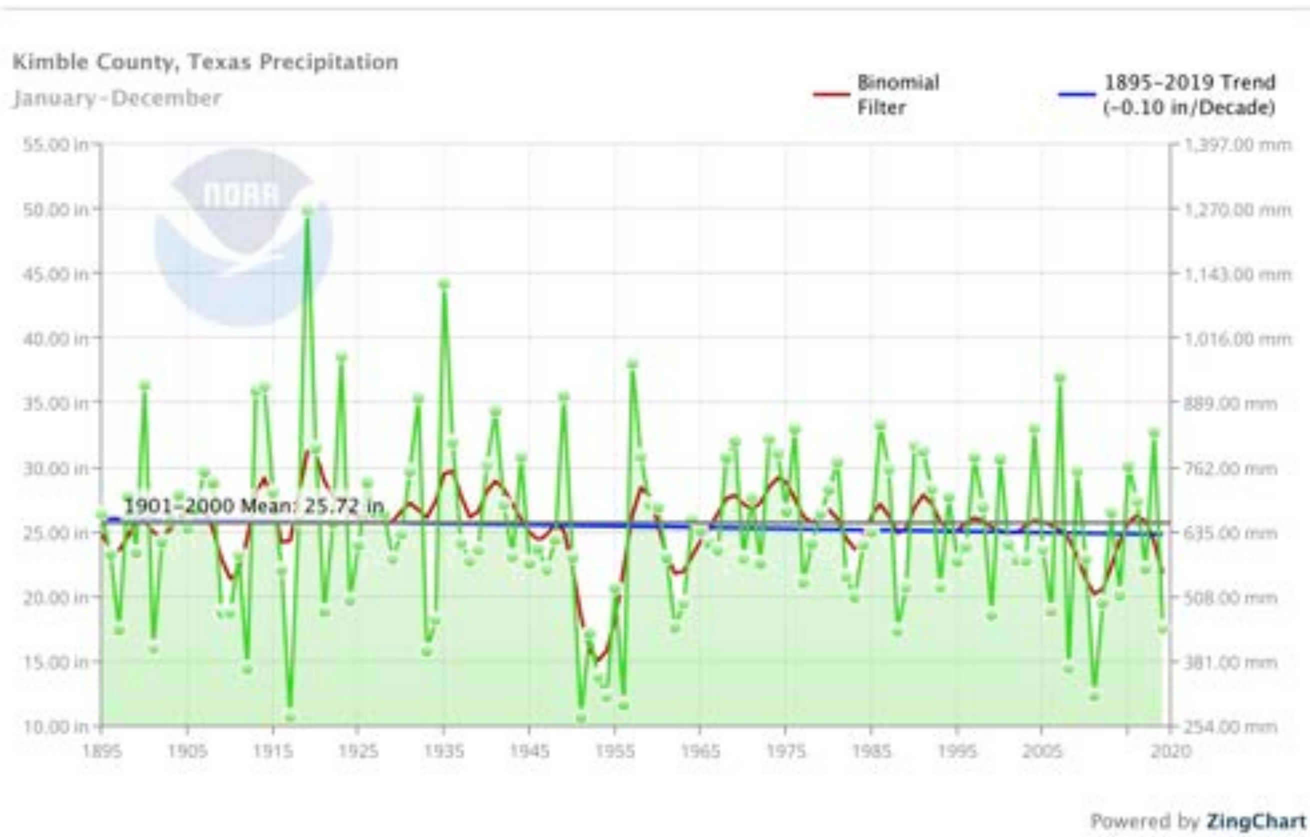

Figure 4 - Trends in Annual Average Precipitation for Kimble County, 1895-2019.

projected to be more severe. Increases in temperature will likely result in increases in evapotranspiration, the dominant hydrologic component for the Llano, resulting in less recharge to aquifers and more evaporation from surface waters. The increases in temperature will also avail more energy to storms, resulting in increased severity and intensity of storms. Understanding how these larger droughts and floods will impact the flows of the Llano watershed will be an important component of their preservation.

Flows of the Llano

The USGS maintains several stream gages on the Llano River and North and South Llano rivers. Long-term stream gages have been located on the North Llano River above Junction and the Llano River below Junction and the confluence with the South Llano since 1915 . USGS installed a gage on the Llano River at Llano in 1938, and on the Llano River near Mason in 1967. There is also a USGS gage on Beaver Creek in Mason County; it was installed in 1962. More recently, USGS installed a gage on the South Llano at Flatrock Lane in 2012 and a gage on the Llano River near CR 102 (Scott's Crossing) in 2018. In addition, the Lower Colorado River Authority (LCRA) maintain gages for its Hydromet System on Johnson Fork, James River, Comanche Creek, Beaver Creek, Willow Creek, Hickory Creek, San Fernando Creek, Little Llano River, and Honey Creek and flood forecast staff gages on the South Llano River near Telegraph and the North Llano River near Roosevelt.

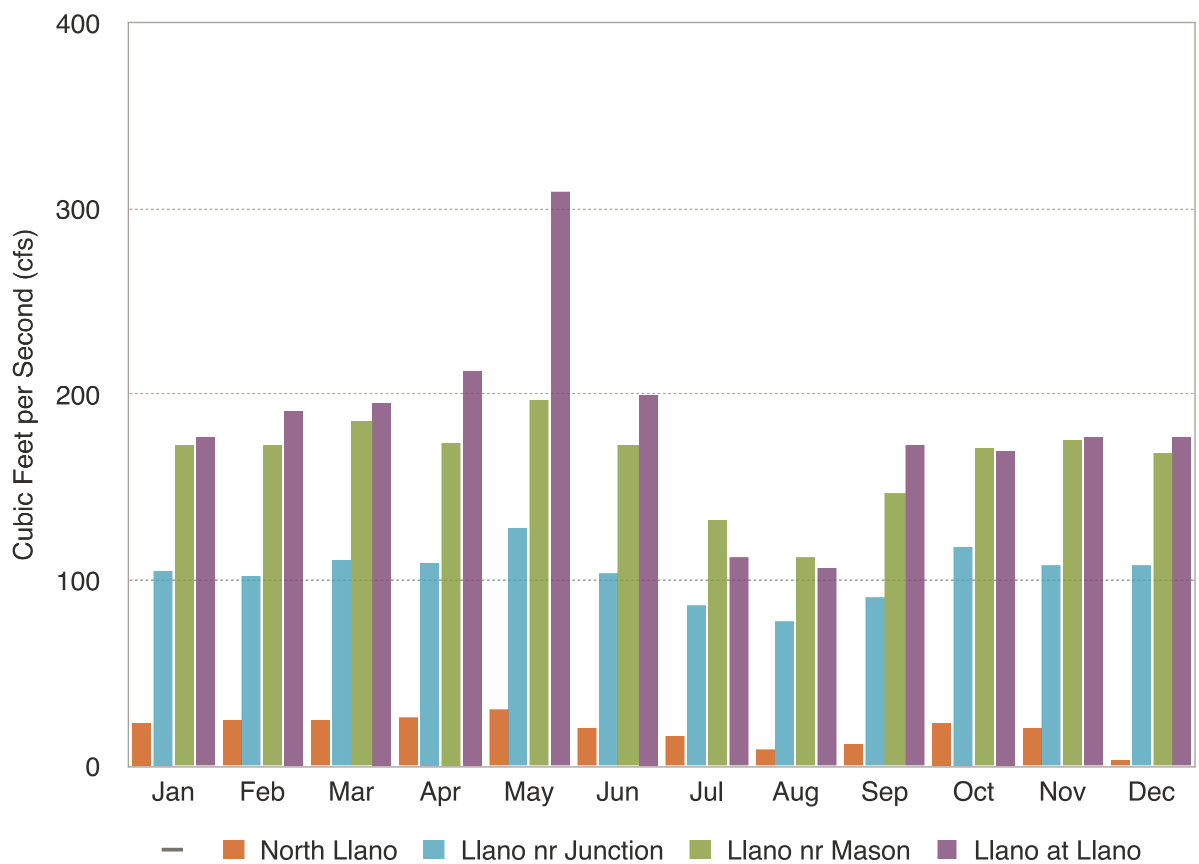

Figure 5 - Median Monthly Discharge Llano Watershed in cubic feet per second

Figure 5 shows the median monthly discharge, or flow, (in cfs or cubic feet per second) for the period of record for four of the USGS gages. The periods of record for the South Llano River gage near Junction and the Llano gage at Scott's Crossing lack sufficient period of length to provide a comparable relationship to the other four gages. The median monthly discharge reflects the area's normal rainfall distribution with the majority of precipitation occurring during late spring and early fall, with the greatest flow during May.[23] Flows increase from upstream to downstream with the exception of July and August where flows near Mason are greater than flows at Llano (especially during periods of low flow) due likely to evaporation and channel losses. Flow variability between months is smallest amongst the upstream gages, where the proximity to headwater springs provides for more constant flows.

Flow Extremes

The Llano River can be an example of extremes. In 2018, the Llano River at Llano had nearly ceased flowing, dropping to 0.03 cfs (13 gallons per minute) by August 8. Just two months later, on October 16, a 40-foot flood wave carrying 278,000 cfs (125 million gallons per minute) passed just beneath the bridge in Llano and destroyed the bridge at Kingsland over

Figure 6 - 2018 Flood Damage at South Llano River Bridge in Junction. Note water level from 1935 flood marks on bridge piling.

[23] The comparatively high median monthly discharge for Llano at Llano in May results from timely rainfall events during the Drought of the 50s.

the Llano Arm of Lake LBJ and severely damaged the Flat Rock Bridge in Junction. This was the second highest Llano flood on record.

Just eight days prior to October 16, 2018, the third highest flood in recorded history on the South Llano in Junction (118,000 cfs) surprised RV campers in the early morning hours. Fifteen campers were rescued by boat and four by helicopter. Tragically, the bodies of four campers were recovered downstream, one as far downstream as LBJ Reservoir. The RV Park where the tragedy occurred is located next to the South Llano River Bridge where the water level of the 1935 flood of record is marked on the bridge piling (Figure 6).

Floods

As previously mentioned, the Edwards Plateau and the Llano River are located within an area referred to as "Flash Flood Alley". Resulting intense rainfall events fall on shallow soils and steep slopes, producing significant runoff in short amounts of time. "Turn Around Don't Drown" is a warning mantra frequently mentioned across the watershed's many low-water crossings.

The Llano's largest flood occurred on June 14, 1935, reaching 41.5 feet with an estimated discharge of 380,000 cfs at Llano and 43.3 feet (319,000 cfs) below Junction.[24] This flood destroyed both the bridge at the City of Llano and the Mason County bridge. Over 18 inches of rainfall was measured near the headwaters of the James River prior to this event.[25] The second highest recorded flood at the Junction gage occurred in September of the following year (158,000 cfs) which also equaled the November 3 flood in Junction in 2000. Additional flood events are discussed in Watersheds Characteristics chapter.

Drought

Because the Llano River and its tributaries are fed by headwater springs issuing from the supplies of water stored within the vast Edwards Plateau, the upper areas of the watershed are more resilient to drought than many other rivers in Texas. Due to large headwater springs on the South Llano River, the Llano River gage downstream at Junction has never recorded zero flow in the 105-year recorded history, although flows did drop below 4 cfs in August of 1956, during the "Drought of the Fifties".

The aquifer feeding the springs on the North Llano River is not as thick as the aquifer feeding the South Llano. As a result, the aquifer beneath the North Llano stores less water, resulting

[24] Discharge estimates were obtained from the Llano River near Castell USGS gage - active from 1923 until 1939.

[25] Tate Dalrymple and others, "Major Texas Floods of 1935". US Geological Survey Water-Supply Paper 796-G, 1939.

in smaller headwater springs and less resilience to drought. The North Llano has recorded zero flow several times, the longest period occurring during the drought-of-record during the 1950s when the river ceased to flow for 246 days. For comparison, during the drought in 2011, the North Llano ceased to flow for 121 days. Over the entire period of record for the North Llano gage (1915 to 1977 and 2001 to 2012) zero flow has been recorded five percent of the time.

Further downstream in Mason and Llano counties, spring flow from Edwards Plateau springs provides less of a buffer against drought. The gage near the Highway 87 bridge in Mason County has been recording data only since 1968, with a period of inactivity between 1993 and 1997. The lowest recorded flow during this period is 9 cfs during August of 2013. Drought has plagued the City of Llano over the years as the river is the City's primary source of water. During the Drought of the Fifties, the river ceased to flow for 128 days, the longest stretch being for 67 days during 1956 when water had to be imported to the City via railcar. Zero flows were also recorded during 1964 and for two days in 1984.

While the Edwards Plateau springs provide some resistance to droughts, these springs are very susceptible to reductions in recharge associated with reductions in annual average precipitation. Although based on sound hydrologic principles, estimates of the volume of water available in the Edwards-Trinity (Plateau) aquifer are rough estimates at best. Some of the basic components of the hydrological budget, which are integral to the ability to determine water availability within aquifers, are lacking. The Texas Water Development Board (TWDB) currently estimates recharge in the basin between one and two percent of mean annual precipitation.[26] Because these recharge estimates are applied over large areas, any errors associated with the estimate can have a significant impact on estimates of water availability.

In his analysis of groundwater availability and springflow across the Edwards Plateau, Dr. Ron Green estimates changes in the volume of aquifer recharge with changes in annual precipitation. Dr. Green's concludes that under normal conditions for Real, Edwards, Sutton and Kimble County, where the majority of recharge to the Llano occurs, nearly 400,000 acre-feet is recharged in these counties to aquifer. But as precipitation amounts slowly decrease, recharge volumes decrease significantly. Dr. Green estimates that a 10 percent reduction in precipitation results in recharge decreasing nearly 30 percent and a 20 percent reduction results in nearly a 40 percent reduction. Annual rainfall amounts below 80% result in even

[26] Roberto Anaya and Ian Jones, "Groundwater availability model for the Edwards-Trinity (Plateau) and Cenezoic Pecos alluvium aquifer system, Texas", GAM Report, Texas Water Development Board, 2004.

greater reductions in recharge, with a 30 percent reduction in annual precipitation resulting in a 95% reduction in annual recharge. (Figure 7).[27]

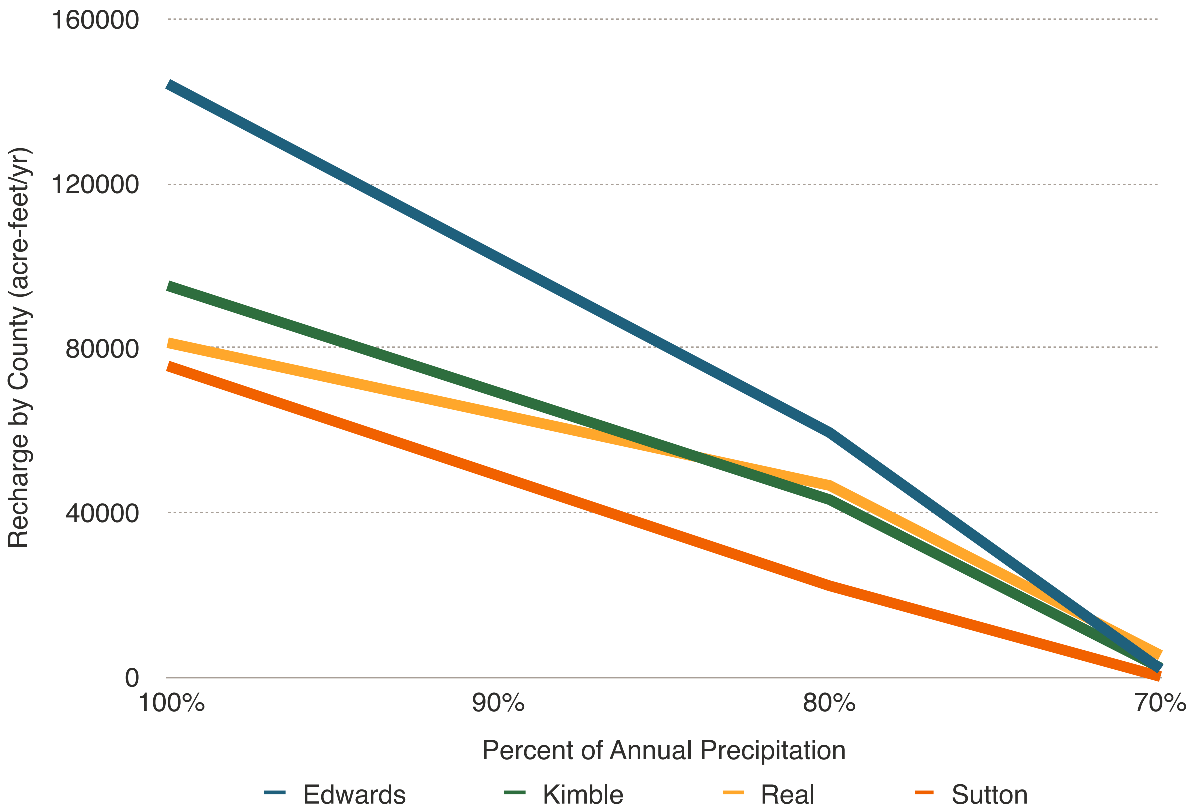

Figure 7 - Annual Recharge v Annual Precipitation for Selected Counties in Edwards Plateau.

Average annual precipitation in Kimble County is 25.7 inches and 70% of average is about 18 inches (Figure 8). Since 1895, there have been 15 years with annual precipitation at 70% of average or less, including three of the last twelve years (2008, 2011, 2019). During the drought of the 50s, five out of six years were below 18 inches, or 70% of average. The most recent dry period is also reflected by the fact that 2010-2020 is the second driest decade in recorded history with the average departure from the mean for annual precipitation by decade at -2.5 inches (Figure 9). Expressed another way, the average annual precipitation for the last decade was about 90% of normal.

The effects of reductions in precipitation and resulting recharge are also evident in streamflow records during low-flow periods. During these periods, all of the flow in the stream can be assumed to be coming from springflow as no precipitation has recently fallen.

[27] Ronald T Green and F. Paul Bertetti, " Investigating the Water Resources of the Western Edwards-Trinity Aquifer." Geosciences and Engineering Division, Southwest Research Institute, Project No. 20-15466, June 2010.

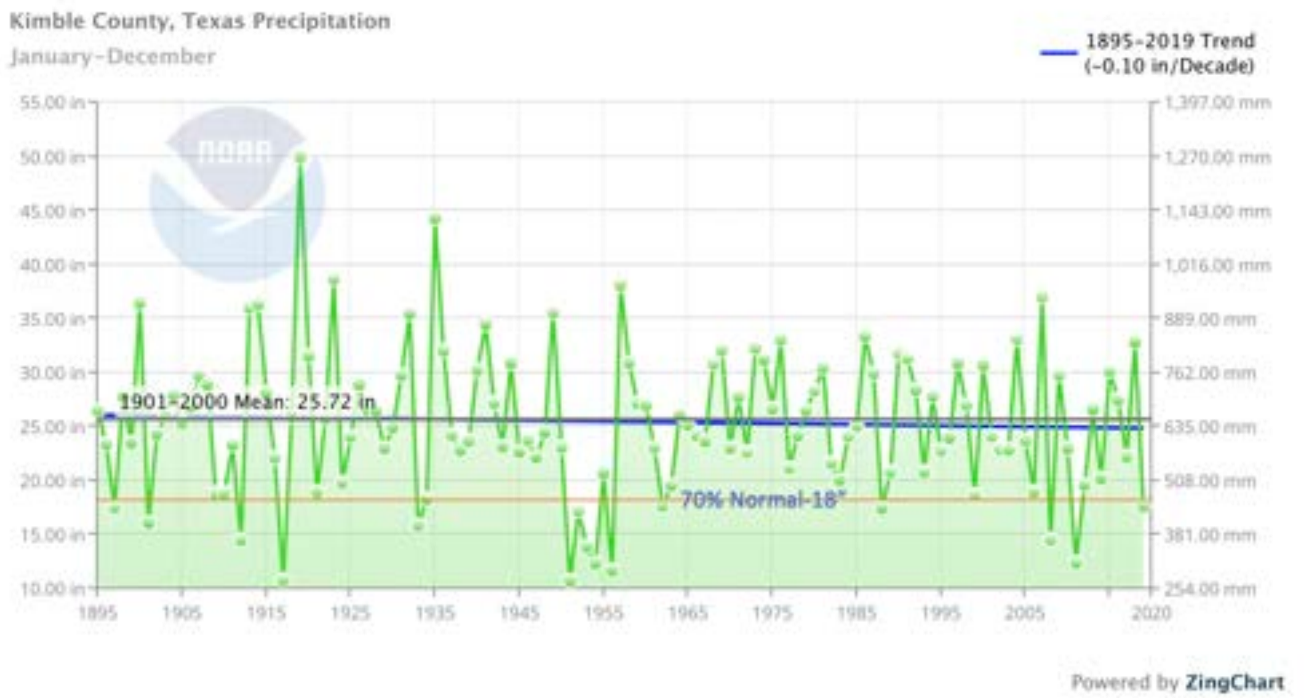

Figure 8 - Annual Average Precipitation (100 and 70 Percent) for Kimble County, 1895-2019

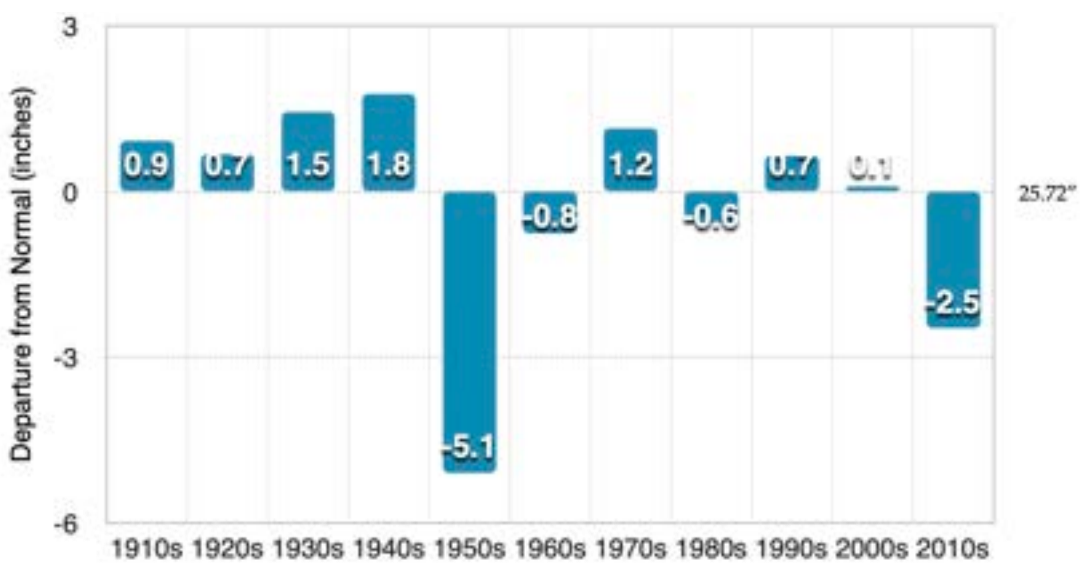

Figure 9 - Precipitation-Average Departure from Normal by Decade-Kimble County

The lowest annual 7-day average streamflow measurement provides a simple metric for comparing low-flow periods and the volume of water coming from the aquifer. In Figure 10, the lowest 7-day average for a three year period is compared to the average annual

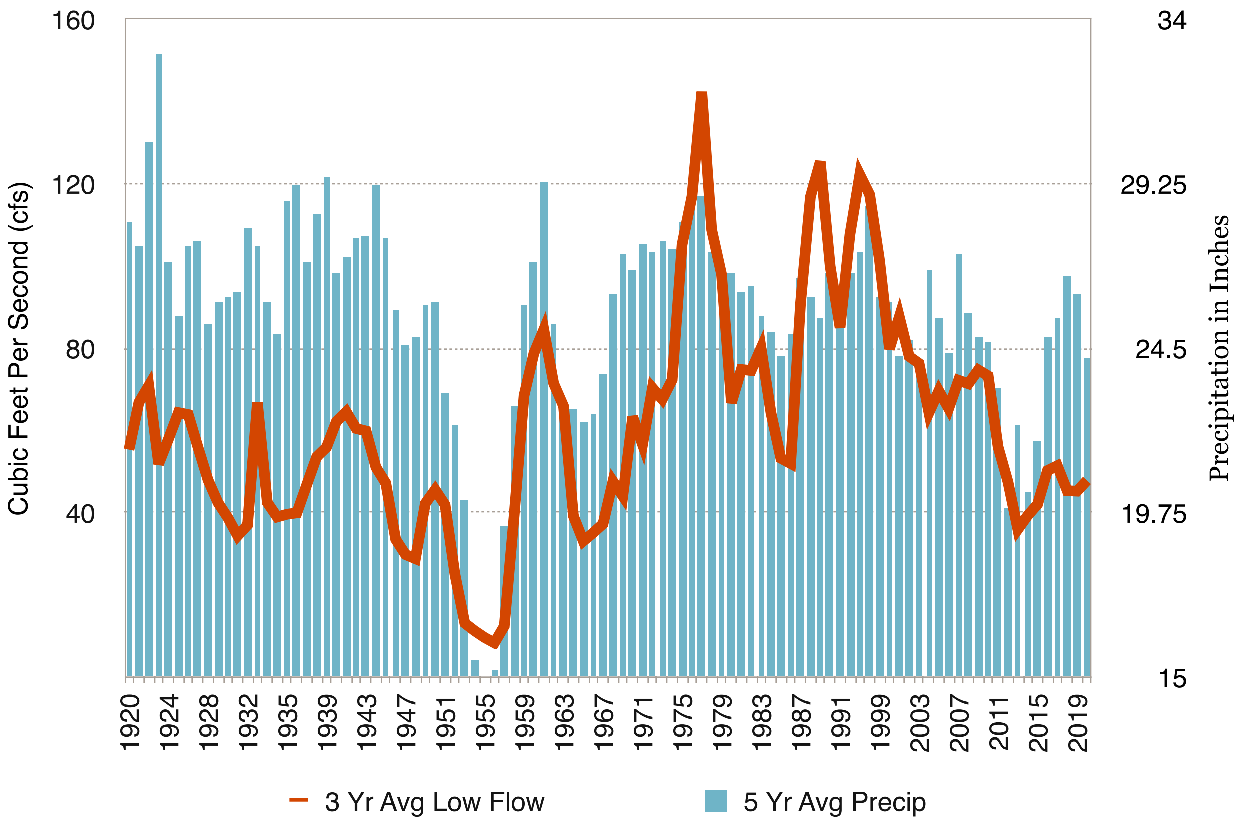

Figure 10- Average Precipitation and Low Flow Conditions for Llano River near Junction

precipitation amount over a 5-year period. The figure highlights several unique components and changes over time to recharge and base flow in the Llano.
First, the effects of precipitation, recharge, and resulting base flow are a multi-year process. The Llano is fed primarily by recharge from the vast Edwards Plateau. As the aquifer underlying the Edwards is a karst aquifer, water travels through the aquifer conduits at a rate faster than through a sand aquifer, such as the Hickory Aquifer. However, this rate is slower than rates in streams fed primarily by surface-water runoff.

Second, the corresponding relationship between precipitation and springflow has changed over time. Prior to the 1950s, precipitation falling on the Edwards Plateau did not produce as much base flow as the same amount of base flow produced after the fifties. Such a change can be explained by looking at the landscape. The first half of the 20th century was a period of overgrazing across the Edwards Plateau. The number of cattle, goats and sheep on the

Plateau grew by decade until reaching a peak in the 1940s. As a result of this practice, the presence of vegetation on the landscape and its resulting capacity to capture water during runoff from rainfall events was severely diminished, resulting in more rapid runoff and less recharge to the underlying aquifer.[28] Since the 1950s and the reduction in stocking rates, woody vegetation has encroached across the landscape, replacing native grasses but providing a mechanism for capturing surface water runoff and storing it in the aquifer. As a result, baseflows have increased in relation to the amount of precipitation. Whether baseflows will increase by returning native grasses to areas now covered in woody vegetation is still a question of debate.

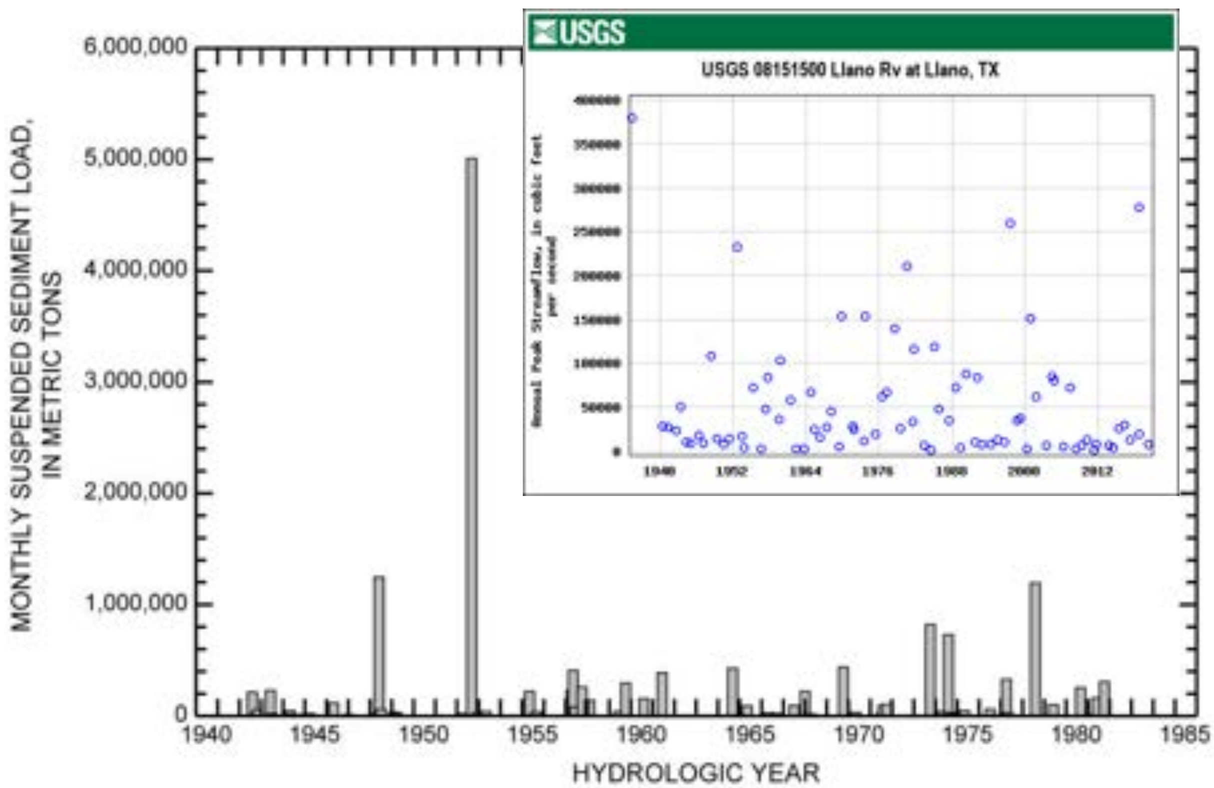

Figure 11- Monthly Suspended Sediment Loads at Llano River @ Llano 1942-1882 and Peak Streamflow for USGS Llano River @ Llano 1939-2019. (From Heitmuller, 2009).

The degraded land-surface conditions during the drought of the fifties are also highlighted anecdotally by sediment data collected by the US Geological Survey at Llano between 1942 and 1982 (Figure 11). By far, the largest volume of suspended sediment measured during this period occurred in 1952 when 5 million metric tons were measured following a 30-foot flood

[28] Bradford P. Wilcox and Yun Huang, "Woody plant encroachment paradox : Rivers rebound as degraded grasslands convert to woodlands." Geophysical Research Letter, Volume 37, Issue 10, April 2010.

event of 232,000 cfs.[29] The next highest measured sediment volumes were just over 1 million metric tons during flood events in 1948 (108,000 cfs) and 1978 (139,000 cfs). All other flood event produced less than 1 million metric tons, including the 1980 flood of 210,000 cfs. Such a large volume of sediment suspended in 1952 suggests little vegetation was present on the landscape to reduce runoff and erosion.

Finally, from Figure 12 below, the relationship between precipitation and springflow over the last ten years appears to be shifting again with precipitation having less of an impact on raising low flows. One hypothesis for this result is that the past decade is the second driest on record (Figure 9), with the upper watershed only receiving 12 inches of rain in 2011. Fortunately, only four years prior to what many consider the 'drought of record', over 37 inches fell during the course of 2007, recharging the aquifer and bringing the discharge from 700 Springs to its third highest recorded reading of 41.8 cfs and an average annual flow of 30.5 cfs.[30] By 2011 however, due to the drought, discharge from 700 Springs was at its lowest recorded measurement of 11.7 cfs and has not fully recovered. Since the drought of 2011, the

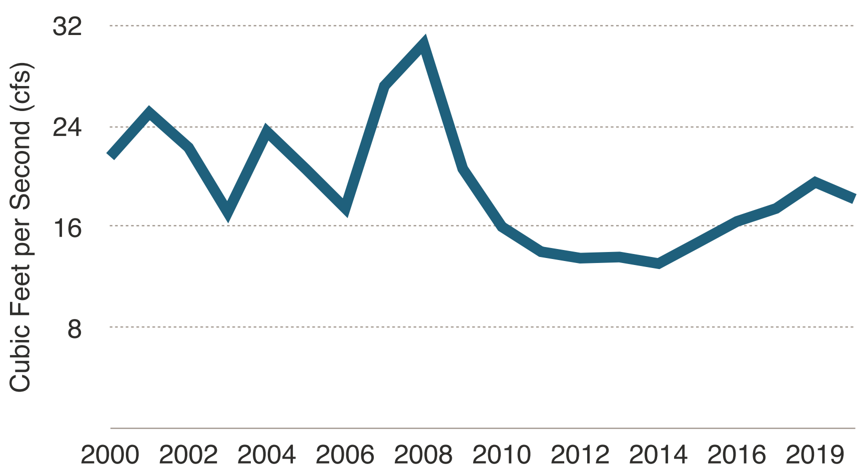

Figure 12- Average Annual Measured Discharge from 700 Springs 2000-2020

timing and volume of precipitation has not been sufficient to fully recharge the aquifer as indicated by continued low discharge measurements from 700 Springs. Precipitation causing the flooding of October 2018 may have occurred over such a short period of time that a smaller percentage of recharge may have occurred than is normal.

Information on what the effect of a prolonged extreme drought would have on the flows of the Llano River is lacking. Currently, the drought of the 1950s is considered the drought of

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[29] Heitmuller, 2009.

[30] The highest measured discharge from 700 Springs occurred in 1973 at 42.5 cfs.

record for the Edwards Plateau. Evidence from a report by Dr. Malcolm Cleaveland on tree ring data has shown that droughts during the 1100s and 1200s, while not as severe in terms of drought intensity, were more severe from the standpoint that the region was in drought conditions for approximately 40-50 years. Dr. Cleaveland notes, "since the world appears to be heading into a period of elevated temperatures…the possibility of experiencing drought similar to the 1100s and 1200s cannot be dismissed lightly." [31]

Watershed Characteristics

The Llano River should be considered two diverse rivers when considering land and water characteristics and necessary stewardship efforts. The upper portion of the river, including the North and South Llano tributaries emanate from springs in the sides of canyons carved into the edge of the limestone Edwards Plateau. This portion of the river is similar to neighboring Hill Country rivers, with well-developed floodplains supporting large native pecan trees. Near the Mason-Kimble county line, the Llano takes on its own unique character as it first crosses the older sedimentary rocks rimming the Llano Uplift, then the igneous and metamorphic center of the ancient Uplift. Here, the river is fed by only a few springs and likely loses some flow through cracks in bedrock channels lined by narrow, steep-sloped floodplains.

This section of the report will characterize both sections of the river and its tributaries, noting available information related to source-water springs, flow, channel characteristics, water use and water quality. The upper section of the river flowing across with Edwards Plateau, for convenience, will be referenced as the "Edwards" segment, while the lower section across the Llano Uplift will be called the "Llano" segment.

Edwards Plateau Segment

The Edwards Plateau segment of the Llano River consists of the North and South Llano and the Llano River from Junction downstream to the mouth of Big Saline Creek near the Kimble-Mason county line. The segment also includes the major tributary of Johnson Fork downstream of Junction, and several smaller tributaries including Big Paint Creek and Cajac (pronounced kayak) Creek, Chalk Creek and Cedar Creek on the South Llano, and Maynard, Copperas, and Bear creeks on the North Llano. Smaller tributaries on the Llano River in this portion of the river include Gentry Creek, Sycamore Creek, Red Creek, and Saline Creek. The flows of all the rivers and tributaries on the Llano in Edwards Plateau are primarily from

[31] Malcolm K. Cleaveland, Professor of Geography, University of Arkansas, "Extended chronology of drought in the San Antonio Area", Revised Report March 30, 2006.

springflow. Further discussion of these tributaries is found in the Sub-watershed section below.

Water that recharges the Edwards Plateau generally makes its way downward more quickly along caves, conduits, and more slowly through the rock matrix until it reaches the underlying Glen Rose limestone. When the water reaches the less permeable Upper Glen Rose Formation, it moves laterally along the top of the formation and through a more permeable layer of the Edwards Limestone known as the 'burrowed zone' until it emerges as spring along the sides of canyons or along the bottom of streams. (Figure 13).[32]

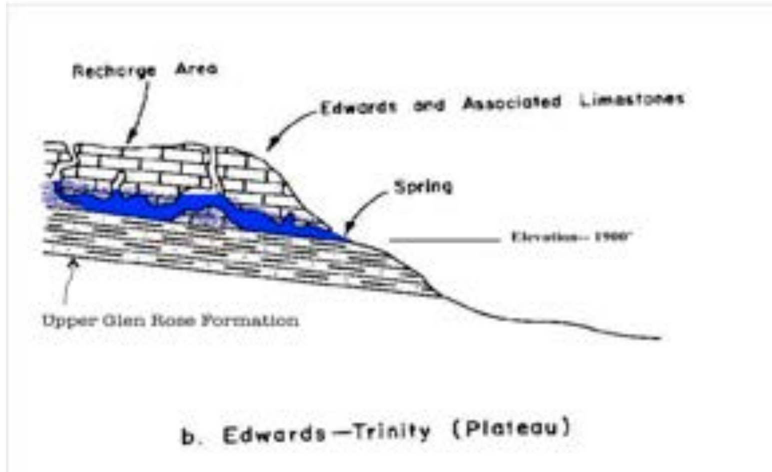

Figure 13- Schematic cross-section of groundwater flow in Edwards Plateau (adapted from Brune).

Although the size of the watersheds for the North Llano (942 square miles) and the South Llano (939 square miles) are almost equal, they exhibit very different hydrologic characteristics. The mean annual flow of the North Llano River is 66 cfs, while the mean annual flow of the South Llano River is 129 cfs. The median daily flow for the North Llano River is 20 cfs, while the median daily flow for the South Llano River is 80 cfs. The principle reason for such a difference in flow results from greater springflow in the South Llano River watershed due to the presence of thicker limestone deposits underlying the South Llano than underlying the North Llano. The limestone deposits are thinner in under the North Llano because they are deposited atop a ridge of uplifted Permian material underlying the Edwards Limestone known as the Roosevelt High.[33] Thicker limestones are able to store more water than the thinner limestones.

Downstream, below the confluence of the North and South Llano, the portion of the watershed of the mainstem Llano River in the Edwards segment encompasses approximately 626 square miles. A remnant finger of the Edwards Plateau dividing the Llano and San Saba rivers provides small headwater springs for tributaries flowing towards the north side of the

[32] Gunnar Brune, *Springs of Texas*, volume 1, Fort Worth, Tex., Branch-Smith, Inc., 1981.

[33] Rene A. Barker and Ann F. Ardis, “Hydrogeological framework of the Edwards-Trinity aquifer system, west-central Texas.” USGS Professional Paper 1421-B, 1996.

Llano River. Except during periods of significant precipitation, however, these tributaries do not flow all the way to the Llano River. Tributaries on the south side of the Llano River in the Edwards segment have more significant flow owing to the portions of the Edwards Plateau east of Junction and portions of the Blue Mountains of southeast Kimble County. These portions also provide springflow to the James River whose mouth is found downstream in the Llano Uplift segment.

There are numerous springs that contribute to the river flow in Edwards segment of the Llano. The Texas Springs Database [34] identifies 27 springs in the North Llano River watershed, 20 springs within the South Llano River watershed, and 20 springs within the Llano watershed of this segment. Many additional springs, not included in the database, are located on USGS topographic maps and are discussed below. While the North Llano watershed has more springs than the South Llano and Llano, it has fewer high-flow springs. Five large springs with flow greater than 0.2 cubic feet per second (100 gallons per minute) are found in the North Llano; eleven large springs are found in the South Llano and five are found in the Llano.

Little is known about the exact origin of the water that feeds these springs. However, some information can be inferred from topography and existing hydrogeological studies. In Figure 14, which reads like a topographic map, Kuniansky and Holligan note that the potentiometric surface (the elevation of the top of the water table) and the flow of groundwater tends to follow the topography in the Edwards Plateau region. [35] There are several areas surrounding the North and South Llano rivers and their tributaries where the elevation of the water table is over 2,000 feet above sea level. The level of the springs along the rivers is approximately 1,900 to 2,000 feet, so it can be assumed that groundwater flows 'down gradient' towards the springs.

Kuniansky and Holligan suggest that the waters that feed the springs from the north side of the North Llano and Llano in Sutton and Kimble counties likely originate from northeastern Sutton County where the potentiometric surface is over 2,200 feet above sea level. From this localized groundwater high, groundwater flows east along the Edwards limestone divide that separates the Llano from the San Saba watershed. As this narrow ridge feeds two river systems, flows from springs along this ridge are small.

Springflow on the south side of the North Llano and west side of the South Llano likely originate from southeastern Sutton and southwestern Kimble County. In the South Llano,

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[34] Heitmuller, F.T., and Reece, B.D., "Data base of historically documented springs and spring flow measurements in Texas", U.S. Geological Survey Open-File Report 03-315, 2003

[35] Eve L. Kuniansky and Kelly Q. Holligan, "Simulations of flow in the Edwards-Trinity aquifer system and contiguous hydraulically connected units, west-central Texas." U.S. Geological Survey Water-Resources Investigations Report 93-4039, 1994.

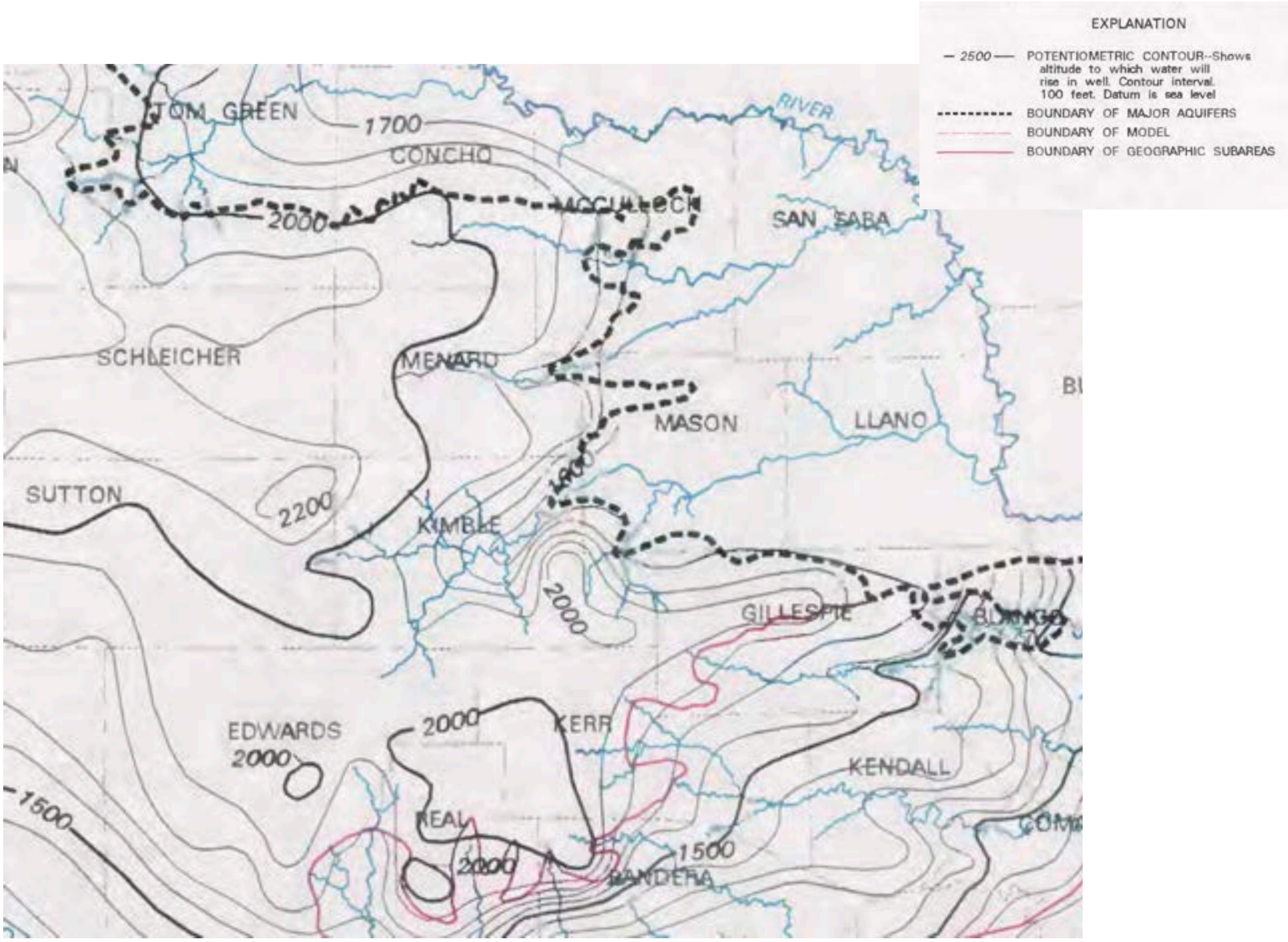

Figure 14 - Historical potentiometric surface of the Edwards-Trinity aquifer system for the Llano River watershed, 1915-1969. (From Kuniansky and Holligan, 1993)

springs along the left bank of the river (such as Seven Hundred and Tanner) probably originate from the area to the west in southwestern Kimble, southeastern Sutton, and northern Edwards counties.

Waters that feed the springs on the east side of the South Llano and along Big Paint Creek probably originate from eastern Edwards, northern Real, and western Kerr counties. This water, located beneath the divide between the South Llano River (to the north), the Nueces, West Nueces, and Frio Rivers (to the south), and Guadalupe River (to the east), is most likely the source of spring flow for all of these river systems. The potentiometric surface ridge located above 2,000 feet above sea level in eastern Kimble County is associated with the Blue Mountains which feed springs along the south side tributaries of the Llano River in the Edwards Plateau segment. Without detailed potentiometric surface mapping and tracer testing, however, it is very difficult to accurately depict actual groundwater basins with any certainty as there are examples where groundwater basin boundaries are not coincident with topographic watershed boundaries

Additional research on groundwater movement in the Edwards Plateau has yielded informative hypotheses. In an analysis of recharge to and baseflow from water stored in the Edwards Plateau, Dr. Ron Green notes the volume of water that discharges from the springs does indicate that the groundwater basins are sizable and probably incorporate hundreds of square miles. Dr. Green hypothesizes that because of karstic nature of the aquifer, precipitation that falls on the North and South Llano watersheds in Sutton and Edwards counties and recharges the aquifer, rather than following the hydrologic divide and discharging to the north, may instead, follow conduits within the rock and discharge to the south in the Nueces and Frio watersheds. Such a phenomena is referred to as 'groundwater piracy'. [36]

Research in Sutton County shows that much of the movement of water in the aquifer occurs along preferential flow paths in close proximity (1.5 miles) to existing stream beds where dissolution (dissolving and erosion) of the Edwards Plateau limestone occurs most frequently. [37] The highest capacity wells on the Plateau tend to be located along these pathways.

In an attempt to better understand groundwater movement on the Edwards Plateau, researchers from University of Texas-San Antonio, Edwards Aquifer Authority, and the Texas Tech University Llano River Field Station released dye into Devil's Sinkhole in northern Edwards County in 2017. To trace the dye, charcoal packets that trap dye particles were deployed at numerous springs and rivers around Devil's Sinkhole, including on the South Llano and Big Paint Springs. Unfortunately, likely due to a lack of rainfall and a lack of dye dispersal via groundwater, no dye was captured by these packets.

NORTH LLANO WATERSHED

The North Llano River watershed begins on the Edwards Plateau nine miles east of Sonora in Sutton County. The River flows intermittently across the plateau for its first 31 miles before becoming perennial for its final 27 miles to its confluence with the South Llano in Junction. The North Llano is considered as three sub-watersheds for the purposes of this report: Upper, Middle and Lower North Llano (Figure 15). The hydrologic characteristics, demographics, and water use for each sub-watershed are discussed in more detail below.

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[36] Green and Bernetti, 2010.

[37] R.T. Green, F.P. Bertetti, M.S. Miller, "Focused groundwater flow in a carbonate aquifer in a semi-arid environment." Journal of Hydrology, Volume 517, 19 September 2014, Pages 284-297.

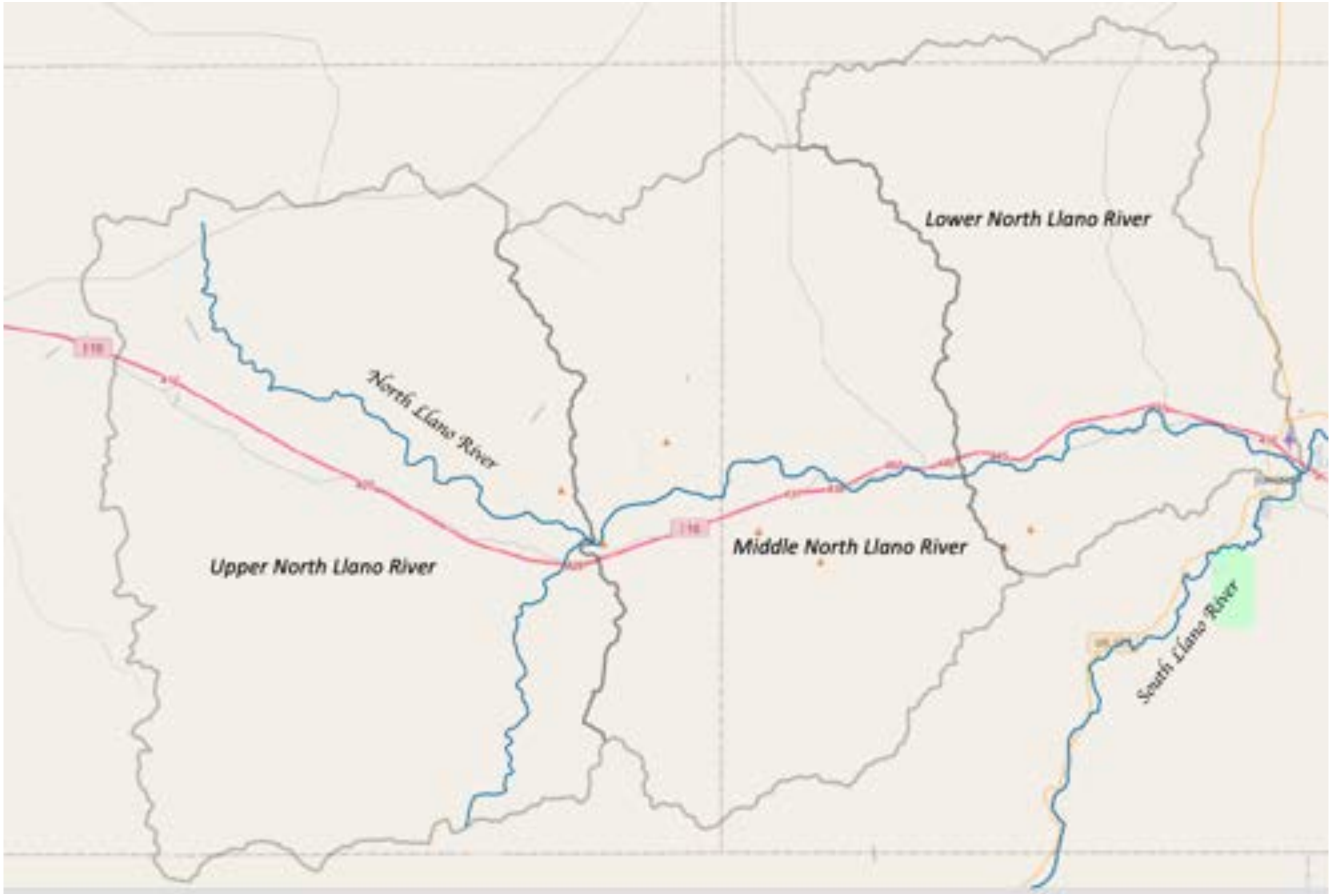

Figure 15-Location of Sub-watersheds North Llano River

Upper North Llano Sub-watershed

The Upper North Llano sub-watershed (Figure 16) is 392 square miles and includes primarily the North Llano River (on some maps called the North Llano Draw), generally to the north of Interstate 10, and the Dry Llano River to the south of Interstate 10. *Ashe*-juniper and live oak are the predominant vegetation followed by savannah grasslands. Ranching and hunting leases and natural gas production are the primary sources of income.

The sub-watershed borders the Devils River to the west, the San Saba River to the north, and the South Llano watershed to the south along a divide approximately 2,400 feet above sea level. This low, nearly level divide is covered by semi-permeable Buda Limestone pocked in areas with small clay-filled playa depressions that temporally hold water following precipitation events. Limestone-derived clayey soils of the Tarrant and Kavett-Tarrant association are the predominant soil type. Along the South Llano River divide, the fairly impermeable Boquillas Formation overlies the Buda Limestone

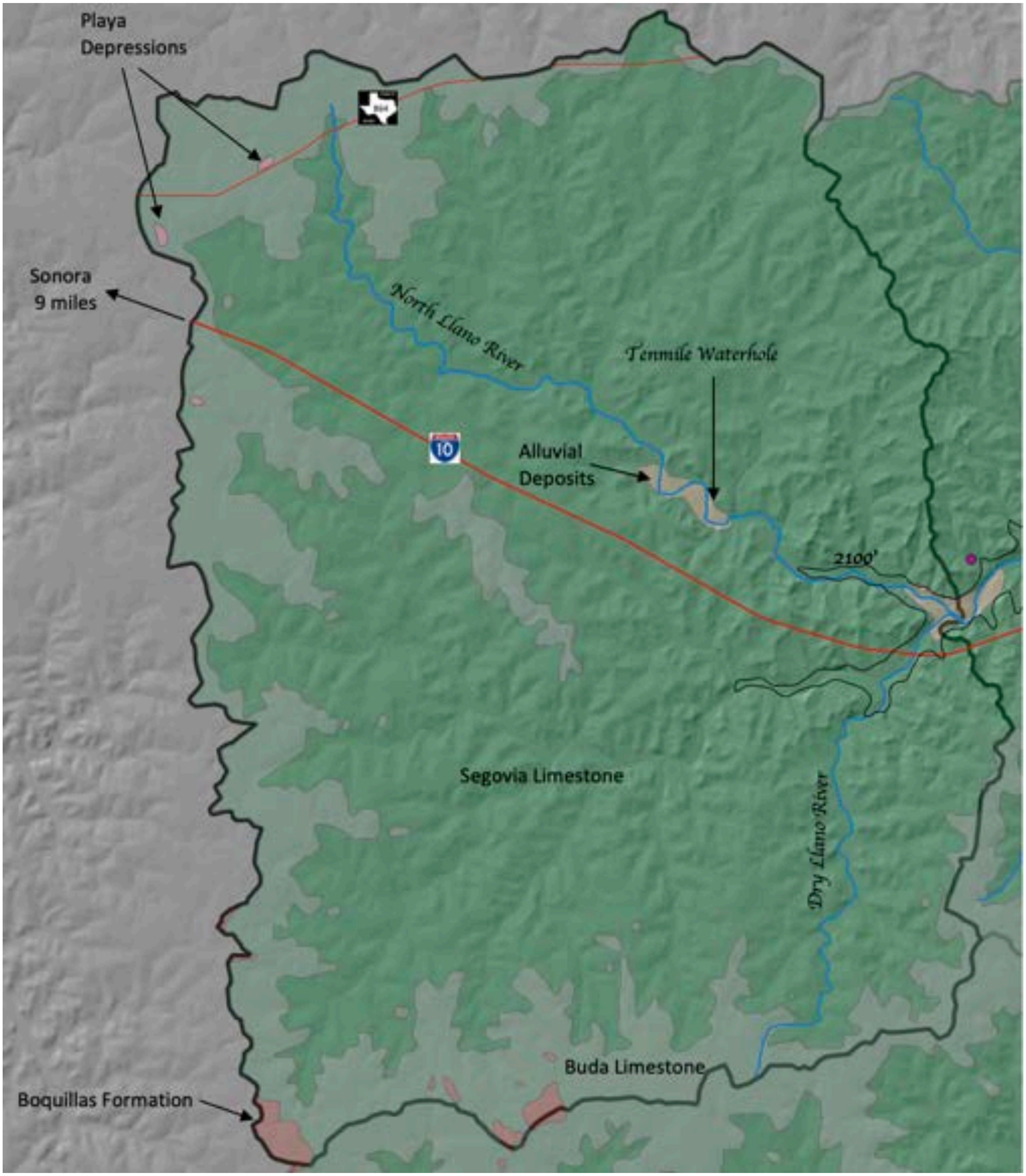

Figure 16 - Upper North Llano Sub-watershed

About one mile from the divide, the ephemeral draws of the Upper North Llano begin to downcut at an overall rate of about 13 feet per mile into clayey soils of the Tarrant association, exposing the underlying Segovia member of the Edwards limestone at about

2,350 feet. This layer of limestone is generally unsaturated, so no springs are found along this 23-mile segment.

About 12 miles from the headcuts of the North Llano, alluvial valleys begin to form along the sinuous draws. Soils along the beds and banks of this ephemeral segment are silty, clay loams of the Rioconcho and Dev association believed to have been eroded from the uplands during wetter periods 6,000 years ago. [38] While the draws of the Upper North Llano do not contain major springs, there are 'waterholes' along the lower reaches. The largest of these water holes is Tenmile Waterhole on the North Llano (Figure 17). These water holes are the result of the silty, clay loams in the riverbed which have high ability to store runoff. Gunnar Brune in

Figure 17- Tenmile Waterhole on private property- taken from Sutton County Road 306

Springs of Texas [39] reports historical descriptions of these waterholes containing more water than at present due to groundwater seepage.

The North Llano in the lowest two miles of the sub-watershed remains ephemeral as it begins to downcut into the upper sections of the Fort Terrett formation of the Edwards Limestone at an elevation around 2,100 feet.[40] Here, the draw narrows and becomes straighter as it

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[38] Heitmuller, 2009.

[39] Brune, 1981.

[40] Segovia and Fort Terrett formations are not differentiated on the map; demarkation roughly follows the 2,100 foot contour.

becomes more incised into the bedrock. Although Fort Terrett limestone is the source of the major springs on the Llano, the mouth of the sub-watershed at the confluence of the Dry North and the North Llano is 2,025 feet, just above the 'burrowed zone' of Fort Terrett limestone containing the most saturated part of the Edwards Limestone.[41] The area of contact between the overlying Segovia and Fort Terrett formations is the location for the majority of the caves in the region. Recharge features (generally collapsed karst features) found in the beds of ephemeral streams of the North and South Llano contribute to recharge.

Due to the lack of surface water sources, the introduction of the windmill to the Edwards Plateau was critical in the development of the area. Windmills over shallow dug wells began to be used in the 1870s, but these wells dried up during the drought of 1880s. Experimentation with proper windmill size, well depth and diameter continued as many disputes broke out during the drought over the fencing, and subsequent fence cutting, of waterholes (see Green Lake in Upper South Llano). One of the first successful windmills was established over a 52 foot borehole drilled north of Eldorado in the early 1880s by a sheep rancher named Christopher Columbus Doty [42].

The population of the sub-watershed is estimated to be 79 with 91 houses.[43] Today, more than 272 wells in Texas Water Development Board databases are located in the sub-watershed, including 116 drilled in the last 20 years.[44] With the exception of two public supply wells serving a resort, all of the wells are either for domestic or livestock purposes. These wells are generally 300 to 400 feet deep and produce between less than 5 and up to 70 gallons per minute. According to the Sutton County Underground Water Conservation District, water levels in the aquifer are highest, or closest to the surface, along the northern eastern boundary of the sub-watershed (2,160 feet above sea level) and lowest along the southwestern boundary (1,940 feet), suggesting a direction of groundwater flow to the southwest, from highest elevation to lowest.[45] Groundwater level fluctuation in ten observation wells shows average fluctuations over the last decade to be between 3 feet and 120 feet, with a median fluctuation of 17 feet.

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[41] Rene A. Barker, Peter W. Bush, and E.T. Baker, Jr, "Geologic History and Hydrogeologic Setting of the Edwards-Trinity Aquifer System, West-Central, Texas. U.S. Geological Survey Water-Resources Investigations Report 94-4039.

[42] Daniel B. Welborn, "Windmills". Texas State Historical Association, available online at https://www.tshaonline.org/handbook/entries/windmills, 1976.

[43] It is assumed approximately 2/3 of these homes second family homes. As the persons per household value in Sutton County is 2.69, approximately 29 homes are estimated to be primary homes; (79 / 2.69 = 29.4. 29.4 / 91 = .32). See Appendix A for more information.

[44] Not all wells drilled before 2000 are listed in the Texas Water Development Board database.

[45] Sutton County Underground Water Conservation District, "Water is Life", available at http://www.suttoncountyuwcd.org/storage/UserFileFolder/4_18_13_Water_Is_Life_41513.pdf

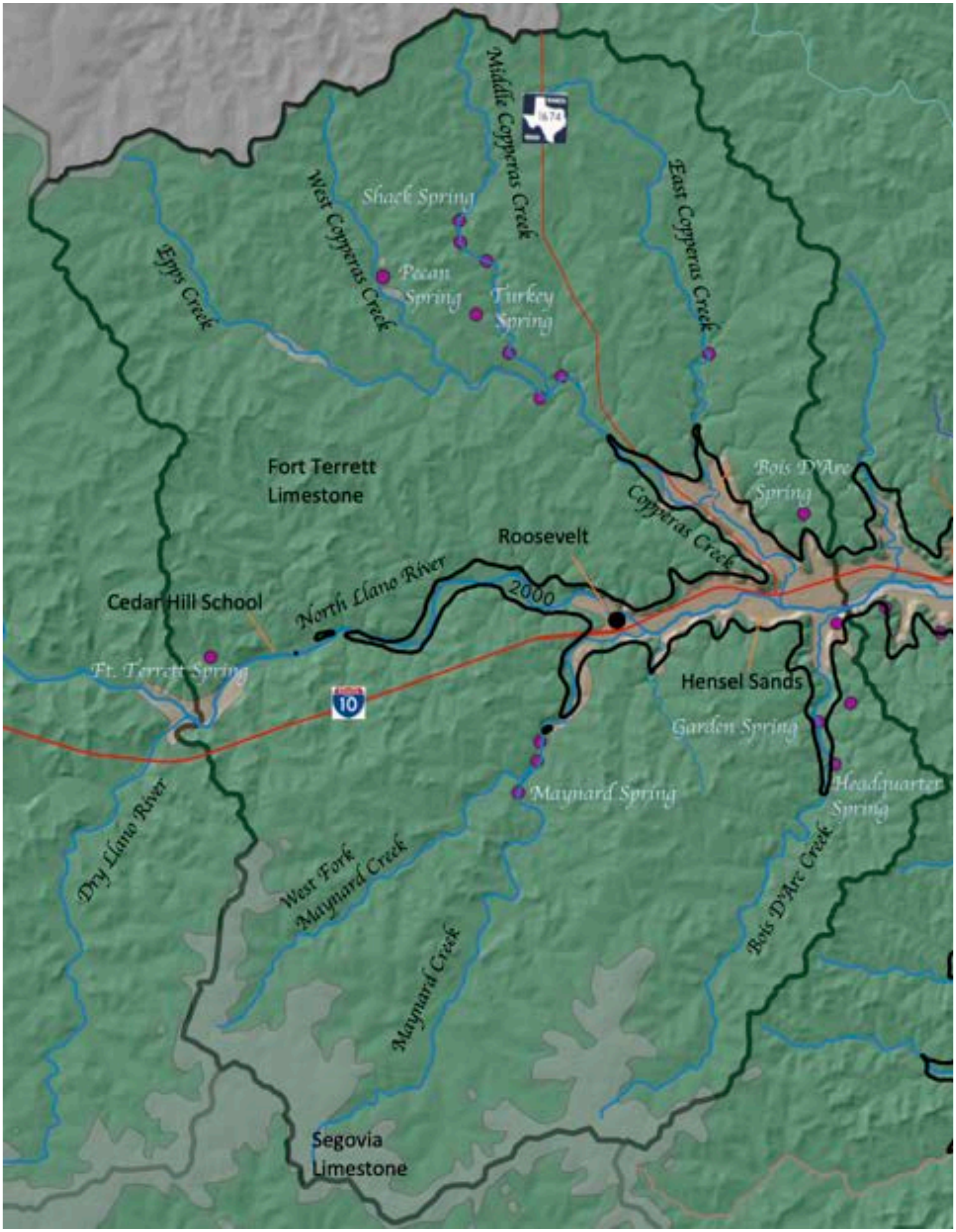

Figure 18 - Middle North Llano Sub-watershed

Numerous natural gas wells also dot the landscape especially along the western and southern borders of the Upper North Llano. Portions of the sub-watershed overlie the Barnett-Woodford Shale Play and over 110 of these wells are considered "High Cost Tight Gas", meaning they require some stimulation, such as fracking, to produce profitable rates. [46] The volume and source of the water used for fracking is unknown, but fracked wells generally require a minimum of one million gallons of water.

<u>Middle North Llano Sub-watershed</u>

The Middle North Llano (Figure 18) is a 310 square-mile basin flanked by the San Saba to the north and Upper South Llano to the South. *Ashe*-juniper and live oak are the predominant vegetation (75%) and ranching and hunting leases and oil production, the primary source of income. The population of the sub-watershed is 217 inhabitants with 320 housing units. The average persons per household for Sutton and Kimble counties is 2.56; it is estimated that 84 of the housing units (about 26%) are primary residences and the remainder are second homes belonging to absentee landowners.

Soils of the Middle North Llano are primarily Tarrant and Kavett-Terrett, shallow clayey soils derived from limestone. Soils along the beds and banks of this perennial segment are silty, clay loams of the Rioconcho and Dev association.

The Middle North Llano Sub-watershed begins below the confluence of the North Llano and the Dry Llano and terminates at the confluence of the North Llano with Bois d'Arc Creek. This 17-mile segment has a gradient of 11 feet per mile. The major tributaries include Maynard Creek, and Bois d'Arc Creek to the south side of Interstate 10 and Copperas Creek to the north side.

Just below the confluence with the Dry Llano, the river erodes into the Fort Terrett limestone to expose the "burrowed section" of the formation. It is here that Fort Terrett Spring forms the headwaters of the North Llano. The spring is located at 2,020 feet above sea level. Because of the tilting of the limestone atop the Edwards Plateau, the burrowed zone of headwater springs is 120 feet higher in the North Llano than in the South Llano. As previously mentioned, springs on the North Llano generally have less flow than springs on the South Llano as the thickness of the aquifer feeding the springs on the North Llano is thinner due to the Edwards Limestone being deposited on top of basement rocks of higher relief than in the South Llano.

The springs served as a water supply source for Fort Terrett which served as a frontier fort from 1852 to 1854. The ruins of the fort are located on private property, but a State Historical

[46] Texas Railroad Commission Public GIS Viewer, Version 3.7, accessed November, 2020

Marker on the nearby county road signifies its location. Gunnar Brune, who authored *Springs of Texas*, visited Fort Terrett Springs in 1978. At that time, only 8 gpm leaked through two small dams designed to capture the spring flow. Given the historical significance of the spring, it is likely that the springs flowed at a greater rate previously. Brune notes the presence of bedrock mortars and middens found upstream from Fort Terrett Springs and speculates that the springs originally started about one kilometer upstream from the present spring.[47]

Downstream of Fort Terrett springs, Brune describes Adams Springs (not located on map), composed of one large and many smaller springs "bursting into the north side of the river, chiefly below water line". No measurements are associated with Adams Springs, but stream discharge measurements taken at the uppermost River Road crossing of the North Llano River (below Fort Terrett and Adams Springs) are shown in Table 1. These measurements were taken during extended dry periods, minimizing the influence of surface water runoff from precipitation and providing a conservative estimate of flow from the groundwater system. Even during the drought of 2011, some flow was still measured in the upper reaches of the North Llano due to Fort Terrett and Adams springs (Figure 19).

Table 1. Measured Flows in cubic feet per second and gallons per minute for North Llano River below Fort Terrett Springs and Adams Springs

Date	Flow (cfs)	Flow (gpm)
Feb 1925	13	5,700
Dec 1978	15	6,700
Apr 2011	6.5	2,900
Jun 2011	6.2	2,800
Sep 2011	3.0	1,400

The next springs described by Brune, but not located on maps, are near Cedar Hill School. Cedar Hill Springs supplied the Cedar Hill School until it closed in the 1930s. Flow in 1978 measured 90 gallons per minute. About 1.5 miles further downstream are Logan Springs which flow from beneath the surface of the North Llano, making measurements difficult. In December 1978, Brune measured 26 cfs on the North Llano just above Roosevelt; this measurement includes contributions by the four springs mentioned as well as additional seepage to the river from groundwater.

[47] Brune, 1981.

Just above Roosevelt, the valley floor of the North Llano becomes wider and more sinuous as the river begins to expose the less resistant Hensel Sands of the Trinity Aquifer. Increased erosion produces more alluvial deposits along the riverbanks, providing arable land. The spring-fed North Llano provides irrigation to some parcels along the river. At Roosevelt, the river begins to leave the canyons of the Edwards Plateau, further widening and carving into the Hensel Sands formation.

Figure 19- North Llano River below Fort Terrett on Sutton County Road 307

The Hensel Sands formation resulted from erosion of the older Paleozoic and Precambrian basement rocks prior to the deposition of the Edwards Limestone. There are no large springs in this formation, but some volume of groundwater from the overlying Edwards limestones is believed to penetrate into the Hensel Sands formation and eventually discharges into the Llano and its tributaries.[48]

The community of Roosevelt does not have a public water supply system; local residents rely on shallow groundwater wells. Below Roosevelt, the North Llano valley floor continues to widen as it merges with Maynard Creek, followed by Copperas Creek and Bois d'Arc Creek. Irrigated agriculture, primarily hay production occurs in the alluvial materials along this reach.

Maynard Creek begins at approximately 2,300 feet above sea level in southeast Sutton County. Like other tributaries in this portion of the Llano watershed, the stream is intermittent for much of its 17-mile length. Five miles above the confluence with the North Llano, near the confluence with West Maynard Creek, Maynard Creek exposes the 'burrowed zone' of the Fort Terrett limestone near an elevation of 2,000 feet. Along a one-mile segment of Maynard Creek, three springs issue from the west side of the creek. Maynard Spring is the largest of the three springs and discharged 700 gallons per minute in October of 1965. The other two springs are unnamed and measured 5 and 15 gallons per minute in 1965.

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[48] Stephen Rober Allen, "*Hydrogeology of the Lower Cretaceous Edwards and Trinity Group Formations near Junction (Kimble County) Texas*". Thesis, University of Texas, May 1997.

These springs support a water right from Maynard Creek that now provides irrigation for a golf course on a private guest ranch.

There are four branches that make up Copperas Creek: the 15 mile-long West Copperas Creek; the 10 mile-long Middle Copperas Creek; the 24 mile-long East Copperas Creek; and the four mile-long mainstem of Copperas Creek. The tributaries of Copperas Creek all begin at the divide between the Llano and San Saba rivers at approximately 2,450 above sea level, the highest elevations in the entire Llano watershed.

These intermittent tributaries erode into first the Segovia formation and then the Fort Terrett formation of the Edwards Limestone. Along Western and Middle Copperas creeks, springs first appear at 2,200 feet above sea level, above the 'burrowed zone' of the Fort Terrett formation. These springs, Pecan Springs on West Copperas Creek and Shack Spring and Turkey Holler Springs along with two other unnamed springs on Middle Copperas Creek, are associated with exposed Permian rocks in the river channel. The limestones of the Edwards Plateau overlie the older Permian formation below, but in this area, prior to the deposition of the Edwards Limestone, Permian rocks were uplifted to form what is known as the Roosevelt High.[49] Removal of the Edwards Limestone through erosion by Copperas Creek has now exposed this formation. According to Brune, a discharge of 16 gpm was recorded at Pecan Springs in 1978. Discharge in 1966 from Shack Spring measured 5 gpm, as did Turkey Holler Springs and one of the unnamed springs. The other unnamed spring measured 0.5 gpm.

The main headwater springs for West Copperas and Middle Copperas are located just downstream of the confluence at an elevation of 2,025 feet. This unnamed spring produced 60 gpm when it was measured in 1966. Waters from this spring are used to irrigate pecans. The headwater spring for East Copperas Creek is an unnamed spring located at 2,015 feet with a discharge of 250 gpm, measured in 1966. These springs combine to provide sufficient water for two irrigation water rights along the along the main stem of Copperas Creek. Bois D'Arc Spring is located on a tributary of the North Llano, downstream of Copperas Creek and across from Bois d'Arc Creek. In 1966, discharge measured 7 gpm.

In 1925, a gain/loss study on the North Llano between Roosevelt and the mouth of the river demonstrated that groundwater contributed 6.9 cfs to the flow of the river [50]. During the drought of 2011, April flow in the North Llano River exhibited increasing flows below Fort

[49] Pete R Rose, "*The Wichita Paleoplain in Central Texas"*. To be published in Gulf Coast Association of Geological Societies Journal, September 2021.

[50] Raymond M. Slade, Jr, J. Taylor Bentley, and Dana Michaud, "Results of streamflow gain-loss studies in Texas, with emphasis on gains and losses to major and minor aquifers, Texas, 2000". U.S. Geological Survey Open-File Report 2002-68, 2002.

Terrett. Discharge below the old fort was 6.5 cfs, but 10 cfs below the confluence of Maynard Creek and 12 cfs below the confluence of Copperas Creek.

Bois d'Arc Creek is a 16-mile tributary originating on the divide between the North and South Llano at just over 2,300 feet. As the geologic strata of the Edwards Plateau slope from northwest to southeast, the main headwater springs on Bois d'Arc creek are located slightly lower than the rest of the North Llano (2,000 feet), but higher than South Llano (1,900 feet). Headquarters Spring (1,940 feet) measured 30 gpm in 1966 and Garden Spring (1,920 feet) measured 15 gpm. In addition, tributary springs (not mapped) are located at Cougar Hollow Spring (5 gpm), Bear Hollow Spring (no data) and Road Hollow Spring (1.5 gpm) The combined flow from all the springs on Bois d'Arc Creek is generally not large enough for flows to occur at the creek's confluence with the North Llano.

Texas Water Development Board data show there are 332 wells in the Middle North Llano Sub-Watershed. Of these, 181 wells have been drilled since the turn of the century. The depth of these wells range from less than 50 feet along near the North Llano River, to over 300 feet along the watershed divides. The Edwards-Trinity Aquifer supplies the deeper wells generally at a rate less than 5 gallons per minute, but up to 20 gpm. Shallow alluvial wells along the North Llano also produce less than 20 gpm, but two irrigation wells below Roosevelt produce 70 and 200 gpm. With the exception of these two irrigation wells and one industrial well (gravel production), all wells are used for domestic and livestock supply. Water level fluctuations in observation wells over the last 10 years are less than 10 feet, but one observation well in the Copperas Creek watershed has fluctuated approximately 20 feet.

The Middle North Llano sub-watershed is situated just to the east of the Barnett-Woodford Shale Play, so there are no wells used for fracking. However, the only oil wells in the Llano watershed are located above Camp Allison on the North Llano, approximately half way between Fort Terrett and Roosevelt.

Lower North Llano Sub-watershed

The third sub-watershed of the North Llano is the Lower North Llano, a 216 square-mile basin flanked by the San Saba to the north, Big Saline of the Llano to the east, and Lower South Llano to the south(Figure 20). The population of the sub-watershed is 1,347 inhabitants with 801 homes, primarily in the City of Junction. [51] Farming, ranching, and hunting leases are a major source of income in the rural areas, while retail businesses, especially associated with Interstate 10, are the primary source of income in the Junction area.

[51] Persons per household in Kimble County is 2.43. It is estimated that 554 (70 percent) of the homes in the watershed are primary residences.

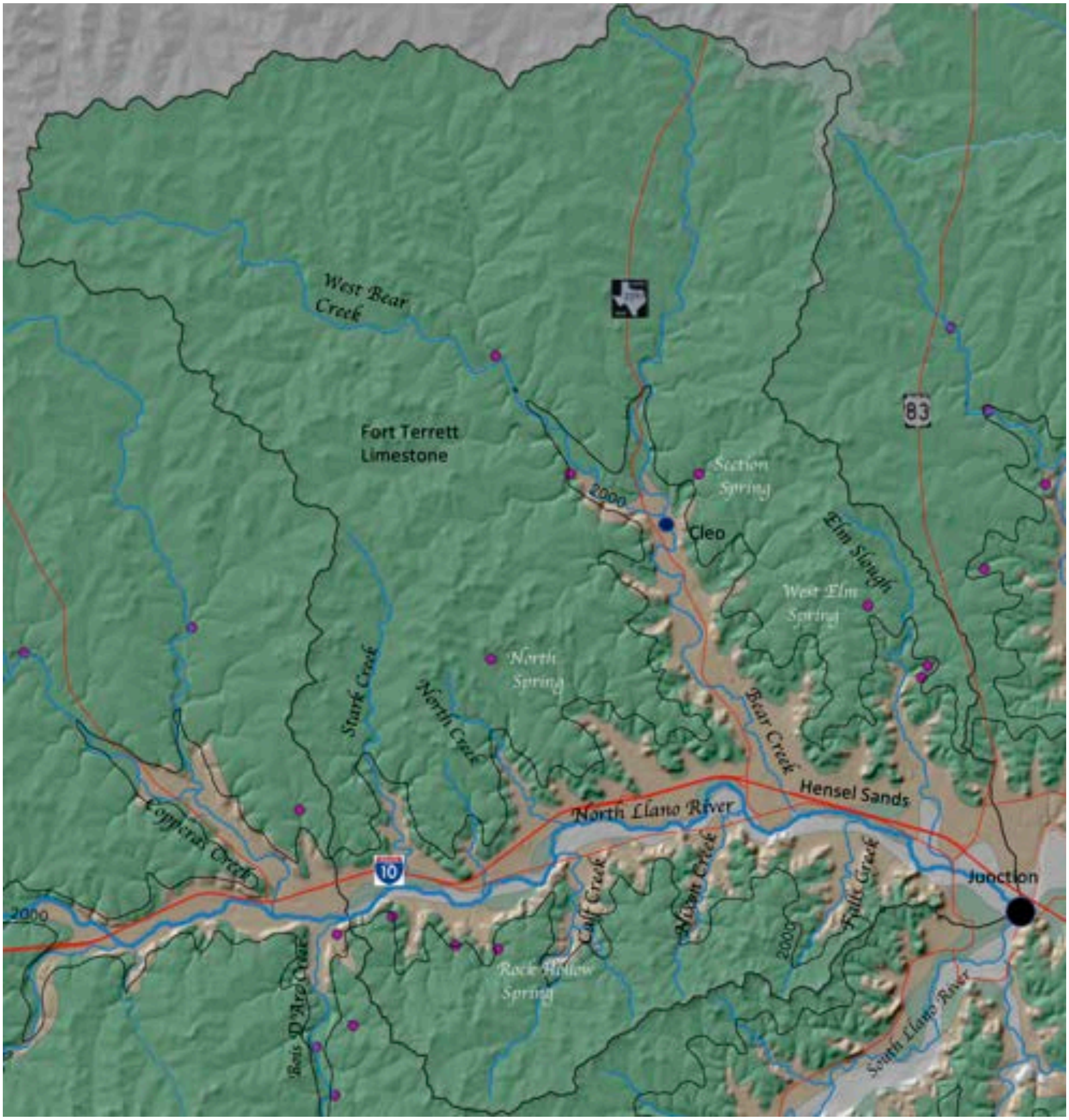

Figure 20 - Lower North Llano Sub-watershed

The Llano North Llano sub-watershed begins below the confluence of the North Llano and the Bois d'Arc Creek and terminates at the confluence of the North Llano with the South Llano in Junction, 16 miles downstream. The gradient of the North Llano in the Lower North Llano sub-watershed is 10 feet per mile.

As with the upper sub-watersheds, the primary soils of the Lower North Llano are Tarrant soils, shallow limestone-derived soils on the uplands. The channel of the North Llano is in silty, clay loamy Dev soils, while Nuvalde clay-loams adjacent to the river supports cultivation. The primary vegetation is *Ashe*-juniper, Live Oak, and savannah grassland.

From its confluence with Bois d'Arc Creek, the North Llano continues to erode into the Hensel Sands of the Trinity Formation all the way to Junction. This formation, recognized by its characteristic red beds seen along road cuts east of the Edwards Plateau (Figure 21), is less resistant to erosion than the Edwards Limestones. Meanders along the North Llano increase as a result, and the valley floor becomes nearly one mile wide. Arable cropland, some of it irrigated with water from the North Llano produces hay, grass seed, and pecans.

The major tributaries on the north side of the sub-watershed are Stark Creek, North Creek, Bear Creek and Elm Slough. Major south side creeks include Calf Creek, Nixon Creek and Falls Creek along with several minor spring-fed tributaries (not mapped): Indian Hollow, Wood Hollow and Rock Springs Hollow.

Stark Creek (8 miles in length) and North Creek (4 miles) intersect the water-bearing zone from the Fort Terrett limestone, but only one spring, North Creek Spring (2 gpm), is found [52].

Figure 21- Hensel Formation along Loop 481 east of Junction, Texas

[52] The TWDB database shows this spring to be located slightly north of its actual location.

The lack of springs is likely the result of the drainage area for Bear Creek extending above the watersheds of these creeks and intercepting most of the recharge zone for these creeks.

Bear Creek is the major tributary of the Lower North Llano sub-watershed. It rises in Menard County and flows 20 miles to its confluence with the North Llano. West Bear Creek is a 24-mile tributary that intersects Bear Creek near the community of Cleo. As with most tributaries of the North Llano, Bear Creek and its tributaries begin as intermittent streams at the divide between the Llano and San Saba Rivers. They become perennial where Section Spring on a tributary of Bear Creek and two unnamed springs on West Bear Creek issue from the burrowed zone of the exposed Fort Terrett Limestone. Section Spring measured 5 gpm when measured in 1966 and the two springs on West Bear Creek measured 1,000 gpm and 1 gpm. Flow from these springs provide sufficient flows for Bear Creek to reach North Llano as a perennial stream. These springs also provide sufficient flows to support irrigated agriculture, primarily around the confluence of West Bear Creek and Bear Creek, near the community of Cleo.

According to a 1902 Irrigation survey, the area around Cleo originally supported a wide variety of irrigated crops such as alfalfa, oats, sweet potatoes, bermuda grass, sorghum, potatoes and onions. [53] A series of timber dams along the two creeks lifted the water into flumes and ditches. Meliton Morales, a native of Mexico, one of the early irrigators, constructed a 3/4 mile stone-lined ditch in 1899 to bring water from West Bear Creek to his 10 acre field near the confluence. Flooding on the Llano destroyed many of the dams and today, irrigation pumps deliver water directly to the fields.

Elm Slough (9 miles in length) is located on the north side of the North Llano, to the east of Bear Creek. The tributary has three springs that intersect the burrowed zone, but all are small as the larger Bear Creek drainage intercepts much of the recharge area. West Elm Spring measured 5 gpm in 1966 and two unnamed springs measured 3 gpm and 1 gpm the same year. Flows from these springs are insufficient to make Elm Slough perennial at its confluence with the North Llano at Junction.

All of the six tributaries on the south side the Lower North Llano watershed intersect the 'burrowed zone' of the Ft Terrett Limestone, yet only the three tributaries furthest to the west (Indian Hollow, Wood Hollow, and Rock Springs Hollow) contain minor springs. As these tributaries are fairly small (less than 4 miles in length), their corresponding recharge zones are also small. Rock Hollow Springs discharged 20 gpm in 1966, while discharge at the other two springs measured 0.5 gpm.

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[53] Thomas U. Taylor, "Irrigation Systems of Texas". U.S. Geological Survey Water-Supply and Irrigation Paper No. 71 - Series I, Irrigation, 13, 1902.

Texas Water Development Board data show there are 359 wells in the Lower North Llano sub-watershed. Of these, 196 wells have been drilled since 2000. The depth of these wells range from less than 50 feet near the North Llano River and certain locations along Bear Creek, to generally less than 300 feet along the watershed divides, although some wells exceed 500 feet. The Edwards-Trinity Aquifer supplies the deeper wells at a rate less than 5 gallons per minute, but up to 35 gpm. Shallow alluvial wells along the North Llano also produce less than 20 gpd, but two irrigation wells produce 250 gpm. With the exception of these two irrigation wells, one public supply well (RV Park) and one industrial well (road base), all wells are used for domestic and livestock supply. Water levels in observation wells have fluctuated up to 10 feet over the last 10 years. .

SOUTH LLANO

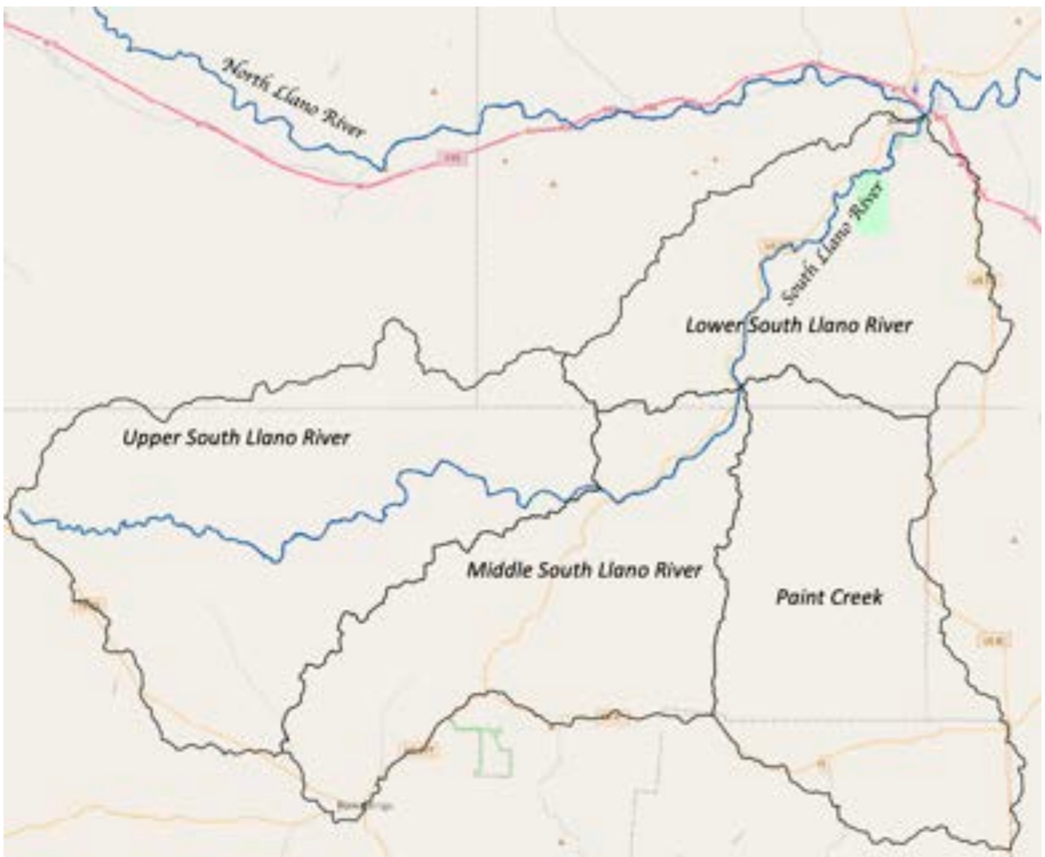

Figure 22-Upper South Llano Sub-watershed

The South Llano River watershed begins on the Edwards Plateau 22 miles northwest of Rocksprings in Edwards County. The River flows intermittently across the plateau for its first 39 miles before becoming perennial for its final 30 miles to its confluence with the North Llano in Junction (Figure 22).

The South Llano is considered as three sub-watersheds for the purposes of this report: Upper, Middle and Lower South Llano. The hydrologic and demographic characteristics for each sub-watershed are discussed further below.

Upper South Llano Sub-watershed

The Upper South Llano sub-watershed is 305 square miles in size flanked by the North Llano to the north, the Dry Devils River to the west and the Nueces River to the south. *Ashe*-juniper, live oak and savannah grasslands are the predominant vegetation and ranching and commercial hunting leases are the primary source of income. The Upper South Llano is very similar to the Upper North Llano watershed, but due to the gradual slope of the Edwards Plateau towards the Gulf of Mexico, the elevation of features in the South Llano is slightly lower than similar features in the North Llano.

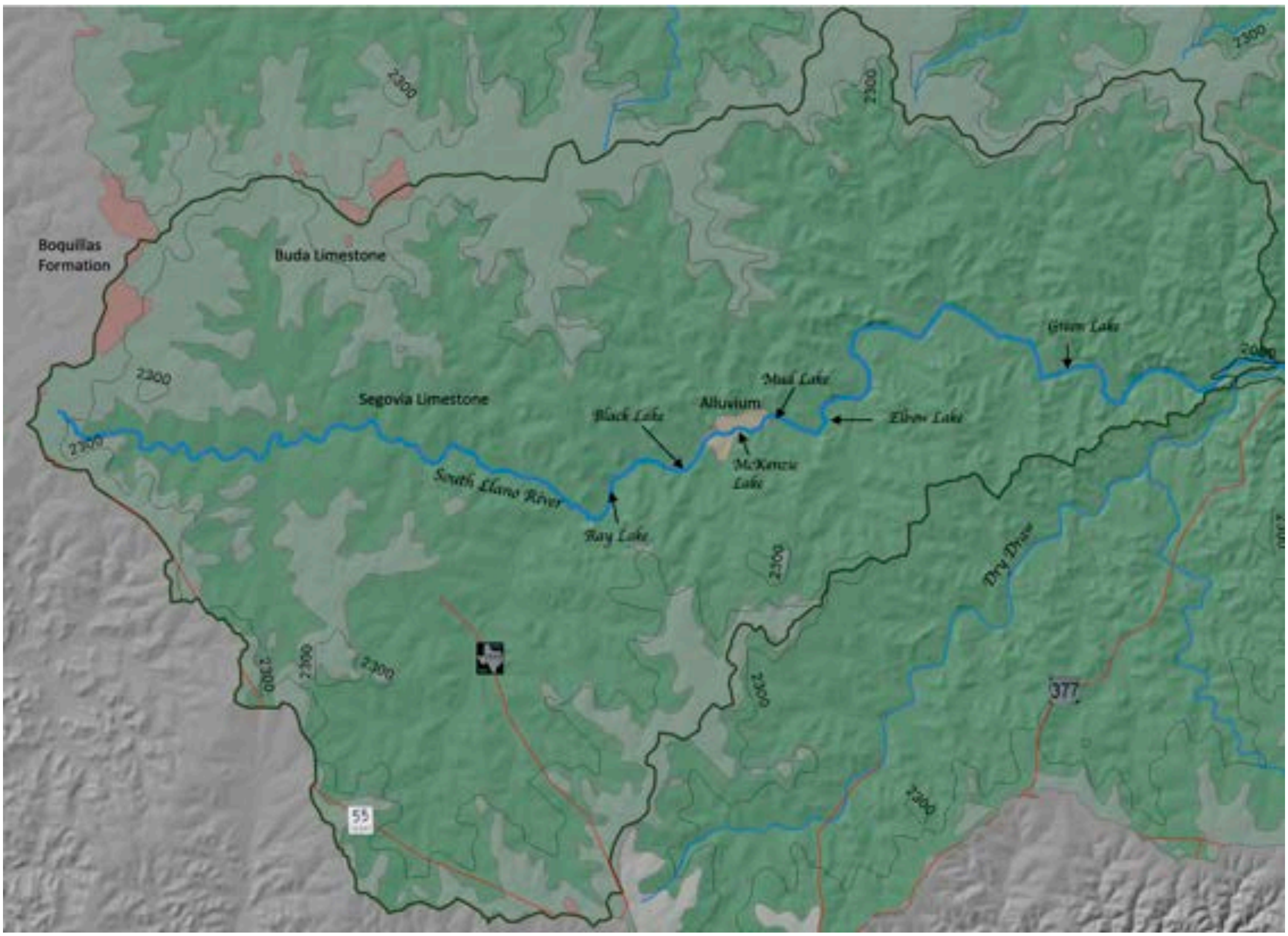

Figure 23-Upper South Llano Sub-watershed

The divide defining the South Llano Watershed is just over 2,320 feet above sea level, compared to 2,400 in the North Llano. As with the North Llano, this low, nearly level divide is covered by Buda Limestone and also includes an additional layer known as the Boquillas formation that lies atop the Buda formation. Both of these fairly impermeable layers are pocked in areas with small clay-filled playa depressions that temporally hold water following precipitation events. These depressions are similar to those in the North Llano, but are fewer in number in the South Llano. Soil types along the divide are primarily silty clay Eckrant-Rock outcrop soils on the uplands.

Less than one mile from the divide, the ephemeral draws of the Upper South Llano begin to erode into the underlying limestone at a rate of nine feet per mile, exposing the Segovia member of the Edwards limestone just below 2,300 feet. This layer of limestone is generally unsaturated, so no springs are found along this 39-mile segment. The Tarrant-Valera complex of soils generally found along this section are cobbly, clay soils.

Figure 24-Green Lake located on private property along the upper reaches of the South Llano River (access provided by landowner).

About 17 miles from the headcuts of the South Llano, alluvial valleys begin to form along the sinuous draws. Soils along the beds and banks of this ephemeral segment are Oakalla clay loams believed to have been eroded from the uplands during wetter periods 6,000 years ago. [54] While the draws of the Upper South Llano do not contain springs, there are 'lakes' along the lower reaches (Figure 24). These lakes (Ray, Black, McKenzie, Mud, Elbow, and Green Lake) formed by a similar process as the water holes on the North Llano, with the depositional material underlying the riverbed having a high ability to store

[54] Heitmuller, 2009

water. Green Lake was the site of a gun-battle between Texas Rangers and 'fence-cutters' in 1883 over dwindling water supplies for sheep and cattle during the drought of the 1880s [55].

The South Llano in the lowest two to three miles of the sub-watershed remains ephemeral as it begins to downcut into the upper sections of the Fort Terrett limestone (not mapped) at an elevation of 2,000 feet. Here, increased drainage area results in increased stream power during precipitation events, incising a narrower and straighter channel into the bedrock as it nears the confluence with Dry Draw. Streambanks transition from gradual alluvial banks to step-like bedrock banks.

The confluence of the South Llano River with Dry Draw is located at 1,950 ft above sea level and just above the 'burrowed zone' of the Fort Terrett limestone, from whence the major springs of the Llano emanate. The area of contact between the overlying Segovia and Fort Terrett formations is the location for the majority of the caves in the region.[56] Recharge features (generally collapsed karst features) found in the beds of ephemeral streams of the Upper South Llano contribute to recharge.

While the lakes along the Upper South Llano do provide some water supply, the majority of water supply in the watershed is from groundwater. The population of the watershed is estimated to be 81 with 86 houses.[57] Today, more than 133 wells [58] in Texas Water Development Board databases are located in the watershed, including 68 drilled in the last 20 years. All of the wells are either for domestic or livestock purposes. These wells are generally 200 to 500 feet deep and produce less than 15 gallons per minute. According to the USGS, water levels in the aquifer under the sub-watershed follow the gradient of the South Llano, moving from southwest to northeast, emerging as springflow in the lower portions of the river. [59] There are no active observation wells in the Upper South Llano.

Numerous natural gas wells also dot the landscape especially along the western and northern borders of the watershed. Nearly 325 of these wells are considered "High Cost Tight Gas", a term that encompasses fracking [60]. The volume and source of the water used for fracking is unknown.

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[55] Jobes, Harold D., "Fence Cutting and a Ranger Shoot-out at Green Lake." Wild West History Association Journal. October 2009.

[56] Veni, G. 1994. Hydrogeology and evolution of caves and karst in the southwestern Edwards Plateau, Texas. Pp. 13–30, in The Caves and Karst of Texas (W. R. Elliott and G. Veni, eds.). National Speleological Society, Huntsville, Alabama. 252 pp.

[57] Approximately 60% of these homes are assumed to second family homes as the persons per household in Edwards County is 2.42.

[58] Not all wells drilled before 2000 are listed in the Texas Water Development Board database.

[59] Kuniansky and Holligan, 1994

[60] Texas Railroad Commission Public GIS Viewer, Version 3.7, accessed November, 2020

Middle South Llano Sub-watershed

The Middle South Llano sub-watershed is 218 square miles and primarily includes Dry Draw, Contrary Creek, and South Llano River from its confluence with Dry Draw to the confluence with Paint Creek (Figure 25). The sub-watershed borders the Nueces watershed watershed to the south and Paint Creek Watershed to the east. *Ashe*-juniper, live oak, and savannah grasslands are the predominant vegetation and ranching and commercial hunting leases are the primary source of income. The City of Rocksprings also benefits from tourism visits to Devil's Sinkhole State Natural Area, located just east of the city and in the Nueces watershed.

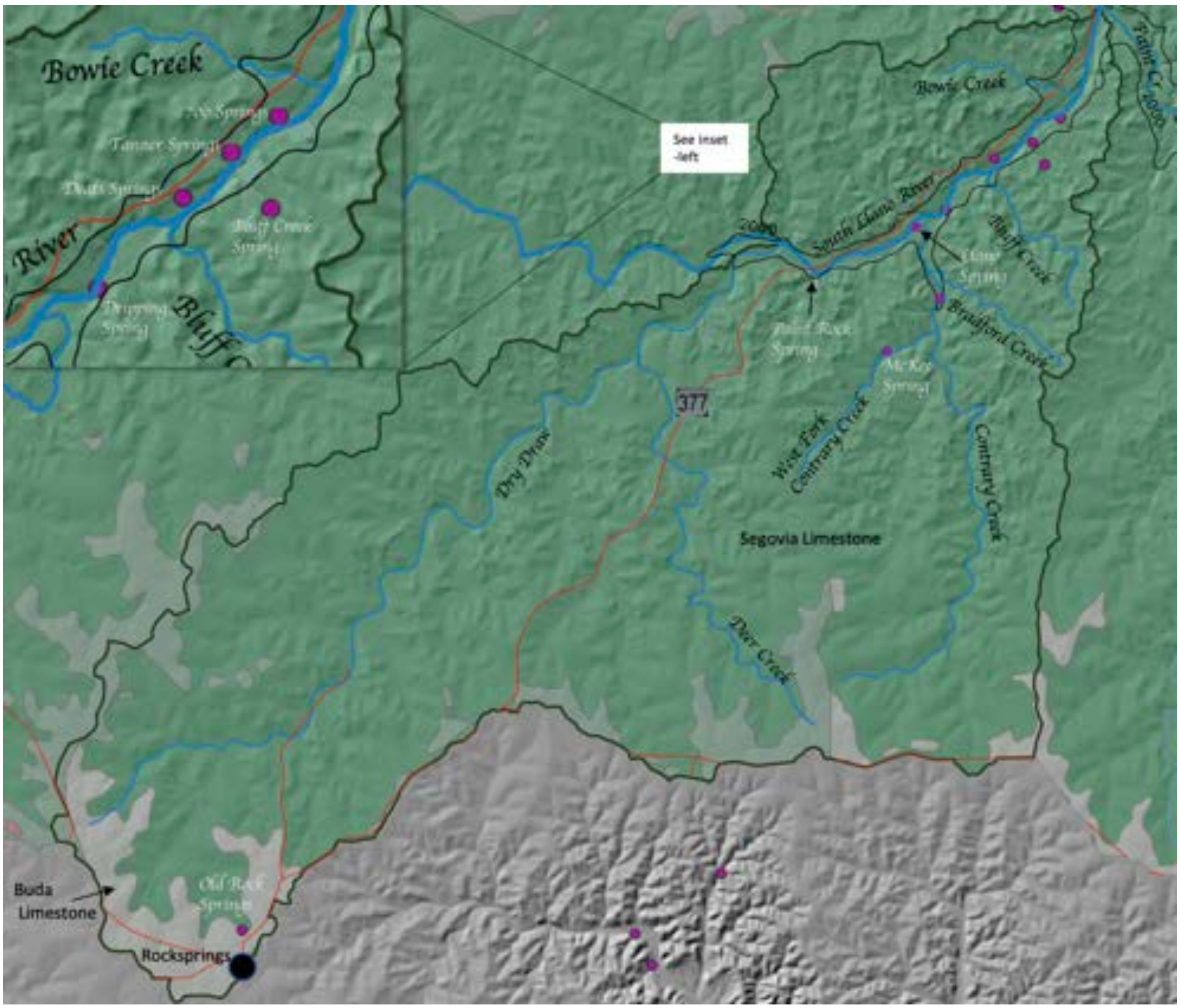

Figure 25 - Middle South Llano Sub-watershed

The hydrologic setting for Dry Draw is very similar to the Upper South Llano River, beginning at a divide of 2,410 feet above sea level near Rocksprings, the county seat of Edwards County. The town is named for Old Rock Springs, just northeast of the city that was an early water supply. These springs differ from most of the springs in the Llano Watershed because they are located at the top of the watershed divide, overlying groundwater perched above the water table on an impermeable layer. Owing to this location, the recharge area for the springs is likely quite small; the springs have been dry for several years, according to the Springs of Texas database.[61] From the initial headcut less than a mile from the playa-covered divide, Dry Draw flows 25 miles over first Segovia formation and then Fort Terrett formation near its confluence with the South Llano. The stream gradient along Dry Draw is 16 feet per mile. Soil profiles along this segment are similar to the Upper South Llano River sub-watershed.

Contrary Creek, so named because it flows into the South Llano River facing in a direction upstream of the flow, is a 14-mile tributary to the Middle South Llano with a gradient of 26 feet per mile. As with Dry Draw, Contrary Creek begins downcutting into the Segovia Formation near its headwaters, eventually contacting Fort Terrett limestone above its mouth on the South Llano. As the mouth of Contrary Creek is situated at 1,920 feet, some 30 feet deeper into the Fort Terrett formation than Dry Draw, an unnamed spring is located just above the confluence with the South Llano. [62] McKee Springs is located at an elevation of 2,100 feet on the West Prong of Contrary Creek; no additional information regarding its source or flow is available.

The middle portion of the South Llano River is a 10-mile long segment beginning at the confluence of Dry Draw and flowing to the mouth of Paint Creek. The stream gradient decreases to 10 feet per mile as the channel continues to incise into bedrock. Just below the confluence of the South Llano with Dry Draw, the South Llano passes US 377 South and Paint Rock Spring. This spring, at an elevation of 1,940 feet, provides anecdotal evidence of how the loss of soil and the shift of upland landscape from a grassland savannah to juniper may impact water resources on the South Llano. Gunnar Brune, in *Springs of Texas*, describes Paint Rock Springs as "much larger around the turn of the century" (1900) when they formed the headwaters of the South Llano River and were a midway stop on the Fort Clark to Fort McKavett road from 1852 to 1883.[63] Today, Paint Rock Springs, so named for Native American pictographs on a nearby bluffs, flows less than 5 gpm and the headwaters of the Llano are located 2.5 miles downstream at Llano Spring at an elevation of 1,910 feet. As only minor

[61] Heitmuller, F.T., and Reece, B.D., 2003, Data base of historically documented springs and spring flow measurements in Texas: U.S. Geological Survey Open-File Report 03-315

[62] No additional information is available for this spring.

[63] Brune, 1981.

groundwater pumping occurs above Paint Rock Springs, the decline in landscape conditions is likely the cause.

Llano Spring is located just west of Blue Hole on the Llano, below Contrary Creek [64]. Here the South Llano River becomes perennial. According to Brune, the spring flowed 70 gallons per minutes (gpm) in 1939, almost went dry during the drought of the 50s, and flowed 350 gpm after a rain in 1979. More recently, following restoration efforts by the landowner, flows were measured at 1,500 gpm or about 4 cfs.[65]

The 'burrowed zone' of the Fort Terrett provides the majority of the springflow to the Llano.[66] The permeable, honeycombed nature of this zone results from preferential leaching of burrow fillings made by inhabitants of the ancient Cretaceous sea sediments. Other springs along this portion of the river fed from the 'burrowed zone' include Dripping Springs (measured at 70 gpm in 1939), Bluff Creek Springs (measured at 100 gpm in 1956), Deats Springs (190 gpm in 1939, dry in the 50s, and 350 gpm in 1979), Tanner Springs, and Seven Hundred Springs (discussed below in further detail). Downstream of Seven Hundred Springs is Bowie Spring (not mapped), a small spring on Bowie Creek, a tributary of the South Llano; little information is available for this feature.

Figure 26-Seven Hundred Springs

Because the South Llano River likely serves as a low point for spring flows from either side of the river, it can be assumed that flows to Dripping Springs and Bluff Creek Springs, located on the right bank originate from the uplands to the east and southeast. Flows to the other springs on the left bank likely originate from the uplands to the northwest and west. [67]

Seven Hundred Springs is the largest springs on the South Llano River (Figure 26). Brune notes the flow of Seven Hundred Springs in 1952 and in 1956 (during the drought

[64] A former TxDot Picnic Area is located above the spring on US 377 just north of the furthest south crossing of the South Llano.

[65] *Personal communication*, Tom Vandivier, landowner, November 25,2020

[66] Rene A. Barker, Peter W. Bush, and E.T. Baker, Jr, "Geologic History and Hydrogeologic Setting of the Edwards-Trinity Aquifer System, West-Central, Texas. U.S. Geological Survey Water-Resources Investigations Report 94-4039.

[67] Seven Hundred and Tanner Springs are located along the west (left) bank of the South Llano River. Springs of Texas database, a source of data displayed in this report, incorrectly shows the Springs to be on the east bank.

of the 1950's) was 11 cubic feet per second (cfs) [68]. The US Geological Survey has taken periodic measurements (two to eight times per year) of Seven Hundred Springs since 1959 and nearby Tanner Springs since 1987 (Table 2).

Table 2. Measured Median and Low Flows in cubic feet per second for 700 and Tanner Springs.

	Seven Hundred Springs	Tanner Springs
Median Flow	19.2	11.5
Lowest Flow (year)	11.7 (2011)	2.0 (2015)
Highest Flow (year)	42.5 (1973)	17.7 (1997

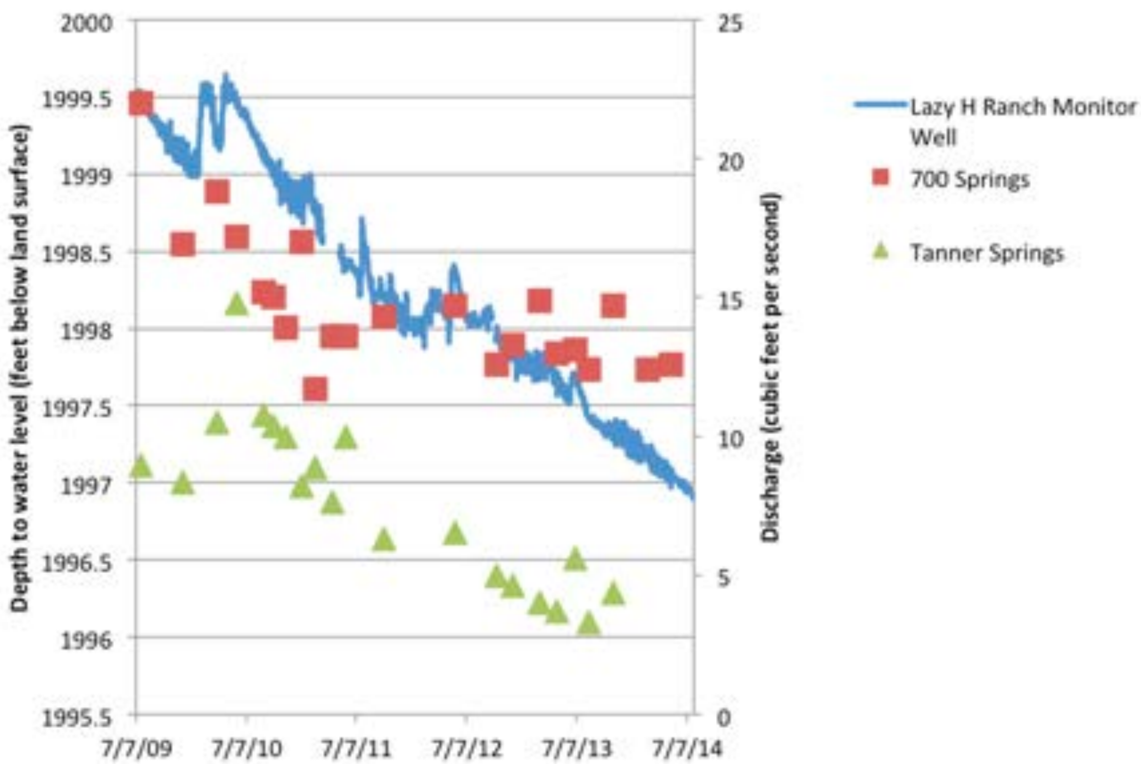

Figure 27- Groundwater levels measured at the Lazy H Ranch in Edwards County and discharge from Seven Hundred springs and Tanner Springs in Edwards County from 2009-2014.

[68] Brune, 1981

Tanner Spring, Seven Hundred Springs, and the other springs along the South Llano River primarily rely on recharge to the Edwards-Trinity Aquifer. Figure 27 depicts declining water levels in a monitoring well near Rocksprings (active 2009-2014) with decreasing springflows in Seven Hundred Springs and Tanner Springs.[69]

While water levels in the well only declined about 2.5 feet, Tanner Springs fell below 5 cfs and registered its lowest recorded flow of 2 cfs in January of 2015. Spring flow at Seven Hundred Springs declined to about 12 cfs and then maintained a fairly continual flow, suggesting that springflow at this spring is fed by multiple sources. These springs reacted in the same manner during the drought of the 1950s.

The springs along the Middle Upper South Llano have served as an important water-supply source for centuries. According to local historian, Frederica Wyatt, Captain Juan deMendoza was the first non-native American to visit the spring in 1638. His Spanish troops camped for six weeks along the 'San Clemente River', so named by deMendoza. More than a century later, in 1767, Marquis deRubi camped along the Rio Chanas (so named for the native Americans who lived along the river) on an inspection of New Spain.[70] It is believed that the name Rio de los Chanas was corrupted over time to become the Rio de los Llanos and later the Llano River.

The open range of Edwards County in the 1880s provided opportunity for many cattlemen and the springs provided an important water source for numerous cattle and later sheep. The channel of the South Llano River also provided an important transportation corridor between Junction and Rocksprings, with the road crossing the river 21 times and Seven Hundred Springs serving as an important rest and camping place [71].

Tanner Springs, according to Brune, was used to power a mill while Llano, Tanner, and Seven Hundred springs have been used to irrigate primarily corn, wheat, and cane using ditches and flumes beginning around 1900, according to the U.S. Geological Survey [72] . A 1907 irrigation water right is associated with these springs.

The majority of the water supply in the watershed, however, is from groundwater. The population of the watershed is estimated to be 1,132 with 585 housing units. The vast

[69] U.S. Geological Survey, 2016, National Water Information System data available on the World Wide Web (Water Data for the Nation), accessed 2016.

[70] Frederica Wyatt, "Places of Interest - Seven Hundred Springs : Source of the South Llano has rich history", in Kimble County Visitor Guide, *The Junction Eagle,* 2005.

[71] Wyatt, 2005.

[72] Taylor, 1902.

majority of this population in Rocksprings. [73] The City of Rocksprings pumps 162 acre-feet per year from wells in the Edwards-Trinity (Plateau) aquifer, or 144,000 gallons per day. Wells serving Rocksprings are the largest producing wells in the entire Llano watershed, providing more than 500 gallons per minute from depths of more than 600 feet. Most other wells in the sub-watershed yield less than 30 gallons per minute.

Today, more than 166 wells in Texas Water Development Board databases are located in the watershed, including 86 drilled in the last 20 years. With the exception of the municipal supply wells in Rocksprings, all of the wells are either for domestic or livestock purposes. These wells are generally 200 to 500 feet deep and produce less than 20 gallons per minute. The deepest wells are located at in the upper reaches of the watershed where depth to water is greatest. Water levels in the aquifer under the watershed follow the gradient of the South Llano topography, moving from southwest to northeast, emerging as springflow around 1,900 feet above sea level.

Numerous natural gas wells also dot the landscape of the Middle Llano Sub-watershed, primarily along Dry Draw. About 30 of these wells are considered "High Cost Tight Gas", a term that encompasses fracking [74]. This is the eastern extent of the Permian Basin oil and gas producing area.

Paint Creek Sub-watershed

Paint Creek is a 32-mile tributary of the South Llano River whose confluence lies just north of the Edwards - Kimble County line at an elevation of 1,850 feet. The Paint Creek Watershed is 219 square miles and includes Earwood Creek, Hunger Creek, and Beasley Draw on the west side of the watershed, and Smith Hollow, Lydle Draw, Post Oak Draw, Live Oak Draw, and Wildcat Draw in the east. [75] Paint Creek sub-watershed borders the Frio and Nueces watersheds to the south, the Guadalupe to the east, Johnson Fork of the Llano to the North, and the South Llano to the west. *Ashe*-juniper, live oak and savannah grasslands are the predominant vegetation with live-oak mottes become more prevalent than elsewhere in the North and South Llano. Eckrant-Rock outcrop, a cobbly silty clay, is the dominant soil type and ranching and commercial hunting leases are the primary source of income.

Paint Creek begins five miles south of Garvin Store at an elevation of 2,405 feet (Figure 28). Unlike the other South Llano sub-watersheds, there is less Buda and Del Rio formations overlying the Segovia formation and there are no playa lakes in the upper reaches of Paint

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[73] Rocksprings had a population of 1,177 and is located in both the Llano and Nueces watersheds. Approximately 20% these homes are assumed to second family homes as the persons per household in Edwards County is 2.42.

[74] Texas Railroad Commission Public GIS Viewer, Version 3.7, accessed November, 2020

[75] Named creeks are shown on the map. Named draws are not shown.

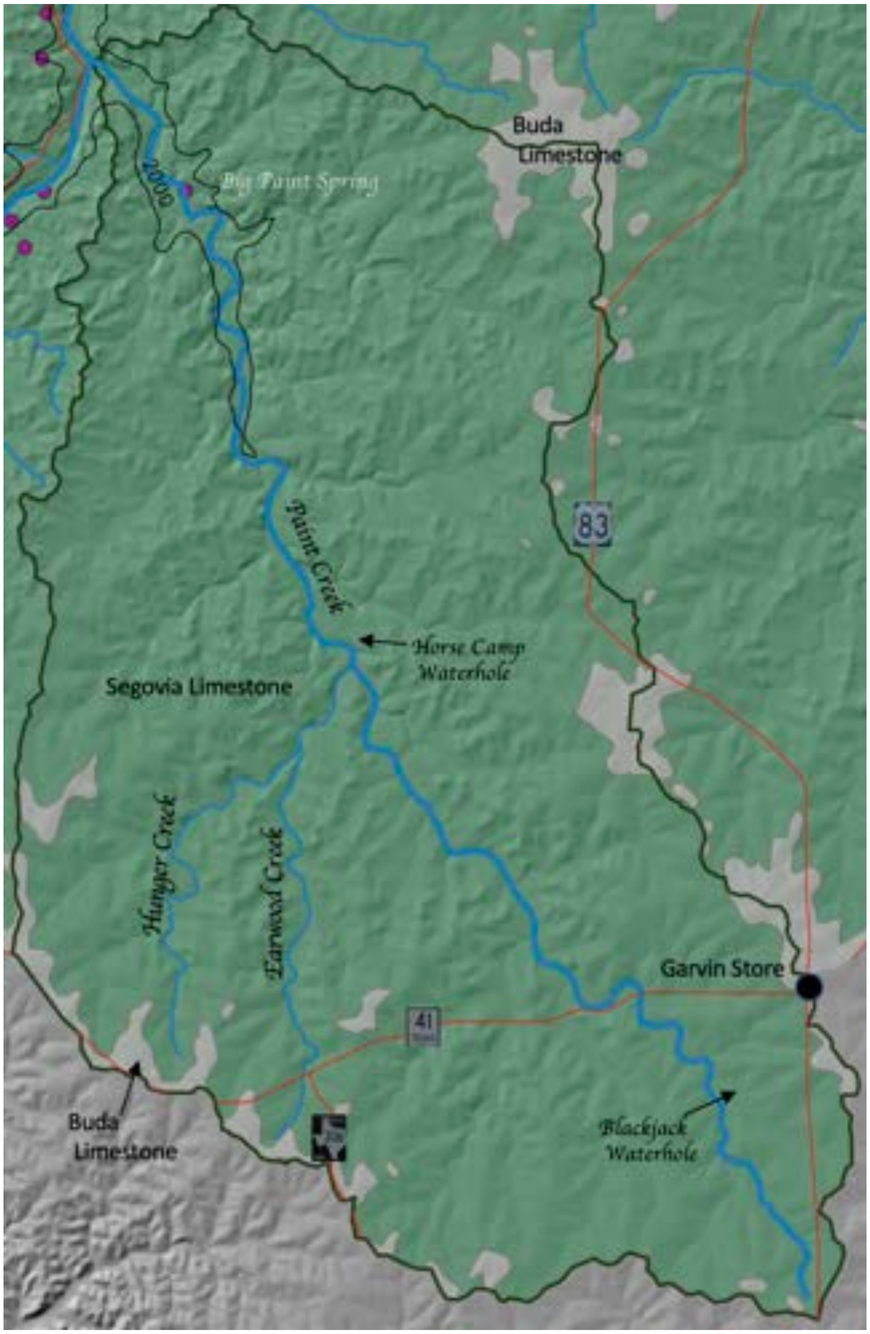

Figure 28 - Paint Creek Sub-watershed

Creek. From the divide, Paint Creek carves into the Segovia formation at a rate of 17-feet per mile to an elevation of 2,030 feet; here it exposes the Fort Terrett formation. Due to the general southeastern tilt of the Edwards Plateau, the elevation of this contact is 120 feet lower than the Segovia/Fort Terrett contact in the Upper North Llano, 35 miles to the northwest.

Alluvial materials in the channel of Paint Creek are Dev-Riverwash, a gravelly loam. The absence of significant clay materials may account for the fact that there are only two named waterholes in the watershed. Black Jack Waterhole is on a tributary of Paint Creek near the headwaters of the watershed; the origin of this waterhole is undetermined. Horse Camp Waterhole is the second waterhole and is located at an elevation of 2,050 above sea level, just above the contact with the Fort Terrett formation.

Numerous springs (unmapped) appear along Paint Creek as the waterway erodes into the burrowed zone of the Fort Terrett limestone at about 1,900 feet above sea level. The largest of the springs and the largest spring in the Llano watershed is Big Paint Springs, also known as Boiling Springs (figure 29) due to spring water bubbling to the surface from fissures in the river bottom. These springs may have been visited by a member of Coronado's army around 1543. [76]

Figure 29 - Sampling an opening in Big Paint or Boiling Springs

Big Paint Springs have only been measured three times; the readings are presented in Table 3, along with the corresponding measurements for Seven Hundred and Tanner Springs. At the time measurements were taken at Big Paint Springs, the flow from these springs accounted for between 35 and 70 percent of the flow in the Llano River at Junction, not accounting for any water withdrawals between the springs and the Junction gage, or water withdrawals below the North Llano River gage. At the time of these measurements, Big Paint Springs had between 42 and 63% more flow than Seven Hundred Springs. Brune reports that water from the Big Paint Springs has been used for irrigation and in 1938 supplied four fish ponds. A 1913 water right is associated with these springs.

Table 3. Comparison of Discharge for Big Paint Springs to Seven Hundred and Tanner Springs in cubic feet per second

Spring	March 1939	Sept 1955	March 1962
Big Paint	22	18	31
Seven Hundred	15	11	22
Tanner	9	-	-
North Llano River	18	6	23
Llano River nr. Junction	64	31	113
Big Paint Contribution to Llano R nr Junction	47%	71%	34%

[76] Brune, 1981

The majority of the water supply for the 88 residents and 177 housing units in the sub-watershed in 2010 is from wells. [77] The Texas Water Development Groundwater database shows 178 wells in the Paint Creek Watershed, including 152 that have been drilled since 2000. The majority of these new wells serve ranchettes located in the middle portion of the sub-watershed. The wells range from 100 to about 250 feet deep and generally produce less than 10 gpm. Groundwater flow in the watershed generally follows the overlying topography, moving from a groundwater mound with an elevation of 2,000 feet towards spring outlets at 1,900 feet. There are no active natural gas wells in the Paint Creek watershed.

Lower South Llano River Sub-watershed

The 190-square-mile area draining to the 21-mile section of the South Llano River from its confluence with Paint Creek to its confluence with the North Llano River comprises the Lower South Llano River sub-watershed. The gradient of the River decreases along this section to about 9 feet per mile. Mapped tributaries on the western side of the sub-watershed include: Christmas Draw; Salina Creek; Little Paint Creek; Cajac Creek; Ratliff Creek, Bailey Creek; Joy Creek; and Potter Creek. Mapped east side tributaries include Chalk Creek, Dry Cedar Creek and Cedar Creek. Paint Creek sub-watershed borders the Lower South Llano on the south and Johnson Fork on the east. *Ashe*-juniper, and live oak are the predominant vegetation across predominantly shallow Tarrant soils derived from the limestone uplands. Total population of the watershed is 1,606, mostly centered on Junction. There are 976 housing units in the watershed, 2/3 of which are estimated to be primary residences.[78]

Archaeological evidence (Perdiz Points and pottery) near the Second Crossing of US 377 north of Telegraph, indicates the Toyah culture lived in this area 700 years ago, having followed the buffalo into the area following a Little Ice Age that brought a cooler climate and an expansion of grasslands.[79] Today, the rearing of domesticated livestock, hay production, and commercial hunting leases are the primary sources of income. In addition, water-related tourism associated with the South Llano River is a long-time economic generator for the area.

Kimble County dubs itself the “Land of Living Waters” owing to the claim that there is more flowing water in Kimble County than any other county in Texas. Prior to the construction of the Highland Lakes, beginning with the construction of Buchanan Dam in 1939, opportunities for water-based recreation in the Hill Country were limited. One exception,

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[77] It is estimated that 80 percent of these housing units are second family homes as persons per household in Edwards County is 2.42.

[78] Kimble County persons per household is 2.43. Dividing this value into the population provides an estimate of housing units occupied as primary residences.

[79] Stephen M Carpenter, K.M. Miller, C.D. Frederick, L.G. Cecil, and M.C. Cody. The Little Paint Site: A Classic Toyah Camp on the South Llano River, Kimble County, Texas. Index of Texas Archaeology, Volume 2012, Article 3, 2012.

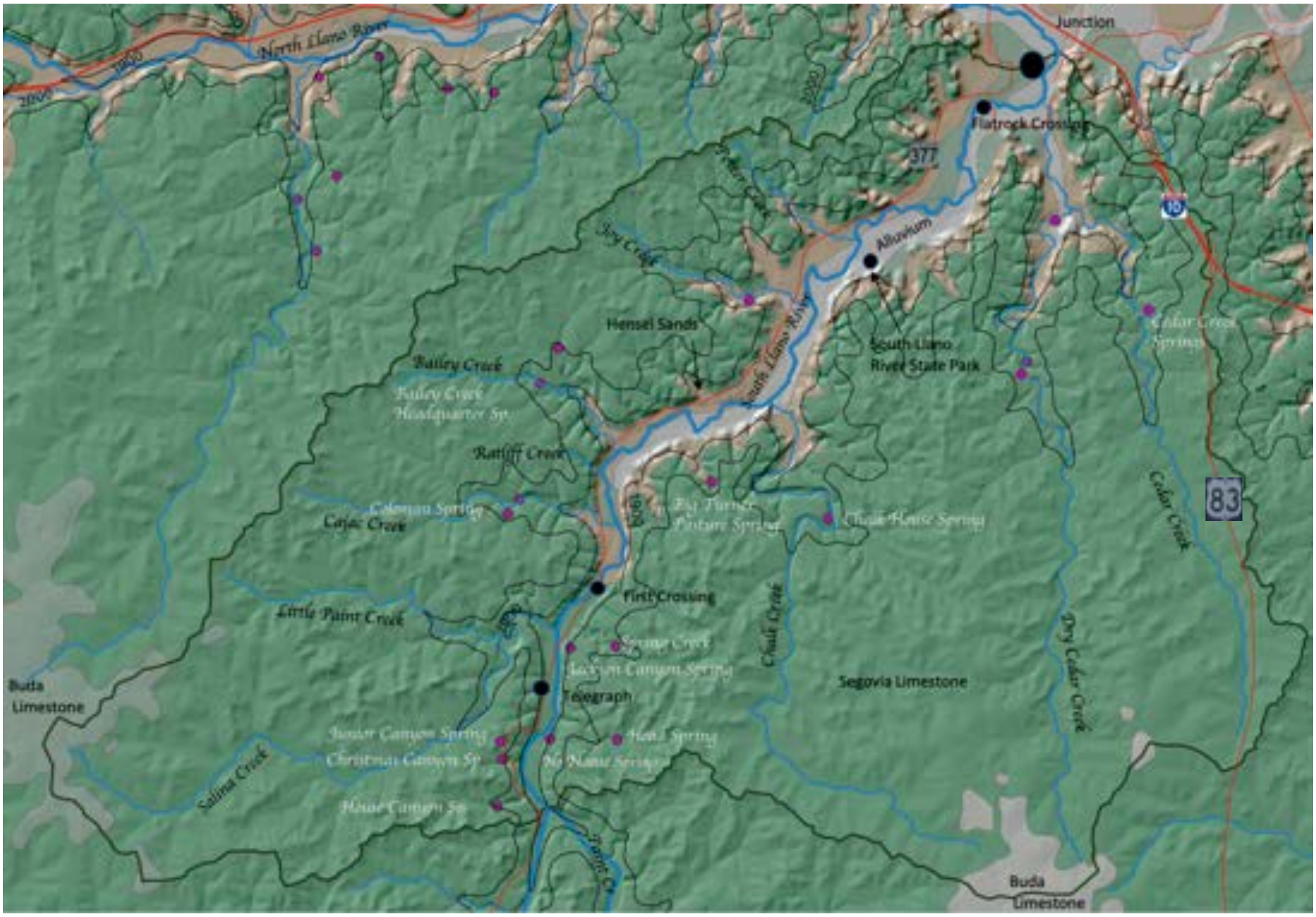

Figure 30 - Lower South Llano Sub-watershed

however, was the spring-fed waters of the South Llano River where numerous tourist cottages were constructed along the river's banks. Several of these cottages are still visible.[80] Today, tourist travel to Junction to enjoy South Llano River State Park and the South Llano River Paddling Trail.

The Lower South Llano River sub-watershed is discussed in four parts in this section: 1) Confluence of Paint Creek to Telegraph; 2) Telegraph to First Crossing; and 3) First Crossing to South Llano River State Park; and 4) State Park to confluence with North Llano in Junction.

Confluence of Paint Creek to Telegraph

The upper portions of the watershed downstream to Telegraph are very similar to the upstream segment of the South Llano below the headwater springs, being fairly straight and incised into bedrock. Soils along this segment of river are Frio silty clay loam.

[80] Frederica Wyatt, "Touring Junction and Kimble County", in "Visit Junction and Kimble County", supplement to the *Junction Eagle,* 2020.

While the channel elevation of the South Llano River has eroded below 1,900 feet, the elevation of most of the nearby springs, the tributaries of the South Llano expose the burrowed section of the Fort Terrett limestone, exposing additional springs. Less than a mile below the confluence of Paint Creek and the South Llano, House Canyon Spring (100 gpm), Christmas Canyon Spring (5,000 gpm or 11 cfs), and Junior Canyon Springs (2,000 gpm) issue from tributaries of the west bank of the South Llano, while No Name Springs (25 gpm) issues from the right bank. All measurements for these springs were taken in 1966. Water from Christmas Canyon Spring historically was carried under the South Llano in a 300-foot long iron pipe to irrigate about 25 acres of corn and cane on the east bank. An 1895 water right is associated with the Christmas Canyon Spring. Further downstream, across the river from Telegraph, Head Spring is located in the upper reaches of Telegraph Canyon. Twenty-five gallons per minute was measured at this spring in 1966.

Telegraph to First Crossing

Between Telegraph and the First Crossing (lowest crossing) of US 377, the river beings to expose the more erosive Hensel Sands of the Trinity Formation. As a result, the river valley widens and the channel becomes more sinuous, changing from primarily a bedrock channel to one consisting of pebbles and cobbles. Soils are Dev very gravelly loam, and in places, irrigation of hay using surface water from the South Llano occurs presently.

Springs issue from the burrowed zone of the Fort Terrett limestone along several tributaries to the South Llano in this segment. These springs and the volume of discharge they produced in 1966 include Jackson Canyon Springs (150 gpm), Spring Creek (300 gpm), and Ford Canyon (15 gpm) [81], all on the east side of the river. The west side contains only one unnamed and unmeasured spring on Little Paint Creek. Around the turn of the last century, water from Little Paint Creek was used to grow corn and cotton while water from Fleming Draw (Spring Creek) was used to grow corn, oats, cane and alfalfa.[82] A water right for Little Paint Creek dates from 1910, while the water right for the Fleming Draw diversion dates to 1881.

In 1918, and again in 1925, a gain-loss study was done on the South Llano River to understand the contributions of various tributaries to the river. [83] Table 4 shows these contributions to the river. The 1918 study showed that 62% of the flow in the South Llano came from Big Paint Creek; the 1925 study showed that the contribution from Big Paint was 50%. It should be noted that from below the confluence of Big Paint Creek and the South Llano River to the confluence with the North Llano River, the South Llano River gained an

[81] Ford Canyon Spring is unmarked on the map but lies due east of First Crossing.

[82] Brune, 1981

[83] Raymond M. Slade, Jr., J. Taylor Bentley, and Dana Michaud, "Results of Streamflow Gain-Loss Studies in Texas, With Emphasis on Gains From and Losses to Major and Minor Aquifers". U.S. Geological Survey Open-File Report 02-068, 2002.

additional 2.3 cfs in 1918 and an additional 3.5 cfs in 1925. It is presumed that these additional flows came from other springs discharging to the river.

Table 4. Measurements in cubic feet per second from Gain-Loss Studies on the South Llano

	April 1918	February 1925
Big Paint Creek	23.1	36.5
South Llano above Big Paint Creek	11.7	32.6
South Llano above N Llano River	37.1	72.6

These gain-loss studies demonstrate, but do not specifically quantify, the contribution that spring flow makes to the flow of the South Llano River. However, a 1989 US Geological Survey [84] study estimates that baseflow (that part of streamflow that is not direct surface runoff) accounted for approximately 81% of all flow passing the Llano River gage at Junction between 1974 and 1977. While the North Llano River does contribute some baseflow to the gage, the majority of the flow comes from the South Llano River.

First Crossing to South Llano River State Park

Beginning at the First Crossing, the river flows towards South Llano River State Park across older, less permeable Trinity Hensel Sand formation, consisting of sands, silts, and clays. Contribution to springflows do occur from the Hensel Sand from water infiltrating from the overlying Edwards, but these contributions are considerably less than springflow contributions from the Edwards. [85]

Tributary streams to this segment that cross the permeable burrowed zone of the Fort Terrett Formation provide additional flow along this segment. On the west side of the South Llano, springs are identified at an elevation of 1,900 feet on Cajac Creek, Ratliff Creek, Bailey Creek, Joy Creek, and Potter Creek. On eastern tributaries, springs are noted on Chalk Creek and an unnamed tributary to the west of Chalk Creek. Coleman Springs on Cajac Creek measured 750 gallons per minute in 1966 and a nearby unnamed spring on the same tributary measured 100 gallons per minute. On Bailey Creek, discharge at the Headquarters Spring measured 140 gpm; flow at another spring on Bailey Creek was not reported, but it was noted that the spring serves a house by means of a 3,500 foot pipeline. No additional information or discharge data for springs are reported on the west side. On the east side, Chalk House

[84] Kuniansky, 1989.

[85] The author speculates that springs mapped at approximately 1,800 feet on Joy Creek and at the confluence of Dry Cedar and Cedar Creek may be of Hensel Sand origin, but no additional data are available.

Spring measured 25 gpm in 1966, as did Big Turner Pasture Spring on the upstream unnamed tributary. [86]

The water rights for Cajac Creek date back to the 1880s and to 1908 for Bailey Creek. In 1901, 62 acres were irrigated with springflow from Cajac Creek to raise oats, ribbon cane, wheat, vegetables, sweet potatoes and cotton on four separate farms. On one project on Bailey Creek, springflow irrigated four or five acres of cane, sweet potatoes, and corn.[87] Today, hay is the principle irrigated crop along the South Llano.

From the First Crossing to South Llano River State Park, the valley floor continues to widen and riparian zones containing large pecan trees begin to develop. As the channel is no-longer bedrock, meandering low-flow channels erode into the alluvial floodplain material, capped with fine-grained overbank material. This fine-grained material often erodes into steep cutbanks on the outside of meanders, opposite gently sloping point bars consisting of coarser materials.[88]

South Llano River State Park to Confluence

The final section of the Lower South Llano River is from South Llano River State Park to the confluence of the South Llano with the North Llano, the headwaters of the main stem of the Llano River. Along this section, the valley floor continues to widen and low-flow channels form ever-increasing meanders within the alluvium between the valley walls. Over-flow channels paralleling

Figure 31- Exposed irrigation pipe resulting from increased meander erosion.

[86] Brune, 1981.

[87] Taylor, 1902.

[88] Franklin T Heitmuller, Paul F. Hudson, William H. Asquith, “Lithologic and hydrologic controls of mixed alluvial-bedrock channels in flood-prone fluvial systems : Bankfull and macro channels in the Llano River watershed, central Texas, USA”. Geomorphology 232 (2015) 1-19, 2014.

the river channels are common along this segment and wide riparian areas with large native pecan trees are prevalent.

This segment of the Llano is the most dynamic portion of the entire Llano, as the cobble and gravel alluvial material allows the river to easily adjust to changes in the channel resulting from flooding, drought, and anthropogenic impacts. An example of these dynamic changes can be observed downstream of the state park. Here, the river channel travels beneath a suspended irrigation pipe (figure 31). This irrigation pipe, when it was installed, was more than 150 yards from the bank of the river, yet the increasing amplitude of meander bends in this section have now exposed the pipe. One cause for the increasing meanders is that prior to the flood of 2018, there had not been a significant rise in the South Llano in 14 years, resulting in increased sedimentation choking the river and resulting in increased meander size. Another reason for increasing meander sizes originated when the current bridge into South Llano River State Park was constructed [89]. The bridge is constructed in a manner that creates a change in the slope of the channel. As the river drops beneath the bridge into a downstream pool, stream energy is lost and increased deposition results. The original channel that traveled straight became clogged with sediment and a new channel created a mentor to the south (river right), resulting in severe streambank erosion along the river's right bank.

Within the Llano River State Park, the flood of 2018 resulted in the creation of a new channel in the river through a process known as avulsion. Avulsion occurs when floodwaters flow across the bottom of meander, creating a new channel and cutting off the main river flow to the old meander. A previous flood (sometime between 1956 and 1974, based on available maps) avulsed the Llano upstream from Flatrock Crossing, across from the Texas Tech Llano River Field Station. In Texas, the ownership of avulsed lands stays with the original owner; Texas Tech still owns the land up to the abandoned meander, or oxbow, across the river.

In addition to irrigation, the South Llano has provided the drinking water for Junction for over a century. In 1904, the Llano River Irrigation and Milling Company created 4-mile dam to divert and convey water downstream via a canal to the City of Junction for irrigation, milling and city water works. The stone and cypress dam was destroyed by floodwaters in 1932. Remains of the dam are still visible within South Llano River State Park. Beginning in the 1950s, the City constructed three 10-14 foot wide infiltration wells next to the South Llano, tapping into river water stored in the alluvium. In 1965, the current dam on the South Llano was constructed for the City of Junction. This dam is a run-of-river or pass through dam and does not have the capacity to store additional water through the use of floodgates. According

[89] This bridge is currently being replaced.

to the Texas Water Development Board, water use by the 2,700 residents of Junction averages 477,000 gallons per day, or 176 gallons per day per capita. [90]

Cedar Creek is a 29-mile tributary of the South Llano whose confluence is in the reservoir above the City of Junction dam. Three springs, one on Cedar Creek (Cedar Creek Springs - 200 gpm) and two on Dry Cedar Creek (both unnamed and unmeasured) appear just below 1,900 feet where the creek intersects the "Burrowed Zone" of the Fort Terrett limestone. Four irrigation projects along Cedar Creek were described in the 1902 Irrigation Survey. These projects grew corn, oats, wheat, cane and potatoes using a variety of flumes that carried irrigation water back and forth across the Creek as it "bends around precipitous bluffs".[91] Water rights dating back to 1895 are associated with these projects.

In addition to the surface water uses, there are 228 groundwater wells in the Lower South Llano sub-watershed, including 135 drilled since 2000, according to TWDB databases. Many of the wells are located near the river and are less than 50 feet deep, tapping into the water table along the river and producing around 20 to 30 gpm. Groundwater in Texas is generally regulated by groundwater conservation districts. Recently, however, there have been instances where shallow wells that may have an impact on surface-water flow have been subjected to curtailment by TCEQ. This recently occurred along the San Saba River. [92] Wells located away from the river are 200 to 500 feet deep and generally produce less than 10 gpm.

Kimble County Ground Water District maintains a network of observation wells across the county, including four wells in the South Llano Watershed. Shallow wells in the river valleys along with one of the deeper wells (over 100 feet) in the uplands fluctuated about one to two feet from 2006 to present. The fourth well at the headwaters of Cedar Creek has fluctuated 17 feet from 2007 to present.[93]

LLANO RIVER

At Junction, the North and South Llano rivers converge to form the Llano River. From this point, the river flows 116 miles to its confluence with the Colorado at Kingsland. The South Llano watershed drains 939 square miles and the North Llano drains 942 square miles. The watershed of these two rivers account for 42 percent of the total for the entire 4,466 square mile Llano watershed; the Llano river accounts for 58 percent.

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[90] Texas Water Development Board, "Water Use Survey Historical Municipal Use by Region", accessed December 23, 2020.

[91] Taylor, 1902.

[92] Steven C. Young, Robert E. Mace, and Carlos Rubinstein, "Surface water-groundwater interaction issues in Texas". Texas Water Resources Institute, Texas Water Journal, Volume 9, Number 1, December 17, 2018, Pages 129-149.

[93] A fifth well located in the uplands of South Llano River State Park was discontinued as an observation well in 2006.

Downstream of Junction, the watersheds that comprise the Llano River are Johnson Fork, Big Saline Creek, Honey Creek, Little Devils -James River, Comanche Creek, Hickory Creek, San Fernando, and Little Llano (figure 32). Big Saline Creek and Johnson Fork sub-watersheds are similar to Edwards Plateau sub-watersheds discussed in the North and South Llano. The remaining watersheds flow across the older and more resistant rocks of the Llano Uplift and have much different characteristics.

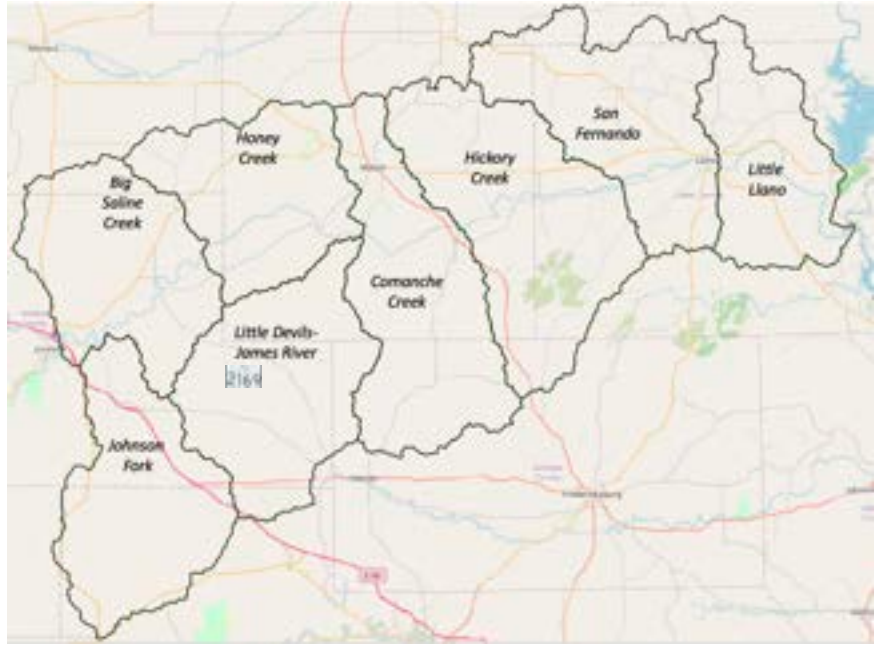

Figure 32 - Sub-watersheds of Llano River

Johnson Fork Sub-watershed

In addition to the North and South Llano, Johnson Fork, along with James River, Beaver Creek, and the Little Llano River are the major tributaries to the Llano. Johnson Fork, not to be confused with Johnson Creek in Llano County, is 29-mile tributary on the south side of Llano River. The gradient of Johnson Fork is 25 feet per mile from its headwaters above Texas Highway 41 to its confluence with the Llano, north of the community of Segovia (Figure 33). Segovia was one of the earliest settlements in Kimble County owing to early farmers utilizing springs on Johnson Fork for irrigation. During the 1920s, Segovia was advertised as a vacation site for camping and fishing.[94] Today the population of Johnson Fork sub-watershed is 495. Approximately 55% of the 461 homes are estimated to be second family homes. The principal economy is based upon ranching, some farming, hunting, and tourism associated with Interstate 10 in Segovia.

The sub-watershed of Johnson Fork is 322 square miles. Nearly half of the sub-watershed is underlain by Tarrant soils, a very cobbly clay derived from limestone bedrock. Vegetation is primarily *Ashe* juniper and live oak woodlands, live oak mottes, and shin oak shrubland (Figure 34).

[94] Anthony B. Gaxiola, "Segovia, TX," *Handbook of Texas Online*, accessed February 14, 2021

LCRA has maintained a stream gage at Johnson Fork just below Interstate 10 since 2000. During this period, the average flow has been 27 cfs and median flow 13 cfs. The highest flow occurred during the flood of 2018, when Johnson Fork crested at 32.6 feet or 107,000 cfs. The lowest flow during this period was 2 cfs in 2001 and in August 2018, two months before the October flood.

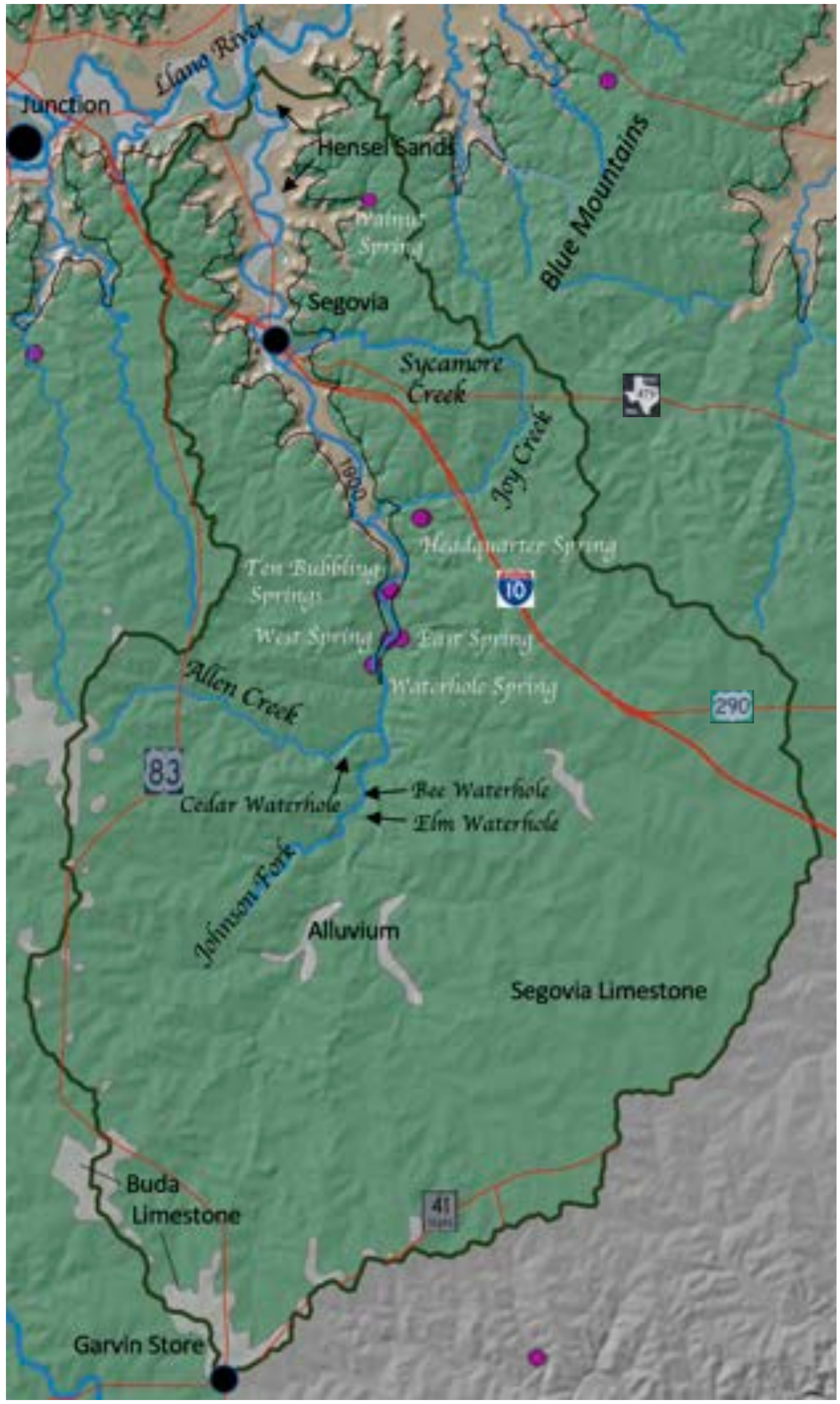

Figure 33 - Johnson Fork Sub-watershed

The headwaters of Johnson Fork begin just north of Garvin Store at the intersection of US Highway 83 and Texas Highway 41 near the YO Ranch. The upper reaches of the creek begin in the Segovia formation of the Edwards Plateau and begin downcutting towards the spring-bearing Fort Terrett formation around 1,900 feet elevation.[95] Above this elevation, gravelly-clay alluvium in the Bonedraw Soil Series provide enough impermeability for waterholes to be formed in the draws. These named waterholes, believed to be similar to the waterholes in the upper reaches of the South Llano, include Bee and Elm Waterholes on Johnson Fork and Cedar Waterhole on Allen Creek, a tributary to Johnson Fork.

[95] As previously noted, the digital map used to prepare this report does not distinguish between the Segovia and Fort Terrett formations. The dividing line between the two formations is approximately 1,900 feet msl.

At approximately 1,900 feet elevation, Johnson Fork exposes springs issuing from the "burrowed zone" of the Fort Terrett limestone. The upper springs include Waterhole Spring East Spring and West Spring. These three springs, located between approximately 1,850 and 1,950 feet, are referred by Brune as the Rio Bonito Springs and flowed at 11 cfs in 1966, the most prolific springs in the sub-watershed.[96]

Figure 34 - Johnson Fork Sub-watershed near Joy Creek

Further downstream, flow into tributary Joy Creek [97] from Headquarters Spring (1,877 feet) measured 600 gpm. In the early 1860s, Wiles Joy irrigated 60 acres on Johnson Fork. During that time, Johnsongrass (*Sorghum halepense*) was introduced to the area as it was believed to be better feed for cattle than native grasses. [98]

Three other nearby springs, including Ten Bubbling Springs also provide flow to Johnson Fork. Only one measurement (25 gpm) was associated with one of the unnamed springs. In the northern portion of the sub-watershed, Walnut Spring on Holden Hollow on the west slope of the Blue Mountains, flowed at 3 gpm in 1970.

In addition to irrigation on Joy Creek, other early irrigation systems utilized small dams, flumes and ditches to irrigate oats, wheat, cane, sweet potatoes, and alfalfa. One of the most elaborate systems belonged A.B. Long. From the 1902 Irrigation Survey…"*The water is raised 3 1/2 feet by means of a 75-foot timber dam…Power is obtained by means of an undershot water wheel 8*

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[96] Brune, 1981.

[97] Not to be confused with Joy Creek in the South Llano watershed.

[98] Anonymous, "Johnson Fork," *Handbook of Texas Online*, accessed February 13, 2021. This invasive was originally introduced to South Carolina from Turkey by Colonel William Johnson around 1840.

feet in diameter and 5 feet long, operating two 6-inch force pumps…, which raise the water 40 feet, through 100 feet of 5-inch iron pie, to a flume. The flume conveys the water 100 feet, to a ditch 1 1/2 feet wide, which carries it 600 feet farther, or to the field. Only 5 acres are irrigated, and only vegetables and fruits will be grown. It is interesting to note that an experiment is being made with strawberries…The plant was constructed about 1898." [99]

A total of 654 acre-feet of water rights have been issued by TCEQ for irrigation from Johnson Fork. The largest water user is Grayson Industries which is authorized to withdraw 2,466 acre-feet per year for the manufacturing of cedar oil. This is the largest industrial water user in the Llano watershed. Grayson is also permitted by TCEQ to discharge the water diverted for cooling water back into Johnson Fork.

Groundwater wells provide the majority of domestic and livestock use in the Johnson Fork sub-watershed. A total of 446 wells are listed in the Texas Water Development Board databases; 331 wells have been drilled since 2000. Only one well, located near the confluence of Johnson Fork and the Llano is used for irrigation. There are several wells in Segovia to monitor remediation efforts for a diesel spill that occurred in 2009.

Wells vary in depth from approximately 100 to 500 feet, depending on location, with wells at the top of ridges being the deepest. The water table in the Edwards Limestone at the top of the ridges lies about 2,000' and fluctuates up and down in some observation wells by about 20 feet. Shallower observation wells in the valley that tap the Hensel Sands of the Trinity have shown a steady 20 foot decline since 2000. Similarly, a deep observation well in Kerr County that taps the Hensel Sands has recorded a steady 20 foot decline in water levels since 2007.

<u>Big Saline Creek Sub-watershed</u>

The Big Saline Creek sub-watershed begins at the confluence of the North and South Llano, which is the beginning of the Llano River, and continues with a gradient of six feet per mile for 28 miles to Big Saline Creek (Figure 35). The 304-square mile watershed is bounded by the San Saba watershed on the north and Johnson Fork on the south. The main tributaries are Gentry Creek, Red Creek, and Big Saline Creek on the north and Sycamore Creek, and Cedar Creek on the south.

The economy of the sub-watershed is primarily based on agricultural production. In addition to traditional livestock rearing, lands are also irrigated for seed production, pecans, hay and vineyards. Hunting leases are also an important component of many ranches in the area. A cedar fiber (*Ashe*-juniper) facility in the sub-watershed produces animal bedding products.

[99] Taylor, 1902.

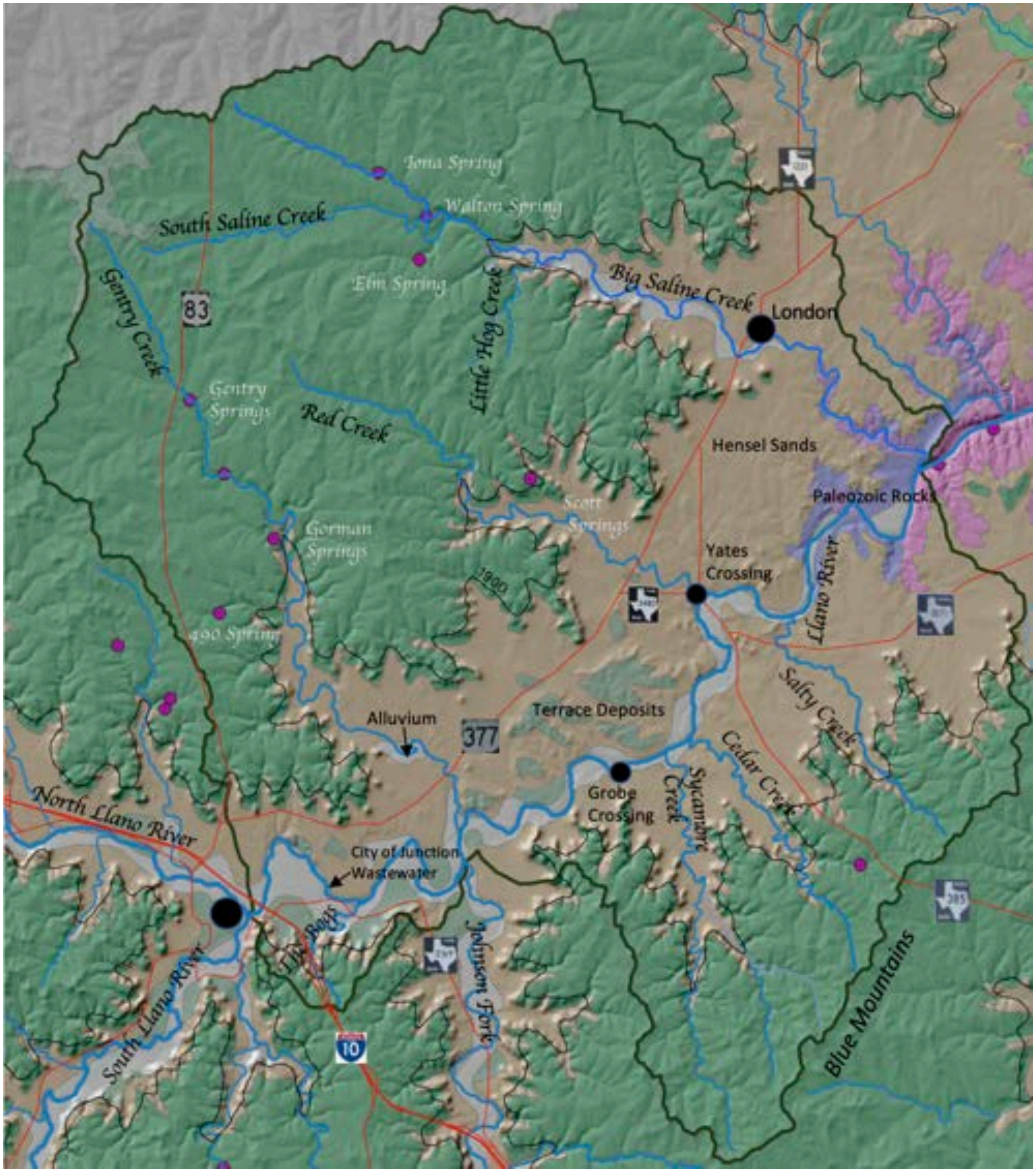

Figure 35 - Big Saline Sub-watershed

The soil type in the Big Saline Creek sub-watershed is similar to other sub-watersheds in the Edwards Plateau, primarily Tarrant soils, shallow clays derived from limestone. *Ashe* Juniper, live oak, and grassland cover the majority of sub-watershed, with mesquite beginning to become more prevalent than in the North and South Llano.

The Llano River flows primarily across the Hensel Sands geological formation as it crosses the sub-watershed. These sands are overlain by fingers of the Edwards Plateau along the watershed divide with the San Saba and along the Blue Mountains separating the Big Saline from the James River sub-watershed. Due to the erodible nature of the Hensel Sands, this section of river has numerous large meanders. Geomorphologist suggest these enlarged meander bends could be the result of more humid conditions 4,500 to 1,000 years ago. [100] The erodible nature of the Hensel Sands is also represented by the presence of terrace deposits, formed by the river downcutting into its former floodplain, suggesting that the river has meandered back and forth across this segment over long periods of geologic time.

Where the Llano completes its first meander below Junction near Ranch Road 2169, the river has avulsed a channel through bedrock. Avulsion, as previously mentioned, results when a river cuts across the bottom of a meander. The old river channels prior to avulsion can be seen along the highway.

Near the same location as the avulsion channel, the City of Junction discharges wastewater into the Llano. The facility was moved to this location in the 1990s after gravel operations in the North Llano caused the river to shift course to the south and threaten to erode the original facility, located at the confluence of the North and South Llano.

The Texas Commission on Environmental Quality permits the City of Junction to discharge wastewater into the Llano in accordance with limits on *E-coli* and Biological Oxygen Demand (BOD). The presence of *E-coli* in waters indicates the presence of bacteria and BOD indicates the amount of oxygen being consumed by bacteria and other microorganisms during decomposition. There are no limits on nutrients in the current TCEQ permit. Since 2017, the City has often exceeded the permit limits for *E-coli* and BOD.[101]

Just upstream of the wastewater treatment plant is the USGS stream gage for the Llano River. As with the North Llano gage, this gage was installed in 1915. Just upstream of the gage are the ruins of Kimble County Road 310 bridge over the Llano which was destroyed in the 1980s. These ruins create a navigation hazard for boaters (Figure 36).

Further downstream, Johnson Fork enters the Llano at the south end of the fourth meander of the Llano below Junction. Johnson Fork is discussed in more detail in the previous section.

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[100] Heitmuller, 2009.

[101] Detailed Facility Report for City of Junction Wastewater Treatment Plant, Enforcement and Compliance History Online, Environmental Protection Agency, accessed February 11, 2021.

During October of 2018, floodwaters flowed across the meander creating a temporary island. The river however, did not create an avulsion channel as a result of the flood and still remains in the historic channel.

Figure 36 - Ruins of County Road 310 Bridge

Gentry Creek enters the Llano downstream of Johnson Fork. The headwaters of this 21-mile creek are fed by four springs located in the Fort Terrett Limestone, located between about 1,900 and 2,000 feet. The highest spring is Gentry Spring (measured flow was 10 gpm in 1966) at an elevation of 2005 feet above sea level. Three other springs, 490 Spring (25 gpm in 1966), Gorman Spring (10 gpm) and an unnamed spring (25 gpm) are located around 1900 feet above sea level on Gentry Creek. According to the *Handbook of Texas*, when Raleigh Gentry moved to the mouth of Gentry Creek in 1862, the creek flowed year round and was inhabited by beaver. Today, the Gentry Creek is intermittent at the mouth. [102]

Another example of avulsion occurs in the last of the series of meander bends below Junction, just above Grobe Crossing (Kimble County Road 314). It is uncertain when the Llano cut across this meander bend, but today, flow occurs on both sides of the island. Unlike other islands on the Llano, this island is privately owned, as landowners do not lose possession of lands that are avulsed.

Sycamore Creek and Cedar Creek [103] drain the Blue Mountains to the south and enter the Llano below Grobe Crossing. These creeks are less than five miles in length, but Sycamore Creek has headwater springs (unnamed and unmapped) on each of its three tributaries and Cedar Creek has one headwater spring, occasionally named 800 Pasture Spring. All of these springs are located about 1,950 feet above sea level. The spring on Cedar Creek flowed 2 gpm

[102] Anonymous, "Gentry Creek," *Handbook of Texas Online*, accessed June 08, 2022, https://www.tshaonline.org/handbook/entries/gentry-creek.

[103] Not to be confused with Cedar Creek that flows into Junction Lake.

Figure 37 - Mouth of Red Creek near Yates Crossing

in 1965; no additional information is available for the springs on Sycamore Creek.

Red Creek, so named for the red color of the Hensel Sands (Figure 37), enters the Llano from the north just above Yates Crossing (Ranch Road 385). The flow of this fourteen mile creek is supplemented by Scotts Spring, located on a tributary of Red Creek at an elevation of 1,945 feet. No flow data are available for this spring, but Brune notes a battle with with Lipan Apache took place at these springs.[104]

Below Red Creek, the Llano begins another series of enlarged meander bends. These meanders result from an increase in alluvial materials being deposited upstream of the location where the Llano River begins to enters the Paleozoic rocks of the Llano Uplift near the mouth of Big Saline Creek. As the rocks of the Uplift are more resistant, the river profile, or gradient, decreases, lessening the ability of the river to carry sediment. This is discussed in more detail in the Llano Uplift section.

In the early 1900s, at the beginning of the last meander upstream of Big Saline Creek, a dam was installed on the Llano River to lift river water into an aqueduct for irrigation. Today, the ruins of four silos and the aqueduct are visible from the river.

Big Saline Creek is a 22-mile tributary of the Llano with headwaters in the Cretaceous remnants of the Edwards Plateau dividing the Llano and the San Saba River. Three springs from the Fort Terrett formation feed Big Saline and its tributaries at an elevation just below 2,000 feet above sea level. Iona Springs, at 600 gpm, is the largest of these springs, followed by Walton Spring (25 gpm) and Elm Spring (15 gpm). Brune reports that Iona Spring in the

[104] Brune, 1981

1850s were described as “sparkling springs with 50 pound catfish and beaver” and had a discharge in 1965 of 1.3 cfs. Big Saline Creek passes near the community of London.

There are 750 residents living in the Big Saline sub-watershed. The majority of the population is located near Junction and about 180 residents are in the community of London. There are 734 housing units in the sub-watershed; it is estimated that more than half of these are second family homes. [105]

There are several water rights downstream of Junction that utilize Llano River water to irrigate hay, pecans, and grass and plant seeds. There are also 593 wells in the TWDB database located in the sub-watershed, 350 of which have been drilled since 2000. Thirteen of these wells are used for irrigation and draw from the alluvium next to the river or from deeper Ellenburger Limestones or Hickory Sands. Four wells are utilized by the community of London for public water supply. These are deep wells (>1,700 feet) and tap the Hickory Formation.

Llano Uplift

The segment of the Llano watershed where the mainstream of the river flows across the Llano Uplift is referenced as the “Uplift” segment in this report. It consists of the mainstream of the Llano, from the Mason-Kimble county line downstream to LBJ Reservoir, and the major tributaries, in downstream order: Honey Creek, James River; Comanche Creek; Beaver Creek; Hickory Creek; San Fernando Creek; Johnson Creek; Little Llano River; and another Honey Creek. Smaller tributaries flowing to the Llano from the north include Little Saline, Leon, Bluff, Honey and Martins Creeks in Mason County and Elm Creek and Pecan Creek in Llano County. Creeks flowing into the Llano River from the south in Mason County include Schep and Panther Creek and in Llano County, Six Mile and Oatman Creek.

The Llano Uplift is the remnant of an ancient mountain range uplifted over one billion years ago, but eroded over time and later covered and then uncovered by the Edwards Plateau. Despite being referred to as an “uplift”, on the surface, the Llano Uplift is a basin of Precambrian metamorphic and igneous rocks. Faulting resulting from the collision of continental plates uplifted these billion year old rocks several times over the ages. The rocks of the Llano Uplift consist of a relatively equal mix of Town Mountain Granite, Valley Spring Gneiss, and Packsaddle Schist, along with a smaller mix of younger granites and gneisses. Although the matrices of these rocks are fairly impermeable, weathering of the surface rocks and fractures within the formation, provide some pathways for water to enter and be stored as groundwater.

[105] Persons per household is 2.43 in Kimble County. Dividing the population by the persons per household estimates the number of primary homes in the sub-watershed; the remaining homes are assumed to be second homes.

Groundwater production from from wells drilled in the Precambrian rock range from 0.1 gpm to 200 gpm, with a median well yield of 11 gpm. The average depth to water is 23 feet and water level fluctuations range from 5 - 26 feet. Thirty percent of the wells drilled into these rocks are 'dry holes' with insufficient water.[106]

Sitting atop these basement rocks is a ring of Paleozoic rocks including Hickory Sandstone and Marble Falls, Ellenberger and San Saba limestones. These sedimentary rocks were deposited atop the Llano Uplift approximately 500 million years ago. Subsequent faulting beneath the Uplift removed much of the overlying material, except along the periphery of the Uplift. Some locations towards the center of the Uplift also retain Paleozoic materials. As plate tectonics again forced the Llano Uplift vertically, some of the overlying materials were dropped down into the Precambrian materials along southwest to northeast trending faults. These down-dropped blocks, or grabens, more resistant to erosion than the surrounding materials, are today present as topographical features such as Riley Mountain and Lone Oak Mountain in southeast and northwest Llano County.

The Paleozoic rocks holding the groundwater in the Llano watershed are known as the Ellenburger-San Saba Aquifer. This aquifer is made up of tilted limestone and dolomite strata overlying the granite slopes of the ancient Llano Uplift. Groundwater flow in this aquifer is

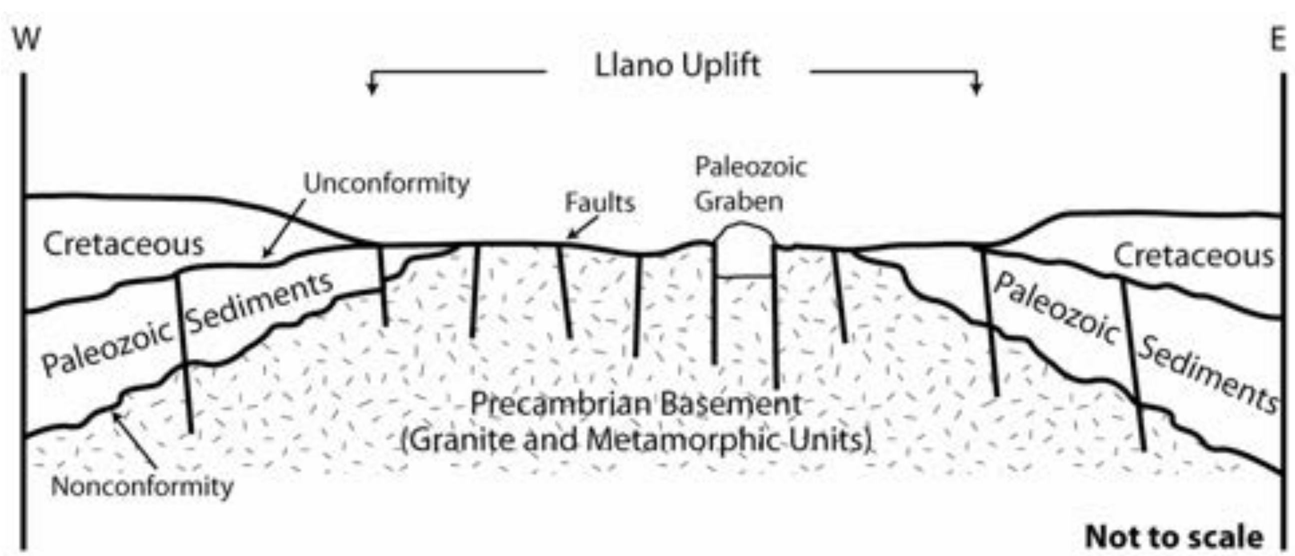

Figure 38 - Schematic cross section of the Llano Uplift (modified from Preston and others, 1996). From Brian Hunt, 2006

[106]Hunt, Brian. (2008). "Crystalline Basement Aquifer, Llano Uplift, Central Texas: An Overlooked Minor Aquifer of Texas". Gulf Coast Association of Geological Societies, Houston, Texas

not well understood due to the complex nature of its geological formations and fault patterns (Figure 38).

According to the Texas Springs Database, there are 43 springs located in this segment of the river. The majority of the springs (33) that contribute significant flow to the Llano are located in Mason County, Gillespie County and eastern Kimble County along the James River and Beaver Creek, where the more permeable Paleozoic limestones and sandstones of the Llano Uplift are found. Five springs from the Hickory Sands Aquifer in the Pontotoc and Valley Spring area contribute local flow to rivers and streams. The remainder of the springs are found in less permeable Precambrian granites, gneisses, and schists that characterize more of Llano County; flow from these springs is 20 gallons per minute or less.

Springflow on the Llano Uplift is quite different than on the Edwards Plateau. Whereas, springflow in the Edwards results from water moving through conduits and porous limestone, the rocks of the Llano Uplift are generally impermeable. While some springs in the Uplift result from water moving through more porous rocks of the Hickory and Wilberns formations, the majority of the springflow occurs along tectonic faults and fissures in the rock or between geologic formations, especially where remnant Paleozoic rocks have been wedged as grabens into underlying Precambrian rocks due to faulting.[107]

The portion of the Llano River in the Llano Uplift covers approximately 31 percent of the entire Llano watershed. Tributaries on the north side of the river downstream to Bluff Creek, like those tributaries upstream in the Edwards segment, emanate from a remnant finger of the Edwards Plateau dividing the Llano and San Saba rivers. Because this finger of the Plateau is small and dissected on two sides, it produces only small headwater springs providing localized flow to these tributaries. Edwards Plateau springs also provide flow in the headwaters reaches of the larger tributaries on the south side of the Llano River, specifically the James River and Beaver Creek.

With the exception of the James River and Beaver Creek, spring flows are not large enough to provide continuous base flows to river and streams in this segment and tend to cease flowing during periods without rainfall. Due to the lack of springflow and potential channel losses to fissures in the bedrock channels of the Llano Uplift, the lower section of the Llano River is less influenced by springflow. Consequently, river flows fluctuate at a more variable rate than in the upstream segment associated with the Edwards.

[107] Brian B. Hunt, P.G., “Precambrian basement aquifer, Llano Uplift, Central Texas”. Volume 2 - Austin Geological society Bulletin - 2006.

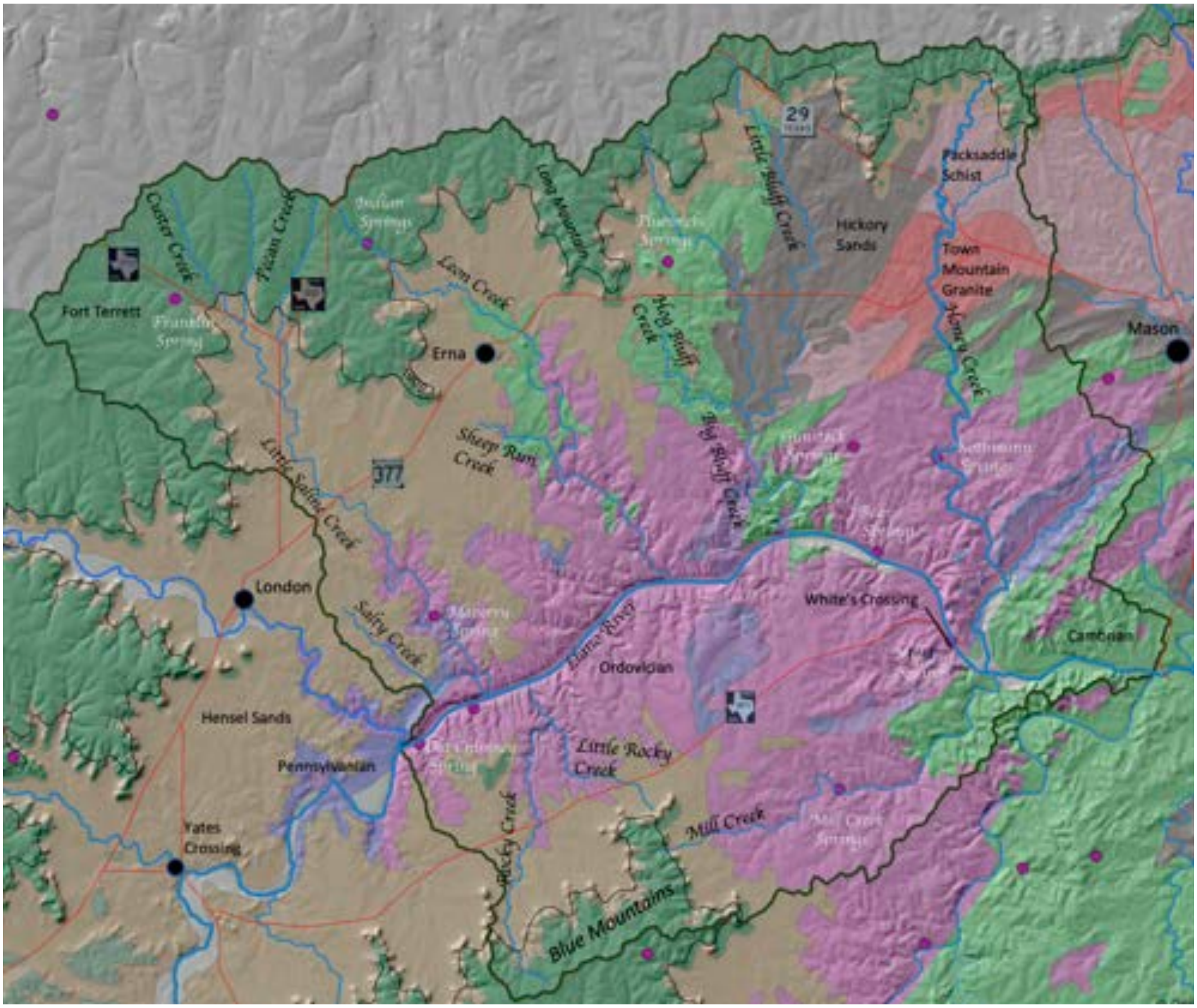

Figure 39 - Honey Creek - Llano River Sub-watershed

<u>*Honey Creek - Llano River*</u>

The Llano River dramatically changes its character in the Honey Creek Sub-watershed (Figure 39). Near the Kimble and Mason county line, the Llano leaves the more easily eroded sedimentary limestone rocks of its Edwards Plateau origin and begins to cross older, more resistant Paleozoic sedimentary rocks forming the upper layers and outer ring of the Llano Uplift. As the river crosses onto the uplift, the predominantly bedrock river channel becomes more resistant to erosion and straightens, except where bedrock joints or fractures cause bends in the channel. The riparian zone becomes narrower and steeper and mid-channel bedrock islands become more common.

The 282 square mile Honey Creek - Llano River Sub-watershed begins at the confluence of the Llano and Big Saline Creek and ends at the confluence of the James River. The Llano flows 19 miles between these points with a gradient of 9 feet per mile.

Just above Big Saline Creek (previously described), the river channel of the Llano leaves the Hensel Sands of the Cretaceous age and begins eroding into more resistant Pennsylvanian and Ordivician Paleozoic rocks ringing of the Precambrian rocks of the Llano Uplift. As the bedrock becomes more resistant, the slope of the channel decreases, forcing alluvium to be deposited upstream and resulting in the development of floodplains and sinuous channels more typical of the upper Llano.[108]

Unusual entrenched meanders are found near the mouth of Big Saline Creek and along portions of Bluff Creek and Honey Creek. Here, the flow of these tributary streams are forced around perpendicular faults in the Paleozoic rock.

The main vegetation and soil type in the Honey Creek sub-watershed is similar to upstream watersheds, as the upper reaches of the sub-watershed include Cretaceous Limestones of the Edwards Plateau. *Ashe* juniper, live oak, savannah grassland and, additionally, mesquite cover the majority of sub-watershed, while Tarrant Soils, a shallow cobbly clay soil derived from limestone is the major soil type.

Figure 40 - Fissures in riverbed and secondary bedrock flood channels in the Llano River below Little Saline Creek.

Two springs are located along the south bank of the Llano River between Big and Little Saline Creek. Old Chimney Spring and an unnamed spring both measured 15 gpm in 1966. These springs are located in rock of Ordovician age (443-448 million

[108] Heitmuller, 2009

years). Maberry Spring on Little Saline Creek, near its confluence with the Llano, emanates from younger Pennsylvanian rocks (around 310 million year) and flowed at 65 gpm in 1965. Franklin Springs on a headwaters tributary of Little Saline Creek at 1,915 feet is in Fort Terrett Limestones; no data are available for these springs.

Below Little Saline Creek, the Llano River becomes confined between 100 foot valley walls of more resistant Paleozoic sedimentary rocks. Secondary bedrock flood channels often parallel the main channel. As the river is crossing a series of faults in the rocks, fissures riddle the channel (Figure 40). A gain-loss study across this segment in 1962 documented about 7 cfs of water was lost to these fissures. [109] Due to the wide-shallow channel here, this 20-mile segment of river can be the most tedious on the river to paddle without recent and significant precipitation.

Leon Creek flows near the community of Erna, entering the north side of the Llano four miles below the Kimble - Mason County line. Indian Spring and other headwaters springs are located at an elevation of about 1,900 feet above sea level in the Fort Terrett Formation. Indian Springs flowed 2 gpm in 1990. Headwater springs also feed Muskhog (javelina) Hollow, an unmapped tributary of Leon Creek. No additional information is available for this spring.

Big Bluff Creek originates in a narrow band of remnant Edwards Plateau between the Llano and San Saba River. Pluenneke Springs, north of US 377 near Big Bluff Creek, was a stop on the Old Chihuahua Road and the Western Cattle Trail. It surfaces along a contact between two layers of Cambrian formation east of Long Mountain. It flowed 0.7 cfs in 1925, 20 gpm in 1939 and 2 cfs in 1962. Gunstock Spring emanates from Ordovician materials on a tributary of Big Bluff Creek. No flow information has been recorded for Gunstock Spring.

Honey Creek is a 22 mile-long stream flowing into the north side of the Llano River in western Mason County. Kothmann Springs, according to Gunnar Brune[110], issuing from a fault in the Ellenberger limestone (Ordovician), had a flow of 7.8 cfs in 1918, 0.01 cfs in 1939, and 3 cfs in 1962. It also served as a stop on the Old Chihuahua Road and later the Western Cattle Trail. The *Handbook of Texas* notes that manganese and iron-ore was discovered in the creek in 1887 and a short-lived mining company was established, but ceased operations due to lack of transportation. [111]

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[109] Pat Holland and H.B. Mendieta, "Base-flow studies Llano River, Texas - Quantity and quality" - Texas Water Commission Bulletin 6505, March 1965.

[110] Brune, 1981

[111] Anonymous, "Honey Creek (Mason County)," *Handbook of Texas Online*, accessed June 08, 2022, https://www.tshaonline.org/handbook/entries/honey-creek-mason-county.

Along the Llano, two additional springs are located between Bluff Creek and Honey Creek. Bear Spring measured 30 gpm in 1990 and Mill Springs flowed 2 cfs in 1962. Both of these springs originate in Ordovician sediments.

Mill Creek enters the Llano on the south side of the river, just below Whites Crossing (Ranch Road 1871) and Honey Creek. In 1855, the first gristmill in Mason County was established on the 11-mile tributary. A flow of 619 gpm was recorded at Mill Creek Spring in 1961, flowing from Ordovician limestones.

In addition to the above mentioned springs, the author is aware of additional springs originating in the Blue Mountains, a remnant extension of the Edwards Plateau to south of the Llano. Turtle Creek, a tributary of Honey Creek, also contains springs originating from Paleozoic sediments.

While springs helped with early settlement in this portion of the Llano, today water wells are the primary water source for the 502 residents of the sub-watershed. [112] There are 546 wells in the sub-watershed that are listed in the TWDB database; 275 of these wells drilled have been drilled since 2000. TCEQ lists no surface water rights in the sub-watershed. The local economy is based primarily on ranching operations, often supplemented by hunting leases along with the irrigation of hay and vineyards. A sand-mine for producing fracking sands near Erna closed in 2020.

Fossilized microbial reefs are located along the banks of the Llano from the mouth of Mill Creek downstream towards the James River. These bioherms, as they are often referred, are located in the approximately 500 million year old Points Peak Formation and present a record of some of the earliest life forms on Earth.[113]

James River/Little Devils sub-watershed

The James River is a 37-mile tributary of the Llano River draining 339 square miles of Kimble, Gillespie, Kerr and Mason counties (Figure 41). The headwaters of the James begin in Kerr County east of the intersection of US 290 and Interstate 10 at an elevation over 2,200 feet above sea level. The river flows in a northeasterly direction, dropping 24 feet per mile to its confluence with the Llano River about seven miles south of the city of Mason. As the headwaters of the James-Little Devils are on a remnant of the Edwards Plateau, the predominant vegetation type more reflects the upper sub-watersheds of the Llano: *Ashe-juniper* and Live Oak Woodland (24%), followed by Live Oak Motte and Woodland (23%),

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[112] Based on per-capita housing rates roughly 47 percent of the 383 homes in the sub-watershed are second-family residences .

[113] Pankaj Khanna, Heath H. Hopson, and Andrew W. Droxler et al, "Late Cambrian microbial build-ups, Llano Area, Central Texas: A three-phase morphological evolution. Sedimentology, 2019.

and then Savannah Grassland (11%). Tarrant Soils comprise nearly 50 percent of the sub-watershed's 65 soil types.[114]

As with the larger tributaries of the Edwards Plateau segment, the James River and its tributary, the Little Devils River (known until 1976 as the East Fork of the James River), flow intermittently across the Edwards Plateau for the first few miles. Just to the south of Ranch Road 479, both tributaries have carved small canyons into the Fort Terrett Formation of the Edwards Plateau at an elevation of 1,900 to 2,000 exposing James River Springs and The Big Springs. The James River Spring, at an elevation of 2,000 feet above sea level, forms the headwaters of the James River. Estimated flow from this spring was 200 gallons per minute in 2009. The Big Springs, form the headwaters of the Little Devils River, Its flow was

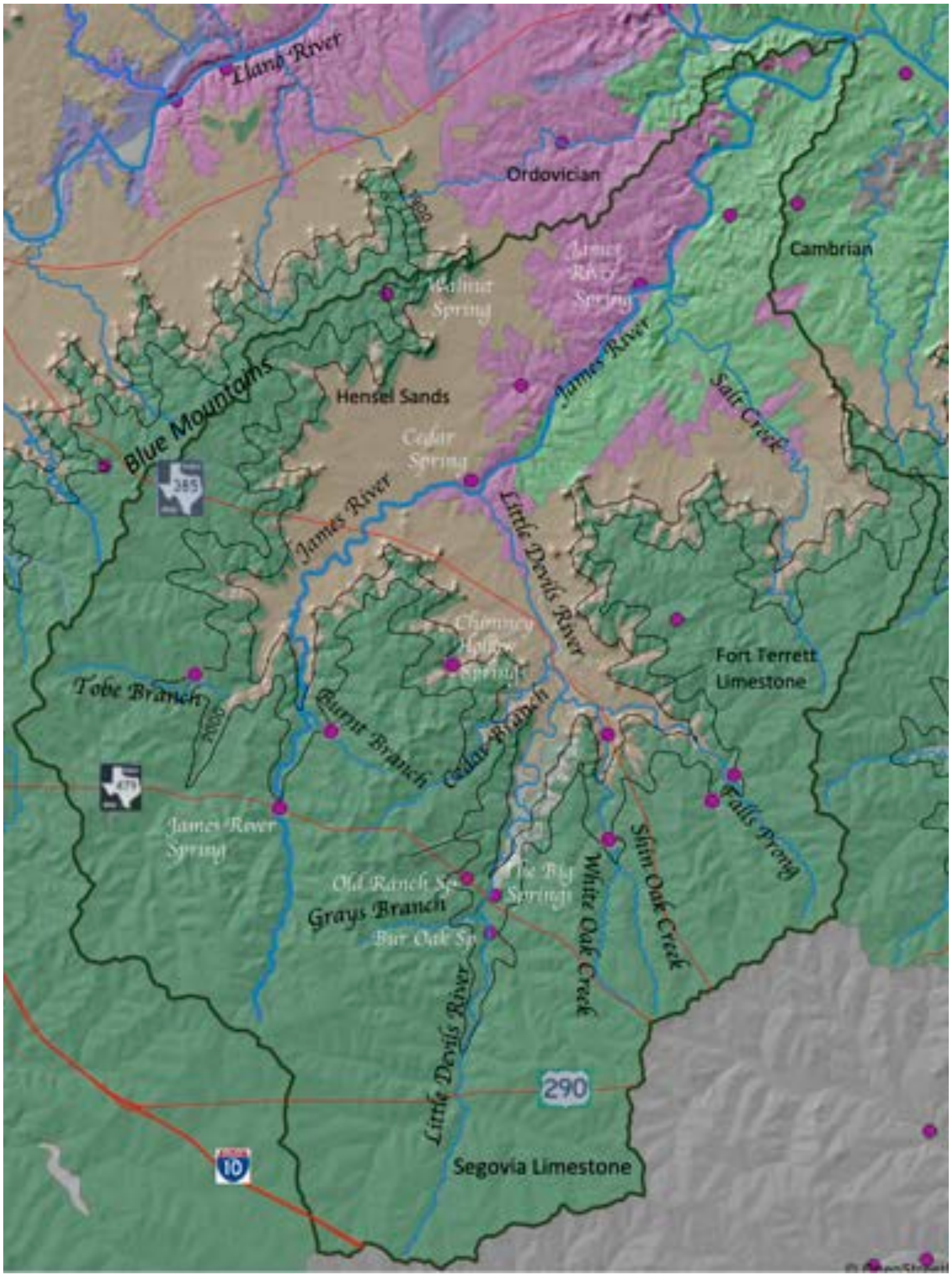

Figure 41 - James River Little Devils Sub-watershed

[114] For additional detail on the James River, *see* "Unknown River of Central Texas", Environmental Defense Fund, 2010.

estimated to be 290 gpm in 1966 and 135 gpm in 1996.

Several tributaries on the James River also contain springs where the tributaries intersect the burrowed zone of the Fort Terrett Limestone. Burnt Branch Spring on Burnt Branch Creek is located at 2,000 feet, and Tobe Spring on Tobe Branch, is located at about 1,960 feet. No additional data are available for these two springs.

Tributaries with springs off of the Little Devils include: Bur Oak Spring on Bur Oak Creek (elevation 1,980 ft); Old Ranch Spring on Gray's Branch (1,990 feet); and an unnamed spring on Monroe Hollow near Noxville Cemetery (1,920 ft). South Pasture Spring is located along a tributary of Cedar Branch.[115]

Falls Prong, a tributary to the Little Devils contains Falls Prong Spring, located at 2,000 feet, and an unnamed spring, also located at the same elevation. Parker Springs and Shin Oak Springs (2,000 feet) are located near the confluence of White Oak and Shin Oak Creek. Two unnamed springs are located above the confluence of White Oak and Falls Prong; these springs are located between 1,800 and 1,900 where the Fort Terrett formation is in contact with the underlying Hensel Sands.

Chimney Hollow, another tributary of the Little Devils, located north of Cedar Branch, has seven springs, the most for any small tributary on the Llano. These springs include Chimney Hollow Spring, Flat Rock Spring, Hollow Pasture Spring, Trough Spring, Cave Hollow Spring, Walker Spring and Hollow Pasture Spring. These are marked on Figure 41 as Chimney Hollow Springs. In addition there are two unnamed springs feeding Chimney Hollow. The majority of these springs are between 1,900 and 2,000 feet above sea level and emanate from the Fort Terrett formation.

Below these springs, the two rivers take on a more perennial nature down to their confluence, where they intersect the Paleozoic rocks rimming the Llano Uplift and change from mostly gravel to primarily bedrock channels. Here the channel widens to over 200 feet in places and forms steep-walled canyons up to 100 feet tall (Figure 42). Although the confluence with the Llano River is 17 miles downstream, gravels from the upper section of the river are transported easily across the bedrock channel and deposited on James River Island below its confluence with the Llano River (Figure 43).

Just above the confluence of the James and Little Devils is Cedar Spring. Flow was estimated to be 424 gpm in 1961 and 100 gpm in 1999. While the rocks of the Llano Uplift are less permeable than the Edwards Plateau, along the margins of the uplift, springs form along

[115] The scale of the map in Figure 41 does not permit all springs and tributaries to be presented. See U.S. Geological Survey topographic maps for more detail.

contacts between geological formations. Cedar Spring forms along a contact between Hensell Sands and rocks of Ordovician age.

Three additional springs in the James River/Little Devils sub-watershed are located in the Llano Uplift. One unnamed spring is located on a tributary of the James River, three miles below the confluence with the Little Devils. James River Spring, not to be confused with the headwater spring in Kimble County, is located above the James River Road Crossing, approximately 10 miles above the mouth. Flow here was recorded to be 3 gpm in 1940. The largest spring on the James River in the Llano Uplift is a 300 gpm unnamed Cambrian spring (estimated 1961) on an unnamed tributary eight miles above the river's mouth.

Figure 42 - James River below confluence with Little Devils River

Walnut Spring, located west of James River Spring, flows from a remnant arm of the Edwards Plateau separating the James River from the Llano River.

The bedrock channel of the James River flowing across the Llano Uplift generally flows parallel to the southwest-northeast trending faults in the Llano Uplift. However, along the lower portions of the river, meanders occur across these faults, similar to Llano tributaries in the Honey Creek sub-watershed.

LCRA has maintained a gage on the James River since 1999. The average flow of the James during this period is 17 cfs and the median flow is 5 cfs. The highest flow, 112,000 cfs, occurred during the 2018 flood. This flood had a recurrence interval of 1 in 100, often referenced as the 100-year flood. Since 1999, the James River has had zero discharge 4 percent of the time.

Anglo settlement came to the James River around 1860, utilizing springflows to irrigate crops. When the Great Western Trail blazed through the area in 1874, the lands of the James River sub-watershed began to be used for ranching. Today a large source of income for these ranches is hunting leases for white-tailed deer and exotic species. A wallboard manufacturing company operates a mine in the northeastern portion of Kimble County within the sub-watershed.

Today, the population of the sub-watershed is 658. The majority of this population lives in the upper portion of the basin near Harper, which is becoming a bedroom community for Kerrville. It is estimated that there are 505 housing units. As persons per household for Kimble County is 2.46, it is estimated that 49 percent of these homes are second residences. TWDB data lists 509 wells in the James-Little Devils sub-watershed; 399 have been drilled since 2000.

<u>Comanche Creek - Llano River Sub-watershed</u>

The Llano River begins flowing through the Comanche Creek - Llano River sub-watershed just below James River and terminates at the mouth of Beaver Creek. The length of this river segment is 11 miles with a gradient of eight feet per mile. The western portion of the sub-watershed consists of Paleozoic rocks (Cambrian) that are about 500 million years old, while the eastern portion of the sub-watershed is underlain by Precambrian rocks (schist) greater than one billion years in age. Both the northern and southern edges of the sub-watershed are underlain by Edwards Limestones, some 65 million years in age.

Ashe-juniper does not grow well in the sandy soils of the Llano Uplift, so the primary vegetation are live oak mottes and woodlands, grasslands, and mesquite. Owing to the complexity of the geology in the Comanche Creek sub-watershed, there are 71 different soil types identified. The most widespread type is Tarrant soil associated with the Edwards Plateau remnants. These different rock types and resulting soil types have a direct influence on the hydrologic character of the watershed.

Figure 43 - Mid-channel gravel bar at James River Crossing below confluence of James River (left) and Llano River. Photo taken December 2018, following the October flood.

The channel of the Llano River as it continues across Paleozoic sediments is a confined and

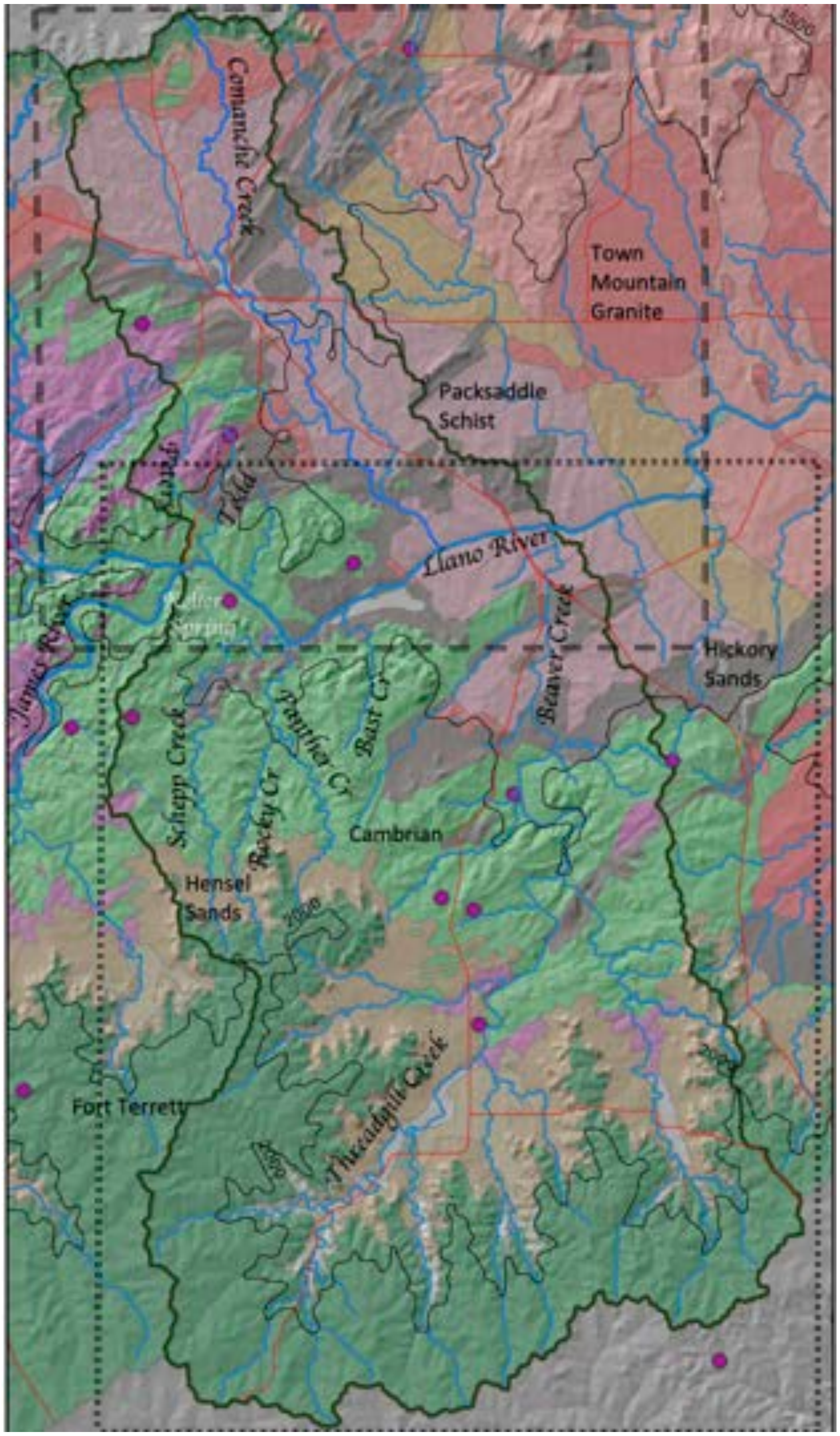

Figure 44. Comanche Creek-Llano River Sub-watershed. Boxes outline more detailed maps in Figure 44(a) and 44(b)

relatively straight bedrock channel. The river channel becomes wider than in upstream sections and river sediments are primarily cobbles and gravels. A large gravel and cobble deposit occurs at the large mid-channel gravel bar at James River Crossing of the Llano (Figure 43). These sediments are primarily derived from the James River. [116]

Several tributaries with headwater springs enter the Llano along the Paleozoic section of the sub-watershed, but flows from these springs are small and the tributaries are intermittent (for more detailed maps, see Figures 44a & 44b). Intermittent tributaries from the north include Peters Creek and its tributary Todd Creek. Headwater springs on both creeks are present where Hickory Sandstones contacts Ordovician Limestones along a fault. No flow was noted at the Todd headwater springs in 2008; no additional information is available for the unnamed Peter's Creek spring. Intermittent tributaries from the south are Schepp Creek and Panther Creek. There are no springs along these tributaries.

[116] Heitmuller, 2015

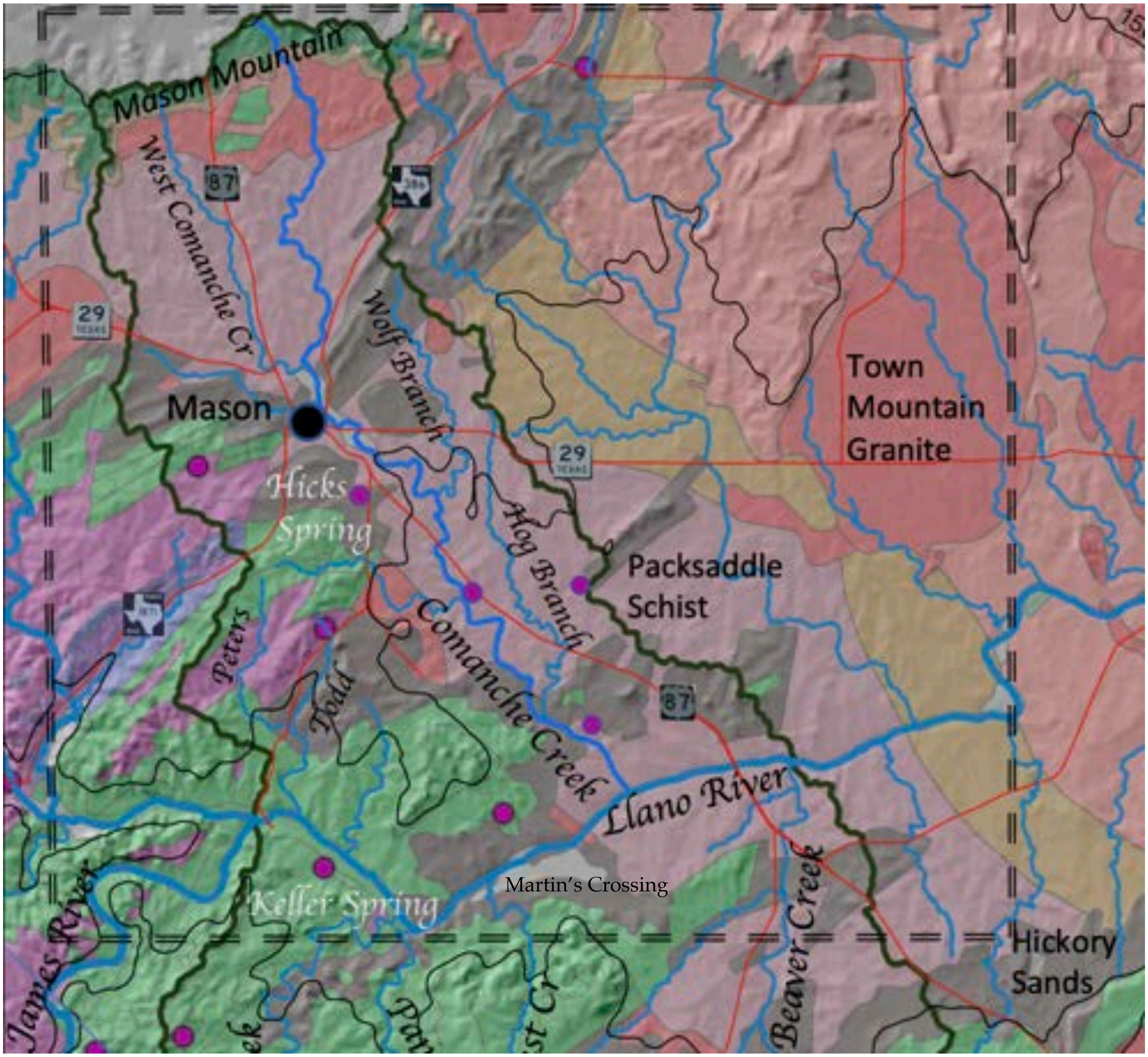

Figure 44a - Comanche Creek - Llano River Sub-watershed north from the Llano River

Confined aquifers, where permeable water bearing formations are under pressure due sloping strata with a confining geologic layer above, are uncommon in the Llano watershed, but are found in this section (represented on US Geological Survey topographical maps) as flowing wells on both sides of the river. Flowing wells result when the water level upslope in the confined aquifer is higher than the top of the well along the downslope surface. Flowing wells (over 500 foot deep and producing up to 185 gpm) are located along the south side of the river, just downstream of James River Crossing. Historically, they were used for aquaculture operations or irrigation. Keller Spring, located in Cambrian materials, but reported by TWDB to be of Hickory Sandstone origin, is also near these flowing wells.

The channel of the Llano River is generally straight across the Paleozoic sediments, but below Panther Creek, the Llano bends to the northeast along a relatively weak joint in the surface Hickory Sandstone, exposing the Llano River's iconic Martin's Bluffs (H.L. Bluffs on topographic maps). The river continues across Paleozoic sediments to Martin's Crossing just below Bast Creek. *Old Yeller* author, Fred Gibson, lived along this reach of the river.

Two small tributary springs are found along Bast Creek on the south and an unnamed tributary across the river on the north. No information is available for these springs, but flows are likely small or no longer exist.

Above the mouth of Comanche Creek, the Llano leaves Paleozoic sediments (Cambrian and Hickory Sands) and begins to flow across Precambrian igneous and metamorphic rocks (here, primarily Packsaddle Schist). The morphology of the Llano River channel is not significantly altered at this transition. The channel remains fairly confined and straight. The biggest change is the composition of the channel material. Below this Paleozoic/Precambrian contact, sand becomes the dominant channel material as these older rocks tend to have weathered in-situ (in place) before being transported. [117] Llano tributary streams draining Precambrian materials also tend to be sand-filled.

Comanche Creek joins the Llano from the north above the US 87 bridge. The 21-mile watercourse begins on Mason Mountain, a remnant finger of the Edwards Plateau north of the City of Mason. Although Mason Mountain consist of Edwards Limestone, the formation is too narrow to hold sufficient volumes of groundwater to support springflow.

Comanche Creek runs through the City of Mason, named for Fort Mason that was established in 1851. Gamel Spring (located in the City of Mason), emanating from a fault in the Hickory Sandstone, supplied water to the Fort. According to Brune, the spring ran at 14 gpm into the Mason swimming pool in 1940, but no longer flowed in 1971. Brune also notes that bedrock mortars for grinding corn, nuts, and mesquite beens were located here. In 1923, Jesse Edwards Grinstead wrote, "…*but the wonderful spring from which the garrison secured water still gurgles forth, and ripples down the mountain side to Comanche Creek. In these peaceful times the children from the Mason Grammar School play in the riffles, and drink from the spring."*[118] Another unnamed spring is located on a tributary of Comanche Creek west of Mason; flow from the spring was reported at 30 gpm in 1939.

Accounts of Comanche Creek noted that in early times, the creek had many deep pools and was a popular fishing spot. By 1928, however, it appears as it does today, a dry watercourse

[117] Heitmuller, 2015.

[118] Grinstead's Graphic, Volume 3, Number 8, August 1923, page 14.

with a sandy bottom.[119] It is not clear from historical groundwater records, or other available data, the reason for the diminishment of Comanche Creek nearly 100 years ago. The fact that Comanche Creek is now an intermittent stream rather than a perennial one suggests that the water table below the creek has been lowered.

As one drives around the City of Mason, numerous old cisterns may be observed. Although Fort Mason and much of the city are located over water-bearing Hickory Sandstones, much of the city overlies impermeable Packsaddle Schists. Until the creation of a municipal water supply around 1940, many home over these schists had to rely upon cisterns.

The City of Mason's water supply relies on eight wells from the Hickory Aquifer to supply its 2,114 customers. The Hickory Aquifer has naturally occurring radium in its waters as a result of the surrounding Precambrian rocks. Well water in Mason is just above the Environmental Protection Agency (EPA) limit for radionuclides of 5 picocuries per liter. In 2018, Texas Water Development Board issued over two million dollars in loans for the City to install a filtration system to reduce the levels of radium and meet EPA standards.

While the Comanche Creek does not serve as a water supply for the City of Mason, the creek does serve as the discharge source for the City's wastewater treatment plant. Flows from this plant help to maintain flows and riparian habitat through the City's Fort Mason Park, however, exceedances in nutrient discharges from the plant have created problems with algal blooms. Stream in the Texas Hill Country naturally have few nutrients, so even small additional amounts of nutrients from wastewater facilities can result in algal growth caused by excess nutrients.

LCRA has maintained a gage on Comanche Creek at the US 87 bridge since 2000. The average flow recorded at this gage is 4 cfs with a maximum daily discharge of 1,270 cfs occurring in 2000 and an instantaneous peak discharge of 2,000 cfs during the 2018 flood. Discharge from the wastewater treatment facility upstream may help maintain some base flow, but Comanche Creek is still without flow 45 percent of the time.

Below Mason, several additional springs are noted on tributaries of Comanche Creek. These include Hicks Spring and three other unnamed springs. All but one of these springs are fed by Hickory Sandstones; the source of flow for the other spring is uncertain as it occurs in Packsaddle Schist which is not conducive to spring flow.

Beaver Creek (Figure 44b) is the last major tributary along this segment of river, entering the Llano just over one mile below the US 87 bridge. Thirteen miles above its mouth, it splits into two tributaries, Squaw Creek (12 miles long) and Threadgill Creek (24 miles).

[119] J. Marvin Hunter, "Brief History of Mason County," *Frontier Times*, November, December 1928; January, February, March 1929.

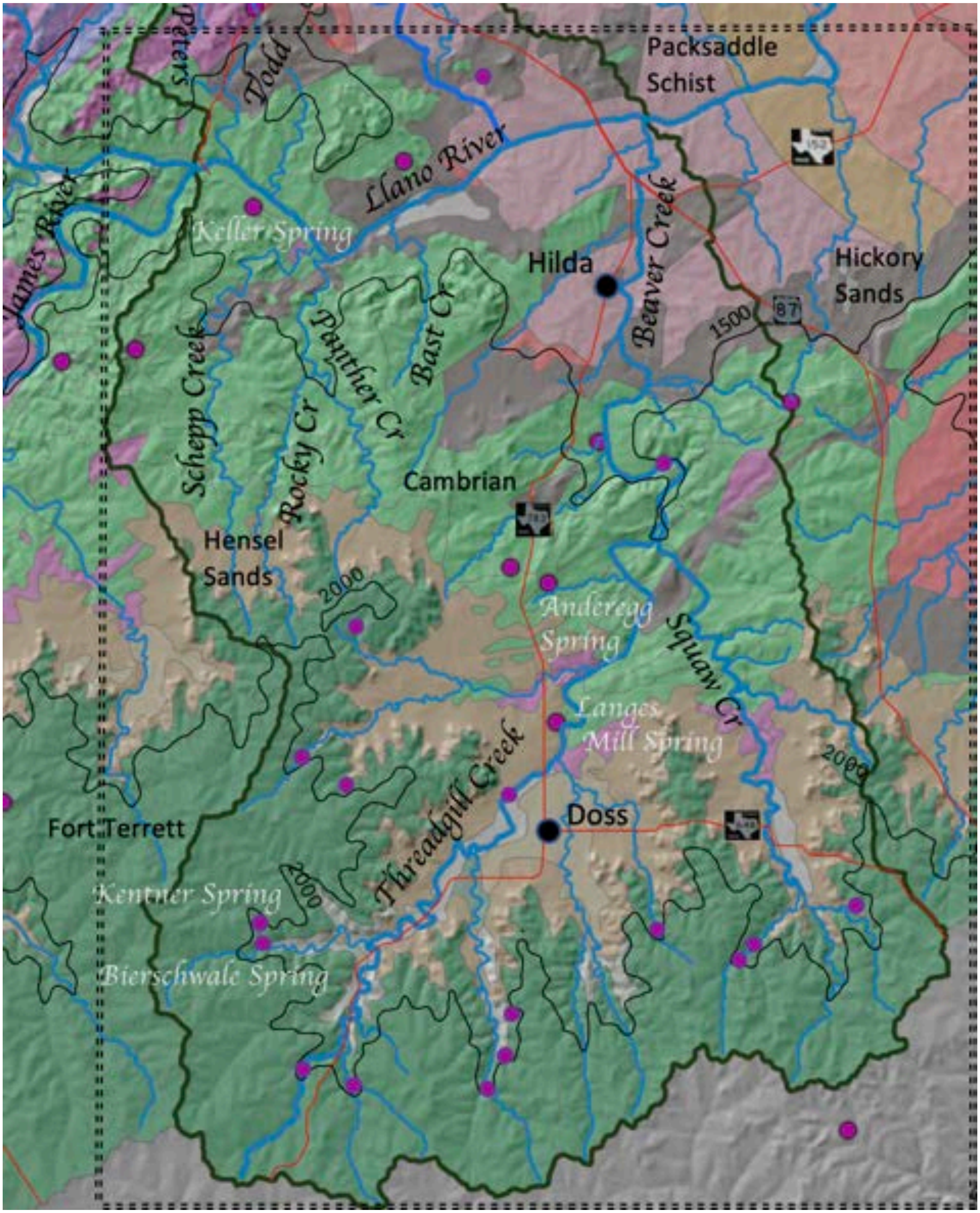

Figure 44b - Comanche Creek-Llano River Sub-watershed south from the Llano River

The headwaters of Beaver Creek originate in the an eastern extension of the Edwards Plateau, and consequently, have numerous springs which maintain considerable base flows. A USGS gage has been located at the US 87 Bridge over Beaver Creek since 1963. The average discharge of Beaver Creek at the gage is 19 cfs and median flows are 3 cfs. The maximum flow was 38,900 cfs during the 2018 floods. Zero flow has been recorded at the gage only three percent of the time.

Figure 45- Lange's Mill (source: Cattle Raisers Museum in partnership with The Portal to Texas History - University of North Texas Libraries).

There are eleven headwater springs located on Threadgill Creek and its numerous tributaries; with the exception of Bierschwale and Kentner Spring, all are nameless. Three unnamed springs are also located along Squaw Creek and its tributaries. As with the springs in the Upper Llano, these springs are located in the 'burrowed formation' of the Fort Terrett formation just below 2,000 feet. No additional information is available for these springs, but they provide localized flows to the headwaters tributaries. An additional spring northwest of Doss is located on Threadgill Creek; the source of this spring is likely Hensel Sands fed by overlying Fort Terrett formations.

The Hensel Sands are also the source of the most historically significant spring on Threadgill Creek, Lange's Mill Spring. In 1849, the Doss brothers, using slaves they brought when they immigrated from Virginia, constructed a saw mill, grist mill, and distillery at this location. F.W. Lange, a German barrel maker who made beer barrels for the Menger Hotel brewery, obtained the property after 1865 and milled corn and wheat until his death in 1877. His son operated the mill, which stands today, until 1888. [120] Discharge at the spring was 300 gpm in 1937 and 400 gpm in 1984.

[120] Michael Barr, "*Looking back at Lange's Mill*", TexasEscapes.com, 2019.

Anderegg Spring, to the north of Lange Spring, served as a stop on the old Chihuahua Road to Mexico and was the site of Swiss Johann Anderegg's cheese factory in 1850. Discharge from the Paleozoic sediments at this spring was recorded at 30 gpm in 1940.

Beaver Creek starts at the confluence of Threadgill and Squaw Creek, below Lange's Mill. Here, the waterway carves through Paleozoic Cambrian sediments exposing unnamed springs on Beaver Creek and on Deer Creek, a tributary. There is no other information associated with these springs except for the comment, 'never fails'. Below Hilda, Beaver Creek crosses Precambrian materials (primarily Packsaddle Schist) and no significant additional spring flows are added.

The economy of the sub-watershed is primarily ranching and hunting and commercial establishments serving the residents and tourist of historic Mason. There are a few small surface water rights for irrigation, but the great majority of use in the sub-watershed is groundwater. All of the 3,315 people in the sub-watershed obtain water from either the City of Mason wells or private water wells.[121] According to TWDB, there are 867 wells drilled in the sub-watershed, with more than 700 being drilled since 2000. Most wells are between 100 and 300 feet deep, depending on the location, but many well owners in the southern part of the sub-watershed must drill more than 600 feet to reach water in the Hickory Aquifer. As the Hickory Aquifer is confined and sloping to south, away from the Llano Uplift, the water in the aquifer is under artesian pressure and rises several hundred feet in the well casing. For example, one well drilled near Doss is 800 feet deep, but the water level in the well is only 70 feet below the top of the well.

<u>Hickory Creek - Llano River Sub-watershed</u>

Hickory Creek - Llano River sub-watershed is the largest sub-watershed in the Llano basin at 422 square miles. The sub-watershed is bordered on the south by Sandy Creek and on the north by the San Saba.

The earliest German settlements north of Fredericksburg occurred along the this segment of the Llano. Founded in 1847, the community of Bettina on the north bank of the Llano was the first settlement attempted within the Fisher-Miller Land Grant. The southern boundary of the Grant, purchased by the Adelsverein (officially the Society for the Protection of German Immigrants in Texas) was the Llano River. Of the five communities established along the Llano, only Castell remains. Today, the population of the sub-watershed is 910 persons with

[121] There are 1953 housing units in the sub-watershed. Based on housing per capita values, it is estimated that 30% of the homes are second family homes.

843 housing units. Given the average persons per household for Llano and Mason County is 2.43, it is estimated that about 55% of these homes are second-family homes.

The Llano River flows 19 miles across the Hickory Creek sub-watershed from Beaver Creek to Hickory Creek (Figure 46). As the channel flows across resistant Precambrian schists, gneisses, and granites, the gradient of this reach is only 8 feet per mile. Grasslands comprise 45 percent of the sub-watershed, followed by post oak (17%) and mesquite (11%). Due to the complexity of the geology, over 100 different soil types are identified; Castell Sandy Loam

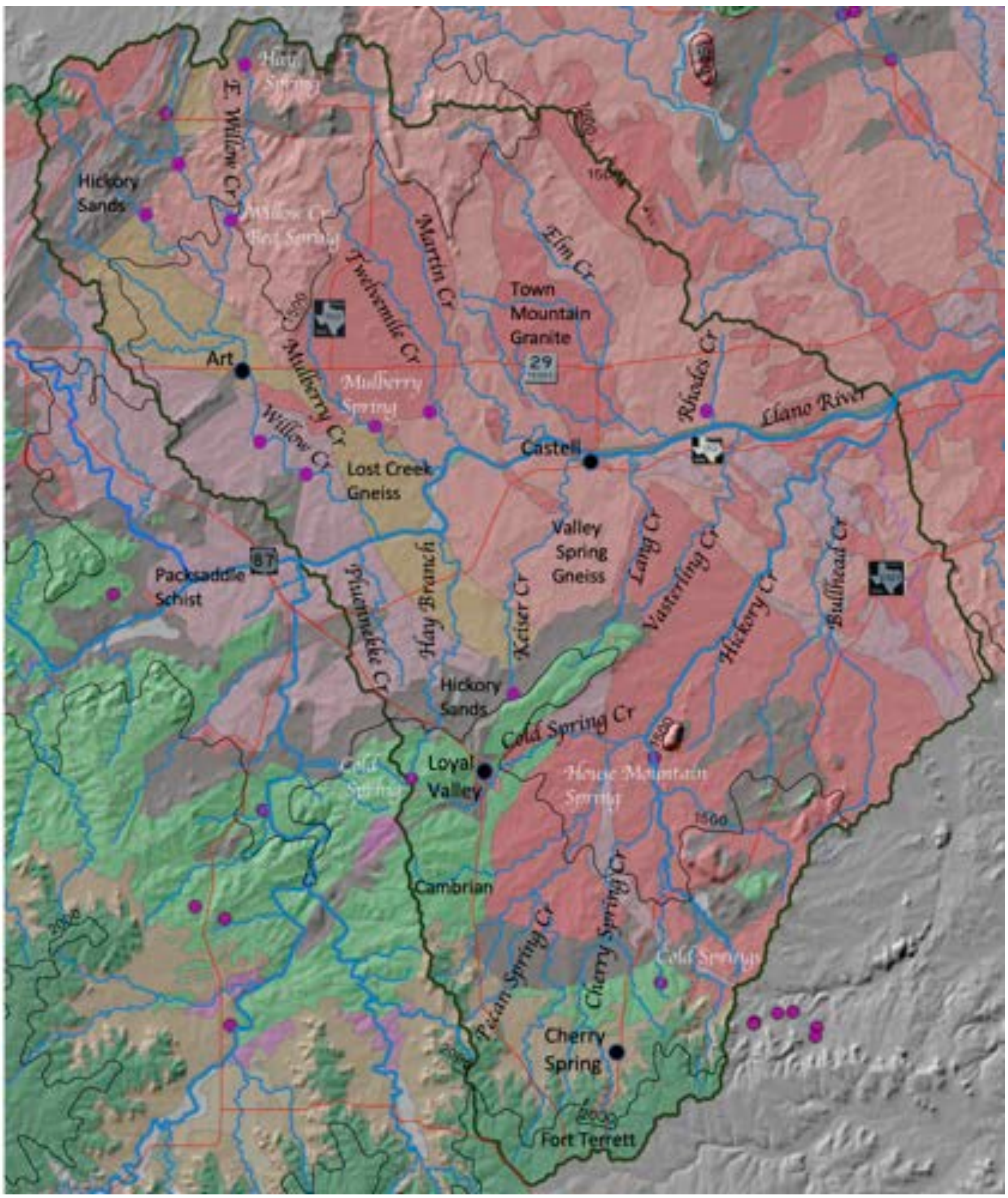

Figure 46 - Hickory Creek - Llano River Sub-watershed

derived from gneiss rocks are the most prevalent (14%) and Keese Lou Rock outcrop complex, a sandy loam from weathered gneiss or granite is the second most prevalent (11%).

Pluennekke Creek is the first tributary to intersect the Llano in this section of the river. Many tributaries in this portion of the Llano Watershed have headwater springs where permeable Hickory Sandstones are in contact with less permeable Precambrian formations, forcing water stored in the Hickory to the surface. The headwaters of 5-mile Pluenneke Creek originate from Hickory Sandstones, but the sandstones here are of insufficient size and depth to provide notable springs.

Willow Creek is the next tributary along this section, and largest tributary draining the north side of the Llano in the sub-watershed. This 21-mile tributary has its headwaters north of the City of Mason in Hickory Sandstones and in the Edwards Limestones of Mason Mountain, an erosional remnant of the Edwards Plateau. There are five headwater springs on Willow Creek and its tributaries. Hay Spring, which produced 20 gpm in 1939 is located on East Willow Creek; Capp Springs (15 gpm in 1939) is located on Willow Creek. At the confluence of these two streams is Willow Creek Bed Spring which measured 10 gpm in 1939. All other springs are unnamed. All but the Willow Creek Bed Springs are associated with groundwater from the Hickory Sandstone being forced to the surface along a contact with Precambrian formations. The source of the Willow Creek Bed Springs cannot be discerned from geologic maps. At least 33 irrigation wells utilize the Hickory Sandstone north of Mason, primarily to produce hay.

LCRA has had a stream gage on Willow Creek at Highway 29 in Art since 1999. The average flow during this time is 4 cfs. The largest flow occurred during the October 2018 floods when 4,885 cfs was recorded as the peak discharge. Sixty percent of the time, no flow is recorded at Willow Creek, so it does appear that the headwater springs of Willow Creek are large enough to maintain base flows. Two additional springs on Willow Creek are located below the gage. Geologic maps suggest these springs are associated with small Hickory Sandstone outcrops surrounded by the Precambrian; no discharge information is available.

Hay Branch is the next tributary downstream of Willow Creek. The headwaters of the tributary are to the south of the river at Cold Spring. This spring appears to be the result of faulting along Cambrian Welge formations near Loyal Valley. The Welge is a water-bearing formation located below the San Saba Formation and above the Hickory. No additional data are available.

The channel of the Llano as it crosses Precambrian formation is typically straight as bedrock channels do not lend themselves to erosion. The direction of flow is generally to the east. However, below Hay Branch, the Llano River makes a significant bend back to the northwest.

Downstream of the City of Llano, there are two bends in the river associated with nearby faulting. However, there are no faults identified along this section of the river. Rather, the river seems to follow the path of least resistance along a contact between two types of gneiss,

Figure 47 - Flood debris from October 2018 flood deposited 300 yards inland from Llano River where river bends to the northwest

Lost Creek Gneiss and Valley Springs Gneiss. In the opinion of the author, the most extensive flood damage during the October 2018 occurred along this bend where fast-moving floodwaters and debris were forced to make a sharp turn to the north (figure 47).

Mulberry Creek enters the Llano from the west along this bend. Although the creek is only 5 miles in length and crosses generally impermeable Precambrian rock, there are three springs found along its banks, including Mulberry Spring. There is no information available for Mulberry Spring and the two unnamed and unmapped springs located nearby. A nearby irrigation well, something not often associated with Precambrian formations, yields 50 gpm from 45 feet of weathered granite called regolith. Such weathering creates a hydrologically permeable layer overlying impermeable bedrock. Springs located about two miles above the mouth of Twelvemile Creek, whose confluence with the Llano is below Mulberry Creek, may also result from regolith.

As the Llano resumes its generally eastward direction of flow towards Castell, Martin Creek enters the Llano from the north. This 16-mile tributary originates in Hickory Sandstones near Fly Gap, but no springs are documented. Just before Castell, Keyser Creek enters the Llano from the south. Two springs located in Hickory Sandstones support very localized flow in the headwaters of this 10-mile creek. The community of Castell was laid out by German settlers in 1847 around Castell Spring, but no additional information is available regarding this spring.

The early German community of Bettina was located at the mouth of Elm Creek, a 14-mile tributary entering the Llano from the north below Castell. As Elm Creek drains an area exclusively of granites and gneiss, no springs are found along the creek. Three-mile Rhodes Creek, the next tributary from the north on the Llano, also drains an area exclusively of granites and gneiss, but does contain one spring of unknown origin.

On the south side of the river below Castell, the primary tributaries are Lang Creek (formerly known as Bear Spring Branch), Vasterling Creek and Hickory Creek. All of these creeks drain areas underlain by the the same granitic pluton that forms Enchanted Rock and is ringed by Hickory Sandstones. Yet, only Hickory Creek maintains headwater springs.

Lang and Vasterling Creek are both about 8 miles in length with headwaters in an erosional-remnant Paleozoic graben near the Mason - Llano County line. Hickory Creek is a 19-mile stream with numerous tributaries that intersects remnant Paleozoic grabens that are adjacent to more permeable Edwards Limestones.

House Mountain Spring is the lowest spring on Hickory Creek and may be associated with regoliths (weathered material) overlying granite. In 1993, flow was estimated between 5 and 10 gpm. Other springs include Cold Spring and Lower Cold Springs (just to the north) on Cottonwood Creek, with an estimated 1 to 2 gpm flowing from faulting along Cambrian Welge formations. [122] Localized creek and community names suggest the existence of additional springs : Cold Spring Creek; Pecan Spring Creek; and Cherry Spring. The community of Cherry Spring was founded by German settlers in 1852 on Cherry Springs Creek.

LCRA has maintained a gage near the mouth of Hickory Creek since 2000. Average flows during this period have been 23 cfs, with the largest flow of 37,600 cfs occurring during the October 2018 flood. Zero flow occurs at the Hickory Creek gage 45% of the time, suggesting that while headwaters spring flows are important to support local flows and aquatic habitats, they are not adequate to support base flow along the entire waterway.

[122] The Cold Springs on Cottonwood Creek are not to be confused with Cold Spring on Hay Branch or Cold Spring Creek also located in the sub-watershed.

There are only a few irrigation water rights in the Hickory Creek - Llano sub-watershed. The majority of the use is from groundwater, primarily in the areas underlain by Hickory Sandstones. There are 1,013 wells in the TWDB database, with 922 of them drilled since 2000. About 50 of these wells are utilized for irrigation of hay, vegetables, and vineyards. The remaining wells are used primarily for domestic and livestock use.

<u>San Fernando Creek - Llano River Sub-watershed</u>

San Fernando Creek-Llano River Sub-Watershed is a 336 square-mile basin draining northwestern portions of Llano County as well as part of Mason and San Saba counties. The San Saba River bounds the watershed on the north and Sandy Creek bounds it on the south. In addition to San Fernando Creek, the other main tributaries are Johnson Creek and Pecan

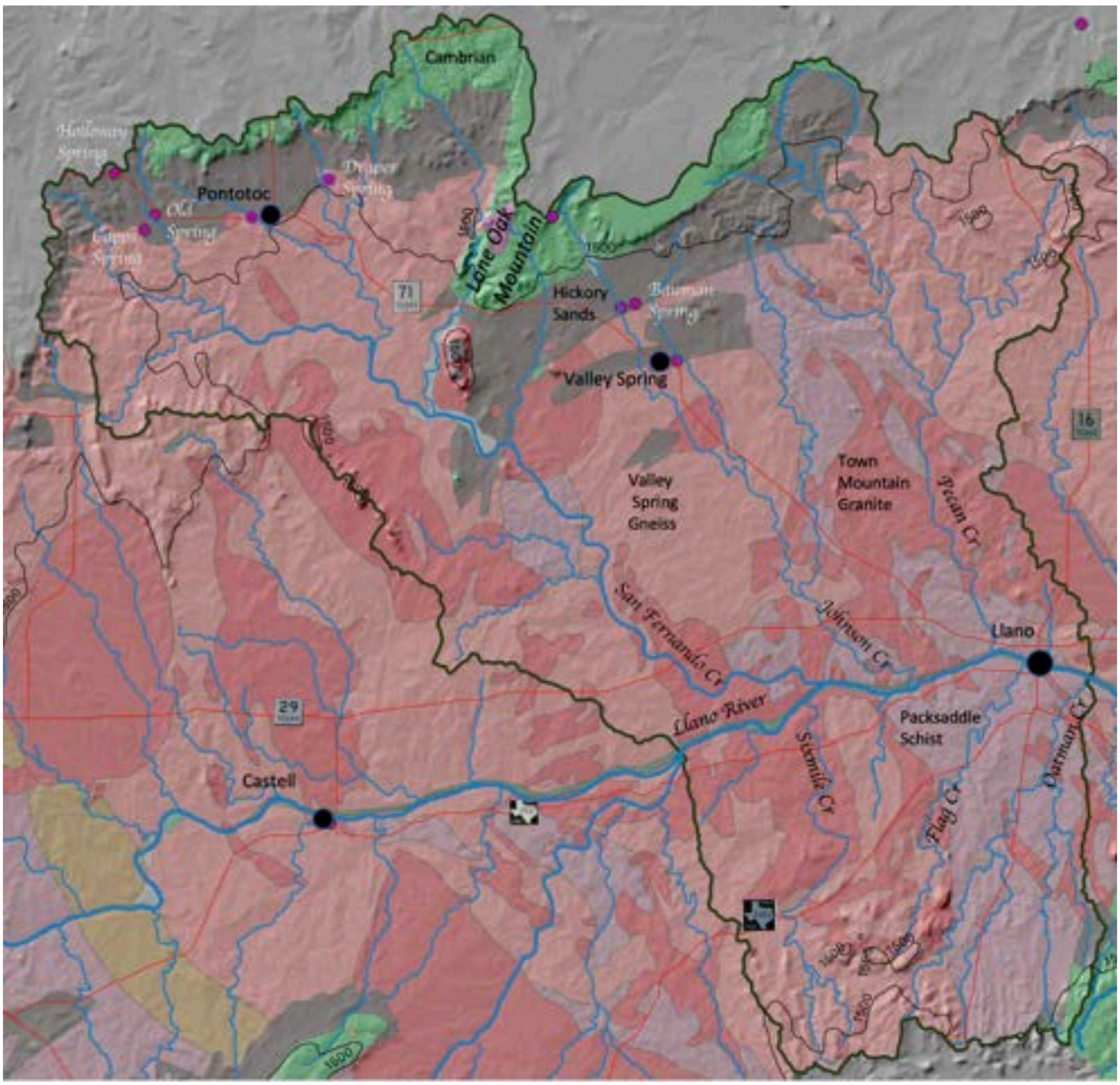

Figure 48 - San Fernando - Llano River Sub-watershed

Creek draining into the north side of the Llano and Six Mile Creek, Flag Creek and Oatman Creek on the south (Figure 48).

There are 78 soil types in the San Fernando sub-watershed, with Castell Sandy Loam (17%) being the most prevalent. The most prevalent vegetation types are grassland, post oak woodland, and mesquite.

The upper end of the sub-watershed begins at the confluence of Hickory Creek and the Llano River and ends at the confluence of Oatman Creek and the Llano. The 11-mile long segment flows over resistant Precambrian gneiss, granite and schist, resulting in a gradient of 9 feet per mile.

As the City of Llano is located in the San Fernando Creek - Llano River sub-watershed, it is the most populous in the Llano, with a population of 4,802 and 2,641 housing units. Of this total, 3,232 people live within the City of Llano. Given a persons per household value of 2.4 for Llano County, it is estimated that about 25% of these homes are second-family homes.

In contrast to the upper portion of the Llano watershed, where erosion of Cretaceous limestones produce gravels, erosion of Precambrian granites, schists and shales in the lower portion of the Llano produce sand. As a result, large volumes of sand are deposited along the channels of the Llano and its tributaries. Because of the resistant nature of the bedrock, the main channel is wide and relatively straight, as it is easier for the river to increase its width rather than its depth. Braided channels are common due to the large volumes of sand and exposed bedrock outcrops, which cause the river to form numerous channels. Tributaries flowing across these Precambrian formations are prone to having very wide, shallow, and sandy channels as well.

Below the confluence with Hickory Creek (discussed in the previous section), the Llano passes Six Mile Creek on the south side of the river, six miles west of Llano. The tributary is 14-mile long and is intermittent at the confluence with the Llano. The headwaters of Six Mile Creek are located in impermeable Valley Spring Gneiss and there are no significant springs to maintain baseflows in the creek.

Downstream, 25-mile-long San Fernando Creek enters along the north bank of the Llano. As much of the San Fernando Creek's 135-square mile watershed is underlain by impermeable Precambrian rocks, runoff from rainfall events can be significant. LCRA has maintained a stream gage on San Fernando Creek at Highway 29 since 1999. The average flow of the creek is 16 cfs, but this value is skewed by large runoff events, such as 40,330 cfs during the 2018 floods. San Fernando Creek has no flow at the gage 54% of the time.

Paleozoic Hickory Sandstones located in the headwater tributaries of San Fernando Creek feed several springs. These spring occur where permeable Hickory Sandstone is in contact with impermeable Precambrian formations. The largest of these springs is Capps Spring and an unnamed spring just west of Pontotoc. Both of these springs flowed 40 gpm when they were measured in 1939. Other named springs include Old Spring (10 gpm in 1939), Holloway Spring ("flowing" in 1939), and Draper Spring (2 gpm in 1938). Due to irrigation pumping from shallow Hickory wells, many smaller springs, such as Holloway Spring, no longer flow. However, the larger springs provide localized perennial flow along the headwater tributaries.

Johnson Creek is a 17-mile tributary that flows into the Llano River two miles below the confluence of the Llano and San Fernando Creek. Similar to its upstream watershed, the 59 square mile watershed flows across impermeable Precambrian formations but springs from Hickory Sandstones provide localized flow along headwater tributaries. The average flow at the LCRA Johnson Creek gage at Highway 29 is 3.6 cfs, with the largest flow, 15,448 cfs, occurring during October 2018. Since 2003, no flow has been recorded at the Johnson Creek gage 77% of the time.

Valley Spring is a community nine miles northwest of Llano. The community's namesake, along with nearby Bauman Spring and one unnamed spring, provide localized flow to Johnson Creek and tributaries. As with the springs at the headwaters of San Fernando Creek, these springs appear where Hickory Sandstones are in contact with surrounding Precambrian rocks. Only one of the springs has an estimated flow (between 10-15 gpm), but the owner reports that the Bauman Spring never failed, even during the drought of the fifties. According to Brune, the Valley Spring powered a mill there in 1854. [123] An additional spring near the headwaters of Johnson Creek flowed 8.5 gpm in 1987 and 2 to 3 gpm in 2008 from a fault along the side of Lone Oak Mountain.

Less than one mile below the confluence with Johnson Creek, the Llano River flows into the City of Llano's Park Lake, the upper of two reservoirs that make up the City's water supply. Both of these reservoirs impound the river utilizing run-of-river dams that only store water to the level of the dam. During periods of low flow, the City is permitted to store additional water by placing flash-boards on top of the dam.

During the Drought of the Fifties, the river ceased flowing for 128 days at Llano. During 1956, with water supplies at critical levels, the City of Llano imported water via railcar. During the drought of 2011, the City of Llano issued a "call" to TCEQ that required that agency suspend pumping by upstream junior water right holders. Over the last ten years, the City has proposed plans to develop alternative groundwater supplies from surrounding areas, but no supplies have been formalized.

[123] Brune, 1981.

Park Lake (also known as Robinson Lake), along with Llano Lake just above the bridge in Llano, are very prone to capturing much of the sandy sediment that is prevalent in the Llano Uplift portion of the Llano Watershed. In an effort to increase water storage, the City began dredging sediment from the reservoirs in 2015. The dredging was completed just prior to the October 2018 floods, which refilled the reservoirs with sediment. Prior to the beginning of dredging operations, a fresh-water mussel survey in Park Lake found more than 1,000 freshwater mussels in the Lake, the majority of which were *Lampsilis bracteata* (Texas fatmucket), a candidate for the endangered species list. [124]

The next tributary is Pecan Creek which enters the river at the upper end of Llano Lake. Although the headwaters of this 8-mile tributary are located in Hickory Sandstones, unlike San Fernando and Johnson Creek, no springs are known to be located in these headwaters.

Flag Creek enters the Llano near the lower end of Llano Lake. This 10-mile tributary drains an area of Precambrian rocks south of the City of Llano. As with Sixmile Creek to the west, there are no significant springs to maintain base flows on the creek.

The confluence of Oatman Creek and the Llano River downstream of the City of Llano marks the terminus of the San Fernando - Llano River sub-watershed. The 11-mile tributary begins south of Llano where a small outcrop of Hickory Sandstone is in contact with Precambrian rocks. As the thickness and size of this outcrop apparently are not of sufficient proportions to produce springflow, Oatman Creek is an intermittent stream.

The City of Llano is the largest user of surface water in the Llano watershed. The City has two water rights associated with each reservoir for municipal use and to irrigate the City's golf course at Robinson Park, In 2014, the last year water rights data are available, Llano used 690.77 acre-feet (617,000 gallons per day) for municipal supply and 59 acre-feet for irrigation. Per capita use for the City of Llano's 3,325 customers is 185 gallons per day.

The economy of the sub-watershed is primarily based on the rearing of livestock, hay production, viniculture, and tourism. As Llano claims the title, "Deer Capital of Texas", hunting leases also provide significant supplemental income to local ranches.

There are only a few irrigation water rights from the Llano along this section of the river. The vast majority of water use in the San Fernando - Llano River Sub-watershed is associated with groundwater pumping from the Hickory Sands Aquifer. This productive aquifer consists of pockets of sandstone located along the outer rim of the Llano Uplift. In the sub-

[124] Kyle T. Sullivan, Bradley M. Littrell "Freshwater Mussel Assemblage Structure in a Small Edwards Plateau Impoundment with Comments on Conservation Implications for Texas Fatmucket, *Lampsilis bracteata* (Gould 1855)," Freshwater Mollusk Biology and Conservation, 23(1), 36-41, (8 April 2020)

Figure 48 - Run of river dam for water supply to City of Llano. The photo was taken in August of 2018 during drought conditions; no water was flowing over the dam. Two months later, floodwaters nearly reached the top of the bridge pilings.

watershed, there are more than 1,228 wells catalogued in the TWDB database, the largest concentration of wells in the Llano watershed. More than 1,000 wells have been drilled in the watershed since 2000.

The majority of the irrigation wells are in and around the communities of Valley Spring and Pontotoc. These sixty wells tend to be shallow (less than 200 feet) and yield more than 100 gallons per minute. Historically, these wells were used to irrigate peanuts, but following the elimination of subsidies for this crop in the mid-1990s, irrigation now is primarily for hay production and vineyards. Since 2000, over 100 wells have been drilled in and around the City of Llano. Approximately 35 of these low-production wells (less than 5 gpm) have a proposed use of irrigation and are used irrigate lawns when City of Llano drought restrictions on surface water supplies are in place. Private water wells are generally exempt from municipal drought restrictions in Texas. Additionally, unlike the other counties in the Llano watershed, Llano County does not have a groundwater district to govern the drilling, spacing, and pumping of wells.

Little Llano - Llano River Sub-watershed

The Little Llano-Llano River sub-watershed is the last watershed on the Llano before its terminus in Lake LBJ and the Highland Lakes. The 238- square-mile basin encompasses the Llano River and its tributaries from its confluence with Oatman Creek just east of Llano to the mouth of Llano at the confluence with the Colorado River in Kingsland (Figure 49). The sub-watershed is bounded by the Cherokee Creek to the north, Lake Buchanan to the east, and Sandy Creek to the south. The 24-mile long segment flows over resistant Valley Spring Gneiss and Town Mountain Granite and has a low gradient of 7 feet per mile, adjusted for the elevation of the last 5 miles of the river being influenced by the level of Lake LBJ. There are 58 soil types in the watershed, with Ligon and Katemcy sandy loams being the most prevalent. Grassland, post-oak woodland, and mesquite are the predominant vegetation types.

The Little Llano sub-watershed is one the most populous in the Llano, owing to existence of Lake LBJ. The population of the watershed is 4,327 with 2,552 housing units. In Llano County, an average of 2.4 persons live in each household, suggesting that about 70% of the housing units in the Little Llano are primary residences.

Archaeological evidence below the confluence of the Llano and Colorado rivers suggests that this area was inhabited around the turn of the first millennium. Kingsland, the main community on Lake LBJ in the Llano watershed, began as a small trading center with a cotton gin in the 1870s. The community grew to 750 people with the arrival of the railroad in 1901. The construction of Granite Shoals Dam (now named Wirtz Dam) created Lake LBJ in 1950 and transformed Kingsland into a retirement and recreational center. By 1990, the population was 2,725 and in 2019 was over 7,000. Lake LBJ, originally named Lake Granite Shoals, was renamed in 1965 in honor of President Johnson who owned a ranch on the south side of the lake across from Kingsland.

From Oatman Creek, the Llano River flows over Valley Spring Gneiss past the City of Llano's waste-water treatment plant. The plant historically utilized land application (irrigation of 200 acres of hay fields) to dispose of its wastewater. In 2017, TCEQ issued a permit to the City to allow re-use of the wastewater. The permit, also provides the City the flexibility to discharge treated wastewater to the river during wet-weather periods when disposal via irrigation is not practical. Phosphorous levels in the wastewater must meet state requirements prior to being discharged.

As previously noted, the channel of the Llano River across pre-Cambrian rock is generally confined and straight. However, below Llano, faulting associated with the Riley Mountains southeast of Llano forces the river around a 2-mile mile meander to the north. As a result of this meander, there are no significant tributaries along the south bank of the Llano for the first 12 miles of this river segment.

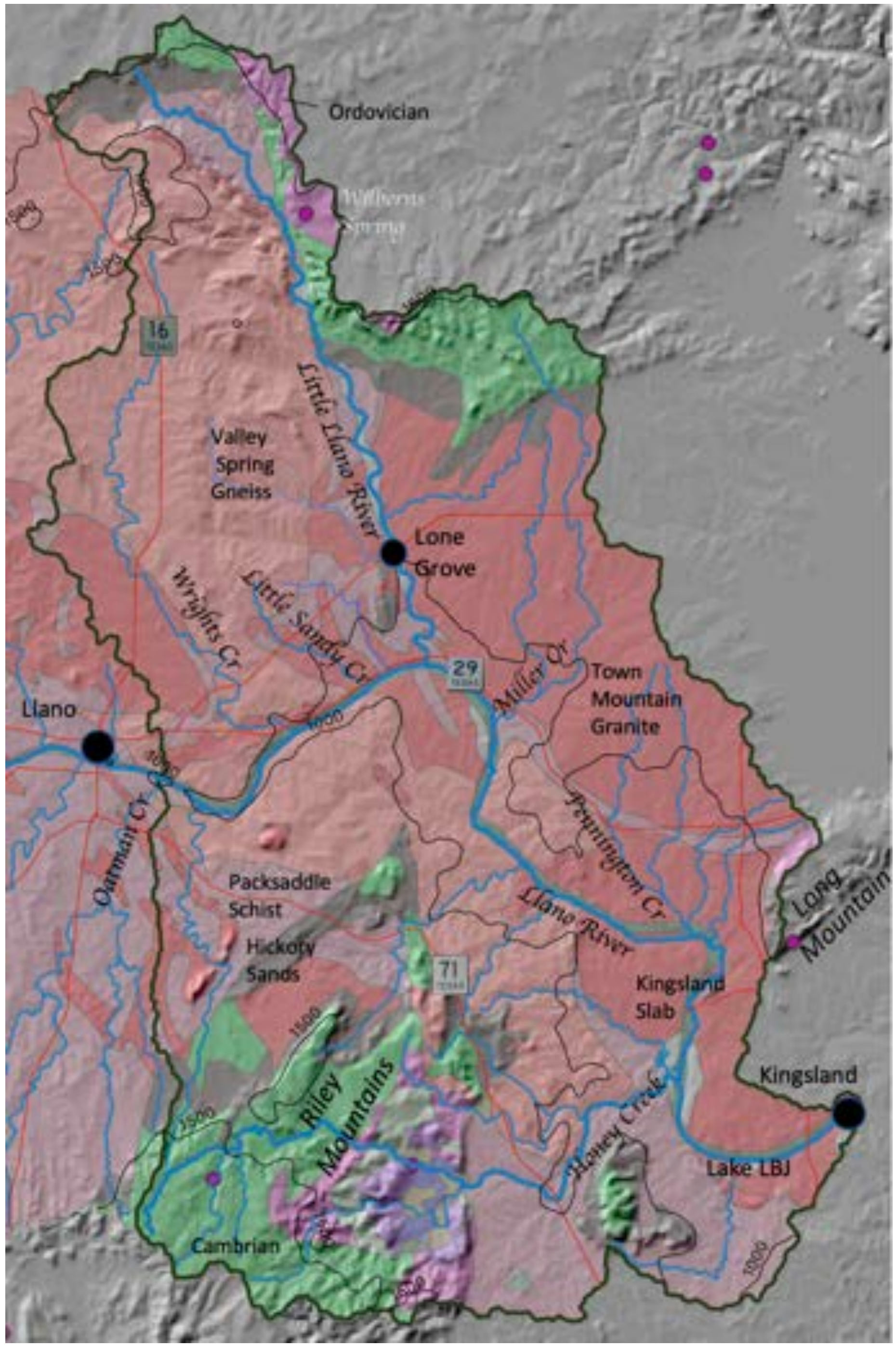

Figure 49 - Little Llano - Llano River Sub-watershed

Main tributaries along the north bank of this segment include Wrights Creek, Little Sandy Creek, Little Llano River, Miller Creek and Pennington Creek. Of these tributaries, Wrights Creek and the Little Llano River are the most significant.

Wrights Creek flows 14 miles across Precambrian rock, mostly Valley Springs Gneiss; there are no mapped springs on this tributary. According to the *Handbook of Texas,* Wrights Creek used to be a perennial stream.[125]

[125] Anonymous, "Wright's Creek," *Handbook of Texas Online*, accessed January 30, 2021, https://www.tshaonline.org/handbook/entries/wrights-creek. Published by the Texas State Historical Association.

There are five named 'rivers' in the Llano Watershed: Llano, North and South Llano, James and Little Llano. The Little Llano, at 16-miles in length, is the shortest river of these rivers. It begins at an elevation of 1,420 feet above sea level in the northern tip of the sub-watershed and drops off the escarpment rimming the Llano Uplift, intersecting the Llano River at an elevation of 925 feet, south of the community of Lone Grove. This river gradient of 31 feet per mile is the steepest river in the watershed.

Wilberns Springs, located in Wilberns Glen just south of the San Saba - Llano County line, is the principal spring on the Little Llano. In the historical account, *"Old Man and the Glen"*, Roy Wilbern describes Wilberns Springs: *"The large spring boils from the ground at the Summit of the hill"…. "waterway courses through rugged terrain down a steep side of the predominately limestone hill forming a stairway of pools and formations as this crystal stream falls from one level to a lower one before it finally flows into the Little Llano River"*.[126]

Wilberns Springs (elevation 1,375 ft) boils from the ground at the summit of the hill because it is associated with faulting along the Little Llano Fault. Here, groundwater stored in limestones of the Ellenburger Formation (Ordovician age) are forced to the surface by faulting. Wilberns Springs was measured at 800 gpm in 1940 and does provide localized flow to the Little Llano.

LCRA has maintained a stream gage on the Little Llano River below Lone Grove since 1999. The average flow of the river during this period is 4.6 cfs with the highest flow, 3,847 cfs, recorded during the October floods of 2018. The Little Llano is dry 59% of the time since 1999.

Below the confluence with the Little Llano River, the main Llano completes its meander around faults associated with the Riley Mountains and continues in a fairly straight southeastward direction along a confined channel. Braided channels are common due to the large volumes of sand. As the Little Llano - Llano sub-watershed is lowest watershed in the Llano with the largest upstream drainage area, large volumes of sand are located along the channel. Some of these sands are mined from the floodplain of the river.

As the Llano River continues towards its culmination in Kingsland, the channel crosses granitic bedrock. Making its way across this bedrock, the river forms numerous low-flow channels around exposed mid-channel outcrops. The largest of these outcrops is Eagle Rock, located where the Llano turns to south towards Kingsland (figure 50).

The bend of the Llano to the south towards Kingsland is likely the result of faulting associated with Long Mountain to the north of Kingsland. In fact, topography suggests that prior to the formation of Long Mountain, the old channel of the Llano continued straight and

[126] Roy Wilbern, "The Old Man of the Glen : Ferdinand Columbus Willbern, 1827-1903. Nortex Press; 1st edition (January 1, 1991.

met the Colorado River about 1.5 miles above its current confluence.

Figure 50. Eagle Rock on Llano River above Kingsland.
Photo Credit: Tim Birdsong

As a result of the channel meander resulting from Long Mountain, all of the major tributaries to the Llano nearby are along the west side of the river channel. The largest of these tributaries is Honey Creek, a 14 mile spring-fed tributary rising in the sedimentary Riley Mountains, a graben surrounded by Precambrian rock by faulting. LCRA has maintained a stream gage on Honey Creek at Highway 71 since 2002. The average flow of the river during this period is 5.4 cfs with the highest flow, 2,798 cfs, recorded in 2007. The flow during the October floods of 2018 was 1,411 cfs. Honey Creek was dry 27% of the time between 2002 and 2020.

The Springs of Texas Database indicates two springs feeding Honey Creek; neither of these springs has an official designation [127]. One spring is located at an elevation of 1,540 feet, on top of Riley Mountain, and in 1961 flowed less than 50 gpm. The second spring, located at 1,186 feet, measured 2 cfs (900 gpm) in 1961. These springs result from groundwater stored in the sedimentary rocks being forced to the surface by faulting.

There are only three water rights for irrigation in the Little Llano - Llano River sub-watershed. Two are located along the mainstem of the Llano and one right is located on Honey Creek. Kingsland Municipal Supply Corporation diverts water from Lake LBJ under a contract with LCRA.

Within the sub-watershed, there are 843 groundwater wells listed in the TWDB database. These includes 783 wells drilled since 2000. There are 9 public water supply wells, primarily serving subdivisions in and around Kingsland. A total of 22 wells are designated as irrigation wells; all but four of these wells are medium-production wells (10-75 gpm) used to irrigate lawns when Kingsland Municipal Supply Corporation drought restrictions on surface water supplies are in effect. There are at least 150 additional 'domestic' wells drilled within the Corporation boundaries that are often used to circumvent drought restrictions on surface water. The remaining wells are for domestic or livestock use.

[127] The upper spring feeding Honey Creek is located on Buck Springs Ranch.

The majority of the wells in the sub-watershed are drilled into Precambrian formations. As these formations are not very permeable except along fracture lines, yields are generally less than 25 gpm. Well drilled into Precambrian formations are generally less than 100 feet deep, but can be over 200 feet. The Hickory Sandstone formation is the other major aquifer providing water to wells in the sub-watershed. Wells in the Hickory formation are 50 to 200 feet in depth and yield up to 50 gpm. The Hickory formation also provides water to wells located on top of Riley Mountain. These wells are 400 feet deep and yield about 30 gpm. There is one active observation well in the Little Llano along Wrights Creek north of Llano. Water levels in this Precambrian well have fluctuated about six feet since 2011.

WATER USE

Irrigation is the largest user of water in the Llano watershed. The majority of surface irrigation is located in Kimble County, while Mason County is predominant in the use of groundwater. TWDB data from 2015-2019 [128] note that for all of Edwards, Kimble, Mason and Llano counties, an average total of 2,501 acre-feet were irrigated from surface water [129] and 5,537 acre-feet were irrigated from groundwater (Table 5). Kimble County is the largest surface-water user for irrigation with 2,281 acre feet (91 percent) while Mason County is the largest groundwater user for irrigation with 4,594 acre feet (83 percent). The majority of this irrigation is for hay and forage, pecans, grapes, vegetables, fruit trees and native seed production. In 1990, when groundwater in Mason County irrigated subsidized peanut crops,

Table 5 - Water Use by County (acre-feet)

Irrigation Water Use	Edwards		Kimble		Mason		Llano	
Year	SW	GW	SW	GW	SW	GW	SW	GW
2015	76	43	2,293	136	83	4,888	163	436
2016	22	240	2,032	344	103	4,791	126	557
2017	41	180	2,022	283	30	4,508	27	541
2018	38	210	2,450	271	16	3,943	151	526
2019	29	175	2,610	297	6	4,839	188	473
Average	*41*	*170*	*2,281*	*266*	48	*4,594*	*131*	*507*

128 Texas Water Development Board, "Water Use Survey Historical Summary Estimates by County", accessed June 2021.

129 Average surface water use for 2015-2019 equates to 3.45 cubic feet per second. One cubic foot per second equates to 724 acre-feet per year.

water production was 17,777 acre-feet per year, nearly four times the current usage. Surface water withdrawn for irrigation in Kimble County has remained fairly consistent since 1985.[130]

TWDB only provides water use data by county, but water-rights use data from TCEQ, though only available up until 2014, provides insights into surface water use by watershed.[131] Irrigation water rights holders on the North Llano reported using 11 percent of the total water use reported, while South Llano users reported using 28 percent. The majority (61 percent) of the reported usage occurred along the mainstem of the Llano. The largest irrigated plots are less than 125 acres, with the majority of plots under 50 acres.

TWDB Water Use Survey Estimates report water use for public supply is the next largest user in the Llano Watershed. In 2019, for the communities of Rocksprings (which is partially in the Llano watershed), Junction, London, Mason, Llano, and Kingsland, 1,375 acre feet of groundwater were withdrawn and 4,080 acre-feet of surface water was withdrawn. Rocksprings, London, and Mason rely on groundwater, while Junction, Llano and Kingsland rely on surface water. Reuse of water for public supply was 437 acre-feet, all in Llano County.

Groundwater used for livestock watering in the Llano watershed in 2019 totaled 1,467 acre-feet; surface water use was 609 acre-feet. The largest livestock groundwater use is in Mason County and the largest surface-water use in Llano County.

Water use for mining is the fourth largest user, with 238 acre-feet of surface water used in Llano County and 176 acre-feet of groundwater used in Mason County. Water use for manufacturing is the fifth largest user. In 2019, only 5 acre-feet were withdrawn from groundwater, but 516 acre-feet of surface water was utilized for manufacturing.[132]

There are also other important considerations regarding water use in the Llano watershed. The Llano River also supplies water to the Highland Lakes, a critical supply not only for downstream municipalities and irrigators, but also for aquatic species that rely on adequate flows within the river and into Matagorda Bay. On average, the Llano River provides about 27 percent of the flow into these reservoirs. However, during periods of drought, such as the summer of 2006, the spring-fed Llano River contributes approximately 75 percent of the inflow to the reservoirs [133].

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[130] U.S. Geological Survey, "Water Use Data for Texas", 2018.

[131] Texas Commission on Environmental Quality, "Water Use Data Files from 2000 through 2014".

[132] Llano County reports 1,054 acre-feet of surface water used to generate power in 2019. The Ferguson Power Plant associated with this water use is located on Lake LBJ downstream from the Llano watershed.

[133] Environmental Defense Fund, "Land of the Living Waters : A characterization of the South Llano River, its springs, and its watershed," 2008.

WATER QUALITY

The spring-fed waters of the Llano consistently have good water quality. There are only three point sources of pollution in the entire watershed from wastewater discharge facilities or industrial outfalls. However, there is some potential for non-point sources pollution from agricultural runoff, wildlife, or septic systems that might impact the river.

Groundwater wells located in some areas of the watershed tend to have hard water as a result of limestone aquifers. Quite a few wells in the watershed have elevated levels of nitrates, possibly resulting from poor well location and construction, agricultural runoff or inadequate septic systems.

Surface Water

Surface water quality in the Llano River watershed is to be protected for primary contact recreation (wading, swimming), high quality aquatic life, fish consumption and public water supply by TCEQ. From time to time, sections of the Llano River watershed, primarily the North Llano, experience sporadic exceedances of water quality standards for these parameters due to low-flow conditions, resulting in increased water temperatures. Field observations have noted that the presence of feral hogs may also impact E-coli results. Hogs, along with other exotic wildlife such as axis deer, significantly impact local water quality in the Llano. These impacts are further discussed in the chapter on Riparian Habitat.

Dissolved Oxygen (D.O.), a measure of the level of oxygen in the water, is essential for aquatic life. D.O. levels naturally exhibit diel (24-hour) patterns with levels increasing during the day as plants photosynthesize and decreasing at night as plants and other organisms respire. Extreme spikes and drops in D.O. concentrations may be an indicator of excessive nutrients or organic carbon loading. Extreme drops in D.O. levels are the most hazardous because levels <2 mg/L can cause death of fish and other aquatic organisms. In Hill Country streams, the level of D.O. necessary for exceptional aquatic life should typically remain above 5.0 mg/L over a 24-hour period.

Escherichia coli (*E. coli*) are an indicator of fecal pollution and the potential threat of harmful bacteria, viruses and protozoans. All warm-blooded animals are sources of *E. coli*. Commonly cited sources of contamination include septic systems, wastewater treatment facilities, livestock and wildlife. The allowable limit for protecting primary contact recreation for *E. coli* bacteria is a geometric mean of 126 colony forming units (cfu) per 100 ml. A water body is considered impaired for E-coli only if 25 percent of the samples exceed the recommenced level. None of the waterways in the Llano watershed are considered impaired.

The 2020 Texas Integrated Report [134] summarizes the condition of the state's surface waters (for the period 2011 to 2018) regard to aquatic life, contact recreation, and specific pollutants along with the possible sources of contamination. For the Llano watershed, the report assesses six segments of the Llano plus Johnson Fork and James River. The exceedances are listed in Table 6.

Table 6. Parameter Exceedances for Llano Watershed - from 2020 Texas Integrated Report

Segment	Parameter	# Samples	# Exceedances	Criteria	Value of Exceedance
Llano River - Llano Dam to Honey Creek	Nitrate	80	1	1.95	2.19
Llano River - Junction to Big Saline Creek	Nitrate	47	1	1.95	2.61
North Llano River	Dissolved Oxygen	62	5	5.0	4.52
Johnson Fork	Dissolved Oxygen	27	1	5.0	4.4
Johnson Fork	Nitrate	27	1	1.95	3.7

For the Llano watershed, there were few exceedances for the sample period December 2011 - December 2018. The North Llano was the most problematic with five out of 62 DO samples falling below the criteria of 5.0 mg/l.

The 2020 Texas Integrated Report also notes specific pollutant exceedances for chlorophyll-a on Johnson Fork, the North Llano, and the Llano downstream of Llano, and one exceedance of pH each on the North Llano and the South Llano. High chlorophyll-a levels suggest an overabundance of nutrients in the water. High pH levels are likely a naturally-occurring result of limestone underlying the watershed.

The Texas Integrated Report does not provide the timing of these exceedances, so it is often difficult to ascertain the cause of the problem. LCRA regularly monitors and records water quality data for the Llano and twenty sampling events conducted from 2012–2015 for

[134] Texas Commission on Environmental Quality, "2020 Texas Integrated Report of Surface Water Quality for Water Act Sections 305(b) and 303(d) - Water Body Assessments by Basin."

development of the Upper Llano River Watershed Protection Plan (WPP) provide additional insight [135].

On the North Llano, LCRA monitors, on a quarterly basis, a site 75 meters upstream of the US 377 bridge in Junction. Of the 21 readings collected between 2014 and 2019, three samples for DO were below 5.0 Mg/L. In addition, nine sampling locations on the North Llano for the WPP observed three samples below 5.0 mg/L on the Middle North Llano at CR 274 and CR 275 (below the confluence of Copperas Creek) crossings; all of these DO readings occurred during summer sampling events under low-flow conditions.

LCRA also samples for E-coli at the North Llano site in Junction. One sample, taken in August of 2015 during low-flow conditions, had one exceedance of >2000 per 100 ml. Despite the high result, the geometric mean for this site is 61 per 100mL, below the 126 per 100mL required to be maintained for contact recreation. Upstream of this location, three sites sampled as part of the WPP had a geometric mean for E Coli above 126 per 100mL. These sites include North Llano at River Road above Roosevelt, North Llano at CR 275, and Bois d'Arc Spring on Bois d' Arc Creek. Field records indicate the presence of feral hogs at all three sites. Although these locations exceed the geometric mean for *E. coli*, the exceedances do not result in the water body being considered impaired as some of the samples were obtained during extreme low-flow events.

For the South Llano, LCRA samples quarterly at two sites. One site is above the second crossing near Telegraph and the other is at South Llano River State Park. In addition, the WPP sampled 11 sites on the South Llano. No exceedances were noted at any of the WPP sites and only one exceedance was noted at an LCRA site. In 2018, the E-coli count at Telegraph was 770 one day after the first significant rainfall in 75 days. This result can be considered an outlier as the geometric mean for this site is 20, well below the TCEQ limit of 126 for contact recreation.

Below Junction, LCRA obtained quarterly samples from 1999 to 2015 upstream of the City of Junction wastewater treatment plant on the Llano River. Out of 34 samples taken during this time period, there were no exceedances for DO and the geometric mean for E-coli was 62. One nitrite sample recorded 2.32 Mg/l, above the 1.95 Mg/l criteria. LCRA no longer samples at this location.

LCRA has monitored water quality quarterly on Johnson Fork since 1993. During this period, there has been only one exceedance for DO (4.4 Mg/l in August, 2018) and one exceedance for nitrates (3.7 Mg/l in October 2018).

[135] Upper Llano Watershed Coordination Committee, "Upper Llano River Watershed Protection Plan", May 2016.

The Llano River at Ranch Road 385 is known as Yates Crossing. LCRA has collected water quality data here since 1994. There have been no exceedances regarding DO and the only exceedance regarding nitrates occurred in October 2018, following the flood.

In addition to Johnson Fork, LCRA also monitors James River. Despite often low-flow conditions, DO remains high. Since 2007, the lowest DO reading is 7.8 Mg/l with an average of 11 Mg/l. There are no exceedances for nitrite and the geometric mean for E-coli is 48.

LCRA monitored water quality below the US 87 Bridge in Mason County on a quarterly basis from 1999 to 2015. Of the 75 samples collected, only two DO samples fell below 5.0 Mg/l; this occurred in 2006. Several E-coli counts were recorded to be greater than 1,000 on two occasions (October 2003 and August 2014), but the geometric mean for E-coli is 11.

Below Castell at Scott's Crossing (Llano CR 102), LCRA has obtained water quality samples since 1984. For all the samples, DO has always been above exceedance levels, with the lowest value at 6.2 Mg/l. No Nitrite exceedances have been recorded and the geometric mean for E-coli is 16.

LCRA has also recorded water quality data below the Llano River bridge in Llano since 1984. As water passes over or through the City of Llano dam just upstream, DO has consistently remained high, with consistent readings at 8 Mg/l even during low flow conditions. All nitrite readings have remained below limits and the geometric mean for E-coli is 36 despite having six readings over 1000 since 2000, including a reading of 11,000 in April 2017 following a precipitation event. This sampling site is located in an area with significant contact recreation during the summer months.

The most downstream sampling site on the Llano maintained by LCRA is the Kingsland Slab at Ranch Road 3404. As this is also significant contact recreation site, water quality has been monitored monthly or bimonthly since 1980. As the waters of the Llano are well aerated as they pass over granite shoals, DO readings consistently remain above 8.0 Mg/l, although one reading of 4.7 was recorded in August of 1998. With the exception of one occurrence in 1985, nitrites have remained within water quality standards. The geometric mean for E-coli is 18, but readings as high as 25,000 have been associated with peak stream-flow events. August readings for E-coli, when contact recreation is greatest, are generally less than 10.

Groundwater Quality

Primary drinking water standards for groundwater are those that may pose a threat to human health if exceeded. Primary drinking-water standards are for *E. coli* and nitrate. *E.* Coli for drinking water should be undetectable and nitrate levels should be less than 10 mg/

L. Levels greater than this may cause shortness of breath and blue-baby syndrome in infants [136]. There are natural nitrate sources (e.g., precipitation, bedrock, nitrogen-fixing bacteria and nitrogen-laden geological deposits), and anthropogenic sources of nitrate from faulty septic systems, livestock manure or fertilizers.

In June of 2013, 46 wells were screened as part of the Texas Well Owner Network seminar and water screening in Junction. Of these wells, 63% tested positive for total coliform and 13% tested positive for *E. coli*. Similar screenings by the local groundwater district in 2014 showed 23% (of 35 wells) testing positive for *E. coli* and 14% for nitrates. In 2015, 15% (of 34 wells) tested positive for *E. coli* and 9% for nitrates. These positive tests suggest inadequate waste disposal or a potential contamination of the sample by the landowner preparing the sample.

Texas Water Development Board reports groundwater quality data by county over the last 20 years.[137] In Sutton County in the Upper North and Middle North Llano Watersheds, groundwater quality reports are available for 109 wells. Of these, 17 wells exceed the standard for nitrate. Except for one well drilled in the alluvium, all wells that exceeded nitrate standards are located in the Edwards-Trinity Aquifer.

For the portion of Edwards County in the South Llano Watershed, groundwater quality reports are available for 30 wells. Of these, five wells have nitrate levels that exceed the nitrate standard over the last 20 years, and all are located in the Edwards-Trinity Aquifer.

For the portion of Kimble County on the North Llano, 10 of 35 sampled water wells have exceedances of nitrate. With the exception of one alluvial well, all of these wells are drilled in the Edwards-Trinity Aquifer. For the South Llano Watershed, six of 21 Edwards-Trinity wells have issues with nitrates in groundwater. On the main Llano, 17 of 53 wells sampled had exceedances for nitrates. With the exception of two Ellenburger wells and one alluvial well, all wells are located in in the Edwards-Trinity Aquifer.

Two of the three wells with water quality data in the portion of Real County that feeds the South Llano have nitrate exceedances. These wells are located in the Edwards-Trinity Aquifer, as is the one well with nitrate exceedances (out of 5) in the portion of Kerr County that feeds the Llano River.

In Mason County, 27 wells in the county have water quality data from the last 20 years. Of these 27, one-third of them have excesses for nitrogen or total dissolved solids or both. Seven of these wells are in the Hickory and one each are in Ellenberger and Packsaddle Schist aquifers.

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136 US Environmental Protection Agency, "Estimated Nitrate Concentrations in Groundwater Used for Drinking. 2021.

137 Texas Water Development Board, "Groundwater Database (GWDB)-Well Water Quality Report", available online.

In Gillespie County, 41 of the wells within the drainage of the Llano Watershed contain water quality information. Of these 15 have exceedances for nitrates. Two of these wells draw from the Hickory Sandstones, 2 draw from the Ellenburger, and the remainder draw from the Edwards-Trinity.

The highest percentage groundwater wells with a history of nitrate contamination over the last 20 years is in Llano county. Of the 80 wells sampled in the Llano Watershed, 32 (40%) of the wells have nitrate issues. The largest region with this issue is the Valley Spring area, where shallow hickory wells are subject to contamination.

HABITAT

In addition to being an important water resource, the Llano River and its watersheds provide important and unique aquatic, terrestrial, and riparian habitats. These habitats play a crucial role in the biological diversity and recreational opportunities of the area.

Aquatic

The Llano River provides some unique aquatic habitat for a variety of species. One of the most notable species is the Guadalupe Bass, the State Fish of Texas. This sought-after sport fish is a key economic generator for the local economy. A 2010 socioeconomic survey of the Edwards Plateau showed that over a 16-month period, more than $74 million in direct angler expenditures was spent on fishing trips to the region, supporting 776 full-time jobs. The Guadalupe Bass are also listed as a species of special concern due to habitat degradation and hybridization with smallmouth bass, a species that was introduced to the South Llano from 1958 to 1960.[138] Between 2011 and 2017, Texas Parks and Wildlife, in

Figure 51 - Releasing Guadalupe Bass fingerlings into South Llano River (photo source : Chase A. Fountain, TPWD)

[138] Zack Thomas, Tom Arsuffi and Steve Magnelia, "Fishing Warmwater Streams with Limited Public Access: Angling behavior, economic impact, and the role of Guadalupe Bass in a 24-county region of Texas. Black Bass Diversity : Multidisciplinary Science for Conservation. American Fishery Society Publications. 2014.

partnership with the Texas Tech Llano River Field Station and the Llano River Watershed Alliance, released 700,000 genetically-pure Guadalupe Bass into the South Llano, driving the percentage of hybridized bass to less than 2 percent (Figure 51). [139]

Fish community sampling effort during periods of low flow evaluated several sites along the Llano during 2010 and 2011. Sampling sites were evaluated by reach with two sites on the South Llano representing the "upper reach", two sites on the Llano representing the "middle reach", two sites in Llano County representing the "lower reach". The North Llano, Johnson Fork and James River represent "tributary sites". Guadalupe Bass (*Micropterus treculii*), along with Texas Shiners (*Notropis amabilis*) and Greenthroat Darters (*Etheostoma lepidum*) were found in each of the reaches. Texas Shiners and Greenthroat Darters are considered Indicator Species, indicating good ecosystem health. [140] In these samples, Guadalupe Bass account for about 1.7 percent of the fish relative abundance in the upper reaches, about 1 percent in the middle and lower reaches and 0.5 percent in the tributaries.. The relative abundance of Texas Shiner on the South Llano (upper reach) is 11.7 percent, 7.2 percent in the middle reach, 0.1 percent in the lower reach, and 15.4 percent in the tributaries. The relative abundance for Greenthroat Darters is 0.4 percent for the upper and middle reaches, less than 0.1 percent for the lower reaches and 0.6 percent for the tributaries. [141] These results highlight the important contributions good aquatic habitat in the headwater tributaries make to the aquatic health of the Llano River.

Figure 52 - Texas Fatmucket (photo source : Gary Pandolfi, USFWS)

Freshwater mussels, colloquially known as the "Livers of the Rivers", also serve as an indicator species of water quality. As filter-feeders, mussels are capable of filtering one liter of water every 30 minutes. The waterways of the Llano watershed provide habitat for three species of freshwater mussels listed as candidates for the endangered species list: the Texas Fatmucket (*Lampsilis bracteata*) (Figure 52); Texas Fawnsfoot (*Truncilla macrodon*); and Texas Pimpleback (*Quadrula*

[139] Birdsong, T., J. Botros, M. De Jesus, K. Eggers, A. England, P. Fleming, J. Graham, T. Heger, K. Hoenke, A. Kalmbach, P. Ireland, C. Kittel, G. Linam, D. Lutz-Carrillo, S. Magnelia, M. Matthews, K. Meitzen, R. McGillicuddy, A. Orr, M. Parker, S. Robertson, N. Smith, and T. Tidwell. 2019. Guadalupe Bass Restoration Initiative 2019 Annual Report. Texas Parks and Wildlife Department. PWD RP T3200-2079 (1/2020). Austin, TX. 16 pp.

[140] Robert J. Edwards, Gary P. Garrett, and Nathan L. Allen, "Aquifer-dependent fishes of the Edwards Plateau region", in Aquifers of the Edwards Plateau, Texas Water Development Board Report 360, 2004.

[141] Curtis, S.G. and T.H. Bonner. 2012. Project A – Spatial and Temporal Patterns in the Biological Communities and Instream Habitats of the Llano River *in* Birdsong, T. 2017. Coordinating Implementation of the Aquatic Resource Conservation Objectives of the Texas Conservation Action Plan. Final Report for State Wildlife Grants Program T-60-1. Texas Parks & Wildlife Department, Austin, Texas.

petrina). [142] Threats to these mussel species include degradation of water quality, increased sedimentation, and changes to river flow resulting from diversions and dams. Dams also have the potential to block the movement of host fish species required by mussels for reproduction.

Aquatic insects (macroinvertebrates) are also an important component of aquatic diversity and an indicator of stream health. Macroinvertebrates were sampled in preparation for the Upper Llano River Watershed Protection Plan. Of the 13 sites sampled, seven sites were rated 'Exceptional', four sites were rated 'High' and two sights were rated 'Intermediate'. A 1989 study on the James River identified ten species of mayflies and 11 species of caddis flies basin wide. The authors of the study noted the diversity and equitability of these and other benthic macro invertebrate (bottom dwelling species without skeletal structure) species observed in the James River is the highest observed in more than 12 years of surveillance on Texas streams. [143]

Terrestrial

The Llano River is also a principal component of unique biological communities and ecological systems found in the Edwards Plateau region: Lacey-oak-Ashe-juniper woodland; Southern Great Plains canyon forests; Edwards Plateau shaded cliff and rock outcrops; and Southern Great Plains stream bed herbaceous vegetation. [144] These unique areas provide habitat for native hardwoods such as Spanish oak, Escarpment Black Cherry, and Texas Mountain laurel, as well as a variety of moss found only within 700 Springs in Edwards County.[145] The Endangered

Figure 53 - Tobusch Fishhook Cactus (photo source : Jackie Poole, TPWD)

[142] Charles R. Randklev, N.B. Ford, Mark Fisher, Ross Anderson, Clint R. Robertson, Michael Hart, Jennifer Khan and Roel Lopez. 2020. Mussels of Texas Project Database, Version 1.0.

[143] Stephen R. Twidwell and Jack R. Davis, "An assessment of six least disturbed unclassified Texas streams". Texas Water Commission, LP 89-04, July 1989.

[144] The Nature Conservancy, A biodiversity and conservation assessment of the Edwards Plateau Ecoregion, Edwards Plateau Ecoregional Planning Team, The Nature Conservancy, San Antonio, Texas, 2004,

[145] Howard Crum and Lewis E. Anderson, Donrichardsia, a new genus of Amblystegiaceae (Musci) in Fieldiana Botany, New Series, v 1., 1979.

Tobusch Fishhook Cactus (Figure 53) grows in shallow gravelly soils in the shortgrass areas within live-oak juniper shrublands of the watershed. [146] There are an additional 27 endemic plants in the Llano watershed, including Basin Bellflower (*Campanula reverchonli)*, Llano butterweed (*Packera texensis),* and Enquist's Sandmint (*Brazoria enquistii)* and Springrun whitehead (*Shinnersia rivularis),* an aquatic plant located in streams of the Edwards Plateau.[147]

The endangered Golden-cheeked Warbler and previously endangered Black-capped Vireo are found in the Llano watershed as well. Dense stands of old growth juniper in the canyons provide nesting material and habitat for Warbler populations [148], while the Vireo populations prefer more open habitat with less juniper cover and more shrubby deciduous cover. [149] The Vireo was removed from the Endangered Species list in 2018.

The Llano pocket gopher (*Geomys texensis llanernsis)* is found only Llano and Mason counties, but is not a candidate species for listing as an endangered species. Other endemic species in the Llano watershed include Texas map turtle (*Graptemys versa)* and Plateau spot-tailed earless lizard (*Holbrookia lacerate).*

Riparian

Riparian zones of streams and rivers are recognized critical zones for watershed health. In the Llano, these critical transitional areas between the water and upland systems comprise 3.6% of the watershed area. Although riparian zones often do not have definitive boundaries, they generally include those areas adjacent to streams and rivers including stream banks, floodplains and associated wetlands. A properly managed and functioning riparian area will: "dissipate stream energy associated with high water flows, thereby reducing erosion and improving water quality; filter sediment, capture bedload, and aid in floodplain development; improve flood-water retention and groundwater recharge; and develop root masses that stabilize stream banks against cutting action."[150]

Much of the riparian habitat along the upper portions of the watershed in the Edwards segment consists of stands of mature native pecans. These pecans bottomlands provide flood mitigation, wildlife habitat, bank stability, and enhance aquatic habitat. A study of pecan bottoms in several areas of the Edwards Plateau found that because of intensified browsing

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[146] Tobusch Fishhook Cactus (Sclerocactus brevihamatus subsp. Tobushii), Texas Parks and Wildlife Department Wildlife Fact Sheets.

[147] Texas Natural Diversity Database. [2019]. Element Occurrence data export. Wildlife Diversity Program of Texas Parks & Wildlife Department. [20 March 2019].

[148] Golden-cheeked Warbler (Dendroica chrysoparia), Texas Parks and Wildlife Department Wildlife Fact Sheets.

[149] Black-capped Vireo (Vireo atricapilla), Texas Parks and Wildlife Department Wildlife Fact Sheets.

[150] Prichard, D. 1998. Riparian area management: a user guide to assessing proper functioning condition and the supporting science for lotic areas, Bureau of Land Management. Technical Reference 1737-15

from increased deer and axis populations, very few younger pecan trees or other woody plants are growing under the mature pecans. [151]

In the Uplift segment of the Llano, where riparian areas tend to be narrower and steeper due to incised bedrock channels, maintaining healthy riparian habitats is also critical for providing flood mitigation, bank stability, and providing habitat. Unfortunately, many landowners accustomed to more urban landscapes, remove riparian vegetation in an effort to create a parklike appearance for their property.

Figure 54 - Elephant Ear below Junction

Several aggressive invasive plant species (i.e. elephant ear, *Arundo donax*, and chinaberry) are impacting the riparian corridors of the Llano.[152] Elephant ears were originally introduced from Asia in 1910 as a substitute crop for potatoes. Today these plants are commonly used for ornamental purposes in gardens and ponds. Elephant ears can easily spread through culm fragmentation and budding at the base of the plant, displacing native riparian vegetation and increasing water use from stream-side vegetation (Figure 54). Disturbance encourages spreading of these plants.

Arundo donax (Giant reed) was introduced in the 1800s from western Asia, northern Africa and southern Europe for ornamental purposes and erosion control along ditches (Figure 55). Today, *Arundo* is found throughout the western United States. Little is known about the life history of *Arundo*, except that it can float miles downstream to take root. It grows rapidly and outcompetes native plants. Because of the dense growth and water use, *Arundo* chokes rivers, increases fire potential and reduces habitat for wildlife by completely suppressing native vegetation through the formation of dense monotypic stands.

Chinaberry, a member of the Mahogany family, was originally introduced in the mid-1800s from Asia for ornamental purposes. It most commonly spreads through bird-dispersed seeds.

[151] Rickey L. Jones, "Ecological dynamics of native bottomland pecan communities in the Edwards Plateau of Texas", Master's Thesis, Texas State University, Department of Biology, 2008

[152] Other invasive species such as Malta Star Thistle (*Centaurea melitensis*), Mexican Feather Grass (*Nasella* or *Stipa tenuissima*), and Bermudagrass (*Cynodon dactlyon*) are found in riparian areas of the watershed.

Figure 55 - Arundo donax along South Llano River

Chinaberry is highly resistant to insects, pathogens and predation, outcompeting native riparian vegetation and altering the pH of the soil through its leaf litter. [153]

Exotic and invasive mammals also constitute a serious threat to riparian areas along the Llano. Feral hogs are highly destructive to riparian areas because they create wallows. Feral hogs lack functional sweat glands and must wallow in water to keep cool. Introduced to the United States from Europe as a food source, Texas A&M AgriLife now estimates approximately 1.8 and 3.4 million feral hogs are found in Texas, with an estimated 40,000 in the Upper Llano watershed alone. [154]

Axis deer, and other introduced exotic species such as aoudad and black buck, are also present in the watershed. Native to India, axis deer were introduced to Texas about 1932, and today are the most abundant ungulate in Texas. In 1994, TPWD estimated 5,200 axis to be present in Kimble County. A recently completed dissertation on the ecology of free-ranging axis in the Edwards Plateau now places that estimate at over 61,000, a twelve-fold increase. [155]

Damage from axis deer includes competition with white-tailed deer and livestock (axis can shift their diet to grasses when food is scarce) as well as significant erosion from axis trailing behaviors, especially in riparian areas. The main problem with axis deer is the large population size. Herds often consist of over 100 deer and can contribute to bacteria and nutrient loading in streams.

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[153] Reemts, C. (undated fact sheet). Plant Conservation Alliance's Alien Plant Working Group: Least Wanted, The Nature Conservancy.

[154] Upper Llano Watershed Coordination Committee, 2016.

[155] Matthew J. Buchholz, "Ecology of Free-ranging Axis Deer (*Axis axis*) in the Edwards Plateau Ecoregion of Central Texas: Population Density, Genetics, and Impacts of an Invasive Deer Species", PhD diss., Texas Tech University, 2022.

Land Use

Land use changes have occurred across most of the terrestrial habitats of the Llano Watershed during the last one and a half centuries. Prior to European settlement in the mid-1800s, the uplands of the Texas Hill Country were a grassland savannah that was maintained through grazing of bison, antelope and frequent fires (natural and man-made). This type of rotation favored a variety of forms and grasses. Crop and hay production begun by early settlers along fertile bottomlands, as well as livestock grazing in the bottomlands and uplands, has greatly influenced the current landscape across the Edwards Plateau. In some areas, historical overgrazing and the resulting loss of soil, along with the suppression of fire, have changed the Edwards Plateau from predominantly grassland savannah to Ashe juniper woodlands.[156] An exception to these land-use changes can be found in the mesic canyon sides. These canyons may have been less impacted by grazing and fire suppression as inaccessibility reduced grazing pressure and the steep slopes limited the ability of fire to become a dominant ecological process.[157]

While pre-settlement data are not available, today vegetation mapping shows that Ashe-juniper is found on 67 percent of the Llano Watershed in the Edwards Plateau. In the sandy soils of the Llano Uplift portion of the watershed, where Ashe-juniper does grow as well, coverage is roughly 20 percent of the watershed. [158]

As discussed below, the encroachment of woody vegetation may have multiple impacts on the hydrology of the spring-fed canyon systems in the Edwards Plateau. Currently, there are efforts to mitigate these impact through land stewardship and brush control, although the science behind brush control and hydrologic response remains unsettled amongst scientist, due to the scope and scale of the necessary experimentation.

Another harmful land-use change is the transformation of large ranch holdings to smaller ranchettes , fragmenting the landscape, complicating large-scale land management efforts, and potentially resulting in additional impacts to wildlife habitat and water resources. Additional recent events have also placed strains on aquatic, terrestrial, and riparian resources.

[156] Bradford P. Wilcox, Yun Huang, and John W. Walker, “Long-term trends in streamflow from semiarid rangelands: uncovering drivers of change”, in Global Change Biology, (2008) 14, 1676-1679.

[157] The Nature Conservancy, 2004.

[158] Texas Parks and Wildlife Department, Ecological Mapping Systems of Texas, 2014.

Land Stewardship and Brush Management

Land stewardship utilizes a variety of management practices to balance, preserve and enhance natural ecological systems. Such practices include prescribed burns to enhance grasslands, game management to decrease over-browsing and enhance wildlife populations, and creation of upland water sources to reduce pressure on riparian habitats. One land stewardship technique widely used across the Edwards Plateau is brush control.

The control, clearing, and sculpting of brush species, especially *Ashe* juniper, is a popular technique to improve livestock grazing, wildlife habitat, and biodiversity. Brush management overlying karst areas is also believed to increase spring flows. Some studies have shown that because juniper is evergreen and has a high leaf area, the canopy and litter of a juniper tree can intercept as much as 40% of the precipitation falling on a tree. [159] Alternatively, with grassland cover, precipitation reaching the ground is slowed by grasses and infiltrates into the soils and eventually the underlying water table. With the loss of soil and grasses and an increase in woody species, especially juniper, more precipitation is kept from reaching the ground, and what does reach the ground runs off more quickly, rather than infiltrating down to the water table.

Historical discussions by Brune of springs in the Llano suggest that springs were more numerous and prolific in earlier times prior to the degradation of the landscape. As much soil has been lost to overgrazing, it is unlikely that such conditions will return. However, questions remain as to whether it is possible to restore some springflow with land stewardship practices such as brush management.

There is anecdotal evidence on a small scale that removal of brush results in increases in springflow, but much debate exists in the scientific community as to whether such brush removal increases water supply at a large scale. To complicate matters, the majority of the research regarding hydrologic response to brush removal has been to the east of the Llano watershed, [160] where climatic conditions, especially evapotranspiration (eT) rates are lower. Small adjustments to eT rates can appreciably change hydrologic model output across an area as vast and diverse as the Edwards Plateau. Recent model output also suggests the need for a temporal analyses of changes in eT. Ecological modeling for the Upper Llano River Watershed Protection Plan suggest that over the course of 25 years, removing 9,000 acres of brush annually in select locations in the watershed, in combination with prescribed burning, will decrease evapotranspiration by 75,000 acre-feet. However, the positive hydrologic

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[159] Bradford P. Wilcox, M. Keith Owens, William A. Dugas, Darrell N. Ueckert and Charles R Hart, “Shrubs, streamflow, and the paradox of scale”, in Hydrological Processes, 3245-3259, 2006.

[160] Banta, J.R., and Slattery, R.N., 2011, Effects of brush management on the hydrologic budget and water quality in and adjacent to Honey Creek State Natural Area, Comal County, Texas, 2001–10: U.S. Geological Survey Scientific Investigations Report 2011–5226, 35 p.

response to removing brush in the watershed - i.e. increased water availability resulting from decreased evapotranspiration- has a lag time of approximately 11 years following brush removal. [161] To date, there have been no studies to validate these predictions.

While decreases in evapotranspiration resulting from conversion of *Ashe*-juniper woodlands to more grasslands suggest an increase in recharge and a resulting increase in spring flows, this may not necessarily be a totally accurate assumption. The role that plant root depth [162] and epikarst (that weathered layer of rock just below the soil layer)[163] is not fully understood. Additional variables affecting recharge also include rate of vegetation regrowth, soil health and depth of leaf litter.

Ashe juniper in the Llano is a native species, but it is likely more widespread today than it was historically. Yet, *Ashe*-juniper still plays an important role in the ecological health of the watershed. In areas with little or no existing soil cover, *Ashe*-juniper actually serves to re-create the lost soil layer through leaf fall and trapping of sediment and organic debris. *Ashe*-juniper also helps sequester additional carbon and strips of bark from old-growth *Ashe*-juniper provide critical nesting materials for the endangered Golden-cheeked Warbler.

Control of *Ashe*-juniper and other wood species should not be undertaken without considering factors such as erosion potential, existing and potential damage to soil and potential impacts to wildlife. Some debate exists amongst natural resource managers and landowners regarding the benefits of removing *Ashe* juniper on moderate to steep slopers. The former may be subject to severe erosion during intense rainfall events and the latter will not support the development of continuous grass cover.

Fragmentation

There is a growing trend in Texas whereby large-scale land holdings are being sold and subdivided (fragmented) into smaller parcels, or ranchettes. This trend is driven by the influx of new absentee landowners. As with many areas of the Texas Hill Country, people purchase rural land seeking a weekend retreat to escape urban crowds and reconnect with the land through hunting, fishing, or small-scale agriculture.[164] This trend has further steepened with

[161] Upper Llano River Coordination Committee, 2016.

[162] M.E. Litvak, S. Schwinning and J.L. Heilman, “Woody plant rooting depth and ecosystem function of savannas : a case study from the Edwards Plateau karst, Texas, USA, in Ecosystem Function in Global Savannas: Measurement and Modeling at Landscape to Global Scales (pp.17-134). Chapter 6 Publisher: CRC/Taylor and Francis Editors: MJ Hill, NP Hanan, 2010.

[163] Martin, Linda Leann, “Effects of forest and grass vegetation fluviokarst hillslope hydrology, Bowman’s Bend, Kentucky. (2006). University of Kentucky Doctoral Dissertations. 362p.

[164] American Farmland Trust, “Going, going, gone. Impacts of land fragmentation on Texas agriculture and wildlife”. A summary study from American Farmland Trust, Texas Regional Office, 2003

the development of telecommuting during the Covid pandemic. Because these new landowners have outside sources of income, they generally do not need to make a living off of the land. This has the potential to take pressure off of grasslands and other forage that are usually stressed during times of drought. On the other hand, these changes also result in a marked increase in land values and increased pressure on water resources and wildlife habitat.

As new owners purchase lands for scenic and recreational value, rather than for production value, land prices escalate. Such escalation places pressure on traditional rural agricultural economies, as producers are able to make more money from the sale of land than from production from the land, resulting in less land being utilized for agriculture. The subdividing of large ranches into smaller tracts also increases pressure on wildlife habitat and water resources, as more homes, roads, fences, and more wells and septic systems are introduced to the landscape. It also complicates the efficient implementation of land stewardship practices such as brush control, managed grazing, and controlled burning.

The impacts of fragmentation for the main counties in the Llano Watershed are shown in Table 7. Between 1997 and 2017, the number of acres in large ranches (>2,000 acres) declined by 16 percent in Edwards County, 7 percent in Sutton County, 10 percent in Kimble County and 12 percent in Mason County. It is not clear why Llano County actually saw a slight increase in this category; however, the county did see a decrease of 23 percent for ranches between 1,000 and 1,999 acres.[165]

Table 7- Changes in Ranching Acreage and Land Values - Llano Watershed

	Acres in Ranches > 2,000 acres (in 1,000s acres)		Average Ag Land Value ($ / acre)	
	1997	2017	1997	2017
Edwards County	1,069	895	$253	$1,171
Sutton County	877	817	$200	$1,144
Kimble County	580	522	$408	$2,374
Mason County	319	282	$630	$3,064
Llano County	298	301	$832	$3,953

165 Smith, L.A., R.R. Lopez, A.A. Lund, B.N. Wegner, J.C. Cathey, A. Lopez, R.E. Anderson, G.W. Powers, K.L. Skow, M.A. Crawford. 2019. Status Update and Trends of Texas Working Lands. Texas A&M Natural Resources Institute (NRI), College Station, TX, USA

An additional result of land fragmentation is an increase in the number of septic systems. While no data are collected for septic systems, a rough estimate of the number of septic systems can be derived by assuming that the number of septic system correlates with the number of wells, as residents relying on individual water wells are generally not connected to wastewater treatment facilities. According to TWDB [166], since 2000, 5,564 new wells have been drilled. Over 83 percent of these new wells are in the watershed for the main Llano, and the remaining 17 percent split equally between the North and South Llano.

Wildfire and Drought

The average annual flow for the Llano River in Junction during the 2011 was 60.7 cfs, the lowest annual flow since the drought of the 1950s. This dry period actually began in 2008. [167] On April 26th, 2011, in the middle of this dry period, lightning caused a fire in the South Llano watershed approximately 13 miles southwest of Junction. By the time the fire (known as the Oasis Pipeline fire) was extinguished in the middle of May, an estimated 10,000 acres of upland and riparian habitat was destroyed, along with numerous structures.

Figure 56 - Riparian damage associated with Oasis Pipeline Fire, May 2011.

Fire is a valuable land management tool when used in a prescribed setting and can dramatically increase the health of a landscape. The ecosystem of the Edwards Plateau evolved with fire. However, fires of this magnitude have the potential to cause dramatic increases in sedimentation to the rivers (figure 56).

[166] Texas Water Development Board, Water Data Interactive-Groundwater Data Viewer data assessed 2021.

[167] Annual average flow for the period 2008-2011 was 111 cfs, also the lowest four year period since 1956, See U.S. Geological Survey, National Water Information System (NWISWeb) data, accessed February 1, 2012. Available at http://waterdata.usgs.gov/nwis/dv/?site_no=08151500&referred_module=sw.

Sand and Gravel Extraction

Beginning in the mid-1980s, sand and gravel was extracted from the North Llano River about one mile above the confluence with the South Llano. TPWD oversees the extraction of such materials from navigable waterways through the issuance of Sand and Gravel permits. Although the permit for this operation was retired in 2004, the impacts of these extraction activities are still visible. Most notably, the mining activity within the channel apparently caused the channel downstream to migrate approximately 700 feet to the south. The resulting erosion caused by this migration forced the City of Junction to undertake actions to protect city infrastructure, including the relocation of the wastewater treatment plant (Figure 57).

Figure 57. Channel alteration on the North Llano River between 1974 and 2012 resulting from instream sand and gravel operations upstream.

Urban Runoff

Urban areas comprise less than one percent of the watershed. However, opportunities exist to protect watershed health through improved stormwater management. Pollution of surface water (and potentially groundwater) from urban stormwater runoff is a concern in all four of the cities in the watershed. Untreated runoff from streets runs into nearby creeks and eventually into the Llano River and its tributaries. This is of particular concern in the Junction area.

Interstate 10 in Junction was completed in 1970, two years before the passage of the Clean Water Act. As few protections on surface water were in place at that time, runoff from the highway and the surrounding interchange at US 83 in Junction was designed to flow into a drainage ditch on the southeast corner of the interchange and then directly into the North Llano River. In 2014, an 8-acre truck stop and parking lot were constructed southeast of the interchange. Runoff from the truck parking lot was designed to drain directly into the adjoining drainage ditch, raising additional concerns over urban stormwater runoff into the North Llano (Figure 58). [168]

Figure 58. Aerial view of Junction Truck Stop Site and Drainage Ditch into North Llano River (photo by Bill Neiman)

[168] Robert Rivard, "Truck Stop in Hill Country Threatens Llano River", Rivard Report (now San Antonio Report), August 30, 2014.

WATER MANAGEMENT

There are a number of agencies and organizations that play a role in the natural resource conservation and protection of the watersheds of the Llano. At the local level, groundwater conservation districts manage the groundwater resources of their respective counties. At the regional level, the Lower Colorado River Authority, a non-profit public utility, manages Lake LBJ at the mouth of the Llano, along with five other reservoirs along the Colorado River. State agencies playing on role in resource conservation are Texas Commission on Environmental Quality, Texas State Soil and Water Conservation Board, and Texas Parks and Wildlife Department. At the Federal level, the Natural Resources Conservation Service, an agency within the U.S. Department of Agriculture, works with local and state soil and water conservation boards to coordinate and fund land stewardship efforts in the Llano. Department of the Interior agencies, US Fish and Wildlife Service and US Geological Survey as well as the US Army Corps of Engineers in the Defense Department play important roles as well.

Groundwater Conservation Districts

Groundwater districts are the preferred method for managing groundwater in the State.[169] There are five groundwater districts that encompass counties in the Llano watershed: the Real-Edwards Conservation and Reclamation District, the Kimble County Groundwater Conservation District, the Sutton County Underground Water Conservation District, Headwaters Conservation District (Kerr County), and Hickory Underground Water Conservation District (primarily Mason County). Llano County does not have a groundwater district.

All five of these Districts have rules and management plans that govern the groundwater resources in the counties. State law does not allow groundwater conservation districts to require or issue permits for wells on tracts larger than 10 acres which are used for domestic use and livestock watering and produce less than 25,000 gallons per day. [170] Most of the wells in all five districts are exempt from permitting; exceptions include wells used for public supply, industrial purposes, and irrigation.

Historically, the amount of water actually available for withdrawal in each aquifer and groundwater district was not definitively quantified. In an effort to better coordinate the

[169] Texas Water Code, Chapter 36.001.

[170] Texas Water Code § 36.117.

determination of availability, the state initiated a process in 2005 that requires groundwater districts within a designated groundwater management area (GMA) to meet on a regular basis, share management plans, and participate in joint planning for the various aquifers within the GMA boundaries. It also requires that each of the groundwater management areas adopt "desired future conditions" for each aquifer within the GMA. Four of the groundwater districts in the Llano watershed are in Groundwater Management Area 7 (GMA-7), the largest GMA in the state, including much of the Llano watershed, but stretching to the Rio Grande and the Pecos River. Kerr County is in GMA 9 which covers from Kerr County to the I-35 corridor between Austin and San Antonio.

As part of the process of adopting a desired future condition (DFC) for an aquifer, the GMA member districts determine their goal for the condition of the aquifer 50 years into the future. A goal can be a particular groundwater level, level of water quality, volume of spring flows, etc. Based on this DFC, the Texas Water Development Board (TWDB) determines the physical volume of groundwater available from the aquifer. The Desired Future Conditions and Modeled Available Groundwater for the five groundwater districts is shown in Table 8. Desired Future Conditions for the Edwards-Trinity Aquifer are small in order to protect springflow.

Table 8. Desired Future Conditions for Groundwater Districts in Llano Watershed

County	Desired Future Condition 2070	Managed Available Groundwater (ac-ft) for all aquifers in county
Edwards	Average drawdown not to exceed 2 feet in Edwards-Trinity	5,676
Sutton	Average drawdown not to exceed 6 feet in Edwards-Trinity	6,400
Kimble	Average drawdown not to exceed 1 foot in Edwards Trinity and 17 feet in Ellenburger-San Saba and 18 feet in Hickory	1,502
Mason	Total net drawdown not to exceed 14 feet in Ellenburger-San Saba and 17 feet in the Hickory	16,649
Kerr	Increase in average drawdown of approximately 30 feet through 2060	318

Lower Colorado River Authority

The LCRA only has limited water management authority in the area. Such authority only applies to the Authority's original statutory district, which stops at the Llano-Mason County line. However, the Authority is involved directly and indirectly in water management activities on the Llano Watershed.

The LCRA does not hold any water rights in the Llano, but collects streamflow, water quality, and aquatic habitat information on the river and its tributaries. LCRA currently manages 13 stream gages and numerous rainfall stations in the Llano through their Hydromet System. As they are the largest holder of downstream water rights in the Colorado River basin, they do have an effect on water distribution from the Llano. Upstream water rights with a priority date later than the LCRA rights, must not withdraw water if there is not enough water available to meet the downstream LCRA demands. Consequently, there is little or no additional surface water available for permitting in the Llano River. Recent permit applications for surface water use have relied on lease agreements with LCRA.

State Agencies

Water withdrawals and discharges are handled at the State level by the Texas Commission on Environmental Quality (TCEQ). This agency administers the state's water right permitting system that is based on the prior-appropriation doctrine where the first in time (oldest) water right has the first right to fully utilize its water appropriation. TCEQ also administers most aspects of water quality both from protection of drinking water supplies to facilities that discharge effluent directly back to streams. Another state agency, Texas State Soil and Water Conservation Board, oversees the non-point discharge programs.

Texas Water Development Board oversees planning and research related to the water resources of the state. In this capacity, the Board oversees the development of groundwater management plans, regional water planning and regional flood planning, and conducts studies of the occurrence, quantity, quality and availability of surface and groundwater in the state. The Board also provides financial assistance to local governments to implement water supply and water quality projects.

Texas Parks and Wildlife Department is charged with overseeing the disturbance of materials in stream beds belonging to the State. Any disturbance of sand, gravel and marl, including construction of a dam on navigable waters, requires a Sand, Gravel and Marl Permit from the Department.

TPWD, through land management and cooperative programming, are also actively involved in stewardship efforts in Llano watershed. TPWD manages the South Llano River State Park, over 2,700 acres of riparian and upland habitat along the South Llano River, for recreation, nature study, and wildlife habitat improvement and protection. In addition, TPWD also manages the 5,300 acre Mason Mountain Wildlife Management Area north of Mason. This former exotic game ranch today provides opportunities to study the effects of African ungulates on local habitat.

TPWD is also involved in cooperative efforts, such as the Guadalupe Bass Restoration Initiative. Partnering with the Llano River Watershed Alliance, TPWD is working to protect Guadalupe bass populations and their habitat by developing networks of willing landowners interested in implementing coordinated landscape conservation actions at watershed-scales. Such conservation actions promote functional riparian and stream systems, and emphasize the conservation of native fish communities and supporting habitats. [171] TPWD also has cooperated with the Alliance on the creation of the South Llano River Paddling Trail and the establishment of seven leased public access sites through the River Access and Conservation Area program. Recently, TPWD, through the State and Tribal Wildlife Grant program, worked with the Alliance to implement proactive conservation actions to keep species healthy and off of the federal threatened and endangered species list. This program funded this characterization report.

Federal Agencies

At the federal level, the Natural Resources Conservation Service, an agency within the U.S. Department of Agriculture, works with local and state soil and water conservation boards to assist local landowners with the conservation, maintenance, and improvement of natural resources. Much of the current effort to improve natural resources is through the Environmental Quality Incentives Program (EQIP). In 2018, the Alliance partnered with other conservation agencies to secure over $5 million in additional NRCS funding for the Hill Country through the Regional Conservation Partnership Program.

Some Federal Agencies have regulatory authority within the Llano, including the US Fish and Wildlife Service and the US Army Corps of Engineers. US Fish and Wildlife Service, part of the US Department of the Interior, oversees the management and enforcement of the Endangered Species Act. The Act prohibits the import, export, or taking of fish and wildlife and plants that are listed as threatened or endangered. In order to avoid, minimize, and mitigate threats to these species, USFWS partners with States and local landowners to offer financial assistance to implement stewardship efforts through the Partners for Fish and Wildlife Program. The Corps of Engineers, part of the Department of Defense, oversees

[171] Texas Parks and Wildlife Department, “Guadalupe bass restoration initiative – Llano river”, undated fact sheet

activities in navigable waters under the Rivers and Harbors Act of 1899 and the Clean Water Act of 1972. In this capacity, the Corp requires permits for dams, levees, weirs, or any dredge or fill activities under its jurisdiction.

The US Geological Survey, part of the Department of the Interior, has no regulatory authority, but is responsible for developing science fundamental to the protection of national and local economic well-being and the protection of life. Within the Llano, USGS maintains six stream gages (in partnership with LCRA) and has conducted numerous studies in the watershed going back to 1902.[172]

CONCLUSION

The Llano River watershed is a very unique ecologic and hydrologic system, unlike any other place. While several Texas rivers find their headwaters in the spring-fed systems of the Edwards Plateau, no other river in the state also adds the geological and ecological diversity resulting from crossing the Llano Uplift, some of the oldest rocks in the country. Unfortunately, this uniqueness also creates vulnerabilities, especially related to future droughts and floods.

Compounding this vulnerability is a rapidly growing urban population in close proximity. While the local population declined or only saw modest increases, the Austin metropolitan area grew by 30% between 2010 and 2020 and San Antonio grew nearly 20 percent over the same time period, an increase of 1.4 million new urban neighbors. At the same time, statewide public recreational access through parks over the last 20 years has only increased by 5,000 acres. This growing population, seeking to escape the urban environment, is increasingly turning to public lands along the Llano River to recreate, or is purchasing their own piece of property. In most counties in the Llano watershed, more than 50% of the land parcels are owned by absentee landowners. This percentage will likely continue to grow as land prices escalate and dividing land holdings into smaller parcels becomes more profitable than ranching and farming.

While there are agencies like Texas Parks and Wildlife and organizations like the Llano River Watershed Alliance working to provide opportunities to enhance and protect the river, ultimately, the preservation of the Llano will require each individual who cares and depends on the Llano to partner with neighboring landowners to learn about the unique characteristics of the Llano and to develop individual solutions to address issues along their unique section of river. The Llano River Watershed Alliance hopes that this report, *Tale of Two Rivers*, will help initiate these efforts.

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[172] Thomas U. Taylor, “Irrigation Systems of Texas”, US Geological Survey Water-Supply and Irrigation Paper No. 71, 1902

Appendix A- Data for Sub-Watersheds in Upper Llano

Sub-watershed	Area (sq miles)	Population	Homes	Wells in TWDB Database	Estimated 2nd Family Homes (%)
Upper North Llano	392	79	91	272	68
Middle North Llano	310	217	320	332	74
Lower North Llano	216	1347	801	359	31
Upper South Llano	305	81	86	133	61
Middle South Llano	218	1132	585	166	20
Paint Creek	219	88	177	178	80
Lower South Llano	190	1606	976	228	33
Johnson Fork	322	495	461	446	56
Big Saline	304	750	734	593	58
Honey Creek-Llano R	282	502	383	546	47
James River	339	658	505	509	51
Comanche Cr-Llano R	370	3315	1953	867	30
Hickory Cr-Llano R	422	910	843	1013	56
San Fernando-Llano R	336	4802	2641	1228	25
Little Llano-Llano R	238	4327	2552	843	29
	4463	20309	13108	7713	