HOW MUCH *Water* is in the GUADALUPE?

A Baseflow Analysis

THE MEADOWS CENTER FOR WATER AND THE ENVIRONMENT

TEXAS STATE UNIVERSITY

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December 2019

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Report #2019-11

THE MEADOWS CENTER
FOR WATER AND THE ENVIRONMENT
TEXAS STATE UNIVERSITY

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LIST OF ACRONYMS

BF: Baseflow

BFI: Baseflow Index

CFS: Cubic Feet per Second

DMR: Discharge Monitoring Program

GBRA: Guadalupe-Blanco River Authority

GRB: Guadalupe River Basin

GVHD: Guadalupe Hydroelectric Valley Division

GW: Groundwater

HYSEP: Hydrograph Separation Program

NCICS: North Carolina Institute for Climate Studies

NLCS: National Land Cover Database

NOAA: National Oceanic and Atmospheric Administration

USACE: US Army Corp of Engineers

USGS: United States Geological Survey

TBWE: Texas Board of Water Engineers

TCEQ: Texas Commission on Environmental Quality

TPDES: Texas Pollution Discharge Elimination System


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EXECUTIVE SUMMARY

The Guadalupe River and its tributaries make up one of the most iconic river systems of the Texas Hill Country known for its crystal clear springs and limestone riverbeds, swimming hole grottos, and canyons lined with towering Cypress trees before passing through forested woodlands, pasture lands and grasslands, eventually reaching the Gulf of Mexico. The river and related aquifers serve as a major source of drinking water for millions of people in the region, are home to many unique and ecologically diverse terrestrial, aquatic, and plant species, including multiple endangered species, and attract millions of visitors each year to its stunning waters.

Over the past several years, the Meadows Center's research, "How Much Water in the Hill Country?" research efforts have set out to gain a clearer understanding of the complex hydrogeology and interconnectedness of Hill Country rivers, aquifers, and springs. Building off a Preliminary Report named "How Much Water is in the Guadalupe? A Preliminary Data Analysis and Gap Analysis", the Meadows Center set out to gauge the health of this complex and vital lifeline of the Hill Country as the region experiences record population growth, rapid urban development, growing water demands, and extreme weather events.

The Preliminary Report confirmed that river flow, dominated by several major springs, has been relatively steady over a 70-year period of record until an evident decline started in 2000. However, it was not clear if the decreases were due to changes in the volume of runoff or baseflow, with runoff being the difference between total streamflow and baseflow. In this study, the Meadows dug deeper to determine key factors that contribute to this overall finding of decreased flow.

Gauging stations in the central basin, such as in Spring Branch, show 1.5 times greater discharge than Hunt, TX near the headwaters, indicating the river is generally gaining between Hunt and Spring Branch though there may be local losing reaches. The long-term trend in both streamflow and baseflow is downward, with streamflow decreasing at a greater rate than baseflow.

The largest spring systems, San Marcos, Comal, and Hueco Springs, show a similar and declining historical trend throughout the study period. The trend is gradual for San Marcos and Hueco Springs, but the regression line is steeper for Comal Springs. Baseflow separation analyses for the gages downstream of San Marcos, Comal, and Hueco Springs indicate average baseflow index (BFI) values since 2000 of 0.99 (San Marcos), 0.99 (Comal), and 0.84 (Hueco), or 99, 99, and 84 percent of the river, respectfully. The BFI values indicate that virtually all the flow measured is baseflow with little or no storm water contribution.

Apart from limited use of rainwater collection, drinking water is either sourced from surface water or groundwater resources. Given the connectivity of surface water and groundwater, it is reasonable to assume that a large portion of the decline in baseflow is due to population growth. Looking forward, population growth is projected to increase from 2020 to 2070 by 702,600, or 227 percent. Water use is projected to increase by 196 percent over the same period.

From 2001 and 2016, developed land use has increased by 57 square miles throughout the basin, much of which occurred along the Interstate 35 corridor. Increasing development creates more impervious cover reducing recharge to the underlying aquifers.

Basin-wide water conservation practices and conserved lands are imperative to sustained flows of the life-giving Guadalupe River System. With land cover changes at a minimal percentage over the last twenty years, now is the time for basin-wide collaborative conservation action to protect the precious resources of the Guadalupe basin to get ahead of the population boom and development that follows.

BACKGROUND AND PURPOSE

Over the past several years, the Meadows Center's "How Much Water is in the Hill Country?" research efforts have focused on developing baseline groundwater-surface water interaction and water quality data on Onion Creek, and the Blanco and Pedernales Rivers to gain a clearer understanding of the complex hydrogeology of Hill Country rivers, aquifers, and springs. The limited geographic focus in the Hill Country was by design since the groundwater/surface water interactions were poorly understood and undocumented. The implications of our findings to date have helped quantify how much of the surface flows of the rivers come directly from groundwater and vice versa. These findings have direct relevance to many communities that rely on Hill Country streams and rivers as the source of their drinking water and livelihood, as well as for aquatic organisms living in the river.

Once we had a better understanding of the groundwater-surface water dynamics of the Blanco, Onion, and Pedernales Rivers, the Meadows Center sought to expand our research using the same methodology in the GRB from the headwaters to the tide waters. The first phase of investigating the Guadalupe River was a desktop study named "How Much Water is in the Guadalupe? A Preliminary Data Analysis and Gap Analysis" (Wierman, 2019). This study is referenced as the Preliminary Report throughout this report.

The findings of the Preliminary Report confirmed that surface water/groundwater interactions are dominated by the flow contribution of several major springs, including the Plateau Edwards headwaters spring system, Comal Springs, San Marcos Springs, Hueco Springs, Pleasant Valley Springs, and Jacob's Well. An analysis of United States Geological Survey (USGS) stream gages with long periods of record (over 70 years) indicate relatively flat linear trends in discharge. Since 2000, all gages in the basin have indicated decreasing discharge trends. The cause of the declines may be from increased withdrawals and/or climate change due to increasing temperatures and decreasing precipitation. Researchers have predicted continuing declines in discharge from major springs due to climate change (Wierman, 2019). Potentially declining groundwater levels in shallow aquifers can result in declining baseflow.

The Preliminary Report identified several data gaps for further study in this next phase of "How Much Water is in the Guadalupe? Headwaters to Gulf." Major data gaps addressed in this report include:

- Is declining discharge due to declines in baseflow or storm runoff, or both;
- Have diversions from the river changed since 2000 and are they effecting flow;
- Are manmade discharges into the river significantly altering stream flow;
- Have there been significant land use changes in the basin that could have an impact on flow; and
- What are the population trends and projected water use in the basin?

STUDY AREA

The study area consists of the GRB from the headwaters in Kerr County to Victoria County near the Gulf of Mexico (Figure 1). Due to the large diversions to the Calhoun Canal System downstream of Victoria and the confluence with the San Antonio River, the lowest reach of the river was excluded from this study. The study did include the Blanco and San Marcos Rivers. According to USGS' 'An Assessment of Streamflow Gains and Losses and Relative Contribution of Major Springs to Streamflow' (2008), the study area is described as follows:

> The Guadalupe River is one of the major rivers of South-Central Texas. The headwaters of the river form in southwestern Kerr County. From there, the river flows easterly for about 250 river miles to Gonzales, then southeasterly for another 150 river miles to join the San Antonio River 11 river miles upstream from Guadalupe Bay, which is part of the San Antonio Bay system. The drainage area of the Guadalupe River is about 10,200 square miles, including the San Antonio River watershed. The study area—the GRB upstream from the confluence of the Guadalupe and San Antonio Rivers—comprises 5,974 square miles and excludes the San Antonio River Basin. The Blanco River and San Marcos River are principal tributaries of the Guadalupe River.

The Guadalupe River originates within western Kerr County as three branches of the river (Johnson Creek, North Fork, and South Fork) which merge west of Kerrville to form the main river course. Johnson Creek is the northernmost of the three river branches and enters the main channel at Ingram. The middle branch, or North Fork, merges with the South Fork at Hunt and, combined, they flow eastward to Ingram where they join Johnson Creek to form the main stem of the Guadalupe River (Ashworth, 2005) to its ultimate destination to the Gulf of Mexico.

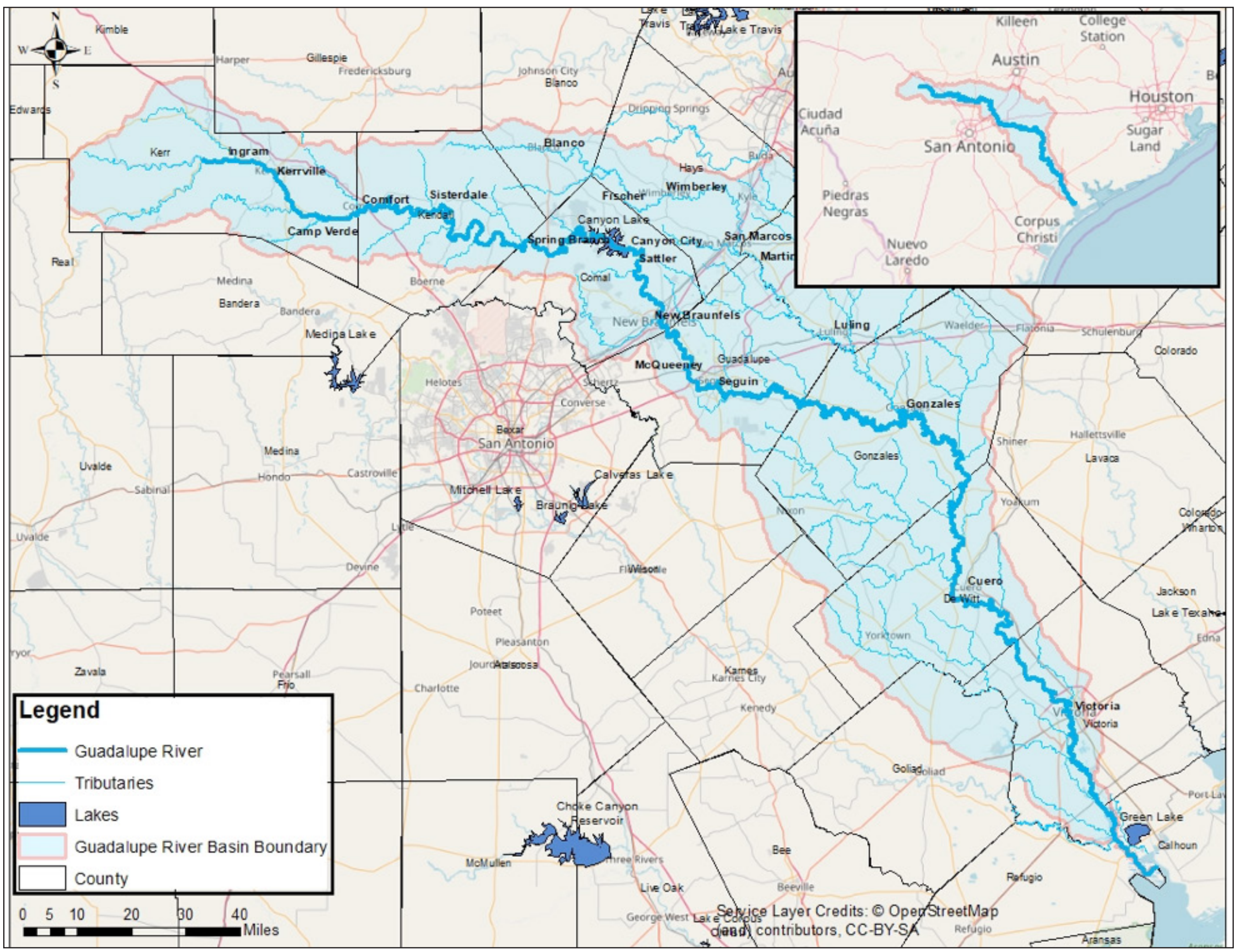


Figure 1. Study Area - Guadalupe River Basin in Texas

The quantity of baseflow within the basin is highly dependent upon the geology and aquifers present. Baseflow in the originating creeks is from various members of the Edwards Formation, such as the Fort Terrett and Segovia. Individual Edwards Formation beds are highly fractured and permeable, thus allowing precipitation to rapidly infiltrate downward to the groundwater table. The underlying Glen Rose limestone contains more clay, is less subject to fracturing, and therefore acts as a semi-impermeable barrier to further downward groundwater migration. Unable to migrate easily downward into the Glen Rose, much of the groundwater in the Edwards Aquifer preferentially moves laterally until it escapes its underground confinement and flows back to the land surface through springs and seeps (Ashworth, 2005).

The number of springs in the headwaters area vary with precipitation. Much of the discharge measured at Comfort originates from the Edwards Formation in the headwaters area. Most springs are relatively small, but collectively, contribute significant flow to the river. The 1965 study by the USGS from the headwaters to Comfort (Kunze, 1966) states:

> The Edwards and associated limestone contributed about 90 percent of the total 120 cubic feet per second (cfs) measured at the lower limit of the investigated reach. Only a small amount, 10 percent or less, was contributed by the Glen Rose Limestone.

The river flows easterly across the lower Cretaceous Upper Glen Rose through Kerrville towards Comfort and Spring Branch, then into Canyon Lake. Downstream from the lake, the river flows across the Edwards Limestone.

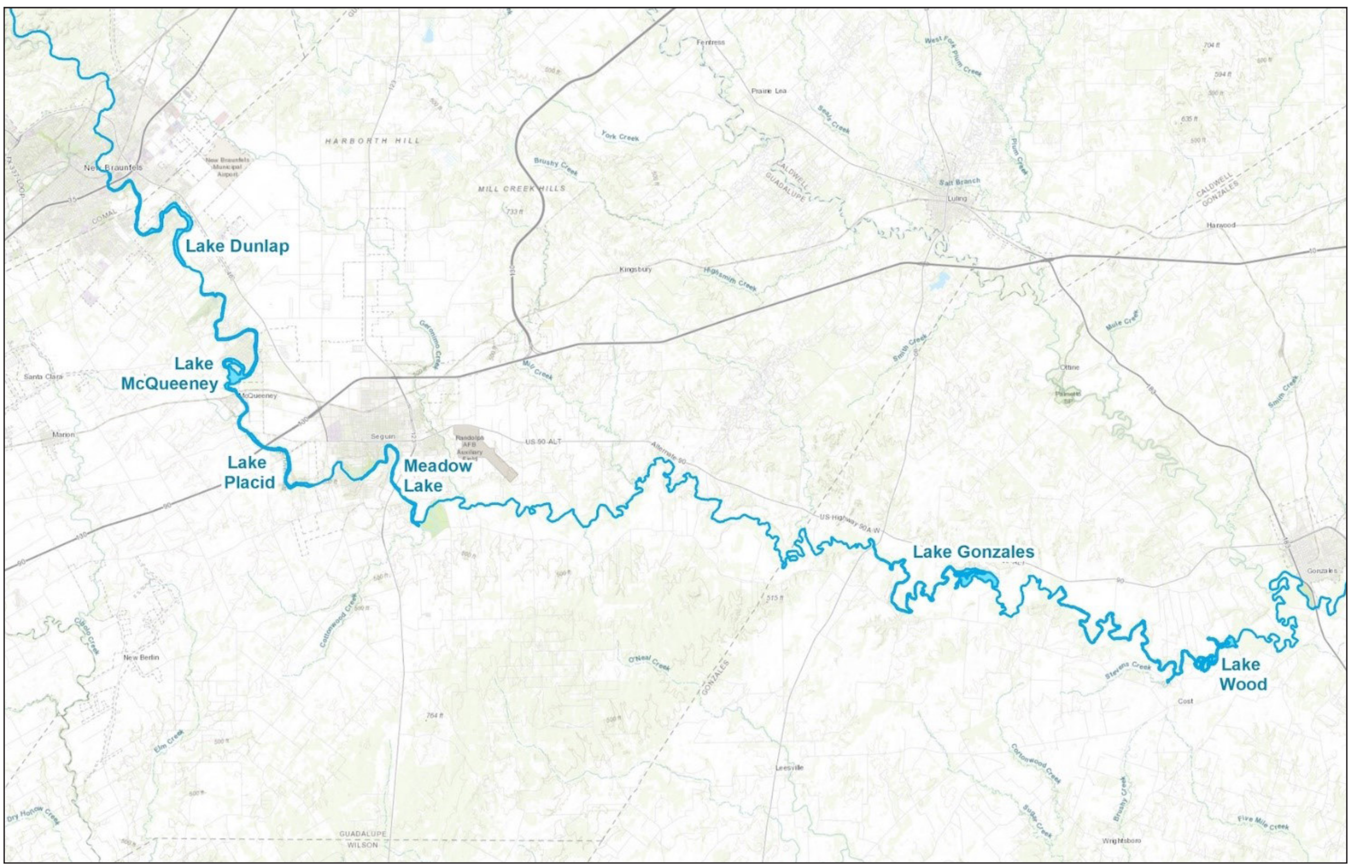


Figure 2. Reservoirs in the Guadalupe River Basin (Source: GBRA, https://gvlakes.com/)

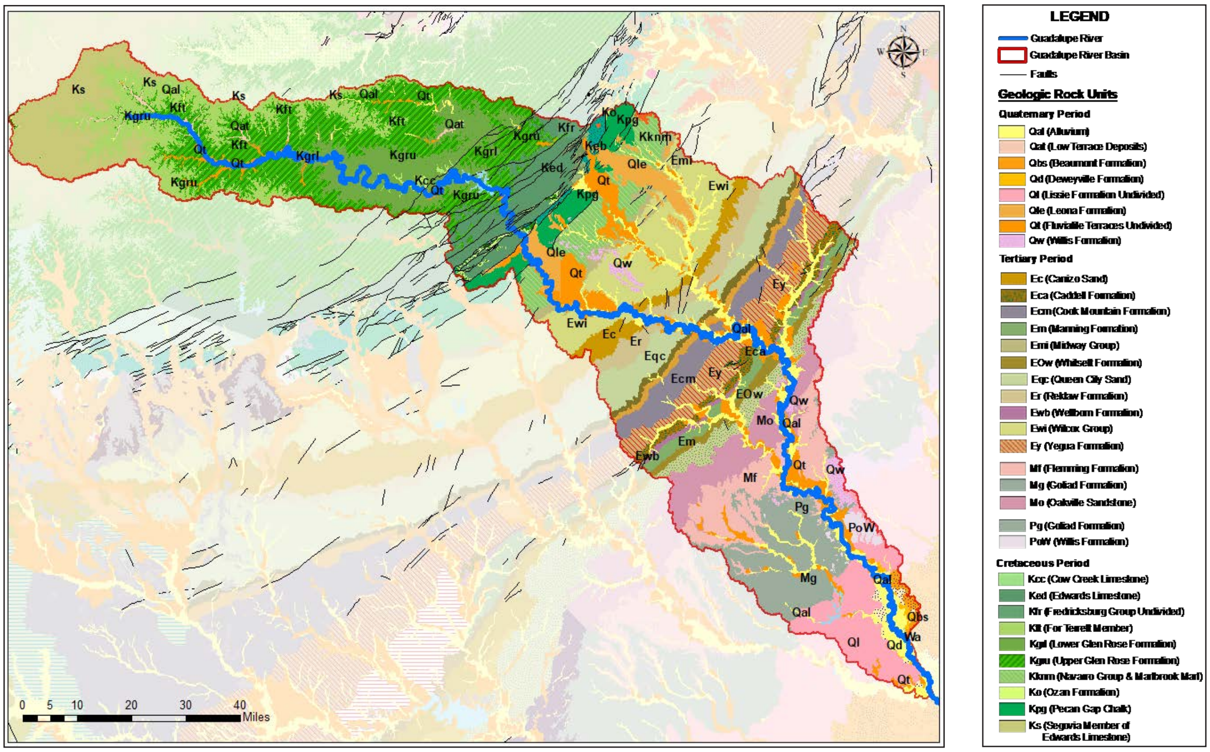


Figure 3. Geologic map of the Guadalupe River Basin (Source: TNRIS, 2018)

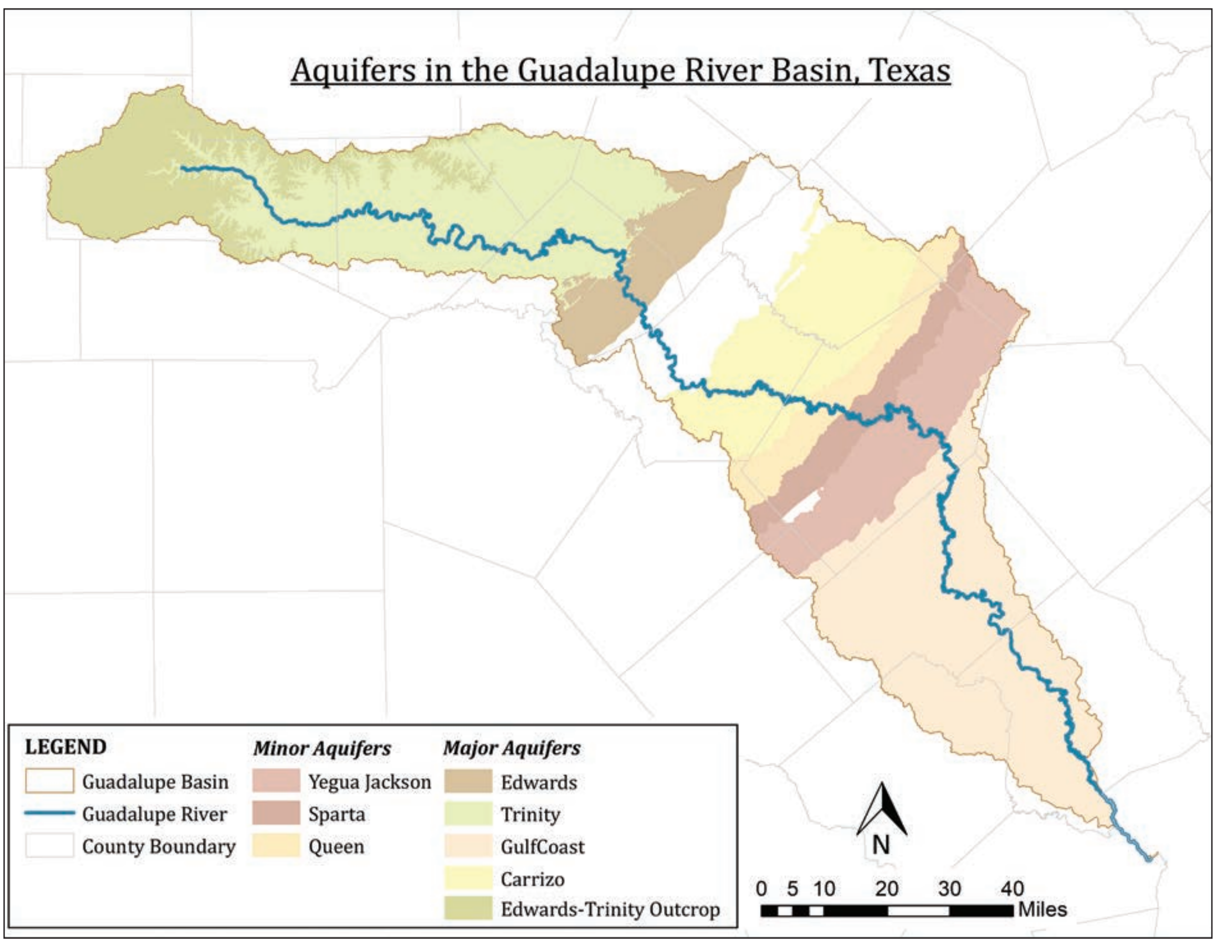


Figure 4. Major and minor aquifers in the Guadalupe River Basin (Source: TWDB)

The GRB includes five major springs: Comal Springs, San Marcos Springs, Hueco Springs, Pleasant Valley Springs, and Jacobs Well. Comal, San Marcos, and Hueco Springs originate in the Edwards Aquifer. Comal Springs provides most of the flow in the Comal River, which joins the Guadalupe River at New Braunfels. The average discharge for Comal Springs for years 1933 – 2010 was 291 cfs (Wehmeyer, 2013). San Marcos Springs, with multiple outlets, provides most of the baseflow for the San Marcos River, which joins the Guadalupe River near Gonzales. The annual average discharge for San Marcos Springs for years 1957 – 2010 was 175 cfs (Wehmeyer, 2013). Hueco Springs occurs on the west side of the Guadalupe River about 3 miles upstream from New Braunfels. The average discharge for Hueco Springs is about 52 cfs (2004-2008) (Wehmeyer, 2013).

Pleasant Valley Springs and Jacobs Well originate from the Trinity Aquifer in the Blanco River Basin and provide the majority of Blanco River discharge at Wimberley, TX. There is a large losing reach in the Blanco River downstream of the springs which provides recharge to the Edwards Aquifer and San Marcos Springs. The Texas Board of Water Engineers (TBWE) (1960) states:

> Available water quality data indicate that the immediate sources of water for Comal and San Marcos Springs are different. The analyses suggest that the Blanco River might be a source of part or all of the flow of San Marcos Springs. It does not appear from that data that the flow of Comal Springs is derived from the usual flow of the Guadalupe River.

Recent dye trace studies have confirmed the connection of the Blanco River and San Marcos Springs (Johnson, 2012).

Major tributaries of the Guadalupe River are the Comal River, the Blanco River/San Marcos River/Plum Creek, Peach Creek, Sandies Creek, Coleto Creek, and the San Antonio River which connects with the Guadalupe River near the gulf where it flows into San Antonio Bay.

Two major reservoirs exist in the GRB. Canyon Lake is the largest impoundment on the Guadalupe River which was completed in 1964 as a cooperative venture between the Guadalupe Blanco River Authority (GBRA) and the US Army Corp of Engineers (USACE). The lake provides both flood control and stored water supply. It is located on the Guadalupe River in Comal County, about 12 miles northwest of New Braunfels (Figure 1). The reservoir impounds runoff from 1,432 square miles of drainage area. At maximum 'conservation pool' level of 90 feet elevation mean sea level (msl), it covers more than 8,200 surface acres and impounds 382,000 acre-feet (1.66 x 10^{10} cubic feet) of water to a depth of 140 feet. At maximum 'flood control pool' elevation of 943 feet msl, the reservoir impounds a total of 732,600 acre-feet of water (GBRA, 2018). Construction of the dam and reservoir began in 1958 and impoundment began in 1964.

Canyon Lake is a major flood control reservoir and can impact down-stream flow analyses in many ways. Slow steady releases of water can look like natural baseflow at down-stream gages whereas sudden, larger releases could be interpreted as storm flow. Capture of a large storm with no immediate release, similar to the upper basin flood of July 1987 (Wierman, 2019), results in no downstream storm surge.

The other large reservoir, Coleto Creek Reservoir, is on Coleto and Perdido Creeks, about 12 miles southwest of Victoria (Figure 2). The dam was completed in 1980 and impounds runoff from 507 square miles of drainage area. Conservation storage for the reservoir is 35,060 acre-feet (1.53 x 109 cubic feet). The primary purpose of the reservoir is to provide cooling water for electric power generation and recreational opportunities.

There are six smaller reservoirs on the main channel of the river between New Braunfels and Gonzales. The reservoirs from upstream to downstream are Lake Dunlap, Lake McQueeney, Lake Placid (Meadow Lake), Lake Nolte, Lake Gonzales and Lake Wood. Hydroelectric power has historically been generated from these lakes. The hydroelectric plants are "run of the river" facilities and the reservoirs were not constructed as flood control facilities. Being "pass through" lakes, they have minimal impact of flow in the river. Due to recent spillway failures in 2016 (Lake Wood) and 2019 (Lake Dunlap), the future of the remaining dams of these six smaller lakes is in question.

BASEFLOW SEPARATION METHODOLOGY

Baseflow has many definitions:

> *"Baseflow is the sustained flow of water in a river including contributions from both interflow and groundwater discharge, independent of dry or wet weather conditions* (Groundwater Dictionary, 2019)*."*
>
> *"Baseflow is the portion of streamflow that comes from "the sum of deep subsurface flow and delayed shallow subsurface flow* (www.definitions.net)*."*
>
> *"Baseflow (also called drought flow, groundwater recession flow, low flow, low-water flow, low-water discharge and sustained or fair-weather runoff) is the portion of streamflow that comes from "the sum of deep subsurface flow and delayed shallow subsurface flow".*
>
> *The USGS defines baseflow as groundwater discharge* (Barlow, 2015).

This report differentiates baseflow from total streamflow with the baseflow index (BFI) being the ratio of baseflow and streamflow. Baseflow can be expressed as a flow rate or as a ratio of baseflow to total stream flow known as the BFI.

A typical hydrograph has two variables presented in the two axes: the Y-axis shows flow (discharge, baseflow, run-off, streamflow, etc.) and the X-axis shows the change over time (Figure 5). In the example in Figure 5, the entire area under the curve is total streamflow. The blue area represents runoff and the green area represents baseflow.

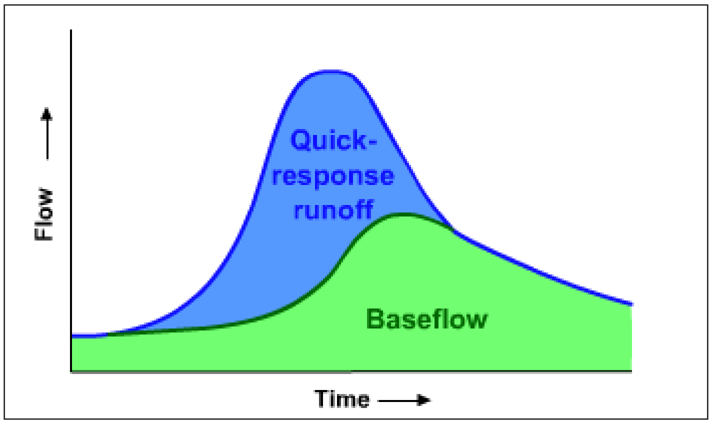


Figure 5. Example of a storm hydrograph (Source: The COMET Program, 2019)

The USGS Groundwater (GW) Toolbox V 1.3.3 (Barlow, 2015) provides a useful method for baseflow separation. The toolbox is a graphical and mapping interface for the analysis of hydrologic data. Six different baseflow separation methods have been either separately or concurrently applied to the discharge data for the selected gaging stations for this research. The purpose of this study is to determine trends of baseflow over time in the GRB, not to analyze the differences in the methods. Each method is slightly different but, in general, they yield similar trend results. The methods of baseflow separation data are based on daily, monthly, or annual time steps. As our period of interest is nearly 20 years, annual data is presented throughout the report. An example of detailed daily data is shown on Figure 6 to illustrate the separation technique. Reference Appendix B for a detailed discussion of baseflow separation methods.

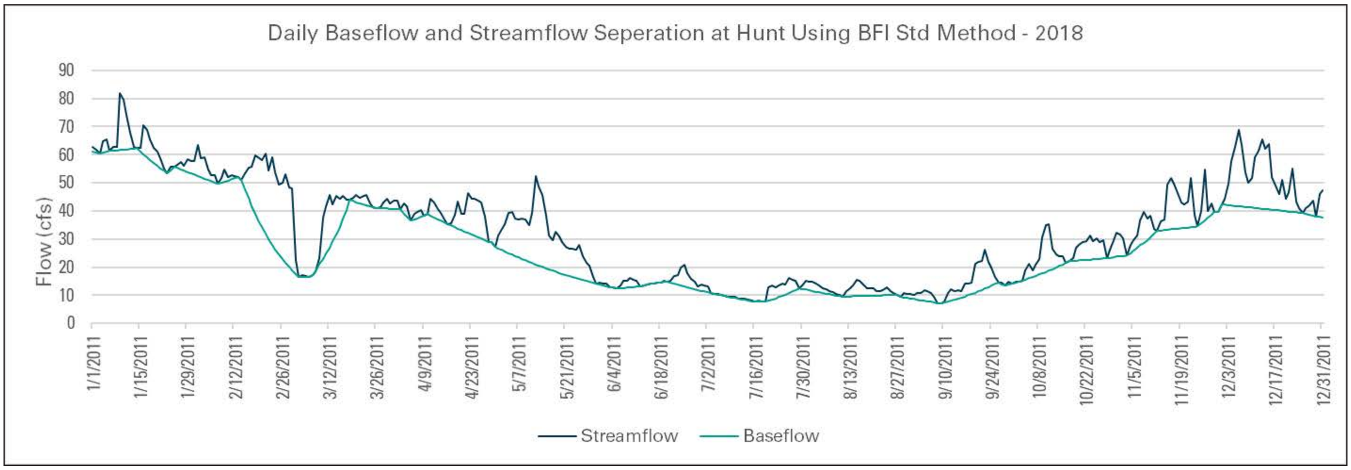


Figure 6. Daily baseflow and streamflow separation at Hunt – 2018

A graphic representation of all the methods is shown on Figure 7 using daily gage data from Hunt as an example. The methods generally track very closely together though there is some separation during high flow periods. A table of deviations of baseflow methods from BFI-Standard (Wahl and Wahl) method is included in Appendix C. The baseflow was generated from the USGS GW Toolbox and the equation used to calculate the deviation was the BFI standard- Specific BF Separation Method (e.g. HYSEP-Fixed, PART, etc.) which was calculated manually in Excel.

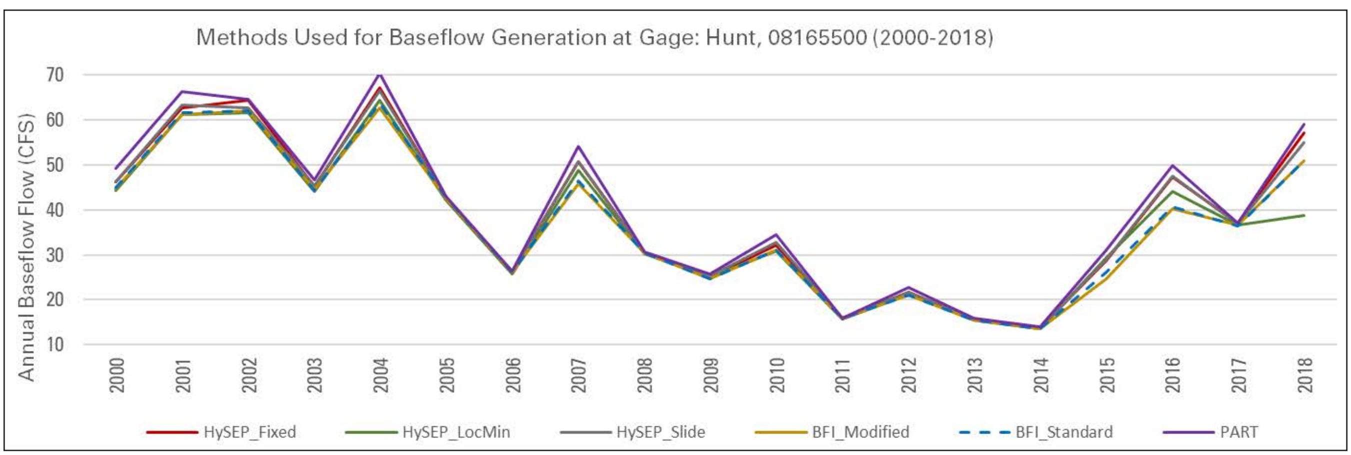


Figure 7. Methods used for baseflow generation at gage: Hunt 08165500 (2000-2018)

Baseflow Trends

A limitation of this study is that the analyses are confined to the location of the data sources (i.e. USGS gages). While there are many gages in the GRB, there are spatial and temporal data gaps. Baseflow and total streamflow for the period 2000 - 2018 have been plotted for select gaging stations. Gaging stations are shown on Figure 8 and a table of gage data is in Appendix A. The Preliminary Report indicates that total flow for nearly all the stations has been decreasing since 2000 but it was not clear if the decreases were due to changes in the volume of runoff or baseflow, with runoff being the difference between total streamflow and baseflow. A discussion of the streamflow and baseflow of the selected gaging stations follows. The stations were selected to provide a representative geographic distribution across the basin. Graphs indicating streamflow, baseflow, and BFI of all gaging stations are included in Appendix C-D.

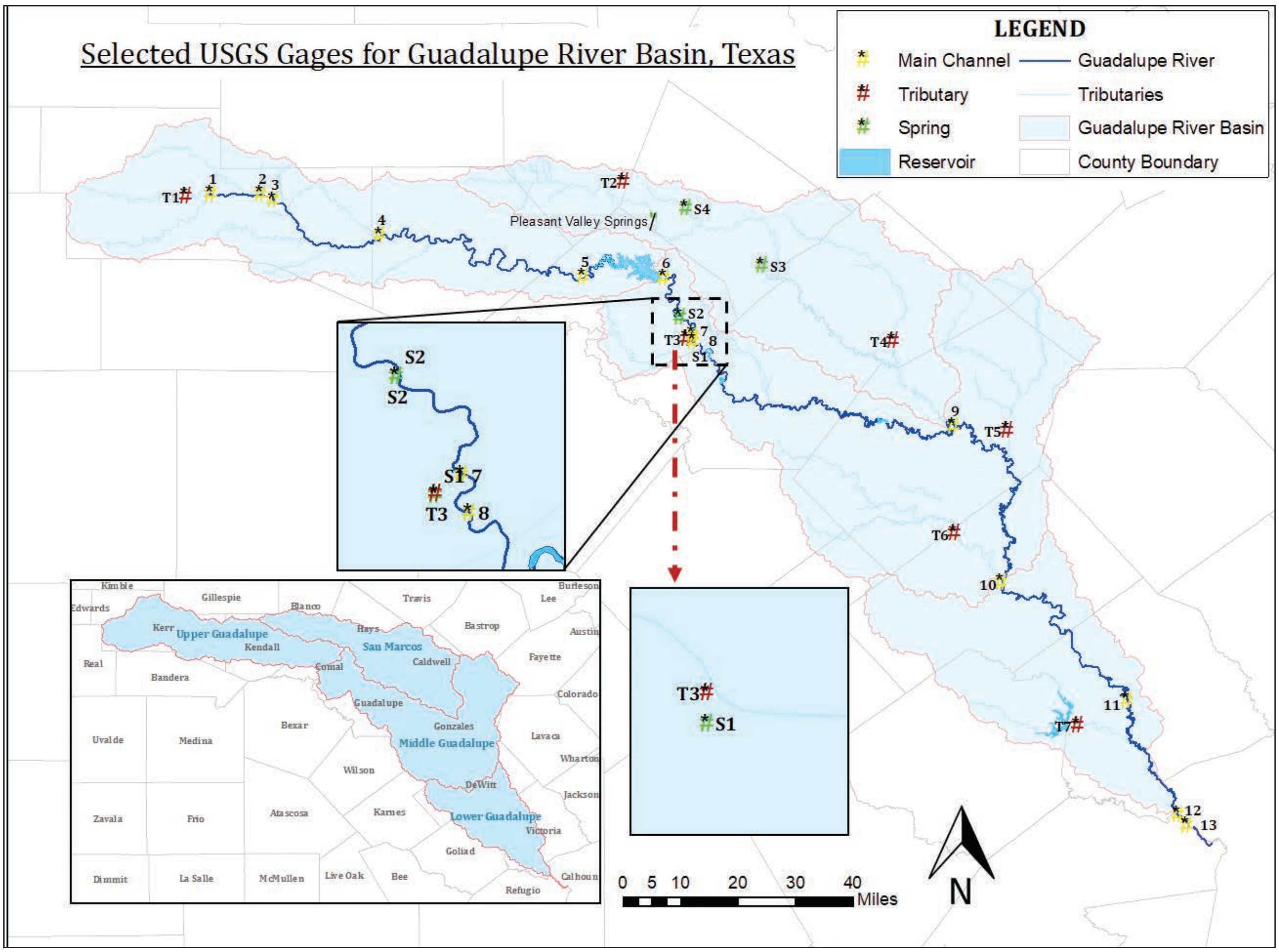
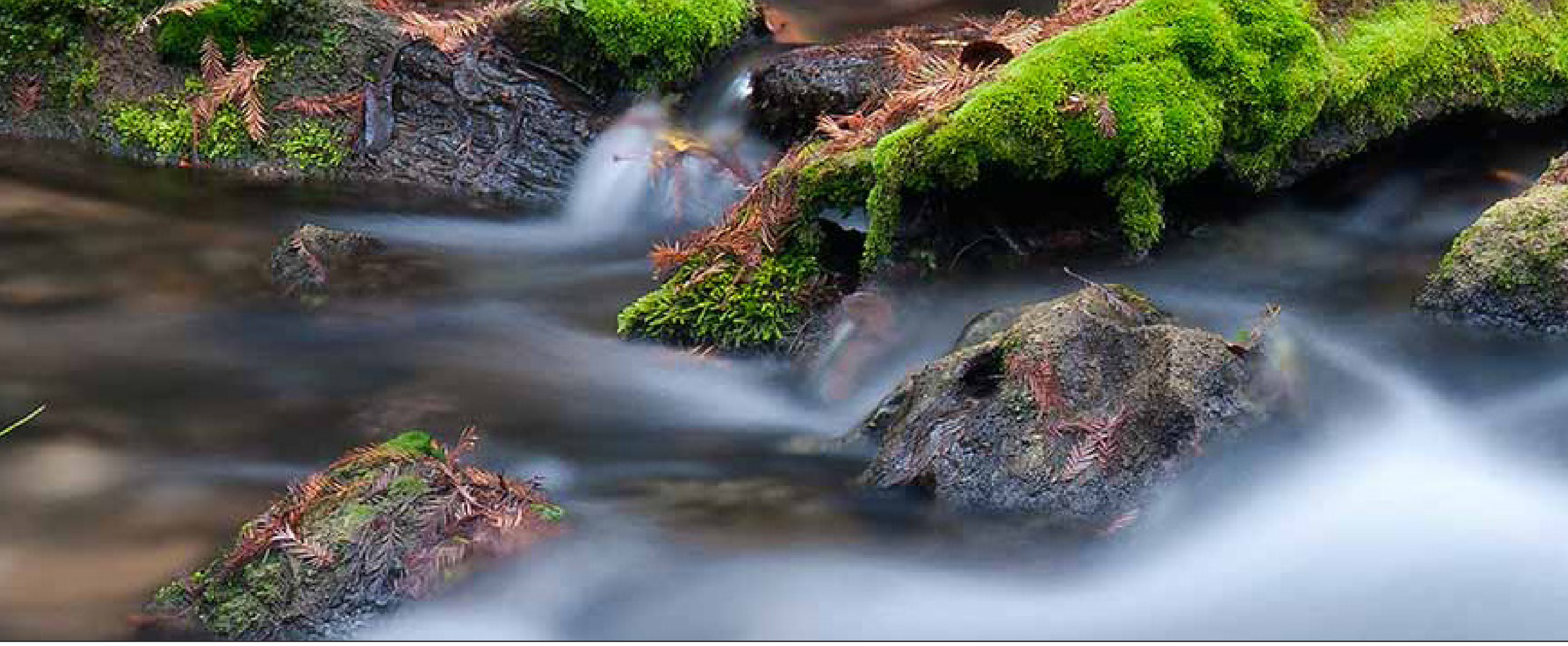


Figure 8. USGS gages selected for the study

Figures 9 and 10 represent annual baseflow separation results at the USGS gages at Hunt and Spring Branch. These gages are in the upper part of the basin and represent baseflow primarily derived from the Edwards Aquifer and to a lesser extent, the Glen Rose Aquifer. Spring Branch has 1.5 times greater discharge than Hunt, indicating the river is generally gaining between Hunt and Spring Branch though there may be local losing reaches. The long-term trend in both streamflow and baseflow is downward, with streamflow decreasing at a greater rate than baseflow. The dry period of 2008 through 2014 tends to drive the downward trend in baseflow and stream flow. Baseflow, being sourced from the underlying aquifer storage, may be buffering the decline in baseflow as opposed to the steeper decline in surface flow which includes short term runoff. Average BFI over the study period was 0.70, or at baseflow 70 percent of the time at Hunt. The range of baseflow was 0.4 to 0.94. Similarly, average BFI over the study period was slightly lower at Spring Branch at 0.60 with a range of 0.33 and 0.87. BFI values were higher during dry periods where most of the flow is derived from baseflow and lower during wet periods.



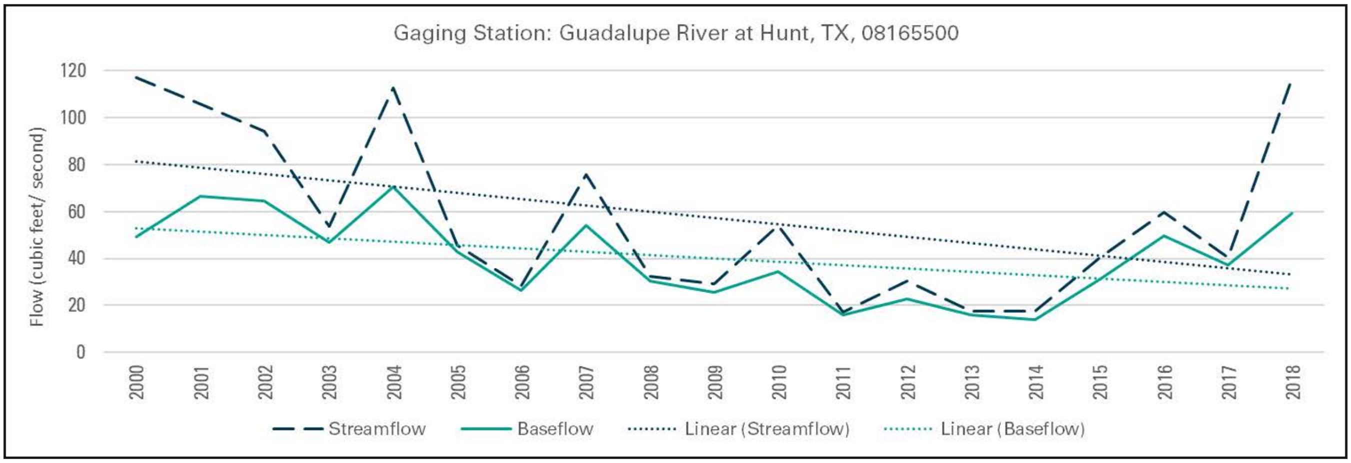


Figure 9. Baseflow separation for the Guadalupe River at Hunt, TX gage (08165500)

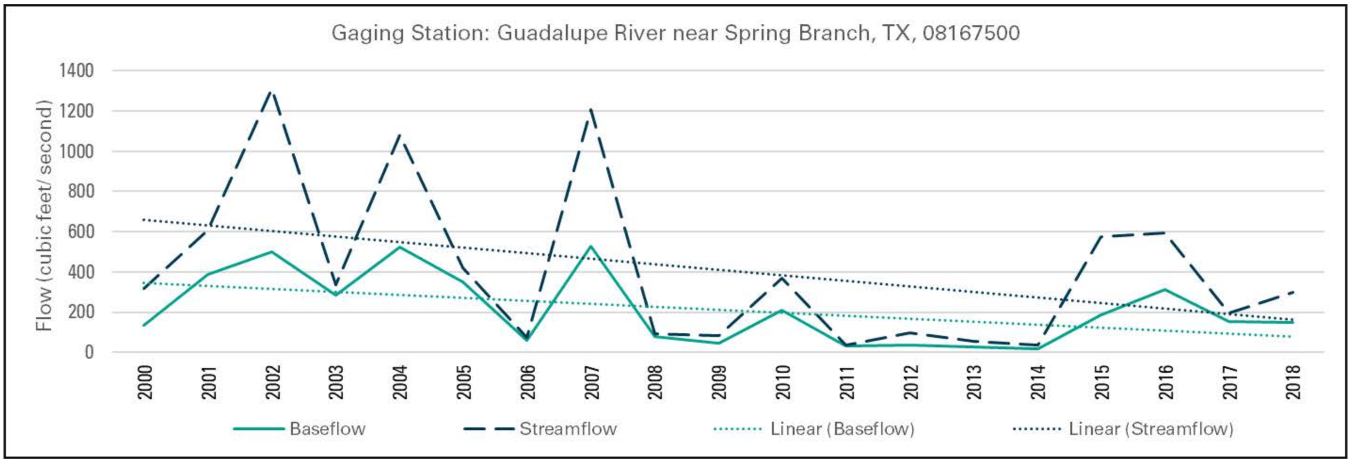


Figure 10. Baseflow separation for the Guadalupe River near Spring Branch, TX gage (08167500)

Figures 11 and 12 show the flow pattern of the Guadalupe River at Gonzales and Victoria. Several limitations with baseflow separation analyses are apparent in the river basin below the gage at Spring Branch. The gages are situated downstream of Canyon Lake which is a major flood control reservoir. Upstream precipitation events can be retained which would tend to make streamflow lower downstream, thus inflating BFI. Conversely, sudden large releases can inflate apparent streamflow. Additionally, slow releases can inflate baseflow downstream of the reservoir. These gages are located downstream of the major springs: Comal Springs, Hueco Springs, and the confluence of the San Marcos River that includes San Marcos Springs.

As stated in the Preliminary Report, "The percentage of total spring discharge to river discharge (as measured at Victoria) ranged from one percent during Hurricane Harvey in 2017 to over 190 percent during the drought of 2011. Any percentage over 100 percent represents water losses (withdrawals and evaporation) between the springs and Victoria. The average contribution is 62 percent. Spring flow is greater than discharge at Victoria 11 percent of the time from 2003 to April 2018." Tropical storms are more frequent in the lower reaches of the basin which will inflate storm runoff. Tropical Storm Bill in 2015 made landfall in Victoria County with a rainfall peaking at 13.05 inches (Wikipedia, 2019). Other factors influencing baseflow separation are anthropogenic impacts such as water diversions and development in the New Braunfels/I-35/Seguin reach of the river.

Despite all of the aforementioned limitations with baseflow separation, the overall trend of baseflow and streamflow is decreasing from 2000 – 2018, similar to the upper reaches in the basin. The difference of the rate of decline in baseflow and stream flow is less than the upper basin. This is likely due to the baseflow buffering due to the major springs, which produce a large part of the flow.

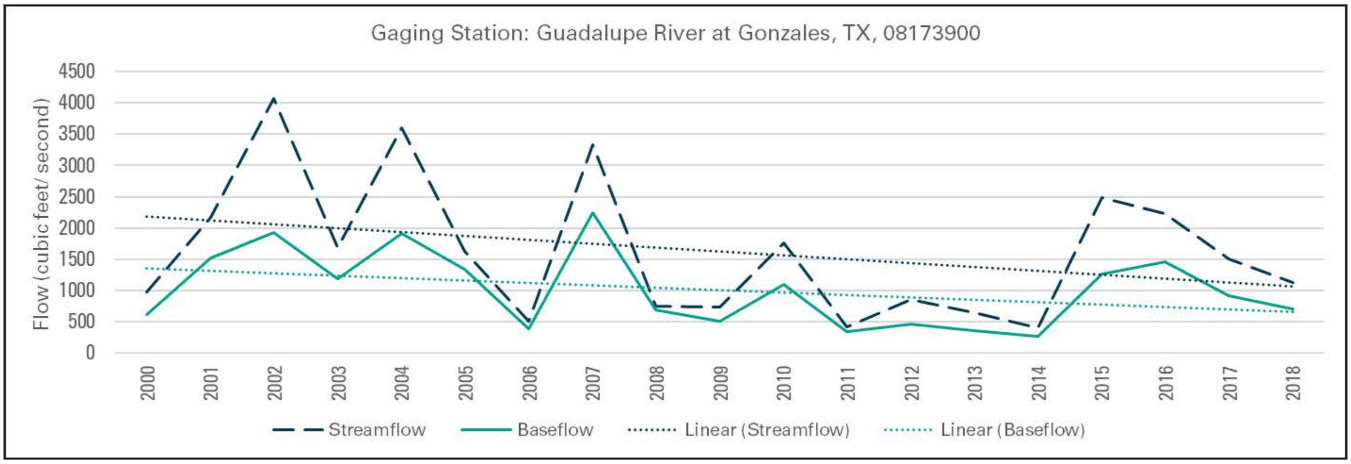


Figure 11. Baseflow separation for the Guadalupe River at Gonzales, TX gage (08173900)

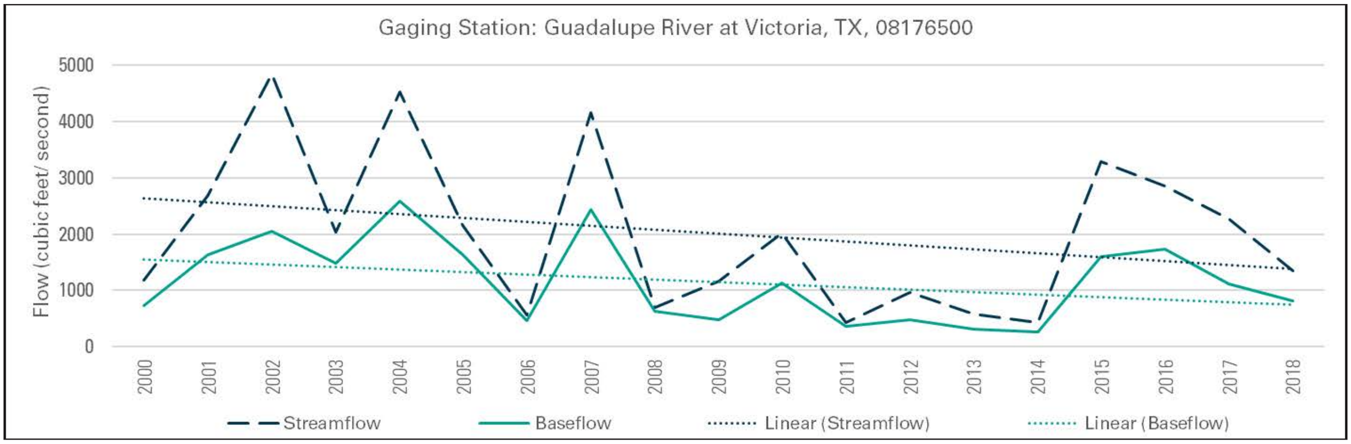


Figure 12. Baseflow separation for the Guadalupe River at Victoria, TX gage (08176500)

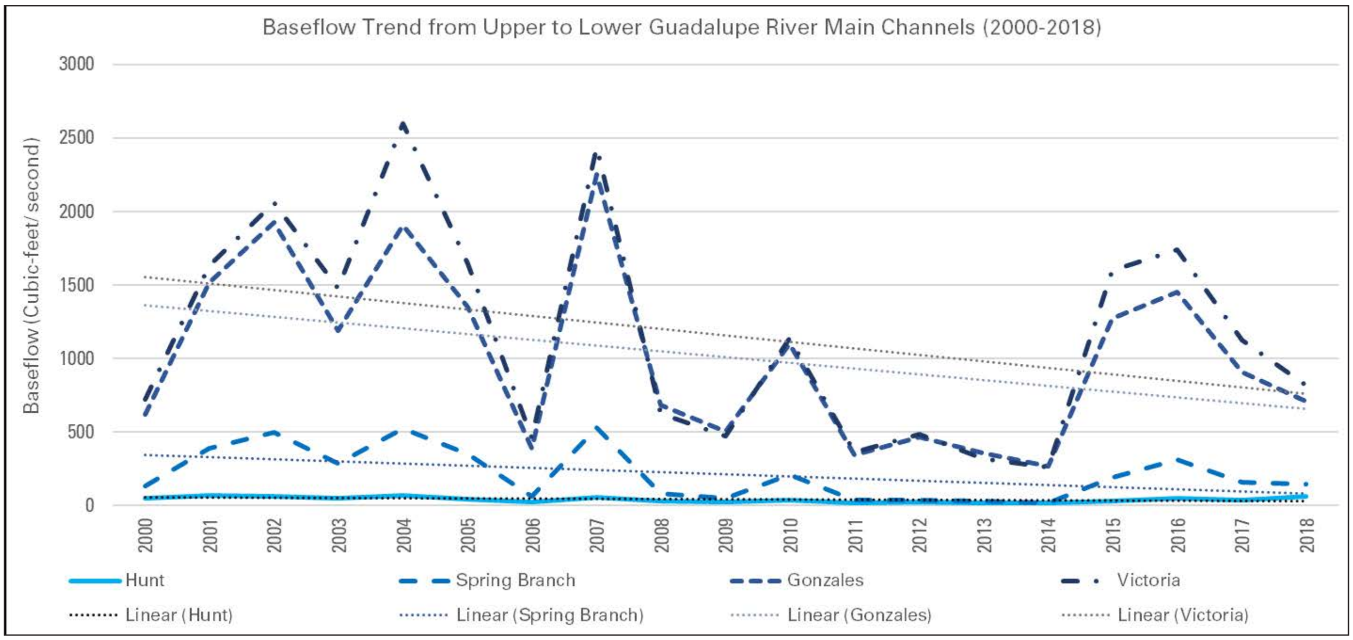


Figure 13. Baseflow trend of four major channel gage stations in the Guadalupe River (Recorded from 2000-2018)

Figure 13 shows the baseflow of all four main channel gage stations which are plotted separately above. These gages represent geographic distribution along the main channel of the study area. The overall trend for baseflow from 2000 to 2018 is decreasing for all four gaging stations. Baseflow at Gonzales and Victoria are very similar for the period 2006-2014 reflecting the major influences from the major Edwards Aquifer springs. For example, the regression analysis of baseflow at Victoria has been reduced by almost half (1500 cfs to 750 cfs). Figure 14 shows the baseflow from major springs.

Figure 14 shows the baseflow pattern of Comal Springs, Hueco Springs, and San Marcos Springs with available data for the study period. All three springs show a similar and declining historical trend throughout the study period. The trend is gradual for San Marcos and Hueco Springs, but the regression line is steeper for Comal Springs. In 2014, the baseflow of the Comal Springs dropped to the baseflow level of San Marcos Springs (approximately 130 cfs). As mentioned earlier in the discussion, the years 2010-2015 are considered the driest years of Texas in the past 20 years (NOAA National Centers for Environmental Information- NCICS 2015). It can be stated that the effects are more visible in Comal Spring's baseflow.

Baseflow separation analyses for the gages downstream of San Marcos, Comal, and Hueco Springs indicate average BFI values since 2000 of 0.99, 0.84 and 0.99, respectfully. The BFI values indicate that virtually all the flow measured is baseflow with little or no storm water contribution.

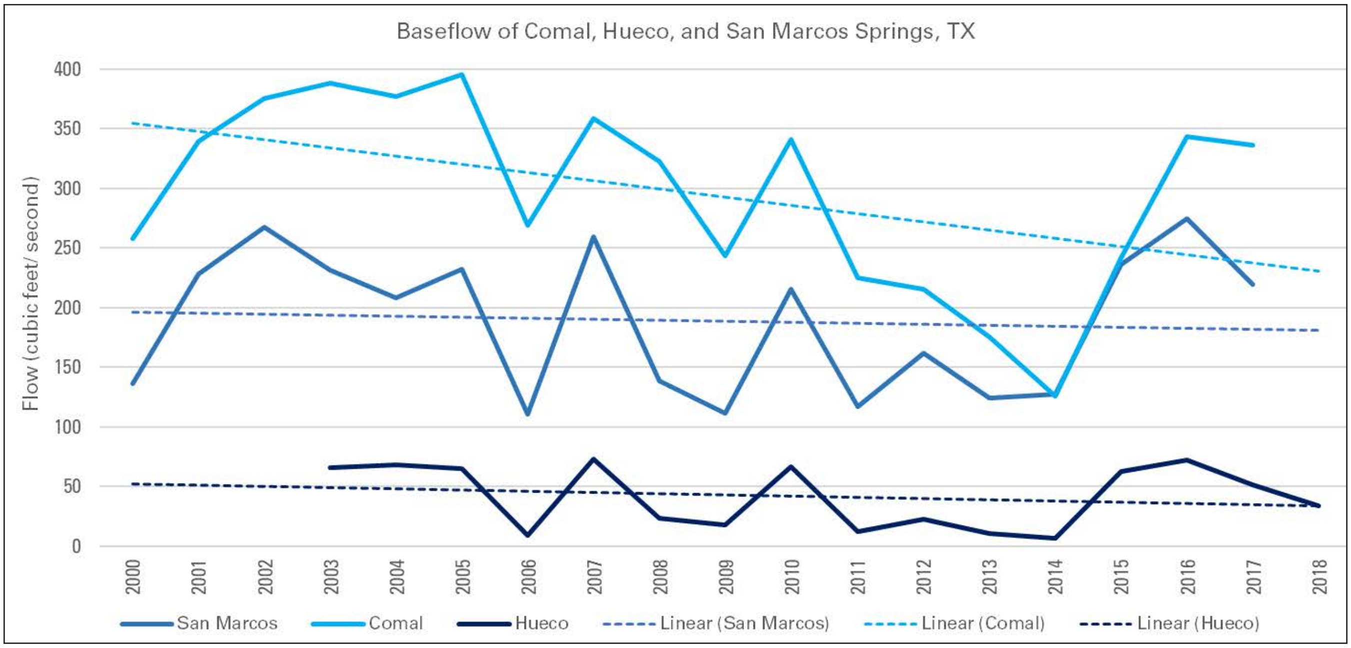


Figure 14. Baseflow pattern of three springs in the Guadalupe River Basin

BASEFLOW SEPARATION – TRIBUTARIES

Several tributaries have flow records for the entire study period, including the Blanco, Comal, and San Marcos Rivers, which are supported by the major springs. Sandies Creek, Plum Creek, and Coleto Creek in the lower part of the basin; and North Fork and Johnson Creek in the upper basin. The Blanco River has several reaches that will typically go dry during much of the year due to recharging the underlying aquifers. The Blanco River provides much of the baseflow to San Marcos Springs (Hunt, 2017), which is within the headwaters of the San Marcos River.

The North Fork of the Guadalupe River is representative of upper basin creeks. Baseflow is maintained by aquifer discharge, primarily from the Plateau Edwards Aquifer, though it is declining similar to the main channel gages. Average BFI over the study period at North Fork was 0.70.

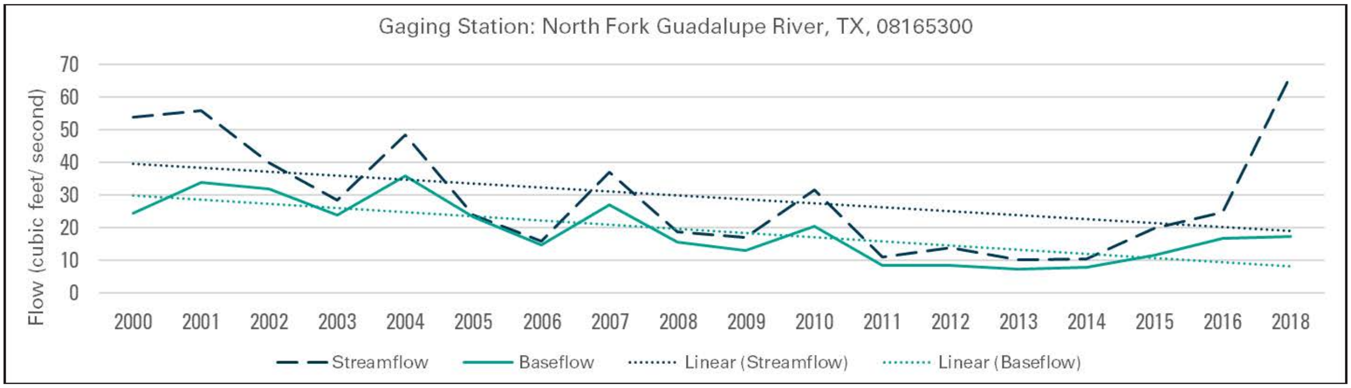


Figure 15. Baseflow separation for the Guadalupe River at North Fork (USGS 08165300)

Plum Creek (Figure 16a.) and Sandies Creek (Figure 16b.) are representative of creeks that originate in the Gulf Coast Aquifer systems. There is little or no flow during drought periods indicating the underlying aquifers are not supporting much baseflow. The creeks flow can maintain average annual flow of over 100 cfs during wet years. The average BFI for Plum Creek and Sandies Creek is 0.23 and 0.13, respectively.

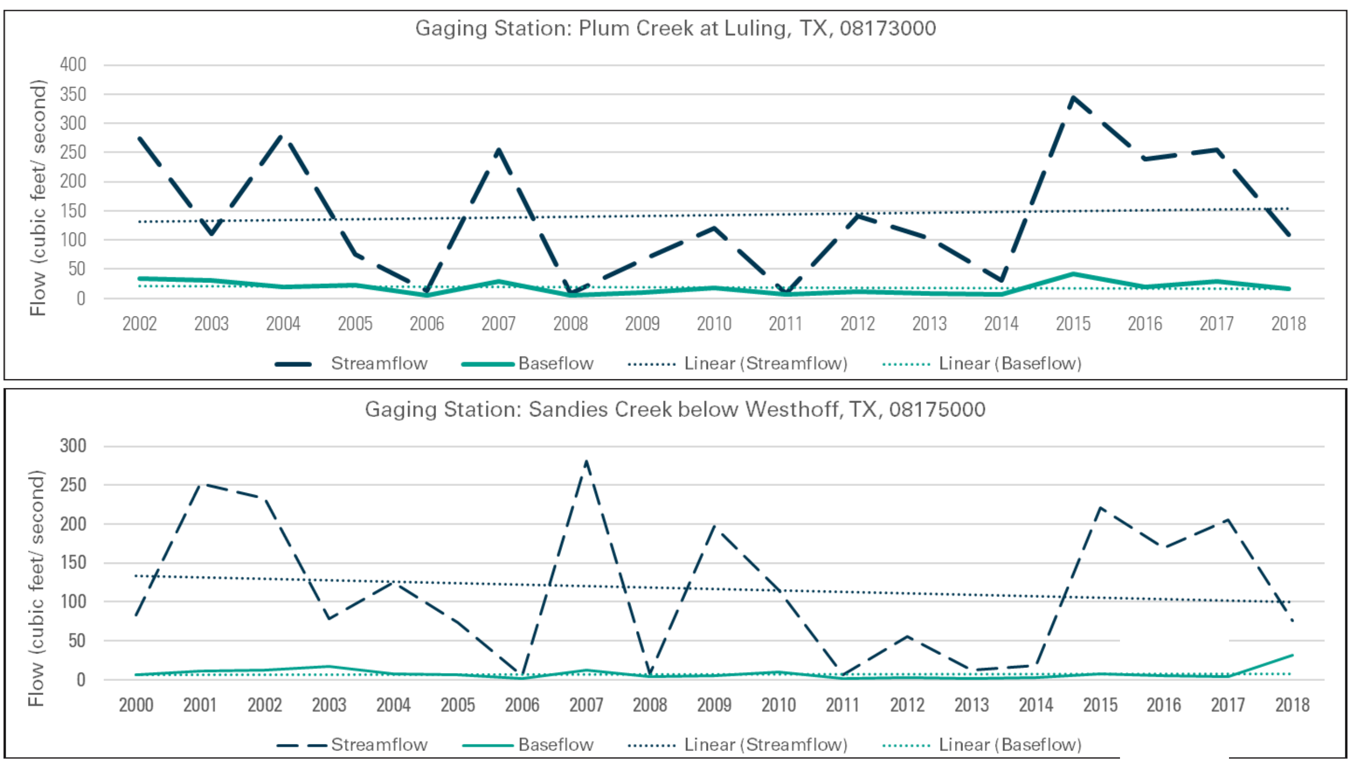


Figure 16a. Baseflow separation for the Guadalupe River at a) Plum Creek (USGS 08173000), b) Sandies Creek (USGS 08175000)

Comparison of Baseflow between Dry and Wet Years: Guadalupe River Basin

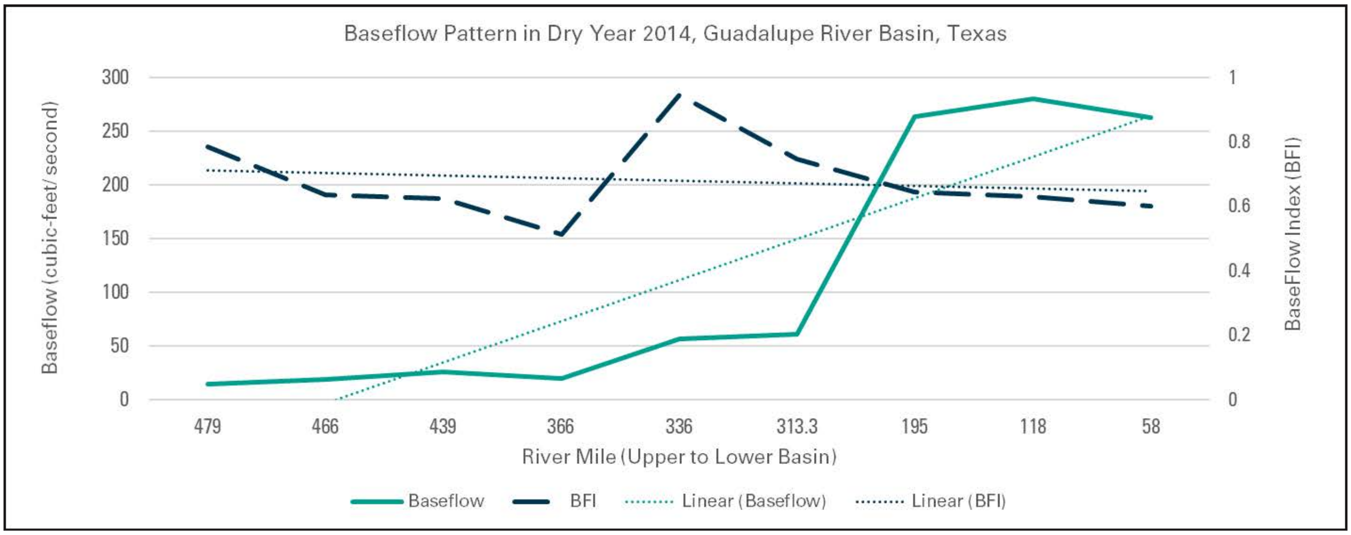


Figure 17. Baseflow pattern in 2014 during a dry year in the Guadalupe River Basin

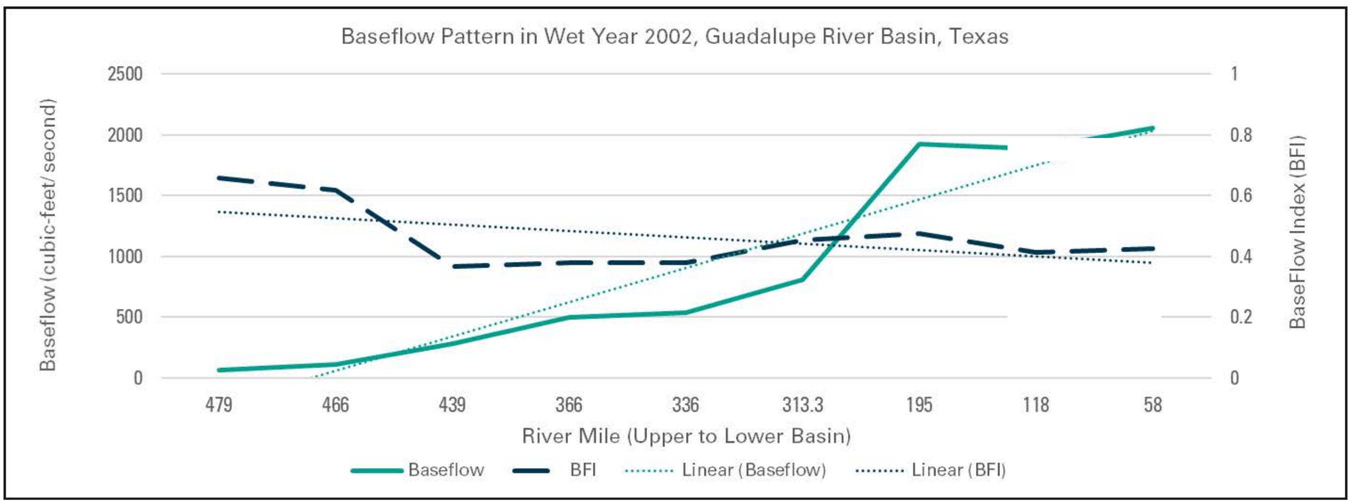


Figure 18. Baseflow pattern in 2002 during a wet year in the Guadalupe River Basin

Figures 17 and 18 illustrate baseflow and BFI in a dry year and a wet year. Two years were chosen from the analysis period 2000-2018: 2002 as a wet year and 2014 as a dry year. All the major gaging stations were plotted from upstream to downstream. The highest discharge of wet year 2002 is almost 10 times greater than dry year 2014. Both base flow discharges show a similar trend with baseflow increasing towards the gulf. In 2002 (wet year) and 2014 (dry year), the average BFI value was 0.46 and 0.68, respectively.

Historic Temperature and Precipitation Pattern

Figure 19a and 19b show the average precipitation and temperature gradient across the counties within the GRB. A general trend of higher temperature is seen in the counties that are close to the gulf whereas lower temperatures occur in the upper portion of the basin. And this trend is consistent throughout the study period. For example: Kerr County has the lowest temperature and precipitation among all the counties throughout 2000-2018. Goliad and Victoria, located near the Gulf, compete between themselves to have the highest temperature, among all counties. There is a slightly different precipitation pattern among the counties located between Hunt and Victoria compared to temperature. Goliad does not happen to have the second highest precipitation most years following Victoria, although, situated in the upper Guadalupe Basin, Comal has the second.

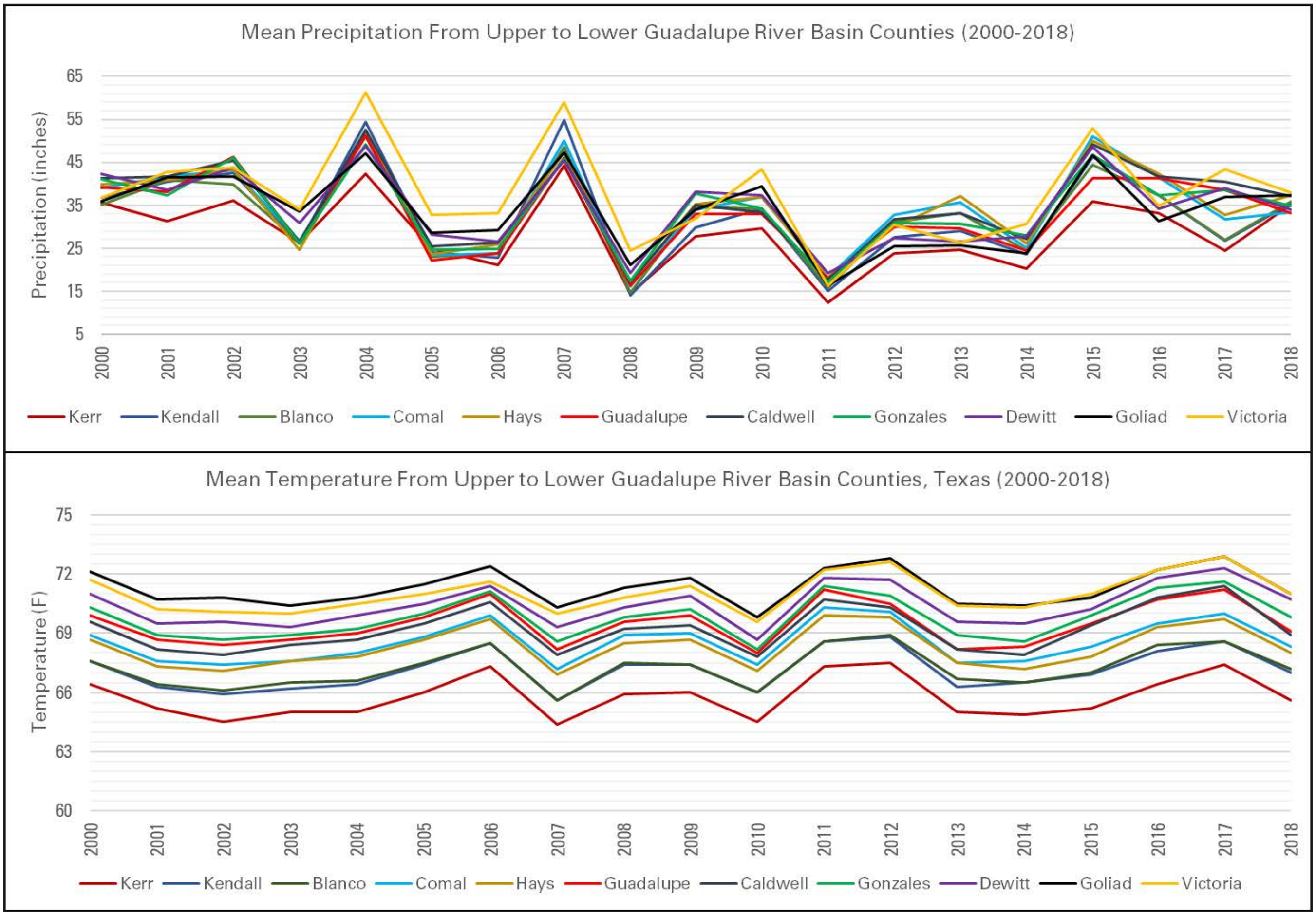
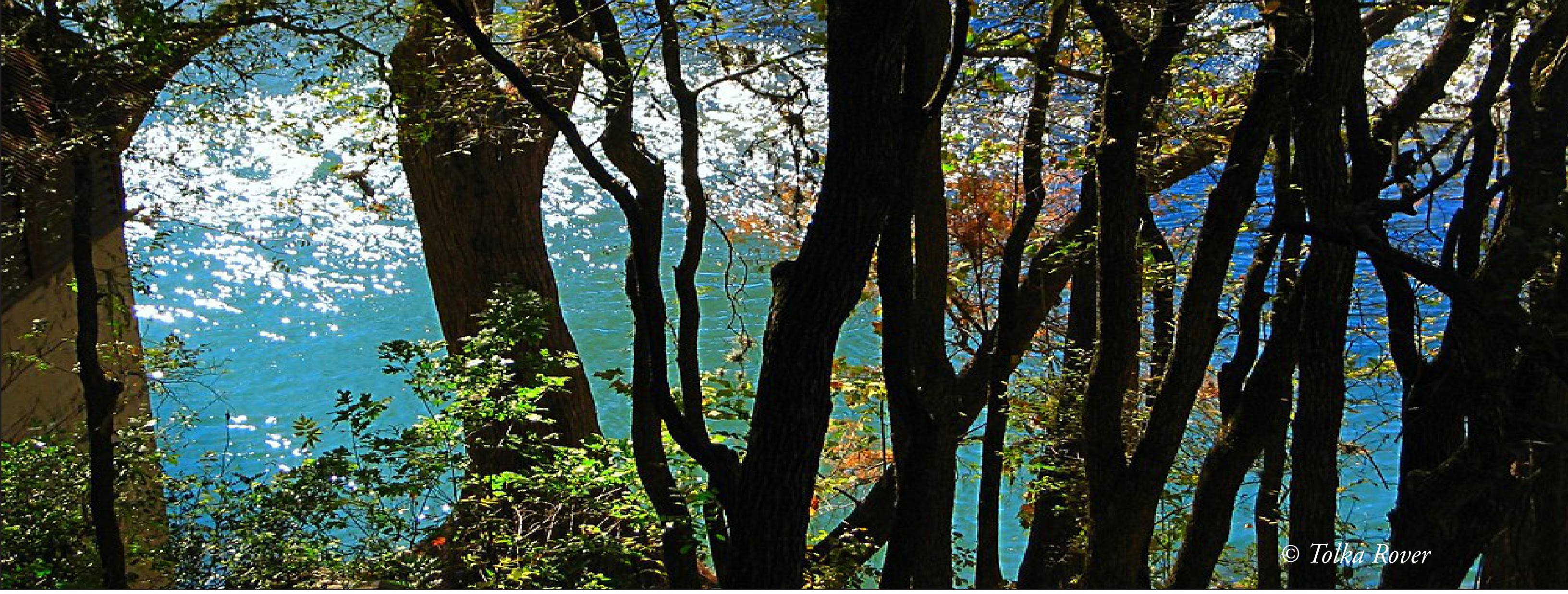


Figure 19. Trends from upper to lower Guadalupe River Basin counties a) Mean precipitation (top) b) Mean temperature (bottom)

Sample gages plotted in Figure 19 are organized in a way from the headwaters towards the bay. Because the GRB is a large basin and lies partially or fully within 11 counties, the climate pattern is analyzed individually by each county in order to compare with the baseflow. Usually climate is considered as an average of 30 years or more of weather data. To keep consistency with the time period for baseflow analysis, climate is also considered for the same record, 2000-2018. Sample climate graphs corresponding to the gaging stations are shown below. See the complete set of graphs in Appendix C.

Figure 20 and 21 show the baseflow of Guadalupe River at Hunt (Kerr County) and Victoria (Gonzales County), respectively. From regression analysis of both gaging stations, the baseflow is decreasing compared to the counties' precipitation, which is relatively flat. Mean annual temperature is increasing by several degrees Fahrenheit, which is similar for both counties. The range of the climate variables does not vary much between the counties. Increasing temperature tends to decrease shallow soil moisture which may reduce recharge to shallow aquifers, reducing baseflow. Increasing temperature may also decrease runoff as more precipitation is necessary to saturate dry ground to allow for runoff. Though not evaluated in the analysis, increasing temperature towards the gulf will increase evaporation, which would reduce baseflow.



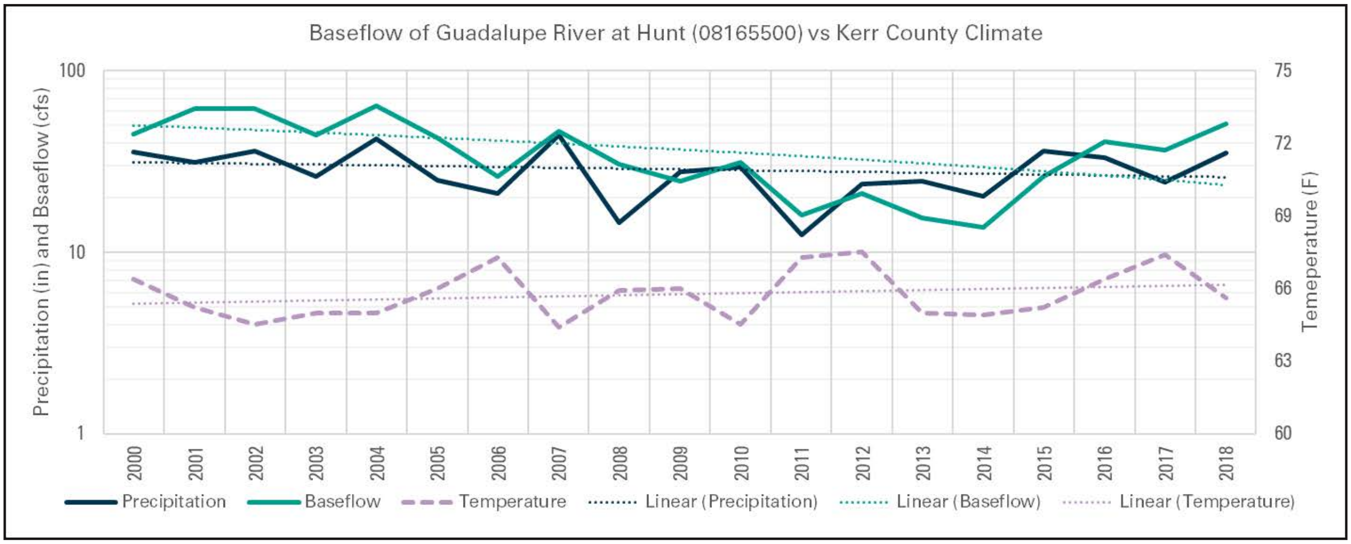


Figure 20. Comparison between the baseflow of Guadalupe River at Hunt, TX gaging station (08165500) and Kerr County climate

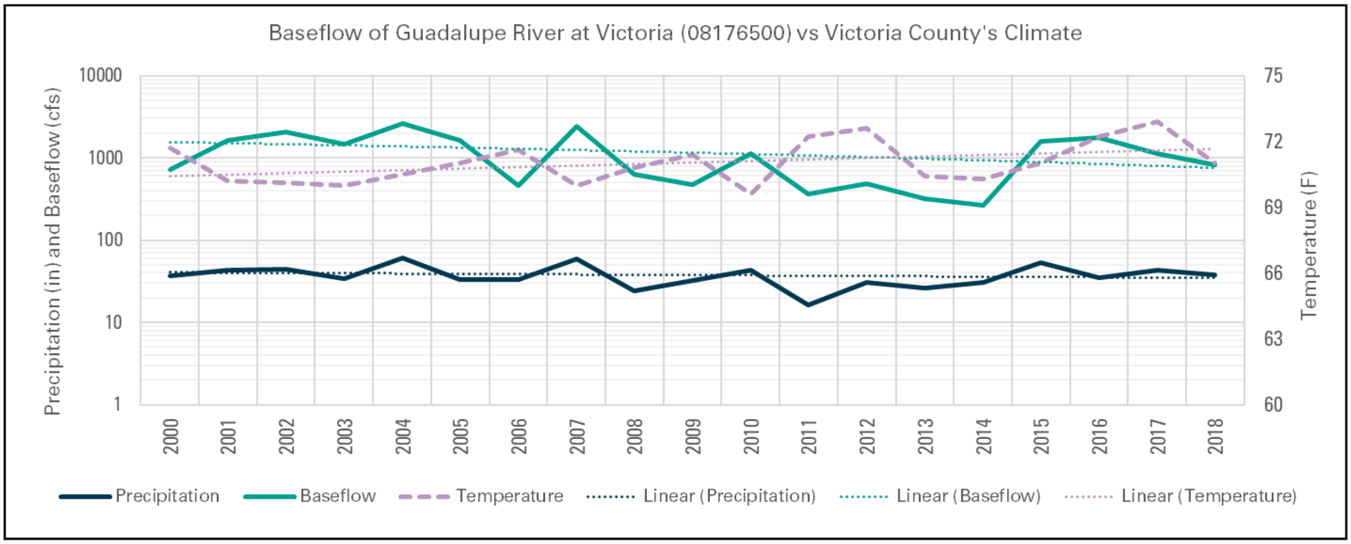


Figure 21. Comparison between the baseflow of Guadalupe River at Gonzales, TX gaging station (08173900) and Gonzales County's climate

Population Growth and Land Cover/Use Change Analysis

The major population centers along the Guadalupe River include Kerrville, New Braunfels, San Marcos, Seguin, Lockhart, Gonzales, Cuero, Luling, and Victoria. The basin includes portions of Kerr, Kendall, Comal, Caldwell, Hays, Guadalupe, Caldwell, Gonzales, De Witt, Goliad, and Victoria counties. The total population growth from 2000 to 2018 was approximately 320,000 people, or an increase of 68 percent.

Table 1. Population growth of counties within the Guadalupe River Basin 2000-2018 (Source: Census Viewer, 2019)

COUNTY	2000	2010	2018	% INCREASE 2000 -2018
Caldwell	32,194	38,066	46,748	145%
Kerr	43,653	49,625	55,505	127%
Kendall	23,743	33,410	42,562	179%
Blanco	8,418	10,497	12,503	149%
Comal	78,021	108,472	141,332	181%
Hays	97,589	157,107	225,340	231%
Goliad	6,928	7,210	8,255	119%
Guadalupe	89,023	131,533	171,409	193%
Gonzales	18,626	19,807	21,871	117%
DeWitt	20,013	20,097	20,770	104%
Victoria	84,088	86,793	91,624	109%
Total	470,102	624,551	791,171	168%

Apart from limited use of rainwater collection, water is either sourced from surface water or groundwater resources. Given the connectivity of surface water and groundwater, it is reasonable to assume that a large portion of the decline in baseflow is due to population growth. Looking forward, population growth is projected to increase from 2020 to 2070 by 702,600, or 227 percent. Water use is projected to increase by 196 percent over the same period.

Table 2. Projected total population and water demand (Source: SCTRWP, 2016)

	2020	2030	2040	2050	2060	2070	% INCREASE 2020-2070
Population	555,051	681,755	814,463	933,374	1,090,528	1,257,651	227%
Water Demand (ac-ft)	194,049	238,393	268,008	305,379	349,619	380,350	196%

This increasing population demands more lands for various purposes (e.g. commercial, agriculture, etc.). This does not only put pressure on the water resources but lands as well. Land use such as urban development can increase impervious cover which tends to increase runoff and decrease infiltration and recharge to groundwater resources. The time period for land use change analysis was 2001-2016 because of the availability of National Land Cover Database (NLCD) Land Use Change Dataset (Multi-Resolution Land Characteristics Consortium, 2019). The calculations were done in four sub-basins of the GRB- the Upper Guadalupe, the Middle Guadalupe, the Lower Guadalupe, and the San Marcos. NLCD classifies 10 major land cover types, with sub-classification of urban and forest cover. The NLCD legend is included in Appendix F. Figures 22 and 23 indicate land cover/use for 2001 and 2016. For clarity, several of the NLCD classifications have been combined.

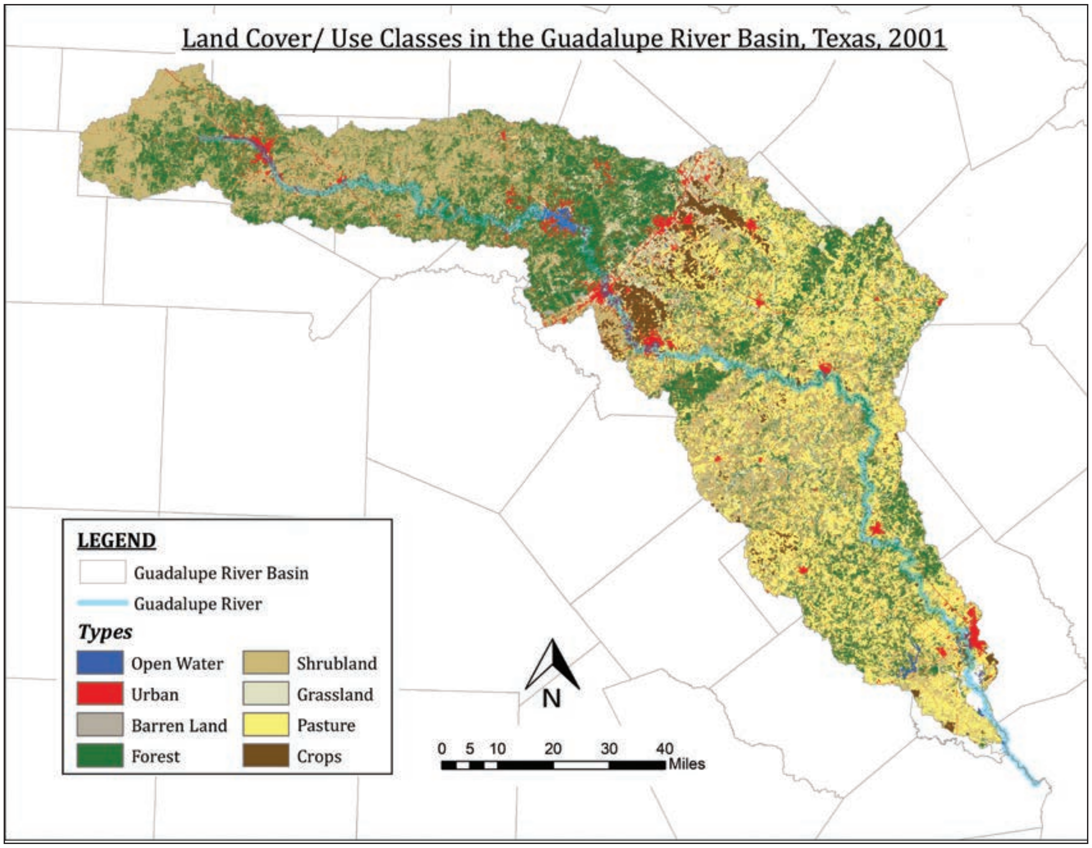


Figure 22. Land cover/ use map of 2001, Guadalupe River Basin

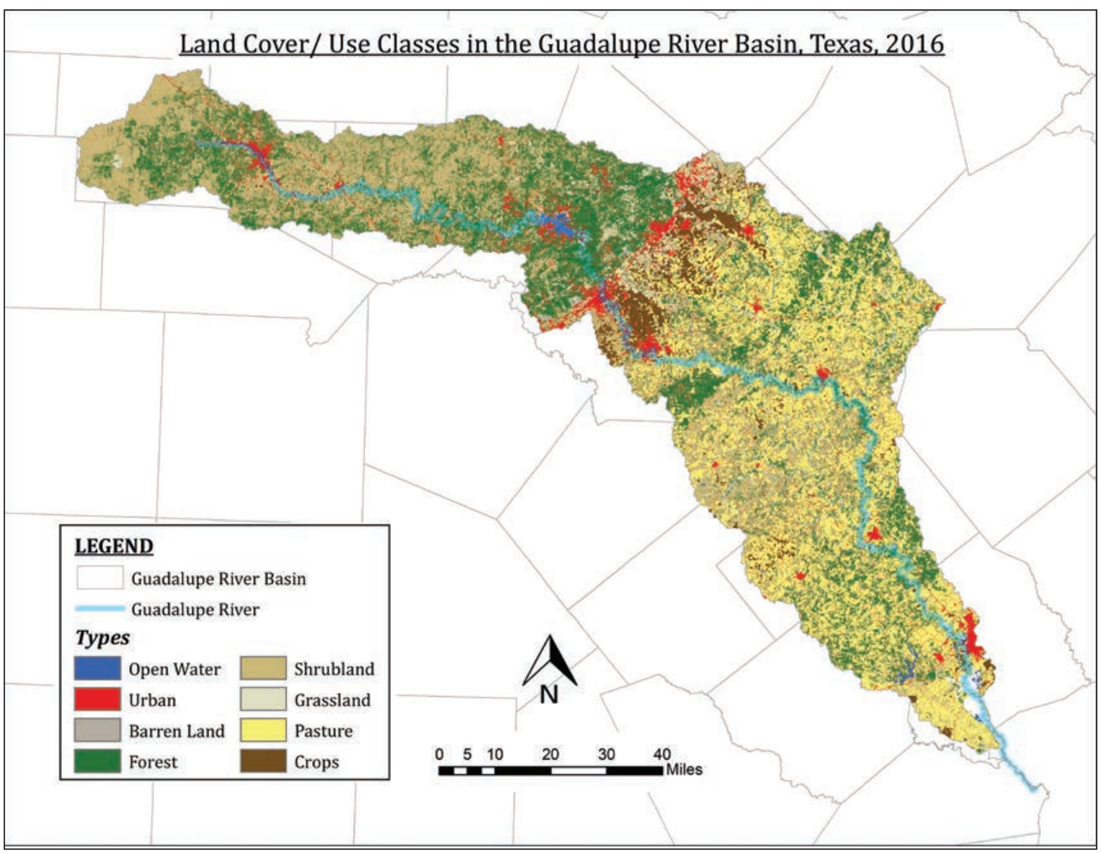


Figure 23. Land cover/ use map of 2016, Guadalupe River Basin

The land cover types vary across the four sub-basins (Table 3). There is a clear distinction between the upper basin and the rest of the basin which is the result of the underlying geology.

The carbonate rocks of the Edwards and Glen Rose formations are not well suited for agricultural purposes and therefore primarily support shrub lands and forests. The middle and lower basins are underlain by the Gulf Coast formations and are predominantly pasture land. The San Marcos basin is a transition between the upper and lower basin and supports both shrub lands and pasture lands. Changes in land use types by sub-basin are included in Table 4 and illustrated on Figure 24.

Table 3. Summary of dominant land use types by sub-basin

SUMMARY OF DOMINANT LAND USE TYPES			
UPPER GUADALUPE	MIDDLE GUADALUPE	LOWER GUADALUPE	SAN MARCOS
Shrub	Pasture	Pasture	Shrub
Evergreen Forest	Shrub	Shrub	Pasture
	Deciduous Forest	Deciduous Forest	Evergreen Forest

Table 4. Land use change by sub-basin 2001-2016 (*Note: Red denotes negative change*)

LOWER GUADALUPE	2001		2016		
LAND USE CLASS	PERCENT	AREA (MILE²)	PERCENT	AREA (MILE²)	CHANGE (MILE²)
Open Water	1.2	12.6	1.3	13.3	0.7
Developed, Open Space	3.5	34.9	3.5	35.8	0.8
Developed, Low Intensity	1.1	10.7	1.2	12.6	1.8
Developed, Medium Intensity	0.5	5.3	0.7	7.3	1.9
Developed, High Intensity	0.2	1.9	0.3	2.6	0.7
Barren Land	0.2	2.1	0.2	2.0	(0.1)
Deciduous Forest	12.2	123.6	11.6	117.3	(6.2)
Evergreen Forest	2.7	27.0	2.7	26.9	(0.1)
Mixed Forest	4.8	48.3	5.0	50.9	2.7
Shrub	16.4	165.4	16.7	168.2	2.8
Grassland	0.2	1.9	0.5	5.2	3.2
Pasture	49.7	502.2	48.8	492.8	(9.4)
Cultivated Crops	2.0	19.8	2.1	21.3	1.5
Woody Wetland	4.2	42.8	4.2	42.7	(0.1)
Emergent Herbaceous Wetland	1.1	11.3	1.1	11.1	(0.1)
TOTAL	**100.00**	**1,009.9**	**100.00**	**1,009.9**	**0.0**

Table 4 cont. Land use change by sub-basin 2001-2016 (*Note: Red denotes negative change*)

MIDDLE GUADALUPE	2001		2016		
LAND USE CLASS	PERCENT	AREA (MILE²)	PERCENT	AREA (MILE²)	CHANGE (MILE²)
Open Water	0.5	11.6	0.6	12.5	0.9
Developed, Open Space	3.9	82.9	4.2	88.8	5.9
Developed, Low Intensity	1.0	21.9	1.4	30.5	8.6
Developed, Medium Intensity	0.4	7.7	0.7	14.9	7.2
Developed, High Intensity	0.2	3.9	0.3	6.3	2.4
Barren Land	0.2	4.5	0.2	4.3	(0.3)
Deciduous Forest	11.9	254.8	11.3	242.0	(12.8)
Evergreen Forest	6.0	128.5	5.6	120.5	(8.0)
Mixed Forest	4.3	91.5	4.2	89.5	(2.1)
Shrub	27.9	596.2	28.1	599.9	3.7
Grassland	1.8	39.1	2.0	42.2	3.2
Pasture	35.5	758.3	34.7	741.3	(17.0)
Cultivated Crops	3.2	68.7	3.6	77.2	8.5
Woody Wetland	3.1	66.3	3.1	65.9	(0.4)
Emergent Herbaceous Wetland	0.1	2.9	0.1	3.0	0.1
TOTAL	**100.00**	**2,138.7**	**100.00**	**2,138.7**	**0.0**

UPPER GUADALUPE	2001		2016		
LAND USE CLASS	PERCENT	AREA (MILE²)	PERCENT	AREA (MILE²)	CHANGE (MILE²)
Open Water	1.1	15.5	1.1	15.7	0.1
Developed, Open Space	4.2	60.8	4.3	61.5	0.7
Developed, Low Intensity	1.1	15.6	1.2	16.9	1.3
Developed, Medium Intensity	0.3	3.7	0.4	5.0	1.3
Developed, High Intensity	0.1	1.0	0.1	1.3	0.3
Barren Land	0.1	1.0	0.1	0.9	(0.1)
Deciduous Forest	4.8	69.2	4.7	67.9	(1.3)
Evergreen Forest	27.4	392.4	25.8	369.1	(23.2)
Mixed Forest	0.0	0.2	0.0	0.2	0.0
Shrub	58.0	831.3	59.1	846.7	15.3
Grassland	2.3	33.6	2.6	37.1	3.5
Pasture	0.2	3.5	0.2	3.5	(0.1)
Cultivated Crops	0.3	4.0	0.4	6.0	2.0
Woody Wetland	0.1	0.9	0.1	0.9	0.0
Emergent Herbaceous Wetland	0.0	0.1	0.0	0.0	(0.0)
TOTAL	**100.00**	**1,432.9**	**100.00**	**1,432.9**	**0.0**

Table 4 cont. Land use change by sub-basin 2001-2016 (*Note: Red denotes negative change*)

SAN MARCOS	2001		2016		
LAND USE CLASS	PERCENT	AREA (MILE²)	PERCENT	AREA (MILE²)	CHANGE (MILE²)
Open Water	0.4	5.7	0.5	6.7	1.0
Developed, Open Space	4.6	62.0	4.8	65.6	3.7
Developed, Low Intensity	1.0	13.3	1.3	18.0	4.7
Developed, Medium Intensity	0.4	4.8	0.7	9.7	4.9
Developed, High Intensity	0.2	2.3	0.3	4.1	1.8
Barren Land	0.2	2.8	0.2	2.6	(0.2)
Deciduous Forest	10.8	146.6	10.6	143.5	(3.1)
Evergreen Forest	14.5	197.6	14.2	192.3	(5.3)
Mixed Forest	1.5	20.3	1.5	20.5	0.2
Shrub	26.6	362.0	26.6	361.5	(0.5)
Grassland	8.1	109.5	7.1	96.3	(13.2)
Pasture	24.2	328.8	22.9	310.7	(18.1)
Cultivated Crops	5.9	79.6	7.7	104.1	24.5
Woody Wetland	1.7	22.6	1.7	22.5	(0.2)
Emergent Herbaceous Wetland	0.1	1.1	0.1	1.1	(0.0)
TOTAL	**100.00**	**1,359.0**	**100.00**	**1,359.0**	**0.0**

For the entire basin, overall land use changed by approximately five percent. Pasture and forests declined in the lower and middle sub-basins. In the upper basin, most of the loss was in evergreen forest. Forests, pastures, and grasslands lost the most area in the San Marcos sub-basin.

Total developed land increased in all basins by approximately 57 square miles. As evident from Figure 24, most of the changes occurred along the I-35 corridor which correlated with the population increases in Hays, Caldwell, Comal, and Guadalupe Counties. The sub-basin increases were 5.3 square miles, 24.1 square miles, 3.7 square miles and 24.1 square miles for the lower, middle, upper, and San Marcos sub-basins, respectively. Developed lands increase impervious cover, which can increase flooding. Additionally, increased impervious cover reduces recharge into shallow aquifers, which can reduce baseflow.

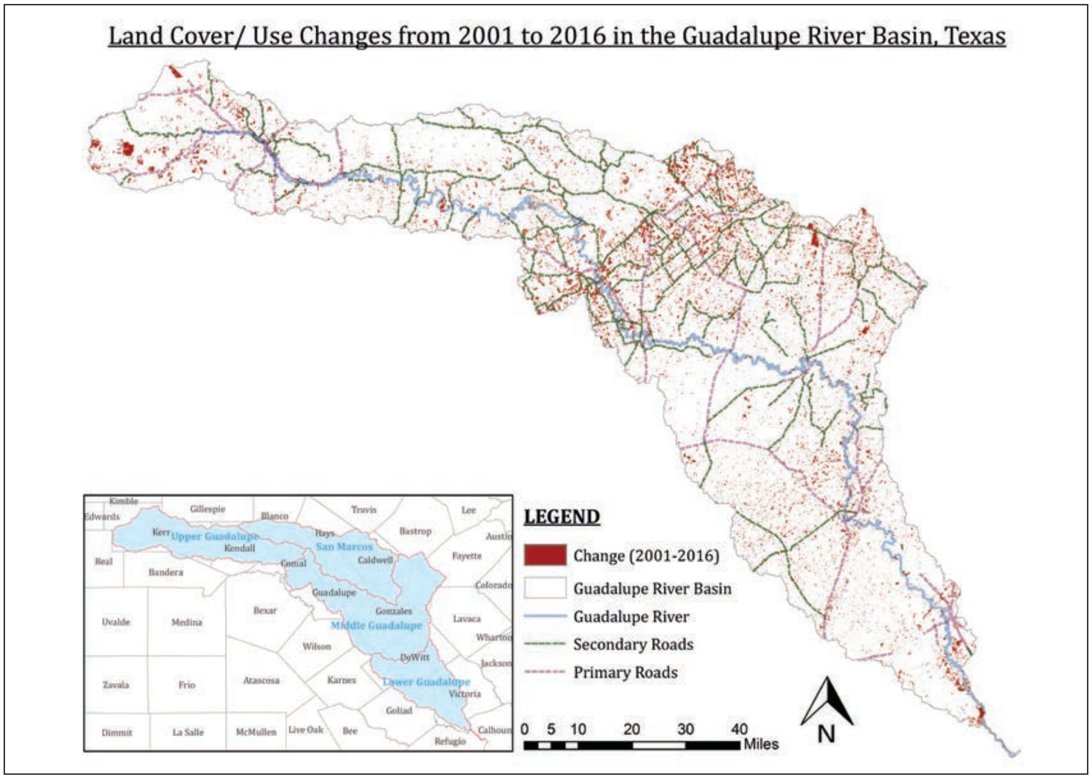


Figure 24. Land cover/ use changes 2001-2016, Guadalupe River Basin, Texas

Power Generation

The impact of declining stream flow and baseflow in the GRB is evident in the hydroelectric power generation by GBRA. Figure 15 shows the power generation of Canyon Lake and all the other reservoirs within the GRB. Guadalupe Hydroelectric Valley Division (GVHD) generation includes Lake Dunlap, Lake McQueeney, Lake Placid (Meadow Lake), Lake Nolte, Lake Gonzales, and Lake Wood. The failure of the dam at Lake Wood in 2016 is also contributing to the decrease in power generation for the last two years of the study period. The failure of the Lake Dunlop dam in 2019 and loss of power generation occurred after the study period.

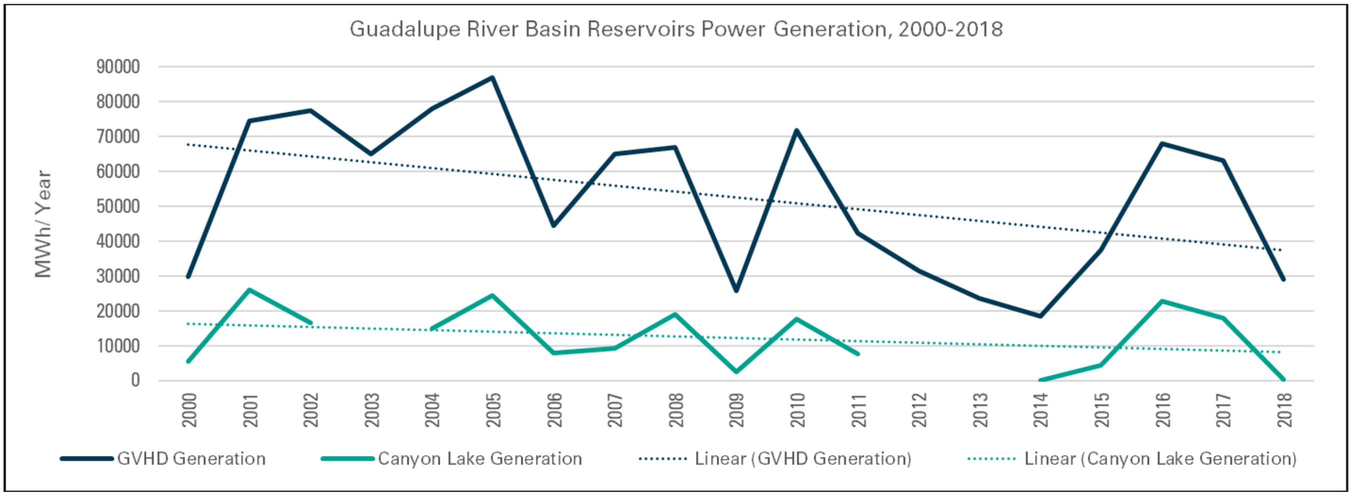


Figure 25. Power generation of the reservoirs in the Guadalupe River Basin (2000-2018) (Source: GBRA Annual Reports. Data for Canyon Lake incomplete.)

Inflows and Diversions

Inflows and diversions are anthropogenic factors influencing the flow of the Guadalupe River. One of the goals of this project was to approximate the significance of inflow and diversions in the study area from the headwaters to Victoria. Major inflows are generally discharges from municipal wastewater treatment plants. Diversions are the lawful withdrawals of water from the river.

As previously stated, the study area does not include the counties downstream of Victoria County. There are two major occurrences south of Victoria that were excluded from the study: The San Antonio River and the Calhoun Canal System. The canal network is for water distribution to industrial, municipal, and agricultural customers in Calhoun County through a series of irrigation canals, checks, pump stations, and pipelines. The Calhoun Canal System delivers a large volume of water to agricultural users, primarily for rice irrigation, but also including row crop, pasture, aqua-culture, and waterfowl operations.

Inflows

Data on inflows was obtained from the TCEQ Discharge Monitoring Report (DMR) database. Regulated entities with Texas Pollution Discharge Elimination System (TPDES) permits are required to report monthly discharge volumes. Discharge is reported in daily average and daily maximum flow rates in cfs. Systems are classified as major or minor. In general, large municipal treatment plants are designated as major facilities and, as such, they tend to have the most complete reporting data sets.

A summary of annual discharge rates and volumes from major dischargers for the period 2013 through 2018 is shown in Table 5. For this period, average annual discharge rates were relatively consistent between 33 and 41 cfs for the basin in the study area. Annual inflows for the basin are generally less than 10 percent of baseflow during normal or wet precipitation years at Victoria (Table 4, Figure 26). During dry or drought years, over 10 percent of the baseflow may be inflows (or treated sewage) at Victoria. At Kerrville, discharge from the wastewater treatment plant approximately equals baseflow during drought periods, such as July 2018.

One caveat regarding the percentage of inflow to baseflow is that the major dischargers are municipalities using surface water in their potable water systems. Surface water is typically diverted upstream of the city and treated effluent is discharged downstream. Generally, less than half of the diverted water is returned to the river as effluent. Gonzales, New Braunfels, Kerrville, Seguin, Victoria, and San Marcos primarily use surface water. Cuero is the only major discharger that uses groundwater.

Table 5. Summary of discharge monitoring reports by County, expressed in mgd (million gallon per day) unless otherwise noted (Source: TCEQ DMR Database)

YEAR	COMAL (NB1)	COMAL (NB2)	COMAL (NB3)	DEWITT (CUERO)	GONZALES (GONZALES)	GUADALUPE (SEGUIN1)	GUADALUPE (SEGUIN2)	HAYS (SAN MARCOS)	KERR (KERRVILLE)	VICTORIA (CITY OF VICTORIA)	ANNUAL TOTAL DISCHARGE (MGD)	AVG. TOTAL INFLOW (CFS)	AVG. TOTAL BASEFLOW @ VICTORIA (CFS)	% OF BASEFLOW @ VICTORIA
2010	2.8	0.5	2.0	1.1	1.1	1.1	2.4	5.2	1.9	6.1	24.2	37	1,138	3%
2011	2.4	0.5	2.0	1.0	1.2	1.3	2.7	4.2	1.4	4.9	21.6	33	360	9%
2012	2.7	0.5	2.0	1.0	1.3	1.3	2.9	5.0	1.5	5.3	23.5	36	486	7%
2013	2.7	0.5	2.0	1.0	1.3	1.2	2.5	4.4	1.5	5.1	22.2	34	317	11%
2014	2.7	0.6	1.9	1.0	1.3	1.3	2.4	3.9	1.5	5.0	21.6	33	262	13%
2015	2.5	0.7	2.8	1.1	1.3	1.5	2.9	5.0	1.8	6.6	26.2	41	1,595	3%
2016	3.7	0.7	2.2	1.5	1.2	1.6	3.2	4.9	2.0	5.7	26.7	41	1,740	2%
2017	2.9	0.6	2.2	1.2	1.2	1.7	3.4	4.6	1.7	5.3	24.7	38	1,125	3%
2018	2.8	0.7	2.1	1.6	1.4	1.7	2.9	4.5	1.5	4.6	23.8	37	817	5%

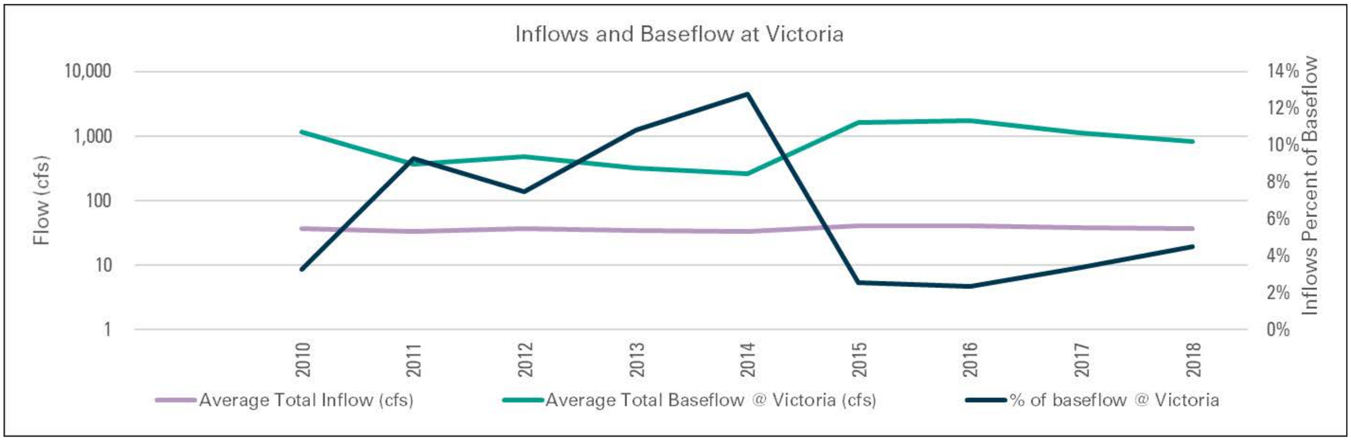


Figure 26: Total Major Inflows for the Guadalupe Basin and Baseflow at Victoria

Diversions

Diversions, or withdrawals, are losses of water from the river based on water rights from the State of Texas. Diversions are self-reported to the TCEQ on a monthly basis in acre-feet. The counties with significant diversions since 2000 include Comal, Gonzales, Guadalupe, Kendall, Kerr, and Victoria (Table 6). Sporadic or one-time diversions were reported in DeWitt, Hays, and Goliad counties.

The counties with the largest diversions were Comal, Gonzales, and Victoria. GBRA is the largest diverter of river water in Comal and Gonzales counties whereas the City of Victoria and INVISTA (Division of Koch Industries) are the largest in Victoria County.

Table 6. Diversions by County 2000-2018 (Source: TCEQ South Texas Watermaster Diversion Database)

YEAR	COMAL (AC-FT)	DEWITT (AC-FT)	HAYS (AC-FT)	GOLIAD (AC-FT)	GONZALES (AC-FT)	GUADALUPE (AC-FT)	KENDALL (AC-FT)	KERR (AC-FT)	VICTORIA (AC-FT)	ANNUAL (AC-FT)	ANNUAL (CFS)
2000	96,683	-	-	-	288,504	4,639	64	4,228	83,934	478,052	660
2001	280,206	-	-	-	1,832,987	4,681	138	5,037	102,344	2,225,393	3,071
2002	125,787	-	-	-	855,580	5,399	135	6,531	48,948	1,042,380	1,438
2003	45,995	-	-	-	857,222	1,807	209	4,759	41,130	951,122	1,313
2004	192,835	-	-	-	926,666	1,946	76	4,052	30,701	1,156,276	1,596
2005	261,895	-	-	-	925,472	4,387	201	4,888	51,689	1,248,532	1,723
2006	74,163	-	-	-	472,597	3,101	309	4,812	55,224	610,206	842
2007	230,809	-	-	-	870,174	2,769	1	3,945	32,170	1,139,868	1,573
2008	142,276	-		-	722,999	3,076	89	4,668	64,092	937,200	1,293
2009	65,203	-	-	-	525,143	2,653	114	3,592	59,650	656,355	906
2010	247,510	-	-	-	1,265,106	2,923	137	4,904	79,709	1,600,289	2,208
2011	59,641	6	-	-	406,242	3,578	65	2,577	43,817	515,926	712
2012	46,653	3,114	-	199	179,633	3,596	65	3,983	41,493	278,736	385
2013	49,185	-	-	-	87,225	3,362	76	3,821	41,829	185,498	256
2014	49,400	-	-	-	74,767	3,734	42	3,389	42,695	174,027	240
2015	154,190	-	-	-	245,390	3,931	76	3,501	40,300	447,388	617
2016	195,530	-	-	-	280,999	4,251	35	4,643	42,214	527,672	728
2017	177,662	-	-	-	197,180	4,462	81	5,276	43,432	428,093	591
2018	144,846	-	4,398	-	8,243	4,994	18	3,627	42,930	209,056	288
										AVERAGE	**1,076**

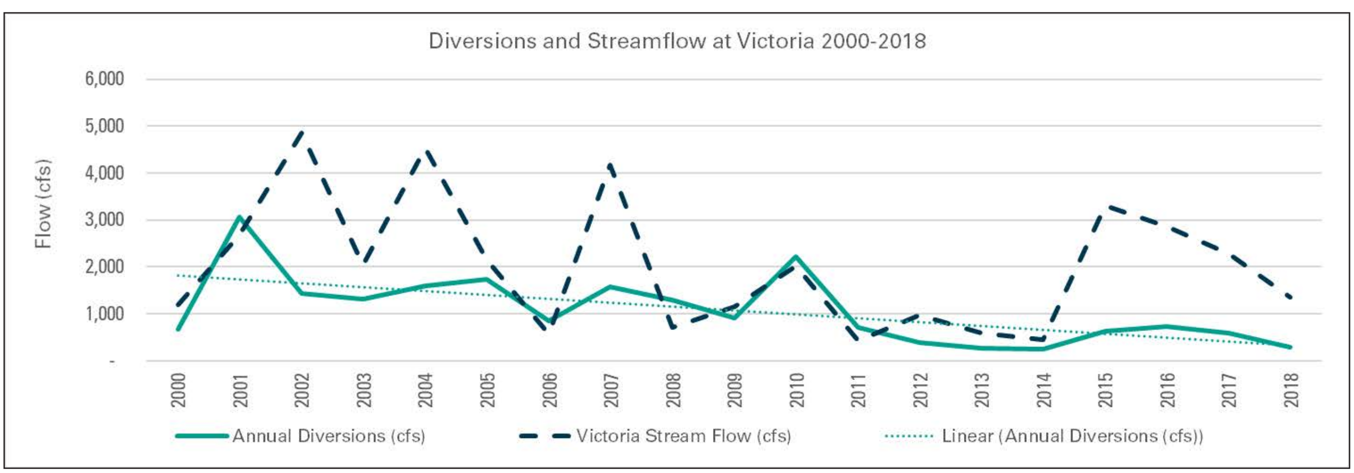


Figure 27. Diversions and streamflow at Victoria 2000-2018

Figure 27 compares the sum of all the diversions upstream of Victoria with stream flow at Victoria. The comparison illustrates the impact of diversions on total flow. From the period 2009 through 2014, total diversions were approximately equal to stream flow which indicates approximately half of the potential flow was diverted. Total basin wide diversions have been trending downward during the study period.

As discussed in the previous section, a small portion of the diverted water is returned as inflow (Table 7). The percentage of inflows compared to diversions from 2010-2018 ranges between two and 14 percent.

Table 7. Percentage of inflows compared to diversions

YEAR	ANNUAL INFLOWS (CFS)	ANNUAL DIVERSIONS (CFS)	INFLOWS/ DIVERSIONS
2010	37	2,208	2%
2011	33	712	5%
2012	36	385	9%
2013	34	256	13%
2014	33	240	14%
2015	41	617	7%
2016	41	728	6%
2017	38	591	6%
2018	37	288	13%

HIGHLIGHTS

Baseflow graphs

- Baseflow separation techniques provide insights into changes in baseflow over time.
- For the selected gage stations in the Guadalupe River, there is a decreasing trend in baseflow overall.
- Runoff is generally decreasing at a much faster rate than baseflow.
- The difference between baseflow and streamflow decreases down towards the Gulf, but is the opposite in the head-waters.
- In some cases, the location of reservoirs and the location of gages and water skew stream flow analyses.
- Tributaries and the main channel in the headwaters upstream for the Balcones Fault zone have a fairly constant source of baseflow from the underlying carbonate aquifers. Baseflow in the tributaries in the lower basin are more intermittent.
- Baseflow, sourced from the underlying aquifer storage, may be buffering the decline in baseflow as opposed to the steeper decline in surface flow which includes short term runoff.

Climate graphs

- Overall temperature is increasing throughout the years while precipitation is slightly decreasing in the GRB.
- The increasing temperature and decreasing precipitation have a negative correlation. A strong negative correlation also occurs between precipitation and water diversion.
- Power generation in Canyon Lake and other reservoirs has decreased due to decreasing stream flow.

Population and Land use

- From 2000-2018, total county population increased 68 percent within the GRB.
- From 2020-2070, estimated population growth is 227 percent and water demand will increase approximately196 percent.
- Effects of rapid population growth have started to be visible on land through change in usage.

Inflows and Diversions

- There are significantly more losses of water from the river through diversions than inflows to the river.
- The counties with largest diversions are Gonzales, Comal, and Victoria in descending order.

CONCLUSION

Baseflow separation is a good indicator to see the quantitative change in sustainable flow for streams. According to the selected gages within the Guadalupe River, baseflow has decreased and is analyzed from the upper versus lower stream channel comparisons. The climate data are added with the baseflow which show increasing temperature and decreasing precipitation trends in the representative counties that support the analysis. Impacts of rapid population growth and dynamic changes in land cover/use cannot be denied in this regard as they are putting pressure on both the ground and surface water. Significant water diversions are occurring across the basin, with only a small portion being returned to the river as inflow. This is an alarming situation for a large river basin like the Guadalupe as the time-period is recent and the changes are taking place very drastically within such a short period of time. Future studies can be conducted analyzing other factors that might impact the basin.

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APPENDIX A. SELECT USGS GAGING STATIONS

Map ID	USGS Gage	River Mile	Location	County	Longitude	Latitude	Drainage Area (m²)	Period of Record (Streamflow)
Main Channels Gaging Stations								
1	08165500	479	Guadalupe Rv at Hunt, TX	Kerr	-99.3217	30.0699	288	1941-2019
2	08166140	469	Guadalupe Rv abv Bear Ck at Kerrville, TX	Kerr	-99.1953	30.0696	494	1978-2019
3	08166200	466	Guadalupe Rv at Kerrville, TX	Kerr	-99.1633	30.0532	510	1986-2019
4	08167000	439	Guadalupe Rv at Comfort, TX	Kendall	-98.8971	29.9652	839	1939-2019
5	08167500	366	Guadalupe Rv nr Spring Branch, TX	Comal	-98.3836	29.8604	948	1922-2019
6	08167800	336	Guadalupe Rv at Sattler, TX	Comal	-98.1800	29.8591	1436	1960-2019
7	08168500	313.3	Guadalupe Rv abv Comal Rv at New Braunfels, TX	Comal	-98.1100	29.7149	1518	1927-2019
8	08169500	311	Guadalupe Rv at New Braunfels, TX	Comal	-98.1066	29.6980	1652	1915-2011
9	08173900	195	Guadalupe Rv at Gonzales, TX	Gonzales	-97.4502	29.4844	3490	1996-2019
10	08175800	118	Guadalupe Rv at Cuero, TX	DeWitt	-97.3297	29.0905	4934	1964-2019
11	08176500	58	Guadalupe Rv at Victoria, TX	Victoria	-97.0130	28.7930	5198	1934-2019
12	08188800	11.4	Guadalupe Rv nr Tivoli, TX	Refugio	-96.8847	28.5058	10128	2000-2019
13	08188810	8.4	Guadalupe Rv at SH 35 nr Tivoli, TX	Calhoun	-96.8627	28.4783	10280	2013-2019
Tributaries (river mile is at the confluence of the Guadalupe River)								
T1	08165300	480	N Frk Guadalupe Rv	Kerr	-99.3869	30.0640	169	1967-2019
T2	08166000	473	Johnson Ck nr Ingram	Kerr	-992827	30.1000	114	1941-2019
T3	08169000	312	Comal Rv	Comal	-98.1222	29.7064	130	1967-2019
T4	08173000	200	Plum Ck at Luling/ San Marcos Rv	Caldwell	-97.6033	29.6994	309	1967-2019
T5	08174600	168	Peach Ck	Gonzales	-97.3163	29.4738	460	1967-2019
T6	08175000	119	Sandies Ck nr Westhoff, TX	DeWitt	-97.4491	29.2150	549	1939-2019
T7	08177500	41	Coleto Ck	Victoria	-97.1383	28.7308	500	1939-2019
T8	08171000	NA	Blanco River at Wimberley, TX	Hays	-98.0886	29.9941	355	1924-2019
Springs								
S1	08168710	-----	Comal Spring	Comal	-98.1222	29.7058	-----	1927-2019
S2	08168000	-----	Hueco Spring	Comal	-98.1397	29.7591	-----	2002-2019
S3	08170000	-----	San Marcos Spring	Hays	-97.9338	29.8888	-----	1956-2019
S4	08170990	-----	Jacobs Well Spring nr Wimberley, TX	Hays	-98.1261	30.0344	-----	2005-2019
S5	08170950	-----	Pleasant Valley at	Hays	-98.2004	30.0006	-----	2016-2019

APPENDIX B. BASEFLOW SEPARATION METHODOLOGY

As in the Preliminary Report, USGS stream gages were the primary source of data used in baseflow analyses. While there are numerous gages in the basin, there are gaps in geographic coverage and varying lengths of the period of record. A partial list of gages is included in Appendix A. As with the Preliminary Report, the period of focus was 2000 to 2018 in this report. As long-term trends were the focus of this report, annual flow data was used in the analysis, versus monthly or daily flow.

Hydrograph analysis is a useful technique which is used for water resource investigation like hydrograph separation. This method separates the baseflow from surface run-off to estimate the contribution of groundwater recharge to stream channels. The USGS Groundwater (GW) Toolbox V 1.3.3 (Barlow, 2015) has been used for baseflow separation. The toolbox is a graphical and mapping interface for the analysis of hydrologic data. Six different baseflow separation methods have been either separately or concurrently applied to the discharge data for the selected gaging stations for this research. The purpose of this report is to determine trends of baseflow over time in the river basin, not to analyze the differences in the methods. Each method is slightly different but, in general, they yield similar trend results. Table B-1 is a comparison of BFI to the other methods at the USGS gage at Hunt. A brief description from Barlow (2015) for each of the methods are given below:

HYSEP: HYdrograph **SEP**aration (HYSEP) is a streamflow analysis technique programmed within the USGS GW Toolbox to separate the baseflow from surface run-off. The daily mean discharge data from stream gaging stations are used for this purpose. It calculates the baseflow based on the data points when the streamflow ceases or remains the lowest. Therefore, connecting the points to create a line result in a baseflow line. The HYSEP technique includes three methods of hydrograph separation: HYSEP Fixed-Interval, HYSEP Sliding-Interval and HYSEP Local-Minimum. The basic difference among these three is the algorithm used by the program.

PART: This baseflow separation method uses the antecedent streamflow recession rather than antecedent precipitation. The important steps are followed to get the baseflow: a) first, the daily streamflow records are used, b) second, linear interpolation method is used in order to estimate the groundwater discharge during surface run-off periods. PART also uses the daily mean discharge data and considers the days when the streamflow is equal to groundwater but does not include interflow (storm flow).

Baseflow Index (BFI): This algorithm for BFI- Baseflow Separation is similar to HYSEP- Local Minimum method with some factors changed. It considers the water year instead of calendar year and determines the minimum discharge. There are two methods of BFI- Baseflow Separation: BFI-Standard and BFI-Modified. The only difference between these two is that BFI- Modified does not use the test factor (f), instead it uses a daily recession index.

Why BFI- Standard? For the purpose of trend analyses in this report, BFI Standard method was chosen. The HYSEP method can sometimes give erroneous results based on regulations or climatic extremes. Regulation includes discharge from flood reservoirs, treatments plants, diversion etc. The effect of water release from these results in baseflow and streamflow difference than the actual. To avoid the bias towards climatic extremes, stations with long term record which represent average climatic condition, should be selected. Besides, the use of HYSEP method requires expert analysis of data prior to the input.

The use of the PART method encounters a similar problem with the time period of data. Smaller time scales like daily discharge data might show variations in baseflow and streamflow. For example, the baseflow might not reflect the same trend during the peak discharge of the stream flow. It is recommended to use at least a year of data for this method. Sometimes the monthly data can also be useful.

On the other hand, the BFI methods can calculate baseflow even with streams with zero flow days. Though only this method was programmed based on water year, it does not exclude the data near the beginning and end of that year. It does not process annual data if any one or more months in that same year has incomplete data, but the daily data can be obtained from the output data files. BFI does not make any adjustments to the baseflow due to errors in reporting data but can be corrected with the daily discharge data. Therefore, for this analysis, the BFI- Standard method has been used which was programmed based on the method proposed by Wahl and Wahl (1988).

One of the major drawbacks of using the USGS GW Toolbox tool is that it cannot differentiate among the various causes that contribute or impact the fluctuations, such as diversions, inputs, storage and release from reservoirs, etc. In that case, users should understand the unique basin/stream conditions and consider them accordingly.

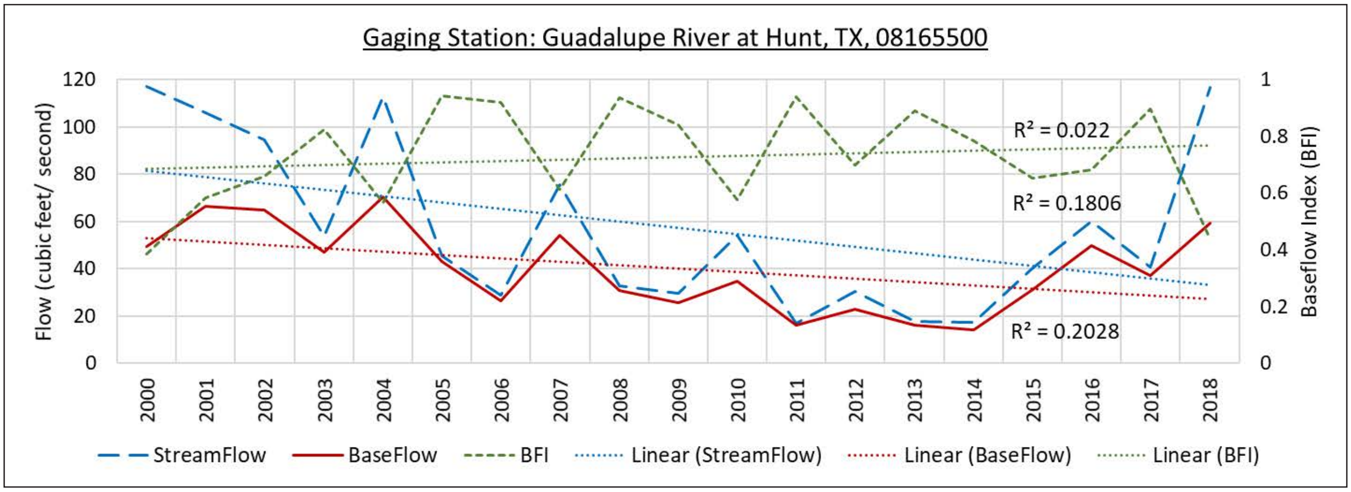
A few observations regarding the potential limitations and use of the USGS gages in a large basin:

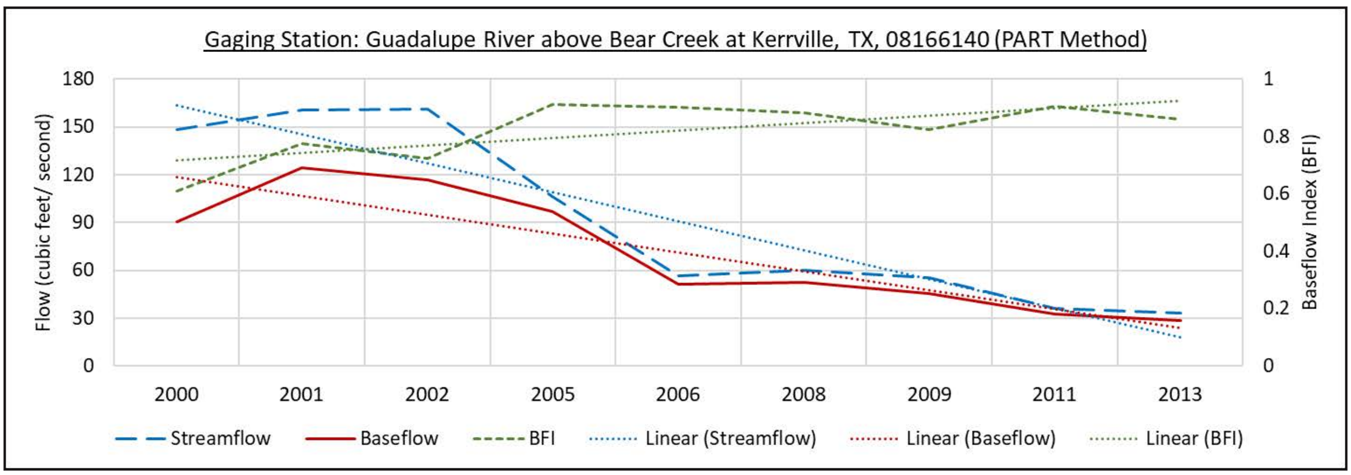
- BFI separation methods are considered more accurate for smaller basins. Basin size for the gages increases in a downstream direction. Each gage's basin is cumulative of all the upstream basins. For example, the basin size for the gage at Victoria includes the entire upstream basin area.
- Overall, the Guadalupe River is a gaining river, but it is likely that there are short losing reaches in the basin, particularly in the vicinity of the Balcones Fault Zone. These losses are considered relatively small compared to the total flow in the river.
- Capture and release of water from Canyon Lake interferes with accurate baseflow calculations downstream of the impoundment. Capturing upstream flow in the impoundment will reduce total flow downstream and artificially increase BFI. Slow release of water from the impoundment will also artificially increase downstream baseflow. Sudden release of water will tend to artificially lower BFI. These effects are most noticeable at the Sattler gage, but tend to be minimized downstream as total flow in the river increases.
- Weather and the overall size of the basin can play a significant role in baseflow separation. For example, a large tropical storm may produce large amounts of rainfall in the lower portions of the basin near the gulf coast where at the same time, the upper, Hill Country portion of the basin may be in drought. These weather variations are somewhat negated by using annual flow data.
- Due to the overall flow in the river and relatively small amount of inflows and diversions, inflows and diversions have a relatively minor impact on baseflow during average flows. During drought conditions, inflows and diversions can have a significant short-term effect on baseflow.

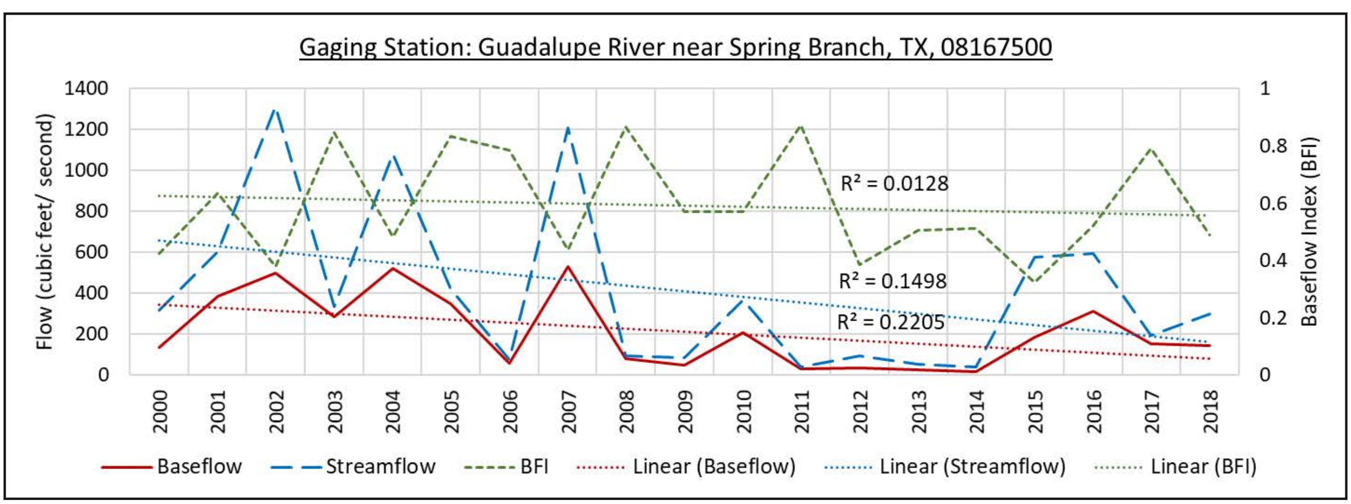
Table B-1. Baseflow deviation of other methods from BFI-Standard (Wahl and Wahl), Hunt, TX (USGS 081655300)

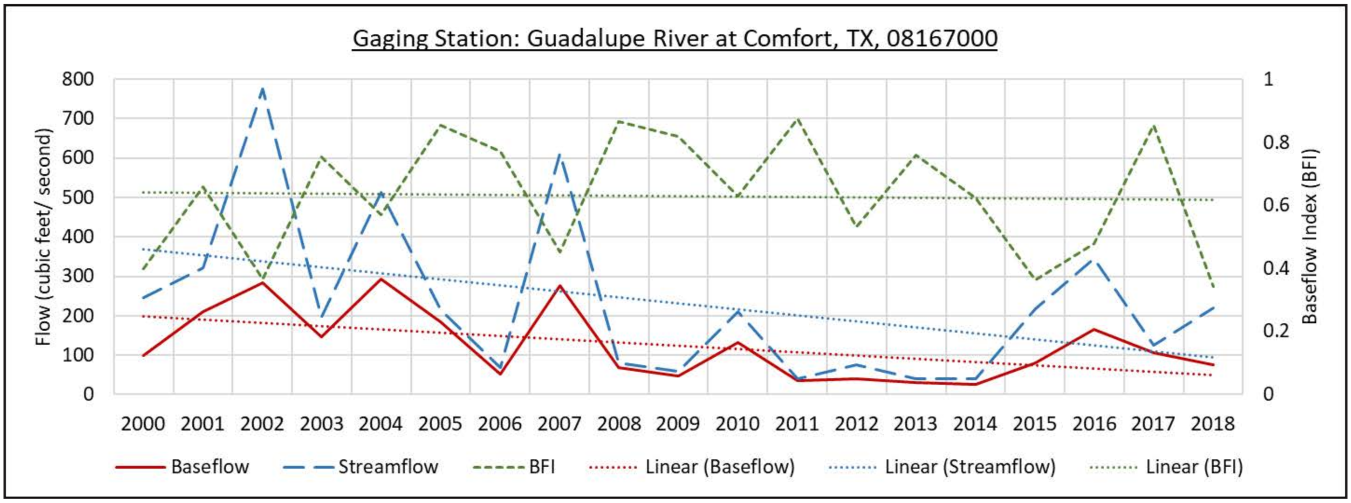
YEAR	BFI STD	BFI MOD	(BFI STD - BFI MOD)	HYSEP-FIXED	(BFI STD - HYSEP FIXED)	HYSEP-LOCMIN	(BFI STD - HYSEP LOCMIN)	HYSEP-SLIDE	(BFI STD - HYSEP SLIDE)	PART	(BFI STD - PART)	STREAM CONDITION
2000	44.97	44.73	0.24	46.31	-1.34	44.3	0.67	46.19	-1.22	49.23	-4.26	W
2001	61.72	61.12	0.6	62.73	-1.01	61.17	0.55	63.32	-1.6	66.37	-4.65	W
2002	62.15	62.1	0.05	64.38	-2.23	61.72	0.43	62.73	-0.58	64.71	-2.56	W
2003	44.26	44.46	-0.2	45.18	-0.92	44.12	0.14	45.4	-1.14	46.76	-2.5	D
2004	63.71	62.77	0.94	67.23	-3.52	64.3	-0.59	66.53	-2.82	70.35	-6.64	W
2005	42.92	42.57	0.35	42.61	0.31	42.15	0.77	42.58	0.34	43.01	-0.09	D
2006	26.22	26.14	0.08	26.15	0.07	25.84	0.38	26.1	0.12	26.39	-0.17	D
2007	46.44	45.86	0.58	50.68	-4.24	48.83	-2.39	50.8	-4.36	54.09	-7.65	W
2008	30.46	30.44	0.02	30.49	-0.03	30.28	0.18	30.48	-0.02	30.59	-0.13	D
2009	24.66	24.69	-0.03	25.11	-0.45	25.02	-0.36	25.44	-0.78	25.73	-1.07	D
2010	31.1	31.13	-0.03	32.12	-1.02	30.95	0.15	32.72	-1.62	34.6	-3.5	W
2011	15.97	15.88	0.09	15.94	0.03	15.77	0.2	15.88	0.09	15.88	0.09	D
2012	21.16	21.08	0.08	21.8	-0.64	21.32	-0.16	21.77	-0.61	22.77	-1.61	D
2013	15.54	15.51	0.03	15.68	-0.14	15.45	0.09	15.65	-0.11	15.92	-0.38	D
2014	13.66	13.68	-0.02	13.89	-0.23	13.62	0.04	13.81	-0.15	14.04	-0.38	D
2015	26.26	24.62	1.64	28.72	-2.46	29.3	-3.04	29.05	-2.79	31.19	-4.93	W
2016	40.71	40.26	0.45	47.23	-6.52	44.2	-3.49	47.56	-6.85	49.82	-9.11	W
2017	36.43	36.66	-0.23	37.16	-0.73	36.61	-0.18	36.82	-0.39	37.17	-0.74	W
2018	50.92	51	-0.08	57.08	-6.16	38.84	12.08	55	-4.08	59.12	-8.2	W

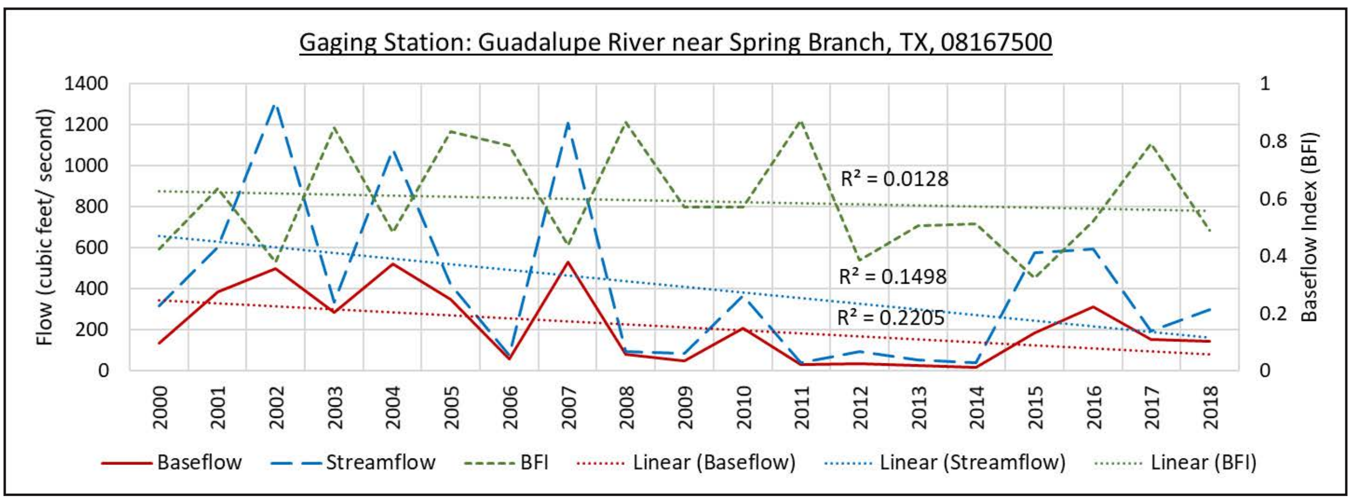
APPENDIX C. HISTORICAL TRENDS OF STREAMFLOW, BASEFLOW AND BFI OF MAIN CHANNEL GAGING STATIONS

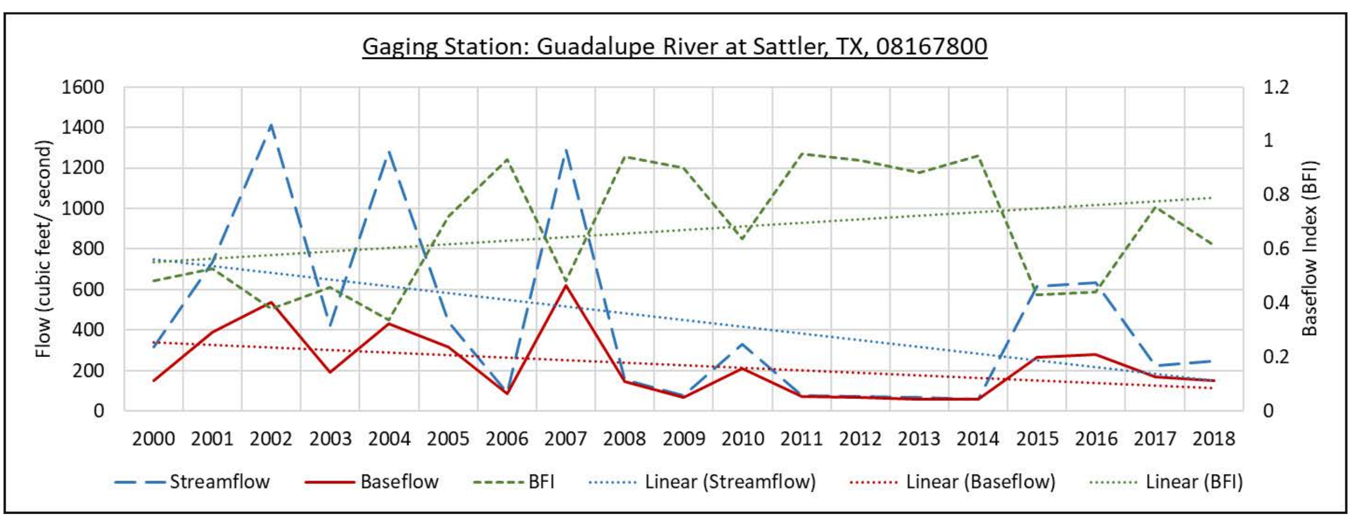


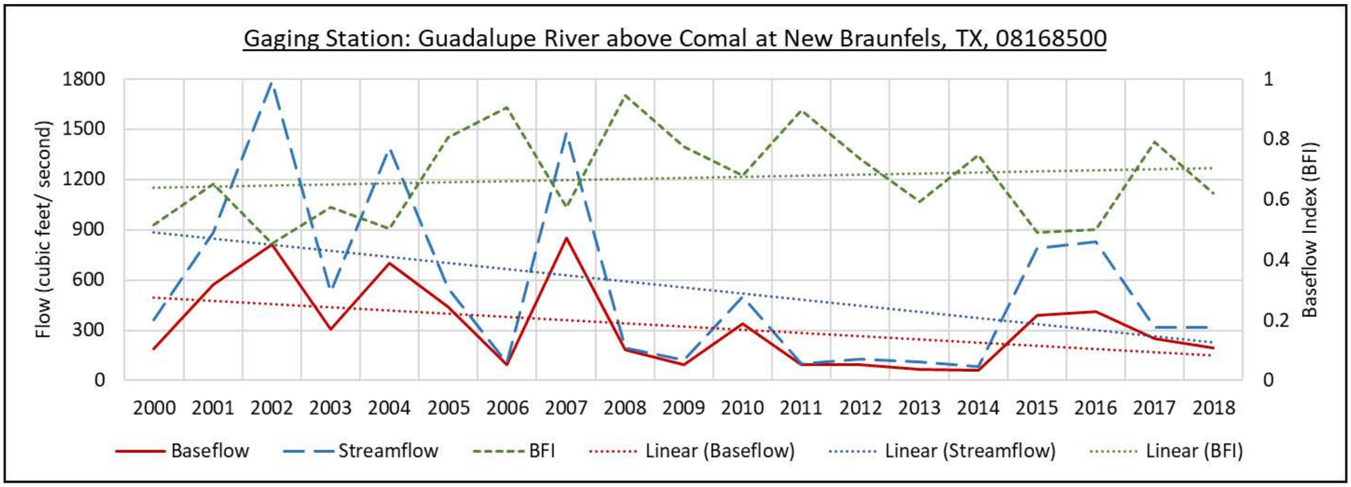


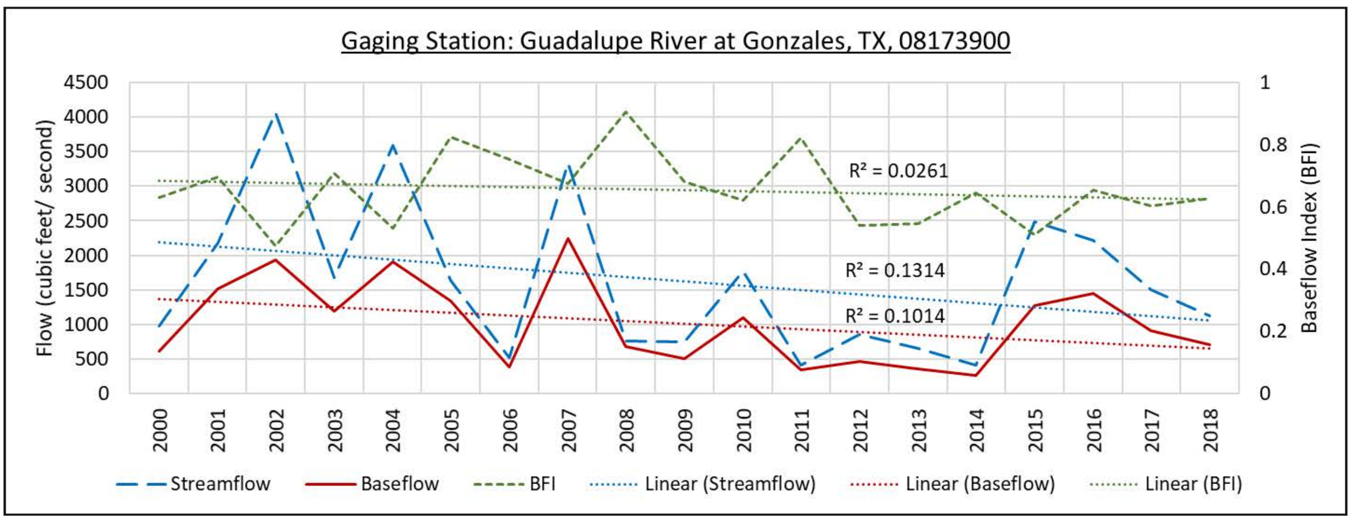


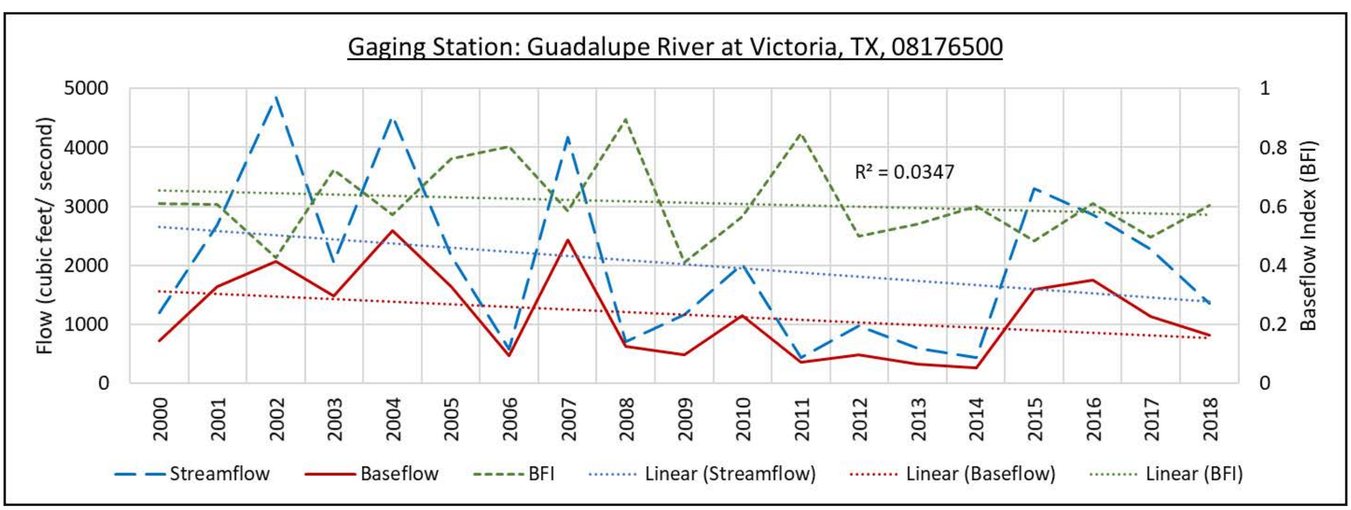

Gaging Station: Guadalupe River at Comfort, TX, 08167000
Flow (cubic feet/ second)
Baseflow Index (BFI)
Baseflow
Streamflow
BFI
Linear (Baseflow)
Linear (Streamflow)
Linear (BFI)

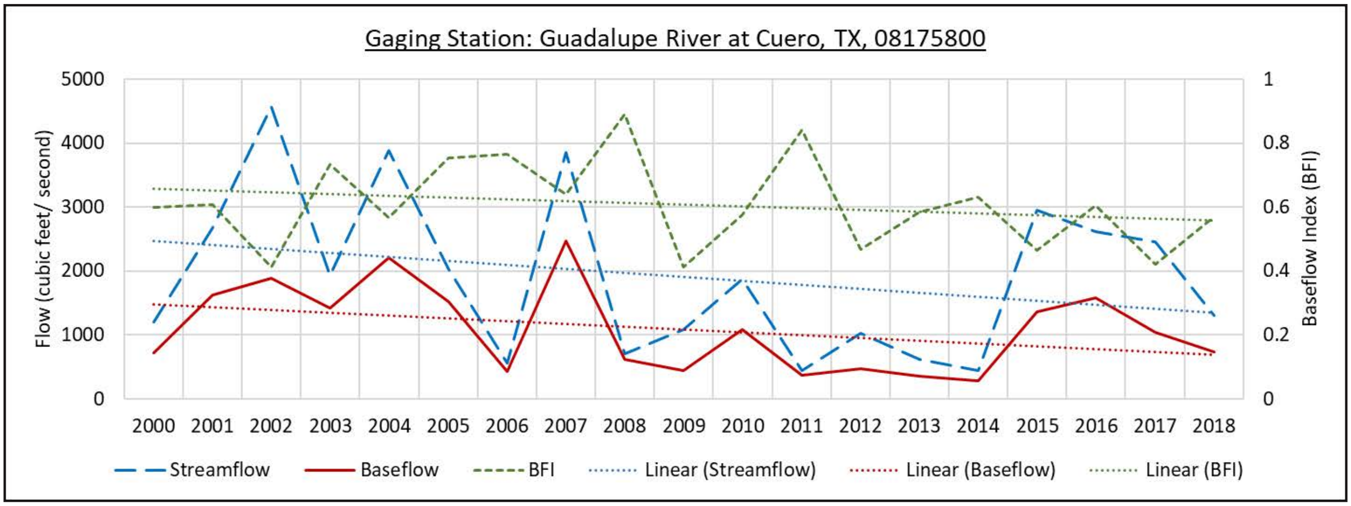

Gaging Station: Guadalupe River near Spring Branch, TX, 08167500
Flow (cubic feet/ second)
Baseflow Index (BFI)
R² = 0.0128
R² = 0.1498
R² = 0.2205
Baseflow
Streamflow
BFI
Linear (Baseflow)
Linear (Streamflow)
Linear (BFI)


Gaging Station: Guadalupe River at Sattler, TX, 08167800
Flow (cubic feet/ second)
Baseflow Index (BFI)
Streamflow
Baseflow
BFI
Linear (Streamflow)
Linear (Baseflow)
Linear (BFI)


Gaging Station: Guadalupe River above Comal at New Braunfels, TX, 08168500
Flow (cubic feet/ second)
Baseflow Index (BFI)
1800
1500
1200
900
600
300
0
1
0.8
0.6
0.4
0.2
0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Baseflow
Streamflow
BFI
Linear (Baseflow)
Linear (Streamflow)
Linear (BFI)

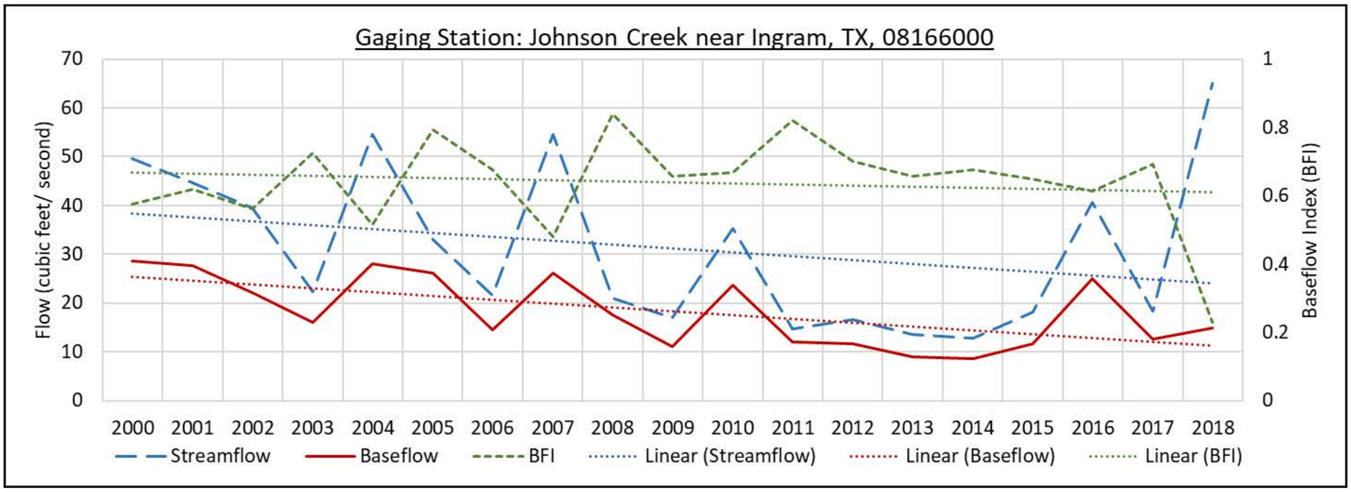

Gaging Station: Guadalupe River at Gonzales, TX, 08173900
Flow (cubic feet/ second)
Baseflow Index (BFI)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1
0.8
0.6
0.4
0.2
0
R² = 0.0261
R² = 0.1314
R² = 0.1014
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Streamflow
Baseflow
BFI
Linear (Streamflow)
Linear (Baseflow)
Linear (BFI)

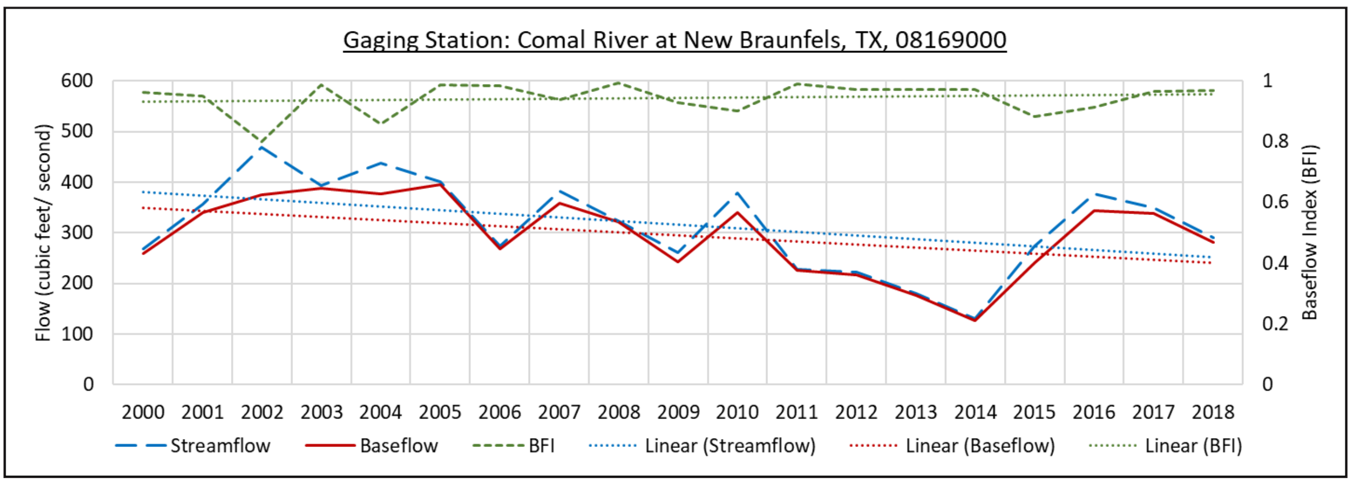

Gaging Station: Guadalupe River at Victoria, TX, 08176500
Flow (cubic feet/ second)
Baseflow Index (BFI)
5000
4000
3000
2000
1000
0
1
0.8
0.6
0.4
0.2
0
R² = 0.0347
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Streamflow
Baseflow
BFI
Linear (Streamflow)
Linear (Baseflow)
Linear (BFI)

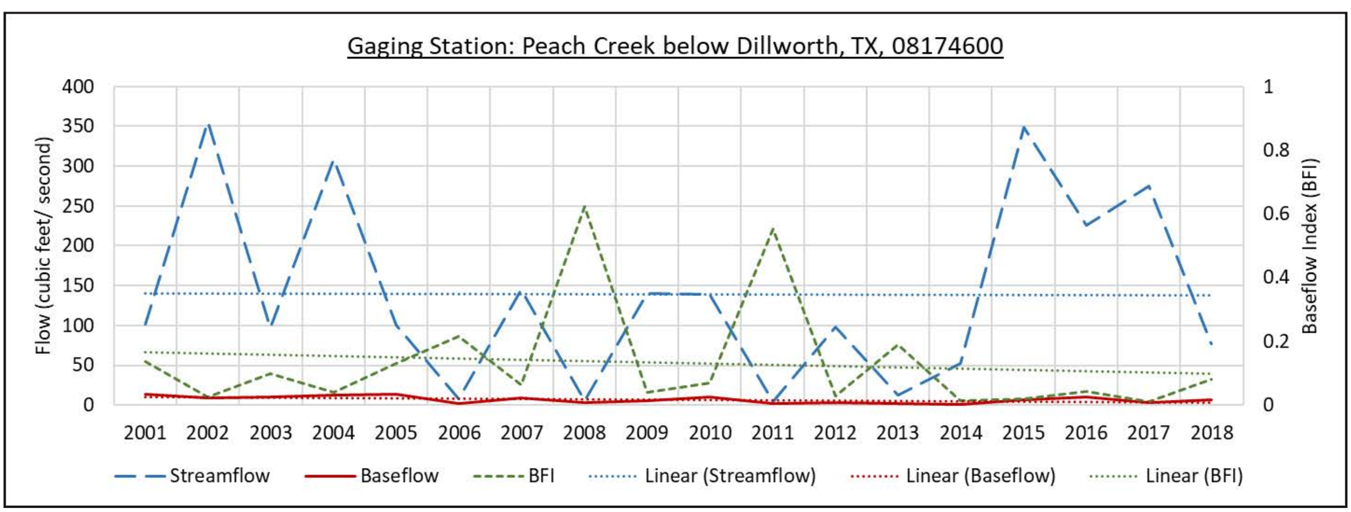


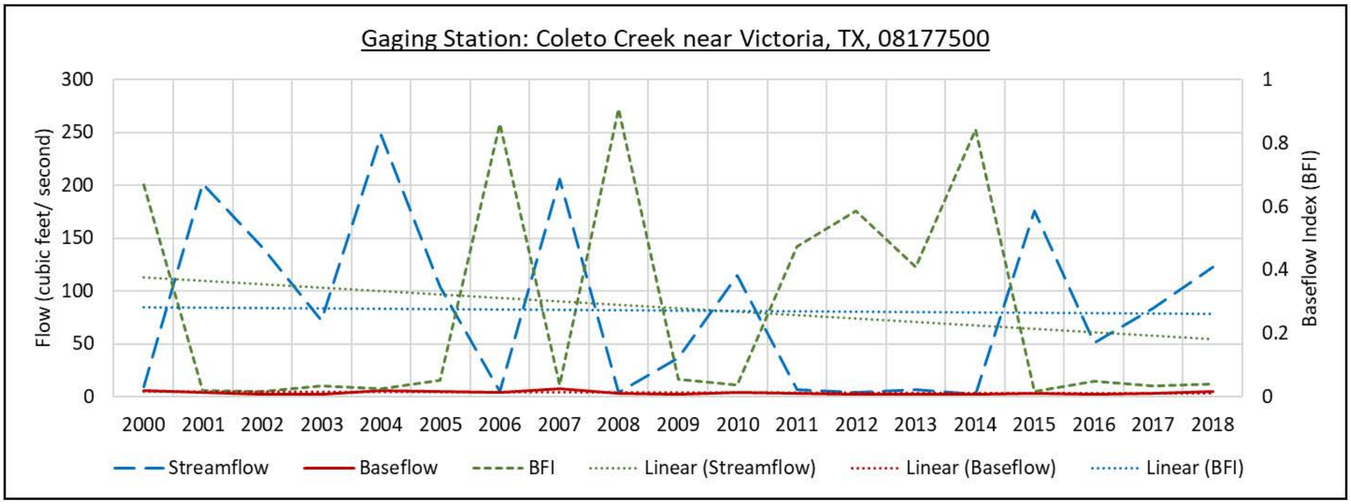
Gaging Station: Guadalupe River at Cuero, TX, 08175800
Flow (cubic feet/ second)
Baseflow Index (BFI)
5000
4000
3000
2000
1000
0
1
0.8
0.6
0.4
0.2
0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Streamflow
Baseflow
BFI
Linear (Streamflow)
Linear (Baseflow)
Linear (BFI)

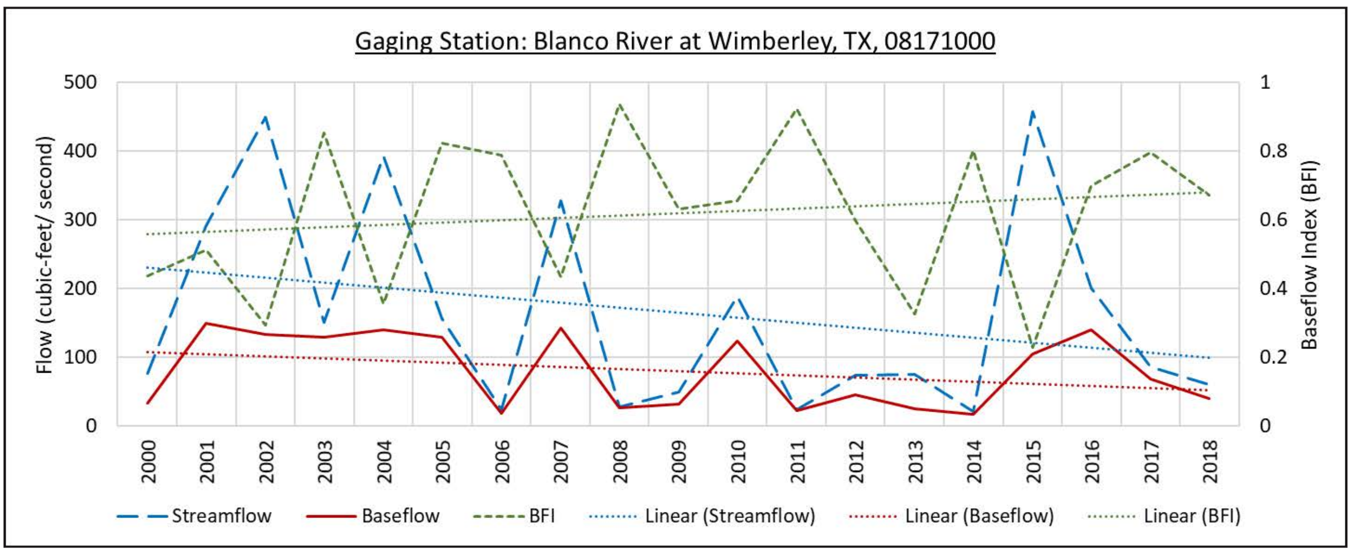
APPENDIX D. HISTORICAL TRENDS OF STREAMFLOW, BASEFLOW AND BFI OF TRIBUTARIES GAGING STATIONS



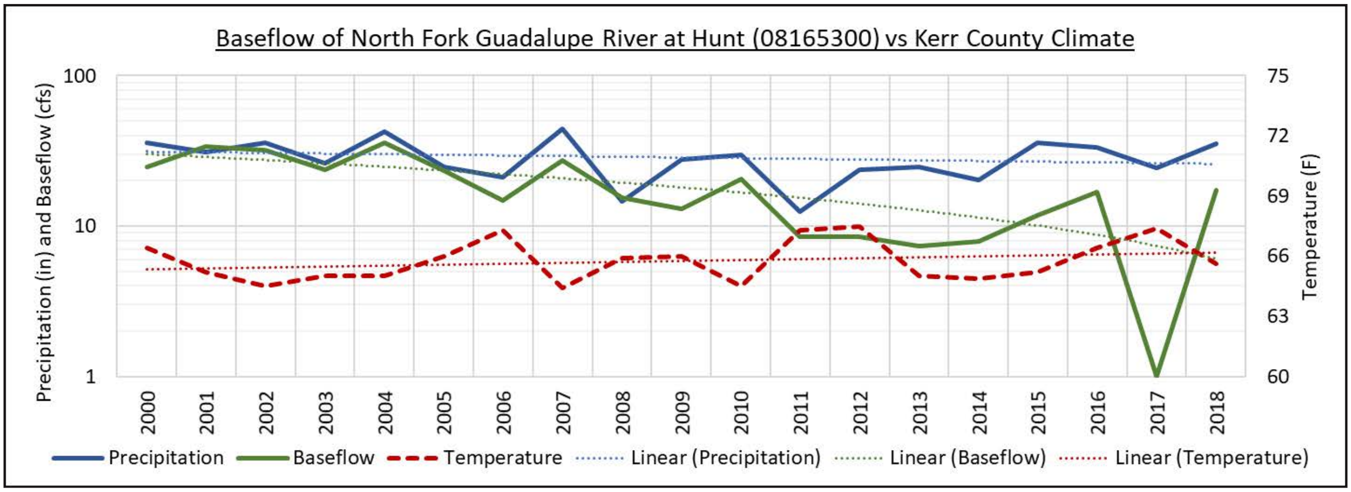


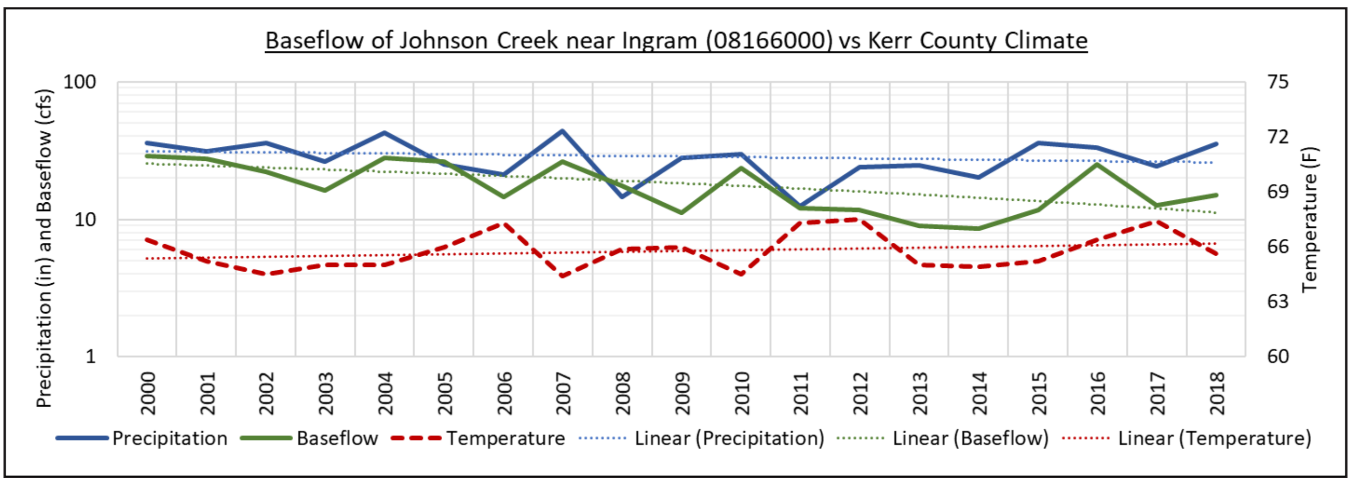


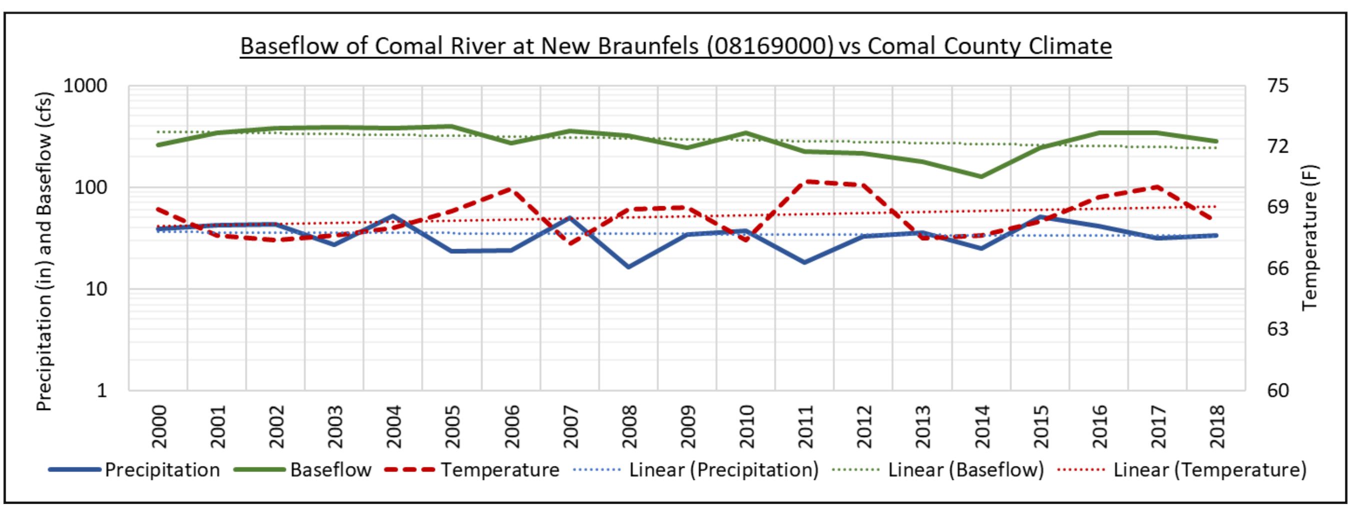

Gaging Station: Coleto Creek near Victoria, TX, 08177500
Flow (cubic feet/ second)
Baseflow Index (BFI)
300
250
200
150
100
50
0
1
0.8
0.6
0.4
0.2
0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Streamflow
Baseflow
BFI
Linear (Streamflow)
Linear (Baseflow)
Linear (BFI)

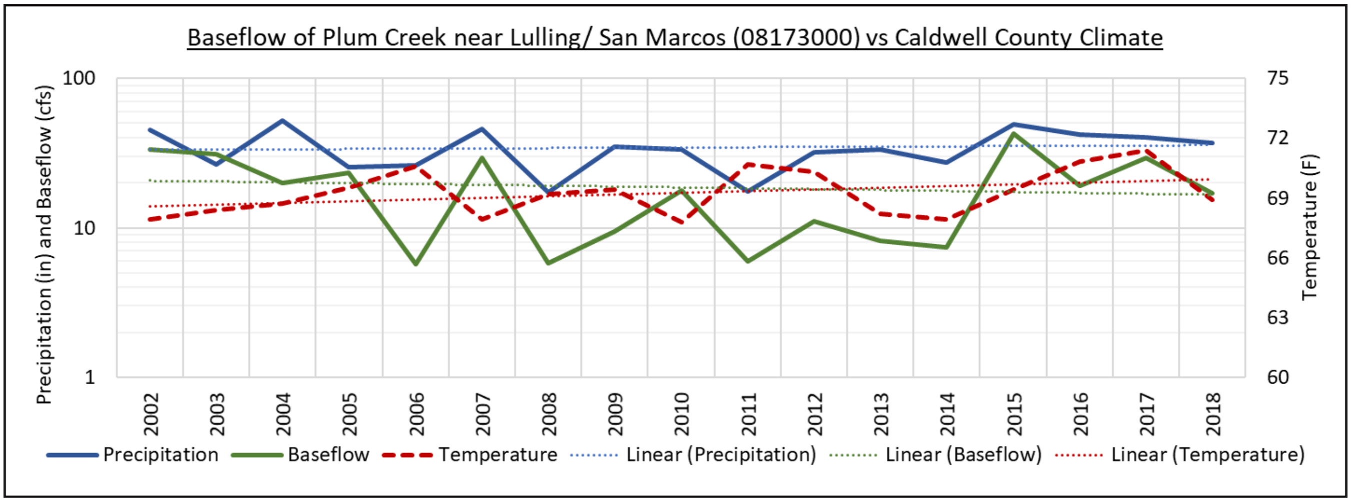

Gaging Station: Blanco River at Wimberley, TX, 08171000
Flow (cubic-feet/ second)
Baseflow Index (BFI)
500
400
300
200
100
0
1
0.8
0.6
0.4
0.2
0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Streamflow
Baseflow
BFI
Linear (Streamflow)
Linear (Baseflow)
Linear (BFI)

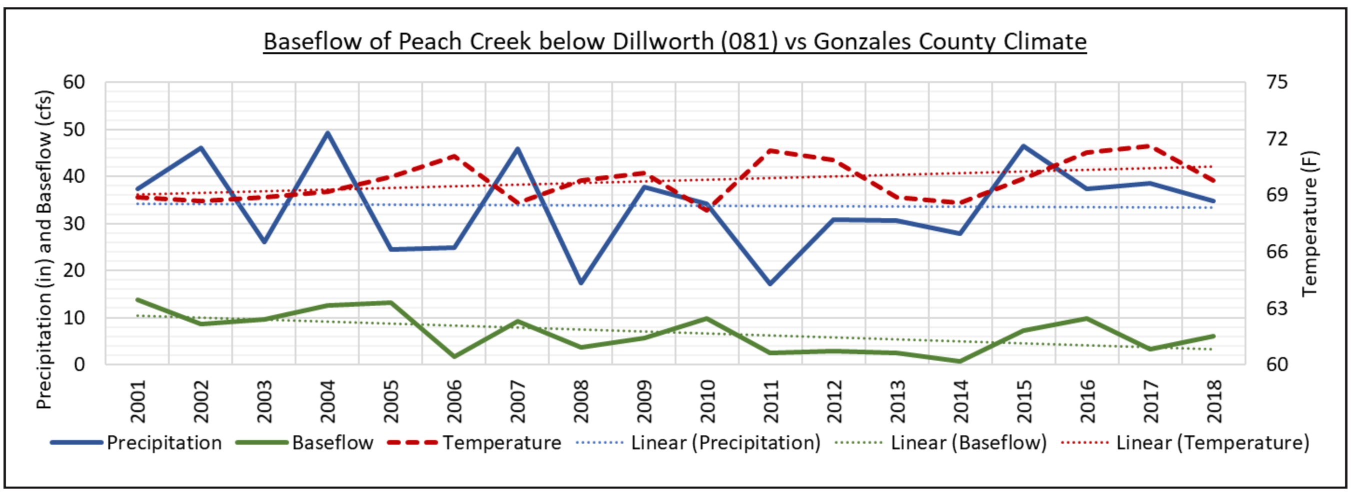
APPENDIX E. HISTORICAL TRENDS OF CLIMATE PATTERN IN COUNTIES AND BASEFLOW OF TRIBUTARIES GAGING STATIONS

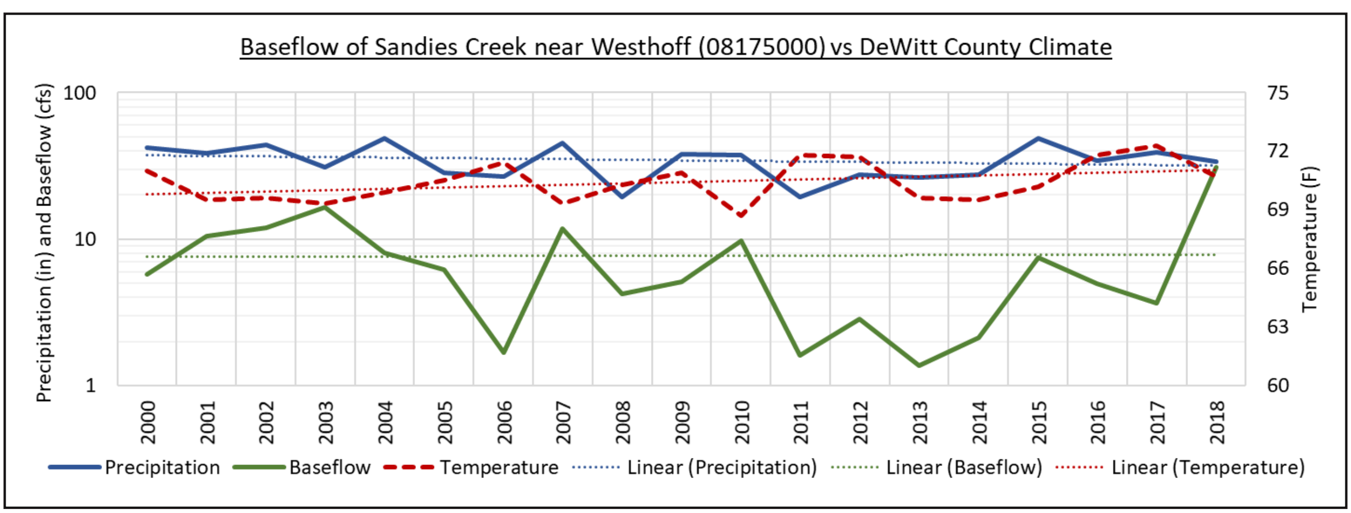


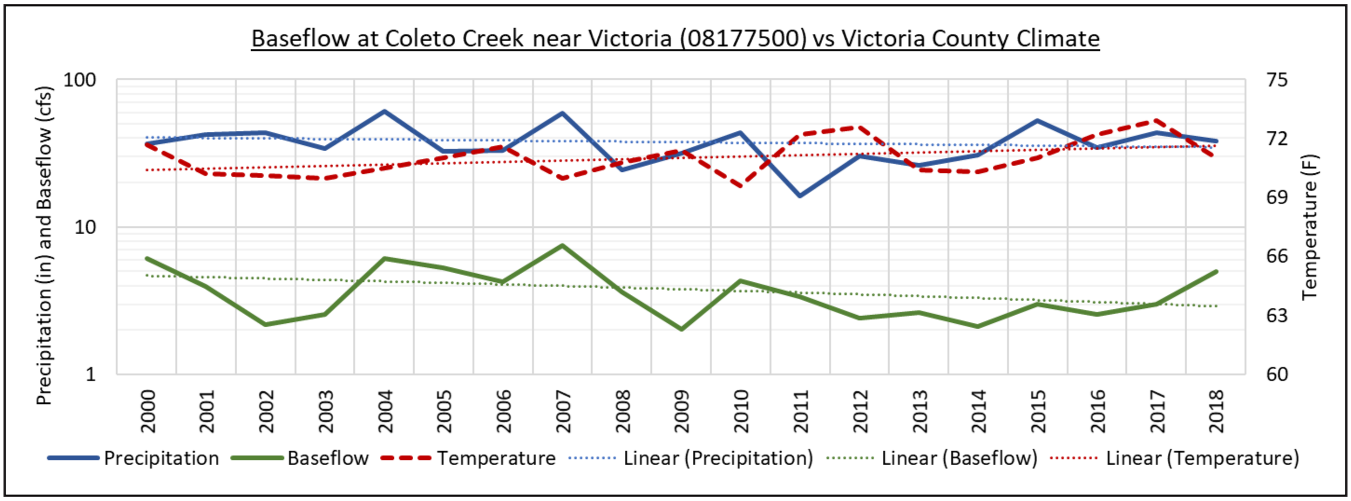





Baseflow of Plum Creek near Lulling/ San Marcos (08173000) vs Caldwell County Climate
Precipitation (in) and Baseflow (cfs)
Temperature (F)
100
10
1
75
72
69
66
63
60
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Precipitation
Baseflow
Temperature
Linear (Precipitation)
Linear (Baseflow)
Linear (Temperature)


Baseflow of Peach Creek below Dillworth (081) vs Gonzales County Climate
Precipitation (in) and Baseflow (cfs)
Temperature (F)
60
50
40
30
20
10
0
75
72
69
66
63
60
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Precipitation
Baseflow
Temperature
Linear (Precipitation)
Linear (Baseflow)
Linear (Temperature)


Baseflow of Sandies Creek near Westhoff (08175000) vs DeWitt County Climate
Precipitation (in) and Baseflow (cfs)
Temperature (F)
100
10
1
75
72
69
66
63
60
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Precipitation
Baseflow
Temperature
Linear (Precipitation)
Linear (Baseflow)
Linear (Temperature)


Baseflow at Coleto Creek near Victoria (08177500) vs Victoria County Climate
100
10
1
Precipitation (in) and Baseflow (cfs)
75
72
69
66
63
60
Temperature (F)
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Precipitation
Baseflow
Temperature
Linear (Precipitation)
Linear (Baseflow)
Linear (Temperature)

APPENDIX F: NATIONAL LAND COVER DATABASE CLASSIFICATION LEGEND

Class\ Value		Classification Description
Water		
	11	**Open Water**- areas of open water, generally with less than 25% cover of vegetation or soil.
	12	**Perennial Ice/Snow**- areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.
Developed		
	21	**Developed, Open Space**- areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
	22	**Developed, Low Intensity**- areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
	23	**Developed, Medium Intensity** -areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
	24	**Developed High Intensity**-highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.
Barren		
	31	**Barren Land (Rock/Sand/Clay)** - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
Forest		
	41	**Deciduous Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
	42	**Evergreen Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
	43	**Mixed Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
Shrubland		
	51	**Dwarf Scrub**- Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
	52	**Shrub/Scrub**- areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
Herbaceous		
	71	**Grassland/Herbaceous**- areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
	72	**Sedge/Herbaceous**- Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
	73	**Lichens**- Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
	74	**Moss**- Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.
Planted/Cultivated		
	81	**Pasture/Hay**-areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
	82	**Cultivated Crops** -areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Wetlands		
	90	**Woody Wetlands**- areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
	95	**Emergent Herbaceous Wetlands**- Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

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