Frio River Watershed

Brush Control Planning, Assessment, and Feasibility Study

Prepared for:

Texas State Soil and
Water Conservation Board

Prepared by:

HDR
HDR Engineering, Inc.

In association with:

Texas A&M University

December 2000

Signature Sheet

____
Adrian J. Huckabee, P.E.
Project Manager
HDR Engineering, Inc.*

____
Samuel K. Vaugh, P.E.
Project Engineer (Hydrology)
HDR Engineering, Inc.*

---

*Note: Section 6 and 7, and Appendices A and B were prepared as part of the TSSWCB contract with Texas A&M University Agricultural Extension Service and not as part of the HDR Engineering, Inc. contract except to the extent of final editing, formatting, and report copying. The professional engineers shown above did not supervise the work of sections prepared by Texas A&M University and were not contractually responsible for those sections except to the extent stated above.

Table of Contents

Section ***Page***

Table of Contents (Continued)

Section ***Page***

Appendices

List of Figures

List of Tables

List of Tables (Continued)

Section 1
Introduction

This report is one of eight prepared under funding from the 1998–1999 Texas Legislature to study the effects of brush removal on water yield in eight watersheds. The watersheds studied are the Canadian River above Lake Meredith, Wichita River above Lake Kemp, Upper Colorado River above Lake Ivie, Concho River, Pedernales River, the watersheds above the Edwards Aquifer, Nueces River above Choke Canyon Reservoir, and the Frio River above Choke Canyon Reservoir, which is this report. The impetus for this series of studies was a modeling study of the North Concho River Watershed (Upper Colorado River Authority, 1998).

The recognition of decreased streamflows coupled with increased brush coverage in the North Concho River in recent decades suggested the possibility of a correlation. During the last 35 years, streamflow on the North Concho River has decreased to less than 22 percent of that of the previous 35 years, even though average annual rainfall has increased slightly in the same period. The North Concho River and its tributaries have ceased to have perennial continuous flow. The North Concho River report concluded that brush infestation had directly influenced reductions in streamflow. The report estimated the costs of controlling brush and concluded that, through brush control, streamflow could increase, groundwater supplies can be enhanced, and relatively inexpensive water supplies were possible.

The method used for determining whether a relationship between brush proliferation and decreasing streamflow exists involves statistical analyses for identification of any trends in rainfall and runoff (on a per unit of rainfall basis) for selected watersheds. Runoff per unit rainfall or percent runoff measures the response of a watershed to rainfall and effectively normalizes highly variable runoff records for many years and many watersheds thereby allowing for equitable comparisons.

A significant change in the relationship between the runoff and rainfall over time may be indicative of a change that has occurred in a watershed. An increase in runoff per unit rainfall concomitant with observed brush proliferation over time generally does not support the hypothesis that brush proliferation has reduced yield (runoff) at the watershed level. An observed decrease in runoff per unit rainfall concomitant with brush proliferation tends to support the hypothesis that brush proliferation has reduced yield. However, further investigation is warranted because there are other factors, such as groundwater level decline, stock pond development, and land management practices that could have a similar effect. Identification of increasing trends in runoff per unit rainfall may eliminate some watersheds from further investigation. On the other hand, identification of decreasing trends in runoff per unit rainfall in some watersheds may provide support for further investigation of the causes of decreasing runoff. Such investigations may include more detailed brush control studies.

Simulations of streamflow resulting from brush control using the SWAT model were made for all sub-watersheds in the Frio River Watershed using the assumptions and data described in Section 6 of this report. Costs were estimated for brush control, rancher benefits, and water supply, and were developed from the assumptions and data shown in Section 7 of this report. However, the only water supply quantities and costs reported in the Executive Summary (Section 2) are those for sub-watersheds in which there is either a clear decrease in runoff or some uncertainty about these results as depicted in Section 5. Appendix A provides background information on the hydrologic simulation model and Appendix B provides background information on the costs used in Section 7.

State and federal agencies have cooperated and assisted one another to undertake this comprehensive study. These include the Nueces River Authority, the Edwards Aquifer Authority, Texas A&M Research and Extension Center, the Texas State Soil and Water Conservation Board, the Blackland Research Center, and the USDA Natural Resources Conservation Service. This assessment will determine whether brush control has a role in enhancing potential water yields and, if so, it will provide the people of Texas with means, procedures, and recommendations of how to recapture and utilize water now consumed by brush for increased public benefit on an entire watershed.

Section 2
Executive Summary

This report presents the background information, technical analyses, and findings regarding the potential to increase water yield through brush control. The background information includes a general description of the watershed in Section 3 and a discussion of historical considerations in Section 4 along with the background hydrological data in Section 5. Section 6 uses the results of regional hydrologic modeling completed by Texas A&M University to estimate costs of additional water supplies that might be created through brush control programs.

The Frio River originates in Real County as a spring-fed stream and flows into the Nueces River system through Choke Canyon Reservoir. The Sabinal River, Hondo Creek, and the Leona River are major tributaries of the Frio. For the purposes of this study, the area represented by the Frio River Watershed includes portions of the following counties: Real, Bandera, Uvalde, Medina, Zavala, Frio, Atacosa La Salle, and McMullen. The Frio River Watershed covers approximately 5,500 square miles, mostly through the natural region known as the South Texas Brush Country.

Vegetation in the watershed is characterized by the two major geographic regions that the river crosses—the Edwards Plateau and the South Texas Brush Country. The Edwards Plateau soils are typically thin and calcareous. The Edwards Plateau is distinctly divided from the South Texas Brush Country by the Balcones Escarpment, which is the origin and north part of the Frio River Watershed. Live oak, shinnery oak, cedar, and mesquite are the dominant woody plants. Woody plants predominate over forage plants in this region. Grasses include tall grasses along rock outcrops, and midgrasses and shortgrasses on the shallow, drier meadows. Tall grasses include bluestem and switchgrass, and shorter grasses include sideoats grama, buffalograss, and Texas grama.

The South Texas Brush Country, which is part of the South Texas Plains, covers several counties in the Frio River Watershed. This area is level to rolling. Upland soils include clayey, loamy, and sandy soils that typically overlay firm clayey soils. Bottom soils are calcareous silt loams and clayey alluvial soils. Mesquite, small live and post oak, prickly pear cactus, and other brush are commonly dense in this region.

From some of the earliest written accounts of the Frio River Watershed, mesquite, oak, cedar, prickly pear, and other brushland plants were observed throughout the region. Some accounts even described rather dense concentrations of trees and brush. The difference between earlier descriptions (1860–1939) and those of the mid-1900s addresses the relative coverage of grasslands; these coverages are difficult, if not impossible, to quantify. As stated early in this section, if the observer has no means of confirming the general description of a region by using aerial, GIS, or other of the tools we typically have today, there is always a question about the validity of the observation. However, two general conclusions can be made for the purpose of this study.

The first conclusion is the change in descriptions regarding the relative importance of grasslands as a major feature in the landscape. It does seem clear that earlier accounts characterize grasses and their coverage more than woody plants in many areas of the watershed. The second conclusion is the increasing number of accounts regarding a concern about the loss of grasslands to brush country. These conclusions support the belief that the vegetation has changed over time.

The topography of the upper portion of the basin is steep. This region of the Hill Country encompasses the Balcones Escarpment to the Edwards Plateau and is characterized by steep, arid terrain. The hills, cliffs, crevasses, exposed rock, and clay soils in this area cause rapid runoff. During large storm events, rainfall rapidly flows to streams and washes, sometimes resulting in flashfloods. Due to the terrain of the Hill Country and its impact on runoff, vegetation has relatively little influence over flash flooding. However, vegetation in the Hill Country can have a significant influence on runoff due to interception of rainfall by cedar canopy. Downstream of the Balcones fault zone, the land is not as steep or hilly and tends to flatten out as the river flows southward and eastward. It is these areas with less dramatic topography in which vegetation may have a greater influence on runoff. The Frio River Watershed crosses four major aquifer recharge zones including the Edwards, Carrizo-Wilcox, Queen City-Bigford, and Sparta-Laredo. The most significant aquifer outcrop or recharge zone spanning the Frio River Watershed is the Edwards Aquifer recharge zone. Streams crossing this recharge zone lose a significant portion of their flow through faults and solution cavities in the limestone formations. At the Edwards Aquifer recharge zone, about 244,000 acft of water per year enters the aquifer from the Frio River and its tributaries.

The periods of record and location descriptions for each of the seven long-term streamflow gages gage in the Frio River Watershed considered herein are listed in Table 2-1. Precipitation or rainfall gages provide information for specific locations in the watershed. To better compare the rainfall data to streamflow data, the watershed was divided into subwatersheds according to the streamflow gage locations and average rainfall over a particular watershed, or areal precipitation, has been calculated. Areal precipitation for each of the seven watersheds considered herein was calculated in the course of earlier studies sponsored by the Nueces River Authority, Edwards Underground Water District, and/or the City of Corpus Christi.

Table 2-1. Summary of Streamflow Gages Used in this Study

USGS Gage #	Location	Drainage Area (sq. mi.)	Period of Record
08195000	Frio River at Concan	389	11/23-9/29, 10/30-12/96
08196000	Dry Frio at Reagan Wells	126	9/52-12/96
08198000	Sabinal River at Sabinal	206	10/42-12/96
08200000	Hondo Creek at Tarpley	96	9/52-12/96
08205500	Frio River at Derby	3,429	8/15-12/96
08207000	Frio River at Calliham	5,491	10/24-4/26, 5/32-8/81 8/81-12/96[1]

[1] USGS #08207000 was discontinued in 1981 when Choke Canyon reservoir construction began. Flows for years 1981-96 were estimated using gage records for the Frio River at Tilden (USGS #08206600) and San Miguel Creek near Tilden (USGS #08206700).

The statistical tests applied to historical annual rainfall and runoff per unit rainfall include the non-parametric Kendall Tau test, and linear regression and sample partitioning, which may be classified as parametric tests. Sample partitioning, in this case, simply involves subdivision of the available historical record into halves so that the means and variances from the earlier and later sub-periods can be compared to one another. Assessment of the statistical significance of differences in sub-period means and variances was accomplished using standard t-tests and F-tests, respectively. Similarly, the statistical significance of the slope of a trendline obtained by linear regression of annual rainfall or runoff per unit rainfall versus time was evaluated using the t-test. Statistical significance is assumed at the 90 percent confidence level in this study.

Significant increases in annual rainfall are indicated for the selected subwatersheds in the headwaters of the Frio River Basin. More specifically, the Frio River at Concan (USGS #08195000), Dry Frio at Reagan Wells (USGS #08196000), Sabinal River at Sabinal (USGS #08198000), and Hondo Creek at Tarpley (USGS #08200000) indicate increasing trends in rainfall that cannot be rejected at the 90 percent confidence level. These headwater areas are in the Hill Country upstream of the outcrop of the Edwards Aquifer.

Additional long-term (1916–1996) statistical analysis of aerial precipitation for these Hill Country sub-basins, however, does not support the short-term indications of increasing rainfall. Nevertheless, further research into the characteristics of Hill Country rainfall in terms of intensity, duration, and frequency as they vary with time may be warranted.

The watersheds above the Frio River at Concan (USGS #08195000) and Sabinal River at Sabinal (USGS #08198000) demonstrated increasing trends in this ratio of runoff per unit of rainfall that cannot be rejected at the 90 percent confidence level. Further investigation into the cause of increased runoff per unit rainfall indicates that greater rainfall can be directly correlated to the increased runoff per unit rainfall. Most importantly, however, none of the Hill Country watersheds considered in this study exhibited any indications of decreasing annual runoff per unit rainfall with time.

One watershed within the Frio River Basin indicated an apparent decrease in runoff per unit rainfall over time. This watershed is in the lower portion of the Frio River basin below the Frio River at Derby (USGS #08205500) and above the Frio River at Calliham (USGS #08207000). This watershed encompasses approximately 2,062 square miles or about 50 percent of the Frio River Basin. In addition to brush proliferation, increased pumpage from the Carrizo Aquifer in recent years may be affecting observed runoff per unit rainfall in this subwatershed.

Analyses of runoff per unit rainfall for the entire Frio River Basin upstream of the streamflow gage located at Derby (USGS #08205500) are reported herein. These analyses did not provide any conclusive indications of increasing or decreasing trend due to the presence of the outcrop of the Edwards Aquifer traversing this portion of the basin, and the indications of increasing trends above the outcrop and decreasing tends below Derby. Further studies focusing on the subwatershed downstream of the Edwards outcrop and above Derby may be appropriate.

In addition, this subwatershed includes the outcrop of the Carrizo Aquifer. Increased pumpage from the Carrizo Aquifer concomitant with brush proliferation in recent years increases the likelihood of decreased runoff per unit rainfall for this subwatershed.

Potential sites for brush control are those sites where observations and statistical analyses indicate decreasing runoff relative to the rainfall. The sites identified in this section are sub-basins that should be considered in future studies. Physical systems are very complex and subject to the influences of many factors. These factors may affect each other in ways that are not historically or currently measured. The nature of explaining trends in physical systems is to continue to identify and quantify sources and sinks in the system. In this study, rainfall is the primary source, streamflow (runoff per unit rainfall) is the main variable of concern, and brush is the main sink considered. However, the question still remains "Is brush proliferation (alone) causing observed changes in runoff per unit rainfall?"

Of the six sub-basins considered in the Frio River Basin, the sub-basin between the streamflow gages at Derby (USGS #08205500) and Calliham (USGS #08207000) is the most promising for brush control. Analyses of runoff as a percentage of rainfall indicate that there is a significant decreasing trend in this sub-basin. In addition, further hydrologic studies may identify decreasing runoff per unit rainfall in the Frio River sub-basin above Derby (USGS #08205500) and below the Edwards Aquifer outcrop. Possible sinks in these two sub-basins include not only brush proliferation, but increased pumpage from and recharge to the Carrizo Aquifer, small reservoir (stock tank) development, and changes in land management practices with time. Further investigations of these sub-basins may more precisely determine the causes of apparent changes in runoff.

The SWAT model simulated streamflow for the watersheds that might warrant further consideration for brush control. Using sub-basins 108-4,5,7,8,10,11,13, and 14 to represent the watershed between the USGS gaging stations at Derby and Calliham, the SWAT model estimated an average increase of about 33,800 acre-feet (acft) per year of streamflow that might be obtained through brush control.

The total cost of additional water is determined by dividing the total state cost share if all eligible acreage were enrolled in the program by the total added water estimated to result from the brush control program over the assumed 10-year life of the program. The brush control program water yields and the estimated acreage by brush type-density category by sub-basin were supplied by the Blacklands Research Center, Texas Agricultural Experiment Station in Temple, Texas. The total state cost share for each sub-basin is estimated by multiplying the per acre state cost share for each brush type-density category by the eligible acreage in each category for the sub-basin. The cost of added water resulting from the control of the eligible brush in each sub-basin is then determined by dividing the total state cost share by the added water yield (adjusted for the delay in time of availability over the 10-year period using a 6 percent discount rate). The cost of added water thus determined averages about $42 per acre-foot for the sub-watersheds evaluated.

Although this cost per acft of water supply might seem particularly attractive as compared to other water supply alternatives in the region, it is understood that the water supply "yields" described above do not represent firm yield or dependable water supply. Continually available in a drought of record. Therefore, comparisons of these unit cost figures to those for other alternatives (e.g. Unit cost information for numerous water supply options presented in the South Central Regional Water Plan[2] is based on firm, dependable water supply available during a report of the drought of record.). A direct comparison would involve numerous considerations:

- Validation that there has been a decrease in streamflow over the period of hydrologic record.
- Confirmation that the decrease in streamflow was not due to factors other than increasing brush coverage such as groundwater level decline, stock pond development, and land management practices.
- Confirmation that the computer simulation accurately reflects the increased runoff under the conditions present in the specific watersheds.
- Determination of which landowners would commit to participate in brush control, including long-term maintenance in the manner prescribed by the inputs into the model.
- Validation that the unit costs used represent actual costs for the specific land on which brush control would be practiced.
- Modification of the project life of brush control programs (10 years) to better approximate competing water supply alternatives, which is typically 50 years.
- Qualification of changes in firm yield with due consideration of drought hydrology, water rights, and existing natural or man-made features. For example, if brush control resulted in a long-term average of 33,800 acft/yr in streamflow entering Choke Canyon Reservoir, but an average increase of only 3,380 acft/yr during the most severe drought on record, the actual increase in firm yield would be only 3,380

---

[2] HDR Engineering, Inc., et. al., "South Central Texas Regional Water Plan," South Central Texas Regional Water Planning Group, San Antonio River Authority, Texas Water Development Board, January, 2001.

acft/yr (neglecting evaporation). The unit cost for increased dependable water supply comparable to other alternatives, therefore, would be approximately ten times greater than a unit cost simply based on the long-term average increase in streamflow.

Section 3
Description of the Watershed

3.1 Area Comprising the Frio River Watershed

The Frio River originates in Real County as a spring-fed stream and flows into the Nueces River system through the Choke Canyon Reservoir. The Sabinal River, Hondo Creek, and the Leona River are major tributaries of the Frio.

For the purposes of this study, the area represented by the Frio River Watershed includes portions of the following counties: Real, Bandera, Uvalde, Medina, Zavala, Frio, La Salle, and McMullen (Figure 3-1). The Watershed covers approximately 5,500 square miles, mostly through the natural region known as the South Texas Brush Country (Figure 3-2). The area is more than 99 percent rural and the rural area consists of approximately 20 percent crops and 79 percent heavy brush, parks, and forest.

3.2 Climate

The climate is warm and dry and is similar among the various counties of the Watershed. Table 3-1 shows that annual rainfall, average minimum January air season are very consistent across the Watershed. The standard deviation for each climate parameter—rainfall, temperature, and number of days of the growing season are also shown. Extreme cold weather including snow, ice, sleet, and prolonged sub-freezing air temperatures is very rare. The Watershed can, however, be influenced by the precipitation from tropical storms and hurricanes. The extreme rainfall events of record are nearly all attributed to such storms.

3.3 Physiography

The Watershed, for the purposes of this report, extends from the Edwards Plateau region at elevation 2,380 feet above mean sea level (msl) to the inlet to Choke Canyon Reservoir, whose spillway elevation is 199.5 feet above msl. The terrain varies from that found in the Hill Country of Texas to that of the vast South Texas Brush Country. The Edwards Plateau (Bandera and Real Counties) is characterized by hilly, rocky terrain, and thin soils. Further downstream and including the remainder of the counties comprising the Watershed, the terrain is typical of the

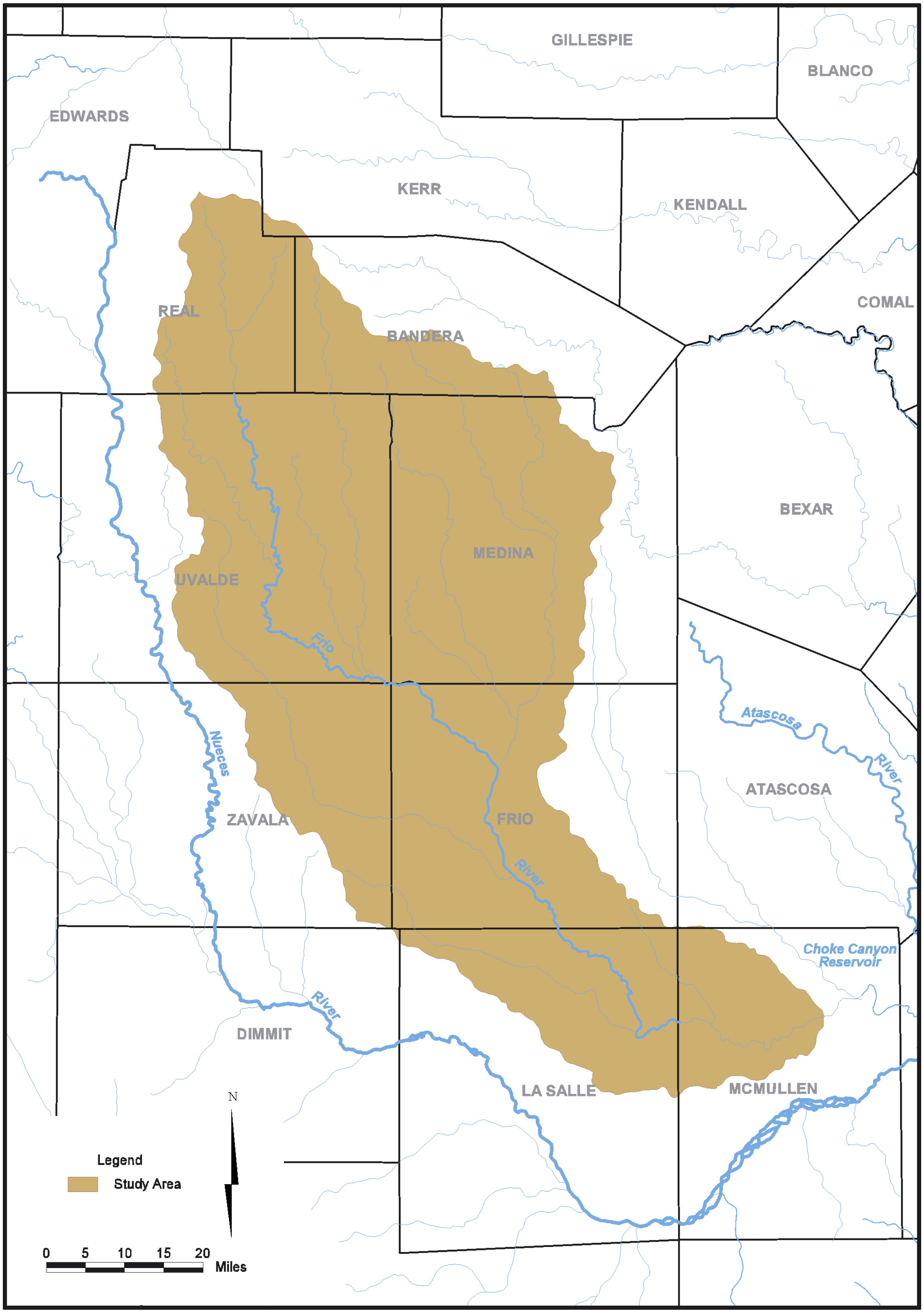


Figure 3-1. Location Map

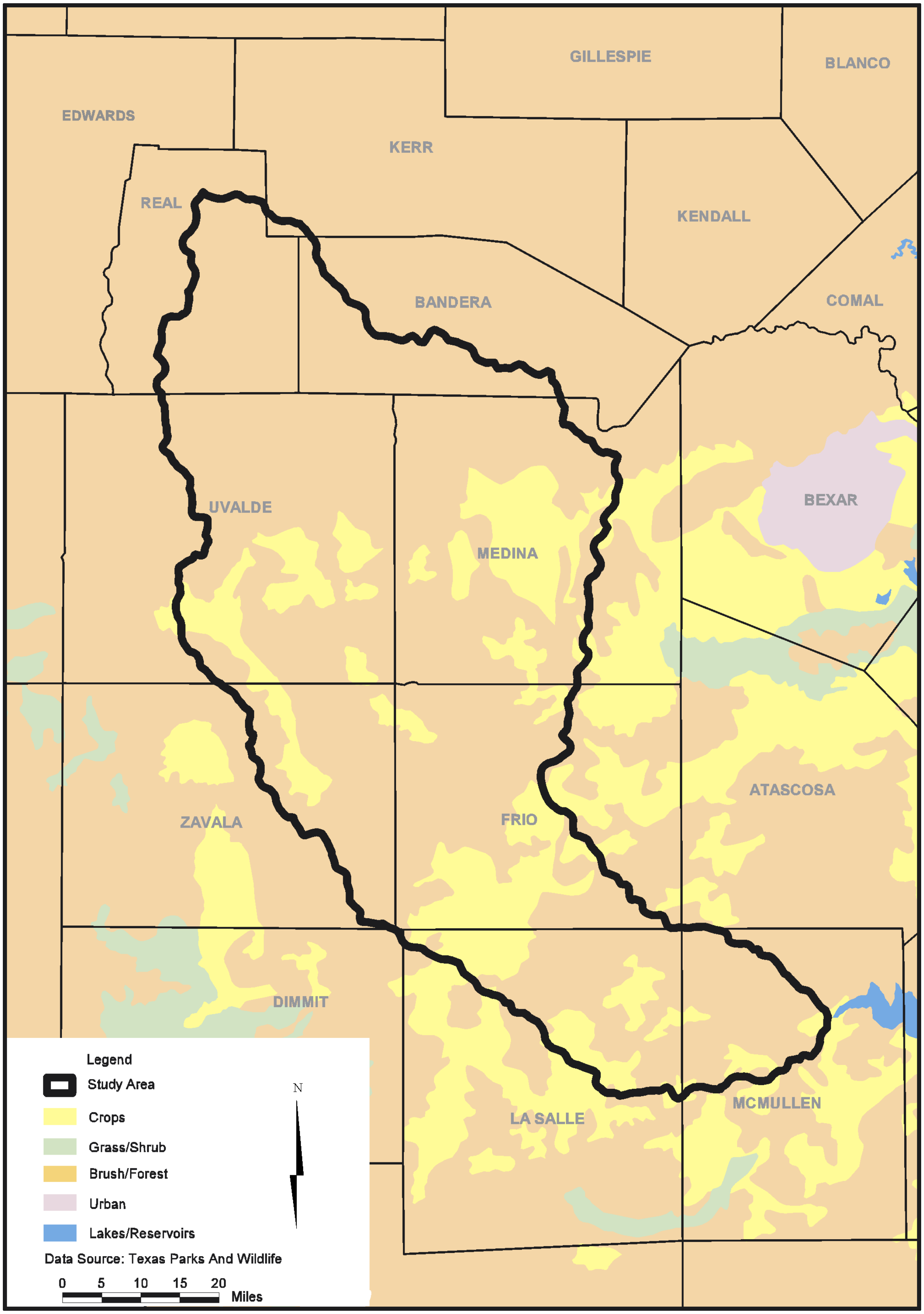


Figure 3-2. Vegetation

Table 3.1. Climate of Frio River Watershed Counties

County	Annual Rainfall (in.)	Jan. Avg. Min. Temp. (F)	July Avg. Max. Temp (F)	Growing Season (days)
Bandera	35.1	31	94	235
Frio	23.9	39	98	291
La Salle	21.6	42	99	288
McMullen	24.4	39	97	291
Medina	28.5	39	98	263
Real	25.7	31	92	236
Uvalde	24.1	37	97	255
Zavala	21.3	41	98	280
Mean	25.6	37.4	96.6	267.4
Standard Deviation	4.47	4.21	2.39	23.62

Source: *Texas Almanac*, 1992–1993.

South Texas Brush Country, which is characterized by flat to gently rolling terrain. Slopes in the Watershed range from 0 to 10 percent, as a broad range.

Surface water features are the Frio River and its tributaries. The Sabinal River, Hondo Creek, and the Leona River are the major tributaries of the Frio River. For the purpose of this report, Choke Canyon Reservoir is not included in the study area. Although spring-fed creeks are prevalent in the Edwards Aquifer, most streams in the Watershed are wet-weather streams, often measuring zero discharge during dry periods.

3.4 Geology

The Watershed extends across three major geologic zones from north to south—Cretaceous (Comanche and Gulf series), Eocene, and Cenozoic. The upper segment of the Watershed is underlain by Cretaceous limestone forming the Edwards Plateau. South of the Edwards Escarpment is Cretaceous chalk, clay, and limestone beds that are younger than Edwards formations. The entire region, including the Frio River Watershed dips to the southeast. Upland soils are dark, calcareous to slightly acid clays, loams, and sands. Bottomlands are brown to gray, calcareous, alluvial soils. An important part of the geologic history of the Balcones Escarpment and the downstream portions of the Frio River Watershed occurred between 10 and 20 million years ago.

The Edwards Plateau region is largely Cretaceous rocks that were marine sandstones, limestones, dolomites, and shales which were deposited in an ancient ocean below sea level about 100 million years ago. One geological theory is that the Edwards Plateau was uplifted along the Balcones Fault Zone as part of a regional uplift across the western United States during the Miocene time, about 10 to 20 million years ago. The Cretaceous rocks were uplifted 2,000 feet with little deformity, as evidenced by the relative levelness of the rock strata. The Balcones Escarpment is the flat terrain above the Balcones fault line through which softer rock (to the southeast) eroded at a faster rate than rock above the fault line. Water erosion has continually worked to flatten the Plateau and is now estimated to be about 50 percent complete with the process. This is demonstrated by the deep erosion of the Hill Country versus the relative uneroded western half of the plateau, which remains higher and flatter. Interaction of water has also shaped the region in ways other than surface erosion.

The geographical proximity of the Balcones Fault Zone and the Cretaceous limestones of the Edwards Plateau resulted in the formation of the Edwards Aquifer. Dissolving of limestone and dolomite along the faulting has created the karst aquifer that contains water-bearing formations ranging in size from a few millimeters to large honeycombed structures. The same dissolution of stone has also created openings (solution holes, fractures, and joints) from the surface into the aquifer. These openings form the Edwards Aquifer recharge zone in outcrops that cross streams. Thus, in the Frio River and its tributaries, there are places where streamflow disappears for a distance because it has entered the aquifer through the surface openings. It is estimated that about 75 percent of the Edwards Aquifer recharge is from surface streams.

Another feature of the upper Watershed of the Frio River in the escarpment is that the dissolution of limestone in the plateau rocks allows for springflow in the downstream (lower) Watershed. This is another key feature of the geology of the region due to the elevated Cretaceous limestone beds channeling water from rainfall and streamflow into natural surface outlets, which form the headwaters of the of the Frio River and its tributaries.

The predictable sequence of strata is from the oldest outcrops in the Balcones Escarpment where the origin of the Nueces River is located (Real and Edwards Counties) to the newest at the lowest segment in Live Oak County. The regional uplift of the Balcones Plateau did not raise the older strata southeast of the Balcones Fault Zone and, over time, the older strata have been covered by newer sediments. In Bandera and Real Counties, lower Cretaceous limestone and dolomite characterize the uplands. The principal formations include the Segovia and Fort Terrett members of the Edwards limestones. Formation thickness ranges from 300 feet to 380 feet. Above the floodplain are Pleistocene deposits; Quaternary deposits undivided consisting of slope wash, alluvial fan deposits, alluvium, colluvium, and older Quaternary rocks.

In the fault zone of Medina and Uvalde Counties, Edwards and associated limestones (Lower Cretaceous) are present along with Anacarcho limestone and Austin and Pecan Gap chalks (Upper Cretaceous). Fluviatile terrace deposits are widespread along the river at the junction of Frio and Zavala Counties. Downstream of the fault zone more recent Tertiary deposits are found. In Frio County, Eocene alluvium formations surround the convergence of the Frio River, Leona River, and Hondo Creek. To the east are Welches Formation and Queen City Sand. The former is greensand, sand, and clay while the latter is sandstone and siltstone. Following convergence, the Frio flows south into LaSalle County. The alluvium narrows at this point passing through Cook Mountain Formation, a clay and sandstone Eocene deposition. Cook Mountain Formation and Sparta Sand border the wide Aluvium in LaSalle County. Cook Mountain is calcareous clay, and sandstone and Sparta is fine quartz sand.

As the river passes through McMullen County, Eocene, Miocene, and Pliocene formations are found. The Jackson Group (Eocene) in McMullen County is subdivided into clay and sandstone units. The Catahoula Formation (Miocene) is tuff and volcanic conglomerate. The Goliad Formation (Miocene) is clay, sand, sandstone, marl, caliche, limestone, and conglomerate.

3.5 Water Resources

The Frio River Watershed includes three major tributaries—Leona River, Sabinal River, and Hondo Creek. For the purposes of this report, the Watershed does not include any major reservoirs. Choke Canyon Reservoir is located on the Frio upstream of its convergence with the Nueces River, but the lake is not included in the study area. The Edwards and Carrizo Aquifers define the groundwater resources. As presented earlier, annual rainfall in the semi-arid basin averages over 25 inches. Rainfall in the basin is highly variable in magnitude and frequency, as most significant rainfall originates from localized convective thunderstorms, or from tropical storms and hurricanes covering wider areas. The sporadic nature of rainfall in the basin results in short periods of high flows in the streams and rivers, preceded and followed by long periods of low or zero flows. This intermittent, variable nature of streamflow in the Frio River Watershed significantly affects water availability.

The Watershed is part of a highly complex hydrologic environment with active surface and groundwater interaction. Streams throughout the basin cross several major aquifer outcrops or recharge zones. The most significant of these is the Edwards Aquifer recharge zone, where an average of 334,000 acft/yr enters the aquifer from the Frio and other rivers that cross the recharge zone during the period 1934 to 1996. Other aquifer outcrops include the Carrizo-Wilcox, Queen City-Bigford, Sparta-Laredo, and Gulf Coast-Goliad Sand.

3.5.1 Surface Water

Although land use in the Frio River Watershed has not specifically been quantified in the Nueces River Basin of which the Frio is part, land use is predominately related to agriculture with 10 percent classified as cropland, 6 percent pastureland, and 84 percent rangeland. The largest municipality located within the basin is the City of Uvalde with a population of about 16,650. The City of Corpus Christi, located in the Nueces-Rio Grande Coastal Basin, is the single largest user of water from the Nueces River Basin. The City of Corpus Christi operates two large reservoirs: Choke Canyon Reservoir (on the Frio River upstream of Three Rivers) with a permitted capacity of 700,000 acft and Lake Corpus Christi (on the Nueces River near Mathis) with a permitted capacity of 300,000 acft. The City of Corpus Christi operates Choke Canyon Reservoir and Lake Corpus Christi as a system in order to supply water to retail and wholesale customers within its regional service area to approximately 400,000 people. A population of approximately 400,000 is provided water supply from these reservoirs. The majority of the water supplied by these reservoirs is released and diverted downstream of Lake Corpus Christi at the Calallen Diversion Dam near Calallen. The next largest permitted capacity of any reservoir operated for water supply in the basin is the Upper Nueces Reservoir, owned by the Zavala-Dimmit Counties Water Improvement District No. 1, with a permitted capacity of 4,010 acft.

Groundwater/surface water interactions play a significant role in the Frio River Watershed. The outcrops of four major aquifers traverse the Frio River Watershed. The most significant of these is the Edwards Aquifer, a highly porous, fractured limestone formation outcropping in Uvalde and Medina Counties. The formation is so efficient in recharging the aquifer that, of the rivers crossing the recharge zone, only the Nueces River sustains a minimal baseflow across the outcrop. The Frio and Sabinal Rivers are very often dry at the downstream edge of the outcrop. Recharge of the Edwards Aquifer in the entire Nueces River Basin averaged an estimated 334,400 acft/yr during the 1934 to 1996 period.

With the exception of a few springs, interactions between groundwater and surface water in the Frio River Watershed occur primarily in the form of recharge in outcrop areas where surface waters may percolate directly into the aquifer. When this recharge occurs in a defined stream, it becomes one component of a more generalized depletion of surface water flows referenced herein as "channel losses." Channel losses may include aquifer recharge, bank storage, over-bank flooding, evaporation, and transpiration by riparian vegetation. Channel losses can be quite significant and become most evident between streamflow gaging stations when intervening runoff is minimal.

In 1996, the Regional Assessment of Water Quality in the Nueces River Basin found that the water quality is generally good. No concerns in the Frio or its tributaries were noted. A few stream segments in the Nueces River Basin had elevated levels of dissolved solids, nutrients, and fecal coliforms (Table 3-2). Water quality in public water supply systems has been described as good.

Table 3-2. Water Quality Concerns by Stream Segment

Surface Water Resource (stream segment number)	***Water Quality Concerns (1996 Assessment for Clean Rivers Program)***
Choke Canyon Reservoir *(2116)*	Nutrients, Dissolved Solids, Fecal Coliforms
Nueces/Lower Frio River *(2106)*	Fecal Coliforms
Lake Corpus Christi *(2103)*	Nutrients
Nueces River Below Lake Corpus Christi *(2102)*	Nutrients, Fecal Coliforms
Nueces River Tidal *(2101)*	None

3.5.2 Groundwater

The major aquifers that lie beneath the region, the Edwards-Trinity, Carrizo-Wilcox, and Edwards Aquifers (Figure 3-3), provide substantial groundwater resources within the Frio River Watershed. The Carrizo-Wilcox Aquifer contains moderate to large amounts of either fresh or slightly saline water. Slightly saline water is defined as water that contains 1,000 to 3,000 milligrams per liter of dissolved solids. Although, this aquifer reaches from the Rio Grande River north into Arkansas, it only underlies parts of McMullen and Live Oak Counties within the Coastal Bend Region. In this downdip portion of the Carrizo-Wilcox Aquifer, the water is softer, hotter (140°F), and contains more dissolved solids.

The Edwards Aquifer has been called "…a long, narrow conduit through which water moves underground across parts of south-central Texas."[1] The aquifer is approximately 175 miles long and varies in width from about 5 to 30 miles. The aquifer exists due to its limestone composition and its proximity to the Balcones Fault Zone, which is a series of close, parallel faults arching across south-central Texas. Because the general drainage pattern is towards the Gulf Coast to the southeast, surface water crossing the fault zone has dissolved extensive areas of the aquifer as it enters the limestone formations through the faults. The resultant karst aquifer is replenished through the natural recharge of surface water from the Frio River and other streams and rivers that cross the fault zone. This characteristic loss of streamflow in the Frio River Watershed is accounted for in the naturalized flows used in the hydrology section of this report.

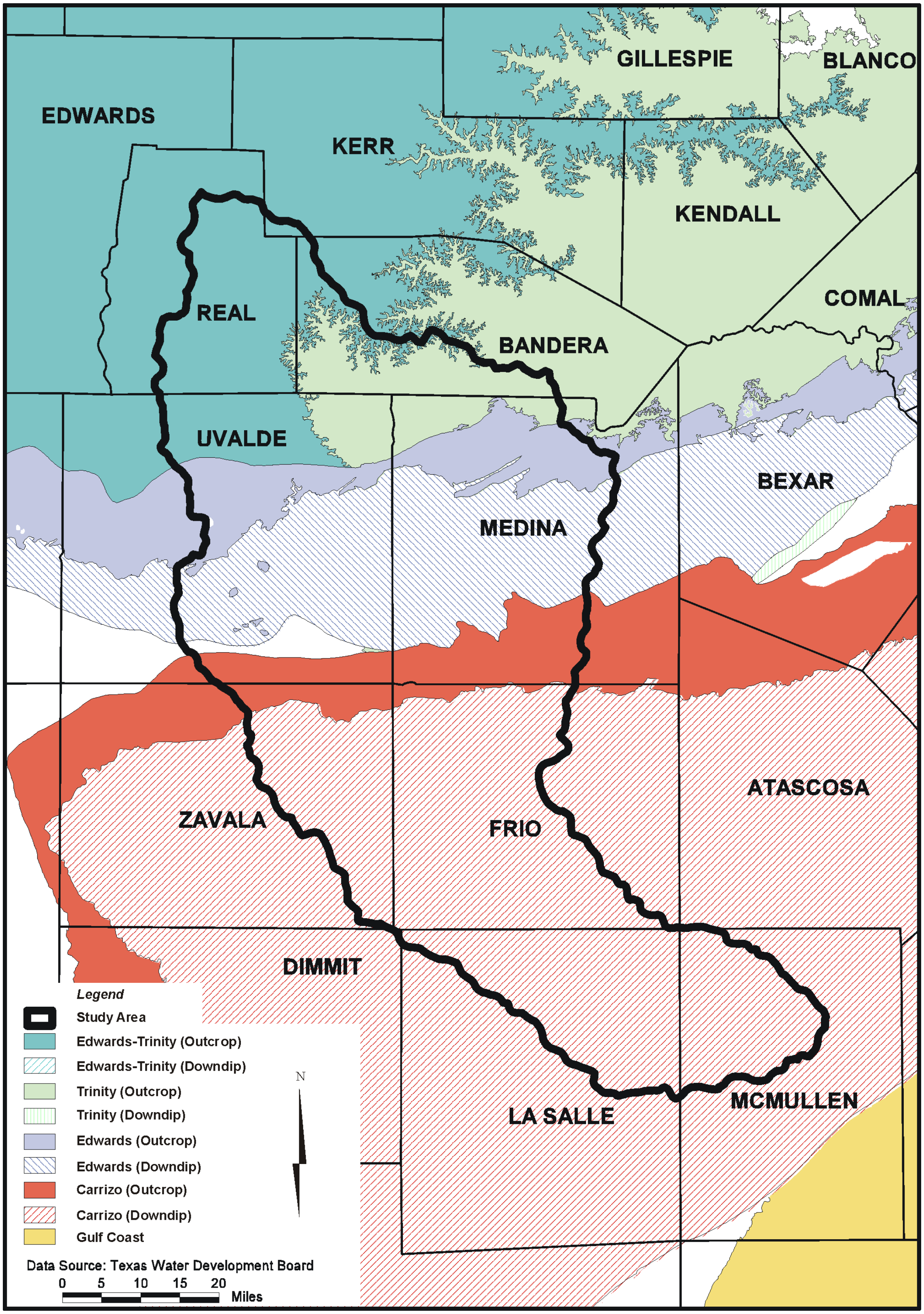
The Edwards Aquifer ranges in thickness from about 400 feet to about 900 feet. Yields of large-capacity wells average about 900 gpm. The Carrizo is 3,000 feet thick in places and produces 700 gpm from large-capacity wells.

3.6 Resource Aspects

While the Watershed is well known for its valuable mineral resources, especially oil and gas, the area is also rich and diverse in living natural resources. Ecosystems consist of the South Texas Brush Country characterizing the inland portion of the Coastal Bend Region and the

---

[1] Harden, Rollin W., "The Edwards Connection. The Edwards Aquifer — Underground River of Texas," Guadalupe-Blanco River Authority, 1988.



Data Source: Texas Water Development Board

Figure 3-3. Aquifers

Edwards Plateau along the northern extent of the Watershed. Because the Watershed is located along many migratory flyways, birds comprise a major portion of the wildlife population of the area.

The Brush Country is host to such a variety of wildlife that two of the state wildlife areas are located in the lower reaches of the Frio River Watershed. The Hill Country natural area in Bandera and Medina Counties is a 4,700-acre tract of gently rolling live oak grassland. White-tailed deer are abundant and primitive camping only is allowed for camping facilities. The James E. Doughtrey WMA in Live Oak and McMullen Counties covers about 8,000 acres. Vegetation is typically mesquite, prickly pear cactus, and blackbrush. Wildlife includes abundant deer, javelina, turkey, quail, and mourning doves.

3.7 Vegetation

Vegetation in the Watershed is characterized by the two major regions of Texas that the river crosses—the Edwards Plateau and the South Texas Brush Country. The Edwards Plateau soils are typically thin and calcareous. The Edwards Plateau is distinctly divided from the South Texas Brush Country by the Balcones Escarpment, which is the origin and north part of the Frio River Watershed. Live oak, shinnery oak, cedar, and mesquite are the dominant woody plants. Woody plants predominate over forage plants in this region. Grasses include tall grasses along rock outcrops, and midgrasses and shortgrasses on the shallow, drier meadows. Tall grasses include bluestem and switchgrass, and shorter grasses include sideoats grama, buffalograss, and Texas grama.

The South Texas Brush Country, which is part of the South Texas Plains, covers several counties in the Watershed. This area is level to rolling. Figure 3-4 shows the generalized soils map of the Watershed. Upland soils include clayey, loamy and sandy soils that typically overlay firm clayey soils. Bottom soils are calcareous silt loams and clayey alluvial soils. Mesquite, small live and post oak, prickly pear cactus, and other brush are commonly dense in this region.

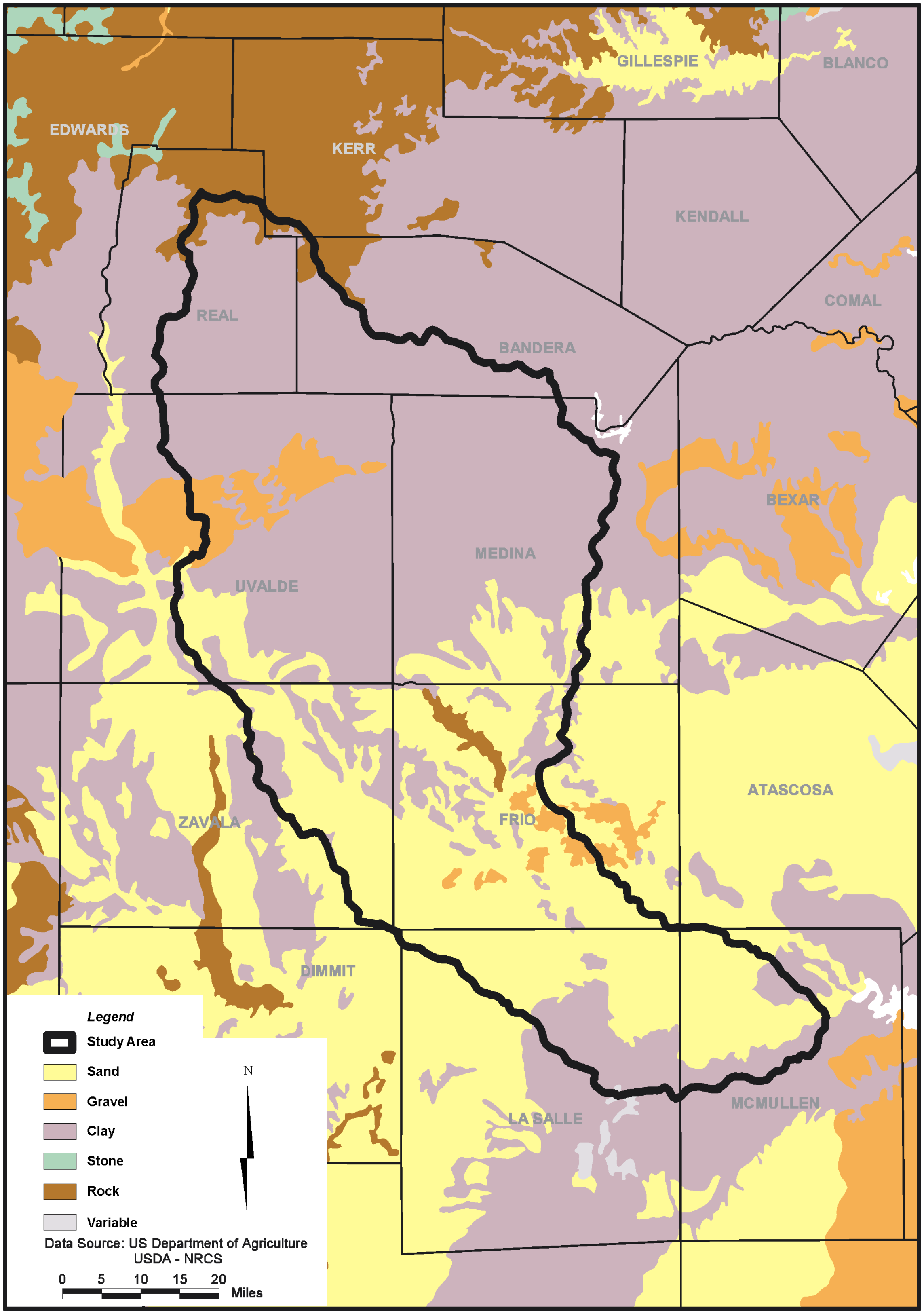


Figure 3-4. Soils

Section 4
Historical Considerations

Mankind can learn about the past only through collecting information on natural phenomenon and human observations, and applying our reasoning to reach valid conclusions about the past. This is the practice in the studies of geology, archaeology, anthropology, and history. The prehistoric humans left traces of their occupation, but no written records. The earliest Europeans who explored Texas provided written accounts of their experiences and observations. It is from fossils, sediments, and these and subsequent written accounts of the land, streams, flora, and fauna of Texas that researchers have suggested that the landscape changed over the course of time. In recent history, the pre-European landscape in this region of Texas is thought to have been one of typical savanna, consisting of short and tall grasses, with intermittent brush and woody plant infestations limited to upper ravines and along watercourses. It has been suggested that this vegetation promoted the enhancement of rainfall runoff and deep drainage, which would contribute to streamflow and springflow, respectively.

Archeological findings and historical anecdotes, presented in this section from earliest to most recent, provide an insight into climate, vegetation, and land use. However, this information is not *prima facie* support for linking water yield to changes in land use for two reasons: (1) written accounts are limited geographically and in other ways such that it always remains questionable whether generalized patterns and characterizations can be discerned from such accounts; and (2) enhancing water yield through brush control is required to be a quantifiable and predictable science because, presumably, economic investments will be needed to effect the desired outcome. The information presented in the following section should be evaluated in terms of indirect evidence that, if climate is the same, there is more water available from grasslands than brushlands. Direct evidence, or correlation, of such would necessarily require quantification and predictability, neither of which can be ascertained from the information presented in this section.

4.1 Paleo-Indian

Evidence of human habitation in the Edwards Plateau and surrounding areas of Texas dates to at least 11,000 years ago.[1] These humans were from the northeast Asian populations that crossed to North America over a temporary land bridge in the Bering Strait during periods of glacial activity. They were hunter-gatherers, not agriculturalists. Evidence of their activities as well as bones of large, extinct mammals have been found in caves and along streams in the southwest part of the Edwards Plateau dating to a period 11,000 to 9,000 years ago. Due to the glacial activity in North America at the time, it is very likely the climate in this part of Texas was cooler and wetter. As glaciers receded, the climate began a gradual change toward the warmer and drier weather we experience now. Pollen fossils dating from 7,000 to 4,000 years ago for this region demonstrate a decrease in tree pollen, and corresponding increase in grass pollen.[2] The drier climate favored expansion of the grasslands at the expense of forests.

Archeological investigations provide evidence that human habitation occurred in areas that were likely to have had a more permanent streamflow than present flow. For example, it is known that acorns were plentiful in the region and a principal source of fat in the human diet. However, it is believed that water was needed to process the acorns into a useable food supply (to remove tannic acids from the acorns),[3] and, thus, permanent water would have to have been reasonably convenient to those early humans. Archeologists use burned rock that has accumulated in large amounts to investigate sites where food processing like this would have occurred. Texas A&M University Research Station researchers found several in the region located far from permanent water supplies,[4] indicating that these streams were perennial at one time have become wet-weather streams today. If convenient water sources were needed to process acorns, and the current sites of burned rock accumulations are far from such sources, it is reasonable to suggest that surface water circumstances may have been very different in past times. This could be the result of having more streamflow because of the greater presence of grasslands, because of simply having a lot more precipitation that we currently experience, or because groundwater supplies were not used and springflows were much greater.

---

[1] Hester, T. R., "Early Human Occupation along the Balcones Escarpment," The Balcones Escarpment, pp. 55–62, Geological Society of America, San Antonio, Texas, 1986.

[2] Bryant, V. M., "Pollen — Nature's Tiny Capsules of Information," Ancient Texans Rock art and Lifeways along the Lower Pecos, pp. 50-55, Gulf Publishing Co., Houston, Texas, 1986.

[3] Taylor, Charles, A., Jr., and Fred E. Smiens, "A History of Land Use of the Edwards Plateau and Its Effect on the Native Vegetation," 1994 Juniper Symposium, Texas A & M University Research Station at Sonora, Texas, April 14, 1994.

Determining whether the Frio River Watershed was mostly a grassland in prehistoric periods requires speculating on what is known about early humans, and then comparing or contrasting that knowledge with other evidence such as sediments, fossils, and other physical records. The more recent the time period, the more difficult it is to find this latter "hard" evidence to support or refute characterizations such as this. The period of the last 8,000 years is one of gradual drying and warming of the climate, but not much, if any, change in land use until the arrival of the Europeans. What is known is that the Indians, unlike the Europeans, did not develop intensive agriculture practices or domesticate wild animals such as the bison, but rather maintained their hunter-gatherer roots. As a result, the human population was limited by the food supply, which was the indigenous wildlife, and fruit and grain harvest. While there were herds of bison and other ruminants, they were not domesticated, and, therefore, experienced natural selection. Another fact is that wildfires were logically more frequent because Indians had no sophisticated means of fire control caused by lightning and careless use by humans. Also, they likely used fires at times for their own purposes (e.g., to hunt). Such frequent wildfires across an abundant, fuel-rich grassland would prevent the growth of large vegetation, thus keeping grasses as the predominant vegetation.

4.2 Spanish Influence

The Spanish were the first Europeans known to explore and attempt to settle Texas. Their goal was to establish an empire for the advantage of Spain and the Catholic Church. Their goal necessarily implied that they would have a different perspective of what the land and other resources would be used for than their predecessors, the Indians. The earliest exploration was in 1519 when Alonso Alvarez de Pineda mapped the Gulf Coast. A later expedition lead by Francisco Vazquez de Coronado journeyed across the American Southwest in search of precious metals. His report to Spanish King Charles V recommended Spain not explore or settle what they called New Spain because his journey across the High Plains, Oklahoma, and Kansas was not promising in terms of the kind of natural resources Spain had hoped to exploit. The Spanish presence, though, made permanent and significant changes to how Texas developed, beginning with the introduction of the horse.

The first permanent change brought to Texas by the Spanish was the use of the horse. Historians suggest that the use of horses by the Spanish and the adoption of horses by the

---

[4] *Ibid.*, page 2.

American Indians ultimately increased grazing, mobility, and opportunity for further agricultural changes, such as livestock ranching.[5] The horse allowed the Spanish to first explore the region. The early written accounts of these explorations are useful in understanding what those observers saw in Texas.

Perhaps the earliest such account, although not in the Frio River Watershed, was by the Spanish explorer Cabeza de Vaca (1490–1555) in the early 1530s. His account of the San Antonio River suggests there was plenty of water, but the landscape was not limited to grassland savanna. “Here there was plenty of drinking water from the clear streams and springs. And there were great meadows filled with ripe prickly-pear...”[6] As part of the Edwards Plateau region, the upper Frio River Watershed may not have been strictly a grassland prairie, but rather, contained large numbers of brush-like vegetation, such as the prickly pear. One account in 1691 in what is now Uvalde County noted plenty of vegetation and not much notice of grasses, “…river valleys thickly covered in pecan, mesquite and oak trees and …hills and plains covered with mesquite and catclaw…”[7] Another account in 1691 near San Antonio (Teran de los Rios Expedition) supports this idea. “Traveling across prairie country, the men saw huge herds of buffalo, an animal unknown to them in Mexico. Progress slowed when dense thickets of mesquite and cat claw were encountered.”[8] Figure 4-1 shows the approximate route of the Teran Expedition across the region. As cautioned previously, the perspective of the observers in these early expeditions is a limited one, as can be surmised from Figure 4-1 when one considers just how much of the watershed the observer was able to see.

Spanish accounts of the Frio River suggest water and larger vegetation were plentiful. An account of the Frio River by the Basque-Larios Expedition on April 22, 1675: “The water is good. The country is well supplied with nuts and other food products, such as wild turkeys, sweet potatoes, buffalo,…fish… On both sides (of the river) are great bottoms; there is a

---

[5] *Ibid.*, p. 5.

[6] Warren, Betsy, “Explorers in Early Texas,” p. 18, Hendrick-Long Publishing Co., Dallas, Texas, 1992.

[7] Hall, Grant P., “Leona River Watershed, Uvalde County,” Research Report No. 37, 1974.

[8] Santos, Richard G., “Aguayo Expedition into Texas, 1721,” p. 28, Jenkins Publishing Co., Austin, Texas, 1981.

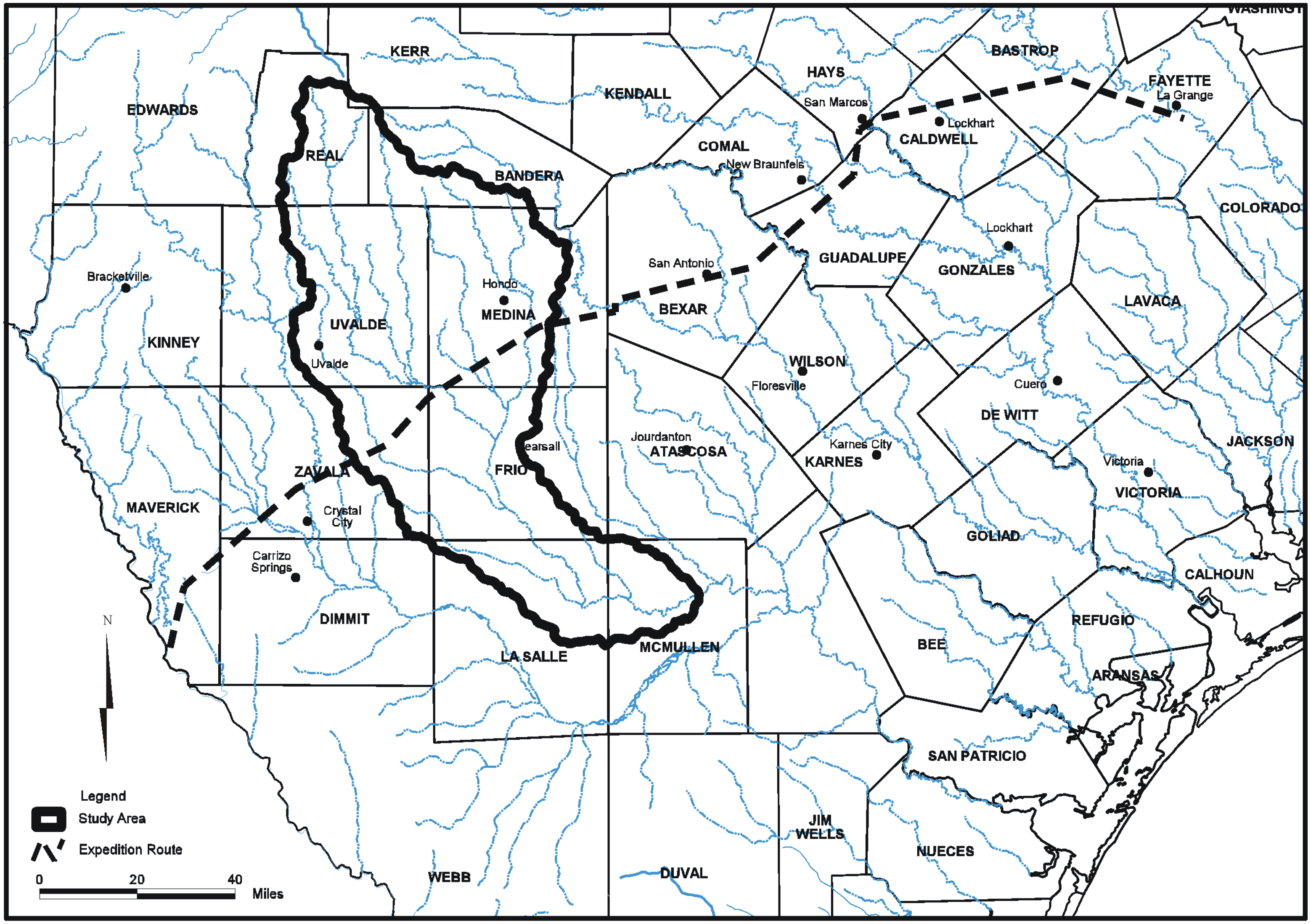


Figure 4-1. Governor Domingo Terán de los Ríos's 1691 - 1692 Expedition

luxuriance of plants, nuts,…wild grapes, good pasturage, a variety of birds and wild hens."[9] Later, during the Teran Expedition of 1691, "We crossed two ravines and stretches of timber and entered a region covered with mesquite. This lasted until we reached the banks of the (Nueces) river."(June 6, 1691)[10] On June 7, 1691, the Teran Expedition noted, "…we worked our way toward the east about two leagues through timber and big pecan tress, cutting a passage for the troops…The country was level and covered with mesquite and cat's claw."[11]

The Aguayo Expedition in the early 1700s suggests more support for the existence of grassland savannas in its accounts. March 28, 1721 at Turkey Creek near the Nueces River, "…abundant water and pastureland; turkey, quail, rabbit and hares found…" The Aguayo Expedition (Figure 4-2) had to cross the river "…by [using] a branch and dirt bridge…"[12] On March 29, 1721 at Tortuga Creek (between Nueces and Leona River east of what are now Crystal City and Carrizo Springs), "…abundant fish, water year round, pool surrounded by a large plain and pasture…found turkey, quail, and peacock…"[13] On April 1, 1721 the Aguayo Expedition documented that the "…road to that point is full of brambles and briars. There are a great number of pecan and other types of trees in the vicinities of the ravine and creek…the land is very beautiful and level. There are many meadow of different kinds of flowers…Seco Creek has water year round…"[14] Tortuga Creek and Seco Creek are not flow-monitored streams, so comparison of recent flows to flows described above is not possible. However, there are several explanations as to why Tortuga Creek and Seco Creek would be seasonal now, but have "…water year round…" in 1721. The creeks could have been spring-fed in places from the Carrizo Aquifer, which was not pumped in those times. It is also not known how the author determined that flow was permanent. It has been documented that some explorers embellished their observations deliberately for the purpose of funding a subsequent exploration, among other reasons.[15] The author may have only been there in the spring during very wet weather. If anything is clear from these few explorer observations of the Frio River Watershed, it is that the

---

[9] Bolton, Herbert Eugence, "Spanish Exploration in the Southwest, 1542-1706," Barnes and Noble, New York, 1908.

[10] Hatcher, Mattie Austin, "The Expedition of Don Domingo Teran de los Rios into Texas," Preliminary Studies of the Texas Catholic Historical Society, Volume 1, No. 1.

[11] *Ibid*., page 13.

[12] Santos, Richard G., "Aguayo Expedition into Texas, 1721," p 28, Jenkins Publishing Co., Austin, Texas, 1981.

[13] *Ibid*., p. 28.

[14] Op. Cit., Santos, Page 29.

[15] Fehrenbach, T.R., "Lone Star: A History of Texas and the Texan," Wings Books, New York, 1968.

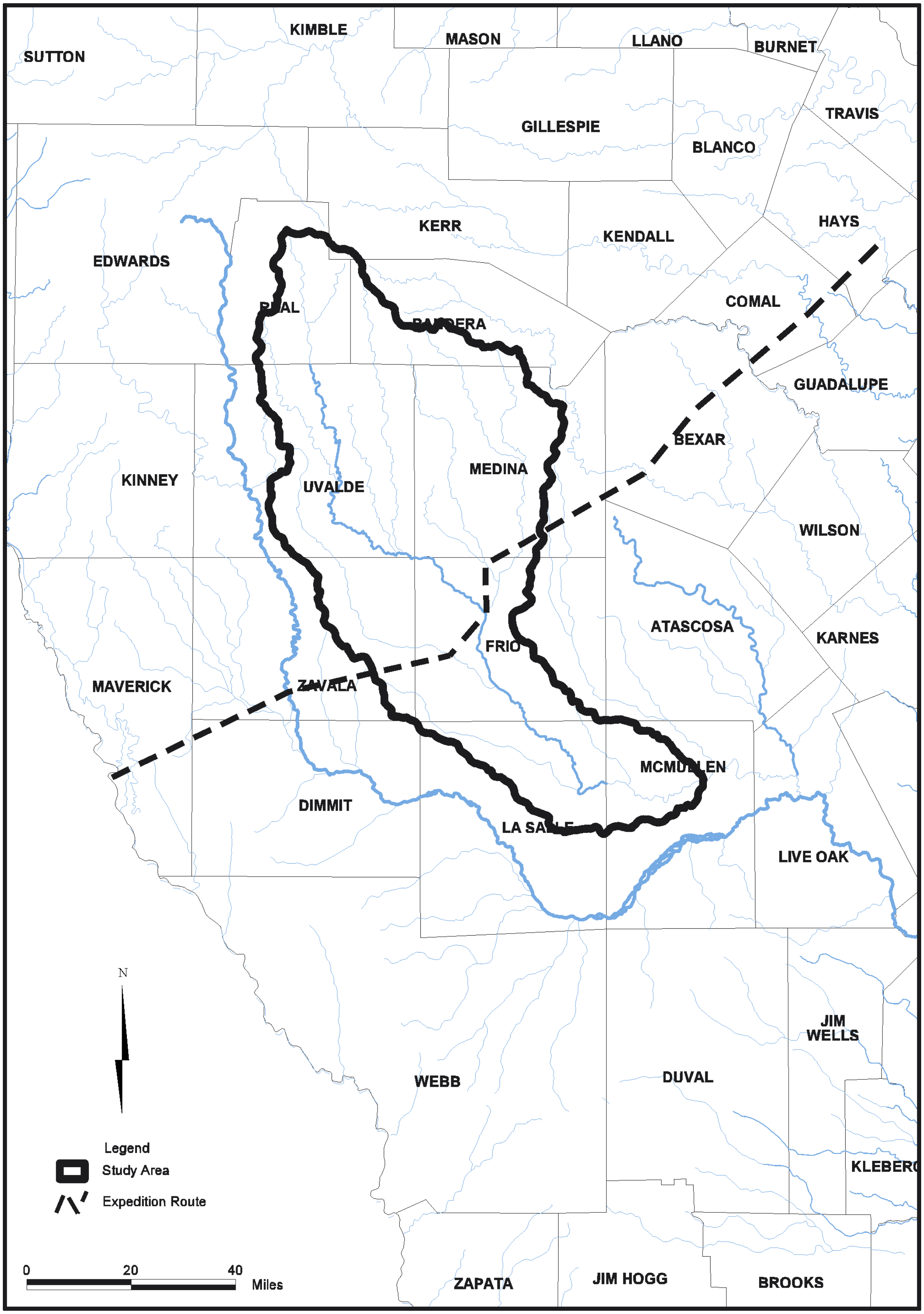


Figure 4-2. Aguayo's Expedition 1721

landscape then had elements in common with the current landscape. The degree of prior brush coverage versus grassland is likely to be debated well into the future, but to say the region was mostly grassland appears to depend upon site-specific information. Obviously, at least some areas were mostly heavy brush and trees.

From the early 1500s until the late 1600s, Spanish interest in Texas was limited except for Catholic missionary involvement in the El Paso area. In 1685, the French—under the famous explorer La Salle—arrived in Matagorda Bay and built a fort near there. Even though Indians quickly destroyed it, the arrival of the French was a warning to the Spanish that another nation might try to colonize "their" land. In response, two missions were established in 1690. The Camino Real (King's Highway) was built between these missions and San Antonio, which had become the Spanish capital of the territory. Throughout the 1700s there were additional French excursions, small increases in Spanish missionary activity and military presence, and continued widespread agitation from Indians.

Major immigration into Texas, however, did not begin until Spain's control over Mexico began to weaken in the 1820s. Seeking to protect itself from Mexican dominance, the Spanish legislature opened all Spanish territories to foreigners. This action opened the way for additional European immigration, but this time from the United States. Mexico won independence from Spain in 1821, but allowed open immigration until 1830, by which time many thousands of new settlers from the United States had arrived, been granted estates, and had begun the movement toward Texas independence from Mexico, which happened in 1836. This brief history of the three centuries of Spanish presence in Texas connects the first European expeditions to the early 1800s when intensive agriculture arrived in Texas from the United States.

4.3 Rangeland History of the Watershed

Domesticated livestock ranching, as we know it, has been practiced in the Frio River Watershed for over 150 years. Initially there were open ranges where livestock roamed freely and followed existing water supplies before groundwater was made available. This section seeks to describe the observations of ranchers and others over three periods—about 1840 to 1900, 1901 to 1939, and 1940 to 1953.

4.3.1 1840 to 1900

In the Escarpment, most accounts in the 1800s noted plenty of timber. For example, Frederick Law Omstead's journey in 1844 through Medina County, "Leaving it (Castroville), we ascended a high hill, and rode for 15 miles through a more elevated and broken country, whose beauty is greatly increased by frequent groves of live oak, elm and hackberry."[16] And in Uvalde County along the Sabinal River in 1854, "…timber: cypress and cedar..."[17] Another account in Bandera County in 1867, "…noted for mountain cedar…"[18] Edwards County was described in 1860 in terms of water availability and vegetation. In 1860, running streams in the upper watershed of the Nueces River in Edwards County were identified as the following:

- East and Middle Fork of the Nueces,
- West Fork of the Frio River,
- South Llano River,
- Cedar Creek,
- Bull Head Creek, and
- Hackberry Creek.

Apparently the most common grass, was mesquite grass and fruits included wild grapes, cherries, and pecans. [19]

West of the Frio River Watershed, a *Texas Almanac* from 1873 described grasses in Webb County near the Nueces River, "There are two kinds of grasses here: (1) the mesquite grass, which is the better of the two, is a coarse grass common to prairie counties; and; (2) the Bermuda grass, which does well, spreads rapidly and soon kills out weeds and other grasses."[20]

Later, the same *Texas Almanac* described changes in prairie fires. "The prairie fires that formerly so often swept over the western plains, destroying every shrub and preventing the growth of timber, have become far less frequent and confined to comparatively narrow limits. Hence, there are now thousands of acres in nearly all the western counties growing up in mesquite and various kinds of timber, where a few years ago, there was not a shrub to be seen."[21] Further description of the region is provided in the *Texas Almanac* regarding the streams:

---

[16] McMurtry, Larry, "A Journey through Texas – Fredereick Law Omstead," p. 278, Austin Texas: University of Texas Press, 1978.
[17] Murray, Myrtle, "Home Life on Early Ranches of Southwest Texas," The Cattlemen, p. 33, 1938.
[18] Stovall, Allan A., "Nueces Headwater Country," p. 12, Naylor Company, San Antonio, Texas, 1959.
[19] Ibid.
[20] "Texas Almanac and State Industrial Guide," p. 109, Richardson, Belo and Co., Galveston, 1873.

"Western Texas (Edwards, Frio, and Nueces Watersheds) is generally undulating prairie…There are numerous rivers or small streams, but most of the smaller ones are subject to become very low or even dry in the dry season, and again subject to overflow, and often impassible during the heavy rains. All of them are lined with timber…cypress, hackberry, cottonwood, pecan, oak of many kinds, and hickory. The wide prairie is covered with grass, what is called mesquite."[22]

The feature of streams crossing the Edwards Aquifer recharge zone and evidence of these streams being dry in places were observed by outside chroniclers of the 1880s. "The Nueces River, although dry in many places, is well-timbered from the heads of its fork to its mouth…Head of fork: chestnut, Texas red oak, scrapberry, wild mulberry, and black willow."[23] The same observer noted dry streams from Uvalde to Eagle Pass, "…drained by several creeks: Turkey, Chuparosa, Live Oak, Comanche, and Penitencia… They are mostly dry, but their courses are well-marked with hackberry, green ash, retama, and black willow."[24]

The noticeable observations during this period contrast accounts of streamflow and wildfires with prior accounts. At least in this sample of accounts, there are more references to "dry streams" than in the sample from earlier periods. Also, the observations reported in the 1873 *Texas Almanac* are insightful because they track well with the maturity of the ranching industry in Texas. By the 1880s the buffalo herds were gone, Indian tribes were defeated, windmills could generate drinking water for livestock, fencing was in use. All of these changes discouraged the previous tolerance for prairie fires. The effectiveness of prairie fires in causing the selection of grasses over larger, woody vegetation underscores the potential for rapid growth of the latter in areas where grasslands previously dominated and fires are suppressed.

The most compelling explanation for less frequent prairie fires in the ranching technology of the late 1800s was the elimination of (1) predators, through the use of fencing; and (2) natural hazards like droughts, through use of windmills offered ranchers the opportunity to over-graze their land. In the Edwards Plateau during this time, ranches were over-stocked with livestock above the carrying capacity of the rangeland. The carrying capacity of rangeland is related to the amount of forage a ruminant animal needs versus the capability of the land to regenerate the forage naturally. It is reasonable, therefore, to suggest that there was a large net loss of grass (fuel). This loss of grass made wildfires more difficult to start and sustain. As historian

---

[21] *Ibid*. Page 117.

[22] *Ibid*., Page 176.

[23] Harvard, Valery, "Report on the Flora of Western and Southern Texas," Vol. 8, No. 29, Washington, D.C., 1885.

Fehrenbach explains, "Two inventions, the windmill and the barb-wire fence, destroyed the seas of grass…It was predictable that the ranchmen would overstock, and that the cattle, which cropped closer than bison, would eventually destroy the rich grass."[25] The lack of fires allowed woody plants that are undesirable forage like junipers and oaks to survive and eventually succeed at the expense of grasses.

4.3.2 1901 to 1939

In certain parts of the Frio River Watershed, accounts from the early 1900s are similar to much earlier times when brush was not as extensive in coverage. In other parts of the watershed, one can argue that dramatic changes in brush had already occurred. The *Texas Almanac* of 1904 contains many of these accounts. For example, in La Salle County, "The Nueces River, a bold, running stream, traverses the center of the county, while the Frio, which ceases to run during droughts, traverses the northern portion."[26] Contrast that account with this one from the same reference (page 267), "The Leona runs dry, but the Frio is never without its deep blue pools of water as clear as a crystal." In Dimmit County, "The general surface is an undulating prairie, with occasional broken and timbered lands along the water courses. Timber is scarce and consists mainly of pecan, hackberry, elm, and live oak in the bottomlands. Mesquite grasses grow on the uplands. Comanche, Pendencia, Rocky Pena, Carrizo, San Lorenzo, and San Ambrosia all are running creeks."[27]

Descriptions of the vegetation offer the suggestion that some areas were changing. In McMullen County, "…trees near streams—live oak, ash, elm, cottonwood, and willow; trees in prairies—mesquite…"[28] Uvalde County, "…mesquite prominent native grass; water inexhaustible, timber throughout county…, northern county—post oak and blackjack; mountain (timber)—large cedar."[29]

By 1939, indications of stress are found in the same areas where there was no such concern previously. One description of watersheds of south-central Texas noted, "…more intensive grazing held the grasses under greater and greater restraint, the "brush" has spread into adjacent more level and fertile areas which formerly supported abundant grass. Prairie relicts are

---

[24] *Ibid.*, Page 462.
[25] *Op. Cit.*. Feherenbach. pp. 566-567.
[26] "Texas Almanac and State Industrial Guide," p. 311, Richardson, Belo and Co., Galveston, 1904.
[27] *Ibid.*, Page 253.
[28] *Ibid.*, p. 325.

still sufficiently numerous and variant to indicate the stages of the progressive invasion by mesquite, acacia, Texas ebony, hackberry, purple sage, etc…."[30] In part of the Nueces River Watershed, "…grazing, especially by sheep and goat, has greatly depleted the wealth of wild flowers which formerly covered the whole region in profusion. At present time, one may drive over the whole region and hardly see any flower but bitterweed."[31] These characterizations contrast notably with those of the region less than two decades later.

Accounts in 1951 from the *Texas Almanac* clearly describe the Texas Brush Country in many counties of the Nueces River Watershed. Uvalde County was "…largely covered with cedar, mesquite, brush…; upland timber—cedar; canyon timber—pecan, cypress, oak, walnut, wild cherry; southern (county) timber—mesquite, small oak, and brush…"[32] In Zavala County, "Timber includes mesquite, catclaw, live oak, mulberry, hackberry, cottonwood, pecan. Part prairie, largely brushland…"[33] Dimmit County was noted to be "Largely covered with mesquite, oak, elm, and brush…a lot of brush covered ranchland…"[34]

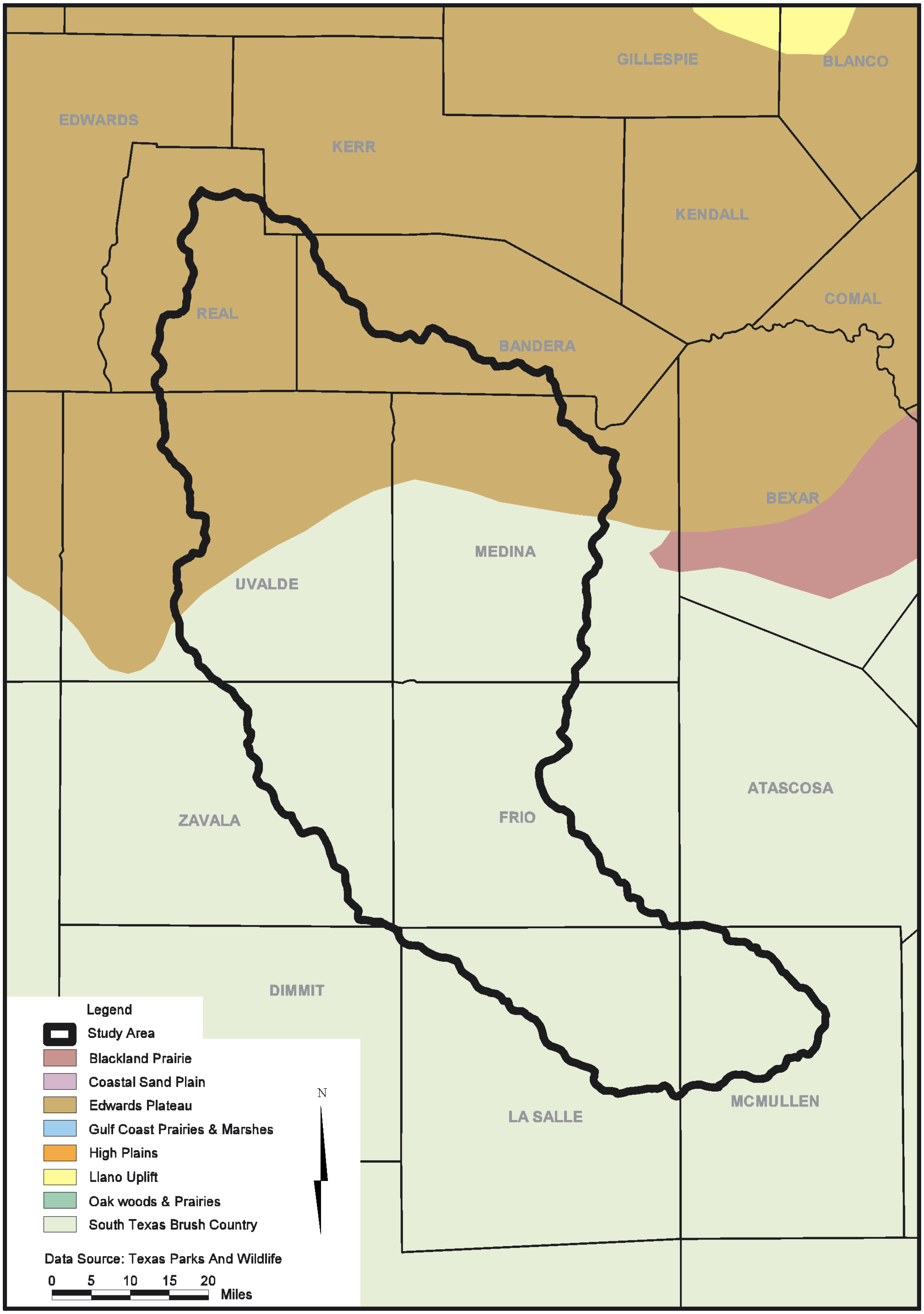
4.4 Summary

From some of the earliest written accounts of the Frio River Watershed, mesquite, oak, cedar, prickly pear, and other brushland plants were observed throughout the region. Some accounts even described rather dense concentrations of trees and brush. The difference between earlier descriptions (1860–1939) and those of the mid-1900s addresses the relative coverage of grasslands; these coverages are difficult, if not impossible, to quantify. As stated early in this section, if the observer has no means of confirming the general description of a region by using aerial, GIS, or other of the tools we typically have today, there is always a question about the validity of the observation. However, two general conclusions can be made for the purpose of this study.

---

[29] *Ibid*., p. 381.
[30] Tharp, Benjamin Carroll, "The Vegetation of Texas," p. 10, The Anson Jones Press, Houston, Texas, 1939.
[31] *Ibid*., p. 21.
[32] "Texas Almanac and State Industrial Guide," p. 610, Richardson, Belo and Co., Galveston, 1951.
[33] *Ibid*., p. 619.
[34] *Ibid*., p. 538.

The first conclusion is the change in descriptions regarding the relative importance of grasslands as a major feature in the landscape. It does seem clear that earlier accounts characterize grasses and their coverage more than woody plants in many areas of the watershed. The second conclusion is the increasing number of accounts regarding a concern about the loss of grasslands to brush country. These conclusions support the belief that the vegetation has changed over time. Figure 4-3 shows the natural regions of the Frio River Watershed as they appear today.



Data Source: Texas Parks And Wildlife

Figure 4-3. Natural Regions

Section 5
Hydrologic Evaluation

5.1 Hydrologic Description of Basin

The approximately 5,500 square miles of drainage area comprising the Frio River Watershed is a sub-basin of the Nueces River Basin. The headwaters are in the Hill Country in Edwards, Real, and Bandera Counties. The Frio River Watershed extends from the headwaters to Choke Canyon Dam located in Live Oak County a few miles upstream of the confluence with the Nueces River. Major tributaries of the Frio River include the Dry Frio River, Sabinal River, Leona River, Hondo Creek, San Miguel Creek, and Seco Creek.

The topography of the upper portion of the basin is steep. This region of the Hill Country encompasses the Balcones Escarpment or uplift to the Edwards Plateau and is characterized by steep, arid terrain. The hills, cliffs, crevasses, exposed rock, and clay soils in this area cause rapid runoff. During large storm events, rainfall rapidly flows to streams and washes, sometimes resulting in flashfloods. Due to the terrain of the Hill Country and its impact on runoff, vegetation has relatively little influence over flash flooding. Downstream of the Balcones fault zone, the land is not as steep or hilly and tends to flatten out as the river flows southward and eastward. It is these areas with less dramatic topography in which vegetation may have a greater influence on runoff.

The Frio River Watershed crosses four major aquifer recharge zones including the Edwards, Carrizo-Wilcox, Queen City-Bigford, and Sparta-Laredo. The most significant aquifer outcrop or recharge zone spanning the Frio River Watershed is the Edwards Aquifer recharge zone. Streams crossing this recharge zone lose a significant portion of their flow through faults and solution cavities in the limestone formations. At the Edwards Aquifer recharge zone, about 244,000 acft of water per year[1] enters the aquifer from the Frio River and its tributaries.

5.1.1 Hydrologic History and Conditions

The Frio River Watershed, much like the rest of South Texas, has experienced extreme droughts and floods. Large storms of record in the Frio River Watershed occurred in 1880,

---

[1] HDR, "Edwards Aquifer Recharge Analysis," Trans-Texas Water Program, West Central Study Area, Phase II, San Antonio River Authority, et. al., March 1998.

1932, 1935, 1936, 1958, and 1966. Table 5-1 lists the largest floods known at several of the long-term gages in the watershed. The largest flow measured for the Frio River near Derby (08205500) is 230,000 cfs on July 4, 1932. The next largest flow is 162,000 cfs for the Frio River at Concan (08195000) on July 1, 1932.

From the period of 1934 to 1996, droughts ranging in severity have occurred throughout the Frio River Basin. The most severe drought prior to 1994 is the drought that started in 1947 and continued through 1956. This drought is referred to as the "drought of the 50s." Annual rainfall during the 1950s drought was 22 to 28 percent less than the long-term average annual rainfall. For instance, the average areal rainfall for the Frio River Watershed above Derby is 24.1 inches and the average rainfall during the 1950s drought was 18.8 inches. Other dry times include 1934, 1962–1964, 1980, 1984, 1988–1989, and 1994–1996.

5.1.2 Precipitation and Naturalized Streamflow Development

Locations of the streamflow gages in the Frio Basin and the period of record for each gage is shown in Figure 5-1. The dark circles indicate the gages considered in this Frio River Watershed study. Daily precipitation data for each gage is available for that station's period of record. The first streamflow gage in the Frio Basin was put into place near Derby and started recording in 1915. Since that time, numerous stream and precipitation gages have been established throughout the basin.

The periods of record and location descriptions for each of the six long-term streamflow gages considered herein are listed in Table 5-2.

Precipitation or rainfall gages provide information for specific locations in the basin. To better compare the rainfall data to streamflow data, the basin has been divided into sub-basins according to the streamflow gage locations and average rainfall over a particular sub-basin, or aerial precipitation, has been calculated. Aerial precipitation for each of the six watersheds considered herein was calculated in the course of two earlier studies[2,3] sponsored by the Nueces River Authority and the City of Corpus Christi. Annual aerial precipitation for each subwatershed corresponding with the selected streamflow gages is listed in Tables 5-3.

---

[2] HDR, "Nueces river Basin Regional Water Supply Planning Study, Phase I," Nueces River Authority, et al., May 1991.

[3] HDR, "Water Supply Update for City of Corpus Christi Service Area," City of Corpus Christi, January 1999.

Table 5-1. Frio River Watershed Flood History Summary

USGS Gage #	Gage Location	Drainage Area (mi^2)	Continuous Record Since	Largest Flood for Period of Record			Largest Flood Outside Period of Record		
				Peak Flow (cfs)	Peak Stage (feet)	Date	Peak Flow (cfs)	Peak Stage (feet)	Date
08195000	Frio River at Concan	389	1930	162,000	34.44	7/1/1932	n/a	n/a	n/a
				119,000	30.65	9/16/1936			
				106,000	29.40	6/14/1935			
				100,000	28.80	9/18/1923			
08196000	Dry Frio River near Reagan Wells	126	1952	123,000	27.60	8/13/1966	n/a	33	1880
				55,000	25.57	10/28/1996	64,700	26.0	6/14/1935
				26,200	21.31	5/29/1987	30,700	23	7/1/1932
08198000	Sabinal River near Sabinal	206	1942	55,200	24.60	6/17/1958	n/a	33	7/2/1932
				52,500	28.5	8/2/1978			
				36,500	24.00	7/15/1973			
08200000	Hondo Creek near Tarpley	95.6	1952	76,900	29.64	6/22/1997	58,500	26	7/1932
				69,800	28.20	6/17/1958			
				57,200	25.70	7/15/1973			
08205500	Frio River near Derby	3,429	1915	230,000	29.45	7/4/1932	n/a	n/a	n/a
				82,500	22.96	8/15/1971			
				68,300	23.68	6/2/1935			
08207000	Frio River at Calliham	5,491	1933[1]	42,800	36.18	8/18/1971	80,200	39.2	7/6/1932
				42,400	36.15	9/23/1967			

[1] USGS #08207000 discontinued in 1981 when Choke Canyon Reservoir construction began

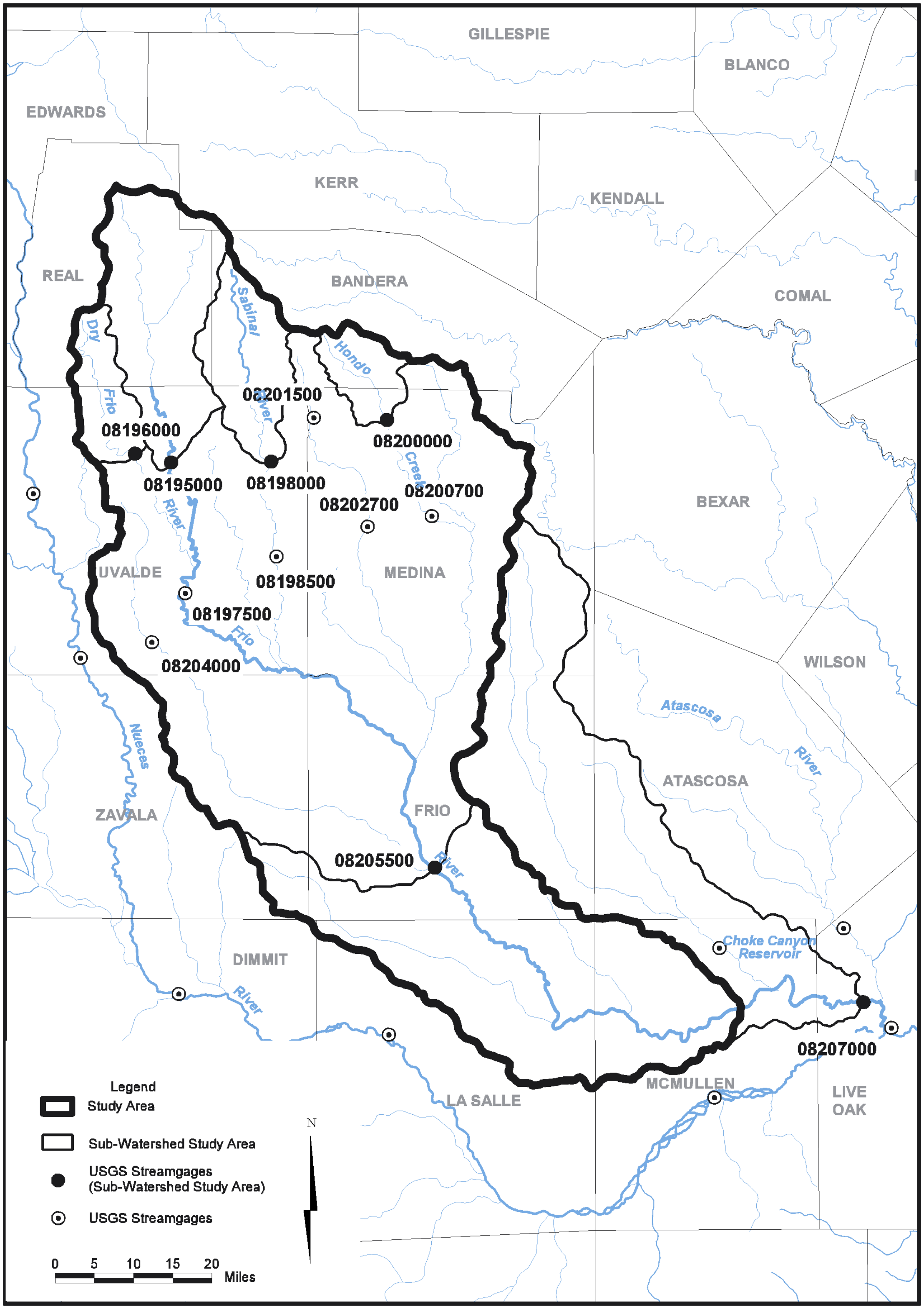


Figure 5-1. USGS Streamgages

Table 5-2. Summary of Streamflow Gages Used in this Study

USGS Gage #	Location	Drainage Area (sq. mi.)	Period of Record
08195000	Frio River at Concan	389	11/23-9/29, 10/30-12/96
08196000	Dry Frio at Reagan Wells	126	9/52-12/96
08198000	Sabinal River at Sabinal	206	10/42-12/96
08200000	Hondo Creek at Tarpley	96	9/52-12/96
08205500	Frio River at Derby	3,429	8/15-12/96
08207000	Frio River at Calliham	5,491	10/24-4/26, 5/32-8/81 8/81-12/96[1]

[1] USGS #08207000 discontinued in 1981 when Choke Canyon reservoir construction began. Flows for years 1981-96 were estimated using gage records for the Frio River at Tilden (USGS #08206600) and San Miguel Creek near Tilden (USGS #08206700).

Streamflow gages measure the discharge in a river at the gage location. To accurately assess the possible presence of trends in the streamflow, the discharge must be "naturalized" to remove man-made influences. Water supply diversions, wastewater effluents, and reservoir influences are typically accounted for in the adjustment of measured flow to obtain naturalized flow. Monthly natural streamflows were developed for each of the gage locations identified in Table 5-2 in the course of previous studies.[4,5] Annual naturalized flow for six stream gages is listed in Tables 5-4.

Five of the six watersheds considered in this study are evaluated as headwater watersheds or watersheds for which natural streamflows at the outlet are considered representative of the entire tributary area. In addition, the intervening watershed between the streamflow gages located on the Frio River at Derby and Calliham (Choke Canyon Dam) is evaluated herein. For this watershed, local historical runoff is estimated by subtracting historical gauged streamflow at Derby (without adjustment) from gauged streamflow at Calliham with adjustment for reported diversions. This provides the best representation of local historical runoff for the intervening watershed.

---

[4] Op. Cit., HDR, May 1991.

[5] Op. Cit., HDR, January 1999.

Table 5-3. Annual Areal Precipitation for Watershed Above Gage

Year	Frio River at Concan USGC #08195000 (acft)	Dry Frio River at Reagan Wells USGS #08196000 (acft)	Sabinal River at Sabinal USGS #08198000 (acft)	Hondo Creek at Tarpley USGS #08200000 (acft)	Frio River at Derby USGS #08205500 (acft)	Frio River at Calliham USGS #08207000 (acft)
1934	10.88	16.84	19.07	23.13	20.00	26.67
1935	44.27	43.52	47.55	52.77	44.78	34.11
1936	36.74	35.82	32.50	39.46	30.02	25.07
1937	21.48	20.82	21.09	24.21	20.57	20.09
1938	18.91	17.72	24.59	25.66	18.83	14.74
1939	20.30	19.47	23.16	23.61	20.97	15.14
1940	24.18	21.89	31.52	31.99	26.99	29.04
1941	32.84	32.41	36.26	35.99	33.84	32.90
1942	28.70	27.82	32.90	34.52	28.07	29.07
1043	20.96	19.38	23.55	24.29	21.52	20.64
1944	27.47	26.95	36.20	37.22	30.57	26.67
1945	19.82	18.69	30.82	31.91	24.61	22.48
1946	25.60	25.48	25.80	25.51	28.71	31.41
1947	24.03	25.03	18.62	18.21	19.68	19.00
1948	18.84	17.66	22.93	22.72	22.99	17.96
1949	35.54	36.38	41.11	44.28	37.64	34.14
1950	20.29	18.80	22.38	23.87	20.41	17.79
1951	19.11	24.71	18.89	18.18	18.41	19.92
1952	21.15	21.80	23.80	27.30	21.73	16.53
1953	12.80	14.55	17.00	22.79	18.54	21.64
1954	17.54	17.55	16.96	17.24	14.75	13.56
1955	22.65	22.54	22.42	22.00	21.08	15.58
1956	8.67	8.64	9.80	11.72	10.80	8.65
1957	33.70	33.00	36.64	40.98	37.06	32.14
1958	45.15	46.14	44.78	40.96	40.62	37.27
1959	28.91	30.43	29.93	30.92	30.75	26.73
1960	28.04	27.84	31.09	37.55	30.17	31.54
1961	26.01	27.36	27.88	28.25	25.64	20.32
1962	15.69	15.33	17.57	21.50	16.35	14.46
1963	17.16	19.78	18.79	20.65	18.71	19.52
1964	25.94	26.64	24.79	22.45	24.28	19.78
1965	26.52	27.57	26.84	23.82	27.64	28.07
1966	33.36	32.17	32.06	34.66	25.00	24.61
1967	25.29	25.00	24.51	26.00	26.69	30.24

Table 5-3. Annual Areal Precipitation for Watershed Above Gage (Continued)

Year	**Frio River at Concan USGC #08195000 (acft)**	**Dry Frio River at Reagan Wells USGS #08196000 (acft)**	**Sabinal River at Sabinal USGS #08198000 (acft)**	**Hondo Creek at Tarpley USGS #08200000 (acft)**	**Frio River at Derby USGS #08205500 (acft)**	**Frio River at Callihamy USGS #08207000 (acft)**
1968	28.63	30.28	30.93	33.46	32.27	31.52
1969	31.77	30.41	31.07	36.12	30.45	25.48
1970	25.04	23.71	24.48	29.86	23.68	23.71
1971	31.03	32.10	32.75	44.13	33.51	30.32
1972	29.19	28.35	28.67	36.35	23.65	21.41
1973	36.10	38.47	39.79	43.61	37.48	33.83
1974	28.19	28.36	31.78	36.78	31.12	25.67
1975	26.24	27.38	27.42	37.38	27.09	26.68
1976	33.13	36.66	36.27	37.41	38.46	37.37
1977	27.22	27.61	26.91	33.34	20.82	18.69
1978	22.05	22.00	23.79	29.34	22.61	24.13
1979	27.76	24.08	33.77	33.00	28.51	21.66
1980	37.56	33.79	38.63	32.29	27.32	26.82
1981	46.76	45.18	43.03	48.65	35.14	31.10
1982	27.00	25.88	25.03	26.28	21.99	22.04
1983	26.54	24.78	31.95	29.71	24.71	21.57
1984	27.11	24.23	31.00	25.85	21.82	17.73
1985	29.18	28.99	29.52	33.83	28.18	28.34
1986	37.04	35.55	38.96	43.50	34.71	30.96
1987	42.65	40.73	44.28	47.73	36.72	25.73
1988	22.99	20.47	22.70	21.31	15.59	14.29
1989	23.26	20.78	26.97	22.87	19.75	16.10
1990	35.84	35.25	39.60	36.41	29.78	13.42
1991	38.07	32.77	54.14	54.48	34.73	22.35
1992	39.04	34.38	45.76	48.04	37.46	32.27
1993	19.16	16.54	24.54	24.89	19.20	32.05
1994	33.60	32.90	34.78	37.58	31.64	17.76
1995	30.66	27.09	35.71	34.62	32.79	31.66
1996	25.39	24.08	26.67	27.34	19.50	22.82
Maximum (in)	46.76	46.14	54.14	54.48	44.78	37.37
Minimum (in)	8.67	8.64	9.80	11.72	10.80	8.65
Average (in)	27.50	26.96	29.76	31.63	26.65	24.21

Table 5-4. Annual Naturalized Streamflow for Watershed

Year	Frio River at Concan USGC #08195000 (acft)	Dry Frio River at Reagan Wells USGS #08196000 (acft)	Sabinal River at Sabinal USGS #08198000 (acft)	Hondo Creek at Tarpley USGS #08200000 (acft)	Frio River at Derby USGS #08205500 (acft)	Frio River at Calliham USGS #08207000 (acft)
1934	21,698	—	—	—	10,848	87,422
1935	321,690	—	—	—	794,205	113,265
1936	173,550	—	—	—	167,164	122,636
1937	53,994	—	—	—	27,581	44,320
1938	49,839	—	—	—	21,175	79,775
1939	53,731	—	—	—	60,825	22,619
1940	46,038	—	—	—	18,547	196,427
1941	115,661	—	—	—	155,683	299,763
1942	68,040	—	—	—	70,632	277,999
1043	32,759	—	11,063	—	25,744	51,189
1944	56,457	—	24,890	—	47,453	89,804
1945	52,282	—	30,762		41,883	71,642
1946	48,103	—	16,592	—	57,970	269,232
1947	58,031	—	16,589	—	21,540	19,914
1948	20,270	—	2,586	—	32,558	12,537
1949	80,677	—	31,258	—	70,973	154,469
1950	27,272	—	9,907	—	2,356	20,549
1951	23,683	—	7,319	—	61,905	93,981
1952	13,092	—	3,244	—	1,193	33,784
1953	11,118	3,967	3,137	7,296	88,202	171,499
1954	23,898	9,451	7,797	3,536	19,641	18,459
1955	15,699	9,434	651	718	8,547	34,001
1956	4,103	736	1,180	417	10,449	45,907
1957	49,547	32,032	33,258	40,932	228,192	201,867
1958	198,334	76,530	158,760	96,020	270,799	202,125
1959	110,682	35,050	58,957	20,559	82,494	53,575
1960	87,120	22,745	55,769	26,054	4,562	92,307
1961	103,549	31,806	54,917	29,948	78,093	47,399
1962	36,703	4,643	4,348	2,036	4,491	7,716
1963	23,757	4,112	4,255	1,604	3,811	28,699
1964	42,646	9,326	16,673	7,644	19,045	9,981
1965	56,679	14,303	21,091	19,109	11,186	81,174
1966	106,003	36,425	38,018	15,678	30,491	54,623
1967	79,744	29,500	46,291	12,396	51,181	347,816

Table 5-4. Annual Naturalized Streamflow for Watershed (Continued)

Year	Frio River at Concan USGC #08195000 (acft)	Dry Frio River at Reagan Wells USGS #08196000 (acft)	Sabinal River at Sabinal USGS #08198000 (acft)	Hondo Creek at Tarpley USGS #08200000 (acft)	Frio River at Derby USGS #08205500 (acft)	Frio River at Callihamy USGS #08207000 (acft)
1968	109,312	34,169	84,127	46,976	62,776	204,269
1969	88,442	28,033	39,432	21,765	56,669	26,162
1970	90,835	23,070	29,924	18,446	27,485	68,872
1971	156,736	44,037	87,331	67,562	435,933	33,573
1972	105,862	15,958	45,682	31,395	56,115	17,622
1973	180,159	63,080	130.980	74,112	308,043	33,965
1974	82,647	22,638	32,971	22,419	153,160	23,727
1975	81,591	20,490	39,152	46,314	109,484	48,639
1976	137,076	51,620	88,989	44,458	201,855	89,035
1977	141,464	24,751	86,252	42,127	150,847	93,107
1978	55,179	9,310	43,619	18,795	55,584	116,123
1979	93,711	28,415	74,726	53,958	169,100	987
1980	75,632	7,902	33,863	13,194	86,412	95,594
1981	261,050	58,309	148,831	66,183	286,954	97,612
1982	71,993	15,197	22,861	7,557	40,863	26,537
1983	52,231	11,875	23,572	12,667	21,862	30,876
1984	67,925	15,576	18,813	6,023	33,515	13,363
1985	122,278	32,606	59,948	40,829	67,160	112,143
1986	90,296	28,420	46,646	30,078	92,572	109,569
1987	285,472	78,970	190,148	117,045	564,288	204,845
1988	87,770	8,790	19,509	5,792	58,429	18,961
1989	37,062	3,956	7,985	3,318	13,914	9,147
1990	104,362	19,286	41,752	19,970	52,875	108,630
1991	151,268	29,830	76,113	57,176	87,722	63,464
1992	255,351	56,563	206,484	114,368	350,256	230,241
1993	54,503	10,628	29,964	12,381	54,035	32,034
1994	82,728	23,984	23,648	8,593	29,669	27,359
1995	83,600	22,094	29,795	13,798	26,608	9,887
1996	85,881	23,138	13,082	1,542	23,270	7,592
Maximum (in)	321,690	78,970	206,484	117,045	794,205	347,816
Minimum (in)	4,103	736	651	417	1,193	987
Average (in)	88,236	25,744	45,102	29,609	99,665	85,911

5.1.3 Analysis Methods

Historical accounts suggest that brush in the Hill Country has increased over the centuries since the Europeans began inhabiting this region of Texas. Accounts of tall prairie grasses and few brush or trees contrast with the current proliferation of brush. These accounts, coupled with recent research in brush control and water yield, have led some researchers to suggest that controlling brush in certain watersheds could increase water yields. One purpose of this study is to determine if historical data supports a relationship between increasing brush coverage and decreasing streamflow. The method used for determining whether a relationship between brush control and streamflow exists involves statistical analysis for identification of any trends in rainfall and runoff (on a per unit of rainfall basis) for related watersheds. Runoff per unit rainfall or percent runoff measures the response of a watershed to rainfall and effectively normalizes highly variable runoff records for many years and many watersheds thereby allowing for equitable comparisons.

A significant change in the relationship between the runoff and rainfall over time may be indicative of a change that has occurred in a watershed. An increase in runoff per unit rainfall concomitant with observed brush proliferation over time does not support the hypothesis that brush proliferation has reduced yield (runoff) at the watershed level. While an observed decrease in runoff per unit rainfall concomitant with brush proliferation tends to support the hypothesis that brush proliferation has reduced yield. Further investigation is warranted, as there are other factors such as groundwater level decline, stock pond development, and land management practices that could have a similar effect. Identification of increasing trends in runoff per unit rainfall may eliminate some watersheds from further investigation. On the other hand, identification of decreasing trends in runoff per unit rainfall in some watersheds may provide support for further investigation of the causes of decreasing runoff. Such investigations may include more detailed brush control studies.

5.4 Trends in Rainfall and Streamflow Characteristics

Historical aerial precipitation or rainfall for each sub-basin defined by the selected streamflow gage locations is plotted as a time series in Figure 5-2. The mean or average annual rainfalls for the first and second halves of the available period of streamflow records are

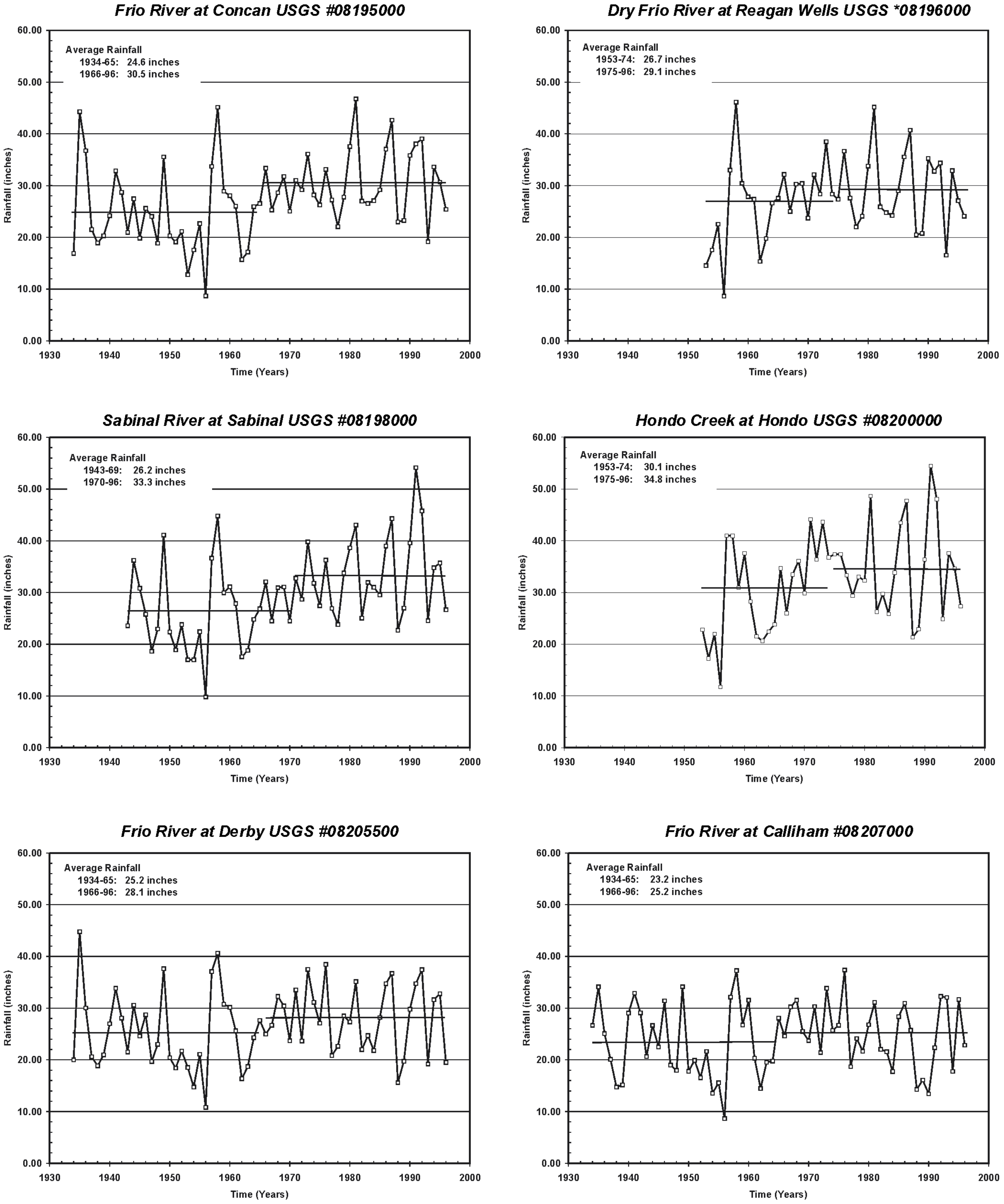


Figure 5-2. Rainfall Time Series for Frio River Watershed
Frio River at Concan USGC #08195000

summarized in Table 5-5 and drawn as horizontal lines one each plot. All of the sub-basins show an increase in average rainfall from the earlier to the latter period. Statistical analyses will assess the significance of these differences.

Table 5-5. Comparison of Average Annual Rainfall and Runoff per Unit Rainfall

Location	*USGC Gage #*	*Drainage Area (mi^2)*	*Period*	*Average Rainfall (in)*	*Average RO/RF (%)*
Frio River at Concan	08195000	389	1934–65	24.6	11.1
			1966–96	30.5	17.1
Dry Frio at Reagan Wells	08196000	126	1953–74	26.7	12.3
			1975–96	29.1	12.6
Sabinal River at Sabinal	08198000	206	1943–69	26.2	8.6
			1970–96	33.3	15.7
Honda Creek at Tarpley	08200000	96	1953–74	30.1	14.2
			1975–96	34.8	16.76
Frio River at Derby	08205500	3,429	1934–65	25.2	1.4
			1966–96	28.1	2.1
Frio River at Calliham[1]	08207000	5,491	1934–65	23.2	3.4
			1966–96	25.2	2.7

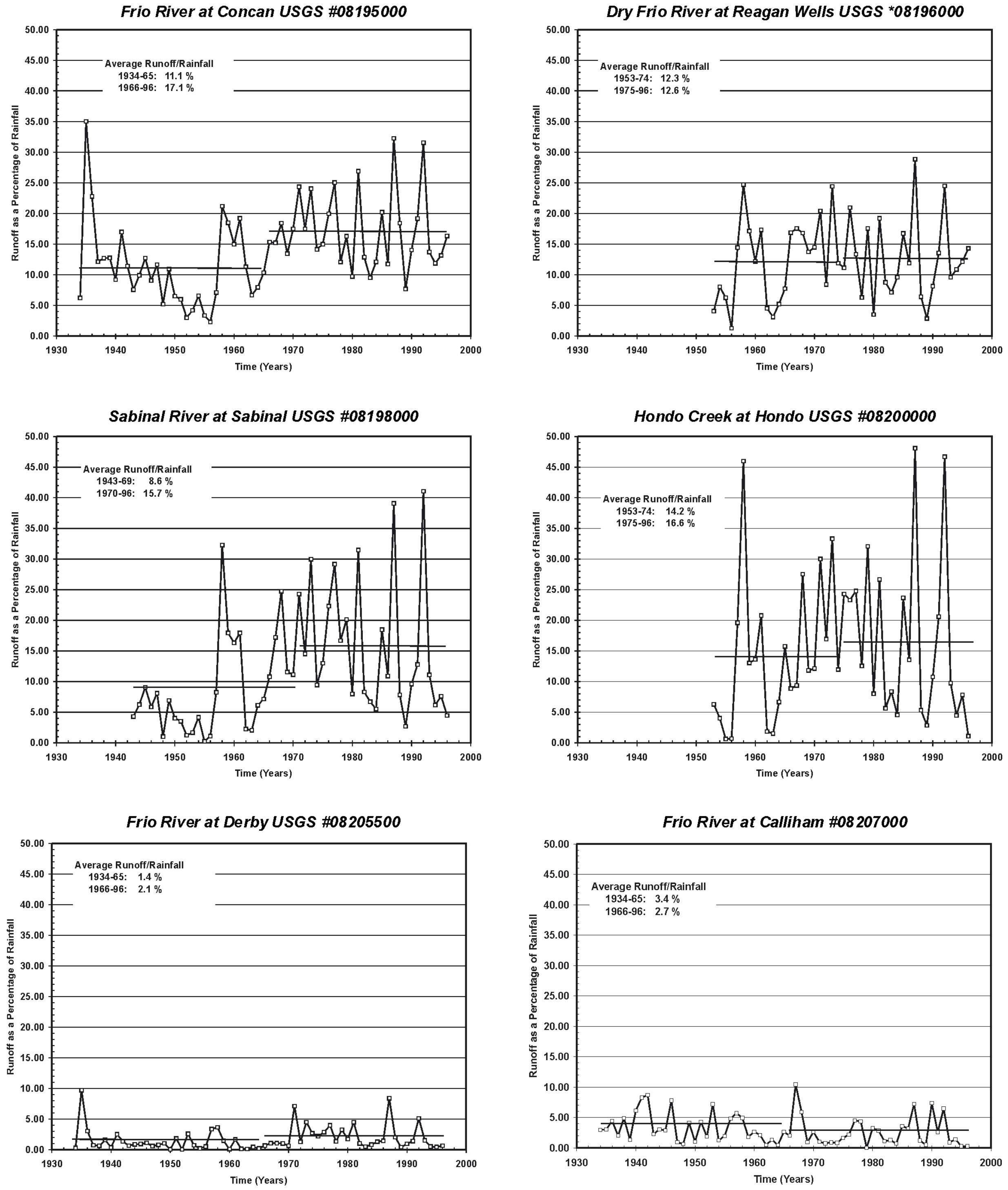
[1] Aerial precipitation and naturalized streamflow for subwatershed above the Frio River at Calliham (USGC #08207000) and below the Frio River at Derby (USGC #08205500)

Runoff as a percentage of rainfall for each of the selected sub-basins is plotted as a time series in Figure 5-3. These plots and Table 5-5 show the average values of runoff as a percentage of rainfall for the first and second halves of the available period of streamflow records. The averages for each watershed show an increase from the first time period to the second, except for the watershed between the Frio River at Derby (USGS #08205500) and Calliham (USGS #08207000) gages. Similar to the consideration of rainfall, statistical tests will assess the significance of these differences.

The statistical tests applied to historical annual rainfall and runoff per unit rainfall included the non-parametric Kendall Tau test,[6] and linear regression and sample partitioning that

---

[6] Maidment, D.R., "Handbook of Hydrology," McGraw-Hill, Inc., 1993.



Frio River at Concan USGS #08195000

Dry Frio River at Reagan Wells USGS *08196000

Sabinal River at Sabinal USGS #08198000

Hondo Creek at Hondo USGS #08200000

Frio River at Derby USGS #08205500

Frio River at Calliham #08207000

Figure 5-3. Runoff as a Percentage of Rainfall Time Series for Frio River Watershed may be classified as parametric tests. Sample partitioning, in this case, simply involves subdivision of the available historical record into halves so that the means and variances from the earlier and later sub-periods can be compared to one another. Assessment of the statistical significance of differences in sub-period means and variances was accomplished using standard t-tests and F-tests,[7] respectively. Similarly the statistical significance of the slope of a trendline obtained by linear regression of annual rainfall or runoff per unit rainfall versus time was evaluated using the t-test. Statistical significance is assumed at the 90 percent confidence level in this study.

The results of statistical tests seeking to identify trends in annual rainfall are shown in Table 5-6. Significant increases in annual rainfall are indicated for the selected subwatersheds in the headwaters of the Frio River Basin. More specifically, the Frio River at Concan (USGS #08195000), Dry Frio at Reagan Wells (USGS #08196000), Sabinal River at Sabinal (USGS #08198000), and Hondo Creek at Tarpley (USGS #08200000) indicate increasing trends in rainfall that cannot be rejected at the 90 percent confidence level. These headwater areas are in the Hill Country upstream of the outcrop of the Edwards Aquifer. Figure 5-4 shows the sub-basins that are indicating increased rainfall for the time periods considered.

Additional long-term (1916–1996) statistical analysis of aerial precipitation for these Hill Country sub-basins, however, does not support the short-term indications of increasing rainfall. Nevertheless, further research into the characteristics of Hill Country rainfall in terms of intensity, duration, and frequency as they vary with time may be warranted.

The results of statistical tests seeking to identify trends in annual runoff as a percentage of rainfall are shown in Table 5-7. Figure 5-5 highlights the sub-basins of increasing and decreasing trends. The watersheds above the Frio River at Concan (USGS #08195000) and Sabinal River at Sabinal (USGS #08198000) demonstrated increasing trends in this ratio that cannot be rejected at the 90 percent confidence level. Further investigation into the cause of increased runoff per unit rainfall indicates that greater rainfall can be directly correlated to the increased runoff per unit rainfall. Most importantly, however, none of the Hill Country watersheds considered in this study exhibited any indications of decreasing annual runoff per unit rainfall with time.

---

[7] Haan, C.T., “Statistical Methods in Hydrology,” Iowa State University Press, 1977.

Table 5-6. Indication of Statistically Significant Trend in Rainfall in the Frio River Watershed — 90% Confidence Level

Statistical Test	**Test Type**	**#08195000 Frio River, Concan**	**#08196000 Dry Frio, Reagan Wells**	**#08198000 Sabinal River, Sabinal**	**#08200000 Hondo Creek, Hondo**	**#08205500 Frio River, Derby**	**#08207000 Frio River, Calliham**
Kendall Tau	Non-parametric	Increasing, Yes	Increasing, Yes	Increasing, Yes	Increasing, Yes	No	No
Simple Regression, t-distribution	Parametric	Increasing, Yes	Increasing, Yes	Increasing, Yes	Increasing, Yes	No	No
Sample Partitioning, Mean Comparison, t-distribution	Parametric	Increasing, Yes	No	Increasing, Yes	Increasing, Yes	Increasing, Yes	Increasing, Yes
Sample Partitioning, Variance Comparison, F-distribution	Parametric	Yes	No	No	No	Yes	Yes

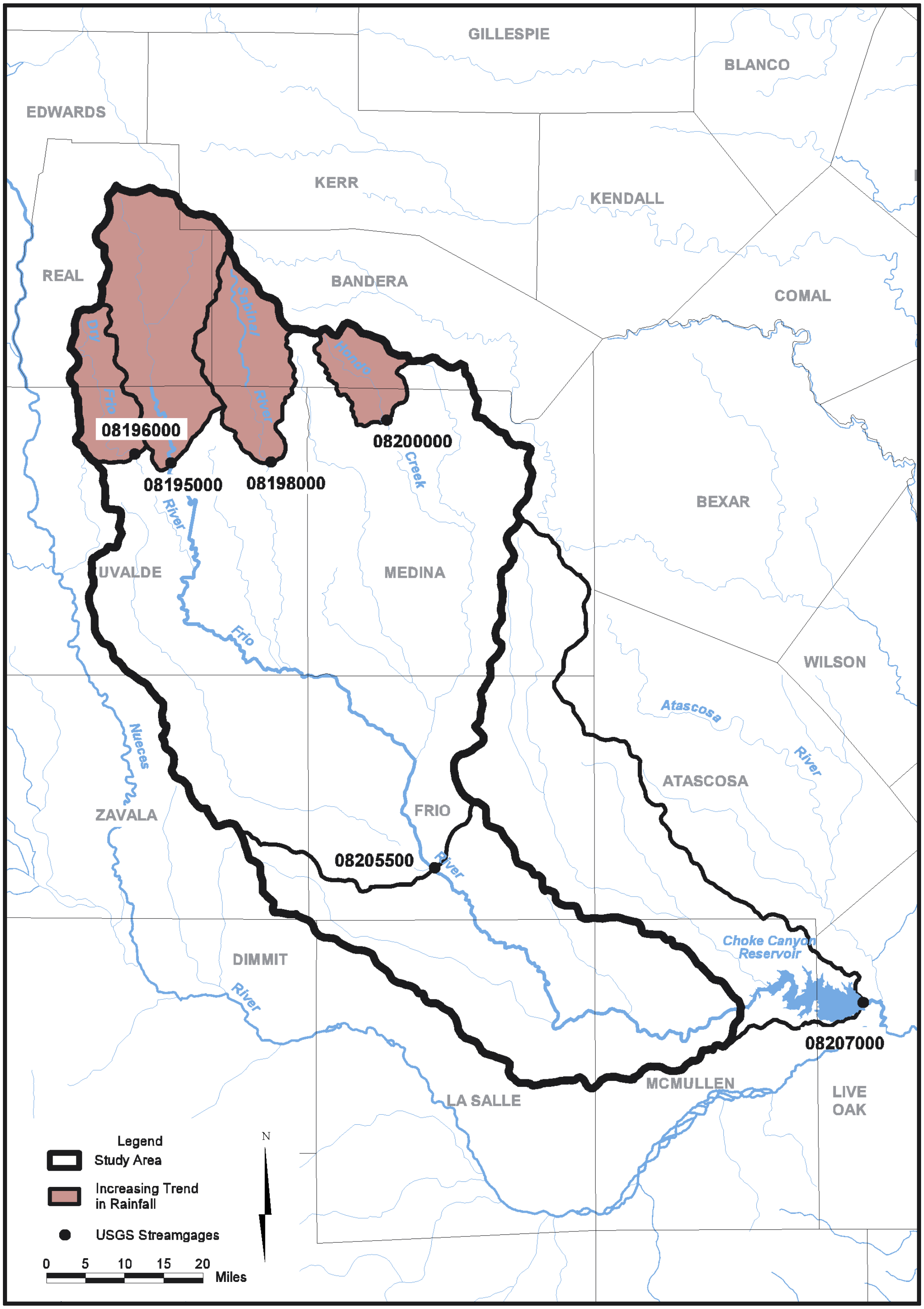


Figure 5-4. Results of Statistical Analyses of Rainfall

Table 5-7. Indication of Statistically Significant Trend in Runoff/Rainfall in the Frio River Watershed — 90% Confidence Level

Statistical Test	Test Type	#08195000 Frio River, Concan	#08196000 Dry Frio, Reagan Wells	#08198000 Sabinal River, Sabinal	#08200000 Hondo Creek, Hondo	#08205500 Frio River, Derby	#08207000 Frio River, Calliham
Kendall Tau	Non-parametric	Increasing, Yes	No	Increasing, Yes	No	No	Decreasing, Yes
Simple Regression, t-distribution	Parametric	Increasing, Yes	No	Increasing, Yes	No	No	Decreasing, Yes
Sample Partitioning, Mean Comparison, t-distribution	Parametric	Increasing, Yes	No	Increasing, Yes	No	Increasing, Yes	Decreasing, Yes
Sample Partitioning, Variance Comparison, F-distribution	Parametric	Yes	No	Yes	No	Yes	Yes

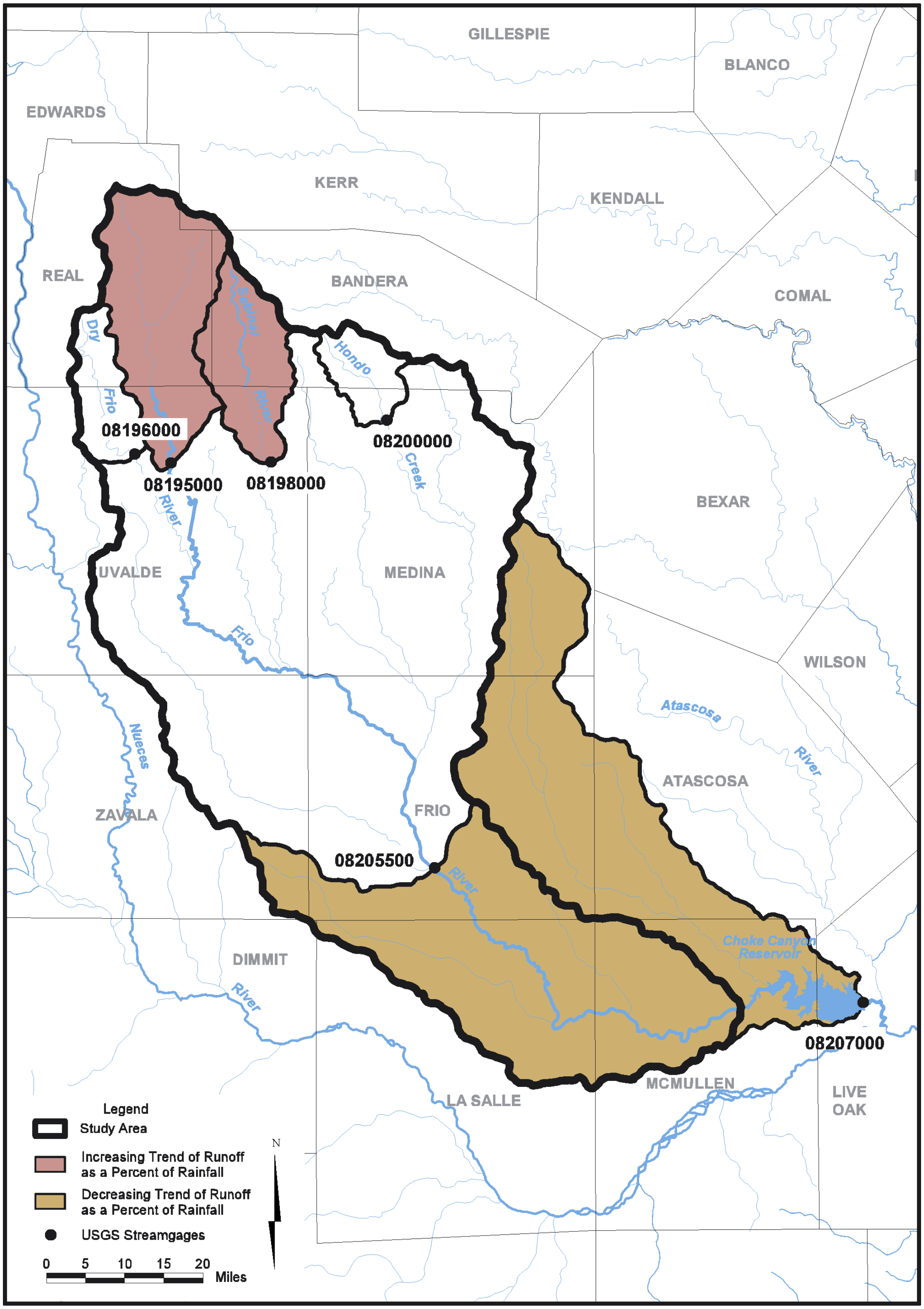


Figure 5-5. Results of Statistical Analyses of Runoff as a Percentage of Rainfall

One watershed within the Frio River Basin indicated an apparent decrease in runoff per unit rainfall over time. This watershed is in the lower portion of the Frio River basin below the Frio River at Derby (USGS #08205500) and above the Frio River at Calliham (USGS #08207000). This watershed encompasses approximately 2,062 square miles or about 50 percent of the Frio River Basin. In addition to brush proliferation, increased pumpage from the Carrizo Aquifer in recent years may be affecting observed runoff per unit rainfall in this subwatershed.

Analysis of runoff per unit rainfall for the entire Frio River Basin upstream of the streamflow gage located at Derby (USGS #08205500) are reported herein. These analyses did not provide any conclusive indications of increasing or decreasing trend due to the presence of the outcrop of the Edwards Aquifer traversing this portion of the basin, and the indications of increasing trends above the outcrop and decreasing tends below Derby. Further studies focusing on the subwatershed downstream of the Edwards outcrop and above Derby may be appropriate. In addition, an increase the likelihood of decreased runoff per unit rainfall from this subwatershed is possible because the subwatershed includes the outcrop of the Carrizo Aquifer concomitant with brush proliferation in recent years.

5.3 Potential Sites for Brush Control

Potential sites for brush control are those sites where observations and statistical analyses indicate decreasing runoff relative to the rainfall. The sites identified in this section are sub-basins that should be considered in future studies. Physical systems are very complex and subject to the influences of many factors. These factors may affect each other in ways that are not historically or currently measured. The nature of explaining trends in physical systems is to continue to identify and quantify sources and sinks in the system. In this study, rainfall is the primary source, streamflow (runoff per unit rainfall) is the main variable of concern, and brush is the main sink considered. However, the question still remains “Is brush proliferation (alone) causing observed changes in runoff per unit rainfall?”

Of the six sub-basins considered in the Frio River Basin, the sub-basin between the streamflow gages at Derby (USGS #08205500) and Calliham (USGS #08207000) is the most promising for brush control. Analyses of runoff as a percentage of rainfall indicate that there is a significant decreasing trend in this sub-basin. In addition, further hydrologic studies may identify decreasing runoff per unit rainfall in the Frio River sub-basin above Derby (USGS #08205500) and below the Edwards Aquifer outcrop. Possible sinks in these two sub-basins include not only brush proliferation, but increased pumpage from and recharge to the Carrizo Aquifer, small reservoir (stock tank) development, and changes in land management practices with time. Further investigations of these sub-basins may more precisely determine the causes of apparent changes in runoff.

5.4 Summary

Average annual rainfall throughout the Frio River Basin has generally increased between the earlier and latter portions of the last five or six decades. Causes of this trend are not known. Statistically, runoff as a percentage of rainfall in the Frio River Basin is significantly increasing in two sub-basins in the Hill Country and decreasing in one downstream sub-basin at the 90 percent confidence level. The decreasing trend in the relationship between runoff and rainfall occurs in the sub-basin between the streamflow gages on the Frio at Derby (USGS #08205500) gage and Calliham (USGS #08207000). The apparent trend may be attributed to the proliferation of brush in the watershed and, possibly, to increasing pumping from the Carrizo Aquifer in the latter part of the 20th Century. Additional studies and field research are recommended for this sub-basin.

Section 6
Hydrologic Simulation

6.1 Methods

6.1.1 Watershed Characteristics

The Frio River Watershed covers a large area of south Texas just north and east of the Nueces River basin. It is within a semiarid climatic region with soils that are primarily Usterts and Ustalfs that generally have high infiltration that allows for high percolation. The watershed generally runs northwest to east and drains into Choke Canyon Lake. Based on the digital elevation map (DEM), the derived sub-basins are shown in Figure 6-1. Due to the fact that part of the watershed lies over the western part of the Edwards Aquifer recharge zone, the watershed was divided into the upper (Edwards) and lower Frio. The upper Frio corresponds to the 8-digit hydrologic response units (HRU) 12110106, and 12110107 and the lower corresponds to the 8-digit HRUs 12110108, and 12110109. The HRU 12110106, 12110107, 12110109 all feed into the HRU 12110108. Actual flow at Derby (outlet of 12110106 and 12110107) served as input into model runs. The streamflow near Choke Canyon (outlet of 1211108; sub-basin 1) was used to calibrate the flows for the Frio.

6.1.2 Climate

For the simulations actual, weather data from 1960–1998 were used. The model used daily maximum and minimum air temperatures, precipitation, and solar radiation. Solar radiation was generated using the WGEN model based on parameters for the specific climate station. Climate stations are shown in Figure 6-2. For each sub-basin, precipitation and temperature data are retrieved by the SWAT input interface for the climate station nearest the centroid of the sub-basin.

6.1.3 Topography

The outlet or "catchment" for the Frio River simulated in this study is Choke Canyon Lake, which is located just downstream of sub-basin number 108_1. The sub-basin delineation and numbers are shown in Figure 6-1. Roads (obtained from the Census Bureau) are overlaid in Figure 6-3.

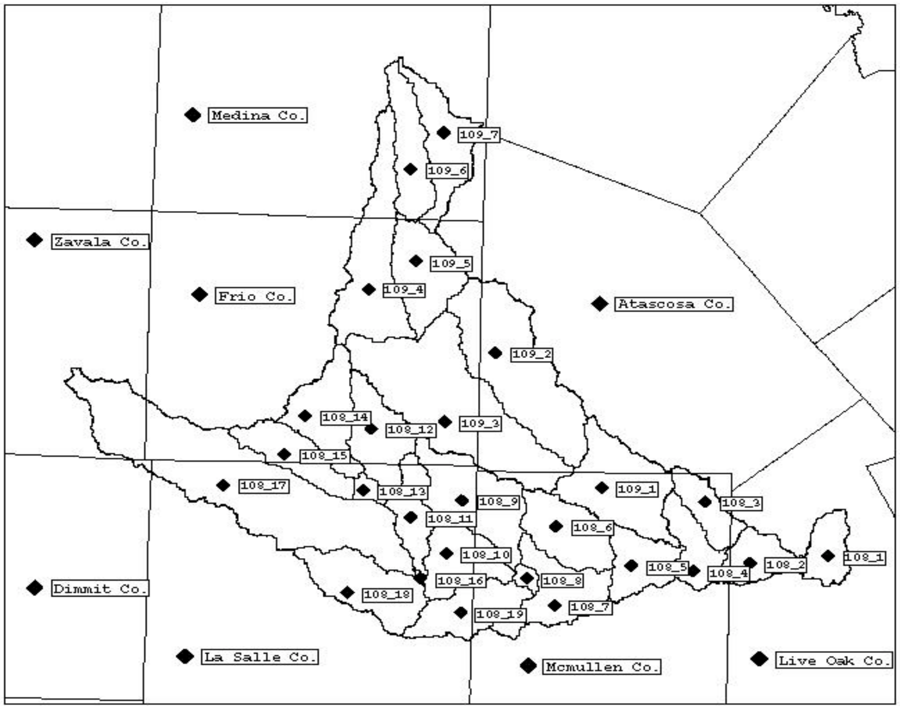


Figure 6-1. Frio River Watershed Sub-Basin Map

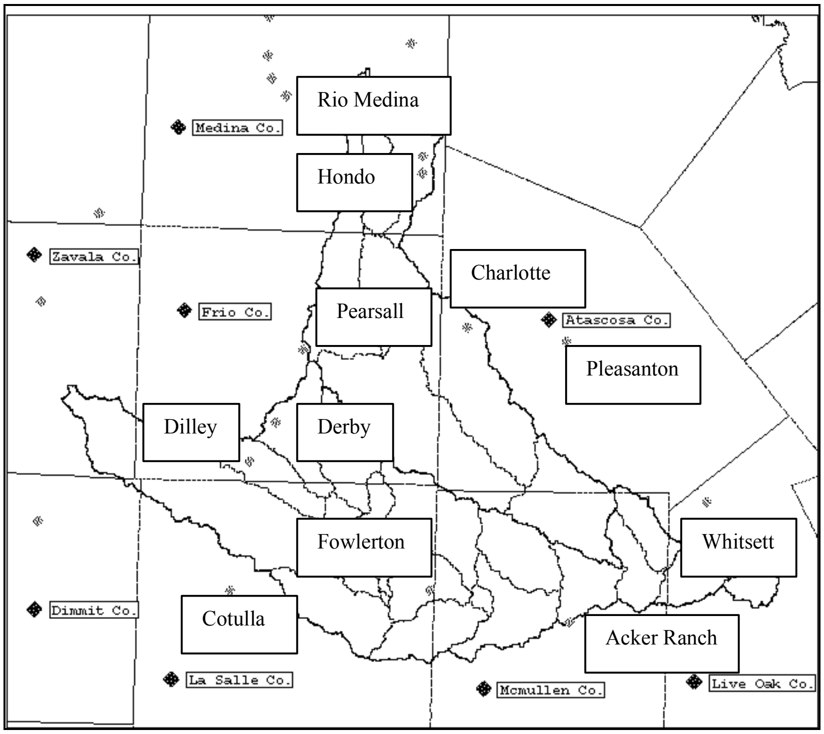


Figure 6-2. Climate Stations in the Frio Watershed

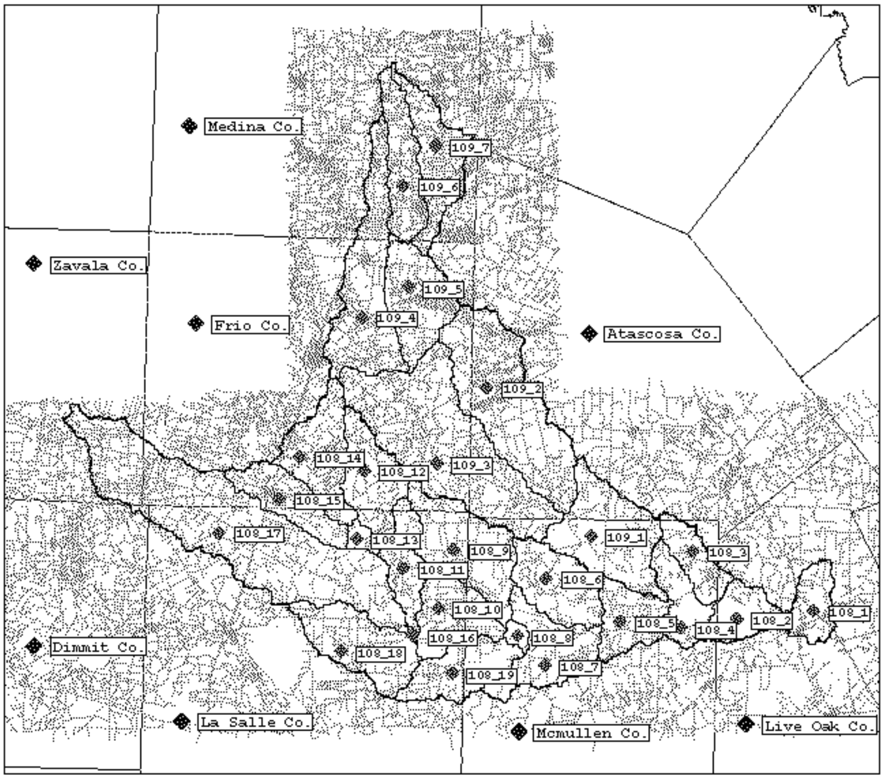


Figure 6-3. Frio River Watershed Roads Map

6.1.4 Soils

The dominant soil series in the Frio River Watershed are Uvalde, Duval, and Monteola. These three soil series represent over 50 percent of the watershed area. A short description of each follows:

- ***Uvalde.*** The Uvalde series consists of deep, well-drained, moderately permeable soils formed in alluvium from limestone. These level to gently sloping or gently undulating soils are on alluvial fans or stream terraces. Slopes range from 0 to 3 percent.
- ***Duval.*** The Duval series consists of deep, well drained, moderately permeable soils that formed in sandy clay loams with interbedded sandstone on uplands. Slopes range from 1 to 5 percent.
- ***Monteola.*** The Monteola series consists of deep, moderately well drained very slowly permeable soils that formed in clays and shaly clays. These soils are on gently undulating uplands. Slopes range from 0 to 8 percent.

6.1.5 Land Use/Land Cover

Figure 6-4 show the areas of heavy and moderate brush in the Frio River Watershed that is the area of brush removed or treated in the no-brush simulation. This corresponds to 69 percent of the total watershed area.

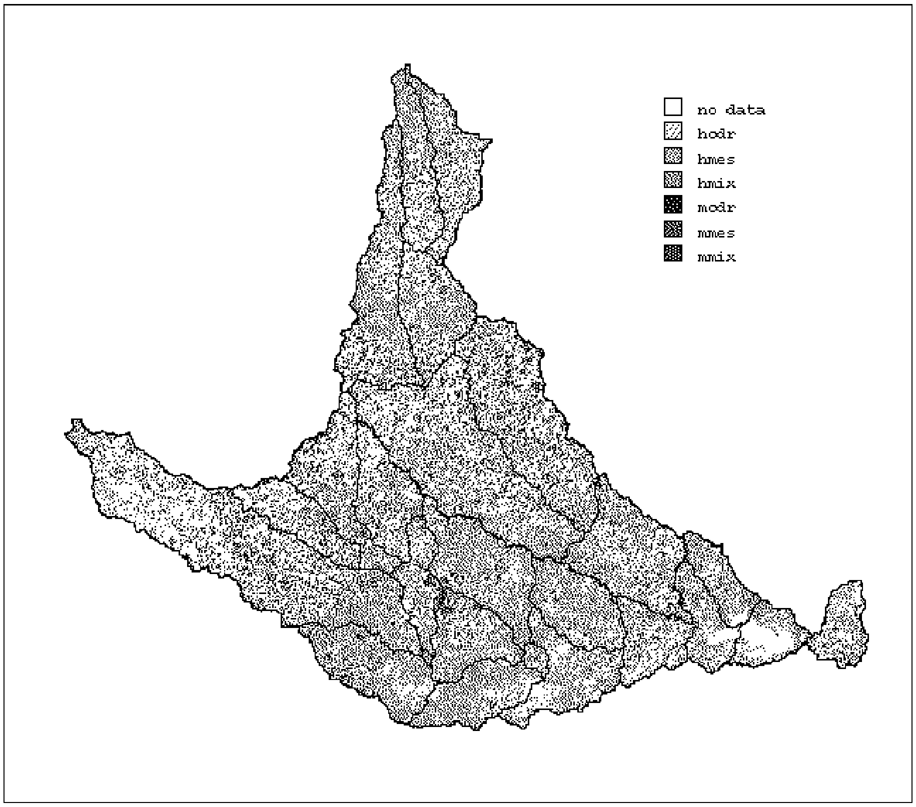


Figure 6-4. Areas of Heavy and Moderate Brush in the Frio River Watershed

6.1.6 Model Input Variables

Significant input variables for the SWAT model for the Frio River Watershed are shown in Table 6-1. Input variables for all sub-basins in the watershed were the same, with the following exceptions:

- It was necessary to decrease the curve number by 8 in order to calibrate flow at streamgauge flowing into Choke Canyon.
- The baseflow factor was calculated to be 0.0264. Also the amount of heat units for the crops to mature were for mixed brush 4,623 degree days, oak 4,325, and brushy range 3,331 degree days.

Table 6-1. SWAT Input Variables for Frio River Watershed

Variable	Brush Condition (Calibration)	No Brush Condition
Runoff Curve Number Adjustment	-9	-8
Soil Available Water Capacity Adjustment (%)	0	0
Soil Evaporation Compensation Factor (in^3 in^{-3})	0.1	0.1
Min. Shallow Aqu. Storage for GW flow (inches)	0	0
Shallow Aqu. Re-Evaporation (Revap) Coefficient	0.4	0.1
Min. Shallow Aqu. Storage for Revap (inches)	0.3	0.3
Potential Heat Units (degree days)	5399	5399
Heavy Cedar	N/A	N/A
Heavy Mesquite	N/A	N/A
Heavy mixed Brush	4623	4623
Moderate Cedar	N/A	N/A
Moderate Mesquite	N/A	N/A
Moderate Mixed Brush	0.039	N/A
Heavy Oak	0	0
Moderate Oak	0	0
Light Brush & Open Range/Pasture	0	0
Plant Roof Depth (feet)		
Heavy and Moderate Brush	6.5	N/A
Light Brush and Open Range/Pasture	3.3	3.3
Maximum Leaf Area Index		
Heavy Cedar	6	N/A
Heavy Mesquite	4	N/A
Heavy Mixed Brush	4	N/A
Moderate Cedar	5	N/A
Moderate Mesquite	2	N/A
Moderate Mixed Brush	3	N/A
Heavy Oak	4	4
Moderate Oak	3	3
Light Brush	2	2
Light Brush & Open Range/Pasture	3.3	3.3
Maximum Leaf Area Index		
Heavy Cedar	6	N/A
Heavy Mesquite	4	N/A
Heavy Mixed Brush	4	N/A
Moderate Cedar	5	N/A
Moderate Mesquite	2	N/A
Moderate Mixed Brush	3	N/A
Heavy Oak	4	4
Moderate Oak	3	3
Light Brush	2	2
Open Range & Pasture	1	1
Channel Transmission Loss (inches/hour)	0.04	0.04
Sub-basin Transmission Loss (inches/hour)	0.015	0.015
Fraction Trans. Loss Returned as Baseflow	0.10	0.10

- It was that assumed the re-evaporation coefficient would be higher for brush than for other types of cover because brush is deeper rooted, and opportunity for re-evaporation from the shallow aquifer is higher. The re-evaporation coefficient for all brush hydrologic response units is 0.4, and for non-brush units is 0.1. Also, for the non-brush condition curve number increased by 4 units to account for the change from fair to good hydrologic conditions and from brush to range conditions.

6.2 Frio River Watershed Results

6.2.1 Calibration

SWAT was calibrated for the flow at streamgauges near Choke Canyon Lake. The results of calibration are shown in Figure 6-5. Measured and predicted average monthly flows compare reasonably well with a 3 percent difference between measured and simulated cumulative flow. At the outlet, the measured monthly mean is 6,263 acft, and predicted monthly mean is 5,969 acft. The coefficient of determination (r^2) was 0.99 between measured and simulated flows. Average baseflow for the entire watershed is 10 percent of total flow.

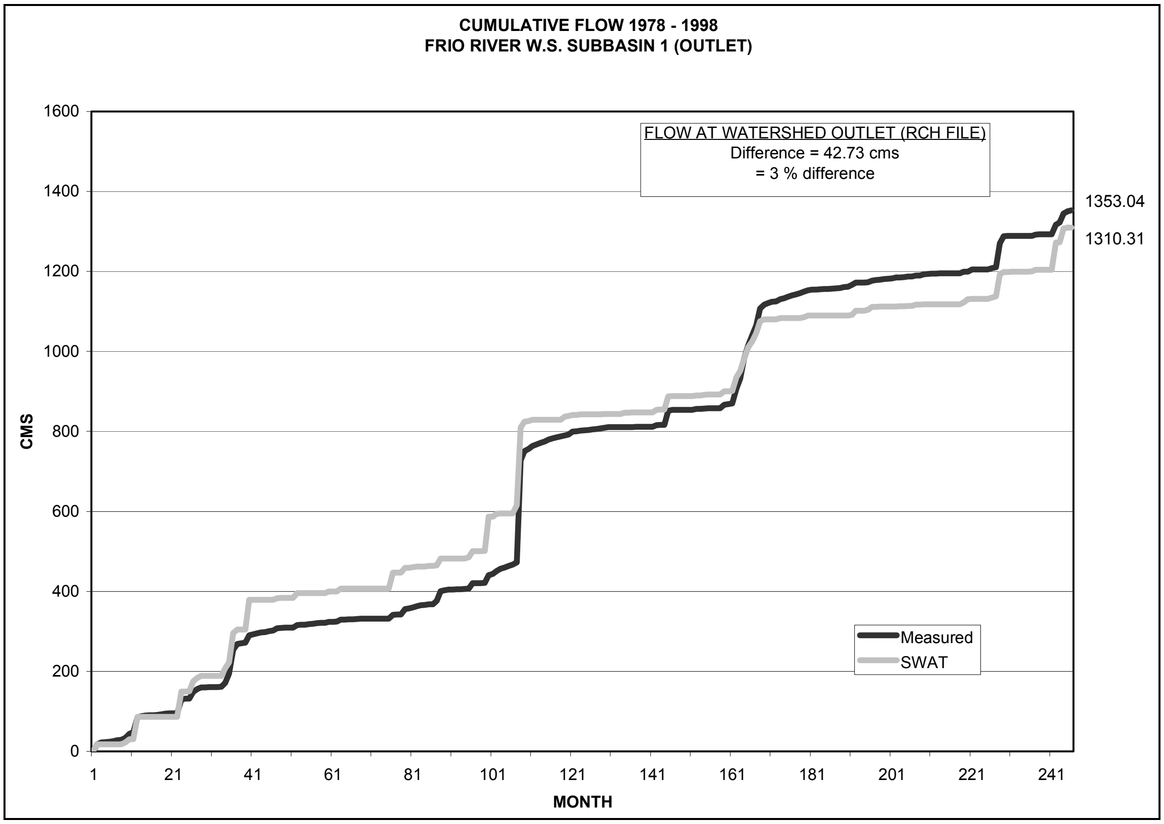


Figure 6-5. Simulated and Measured Cumulative Flow at the Outlet of the Frio

6.2.2 Brush Removal Simulation

The average annual rainfall for the Frio River Watershed is 24.85 inches. Average annual evapotranspiration (ET) in the Frio is 24.20 inches for the brush condition (calibration) and 21.64 inches for the no-brush condition. This represents 98 percent and 87 percent of precipitation for the brush and no-brush conditions, respectively.

The increases in water yield by sub-basin for the Frio River Watersheds are shown in Figures 6-6 and 6-7, and Table 6-2. The amount of annual increase varies among the sub-basins and ranges from 33,557 gallons per acre of brush removed per year in sub-basin number 108-18, to 202,206 gallons per acre in sub-basin number 108-2. Variations in the amount of increased water yield are expected and are influenced by brush type, brush density, soil type, and average annual rainfall, with sub-basins receiving higher average annual rainfall generally producing higher water yield increases. The larger water yields are most likely due to greater rainfall volumes as well as increased density and canopy of brush. In addition, Table 6-2 gives the total sub-basin area, area of brush treated, fraction of sub-basin treated, water yield increase per acre of brush treated, and total water yield increase for each sub-basin.

For the Frio River Watershed, the average annual water yield increases by 125 percent or approximately 223,696 acft. The average annual flow to Choke Canyon could increase by 59,806 acft. The increase in volume of flow to the lake is less than the water yield because of stream channel transmission losses that occur after water leaves each sub-basin.

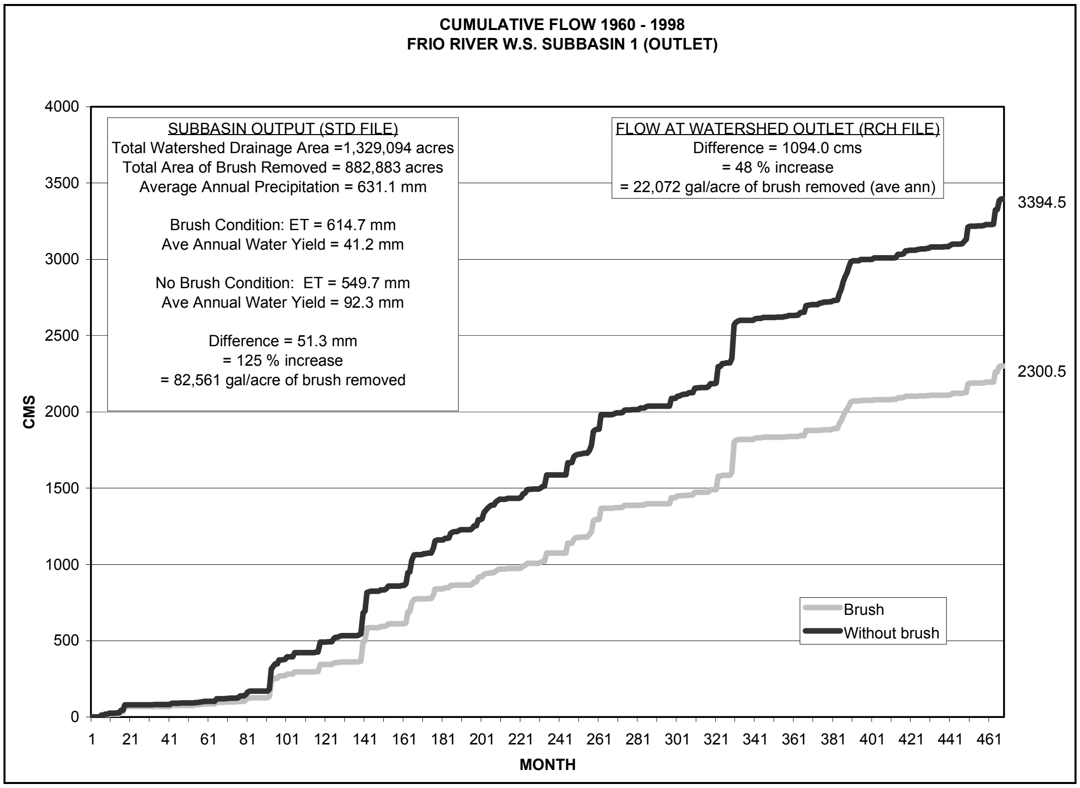


Figure 6-6. Simulated Cumulative Flow at the Outlet for Brush and No Brush Conditions in the Frio

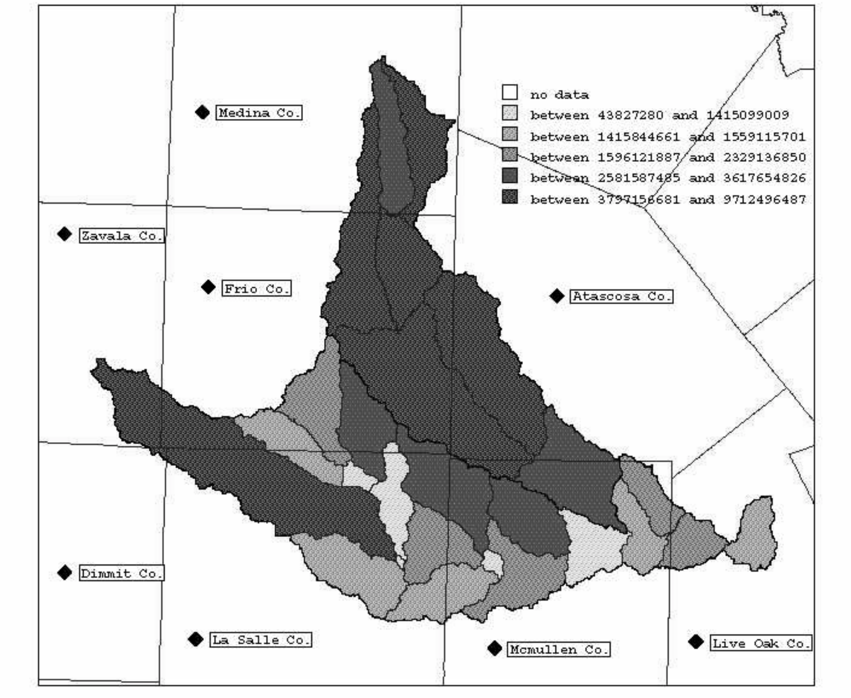


Figure 6-7. Increased Water Yield (Gallons) by Sub-Basin

Table 6-2. Frio Areas and Water Yield

Sub-basin	Ave. Ann Gal. Incr.	Sub-basin in Total Area (acres)	Brush Removal Area (acres)	Fraction of Sub-basin Containing Brush	Increase (gal/ac Water Yield)
108-1	1506088753	25211	15954	0.63	94402
108-2	2283104752	248750	11291	0.45	202206
108-3	1798053066	24741	19385	0.78	92755
108-4	1559115701	27642	18066	0.65	86301
108-5	1415099009	32993	17562	0.53	80577
108-6	3438828182	44913	35086	0.78	98011
108-7	2329136850	45886	29845	0.65	78041
108-8	202848213	4654	3038	0.65	66770
108-9	3617654826	63441	52091	0.82	69449
108-10	1596121887	40167	30702	0.76	571988
108-11	1410685834	28457	18648	0.66	75648
108-12	2581587485	43191	26096	0.60	98927
108-13	434595326	6838	6839	1.00	63547
108-14	2060776742	47339	26505	0.56	77750
108-15	1417183557	36259	18140	0.50	78125
108-16	43827280	909	701	0.77	62521
108-17	7047889265	194816	103020	0.53	68413
108-18	1459411484	53979	43491	0.81	33557
108-19	1415844661	40977	34191	0.83	41410
109-1	3255215997	70615	44558	0.63	73056
109-2	6729221911	109090	71140	0.65	94591
109-3	9712496487	145477	100582	0.69	96563
109-4	5148441909	80492	58750	0.73	87633
109-5	3797156681	50217	34449	0.69	110225
109-6	3058860451	40476	29069	0.72	105228
109-7	4569745200	45464	33684	0.74	135665

Section 7
Economic Analysis

7.1 Introduction

Amounts of the various types and densities of brush cover in the watershed were detailed in Section 6. Changes in water yield (runoff and percolation) resulting from control of specified brush type-density categories were estimated using the SWAT hydrologic model. This economic analysis utilizes brush control processes and their costs, production economics for livestock, and wildlife enterprises in the watershed and the previously described, hydrological-based water yield data to determine the per acft costs of a brush control program for water yield for the Frio River Watershed.

7.2 Brush Control Costs

Brush control costs include both initial and follow-up treatments required to reduce current brush canopies to 5 percent or less and maintain it at the reduced level for at least 10 years. Both types of treatments and their costs were obtained from meetings with landowners and Range Specialists of the Texas Agriculture Experiment Station and Extension Service, and USDA-NRCS with brush control experience in the project areas. All current information available (such as costs from recently contracted control work) was used to formulate an average cost for the various treatments for each brush type-density category.

Obviously, the costs of control will vary among brush type-density categories. Present values (using an 8 percent discount rate) of control programs are used for comparison since some of the treatments will be required in the first and second years of the program while others will not be needed until year 6 or 7. Table 7-1 presents present values of total control costs per acre for the northern portion of the region which consists of sub-basins with the 109 prefix. Present values of total costs range from $170.42 per acre for rootplowing with predozing for control of heavy mesquite or mixed brush to $83.99 per acre for moderate mesquite or mixed brush that can be initially controlled with herbicide treatments. Similar information is presented in Table 7-2 for the southern portion of the region consisting of sub-basins with the 108 prefix. For this portion of the region, present values of total costs range from $140.42 per acre for rootplowing with predozing for control of heavy mesquite or mixed brush to $76.64 per acre for moderate

Table 7-1. Cost of Water Yield Brush Control Programs by Type-Density Category (Northern Portion of Frio River Watershed)

Year	Treatment	Treatment Cost ($/acre)	Present Value ($/acre)
Heavy Mesquite — Chemical Herbicide[1]			
0	Chemical Herbicide	45.00	45.00
4	Chemical Herbicide	40.00	29.40
7	Choice IPT or Burn	25.00	14.59
		Total	88.99
Heavy Mesquite — Rootplow[2]			
0	Rootplow	110.00	110.00
5	Choice IPT or Burn	30.00	20.42
		Total	130.42
Extra Heavy Mesquite — Rootplow with Pre-Doze[3]			
0	Pre-doze and Rootplow	150.00	150.00
5	Choice IPT or Burn	30.00	20.42
		Total	170.42
Heavy Mixed Brush — Chemical Herbicide[1]			
0	Chemical Herbicide	90.00	90.00
5	Choice IPT or Burn	35.00	23.82
		Total	113.82
Heavy Mixed Brush — Chop Method[4]			
0	Choice of Chop Method	45.00	45.00
4	Choice Chop, IPT, or Burn	45.00	33.08
7	Choice IPT or Burn	25.00	14.59
		Total	92.67
Heavy Mixed Brush — Rootplow[2]			
0	Rootplow	100.00	100.00
5	IPT or Burn	30.00	20.42
		Total	120.42
Extra Heavy Mixed Brush — Rootplow with Pre-Doze[3]			
0	Pre-Doze and Rootplow	150.00	150.00
5	IPT or Burn	30.00	20.42
		Total	170.42

Table 7-1. Cost of Water Yield Brush Control Programs by Type-Density Category (Northern Portion of Frio River Watershed) (Continued)

Year	***Treatment***	***Treatment Cost ($/acre)***	***Present Value ($/acre)***
Moderate Mesquite — Chemical Herbicide[1]			
0	Aerial or IPT Herbicide	40.00	40.00
4	Aerial or IPT Herbicide	40.00	29.40
7	Choice IPT or Burn	25.00	14.59
		Total	83.99
Moderate Mixed Brush — Chemical Herbicide[1]			
0	Aerial or IPT Herbicide	40.00	40.00
4	Aerial or IPT Herbicide	40.00	29.40
7	Choice IPT or Burn	25.00	14.59
		Total	83.99

[1] Either aerial or individual chemical application may be used.

[2] Rootplow, rake, stack, and burn.

[3] Heavy tree-doze, rootplow, rake, stack, and burn. Note: canopy cover for this practice is 40% or greater.

[4] Choice of roller-chop, aerator method, or deep disking.

Table 7-2. Cost of Water Yield Brush Control Programs by Type-Density Category (Southern Portion of Frio River Watershed)

Year	Treatment	Treatment Cost ($/acre)	Present Value ($/acre)
Heavy Mesquite — Chemical Herbicide[1]			
0	Chemical Herbicide	45.00	45.00
4	Chemical Herbicide	40.00	29.40
7	Choice IPT or Burn	25.00	14.59
		Total	88.99
Heavy and Extra Heavy Mesquite — Rootplow and Pre-Doze[2]			
0	Pre-Doze and Rootplow	120.00	120.00
5	Choice IPT or Burn	30.00	20.42
		Total	140.42
Heavy Mixed Brush — Chemical Herbicide[3]			
0	Chemical Herbicide	50.00	50.00
4	Choice Chop, IPT, or Burn	60.00	44.10
7	Choice IPT or Burn	25.00	14.59
		Total	108.69
Heavy Mixed Brush — Chop Method[4]			
0	Choice of Chop Method	45.00	45.00
4	Choice Chop, IPT, or Burn	45.00	33.08
7	Choice IPT or Burn	25.00	14.59
		Total	92.67
Heavy and Extra Heavy Mixed Brush — Rootplow with Pre-Doze[2]			
0	Pre-Doze and Rootplow	120.00	120.00
5	IPT or Burn	30.00	20.42
		Total	140.42
Moderate Mesquite — Chemical Herbicide[1]			
0	Aerial or IPT Herbicide	40.00	40.00
4	Aerial or IPT Herbicide	30.00	20.42
7	Choice IPT or Burn	25.00	14.59
		Total	76.64

Table 7-2. Cost of Water Yield Brush Control Programs by Type-Density Category (Southern Portion of Frio River Watershed) (Continued)

Year	Treatment	Treatment Cost ($/acre)	Present Value ($/acre)
Moderate Mixed Brush — Chemical Herbicide[1]			
0	Aerial or IPT Herbicide	40.00	40.00
4	Aerial or PIT Herbicide	40.00	29.40
7	Choice IPT or Burn	25.00	14.59
		Total	83.99

[1] Either aerial or individual chemical application may be used.

[2] Heavy tree-doze, rootplow, rake, stack, and burn. Note: canopy cover for this practice is 40% or greater.

[3] Aerial or individual chemical application may be used. Year 4 choice includes chemicals, choice or chop method or burning if effective.

[4] Choice of roller-chop, aerator method, or deep disking.

mesquite that can be initially controlled with herbicide treatments. Costs of treatments, year those treatments are needed and treatment life for each brush type-density category are detailed in Tables 7-1 and 7-2.

7.3 Landowner and State Cost Shares

Rancher benefits are the total benefits that will accrue to the rancher as a result of the brush control program. These total benefits are based on the present value of the improved net returns to the ranching operation through typical cattle, sheep, goat, and wildlife enterprises that would be reasonably expected to result from implementation of the brush control program. For the livestock enterprises, an improvement in net returns would result from increased amounts of usable forage produced by controlling the brush and, thus, eliminating much of the competition for water and nutrients within the plant communities on which the enterprise is based. The differences in grazing capacity with and without brush control for each of the brush type-density categories in the Frio River Watershed are shown in Tables 7-3 (sub-basins with 109 prefix) and 7-4 (sub-basins with 108 prefix). Data relating to grazing capacity was entered into the investment analysis model.

Table 7-3. Grazing Capacity With and Without Brush Control (Acres/AUY) (Northern Portion of Frio River Watershed)

		Program Year									
Brush Type / Category	**Brush Control**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Heavy Mesquite	Control	36.0	32.0	28.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
	No Control	36.0	36.0	36.1	36.1	36.2	36.2	36.2	36.3	36.3	36.4
Heavy Mixed Brush	Control	36.0	32.0	28.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
	No Control	36.0	36.0	36.1	36.1	36.2	36.2	36.2	36.3	36.3	36.4
Moderate Mesquite	Control	32.0	29.3	26.7	24.0	24.0	24.0	24.0	24.0	24.0	24.0
	No Control	32.0	32.2	32.4	32.5	32.7	32.9	33.1	33.2	33.4	33.6
Moderate Mixed Brush	Control	32.0	29.3	26.7	24.0	24.0	24.0	24.0	24.0	24.0	24.0
	No Control	32.0	32.2	32.4	32.5	32.7	32.9	33.1	33.2	33.4	33.6

Table 7-4. Grazing Capacity With and Without Brush Control (Acres/AUY) (Southern Portion of Frio River Watershed)

		Program Year									
Brush Type / Category	**Brush Control**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Heavy Mesquite	Control	38.0	33.0	28.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
	No Control	38.0	38.0	38.1	38.1	38.2	38.2	38.3	38.3	38.3	38.4
Heavy Mixed Brush	Control	35.0	31.0	27.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
	No Control	35.0	35.0	35.1	35.1	35.2	35.2	35.2	35.3	35.3	35.4
Moderate Mesquite	Control	30.0	27.6	25.3	23.0	23.0	23.0	23.0	23.0	23.0	23.0
	No Control	30.0	30.2	30.3	30.5	30.7	30.8	31.0	31.2	31.3	31.5
Moderate Mixed Brush	Control	30.0	27.6	25.3	23.0	23.0	23.0	23.0	23.0	23.0	23.0
	No Control	30.0	30.2	30.3	30.5	30.7	30.8	31.0	31.2	31.3	31.5

As with the brush control practices, the grazing capacity estimates represent a consensus of expert opinion obtained through discussions with landowners, Texas Agricultural Experiment Station and Extension Service Scientists and USDA-NRCS Range Specialists with brush control experience in the area. In the northern portion of the watershed, livestock grazing capacities range from about 24 acres per animal unit year (AUY) for land on which mesquite is controlled, to 36 acres per AUY for land infested with heavy mixed brush. In the southern portion of the watershed, livestock grazing capacities range from about 23 acres per AUY for land on which mesquite is controlled to 38 AUY for land infested with heavy mesquite.

Livestock production practices, revenues, and costs representative of the watershed were obtained from personal interviews with a focus group of local ranchers. Estimates of the variable costs and returns associated with the livestock and wildlife enterprises typical of each area were then developed from this information into livestock production investment analysis budgets. This information for the livestock enterprises (cattle) in the project areas is shown in Table 7-5. It is important to note once again that the investment analysis budgets are for analytical purposes only, as they do not include all revenues nor all costs associated with a production enterprise. The data are reported per animal unit for each of the livestock enterprises. From these budgets, data were entered into the investment analysis model.

Rancher benefits were also calculated for the financial changes in existing wildlife operations. Most of these operations in this region were determined to be simple hunting leases with deer, turkey, and quail being the most commonly hunted species. Therefore, wildlife costs and revenues were entered into the model as simple entries in the project period. For control of heavy brush categories, wildlife revenues are expected to increase by about $1.50 per acre (from $10.00 per acre to $11.50 per acre) due principally to the resulting improvement in quail habitat. Wildlife revenues would not be expected to change with implementation of brush control for the moderate brush type-density categories.

Table 7-5. Investment Analysis Budget, Cow-Calf Production

Revenue Item Description	***Quantity***	***Unit***	***$ / Unit***	***Cost***
Partial Revenues				
Calves	425.00	Pound	.85	361.25
Cows	111.1	Pound	.40	0
Bulls	250.0	Pound	.50	0
			Total	361.25
Variable Cost Item Description	***Quantity***	***Unit***	***$ / Unit***	***Cost***
Partial Variable Costs				
Supplemental Feed	400.0	Pound	0.10	40.00
Salt & Minerals	50.0	Pound	0.20	10.00
Marketing	1.0	Head	6.25	6.25
Veterinary Medicine	1.0	Head	12.00	12.00
Miscellaneous	1.0	Head	5.00	5.00
Net Replacement Cows[3]	1.0	Head	35.28	35.28
Net Replacement Bulls[4]	1.0	Head	3.09	6.09
			Total	114.62

Note: This budget is for presentation of the information used in the investment analysis only. Values herein are representative of a typical ranch in the Lower Frio and Nueces Watersheds. The budget is based on 1 cow-calf pair per animal unit. Variable costs listed here include only items which change as a result of implementing a brush control program and adjusting livestock numbers to meet changes in grazing capacity. Net returns cannot be calculated from this budget, for not all revenues and variable costs have been included, nor have fixed costs been considered.

With the information presented in Table 7-4, present values of the benefits to landowners were estimated for each of the brush type-density categories using the procedure described in Appendix B. In the northern portion of the watershed, they range from $23.43 per acre for control of moderate mesquite and mixed brush to $39.76 per acre for the control of heavy mesquite and mixed brush (Table 7-5). In the southern portion of the watershed, they range from $21.07 per acre for control of moderate mesquite and mixed brush to $41.60 per acre for the control of heavy mixed brush (Table 7-6).

The state cost share is estimated as the difference between the present value of the total cost per acre of the control program and the present value of the rancher benefits. Present values of the state per acre cost share of brush control in the northern portion of the project area range from $49.23 for control of heavy mesquite with chemical treatments to $130.66 for control of heavy mesquite and mixed brush by mechanical method. State per acre cost share of brush control in the southern portion of the project area range from $50.28 for control of heavy mesquite with chemical treatments to $101.71 for control of heavy mesquite brush by mechanical method. Total treatment costs and landowner and state cost shares for all brush type-density categories are shown by both cost-share percentage and actual costs in Tables 7-6 and 7-7.

Table 7-6. Landowner / State Cost-Shares of Brush Control (Northern Portion of Frio River Watershed)

Brush Type and Density	Control Practice	PV of Total Cost ($/acre)	Rancher Share ($/acre)	Rancher (%)	State Share ($/acre)	State (%)
Heavy Mesquite	Chemical	88.99	39.76	0.45	49.23	0.55
	Rootplow	130.42	39.76	0.30	90.66	0.70
	Doze and Plow[1]	170.42	39.76	0.23	130.66	0.77
Heavy Mixed Brush	Chemical	113.82	39.76	0.35	74.06	0.65
	Chop[2]	92.67	39.76	0.43	52.91	0.57
	Rootplow	120.42	39.76	0.33	80.66	0.67
	Doze and Plow[1]	170.42	39.76	0.23	130.66	0.77
Moderate Mesquite	Treatment Choice	83.99	23.43	0.28	60.56	0.72
Moderate Mixed Brush	Treatment Choice	83.99	23.43	0.28	60.56	0.72
Average		117.24	36.13	0.32	81.11	0.68

Note: Averages are simple averages, and do not reflect actual project averages based on the relative percent of each brush category. Rancher ability to pay is based on the net present value of a 10 year income stream which is realized by engaging in an production agriculture enterprise venture of 100% cow-calf cattle. In this region, 20% of typical ranch resources are assigned to wildlife production, but this budget is based on a 100% assignment of carrying capacity to the livestock operation.

[1] The (pre)doze and plow category is for extra heavy brush canopy cover classifications in excess of 40% canopy cover.

[2] The "Chop" category is for roller chopping, heavy disking, or for the use of heavy "aerator"-type treatments. This category is not for use in areas where mesquite or other plants which sprout from the root crown, unless additional means for controlling those plants are used.

Table 7-7. Landowner / State Cost-Shares of Brush Control (Southern Portion of Frio River Watershed)

Brush Type and Density	Control	PV of Total Cost ($/acre)	Rancher Share ($/acre)	Rancher (%)	State Share ($/acre)	State (%)
Heavy Mesquite	Chemical	88.99	38.71	.43	50.28	0.57
	Doze and Plow[1]	140.42	38.71	.28	101.71	0.72
Heavy Mixed Brush	Chemical (Chop)[2]	108.69	41.60	.38	67.09	0.62
	Chop[3]	92.67	41.60	.45	51.07	0.55
	Doze and Plow[1]	140.42	41.60	.30	98.82	0.70
Moderate Mesquite	Treatment Choice	76.64	21.07	.27	55.57	0.73
Moderate Mixed Brush	Treatment Choice	83.99	21.07	.25	62.92	0.75
Average		104.55	34.91	0.34	69.64	0.66

Note: Averages are simple averages, and do not reflect actual project averages based on the relative percent of each brush category. Rancher ability to pay is based on the net present value of a 10 year income stream which is realized by engaging in an production agriculture enterprise venture of 100% cow-calf cattle. In this region, 20% of typical ranch resources are assigned to wildlife production, but this budget is based on a 100% assignment of carrying capacity to the livestock operation.

[1] The (pre)doze and plow category is for extra heavy brush canopy cover classifications in excess of 40% canopy cover. However, only one category of cost was included for all rootplow treatment options.. A cost average between heavy and extra heavy was used.

[2] This chemical treatment can be used in combinations of chemical or mechanical chop methods for retreatments.

[3] The “Chop” category is for roller chopping, heavy disking, or for the use of heavy “aerator”-type treatments. This category is not for use in areas where mesquite or other plants which sprout from the root crown, unless additional means for controlling those plants

7.4 Cost of Additional Water

The total cost of additional water is determined by dividing the total state cost share if all eligible acreage were enrolled in the program by the total added water estimated to result from the brush control program over the assumed 10-year life of the program. The brush control program water yields and the estimated acreage by brush type-density category by sub-basin were supplied by the Blacklands Research Center, Texas Agricultural Experiment Station in Temple, Texas (see previous Section 6). The total state cost share for each sub-basin is estimated by multiplying the per acre state cost share for each brush type-density category by the eligible acreage in each category for the sub-basin. The cost of added water resulting from the control of the eligible brush in each sub-basin is then determined by dividing the total state cost share by the added water yield (adjusted for the delay in time of availability over the 10-year period using a 6 percent discount rate).

The cost of added water was determined to average $36.95 per acft for the entire Nueces River Watershed (Table 7-8*). Sub-basins range from costs per added acft of $14.94 to $90.03.

Table 7-8. Cost of Added Water from Brush Control by Sub-Basin (Acre-Foot)*

Sub-basin	Total State Cost ($)	Added Gallons per Year	Added Acft/yr	Total Acft 10 Yrs. Dsctd.	State Cost/Acft ($)
108-1	1114233	1506088753	4622.016667	36060.97	30.90
108-2	816678	2283104752	7006.591207	54665.42	14.94
108-3	1402045	1798053066	5518.022244	43051.61	32.57
108-4	1306786	1559115701	4784.750394	37330.62	35.01
108-5	1270332	1415099009	4342.779396	33882.36	37.49
108-6	2537843	3438828182	10553.37618	82337.44	30.82
108-7	2158472	2329136850	7147.85853	55767.59	38.70
108-8	219738.5	202848212.9	622.5183071	4856.888	45.24
108-9	3767742	3617654826	11102.175	86619.17	43.50
108-10	2220531	1596121887	4898.318209	38216.68	58.10
108-11	1298359	1410685834	4329.23586	33776.7	38.44
108-12	1797781	2581587485	7922.601083	61812.13	29.08
108-13	482124.3	434595325.6	1333.724081	10405.72	46.33
108-14	1815742	2060776742	6324.291601	49342.12	36.80
108-15	1219501	1417183557	4349.17664	33932.28	35.94
108-16	50703.33	43827280.22	134.5009843	1049.377	48.32
108-17	7055840	7047889265	21629.17795	168750.8	41.81
108-18	3145849	1459411484	4478.76939	34943.36	90.03
108-19	2473107	1415844661	4345.067717	33900.22	72.95
109-1	3538939	3255215997	9989.891076	77941.13	45.41
109-2	5208147	6729221911	20651.22375	161120.8	32.32
109-3	7696637	9712496487	29806.55725	232550.8	33.10
109-4	4550388	5148441909	15799.98806	123271.5	36.91
109-5	2913267	3797156681	11653.04596	90917.06	32.04
109-6	2458281	3058860451	9387.298031	73239.7	33.56
109-7	2848656	4569745200	14024.03307	109415.5	26.04
Total	65367721			1769158	
Average					36.95

* Frio River Watershed

Appendix A
Brush/Water Yield Feasibility Studies

A.1 Introduction

The Soil and Water Assessment Tool (SWAT) model was used to simulate the effects of brush removal on water yield in eight watersheds in Texas for 1960 through 1998. Landsat7 satellite imagery was used to classify land use, and the 1:24,000 scale digital elevation model (DEM) was used to delineate the watershed boundaries and subbasins. After calibration of SWAT to existing streamgauges, brush removal was simulated by converting all heavy and moderate categories of brush (except oak) to open range (native grass). Treatment or removal of light brush was not simulated. Results of brush treatment in all watersheds are presented. Water yield (surface runoff and base flow) varied by subbasin, but all subbasins showed an increase in water yield as a result of removing brush. Economic and wildlife habitat considerations will impact actual amounts of brush removed.

A.2 Background

Recent droughts in Texas have brought attention to the critical need for increasing water supplies in some water-short locations, especially the western portion of the state. Increases in brush area and density may contribute to a decrease in streamflow, possibly due to increased evapotranspiration (ET).[1,2] A modeling study of the North Concho River Watershed[3] (Upper Colorado River Authority, 1998) indicates that removing brush may result in a significant increase in water yield.

During the 1998–1999 legislative session, the Texas Legislature appropriated funds to study the effects of brush removal on water yield in eight watersheds in Texas. These watersheds are: Canadian River above Lake Meredith, Wichita River above Lake Kemp, Upper Colorado River above Lake Ivie, Concho River, Pedernales River, watersheds above the Edwards Aquifer, Frio River above Choke Canyon Reservoir, and Nueces River above Choke

---

[1] Thurow, T. L. 1998. Assessment of Brush Management as a Strategy for Enhancing Water Yield. Proceedings of the 25th Water for Texas Conference.

[2] Dugas, W.A.; R. A. Hicks; and P. Wright. 1998. Effect of Removal of Juniperus Ashei on Evapo-Transpiration and Runoff in the Seco Creek Watershed. Water Resources Research, Vol. 34, No. 6, 1499-1506.

[3] Upper Colorado River Authority. 1998. North Concho River Authority—Brush Control Planning, Assessment & Feasibility Study.

Canyon. The feasibility studies were conducted by a team from the Texas Agricultural Experiment Station (TAES), Texas Agricultural Extension Service (TAEX), U.S. Department of Agriculture Natural Resources Conservation Service (NRCS), and the Texas State Soil and Water Conservation Board (TSSWCB). The goals of the study were:

- To predict the effects of brush removal or treatment on water yield in each watershed.
- To prioritize areas within each watershed relative to their potential for increasing water yield.
- To determine the benefit/cost of applying brush management practices in each watershed.
- To determine effects of brush management on livestock production and wildlife habitat.

This report will only address the first two.

A.3 Methods

A.3.1 SWAT Model Description

The SWAT model[4] is the continuation of a long-term effort of nonpoint source pollution modeling by the USDA-Agricultural Research Service (ARS), including development of CREAMS[5] (Knisel, 1980), SWRRB[6] (Williams et al., 1985; Arnold et al., 1990), and ROTO[7] (Arnold et al., 1995).

SWAT was developed to predict the impact of climate and management (e.g., vegetative changes, reservoir management, groundwater withdrawals, and water transfer) on water, sediment, and agricultural chemical yields in large un-gauged basins. To satisfy the objective, the model (1) is physically based; (2) uses readily available inputs; (3) is computationally efficient to operate on large basins in a reasonable time; and (4) is continuous time and capable of simulating long periods for computing the effects of management changes. SWAT allows a basin to be divided into hundreds or thousands of grid cells or sub-watersheds.

---

[4] Srinivasan, R. and J. G. Arnold. 1994. Integration of a Basin Scale Water Quality Model with GIS. Water Resources Bulletin, Vol. 30, No. 3, June.

[5] Knisel, W.G. 1980. CREAMS, A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. United States Department of Agriculture Conservation Research Report No. 26.

[6] Williams, J. R., A.D. Nicks, and J. G. Arnold. 1985. Simulator for Water Resources in Rural Basins. J. Hydraulic Eng., ASCE, 111(6): 970–986.

[7] Arnold, J. G., J. R. Williams, D. R. Maidment. 1995. A Continuous Water and Sediment Routing Model for Large Basins. American Society of Civil Engineers Journal of Hydraulic Engineering. 121(2): 171–183.

A.3.2 Geographic Information System (GIS)

In recent years, there has been considerable effort devoted to utilizing GIS to extract inputs (e.g., soils, land use, and topography) for comprehensive simulation models and spatially display model outputs. Much of the initial research was devoted to linking single-event, grid models with raster-based GIS.[8] An interface was developed for SWAT using the Graphical Resources Analysis Support System (GRASS). The input interface extracts model input data from map layers and associated relational databases for each subbasin. Soils, land use, weather, management, and topographic data are collected and written to appropriate model input files. The output interface allows the user to display output maps and graph output data by selecting a subbasin from a GIS map. The study was performed using GRASS GIS integrated with the SWAT model, both of which operate in the UNIX operating system.

A.3.3 GIS Data

Development of databases and GIS layers was an integral part of the feasibility study. The data was assembled at the highest level of detail possible in order to accurately define the physical characteristics of each watershed.

A.3.3.1 Topography

The United States Geological Survey (USGS) database known as Digital Elevation Model (DEM) describes the surface of a watershed as a topographical database. The DEM available for the project area is the 1:24,000 scale map (U.S. Geological Survey, 1999). The resolution of the DEM is 30 meters, allowing detailed delineation of subbasins within each watershed. Some of the 8 watersheds designated for study were further sub-divided for ease of simulation. The location and boundaries of the watersheds are shown in Figure A-1.

The number of subbasins delineated in each watershed varied because of size and methods used for delineation, and ranged from 5 to 312 (Table A-1).

---

[8] Srinivasan, R. and B. A. Engel. 1991. A Knowledge Based Approach to Exact Input Data from GIS. ASAE Paper No. 91-7045, American Society of Agricultural Engineers, St. Joseph, MI.

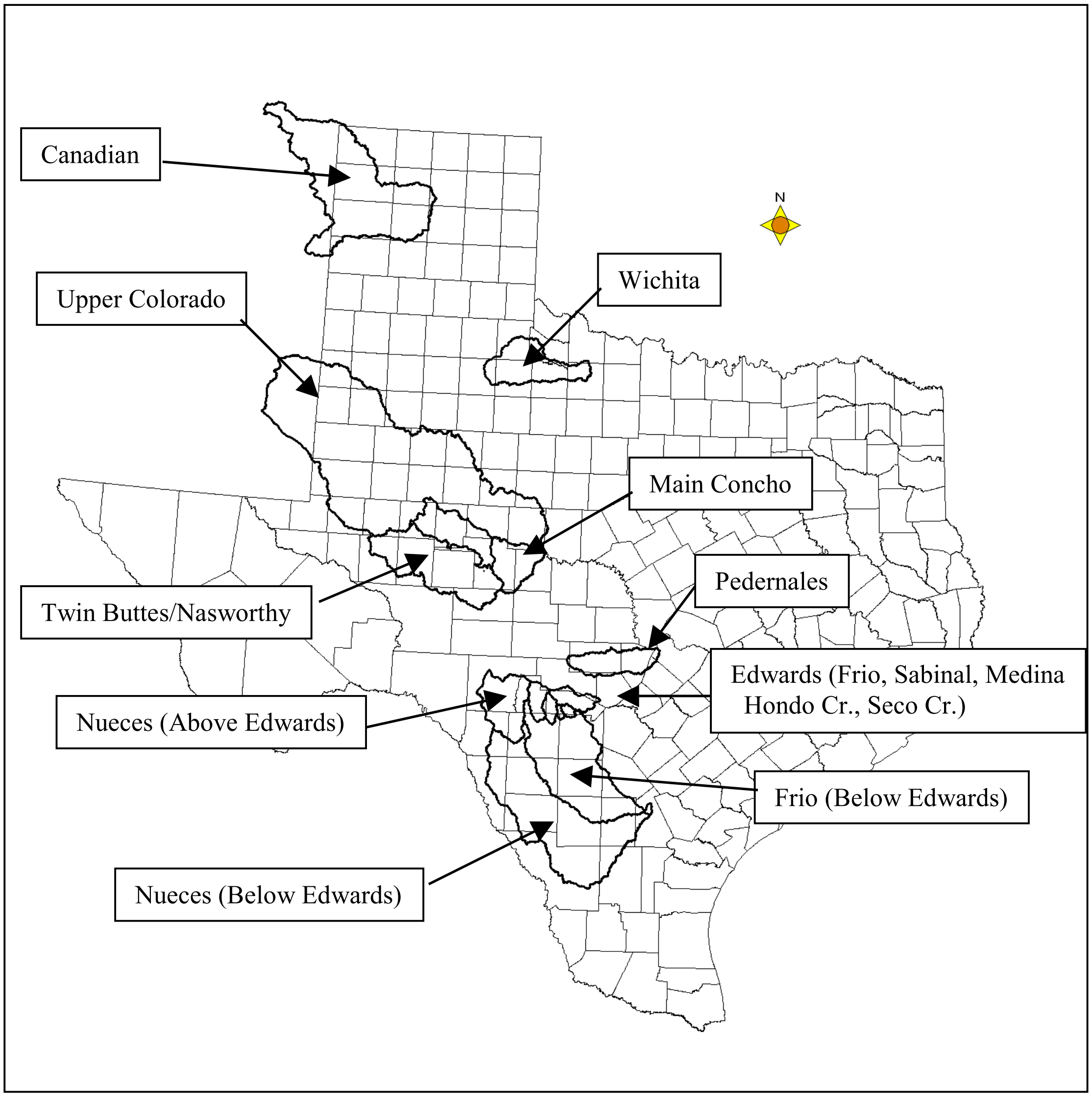


Figure A-1. Watersheds included in the study area.

Table A-1. Subbasin Delineation

Watershed	Number of Subbasins
Canadian River	312
Edwards-Frio	23
Edwards-Medina	25
Edwards-Hondo	5
Edwards-Sabinal	11
Edwards-Seco	13
Frio (Below Edwards)	70
Main Concho	37
Nueces (Above Edwards)	18
Nueces (Below Edwards)	95
Pedernales	35
Twin Buttes/Nasworthy	82
Upper Colorado	71
Wichita	48

A.3.3.2 Climate

Daily precipitation totals were obtained for National Weather Service (NWS) stations within and adjacent to the watersheds. Data from nearby stations were substituted for missing precipitation data in each station record. Daily maximum and minimum temperatures were obtained for the same NWS stations. A weather generator was used to generate missing temperature data and all solar radiation for each climate station. The average annual precipitation for each watershed for the 1960 through 1998 period is shown in Figure A-2.

A.3.3.3 Soils

The soils database describes the surface and upper subsurface of a watershed and is used to determine a water budget for the soil profile, daily runoff, and erosion. The SWAT model uses information about each soil horizon (e.g., thickness, depth, texture, water holding capacity, dispersion, albedo, etc.).

The soils database used for this project was developed from three major sources from the NRCS (USDA-Natural Resources Conservation Service):

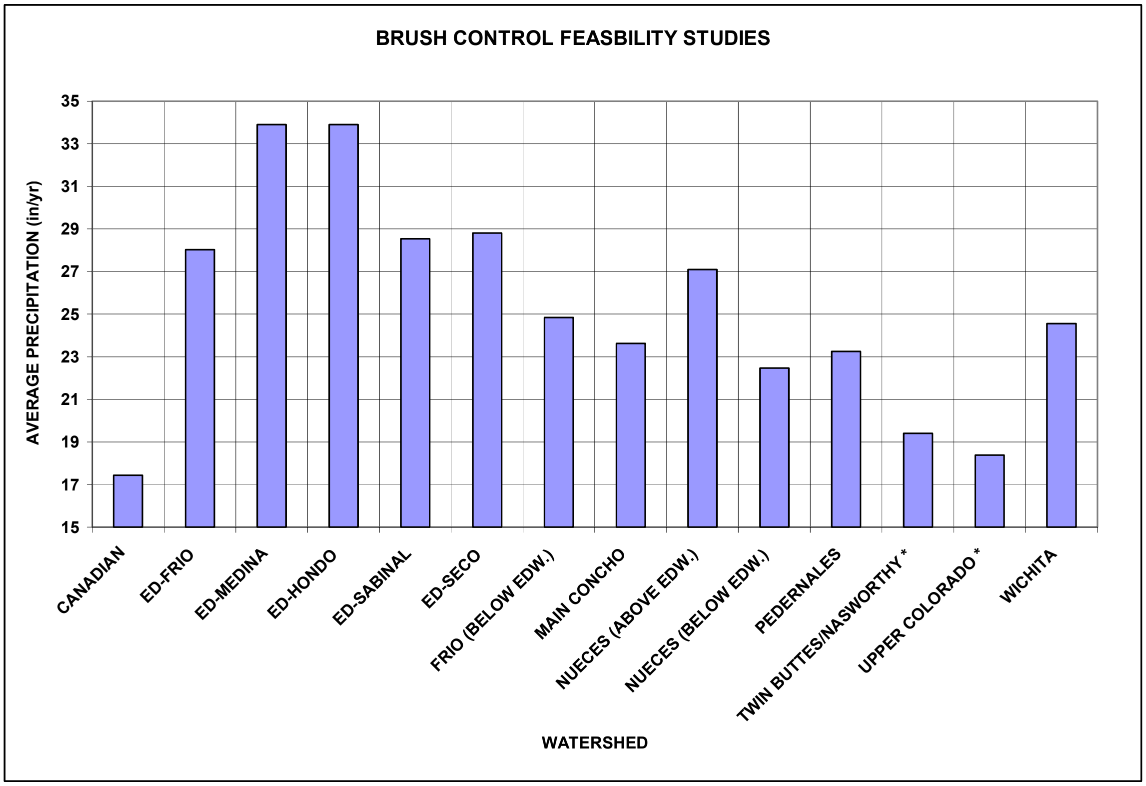


Figure A-2. Average annual precipitation. Averages are for all climate stations in each watershed.

1. **Computer-Based Mapping System (CBMS).** The majority of the information was a grid cell digital map created from 1:24,000 scale soil sheets with a cell resolution of 250 meters. This database was known as the Computer Based Mapping System (CBMS) or Map Information Assembly Display System (MIADS) (Nichols, 1975) soils data. The CBMS database differs from some grid GIS databases in that the attribute of each cell was determined by the soil that occurs under the center point of the cell instead of the soil that makes up the largest percentage of the cell. This method of cell attribute labeling had the advantage of a more accurate measurement of the various soils in an area. The disadvantage was for any given cell the attribute of that cell may not reflect the soil that actually makes up the largest percentage of that cell.
2. **The Soil Survey Geographic (SSURGO).** SSURGO was the most detailed soil database available. This 1:24,000-scale soils database was available as printed county soil surveys for over 90 percent of Texas counties. It was only currently available as a vector or high resolution cell data base at the inception of this project for a few counties in the project area. In the SSURGO database, each soil delineation (mapping unit) was described as a single soil series.

3. **State Soil Geographic (TATSGO).** The soils data base currently available for all of the counties of Texas is the State Soil Geographic (STATSGO) 1:250,000-scale soils data base. The STATSGO database covers the entire United States and all STATSGO soils were defined in the same way. In the STATSGO database, each soil delineation of a STATSGO soil was a mapping unit made up of more than one soil series. Some STATSGO soils were made up of as many as twenty SSURGO soil series. The dominant SSURGO soil series within an individual STATSGO polygon was selected to represent that area.

The GIS layer representing the soils within the project area was a compilation of CBMS, SSURGO, and STATSGO information. The most detailed information was selected for each individual county and patched together to create the final soils layer. In the project area, approximately 2/3 of the soil data was derived from CBMS and the remainder was largely STATSGO data. Only a very small percentage was represented by SSURGO.

SWAT used the soils series name as the data link between the soils GIS layer and the soils properties tabular database. County soil surveys were used to verify data for selected dominant soils within each watershed.

A.3.3.4 Land Use/Land Cover

Land use and cover affect surface erosion, water runoff, and ET in a watershed. The NRCS 1:24,000 scale CBMS land use/land cover database was the most detailed data presently available. However, for this project much more detail was needed in the rangeland category of land uses. The CBMS data did not identify varying densities of brush or species of brush – only the categories of open range versus brushy range.

Development of more detailed land use/land cover information for the watersheds in the project area was accomplished by classifying Landsat-7 Enhanced Thematic Mapper Plus ETM+ data. The satellite carries an ETM+ instrument, which is an eight-band multi-spectral scanning radiometer capable of providing high-resolution image information of the Earth's surface. It detects spectrally-filtered radiation at visible, near-infrared, short-wave, and thermal infrared frequency bands (Table A-2).

Table A-2.
Characteristics of Landsat-7

Band Number	***Spectral Range (microns)***	***Ground Resolution (meters)***
1	.45 to .515	30
2	.525 to .605	30
3	.63 to .690	30
4	.75 to .90	30
5	1.55 to 1.75	30
6	10.40 to 12.5	60
7	2.09 to 2.35	30
Pan	.52 to .90	15

Swath width:	185 kilometers
Repeat coverage interval:	16 days (233 orbits)
Altitude:	705 kilometers

Portions of 18 Landsat-7 scenes were classified using ground truth points collected by NRCS field personnel. The Landsat-7 satellite images used a spectral resolution of six channels (the thermal band (6) and panchromatic band (Pan) were not used in the classification). The imagery was taken from July 5, 1999 through December 14, 1999 in order to obtain relatively cloud-free scenes during the growing season for the project areas. These images were radiometrically and precision terrain corrected (personal communication with Gordon Wells, TNRIS).

Over 1,100 ground control points (GCP) were located and described by NRCS field personnel in November and December 1999. Rockwell precision lightweight Global positioning System (GPS) receivers were utilized to locate the latitude and longitude of the control points. A database was developed from the GCP's with information including the land cover, estimated canopy coverage, areal extent, and other pertinent information about each point. This database was converted into an ArcInfo™ point coverage.

ERDAS's Imagine™ was used for imagery classification. The Landsat-7 images were imported into Imagine (GIS software). Adjoining scenes in each watershed were histogram matched or regression corrected to the scene containing the highest number of GCPs (this was done in order to adjust for the differences in scenes because of dates, time of day, atmospheric conditions, etc.). These adjoining scenes were then mosaiced and trimmed into one image that covered an individual watershed.

The ArcInfo™ coverage of ground points was then employed to instruct the software to recognize differing land uses based on their spectral properties. Individual ground control points were "grown" into areas approximating the areal extent as reported by the data collector. Spectral signatures were collected by overlaying these areas over the imagery and collecting pixel values from the six imagery layers. A supervised maximum likelihood classification of the image was then performed with the spectral signatures for various land use classes. The ground data was used to perform an accuracy assessment of the resulting image. A sampling of the initial classification was further verified by NRCS field personnel.

The use of remote sensed data and the process of classifying it with ground truthing resulted in a current land use/land cover GIS map that includes more detailed divisions of land use/land cover. Although the vegetation classes varied slightly among all watersheds, the land use and cover was generally classified as shown in Table A-3:

Table A-3.

Heavy Cedar, Mesquite, Oak, Mixed	Mostly pure stands of cedar (juniper), mesquite, oak and mixed brush with average canopy cover greater than 30%.
Moderate Cedar, Mesquite, Oak, Mixed	Mostly pure stands of cedar, mesquite, oak and mixed brush with average canopy cover 10 to 30%.
Light Brush	Either pure stands or mixed with average canopy cover less than 10%.
Open Range	Various species of native grasses or improved pasture.
Cropland	All cultivated cropland.
Water	Ponds, reservoirs and large perennial streams.
Barren	Bare Ground.
Urban	Developed residential or industrial land.
Other	Other small insignificant categories.

The accuracy of the classified image was 70 percent – 80 percent. Table A-4 summarizes land use/land cover categories for each watershed in the project area.

A small area of the USGS land use/land cover GIS layer was patched to the detailed land use/land cover map developed using remotely sensed data for the western-most (New Mexico) portion of the Upper Colorado River and Canadian River watersheds, which were not included in the satellite scenes for this study.

Table A-4.
Land Use and Percent Cover

Watershed	Heavy & Mod. Brush (no oak)	Oak	Light Brush (no oak)	Open Range & Pastureland	Cropland	Other (Water Urban, Barren, etc.)
Canadian*	69	0	4	5	18	4
Edwards-Frio	60	22	17	1	<1	<1
Edwards-Medina	56	24	18	1	1	<1
Edwards-Hondo	59	24	15	1	1	<1
Edwards-Sabinal	60	22	16	1	1	<1
Edwards-Seco	65	24	10	1	<1	<1
Frio (Below Edwards)	58	17	18	1	5	1
Main Concho	40	5	19	10	26	<1
Nueces (Above Edwards)	60	23	17	<1	<1	<1
Nueces (Above Edwards)	62	17	19	<1	1	<1
Pedernales	25	50	7	16	1	1
Twin Buttes/Nasworthy*	57	2	31	5	3	2
Upper Colorado*	41	3	21	14	20	1
Wichita	63	4	15	9	7	2

*Percent of watershed where brush removal was planned.

A.3.4 Model Inputs

Required inputs for each subbasin (e.g., soils, land use/land cover, topography, and climate) were extracted and formatted using the SWAT/GRASS input interface. The input interface divided each subbasin into a maximum of 30 virtual subbasins or hydrologic response units (HRU). A single land use and soil were selected for each HRU. The number of HRU's within a subbasin was determined by: (1) creating an HRU for each land use that equaled or exceeded 5 percent of the area of a subbasin; and (2) creating an HRU for each soil type that equaled or exceeded 10 percent of any of the land uses selected in (1). The total number of HRU's for each watershed was dependent on the number of subbasins and the variability of the land use and soils within the watershed. The soil properties for each of the selected soils were automatically extracted from the model-supported soils database.

Surface runoff was predicted using the SCS curve number equation (USDA-SCS, 1972). Higher curve numbers represent greater runoff potential. Curve numbers were selected assuming existing brush sites were fair hydrologic condition and existing open range and pasture sites with no brush were good hydrologic condition. The precipitation intercepted by canopy was based on field experimental work (Thurow and Taylor, 1995) and calibration of SWAT to measured streamflows. The soil evaporation compensation factor adjusts the depth distribution for evaporation from the soil to account for the effect of capillary action, crusting, and cracks. A factor of 0.85 is normally used, but lower values were used in dry climates to account for moisture loss from deeper soil layers.

Shallow aquifer storage is water stored below the root zone. Groundwater flow is not allowed until the depth of water in the shallow aquifer is equal to or greater than the input value. Shallow aquifer re-evaporation coefficient controls the amount of water which will move from the shallow aquifer to the root zone as a result of soil moisture depletion, and the amount of direct water uptake by deep rooted trees and shrubs. Higher values represent higher potential water loss. The amount of re-evaporation is also controlled by setting the minimum depth of water in the shallow aquifer before re-evaporation is allowed. Shallow aquifer storage and re-evaporation inputs affect base flow.

Potential heat units (PHU) is the number of growing degree days needed to bring a plant to maturity and varies by latitude. PHU decreases as latitude increases. PHU was obtained from published data (NOAA, 1980).

Channel transmission loss is the effective hydraulic conductivity of channel alluvium, or water loss in the stream channel. The fraction of transmission loss that returns to the stream channel as base flow can also be adjusted.

The leaf area index (LAI) specifies the projected vegetation area (in units of square meters) per ground surface area (square meters). Plant rooting depth, canopy height, albedo, and LAI were based on observed values and modeling experience.

A.3.5 Model Calibration

The calibration period was based on the available period of record for streamgauges within each watershed. Measured streamflow was obtained from USGS. A base flow filter (Arnold et al., 1999) was used to determine the fraction of base flow and surface runoff at selected gauging stations.

Appropriate plant growth parameters for brush and native grass were input for each model simulation. Adjustments were made to runoff curve number, soil evaporation compensation factor, shallow aquifer storage, shallow aquifer re-evaporation, and channel transmission loss until the simulated total flow and fraction of base flow were approximately equal to the measured total flow and base flow, respectively.

A.3.6 Brush Removal Simulations

T.L. Thurow (Thurow, 1998) suggested that brush control is most likely to increase water yields in areas that receive at least 18 inches of average annual rainfall. Therefore, brush treatment was not planned in areas generally west of the 18 inch rainfall isohyet (Figure A-3). One exception is the Canadian River watershed. Most of this watershed is west of the 18 inch isohyet, and also extends into New Mexico. Brush treatment was simulated in the portion of the Canadian River watershed that lies within Texas.

Some areas in the Upper Colorado and Twin Buttes/Nasworthy watersheds do not contribute to streamflow at downstream gauging stations (USGS, 1999). These areas have little or no defined stream channel, and considerable natural surface storage (e.g. playa lakes) that capture surface runoff. We used available GIS and streamgauge data to estimate the location of

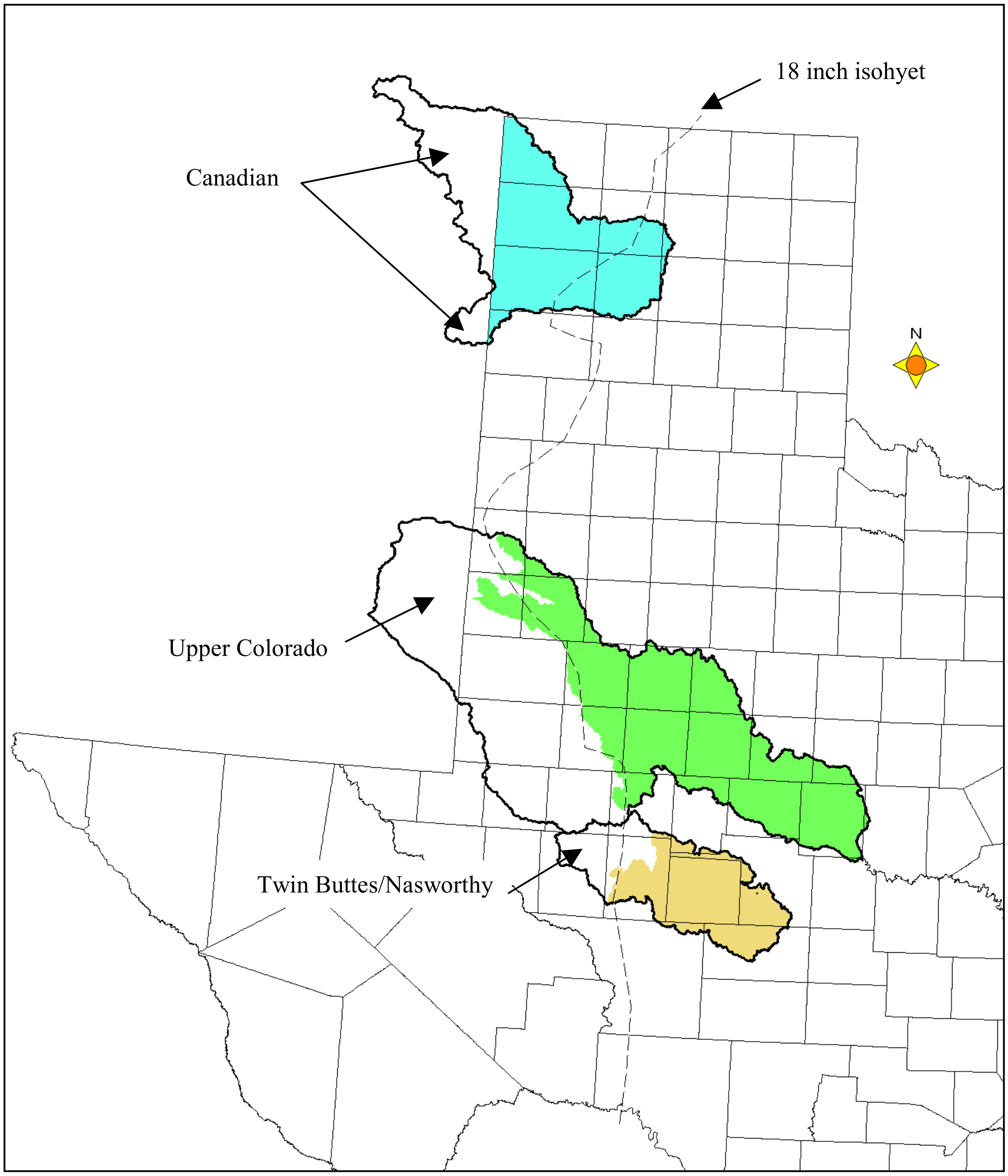


Figure A-3. Areas where brush treatment was not planned (non-shaded portions of each watershed).

These areas, most of which are west of the 18 inch isohyet. Brush treatment was not planned in these areas (Figure A-3).

In order to simulate the "treated" or "no-brush" condition, the input files for all areas of heavy and moderate brush (except oak) were converted to native grass rangeland. Appropriate adjustments were made in growth parameters to simulate the replacement of brush with grass. We assumed the shallow aquifer re-evaporation coefficient would be higher for brush than for other types of cover because brush is deeper rooted, and opportunity for re-evaporation from the shallow aquifer is higher. All other calibration parameters and inputs were held constant.

It was assumed all categories of oak would not be treated. In the Pedernales and Edwards watersheds, oak and juniper were mixed together in one classification. We assumed the category was 50 percent oak and 50 percent juniper and modeled only the removal of juniper.

After calibration of flow, each watershed was simulated for the brush and no-brush conditions for the years 1960 through 1998.

A.4 Results

The results of flow calibration and brush treatment simulations for individual watersheds are presented in the subchapters of this report.

A.4.1 Watershed Calibration

The comparisons of measured and predicted flow were, in most cases, reasonable. Deviations of predicted flow from measured were generally attributed to precipitation variability which was not reflected in measured climate data.

A.4.2 Brush Treatment Simulations

Total area of each watershed is shown in Figure A-4. For watersheds that lie across the 18 inch isohyet, the area shown represents only the portion of those watersheds where brush treatment was planned.

The fraction of heavy and moderate brush planned for treatment or removal in each watershed is shown in Figure A-5. For watersheds that lie across the 18 inch isohyet, this is the fraction of the portion of the watershed where brush treatment was planned.

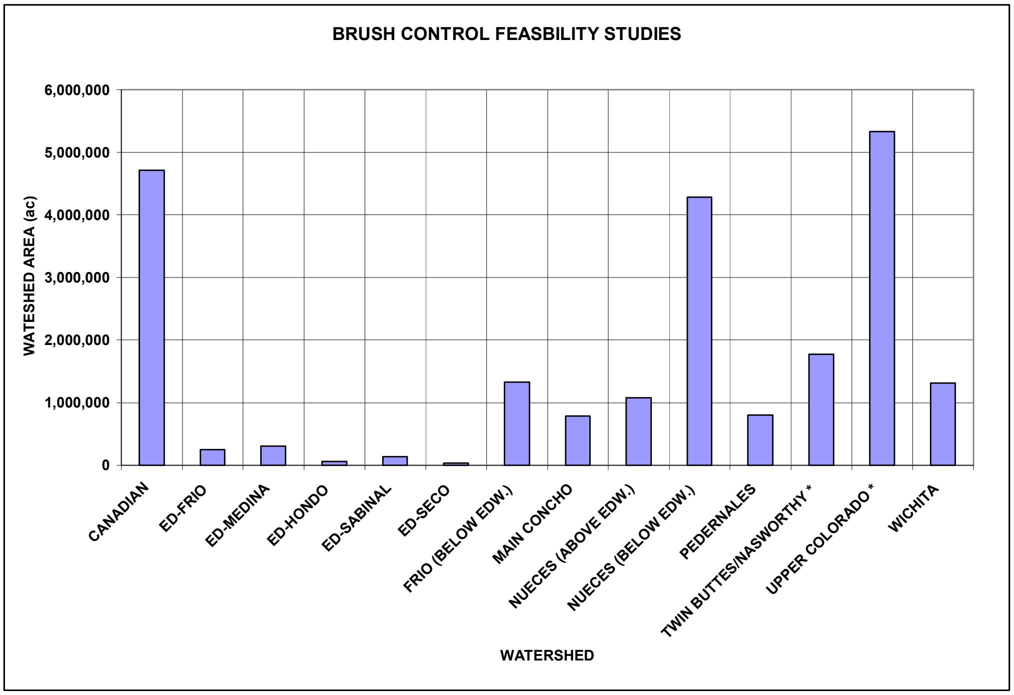


Figure A-4. Watershed area. For watersheds that lie across the 18 inch isohyet, the area shown represents only the portion of those watersheds where brush treatment was planned and simulated.

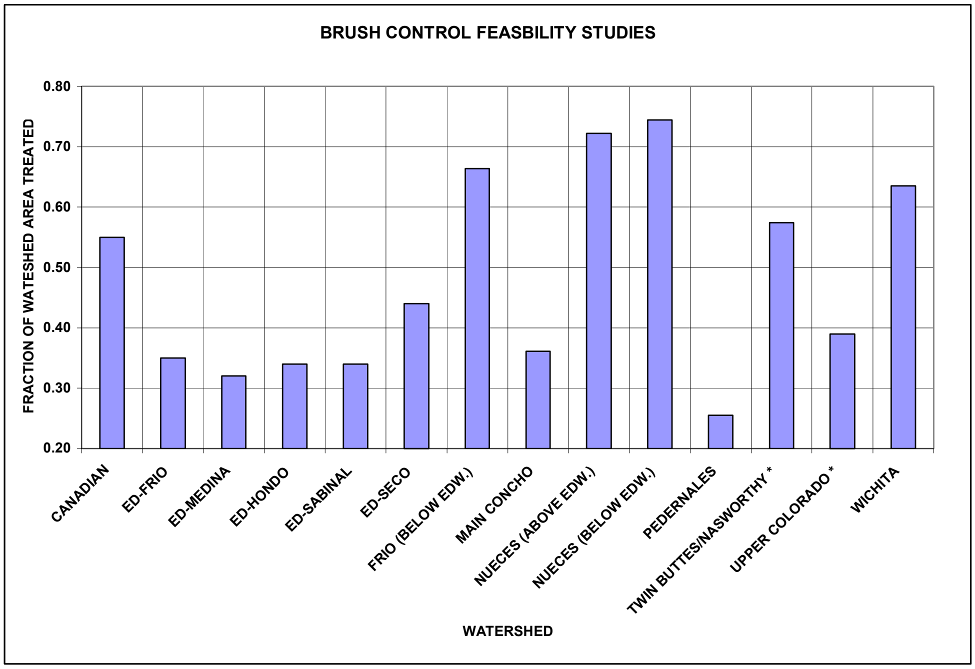


Figure A-5. Fraction of watershed containing heavy and moderate brush that was treated. For watersheds that lie across the 18 inch isohyet, this is the fraction of the portion of the watershed where brush treatment was planned and simulated.

Average annual water yield increase per treated acre varied by watershed and ranged from 13,000 gallons per treated acre in the Canadian to about 172,000 gallons per treated acre in the Medina watershed (Figure A-6).

The average annual streamflow (acft) for the brush and no-brush conditions is shown for each watershed outlet in Figure A-7. Average annual streamflow increase varied by watershed and ranged from 6,650 gallons per treated acre in the Upper Colorado to about 172,000 gallons per treated acre in the Medina watershed (Figure A-8). In some cases, the increase in streamflow was less than the increase in water yield because of the capture of runoff by upstream reservoirs, as well as stream channel transmission losses that occurred between each subbasin and the watershed outlet.

There was a high correlation between streamflow increase and precipitation (Figure A-9). The amount of streamflow increase was greater in watersheds with higher average annual precipitation.

Variations in the amount of increased water yield and streamflow were expected and were influenced by brush type, brush density, soil type, and average annual rainfall, with watersheds receiving higher average annual rainfall generally producing higher increases. The larger water yields and streamflows were most likely due to greater rainfall volumes as well as increased density and canopy of brush.

A.5 Summary

The Soil and Water Assessment Tool (SWAT) model was used to simulate the effects of brush removal on water yield in 8 watersheds in Texas for 1960 through 1998. Landsat7 satellite imagery from 1999 was used to classify current land use and cover for all watersheds. Brush cover was separated by species (cedar, mesquite, oak, and mixed) and by density (heavy, moderate, light). After calibration of SWAT to existing streamgauge data, brush removal was simulated by converting all heavy and moderate categories of brush (except oak) to open range (native grass). Removal of light brush was not simulated.

Simulated changes in water yield resulting from brush treatment varied by subbasin, with all subbasins showing increased water yield as a result of removing brush. Average annual water

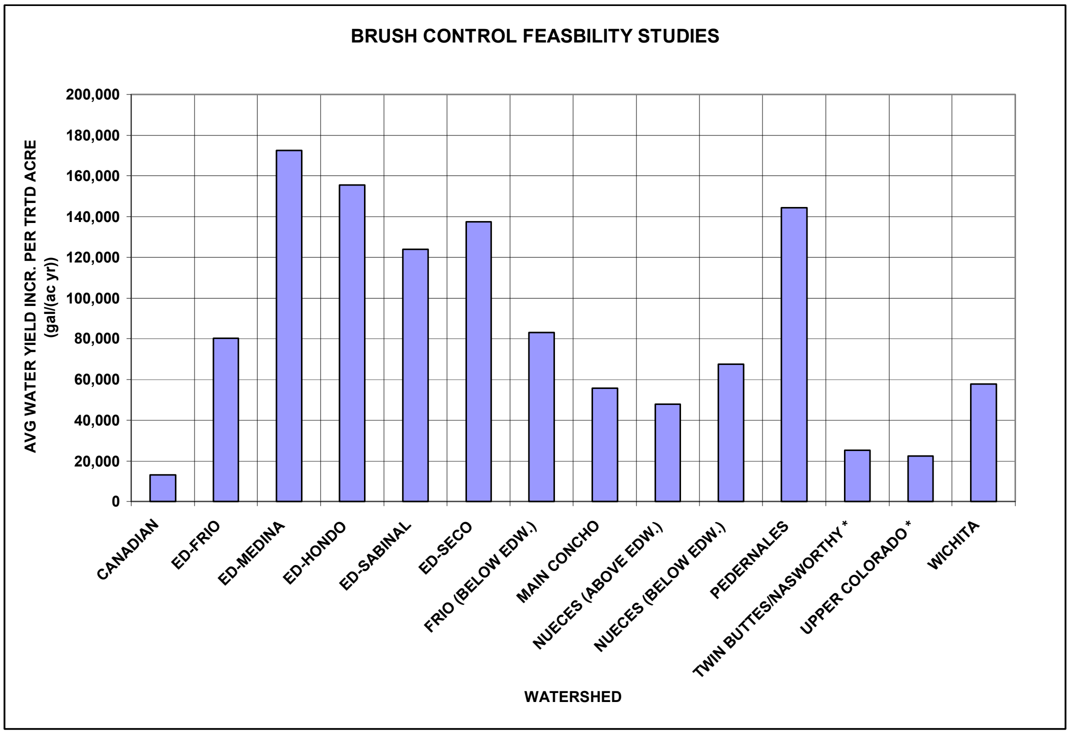


Figure A-6. Average annual water yield increase, 1960 through 1998.

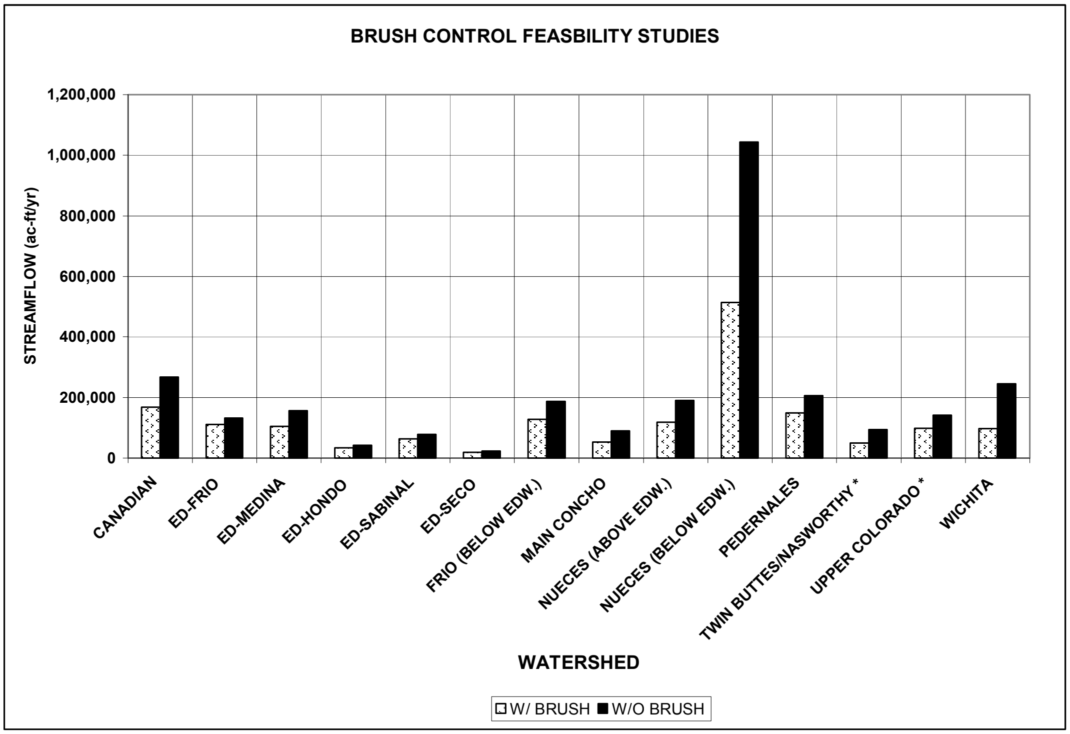


Figure A-7. Average annual streamflow at watershed outlet, 1960 through 1998.

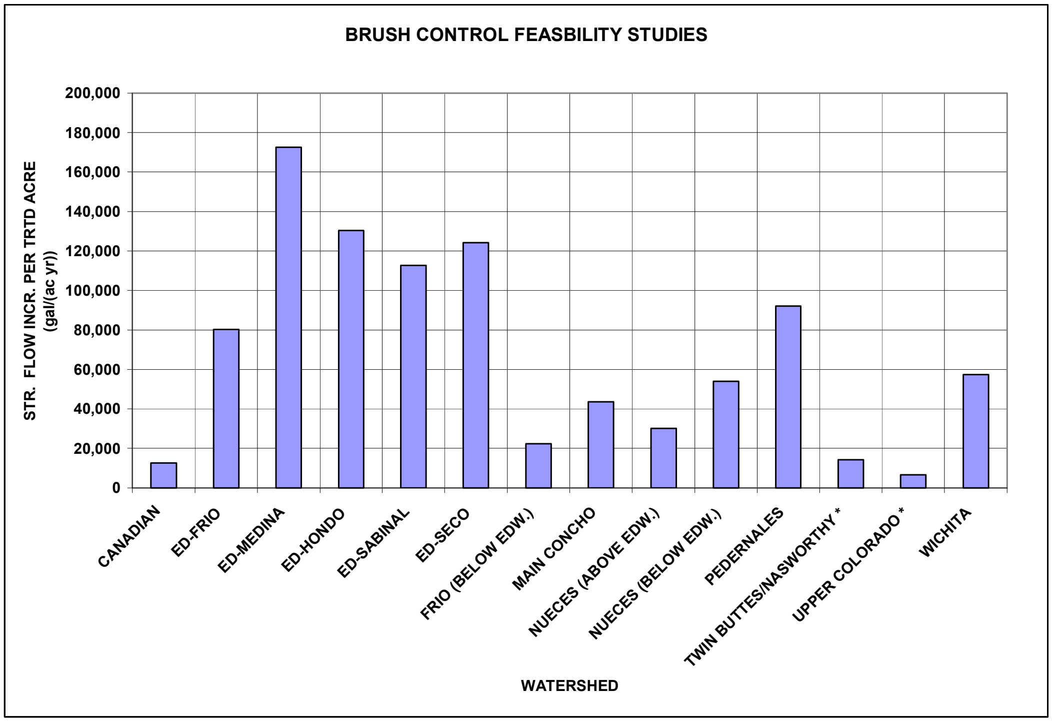


Figure A-8. Average annual streamflow increase at watershed outlet, 1960 through 1998.

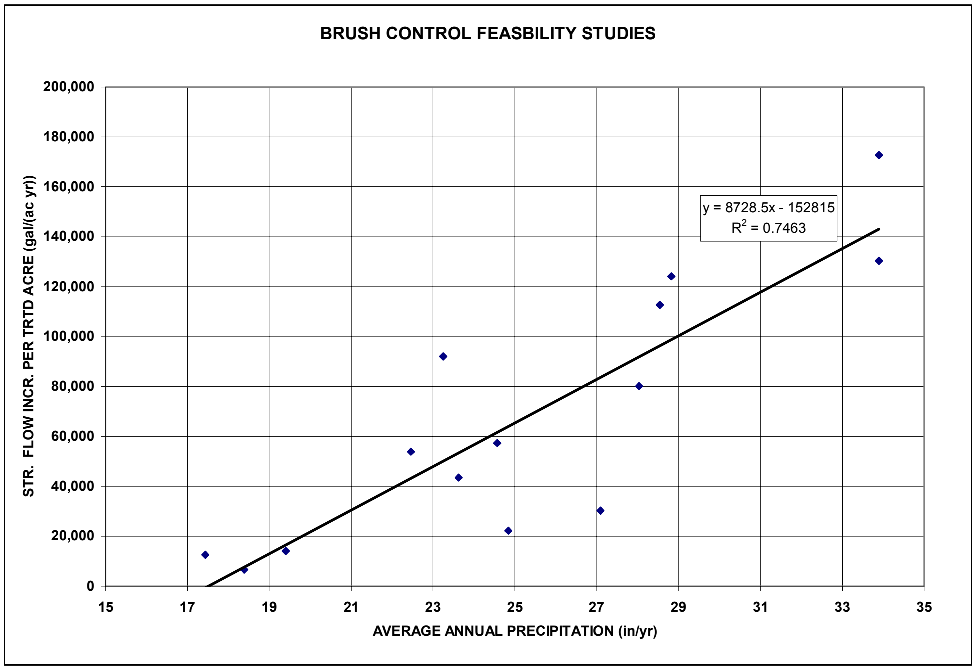


Figure A-9. Average annual streamflow increase versus average annual precipitation, 1960 through 1998. Each point represents one watershed.

yield increases ranged from about 13,000 gallons per treated acre in the Canadian watershed to about 172,000 gallons per treated acre in the Medina watershed.

For this study, we assumed removal of 100 percent of heavy and moderate categories of brush (except oak). Removal of all brush in a specific category is an efficient modeling scenario. However, other factors must be considered in planning brush treatment. Economics and wildlife habitat considerations will impact the specific amounts and locations of actual brush removal.

The hydrologic response of each watershed is directly dependent on receiving precipitation events that provide the opportunity for surface runoff and groundwater flow.

LITERATURE CITED

Arnold, J.G., J.R. Williams, A.D. Nicks, and N.B. Sammons. 1990. SWRRB: A Basin Scale Simulation Model for Soil and Water Resources Management. Texas A&M Univ. Press, College Station.

Arnold, J.G., J.R. Williams, D.R. Maidment. 1995. A Continuous Water and Sediment Routing Model for Large Basins. American Society of Civil Engineers Journal of Hydraulic Engineering. 121(2):171-183.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large Area Hydrologic Modeling and Assessment, Part1: Model Development. Journal of American Water Resources Association. 34(1):73-89.

Arnold, J.G., P.M. Allen, R.S. Muttiah, G. Bernhardt. 1995. Automated Base Flow Separation and Recession Analysis Techniques. GROUND WATER, Vol. 33, No. 6, November-December.

Dugas, W.A., R.A. Hicks, and P. Wright. 1998. Effect of Removal of Juniperus Ashei on Evapo-transpiration and Runoff in the Seco Creek Watershed. Water Resources Research, Vol. 34, No. 6, 1499-1506.

Knisel, W.G. 1980. CREAMS, A Field Scale Model for Chemicals, Runoff, and Erosion From Agricultural Management Systems. United States Department of Agriculture Conservation Research Report No. 26.

Nichols, J.D. 1975. Characteristics of Computerized Soil Maps. Soil Science Society of America Proceedings. Volume 39, No. 5.

National Oceanic and Atmospheric Administration. 1980. Climatology of the United States No. 20, Climatic Summaries for Selected Sites, 1951 – 1980, Texas.

Rewerts, C.C. and B.A. Engel. 1991. Answers on GRASS: Integrating a watershed simulation with a GIS. ASAE Paper No. 91-2621, American Society of Agricultural Engineers, St. Joseph, MI.

Srinivasan, R. and B.A. Engel. 1991. A Knowledge Based Approach to Exact Input data From GIS. ASAE Paper No. 91-7045, American Society of Agricultural Engineers, St. Joseph, MI.

Srinivasan, R. and J.G. Arnold. 1994 Integration of a Basin Scale Water Quality Model With GIS. Water Resources Bulletin, Vol. 30, No. 3, June.

Thurow T.L., and C.A. Taylor Jr. Juniper Effects on the Water Yield of Central Texas Rangeland. Proc. 24th Water for Texas Conference, Texas Water Resources Institute, Austin, Texas January 26-27, 1995; Ed. Ric Jensen.

Thurow, T.L. 1998. Assessment of Brush Management as a Strategy for Enhancing Water Yield. Proceedings of the 25th Water For Texas Conference.

Upper Colorado River Authority. 1998. North Concho River Authority – Brush Control Planning, Assessment & Feasibility Study.

U.S. Department of Agriculture, Soil Conservation Service, 1972. National Engineering Handbook, Section 4-Hydrology, Chapters 4-10.

U.S. Geological Survey. 1999. Water Resources Data, Texas, Water Year 1999. Volume 4.

U.S. Army. 1988. GRASS Reference Manual. USA CERL, Champaign, IL.

Williams, J.R., A.D. Nicks, and J.G. Arnold. 1985. Simulator for Water Resources in Rural Basins. J. Hydraulic Eng., ASCE, 111(6):970-986.

Appendix B
Assessing The Economic Feasibility Of Brush Control To Enhance Off-Site Water Yield

B.1 Introduction

A feasibility study of brush control for off-site water yield was undertaken in 1998 on the North Concho River near San Angelo, Texas. Subsequently, studies were conducted on eight additional Texas watersheds. Economic analysis was based on estimated control costs of the different options compared to the estimated rancher benefits of brush control. Control costs included initial and follow-up treatments required to reduce brush canopy to between 8 percent and 3 percent and maintain it at the reduced level for 10 years. The state cost share was estimated by subtracting the present value of rancher benefits from the present value of the total cost of the control program. The total cost of additional water was determined by dividing the total state cost share if all eligible acreage were enrolled by the total added water estimated to result from the brush control program. This procedure resulted in present values of total control costs per acre ranging from $33.75 to $159.45. Rancher benefits, based on the present value of the improved net returns to typical cattle, sheep, goat, and wildlife enterprises ranged from $52.12 per acre to $8.95. Present values of the state cost share per acre ranged from $138.85 to $21.70. The cost of added water estimated for the eight watersheds ranged from $16.41 to $204.05 per acft averaged over each watershed.

As was reported in Appendix A of this report, a feasibility study of brush control for water yield on the North Concho River near San Angelo, Texas was conducted in 1998. Results indicated estimated cost of added water at $49.75 per acft averaged over the entire North Concho basin[1].

In response to this study, the Texas Legislature, in 1999, appropriated approximately $6 million to begin implementing the brush control program on the North Concho Watershed. A companion Bill authorized feasibility studies on eight additional watersheds across Texas.

---

[1] Bach, Joel P. and J. Richard Conner. 1998. Economic Analysis of Brush Control Practices for Increased Water Yield: The North Concho River Example. In: Proceedings of the 25th Water for Texas Conference - Water Planning Strategies for Senate Bill 1. R. Jensen, editor. A Texas Water Resources Institute Conference held in Austin, Texas, December 1-2, 1998. Pgs. 209-217.

The eight watersheds ranged from the Canadian, located in the northwestern Texas Panhandle to the Nueces which encompasses a large portion of the South Texas Plains (Figure A-1). In addition to including a wide variety of soils, topography and plant communities, the eight watersheds included average annual precipitation zones from 15 to 26 inches and growing seasons from 178 to 291 days. The studies were conducted primarily between February and September of 2000.

B.2 Objectives

This Appendix reports the assumptions and methods for estimating the economic feasibility of a program to encourage rangeland owners to engage in brush control for purposes of enhancing off-site (downstream) water availability. Vegetative cover determination and categorization through use of Landsat imagery, and the estimation of increased water yield from control of the different brush type-density categories using the SWAT simulation model for the watersheds are described in Appendix A. The data created by these efforts (along with primary data gathered from landowners,and federal and state agency personnel) were used as the basis for the economic analysis.

This Appendix provides details on how brush control costs and benefits were calculated for the different brush type-densities and illustrates their use in determining cost-share amounts for participating private landowners,-ranchers, and the State of Texas. SWAT model estimates of additional off-site water yield resulting from the brush control program are used with the cost estimates to obtain estimates of per acre-foot costs of added water gained through the program.

B.3 Brush Control

It should be noted that public benefit in the form of additional water depends on landowner participation, and proper implementation and maintenance of the appropriate brush control practices. It is also important to understand that rancher participation in a brush control program primarily depends on the rancher's expected economic consequences resulting from participation. With this in mind, the analyses described in this report are predicated on the objective of limiting rancher costs associated with participation in the program to no more than the benefits that would be expected to accrue to the rancher as a result of participation.

It is explicitly assumed that the difference between the total cost of the brush control practices and the value of the practice to the participating landowner would have to be contributed by the state in order to encourage landowner participation. Thus, the state (public) must determine whether the benefits, in the form of additional water for public use, are equal to or greater than the state's share of the costs of the brush control program. Administrative costs (state costs) which would be incurred in implementing, administering, and monitoring a brush control project or program are not included in this analysis.

B.3.1 Brush Type-Density Categories

Land cover categories identified and quantified for the eight watersheds in Appendix A included four brush types: cedar (juniper), mesquite, oaks, and mixed brush. Landowners statewide indicated they were not interested in controlling oaks, so the type category was not considered eligible for inclusion in a brush control program. Two density categories, heavy and moderate, were used. These six type-density categories were used to estimate total costs, landowner benefits, and the amount of cost-share that would be required of the state.

Brush control practices include initial and follow-up treatments required to reduce the current canopies of all categories of brush types and densities to 3 to 8 percent and maintain it at the reduced level for at least 10 years. These practices, or brush control treatments, differed among watersheds due to differences in terrain, soils, amount and distribution of cropland in close proximity to the rangeland, etc. An example of the alternative control practices, the time (year) of application and costs for the Wichita Watershed are outlined in Table B-1. Year 0 in Table B-1 is the year that the initial practice is applied while years 1 to 9 refer to follow-up treatments in specific years following the initial practice.

The appropriate brush control practices, or treatments, for each brush type-density category and their estimated costs were obtained from focus groups of landowners, and NRCS and Extension personnel in each watershed. In the larger watersheds two focus groups were used where it was deemed necessary because of significant climatic and/or terrestrial differences.

B.3.2 Control Costs

Yearly costs for the brush control treatments and the present value of those costs (assuming an 8 percent discount rate as opportunity cost for rancher investment capital) are also displayed in Table B-1. Present values of control programs are used for comparison since some of the treatments will be required in the first year to initiate the program while others will not be needed until later years. Present values of total per acre control costs range from $33.75 for moderate mesquite that can be initially controlled with herbicide treatments to $159.45 for heavy mesquite that cannot be controlled with herbicide but must be initially controlled with mechanical tree bulldozing or rootplowing.

B.3.3 Landowner Benefits From Brush Control

As was mentioned earlier, one objective of the analysis is to equate rancher benefits with rancher costs. Therefore, the task of discovering the rancher cost (and thus, the rancher cost share) for brush control was reduced to estimating the 10-year stream of region-specific benefits that would be expected to accrue to any rancher participating in the program. These benefits are based on the present value of increased net returns made available to the ranching operation through increases or expansions of the typical livestock (cattle, sheep, or goats) and wildlife enterprises that would be reasonably expected to result from implementation of the brush control program.

Rancher benefits were calculated for changes in existing wildlife operations. Most of these operations were determined to be simple hunting leases with deer, turkey, and quail being the most commonly hunted species. For control of heavy mesquite, mixed brush and cedar, wildlife revenues are expected to increase from $0.50 to $1.50 per acre due principally to the resulting improvement in quail habitat and hunter access to quail. Increased wildlife revenues were included only for the heavy brush categories because no changes in wildlife revenues were expected with control for the moderate brush type-density categories.

Table B-1. Wichita Water Yield Brush Control Program Methods and Costs by Type- Density Category

Heavy Mesquite Aerial Chemical

Year	Treatment Description	Cost/Unit	Present Value
0	Aerial Spray Herbicide	25.00	25.00
4	Aerial Spray Herbicide	25.00	18.38
7	Choice Type IPT or Burn	15.00	8.75
			$ 52.13

Heavy Mesquite Mechanical Choice

Year	Treatment Description	Cost/Unit	Present Value
0	Tree Doze or Root Plow, Rake and Burn	150.00	150.00
6	Choice Type IPT or Burn	15.00	9.45
			$159.45

Heavy Cedar Mechanical Choice

Year	Treatment Description	Cost/Unit	Present Value
0	Tree Doze, Stack and Burn	107.50	107.50
3	Choice Type IPT or Burn	15.00	11.91
6	Choice Type IPT or Burn	15.00	9.45
			$ 128.86

Heavy Cedar Mechanical Choice

Year	Treatment Description	Cost/Unit	Present Value
0	Two-way Chain and Burn	25.00	25.00
3	Choice Type IPT or Burn	15.00	11.91
6	Choice Type IPT or Burn	15.00	9.45
			$ 46.36

Heavy Mixed Brush Mechanical Choice

Year	Treatment Description	Cost/Unit	Present Value
0	Tree Doze, Stack and Burn	107.50	107.50
3	Choice Type IPT or Burn	15.00	11.91
6	Choice Type IPT or Burn	15.00	9.45
			$ 128.86

Table B-1. (continued) Wichita Water Yield Brush Control Program Methods and Costs by Type-Density Category

Heavy Mixed Brush Mechanical Choice			
Year	Treatment Description	Cost/Unit	Present Value
0	Two-way Chain and Burn	25.00	25.00
3	Choice Type IPT or Burn	15.00	11.91
6	Choice Type IPT or Burn	15.00	9.45
			$ 46.36

Moderate Mesquite Mechanical or Chemical Choice			
Year	Treatment Description	Cost/Unit	Present Value
0	Aerial Spray Herbicide	25.00	25.00
7	Choice Type IPT or Burn	15.00	8.75
			$ 33.75

Moderate Cedar Mechanical or Chemical Choice			
Year	Treatment Description	Cost/Unit	Present Value
0	Chemical or Mechanical – Burn Choice	45.00	45.00
7	Choice Type IPT or Burn	15.00	8.75
			$ 53.75

Moderate Mixed Brush Mechanical or Chemical Choice			
Year	Treatment Description	Cost/Unit	Present Value
0	Chemical or Mechanical – Burn Choice	45.00	45.00
7	Choice Type IPT or Burn	15.00	8.75
			$ 53.75

For the livestock enterprises, increased net returns would result from increased amounts of usable forage (grazing capacity) produced by removal of the brush and, thus, eliminating much of the competition for light, water, and nutrients within the plant communities on which the enterprise is based. For the wildlife enterprises, improvements in net returns are based on an increased ability to access wildlife for use by paying sportsmen.

As with the brush control methods and costs, estimates of vegetation (forage production/grazing capacity) responses used in the studies were obtained from landowner focus groups, Experiment Station and Extension Service scientists and USDA-NRCS Range Specialists with brush control experience in the respective watersheds. Because of differences in soils and climate, livestock grazing capacities differ by location; in some cases, significant differences were noted between sub-basins of a watershed. Grazing capacity estimates were collected for both pre- and post-control states of the brush type-density categories. The carrying capacities range from 70 acres per animal unit year (ac/AUY) for land infested with heavy cedar to about 15 ac/AUY for land on which mesquite is controlled to levels of brush less than 8 percent canopy cover (Table B-2.).

Livestock production practices, revenues, and costs representative of the watersheds, or portions thereof, were also obtained from focus groups of local landowners. Estimates of the variable costs and returns associated with the livestock and wildlife enterprises typical of each area were then developed from this information into production-based investment analysis budgets.

Table B-2. Grazing Capacity in Ac/AUY Before and After Brush Control by Brush Type-Density Category

	Brush Type-density Category & Brush Control State											
	Heavy Cedar		Heavy Mesquite		Heavy Mixed Brush		Moderate Cedar		Moderate Mesquite		Moderate Mixed Brush	
Watershed	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-
Canadian	-	-	30	20	37	23	-	-	25	20	30	23
Edwards Aquifer	60	30	35	20	45	25	45	30	25	20	35	25
Frio – North	50	30	36	24	36	24	40	30	32	24	32	24
Frio – South	-	-	38	23	35	23	-	-	30	23	30	23
Mid Concho	70	35	38	25	50	30	52	35	32	25	40	30
Nueces – North	50	30	39	27	39	27	40	30	35	27	35	27
Nueces – South	-	-	41	26	38	26	-	-	33	26	33	26
Pedernalis	45	28	28	15	40	22	38	28	24	15	34	22
Upper Colorado – East	56	24	32	18	48	21	44	24	28	18	36	21
Upper Colorado – West	70	35	38	25	50	30	52	30	32	25	40	30
Wichita	50	25	32.5	20	38.5	20	40	25	25	20	32.5	20

For ranchers to benefit from the improved forage production resulting from brush control, livestock numbers must be changed as grazing capacity changes. In this study, it was assumed that ranchers would adjust livestock numbers to match grazing capacity changes on an annual basis. Annual benefits that result from brush control were measured as the net differences in annual revenue (added annual revenues minus added annualized costs) that would be expected with brush control as compared to without brush control. It is notable that many ranches preferred to maintain current levels of livestock, therefore realizing benefit in the form of reduced feeding and production risk. No change in perception of value was noted for either type of projected benefit.

The analysis of rancher benefits was done assuming a hypothetical 1,000 acre management unit for facilitating calculations. The investment analysis budget information, carrying capacity information, and brush control methods and costs comprised the data sets that were entered into the investment analysis model ECON[2]. The ECON model yields net present values for rancher benefits accruing to the management unit over the 10-year life of the projects being considered in the feasibility studies. An example of this process is shown in Table B-3 for the control of moderate cedar in the Upper Colorado – West Watershed.

Table B-3 Net Present Value Report - Upper Colorado – West Watershed, Moderate Cedar Control

Year	Animal Units	Total Increase In Sales	Total Added Investment	Increased Variable Costs	Additional Revenues	Cash Flow	Annual NPV	Accumulated NPV
0	0.0	0	0	0	0	0	0	-
1	4.2	1423	2800	520	0	-1897	-1757	-1757
2	9.8	3557	3500	1171	0	-1113	-955	-2711
3	10.1	3557	0	1171	0	2387	1895	-817
4	10.3	3557	0	1171	0	2387	1754	937
5	10.6	3557	0	1171	0	2387	1624	2562
6	10.8	3913	0	1171	0	2742	1728	4290
7	11.1	3913	0	1171	0	2742	1600	5890
8	11.4	3913	0	1171	0	2742	1482	7371
9	11.6	3913	0	1171	0	2742	1372	8743
				Salvage Value:		6300	3152	11895

Since a 1,000 acre management unit was used, benefits needed to be converted to a per acre basis. To get per acre benefits, the accumulated net present value of $11,895 shown in Table B-3 must be divided by 1,000, which results in $11.90 as the estimated present value of the per acre net benefit to a rancher. The resulting net benefit estimates for all of the type-density categories for all watersheds are shown in Table B-4. Present values of landowner benefits differ by location within and across watersheds. They range from a low of $8.95 per acre for control of

---

[2] Conner, J.R. 1990. ECON: An Investment Analysis Procedure for Range Improvement Practices. Texas Agricultural Experiment Station Documentation Series MP-1717.

moderate mesquite in the Canadian Watershed to $52.12 per acre for control of heavy mesquite in the Edwards Aquifer Watershed.

Table B-4 Landowner and State Shares of Brush Control Costs by Brush Type-Density Category by Watershed

	Brush Type-density Category											
	Heavy Cedar		Heavy Mesquite		Heavy Mixed Brush		Moderate Cedar		Moderate Mesquite		Moderate Mixed Brush	
Watershed	Rancher Benefits	State Costs	Rancher Benefits	State Costs	Rancher Benefits	State Costs	Rancher Benefits	State Costs	Rancher Benefits	State Costs	Rancher Benefits	State Costs
Canadian	-	-	10.37	40.33	10.44	54.93	-	-	8.95	26.10	10.48	23.43
Edwards Aquifer	43.52	138.5	52.12	98.49	45.61	105.00	23.27	93.75	20.81	43.71	23.88	40.64
Frio – North	30.69	79.81	39.76	90.18	39.76	84.57	10.44	92.29	23.43	60.56	23.43	60.56
Frio – South	-	-	38.71	75.95	41.6	72.32	-	-	21.07	55.57	21.07	62.92
Mid Concho	16.59	78.30	15.66	57.46	16.35	78.54	11.79	53.10	10.49	41.76	9.91	54.98
Nueces – North	30.69	79.81	34.49	95.45	34.49	89.84	10.44	92.29	19.73	64.26	19.73	64.26
Nueces – South	-	-	35.69	79.02	36.53	77.40	-	-	17.14	59.50	17.14	66.85
Pedernalis	31.86	108.56	40.61	88.77	33.31	96.07	25.74	54.68	21.22	49.20	21.22	49.20
Upper Colorado – East	14.90	69.99	17.22	60.62	16.35	83.54	11.32	58.57	12.07	42.68	10.92	58.97
Upper Colorado – West	16.76	42.14	15.89	57.23	15.07	64.82	11.90	32.99	10.55	29.84	10.25	34.64
Wichita	18.79	68.82	18.70	87.09	21.80	65.81	15.13	38.62	12.05	21.70	19.09	34.65

Note: Rancher Benefits and State Costs are in $/acre.

B.3.4 State Cost Share

If ranchers are not to benefit from the State's portion of the control cost, they must invest in the implementation of the brush control program an amount equal to their total net benefits. The total benefits that are expected to accrue to the rancher from implementation of a brush control program are equal to the maximum amount that a profit maximizing rancher could be expected to spend on a brush control program (for a specific brush density category).

Using this logic, the State cost share is estimated as the difference between the present value of the total cost per acre of the control program, and the present value of the rancher participation. Present values of the state cost share per acre of brush controlled are also shown in Table B-4. The State's cost share ranges from a low of $21.70 for control of moderate mesquite in the Wichita Watershed to $138.85 for control of heavy cedar in the Edwards Aquifer Watershed.

The costs to the State include only the cost for the State's cost share for brush control. Costs that are not accounted for, but which must be incurred, include costs for administering the program. Under current law, this task will be the responsibility of the Texas State Soil and Water Conservation Board.

B.4 Costs Of Added Water

The total cost of additional water is determined by dividing the total state cost share if all eligible acreage were enrolled in the program by the total added water estimated to result from the brush control program over the assumed 10-year life of the program. The brush control program water yields and the estimated acreage by brush type-density category by sub-basin were supplied by the Blacklands Research Center, Texas Agricultural Experiment Station in Temple, Texas (see Appendix A). The total state cost share for each sub-basin is estimated by multiplying the per acre state cost share for each brush type-density category by the eligible acreage in each category for the sub-basin. The cost of added water resulting from the control of the eligible brush in each sub-basin is then determined by dividing the total state cost share by the added water yield (adjusted for the delay in time of availability over the 10-year period using a 6 percent discount rate). Table B-5 provides a detailed example for the Wichita Watershed. The cost of added water from brush control for the Wichita is estimated to average $36.59 per acre-foot for the entire watershed. Sub-basin cost per added acft within the Wichita range from $17.56 to $91.76.

As might be expected, there is a great deal of variation in the cost of added water between sub-basins in the watersheds. Likewise, there is a great deal of variation from watershed to watershed in the average cost of added water for the entire watershed. For an example that contrasts dramatically with the results shown for the Wichita in Table B-5, the Middle Concho analysis resulted in an estimated average cost across all its sub-basins of $204.05 per acft. Most of the watershed analyses, however, resulted in estimates of costs in the $40 to $100 acft range. Although the cost of added water from alternative sources are not currently known for the watersheds in the study, a high degree of variation is likely, based mostly on population and demand. Since few alternatives exist for increasing the supply of water, these values are likely to compare well.

Table B-5 Cost Per Acft of Added Water from Brush Control by Sub-Basin – Wichita Watershed

Sub-Basin #	Total State Cost ($)	Added Gallons/Acre	Added Acft/Year	Total Acft/ 10-Years	Cost Per Acft ($)
1	457182.65	216078212.22	663.12	5173.66	88.37
2	1772111.33	806617084.67	2475.42	19313.20	91.76
3	344487.78	351071562.48	1077.40	8405.87	40.98
4	270611.17	307249619.41	942.91	7356.62	36.78
5	405303.9	244374185.73	749.96	5851.16	69.27
6	551815.58	321549997.08	986.80	7699.02	71.67
7	1829171.16	1767009344.68	5422.75	42308.32	43.23
8	1620183.78	1949004323.95	5981.27	46665.90	34.72
9	1338434.24	1365709430.82	4191.21	32699.81	40.93
10	590024.3	439341539.12	1348.29	10519.36	56.09
11	343140.75	175512983.29	538.63	4202.39	81.65
12	440716.1	337140645.01	1034.65	8072.31	54.60
13	262233	175936587.60	539.93	4212.53	62.25
14	299909.61	323150451.65	991.71	7737.34	38.76
15	354443.07	369339368.84	1133.46	8843.26	40.08
16	187848	230953440.19	708.77	5529.82	33.97
17	84634.43	88598612.82	271.90	2121.36	39.90
18	522247.77	662499062.28	2033.13	15862.52	32.92
19	124871.5	139554413.54	428.28	3341.42	37.37
20	246020.32	290468000.94	891.41	6954.81	35.37
21	2730475.37	1642473500.85	5040.57	39326.50	69.43
22	110738.33	67570294.84	207.37	1617.87	68.45
23	1369643.8	926200497.94	2842.40	22176.44	61.76
24	1563106.99	1414807304.26	4341.88	33875.38	46.14
25	971017.42	992524276.72	3045.95	23764.46	40.86
26	771619.1	1834810250.24	5630.83	43931.70	17.56
27	1478568.35	2291114837.65	7031.17	54857.21	26.95
28	1801533.32	1678434945.84	5150.93	40187.54	44.83
29	1948506.76	1790375041.38	5494.46	42867.77	45.45
30	3769655.99	3613101057.14	11088.20	86510.14	43.57
31	439757.96	589436154.61	1808.91	14113.14	31.16
32	613063.06	867628625.83	2662.65	20774.03	29.51
33	260808.4	318809382.14	978.39	7633.40	34.17
34	722243.11	1057274449.79	3244.66	25314.81	28.53
35	801913.88	1601922140.98	4916.12	38355.56	20.91
36	472961.33	534304493.17	1639.72	12793.10	36.97
37	522081.31	783102254.46	2403.25	18750.18	27.84
38	293231.45	413705742.62	1269.62	9905.55	29.60
39	3111539.76	4332844817.46	13297.01	103743.29	29.99
40	2006939.15	3063451744.60	9401.39	73349.63	27.36
41	307258.55	350869992.59	1076.78	8401.04	36.57
42	424456.46	732734077.37	2248.68	17544.19	24.19
43	493711.42	637433871.96	1956.21	15262.37	32.35
44	452996.05	793219617.91	2434.30	18992.42	23.85
45	272492.79	501654318.26	1539.52	12011.34	22.69
46	243926.57	353972454.43	1086.30	8475.32	28.78
47	24499.3	39919320.98	122.51	955.81	25.63
48	3371088.17	5745904234.60	17633.53	137576.82	24.50
Total	43,395,224.5		152004.32	1185937.68	
				Average	36.59

Note: Total Acre/Feet are adjusted for time-supply availability of water.

B.5 Additional Considerations

Total state costs and total possible added water discussed above are based on the assumption that 100 percent of the eligible acres in each type-density category would enroll in the program. There are several reasons why this will not likely occur. Foremost, there are wildlife considerations. Most wildlife managers recommend maintaining more than 10 percent brush canopy cover for wildlife habitat, especially white tailed deer. Since deer hunting is an important enterprise on almost all ranches in these eight watersheds, it is expected that ranchers will want to leave varying, but significant amounts of brush in strategic locations to provide escape cover and travel lanes for wildlife. The program has consistently encouraged landowners to work with technical specialists from the NRCS and Texas Parks and Wildlife Department to determine how the program can be used with brush sculpting methods to create a balance of benefits.

Another reason that less than 100 percent of the brush will be enrolled is that many of the tracts where a particular type-density category are located will be so small that it will be infeasible to enroll them in the control program. An additional consideration is found in research work by Thurow, et. al. (2001)[3] that indicated that only about 66 percent of ranchers surveyed were willing to enroll their land in a similarly characterized program. Also, some landowners will not be financially able to incur the costs expected of them in the beginning of the program due to current debt load.

Based on these considerations, it is reasonable to expect that less than 100 percent of the eligible land will be enrolled, and, therefore, less water will be added each year than is projected. However, it is likewise reasonable that participation can be encouraged by designing the project to include the concerns of the eligible landowners-ranchers.

---

[3] Thurow, A., J.R. Conner, T. Thurow and M. Garriga. 2001. Modeling Texas ranchers' willingness to participate in a brush control cost-sharing program to improve off-site water yields. Ecological Economics (in press).