# *Edwards Aquifer Watershed*

## *Brush Control Planning, Assessment, and Feasibility Study*

***Prepared for:***

**Texas State Soil and**
**Water Conservation Board**

***Prepared by:***

**HDR Engineering, Inc.**

***In association with:***

**Texas A&M University**

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# 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, Frio River above Choke Canyon Reservoir, Nueces River above Lake Corpus Christi, and the watersheds above the Edwards Aquifer, 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 Edwards Aquifer 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.

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 analysis, 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. Appendix A and Appendix B contain the background information on the hydrologic simulations and brush control costs, respectively.

For the purposes of this study, the area represented by the Edwards Aquifer Watershed includes portions of the following counties: Edwards, Kerr, Real, Bandera, Kinney Uvalde, and Medina. Because of the relatively small part of the region covered by the watershed relative to the entire Edwards Aquifer region, the descriptions in this section often include areas surrounding the watershed. The watershed covers approximately 2,860 square miles, and is part of the natural region known as the Edwards Plateau and the Balcones Escarpment. The Edwards Plateau is characterized by hilly, rocky terrain and thin soils supporting cedar-covered hills. Much of the watershed is eroded along drainage in Edwards, Kerr, Real, Bandera, and northern Uvalde Counties where there is moderate to major relief and canyons formed by the several streams which originate in the watershed.

Vegetation in the watershed is characterized by that of the Edwards Plateau. 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 Edwards Aquifer Watershed. From some of the earliest written accounts of the Edwards Aquifer 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 address the relative coverage of grasslands. These coverages are difficult, if not impossible, to quantify. The early observer had no means of confirming the general description of a region by using aerial, GIS, or other of the tools we typically have today. Because of this, there is always a question about the validity of the observation. However, two general conclusions regarding changes in vegetation according to the historical record 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. Even though these accounts do not provide quantitative information, it is reasonable to think that the person documenting the scenery would emphasize things that are common and not emphasize things that are uncommon or absent. 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 first streamflow gage in the Edwards Aquifer Watershed in the study area started recording in 1923 on the Nueces River at Laguna. 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 seven long-term streamflow gages 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 has been divided into subwatersheds according to the streamflow gage locations and average rainfall over a particular watershed, or areal precipitation, has been calculated. Aerial 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.

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.

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

| ***USGS Gage*** | ***Location*** | ***Drainage Area (sq. mi.)*** | ***Period of Record*** |
|---|---|---|---|
| 08190000 | Nueces River at Laguna | 737 | 10/23 - 12/96 |
| 08195000 | Frio River at Concan | 389 | 11/23-9/29,<br>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 |
| 08167000 | Guadalupe River at Comfort | 839 | 6/39 -12/96 |
| 08179000 | Medina River near Pipe Creek | 474 | 10/22-6/35,<br>10/52-9/82<br>10/82-12/96[1] |

[1]USGS #08179000 was discontinued in 1982 and 1982-1989 streamflows were estimated from the streamflows at USGS #08178880.

Significant increases in annual rainfall are indicated for all of the watersheds of the Edwards Aquifer Watershed. These watersheds all indicate increasing trends in rainfall that cannot be rejected at the 90 percent confidence level. Additional long-term (1916–1996) statistical analysis of aerial precipitation for three Hill Country sub-basins, however, does not support the short-term indications of increasing rainfall. Even so, further research into the characteristics of Hill Country rainfall in terms of intensity, duration, and frequency as they vary with time may be warranted.

None of the watersheds evaluated in this study area exhibited decreasing trends in runoff as a percentage of rainfall. The watersheds above the Nueces River at Laguna (USGS #08190000), the Frio River at Concan (USGS #08195000), the Sabinal River near Sabinal

(USGS #08198000), and the Guadalupe River at Comfort (USGS #08167000) demonstrate increasing trends in this ratio that cannot be rejected at the 90 percent confidence level. Further investigation of these sub-basins based on modified Soil Conversation Service curve number procedures indicates that increased runoff per unit rainfall may be explained by increased rainfall during the latter times periods. Most importantly, none of the Edwards Aquifer Watersheds considered in this study exhibit any indications of decreasing annual runoff per unit rainfall with time.

Potential sites for brush control are those sites where observations and statistical analyses indicate decreasing runoff relative to 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 seven sub-basins considered in the Edwards Aquifer Watershed, none of the watersheds appear particularly promising for brush control with the primary objective of increasing runoff or water yield. However, further consideration of the Dry Frio River, upper Medina River, and Hondo Creek watersheds may be appropriate. Average annual rainfall throughout the Edwards Aquifer Watershed 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 Edwards Aquifer Watershed is significantly increasing in four sub-basins and showing no trend in three sub-basins at the 90 percent confidence level. The increasing trend in the relationship between runoff and rainfall occurs in the sub-basins above the streamflow gages on the Nueces River at Laguna (USGS #08190000), the Frio River at Concan (USGS #08195000), the Sabinal River at Sabinal (USGS #08198000), and the Guadalupe River at Comfort (USGS #08167000). No significantly decreasing trends in runoff as a percentage of rainfall were indicated from the analyses. Thus, most of the larger sub-watersheds in the Edwards Aquifer Watershed are not recommended for further consideration of brush control management for the purposes of increasing runoff or water yield. However, further consideration of the watersheds above the Dry Frio at Reagan Wells (USGS #08197000), Hondo Creek at Tarpley (USGS #08200000), and the Medina River at Pipe Creek (USGS #08179000) may be appropriate as these watersheds did not exhibit significantly increased runoff per unit rainfall even though increases in rainfall over time proved significant.

The SWAT model simulated streamflow for the watersheds that might warrant further consideration for brush control. For the Frio River, based on 39 years of simulation, it is predicted that there will be an average increase in flow at outlet of 20,561 acre-feet/year (acft/yr) due to brush removal; for Hondo Creek there will be an average increased flow of 7,665 acft/yr due to brush removal; and for the Medina River there will be an average increased flow at outlet of river basin of nearly 50,000 acft/yr.

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 $30.00 per acft for the Hondo Creek Watershed, $27.00 per acft for the Medina River Watershed, and about $52.00 per acft for the Upper Frio River Watershed. Sub-basins range from costs per added acft about $5.00 to $242.00. For the entire Edwards Recharge Zone Watershed, the average costs per added acft of added water is $67.00.

Although these costs 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 continuously available from the Edwards Aquifer during a drought of record. Therefore, comparisons of these cost figures to those for other alternatives (e.g. Unit cost information for numerous water supply options presented in the South Regional Water Plan is based on firm, dependable water supply available during a report of the drought of record.)[1] cannot be made directly. 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.
- 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.
- 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 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.

[1] 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.

# Section 3
# Description of the Watershed

## 3.1 Area Comprising the Edwards Aquifer Watershed

For the purposes of this study, the area represented by the Edwards Aquifer Watershed includes portions of the following counties: Kerr, Real, Uvalde, Bandera, and Medina (Figure 3-1). The Edwards recharge area was assumed to consist of the Upper Nueces watershed and the five river basins: Upper Frio, Sabinal, Seco, Hondo, and Medina. Because of the relatively small part of the region covered by the watershed relative to the entire Edwards Aquifer region (Figure 3-2), the descriptions in this section often include areas surrounding the watershed. The watershed covers approximately 2,860 square miles, and is part of the natural region known as the Edwards Plateau and the Balcones Escarpment (Figure 3-3).

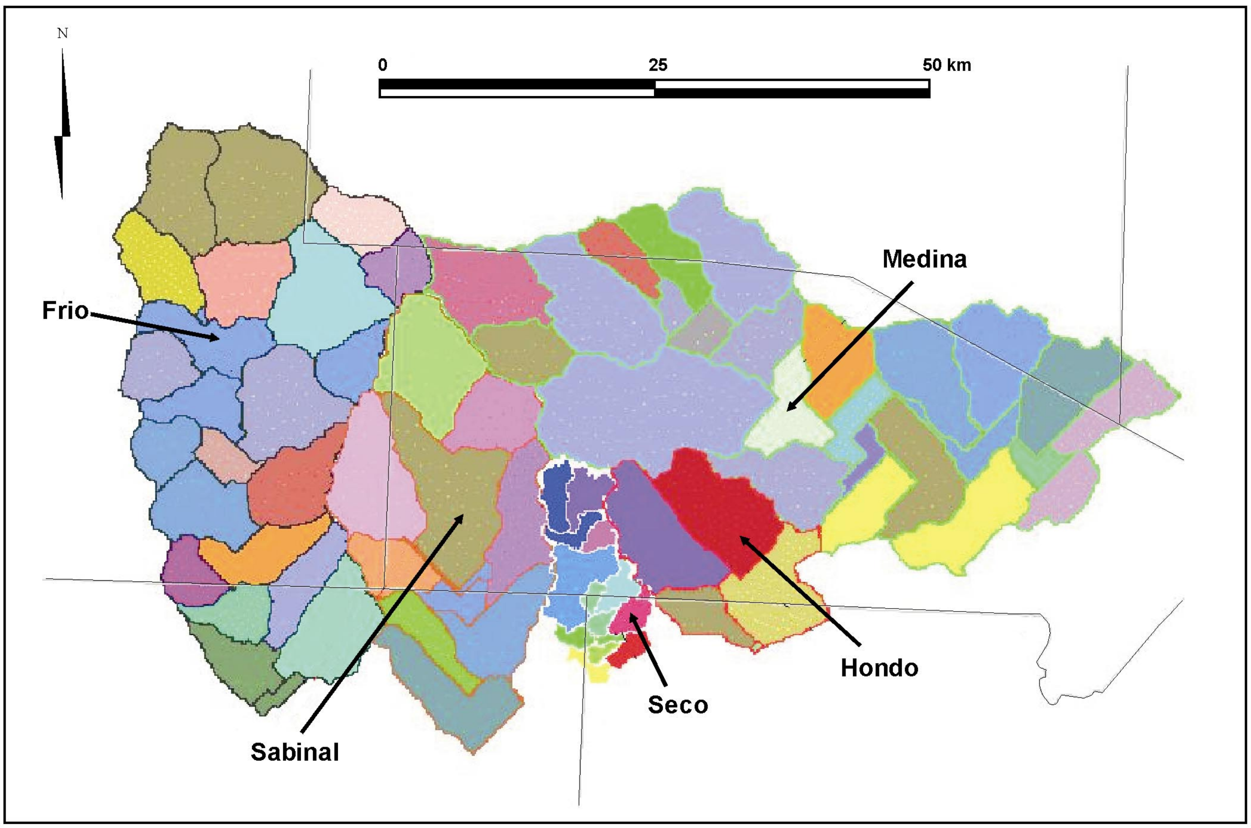


*Figure 3-1. Edwards Aquifer Recharge Sub-basins*

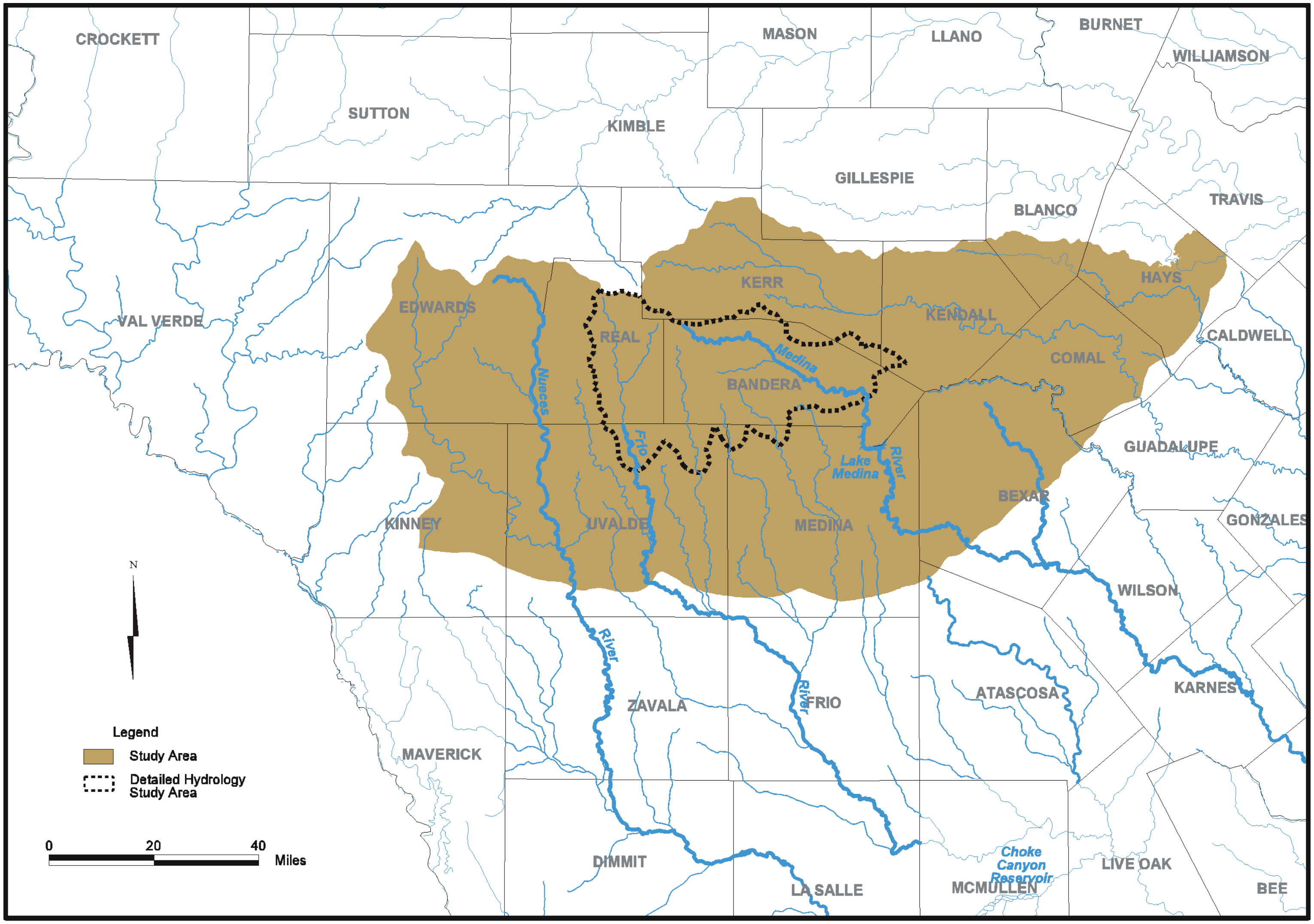


**Figure 3-2. Edwards Aquifer Watershed Location Map**

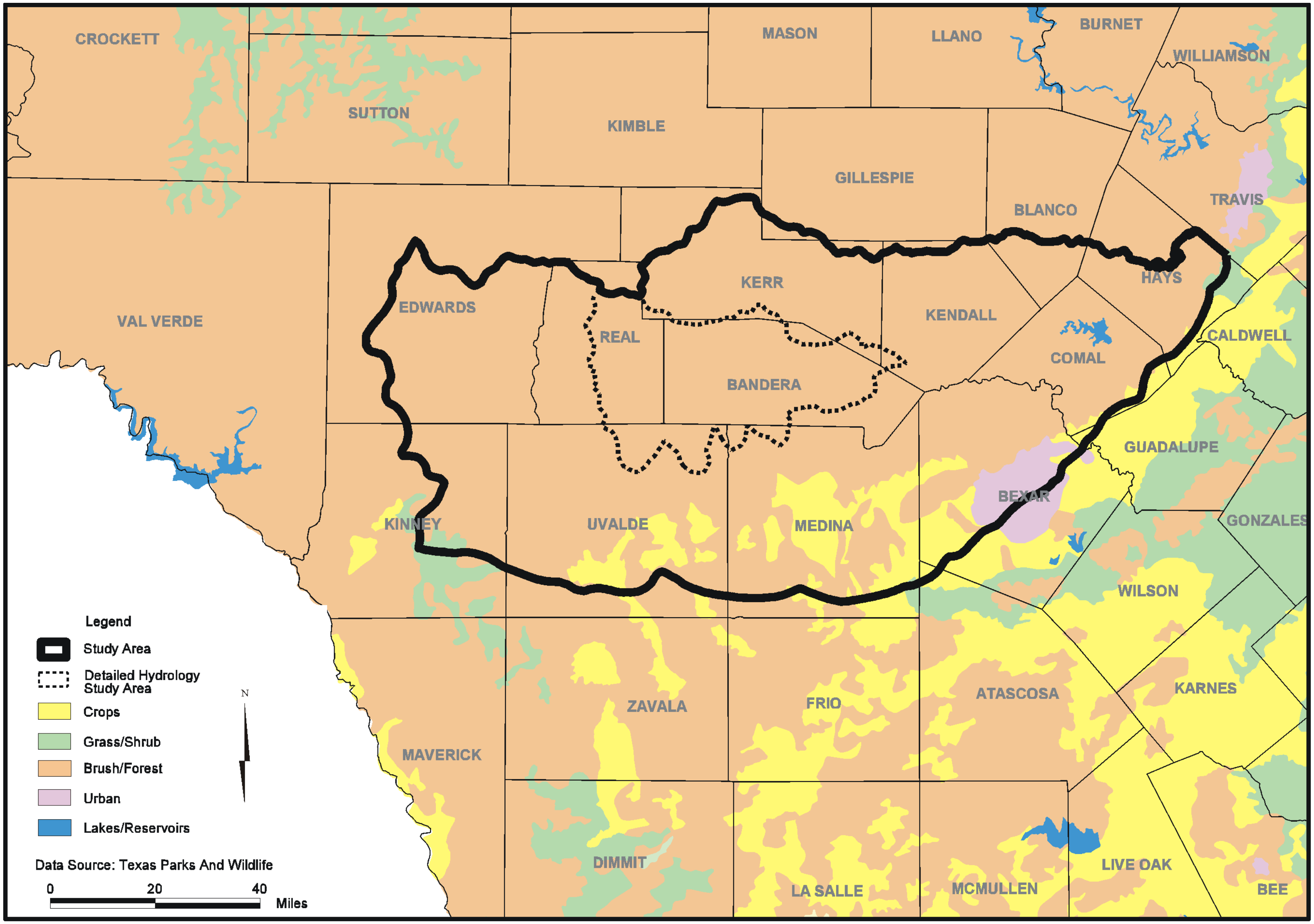


*Figure 3-3. Vegetation*

### 3.2 Climate

The climate is warm and dry and is similar among the various counties of the watershed. Table 3-1 shows that average air temperatures are very consistent across the watershed, whereas annual rainfall varies from over 34 inches in the eastern counties to about 24 inches in Uvalde County. The growing season for any part of the watershed is over 200 days per year. 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.

***Table 3-1. Climate of Edwards Aquifer 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 |
| Kerr | 29.8 | 32 | 94 | 216 |
| Medina | 27.3 | 37 | 94 | 263 |
| Real | 25.7 | 31 | 92 | 236 |
| Uvalde | 24.1 | 37 | 97 | 255 |
| Mean | 28.4 | 33.6 | 94.2 | 241.0 |
| Standard Deviation | 4.3 | 3.1 | 1.8 | 18.5 |
| Source: *Texas Almanac*, 2000-2001. | | | | |

### 3.3 Physiography

The terrain is characteristic of the Hill Country of Texas. The Edwards Plateau is characterized by hilly, rocky terrain and thin soils supporting cedar-covered hills. Much of the watershed is eroded along drainage in Kerr, Real, Bandera, and northern Uvalde Counties where there is moderate to major relief and canyons formed by the several streams which originate in the watershed. The watershed is drained by the Medina River and the Frio portion of the Nueces

River system. Although spring-fed creeks exist in the Escarpment, 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 are Cretaceous chalk, clay, and limestone beds which are younger than Edwards formations. The entire region, including the Edwards Aquifer 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 Edwards Aquifer 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 that 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 that 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, which 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 Edwards Aquifer 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 Frio and Nueces Rivers and their tributaries.

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.

### *3.5 Water Resources*

The Edwards Aquifer Watershed includes two major tributaries—Medina River and the Frio River and its tributaries, Sabinal River, Seco Creek, 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-Trinity and Trinity Aquifers define the groundwater resources. As presented earlier, annual rainfall in the semi-arid basin averages over 28 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 Edwards Aquifer 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 entered the aquifer from the Frio and other rivers, which crossed the recharge zone during the period from 1934 to 1996.

### 3.5.1 Surface Water

Although land use in the Edwards Aquifer 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 Bandera, with a population of about 1,296.

Groundwater/surface water interactions play a significant role in the Edwards Aquifer Watershed. The Edwards Aquifer Watershed is traversed by the outcrops of four major aquifers. 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 to the west sustains a minimal baseflow across the outcrop. The Frio and Sabinal Rivers are very often dry at the downstream edge of the outcrop.

With the exception of a few springs, interactions between groundwater and surface water in the Edwards Aquifer 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 River 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 (Plateau) and Trinity Aquifer (Figure 3-4) provide substantial groundwater resources within the Edwards Aquifer Watershed. 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

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

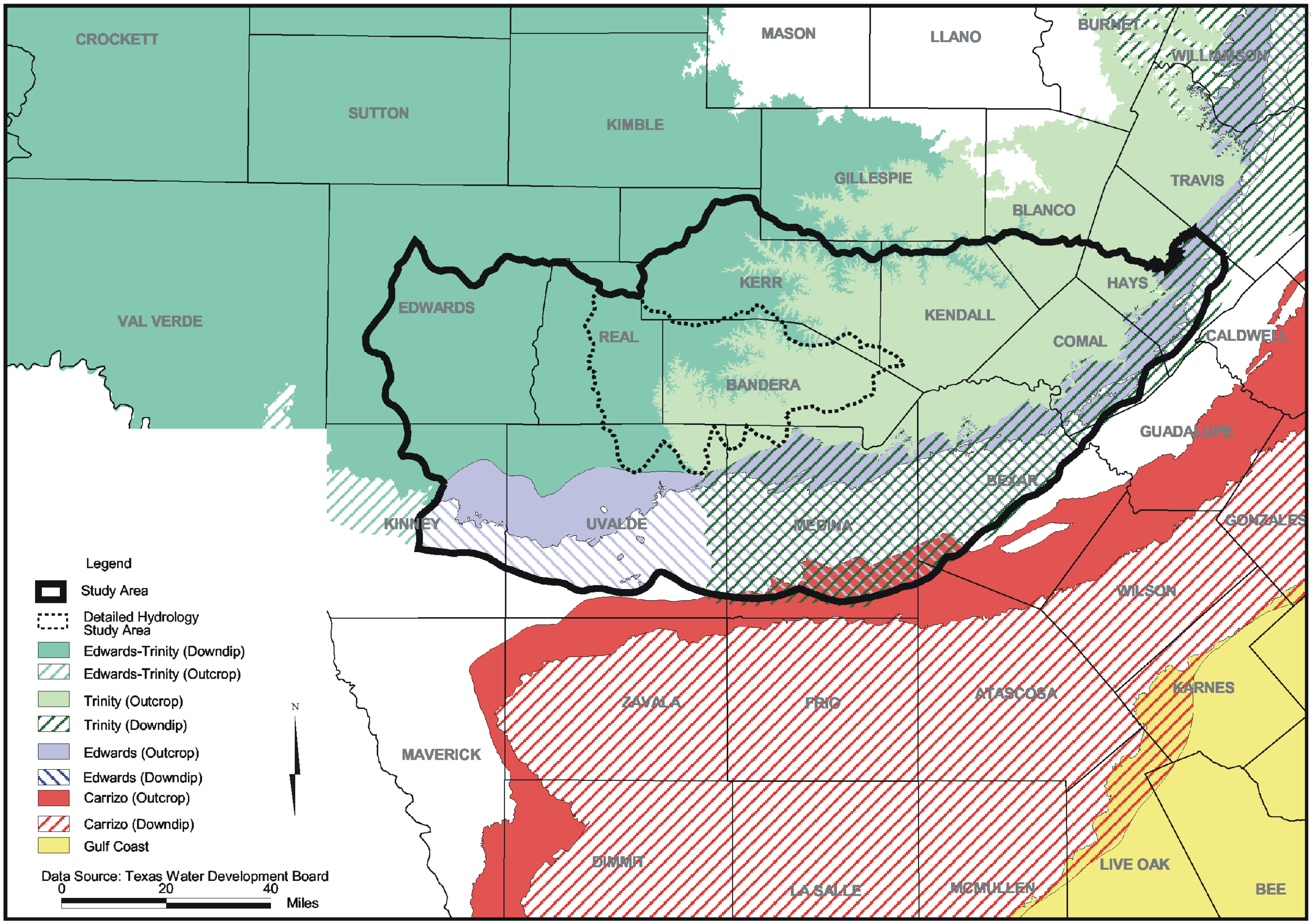


*Figure 3-4. Aquifers*

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 Edwards Aquifer 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.

### *3.6 Resource Aspects*

The watershed is well known for its valuable living natural resources. Ecosystems consist of the 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 region in which the study is located is host to such a variety of wildlife that one of the state wildlife areas are located in the lower reaches of the Edwards Aquifer 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 only primitive camping is allowed for camping facilities.

### *3.7 Vegetation*

Vegetation in the watershed is characterized by the Edwards Plateau. 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 Edwards Aquifer 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.

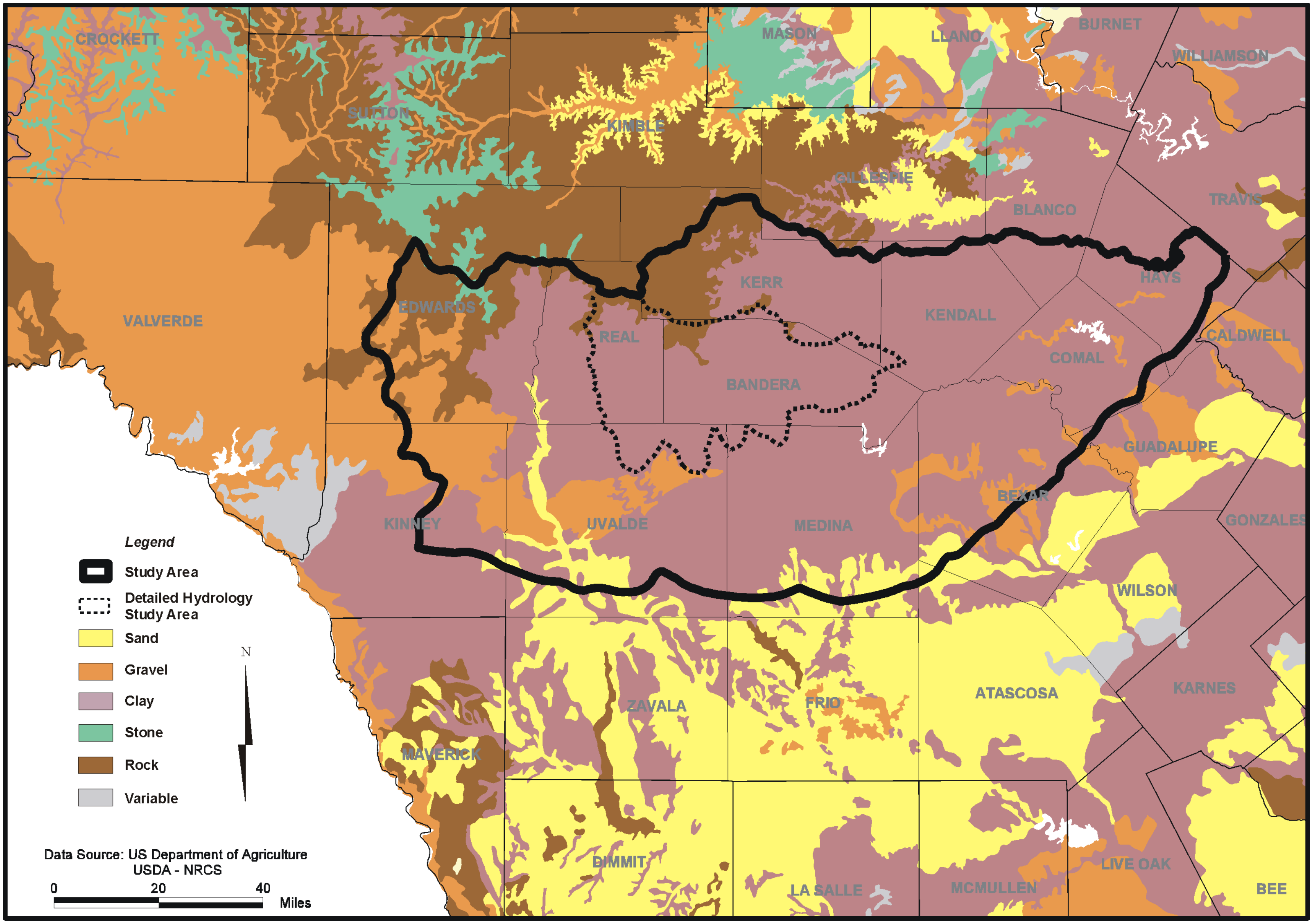


*Figure 3-5. Soils*

# *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 be 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 agriculturists. 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 are wet-weather streams only now. 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, 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 Edwards Aquifer 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, suffered natural selection. Another fact is that wildfires were likely to be 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 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 Edwards Aquifer 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 Edwards Aquifer Watershed may not have been strictly a grassland prairie, but rather contained large numbers of brush-like vegetation such as the prickly pear. However, the Basque-Larios Expedition noted on April 6, 1675, near Salado Creek, "I arrived at a large river, very beautiful with many groves of very large cedars, cottonwoods, and mesquite brush, and with great plains of land which are very pleasing with green grass."[7] 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…"[8] 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."[9] 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.

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[5] *Ibid*., p. 5.
[6] Warren, Betsy, "Explorers in Early Texas," p. 18, Hendrick-Long Publishing Co., Dallas, Texas, 1992.
[7] Bolton, Herbert Eugence, "Spanish Exploration in the Southwest, 1542-1706," p. 294, Barnes and Noble, Inc., New York, NY, 1908.
[8] Hall, Grant P, "Leona River Watershed, Uvalde County," Research Report No. 37, 1974.
[9] Santos, Richard G, "Aguayo Expedition into Texas, 1721," p. 28, Jenkins Publishing Co., Austin, Texas, 1981.

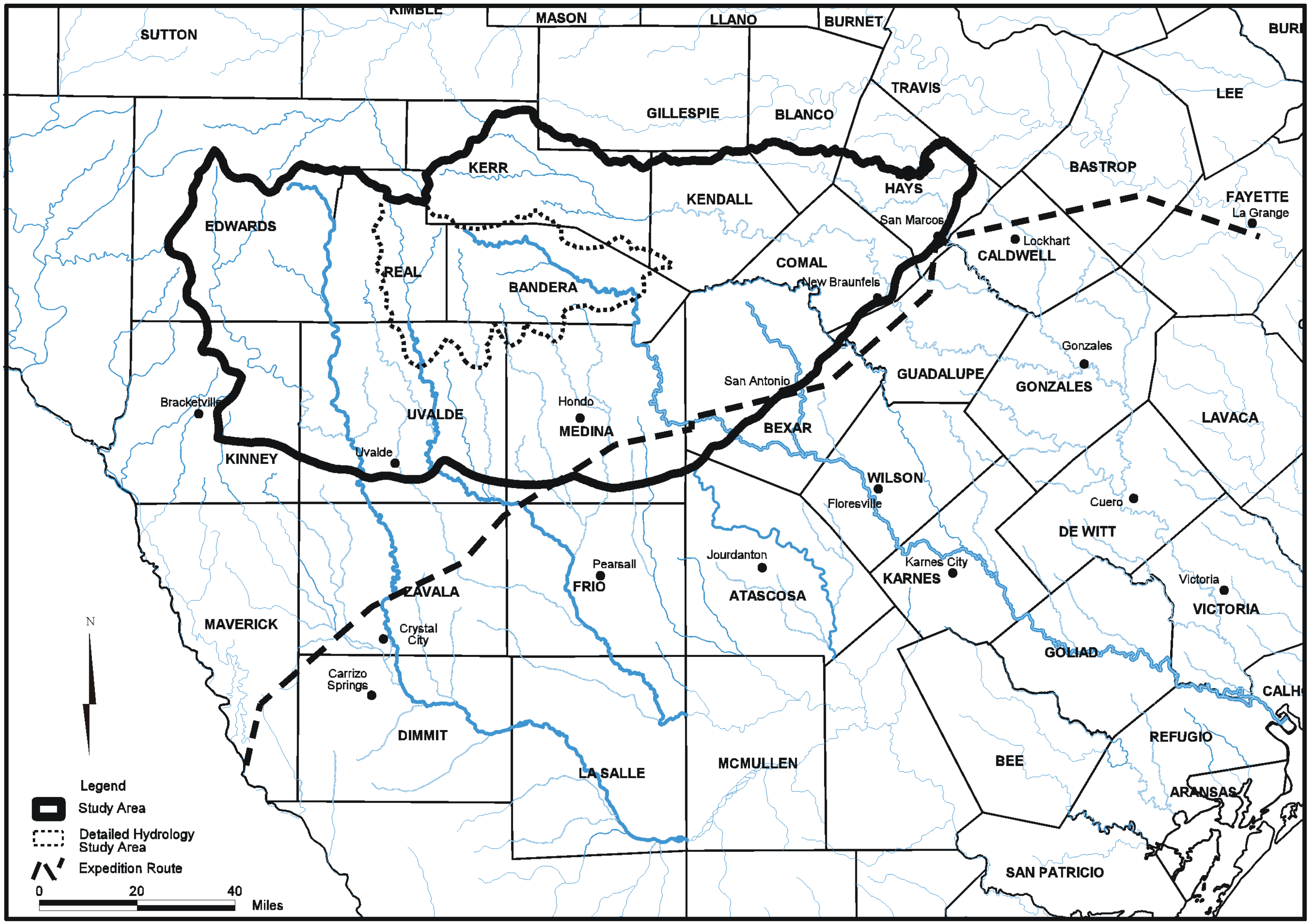


*Figure 4-1. Governor Domingo Teran de los Rios's 1691 - 1692 Expedition*

Spanish accounts of the Edwards Aquifer 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 luxuriance of plants, nuts,…wild grapes, good pasturage, a variety of birds and wild hens.”[10] 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)[11] 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.”[12]

The Aguayo Expedition in the early 1700s noted from Salado to Cibolo Creek, “…brushy terrain with thorny mesquite trees which give a fruit eaten by the Indians. There were also many heavy oak trees.”[13] The same expedition, however, suggests more support for the existence of grassland savannas in its accounts southeast of the Escarpment. 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 a branch and dirt bridge…”[14] From Cibolo Creek to the Guadalupe River, the expedition noted, “…heavy mesquite; no plants without flowers in bloom…so close together that no weeds grew…”[15] If anything is clear from these few explorer observations of the Edwards Aquifer Watershed, it is that the landscape then had elements in common with the current landscape. It is also the case that the accounts describe elements of grasslands and of prairies congested with brush. These account are testimony that in some places there was heavy brush similar to what is found today, but well before there was intensive agricultural practice in the Edwards Aquifer Watershed. 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.

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[10] *Op. Cit*., Bolton, p. 336.
[11] 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.
[12] *Ibid*., p. 13.
[13] Santos, Richard G, “Aguayo Expedition into Texas, 1721,” p. 35, Jenkins Publishing Co., Austin, Texas, 1981.
[14] *Ibid*. p. 35.
[15] *Ibid*.

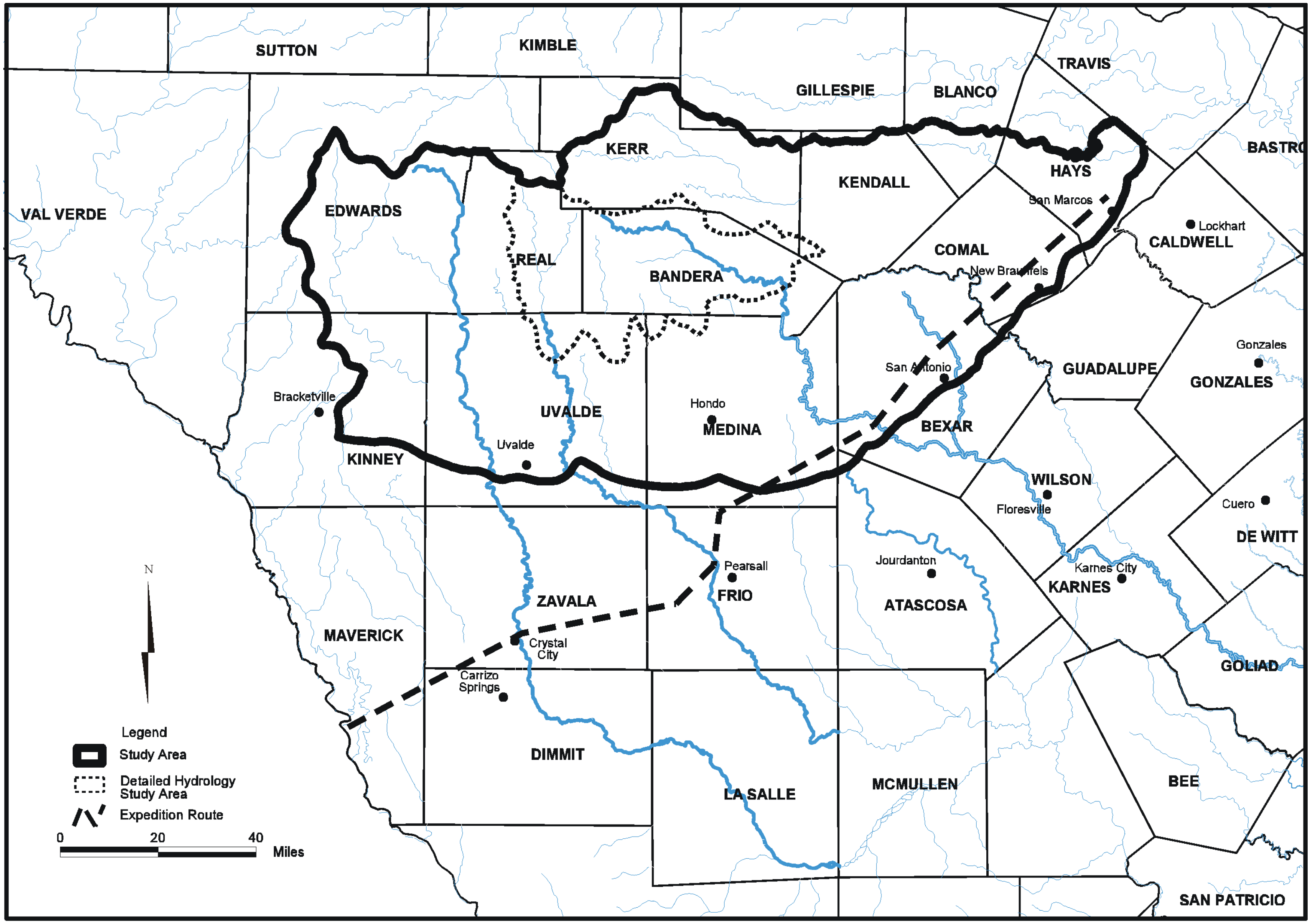


*Figure 4-2. Aguayo's Expedition 1721*

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 Edwards Aquifer 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*

Most accounts of the watershed in the 1800s noted plenty of timber. For example, Frederick Law Omstead's journey in 1844 through the eastern part of the watershed documented grasslands near San Marcos and New Braunfels but brush further south. On the road near San Marcos, "We pitched our tent at night in a live oak grove…Behind us (to the west) were the continuous wooded heights with a thick screen of cedars; before us, very beautiful prairies, rolling off far southward, with the smooth grass surface…"[16] On the road from New Braunfels to San Antonio, he noted, "…trees were live oak but overall were rare; grassland recently burned; mesquite gradually thickened…"[17] He also noted planters have a lack of timber to make fence posts.

Olmstead's accounts note significant grasslands in the areas around San Antonio that are now brushlands, if not cultivated for crops. "We rode before evening to the Medina, 25 miles. Imagine, for the country, a rolling sheet of the finest grass, sprinkled thick with bright, many-hued flowers, with here and there a live oak, and an occasional patch of mesquite trees,…"[18] Near San Antonio, Olmstead made note of the mesquite grass, "It is a fine, short grass, growing with great vigor and beauty over the western prairie. It is usually found in very thick tufts and patches, interspersed with other grasses,…"[19] By 1885, an account near the San Antonio River may have described a dramatic change, "…mesquite dominates area: it is mostly a shrub, sometimes a stunted tree and covers the slopes and much of the tableland."[20]

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. [21]

The *Texas Almanac* describes changes in prairie fires in 1873. "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.

[16] McMurtry, Larry, "A Journey through Texas – Frederick Law Omstead," p. 137, University of Texas Press, Austin, Texas, 1978.
[17] Ibid., p. 147.
[18] Ibid., p. 275.
[19] Ibid, pp. 135-136.
[20] Harvard, Valery, "Report on the Flora of Western and Southern Texas," Vol. 8, No. 29, Washington, D.C., 1885.
[21] Ibid.

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."[22] Further description of the region is provided in the *Texas Almanac* regarding the streams: "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."[23]

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 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."[24] 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.

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[22] "Texas Almanac and State Industrial Guide," p. 109, Richardson, Belo and Co., Galveston, 1873.
[23] *Ibid*., p. 176.

### *4.3.2 1901 to 1939*

In certain parts of the Edwards Aquifer 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 Medina County, "…timber only near rivers; types: cypress, live oak, mesquite, cedar…"[25] Similarly, an account of Bexar County in the *Texas Almanac* (page 213) at that time, "…north of the ridge, the surface is broken, lofty green hills, dotted with live oak and valleys of meadow land and prairie, the whole [is] carpeted with luxuriant native grasses." Comal County was, "…thickly covered with live oak, post oak, walnut, cedar, pecan, mesquite and elm." (page 241) But in Bandera County it was noted, "west: ranges of mountains with forest of cedar and dense undergrowth...(page 209) and …Heavy growths of underbrush, good for goat browsing, cedars, post oak, Spanish oak, live oak, pecans, and cypress along streams…" (page 515).

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 still sufficiently numerous and variant to indicate the stages of the progressive invasion by mesquite, acacia, Texas ebony, hackberry, purple sage, etc…."[26] 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."[27] 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 watershed. In Bandera County were "Heavy growths of underbrush; good for goat browsing, cedars, post oak, Spanish Oak, live oak, pecans, and cypress along streams…"[28] In Zavala County, "Timber includes mesquite, catclaw, live oak, mulberry,

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[24] *Op. Cit.*. Feherenbach, pp. 566-567.
[25] "Texas Almanac and State Industrial Guide," p. 311, Richardson, Belo and Co., Galveston, 1904.
[26] Tharp, Benjamin Carroll, "The Vegetation of Texas," p. 10, The Anson Jones Press, Houston, Texas, 1939.
[27] *Ibid*., p. 21.
[28] "Texas Almanac and State Industrial Guide," p. 610, Richardson, Belo and Co., Galveston, 1951.

hackberry, cottonwood, pecan. Part prairie, largely brushland…"[29] Dimmit County was noted to be "Largely covered with mesquite, oak, elm, and brush…a lot of brush covered ranchland…"[30] Also, in southwest Bexar County, "…undulating prairie and brush-covered coastal plain…timber throughout county: cedar, mesquite, blackjack, post oak, Spanish oak, elm, hickory, pecan…"[31]

### *4.4 Summary*

From some of the earliest written accounts of the Edwards Aquifer 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, and 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. Even though these accounts do not provide quantitative information, it is reasonable to think that the person documenting the scenery would emphasize things that are common and not things that are rare. 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 Edwards Aquifer Watershed as they appear today.

[29] *Ibid*., p. 619.
[30] *Ibid*., p. 538.
[31] Ibid., p. 517.

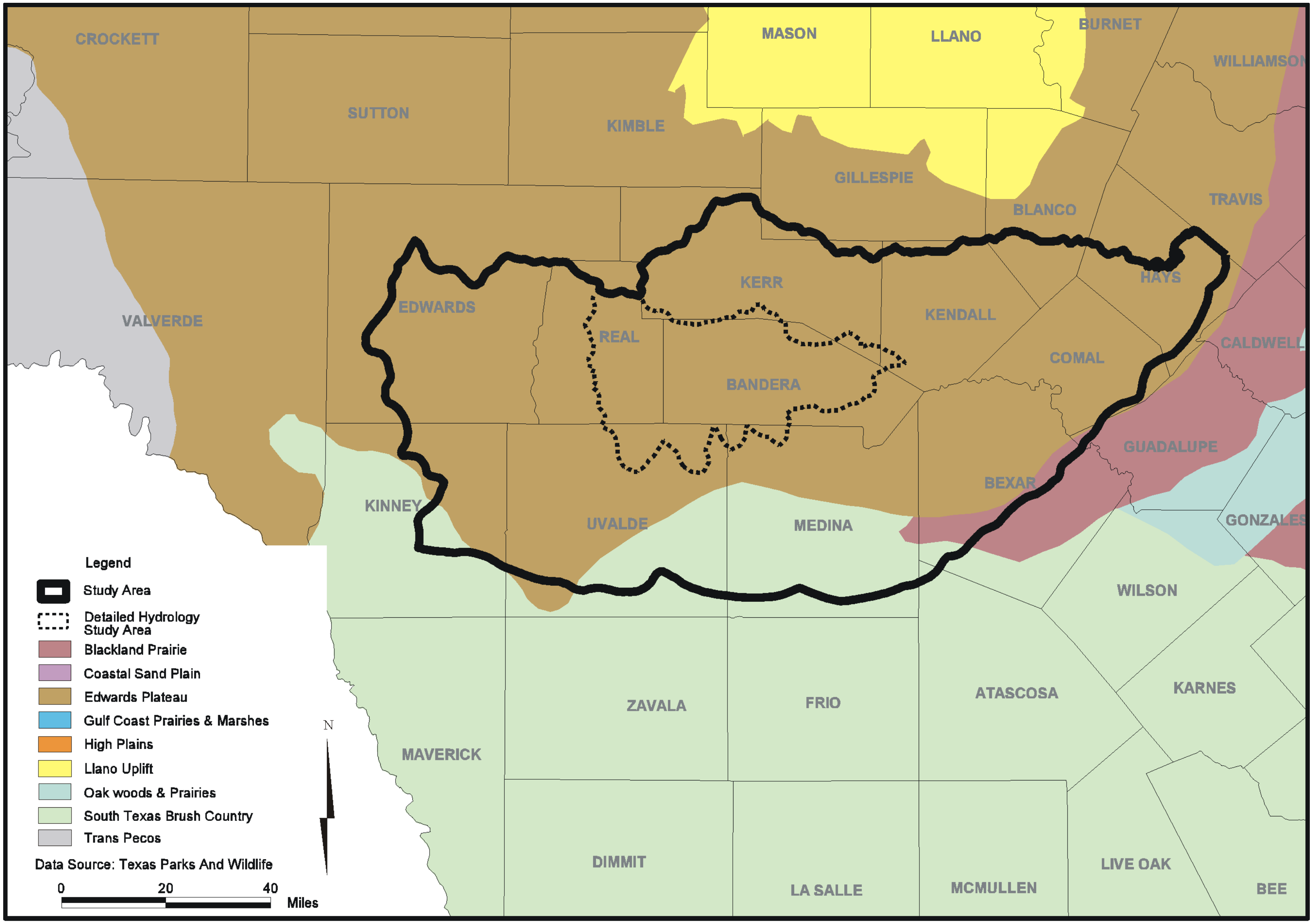


*Figure 4-3. Natural Regions*

# Section 5
# Hydrologic Evaluation

## 5.1 Hydrologic Description of Basin

The study area consists primarily of the Edwards Aquifer Watershed from the Nueces River to the Guadalupe River as shown in Figure 5-1. The Edwards Aquifer Watershed is the drainage area upstream of the downstream extent of the Edwards Aquifer recharge zone, plus additional areas north to the Bad Water Line within the aquifer. Specific watersheds under consideration in thus study encompass approximately 2,860 square miles out of the larger drainage area comprising the Edwards Aquifer Watershed. The Edwards Aquifer recharge zone includes portions of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties. Major rivers of the Edwards Aquifer Watershed study area include the Nueces, Frio, Medina, and Guadalupe Rivers.

The topography of the Edwards Aquifer Watershed 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, vegetation has relatively little influence on runoff, with the exception of cedar where the canopy intercepts extremely large amounts of rainfall. 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 Edwards Aquifer Watershed crosses three major river basins including the Nueces, San Antonio, and Guadalupe River Basins. The Edwards Aquifer is the most significant aquifer outcrop or recharge zone in Texas. 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 653,000 acft of water per year[1] enters the aquifer from these major rivers and their tributaries.

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

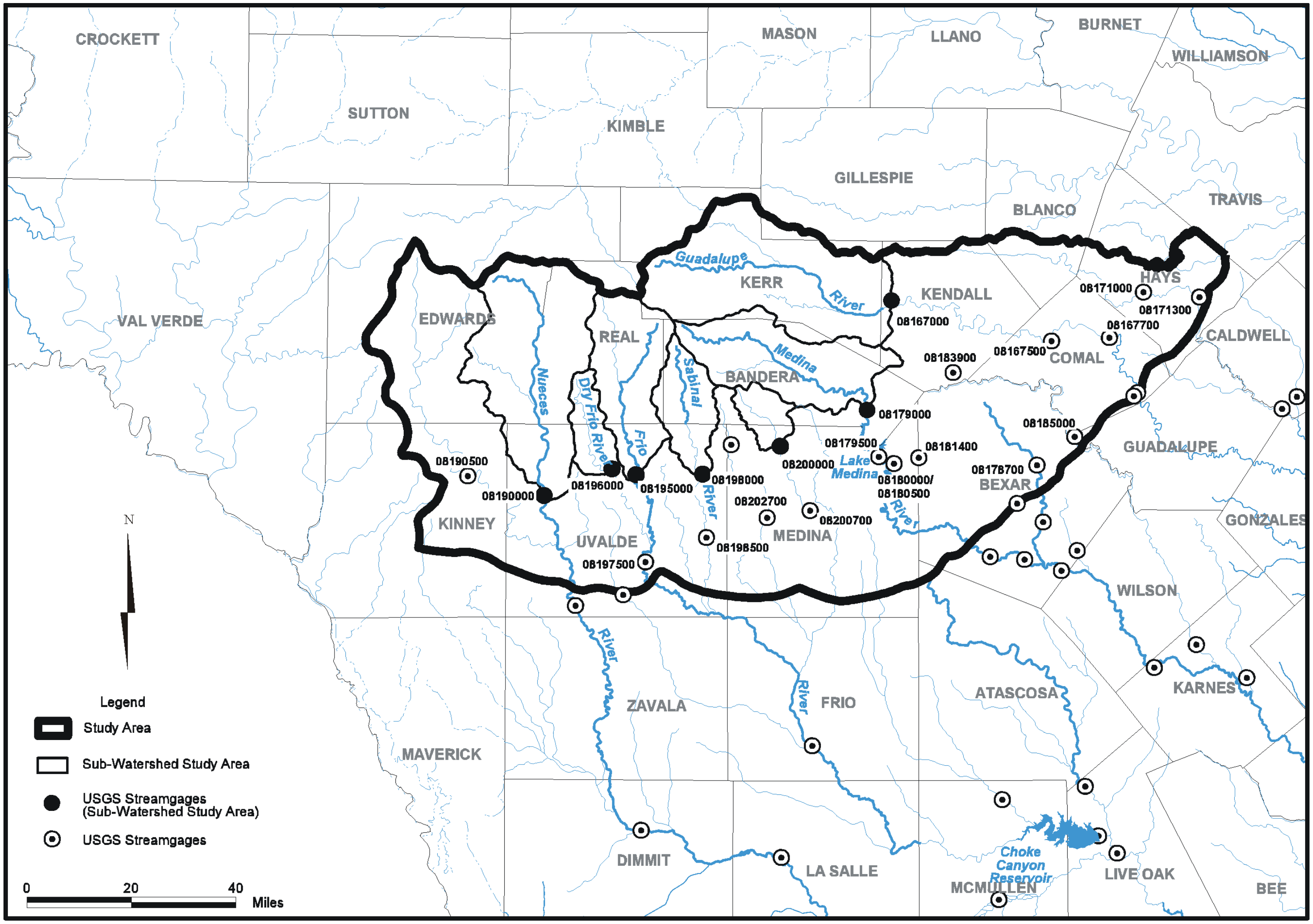


*Figure 5-1. USGS Streamgages*

### 5.1.1 Hydrologic History and Conditions

The Edwards Aquifer Watershed, much like the rest of south-central Texas, has experienced extreme droughts and floods. Large storms of record in the Edwards Aquifer Watershed occurred in 1880, 1932, 1955, 1958, 1966, 1978, and 1997. Table 5-1 lists the largest floods known at several of the long-term gages in the watershed. The largest flow measured for the Edwards Aquifer Watershed is 307,000 cfs for the Nueces River at Laguna (USGS #08190000) on September 24, 1955. The next largest flow is 281,000 cfs for Medina River near Pipe Creek (USGS #08179000) on August 2, 1978.

From the period of 1934 to 1996, droughts ranging in severity have occurred throughout the Edwards Aquifer Watershed. 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 20 to 28 percent less than the long-term average annual rainfall. For instance, long-term average areal rainfall for Nueces River watershed above Laguna is 25.3 inches, and the average rainfall during the 1950s drought was 20.1 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 Edwards Aquifer Watershed and the period of record for each gage is shown in Figure 5-1. The dark circles indicate the gages considered in this Edwards Aquifer Watershed study. The first streamflow gage in the Edwards Aquifer Watershed in the study area started recording in 1923 on the Nueces River at Laguna. 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 seven long-term streamflow gages considered herein are listed in Table 5-2.

Precipitation or rainfall gages provide information for specific locations in the watershed. To better compare the rainfall data to streamflow data, the watershed has been 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

**Table 5-1. Edwards Aquifer Watershed — Flood History Summary**

| USGS Gage # | Gage Location | Drainage Area ($mi^2$) | Continuous Record Since | Largest Flood for Period of Record: Peak Flow (cfs) | Largest Flood for Period of Record: Peak Stage (feet) | Largest Flood for Period of Record: Date | Largest Flood Outside Period of Record: Peak Flow (cfs) | Largest Flood Outside Period of Record: Peak Stage (feet) | Largest Flood Outside Period of Record: Date |
|---|---|---|---|---|---|---|---|---|---|
| 08190000 | Nueces River at Laguna | 737 | 1923 | 307,000 | 32.70 | 9/24/1955 | - | 29 | 6/1913 |
| | | | | 222,000 | 26.40 | 7/13/1939 | 160,000 | 26.5 | 9/21/1923 |
| 08195000 | Frio River at Concan | 389 | 1930 | 162,000 | 34.44 | 7/1/1932 | - | - | - |
| | | | | 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 | - | 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 | 28.30 | 6/17/1958 | - | 33 | 7/2/1932 |
| | | | | 52,500 | 28.50 | 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 | | | |
| 08167000 | Guadalupe River at Comfort | 839 | 1939 | 240,000 | 40.90 | 8/2/1978 | - | 42.3 | 7/1869 |
| | | | | 130,000 | 31.50 | 7/17/1987 | | 38.4 | 7/16/1900 |
| | | | | 111,000 | 33.15 | 10/4/1959 | | 38.4 | 7/1/1932 |
| 08179000 | Medina River near Pipe Creek | 474 | 1952 | 281,000 | 49.60 | 8/2/1978 | - | 43 | 1919 |
| | | | | 72,900 | 37.30 | 7/15/1973 | | | |

watersheds considered herein was calculated in the course of two earlier studies[2,3,4] sponsored by the Nueces River Authority, Edwards Underground Water District, and/or the City of Corpus Christi. Annual areal precipitation for each subwatershed corresponding with the selected streamflow gages is listed in Table 5-3.

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

| USGS Gage # | Location | Drainage Area (sq. mi.) | Period of Record |
|---|---|---|---|
| 08190000 | Nueces River at Laguna | 737 | 10/23 - 12/96 |
| 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 |
| 08167000 | Guadalupe River at Comfort | 839 | 6/39 -12/96 |
| 08179000 | Medina River near Pipe Creek | 474 | 10/22-6/35, 10/52-9/82<br>10/82-12/96[1] |

[1]USGS #08179000 was discontinued in 1982 and 1982-1989 streamflows were determined from the streamflows at USGS #08178880.

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.5,6,7 Annual naturalized flow for seven streamgages is listed in Table 5-4.

[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.
[4] HDR, “Guadalupe-San Antonio River Basin Recharge Enhancement Study,” Edwards Underground Water District, September 1993.
[5] Op. Cit., HDR, May 1991.
[6] Op. Cit., HDR, January 1999.
[7] Op. Cit., HDR, September 1993.

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

| Year | Nueces River at Laguna USGS #08190000 (in) | Frio River at Concan USGS #08195000 (in) | Dry Frio River at Reagan Wells USGS #08195000 (in) | Sabinal River at Sabinal USGS #08198000 (in) | Hondo Creek at Tarpley USGS #082000000 (in) | Guadalupe River at Comfort USGS #08167000 (in) | Medina River at Pipe Creek USGS #08179000 (in) |
|---|---|---|---|---|---|---|---|
| 1934 | 13.94 | 16.88 | 16.84 | 19.07 | 23.13 | 23.34 | 24.46 |
| 1935 | 43.00 | 44.27 | 43.52 | 47.55 | 52.77 | 49.37 | 49.63 |
| 1936 | 35.82 | 36.74 | 35.82 | 32.50 | 39.46 | 46.75 | 46.55 |
| 1937 | 20.82 | 21.48 | 20.82 | 21.09 | 24.21 | 26.43 | 27.57 |
| 1938 | 17.29 | 18.91 | 17.72 | 24.59 | 25.66 | 21.01 | 21.43 |
| 1939 | 19.47 | 20.30 | 19.47 | 23.16 | 23.61 | 27.58 | 27.29 |
| 1940 | 21.89 | 24.18 | 21.89 | 31.52 | 31.99 | 36.24 | 32.76 |
| 1941 | 30.10 | 32.84 | 32.41 | 36.26 | 35.99 | 35.41 | 33.45 |
| 1942 | 28.45 | 28.70 | 27.82 | 32.90 | 34.52 | 27.48 | 29.86 |
| 1943 | 22.39 | 20.96 | 19.38 | 23.55 | 24.29 | 20.58 | 21.75 |
| 1944 | 24.03 | 27.47 | 26.95 | 36.20 | 37.22 | 33.31 | 37.56 |
| 1945 | 17.71 | 19.82 | 18.69 | 30.82 | 31.91 | 27.41 | 31.42 |
| 1946 | 24.45 | 25.60 | 25.48 | 25.80 | 25.51 | 33.30 | 29.62 |
| 1947 | 22.02 | 24.03 | 25.03 | 18.62 | 18.21 | 24.77 | 20.73 |
| 1948 | 20.29 | 18.84 | 17.66 | 22.93 | 22.72 | 24.46 | 23.00 |
| 1949 | 40.03 | 35.54 | 36.38 | 41.11 | 44.28 | 36.15 | 41.48 |
| 1950 | 18.19 | 20.29 | 18.80 | 22.38 | 23.87 | 20.48 | 22.99 |
| 1951 | 16.87 | 19.11 | 24.71 | 18.89 | 18.18 | 16.57 | 17.63 |
| 1952 | 18.56 | 21.15 | 21.80 | 23.80 | 27.30 | 32.29 | 29.77 |
| 1953 | 16.17 | 12.80 | 14.55 | 17.00 | 22.79 | 20.86 | 21.32 |
| 1954 | 18.89 | 17.54 | 17.55 | 16.96 | 17.24 | 15.01 | 15.26 |
| 1955 | 22.08 | 22.65 | 22.54 | 22.42 | 22.00 | 25.01 | 21.26 |
| 1956 | 8.23 | 8.67 | 8.64 | 9.80 | 11.72 | 12.96 | 11.65 |
| 1957 | 32.01 | 33.70 | 33.00 | 36.64 | 40.98 | 43.09 | 43.79 |
| 1958 | 40.07 | 45.15 | 46.14 | 44.78 | 40.96 | 36.65 | 40.44 |
| 1959 | 29.79 | 28.91 | 30.43 | 29.93 | 30.92 | 30.35 | 31.59 |
| 1960 | 25.87 | 28.04 | 27.84 | 31.09 | 37.55 | 33.49 | 35.12 |
| 1961 | 22.26 | 26.01 | 27.36 | 27.88 | 28.25 | 22.57 | 26.99 |
| 1962 | 15.98 | 15.69 | 15.33 | 17.57 | 21.50 | 18.50 | 19.85 |
| 1963 | 21.86 | 17.16 | 19.78 | 18.79 | 20.65 | 19.65 | 20.63 |
| 1964 | 26.00 | 25.94 | 26.64 | 24.79 | 22.45 | 29.67 | 27.71 |
| 1965 | 21.91 | 26.52 | 27.57 | 26.87 | 23.82 | 32.29 | 32.90 |
| 1966 | 24.46 | 33.36 | 32.17 | 32.06 | 34.66 | 29.04 | 31.53 |
| 1967 | 24.85 | 25.29 | 25.00 | 24.51 | 26.00 | 25.66 | 25.82 |

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

| Year | Nueces River at Laguna USGS #08190000 (in) | Frio River at Concan USGS #08195000 (in) | Dry Frio River at Reagan Wells USGS #08195000 (in) | Sabinal River at Sabinal USGS #08198000 (in) | Hondo Creek at Tarpley USGS #082000000 (in) | Guadalupe River at Comfort USGS #08167000 (in) | Medina River at Pipe Creek USGS #08179000 (in) |
|---|---|---|---|---|---|---|---|
| 1968 | 29.58 | 28.63 | 30.28 | 30.93 | 33.46 | 31.09 | 34.48 |
| 1969 | 31.74 | 31.77 | 30.41 | 31.07 | 36.12 | 30.45 | 35.05 |
| 1970 | 22.16 | 25.04 | 23.71 | 24.48 | 29.86 | 20.00 | 27.05 |
| 1971 | 34.57 | 31.03 | 32.10 | 32.75 | 44.13 | 33.74 | 41.85 |
| 1972 | 25.71 | 29.19 | 28.35 | 28.67 | 36.35 | 29.37 | 35.84 |
| 1973 | 31.63 | 36.10 | 38.47 | 39.79 | 43.61 | 34.67 | 43.17 |
| 1974 | 25.89 | 28.19 | 28.36 | 31.78 | 36.78 | 35.10 | 36.38 |
| 1975 | 30.30 | 26.24 | 27.38 | 27.42 | 37.38 | 28.81 | 34.62 |
| 1976 | 38.23 | 33.13 | 36.66 | 36.27 | 37.41 | 32.46 | 37.18 |
| 1977 | 23.98 | 27.22 | 27.61 | 26.91 | 33.34 | 29.16 | 32.57 |
| 1978 | 20.90 | 22.05 | 22.00 | 23.79 | 29.34 | 40.07 | 36.73 |
| 1979 | 22.27 | 27.76 | 24.08 | 33.77 | 33.00 | 33.45 | 32.31 |
| 1980 | 24.33 | 37.56 | 33.79 | 38.63 | 32.29 | 28.51 | 30.20 |
| 1981 | 41.52 | 46.76 | 45.18 | 43.03 | 48.65 | 39.11 | 46.58 |
| 1982 | 22.91 | 27.00 | 25.88 | 25.03 | 26.28 | 23.84 | 26.23 |
| 1983 | 23.71 | 26.54 | 24.78 | 31.95 | 29.71 | 24.61 | 30.20 |
| 1984 | 21.82 | 27.11 | 24.23 | 31.00 | 25.85 | 25.85 | 26.45 |
| 1985 | 25.91 | 29.18 | 28.99 | 29.52 | 33.83 | 33.67 | 34.61 |
| 1986 | 34.49 | 37.04 | 35.55 | 38.96 | 43.50 | 38.97 | 42.76 |
| 1987 | 34.18 | 42.65 | 40.73 | 44.28 | 47.73 | 44.82 | 47.43 |
| 1988 | 17.43 | 22.99 | 20.47 | 22.70 | 21.31 | 28.51 | 24.49 |
| 1989 | 19.49 | 23.26 | 20.78 | 26.97 | 22.87 | 23.64 | 23.15 |
| 1990 | 34.07 | 35.84 | 35.25 | 29.60 | 36.41 | – | – |
| 1991 | 31.75 | 38.07 | 32.77 | 54.14 | 54.48 | – | – |
| 1992 | 27.95 | 39.04 | 34.38 | 45.76 | 48.04 | – | – |
| 1993 | 14.62 | 19.16 | 16.54 | 24.54 | 24.89 | – | – |
| 1994 | 31.10 | 33.60 | 32.90 | 34.78 | 37.58 | – | – |
| 1995 | 22.24 | 30.66 | 27.09 | 35.71 | 34.62 | – | – |
| 1996 | 24.47 | 25.39 | 24.08 | 26.67 | 27.34 | – | – |
| Maximum (in) | 43.00 | 46.76 | 46.14 | 54.14 | 54.48 | 49.37 | 49.63 |
| Minimum (in) | 8.23 | 8.67 | 8.64 | 9.80 | 11.72 | 12.96 | 11.65 |
| Average (in) | 25.31 | 27.50 | 26.96 | 29.76 | 31.63 | 29.42 | 30.97 |

## Table 5-4. Annual Naturalized Streamflow for Watershed

| Year | Nueces River at Laguna USGS #08190000 (in) | Frio River at Concan USGS #08195000 (in) | Dry Frio River at Reagan Wells USGS #08195000 (in) | Sabinal River at Sabinal USGS #08198000 (in) | Hondo Creek at Tarpley USGS #082000000 (in) | Guadalupe River at Comfort USGS #08167000 (in) | Medina River at Pipe Creek USGS #08179000 (in) |
|---|---|---|---|---|---|---|---|
| 1934 | 18,007 | 21,698 | – | – | – | – | – |
| 1935 | 465,058 | 321.690 | – | – | – | – | – |
| 1936 | 233,426 | 173,550 | – | – | – | – | – |
| 1937 | 62,030 | 53,994 | – | – | – | – | – |
| 1938 | 72,578 | 49,839 | – | – | – | – | – |
| 1939 | 158,485 | 53,731 | – | – | – | – | – |
| 1940 | 52,903 | 46,038 | – | – | – | 117,941 | – |
| 1941 | 86,769 | 115,661 | – | – | – | 243,841 | – |
| 1942 | 96,175 | 68,040 | – | – | – | 144,505 | – |
| 1943 | 43,593 | 32,759 | – | 11,063 | – | 60,518 | – |
| 1944 | 63,885 | 56,457 | – | 24,890 | – | 166,265 | – |
| 1945 | 45,561 | 52,282 | – | 30,762 | – | 145,423 | – |
| 1946 | 66,856 | 48,103 | – | 16,592 | – | 114,890 | – |
| 1947 | 66,087 | 58,031 | – | 16,589 | – | 128,074 | – |
| 1948 | 39,664 | 20,270 | – | 2,586 | – | 40,961 | – |
| 1949 | 183,620 | 80,677 | – | 31,258 | – | 88,504 | – |
| 1950 | 47,520 | 27,272 | – | 9,907 | – | 37,330 | – |
| 1951 | 19,765 | 23,683 | – | 7,319 | – | 37,312 | – |
| 1952 | 22,685 | 13,092 | – | 3,244 | – | 62,684 | – |
| 1953 | 23,063 | 11,118 | 3,967 | 3,137 | 7,296 | 32,685 | 33,977 |
| 1954 | 60,161 | 23,898 | 9,451 | 7,797 | 3,536 | 19,653 | 11,279 |
| 1955 | 195,063 | 15,699 | 9,434 | 651 | 718 | 30,275 | 12,892 |
| 1956 | 16,352 | 4,103 | 736 | 1,180 | 417 | 8,434 | 4,000 |
| 1957 | 62,977 | 49,547 | 32,032 | 33,258 | 40,932 | 156,875 | 88,085 |
| 1958 | 273,602 | 198,334 | 76,530 | 158,760 | 96,020 | 217,547 | 158,438 |
| 1959 | 161,431 | 110,682 | 35,050 | 58,957 | 20,559 | 167,807 | 97,460 |
| 1960 | 117,876 | 87,120 | 22,745 | 55,769 | 26,054 | 196,560 | 119,850 |
| 1961 | 134,566 | 103,549 | 31,806 | 54,917 | 29,948 | 172,701 | 123,140 |
| 1962 | 54,500 | 36,703 | 4,643 | 4,348 | 2,036 | 42,265 | 26,348 |
| 1963 | 56,475 | 23,757 | 4,112 | 4,255 | 1,604 | 33,039 | 11,822 |
| 1964 | 141,029 | 42,646 | 9,326 | 16,673 | 7,644 | 88,353 | 12,867 |
| 1965 | 80,148 | 56,679 | 14,303 | 21,091 | 19,109 | 110,208 | 72,520 |
| 1966 | 145,866 | 106,003 | 36,425 | 38,018 | 15,678 | 104,311 | 76,965 |
| 1967 | 75,052 | 79,744 | 29,500 | 46,291 | 12,396 | 65,235 | 47,275 |
| 1968 | 140,676 | 109,312 | 34,169 | 84,127 | 46,967 | 184,882 | 153,908 |
| 1969 | 117,925 | 88,442 | 28,033 | 39,432 | 21,765 | 137,754 | 22,195 |
| 1970 | 115,207 | 90,835 | 23,070 | 29,924 | 18,446 | 119,490 | 86,589 |

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

| Year | Nueces River at Laguna USGS #08190000 (in) | Frio River at Concan USGS #08195000 (in) | Dry Frio River at Reagan Wells USGS #08195000 (in) | Sabinal River at Sabinal USGS #08198000 (in) | Hondo Creek at Tarpley USGS #082000000 (in) | Guadalupe River at Comfort USGS #08167000 (in) | Medina River at Pipe Creek USGS #08179000 (in) |
|---|---|---|---|---|---|---|---|
| 1971 | 278,146 | 156,736 | 44,037 | 87,331 | 67,562 | 213,994 | 32,676 |
| 1972 | 130,543 | 105,862 | 15,958 | 45,682 | 31,395 | 152,436 | 58,903 |
| 1973 | 233,006 | 180,159 | 63,080 | 130,980 | 74,112 | 174,039 | 86,989 |
| 1974 | 103,273 | 82,647 | 22,638 | 32,971 | 22,419 | 214,398 | 116,919 |
| 1975 | 103,885 | 81,591 | 20,490 | 39,152 | 46,314 | 282,592 | 68,760 |
| 1976 | 170,641 | 137,076 | 51,620 | 88,989 | 44,458 | 128,242 | 130,352 |
| 1977 | 157,812 | 141,464 | 24,751 | 86,252 | 42,127 | 235,259 | 90,891 |
| 1978 | 56,929 | 55,179 | 9,310 | 43,619 | 18,795 | 411,758 | 93,795 |
| 1979 | 66,191 | 93,711 | 28,415 | 74,726 | 53,958 | 251,656 | 64,428 |
| 1980 | 34,745 | 75,632 | 7,902 | 33,863 | 13,194 | 124,713 | 83,875 |
| 1981 | 266,614 | 261,050 | 58,309 | 148,831 | 66,183 | 366,989 | 91,533 |
| 1982 | 74,355 | 71,993 | 15,197 | 22,861 | 7,557 | 123,146 | 66,493 |
| 1983 | 59,015 | 52,231 | 11,875 | 23,572 | 12,667 | 72,689 | 43,515 |
| 1984 | 68,046 | 67,925 | 15,576 | 18,813 | 6,023 | 73,706 | 33,035 |
| 1985 | 136,979 | 122,278 | 32,606 | 59,948 | 40,829 | 331,725 | 122,807 |
| 1986 | 128,071 | 90,296 | 28,420 | 46,646 | 30,078 | 231,811 | 117,805 |
| 1987 | 29,315 | 285,472 | 78,970 | 190,148 | 117,045 | 550,558 | 74,992 |
| 1988 | 73,244 | 87,770 | 8,790 | 19,509 | 5,792 | 192,944 | 66,604 |
| 1989 | 39,543 | 37,062 | 3,956 | 7,985 | 3,318 | 84,025 | 29,371 |
| 1990 | 170,572 | 104,362 | 19,286 | 41,752 | 19,970 | – | 79,502 |
| 1991 | 193,509 | 151,268 | 29,830 | 76,113 | 57,176 | – | 147,729 |
| 1992 | 255,172 | 255,351 | 56,563 | 206,484 | 114,368 | – | 325,911 |
| 1993 | 47,161 | 54,503 | 10,628 | 29,964 | 12,381 | – | 45,247 |
| 1994 | 80,909 | 82,728 | 23,984 | 23,648 | 8,593 | – | 48,343 |
| 1995 | 66,971 | 83,600 | 22,094 | 29,795 | 13,798 | – | 59,498 |
| 1996 | 167,001 | 85,881 | 23,138 | 13,082 | 1,542 | – | 27,379 |
| Maximum (acft) | 463,058 | 321,690 | 78,970 | 206,484 | 117,045 | 550,558 | 325,911 |
| Minimum (acft) | 16,352 | 4,103 | 736 | 651 | 417 | 8,434 | 4,000 |
| Average (acft) | 115,401 | 88,236 | 25,744 | 45,102 | 29,609 | 149,860 | 76,522 |

All of the 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.

### 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,[8,9] 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 proliferation and decreasing streamflow exists involves statistical analysis 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 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.

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[8] "North Concho River Watershed, Brush Control Planning, Assessment & Feasibility Study," Upper Colorado River Authority, et al.

[9] Dugas, W.A., et al., "Effect of Removal of *Juniper ashei* on Evapotranspiration and Runoff in the Seco Creek Watershed," Water Resources Research, Vol. 34, No. 6, pp. 1499-1506, June 1998.

## *5.2 Trends in Streamflow Characteristics*

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

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

| Location | USGS Gage # | Drainage Area (mi2) | Period | Average Rainfall (in) | Average RO/RF (%) |
|---|---|---|---|---|---|
| Nueces River at Laguna | 08190000 | 737 | 1934–65 | 23.6 | 9.7 |
| | | | 1966–96 | 27.0 | 11.8 |
| Frio River at Concan | 08195000 | 389 | 1934–65 | 24.6 | 11.1 |
| | | | 1966–96 | 30.5 | 17.1 |
| Dry Frio River 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 |
| Hondo Creek at Tarpley | 08200000 | 96 | 1953–74 | 30.1 | 14.2 |
| | | | 1975–96 | 34.8 | 16.6 |
| Guadalupe River at Comfort | 08167000 | 839 | 1940–64 | 27.1 | 7.8 |
| | | | 1965–89 | 31.1 | 13.5 |
| Medinal River at Pipe Creek | 08179000 | 474 | 1953–70 | 27.9 | 8.2 |
| | | | 1971–89 | 34.9 | 8.8 |

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. Similar to the consideration of rainfall, statistical tests are used to assess the significance of these differences.

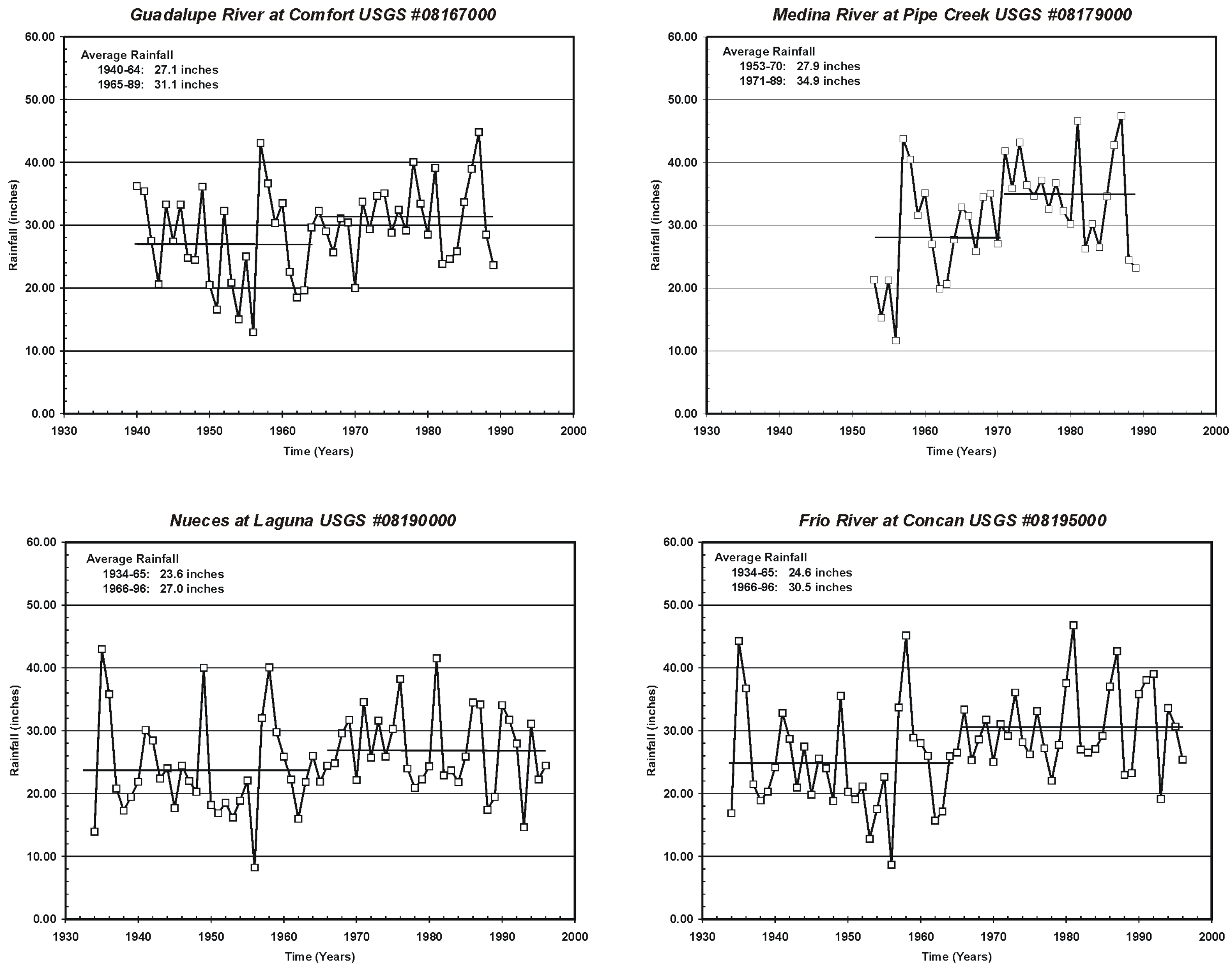


***Figure 5-2. Rainfall Time Series for Edwards Aquifer Watershed***

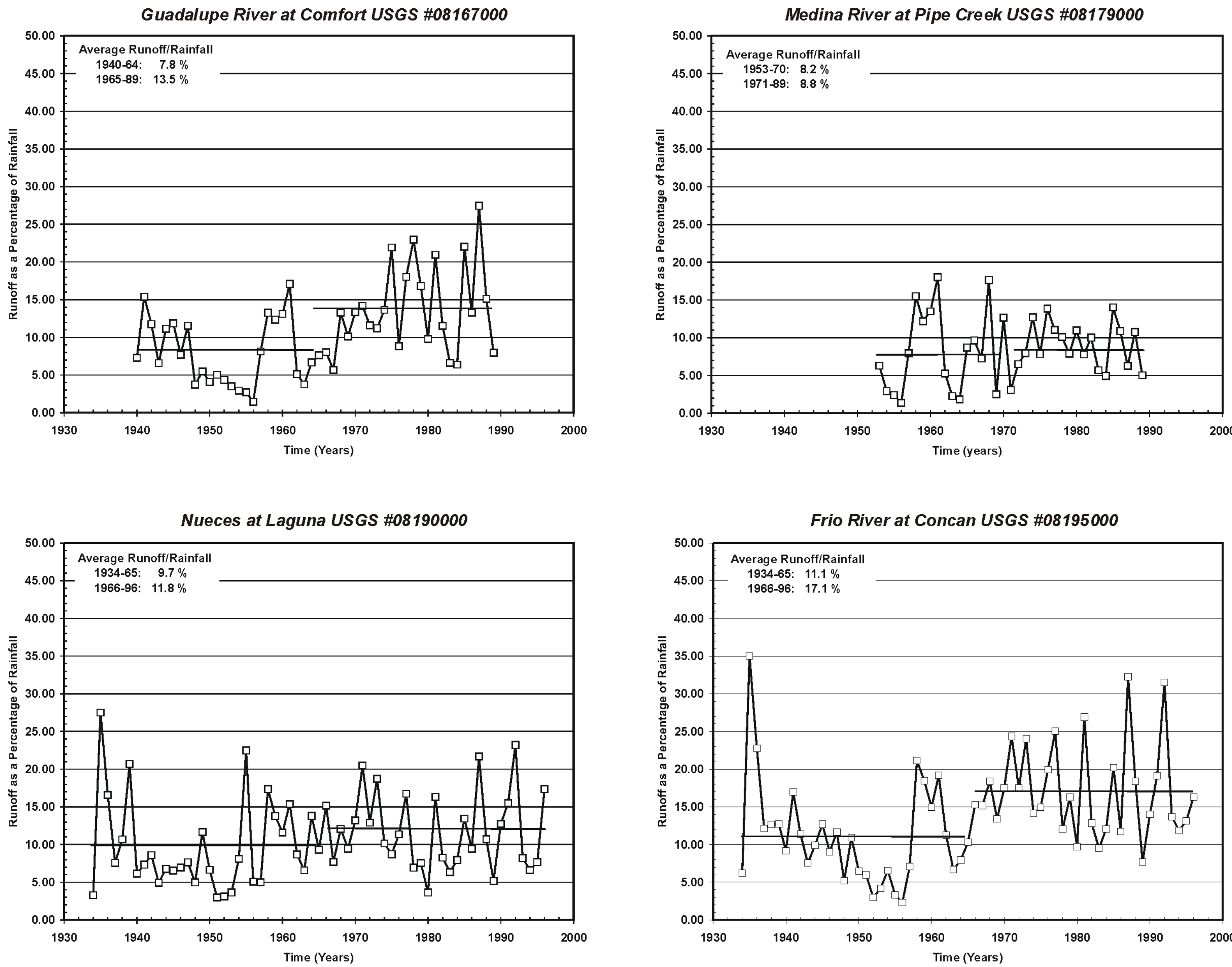


*Figure 5-3. Runoff as a Percentage of Rainfall Time Series for Edwards Aquifer Watershed*

The statistical tests applied to historical annual rainfall and runoff per unit rainfall include the non-parametric Kendall Tau test,10 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,11 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 all of the watersheds of the Edwards Aquifer Watershed. These watersheds all indicate increasing trends in rainfall that cannot be rejected at the 90 percent confidence level. 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 areal precipitation for three 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 trends. None of the watersheds evaluated in this study area exhibited decreasing trends in runoff as a percentage of rainfall. The watersheds above the Nueces River at Laguna (USGS #08190000), the Frio River at Concan (USGS #08195000), the Sabinal River near Sabinal (USGS #08198000), and the Guadalupe River at Comfort (USGS #08167000) demonstrate increasing trends in this ratio that cannot be rejected at the 90 percent confidence level. Further investigation of these sub-basins may more precisely determine the causes of apparent changes in runoff. Further investigation based on modified Soil Conservation Service curve number procedures[12] indicates that increased runoff per unit rainfall may be explained by increased

[10] Maidment, D.R., "Handbook of Hydrology," McGraw-Hill, Inc., 1993.
[11] Haan, C.T., "Statistical Methods in Hydrology," Iowa State University Press, 1977.

**Table 5-6. Indication of Statistically Significant Trend in Rainfall — 90% Confidence Level**

| ***Statistical Test*** | ***Test Type*** | ***#08190000 Nueces River, Laguna*** | ***#08195000 Frio River, Concan*** | ***#08196000 Dry Frio River, Reagan Wells*** | ***#08198000 Sabinal River, Sabinal*** | ***#08200000 Hondo Creek, Hondo*** | ***#08167000 Guadalupe River, Comfort*** | ***#08179000 Medina River,` Pipe Creek*** |
|---|---|---|---|---|---|---|---|---|
| Kendall Tau | Non-parametric | Increasing, Yes | Increasing, Yes | Increasing, Yes | Increasing, Yes | Increasing, Yes | No | Increasing, Yes |
| Simple Regression, t-distribution | Parametric | Increasing, Yes | Increasing, Yes | Increasing, Yes | Increasing, Yes | Increasing, Yes | Increasing, Yes | Increasing, Yes |
| Sample Partitioning Mean Comparison, t-distribution | Parametric | Increasing, Yes | Increasing, Yes | No | Increasing, Yes | Increasing, Yes | Increasing, Yes | Increasing, Yes |
| Sample Partitioning, Variance Comparison, F-distribution | Parametric | Yes | Yes | No | No | No | Yes | No |

***Table 5-7. Indication of Statistically Significant Trend in Rainfall/Runoff — 90% Confidence Level***

| ***Statistical Test*** | ***Test Type*** | ***#08190000 Nueces River, Laguna*** | ***#08195000 Frio River, Concan*** | ***#08196000 Dry Frio River, Reagan Wells*** | ***#08198000 Sabinal River, Sabinal*** | ***#08200000 Hondo Creek, Hondo*** | ***#08167000 Guadalupe River, Comfort*** | ***#08179000 Medina River,` Pipe Creek*** |
|---|---|---|---|---|---|---|---|---|
| Kendall Tau | Non-parametric | Increasing, Yes | Increasing, Yes | No | No | No | Increasing, Yes | No |
| Simple Regression, t-distribution | Parametric | Increasing, Yes | Increasing, Yes | No | Increasing, Yes | No | Increasing, Yes | Increasing, Yes |
| Sample Partitioning Mean Comparison, t-distribution | Parametric | Increasing, Yes | Increasing, Yes | No | Increasing, Yes | No | Increasing, Yes | No |
| Sample Partitioning, Variance Comparison, F-distribution | Parametric | Yes | Yes | No | Yes | No | Yes | No |

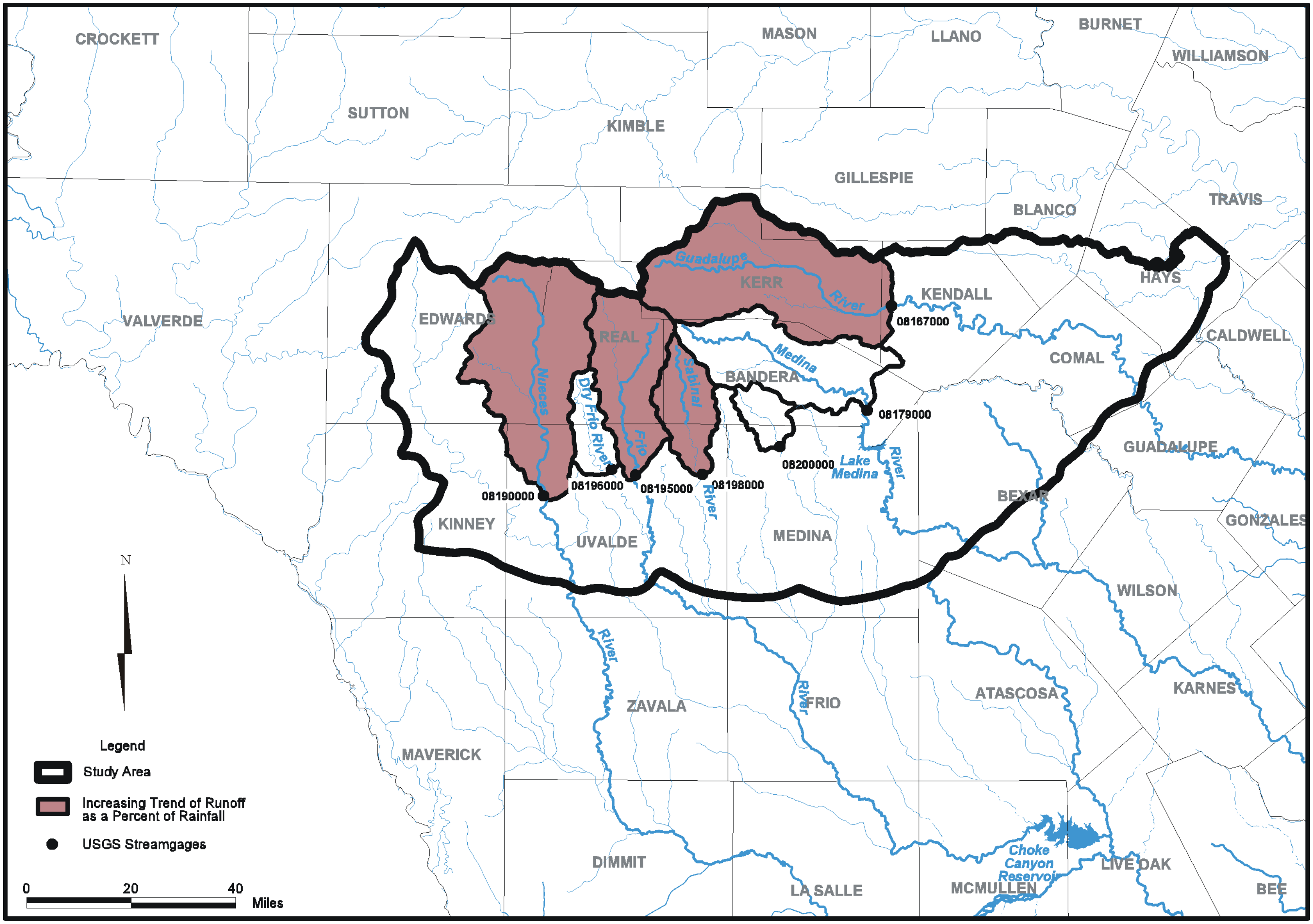


*Figure 5-5. Results of Statistical Analyses of Runoff as a Percentage of Rainfall*

rainfall during the latter time periods. Most importantly, however, none of the Hill Country watersheds considered in this study exhibits any indications of decreasing annual runoff per unit rainfall with time.

Although none of the Edwards Aquifer Watersheds considered in this study exhibit any indications of decreasing annual runoff per unit rainfall with time, runoff from these watersheds did not respond to statistically significant increases in rainfall to the same degree as others. Additional studies focusing on characteristics of these watersheds (including brush infestation) may be appropriate.

### *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 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 seven sub-basins considered in the Edwards Aquifer Watershed, none of the watersheds appear particularly promising for brush control with the primary objective of increasing runoff or water yield. However, further consideration of the Dry Frio River, upper Medina River, and Hondo Creek watersheds may be appropriate.

### *5.4 Summary*

Average annual rainfall throughout the Edwards Aquifer Watershed 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 Edwards Aquifer Watershed is significantly increasing in four sub-basins and showing no trend in three sub-basins at the 90 percent confidence level. The increasing trend in the relationship between runoff and rainfall occurs in the sub-basins above the streamflow gages on the Nueces River at Laguna (USGS #08190000), the Frio River at Concan (USGS #08195000), the Sabinal River at Sabinal (USGS #08198000), and the Guadalupe River at Comfort (USGS #08167000). No significantly decreasing trends in runoff as a percentage of rainfall were indicated from the analyses. Thus, most of the larger subwatersheds in the Edwards Aquifer Watershed are not recommended for further consideration of brush control management for the purposes of increasing runoff or water yield. However, further consideration of the watersheds above the Dry Frio at Reagan Wells (USGS #08196000), Hondo Creek at Tarpley (USGS #08200000), and the Medina River at Pipe Creek (USGS #0819000) may be appropriate as these watersheds did not exhibit significantly increased runoff per unit rainfall even though increases in rainfall over time proved significant.

# Section 6
# Hydrologic Simulation

The Edwards recharge area was assumed to consist of the Upper Nueces watershed and the five river basins: Upper Frio, Sabinal, Seco, Hondo, and Medina. The hydrologic modeling for Nueces and the five river basins was done separately since the Upper Nueces was modeled in the context of the rest of the Nueces River Basin described in the companion report for the Nueces River Watershed. Therefore, Section 6 consists of two sections. Outflows from the Upper Nueces were used as inflow into the rest of the Nueces below the recharge fault zone. The general methodology for modeling followed that described in Appendix A**.**

## 6.1 Upper Frio, Sabinal, Seco, Hondo, and Medina Watershed Data

### 6.1.1 Location

The primary recharge zones of the Edwards Aquifer are located on the Great Plain and Coastal Plains provinces. The two provinces are separated by the highly fractured Balcones Fault Zone. The Edwards Aquifer recharge areas are underlain by limestone of cretaceous age and marl (sedimentary rock). The Edwards recharge zone watersheds as defined in this report consists of the natural drainage areas defined above the U.S. Geological Survey (USGS) gauging stations west to east on the Frio, Sabinal, Seco, Hondo, and Medina Rivers. Therefore, drainage areas near and around Lake Medina were not defined in this report. The drainage areas are located within Uvalde, Bandera, and Medina Counties capturing most of the recharge area of the Edwards Plateau. The river flows from the Edwards Plateau contributes to the significant springflows in the Edwards Aquifer, which moves laterally eastward to San Antonio. The average annual precipitation within the study area varies generally from about 560 mm (22 inches) to 760 mm (30 inches) west to east. The Edwards Aquifer and the Edwards Plateau are intensely studied sites.[1,2,3,4]

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[1] Dugas W.A., R. A. Hicks, and P.W. Wright. 1998. Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek watershed. Water Resourc. Res. 34:1499-1506.

[2] NOAA. 1980. Climatography of the United States No. 20, Climatic Summaries for Selected Sites, 1951-1980. National Climatic Data Center, Ashville, North Carolina.

[3] Garza, S.1962. Recharge, discharge, and changes in ground-water storage in the Edwards and associated limestones, San Antonio area, Texas. A Progress Report on studies, 1955-1959. Texas Board Water Engineers Bull. 6201. 51 Pp.

[4] Petitt B.M., Jr., and W.O. George. 1956. Ground-water resources of the San Antonio area, Texas. A progress report on current studies. Texas Board Water Engineers Bull 5608. V.1. 85 Pp.

#### *6.1.2 Topography*

Figure 6-1 shows the location of the five river basins on the Edwards recharge zone, and Figures 6-2 through 6-6 show the individual river basins, and the sub-basin numbers. There were a total of 23 sub-basins within Frio, 11 within Sabinal, 13 within Seco, 5 within Hondo, and 25 within Medina.

#### *6.1.3 Weather Stations*

Figure 6-7 shows the weather stations used for study of brush control on the Edwards. The nearest station to each sub-basin was used. Daily weather data (1960-1998) on precipitation, temperature, and solar radiation were collected from National Weather Service (NWS) stations. Missing data for any weather station was filled using the nearest station. Daily relative humidity was generated from monthly measurements.

#### *6.1.4 Soils*

##### *6.1.4.1 Tarrant Series (Thermic Lithic Calciustolls); Clayey-Skeletal, Smectitic*

The Tarrant series consists of very shallow and shallow, well drained, moderately slowly permeable soils on uplands. They formed in residuum from limestone, and include interbedded marls, chalks, and marly materials. Soils are found mainly on 1 to 8 percent slopes and consist of less than 35 percent clay fraction. Tarrant soils consisted of 32.6 percent of the entire studied Edwards Watershed.

##### *6.1.4.2 Eckrant Series (Thermic Lithic Haplustolls); Clayey-Skeletal, Montmorillonitic*

This soil series consists of shallow to very shallow, well-drained, moderately slow permeable soils formed in interbedded limestone, marls, chalks, and marly earths. Slopes generally range from 0 to 40 percent. Eckrant series soils consisted of 30.2 percent of the entire study area.

##### *6.1.4.3 Brackett Series (Thermic Udic Ustochrepts); Fine-Loamy, Carbonatic*

The Brackett series consists of very deep, well-drained moderately permeable soils that formed in marly loamy earth interbedded with chalky limestone. These soils are on uplands with

*Figure 6-1. Loci of Edwards Plateau Recharge River Basins in Texas*

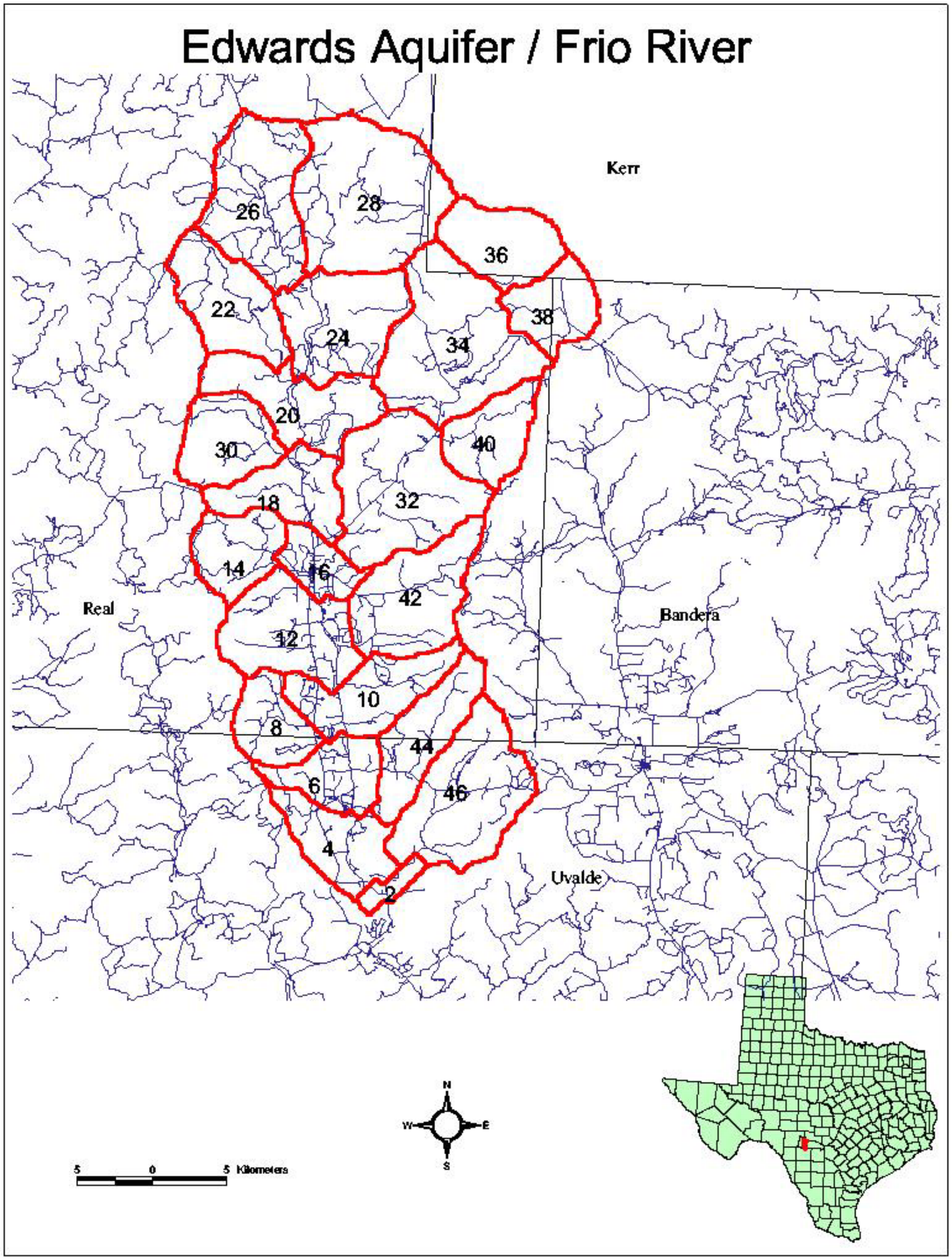



*Figure 6-2. Sub-Basin Numbers for Frio River Basin*

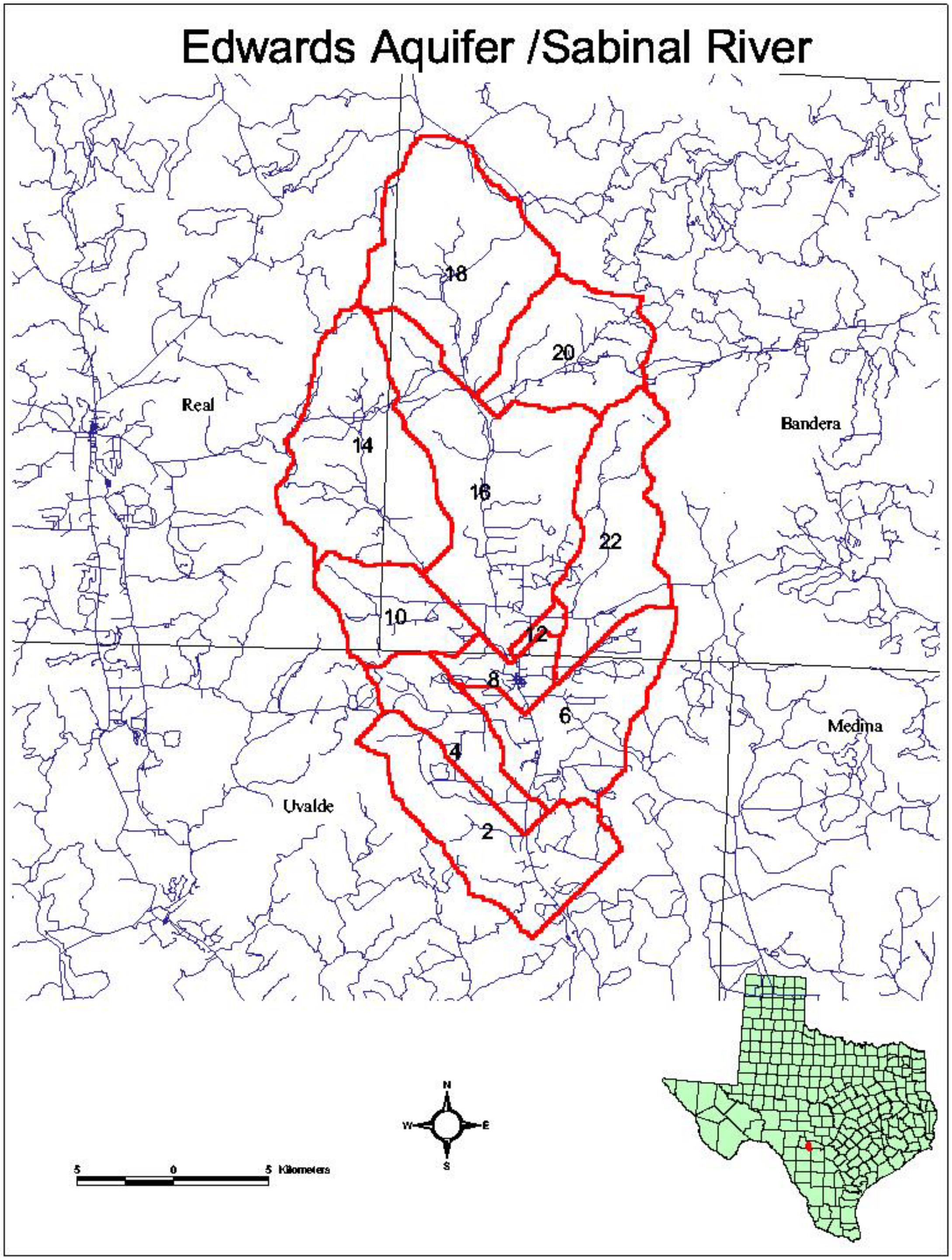



*Figure 6-3. Sabinal River Basin with Associated Sub-Basin Numbers*

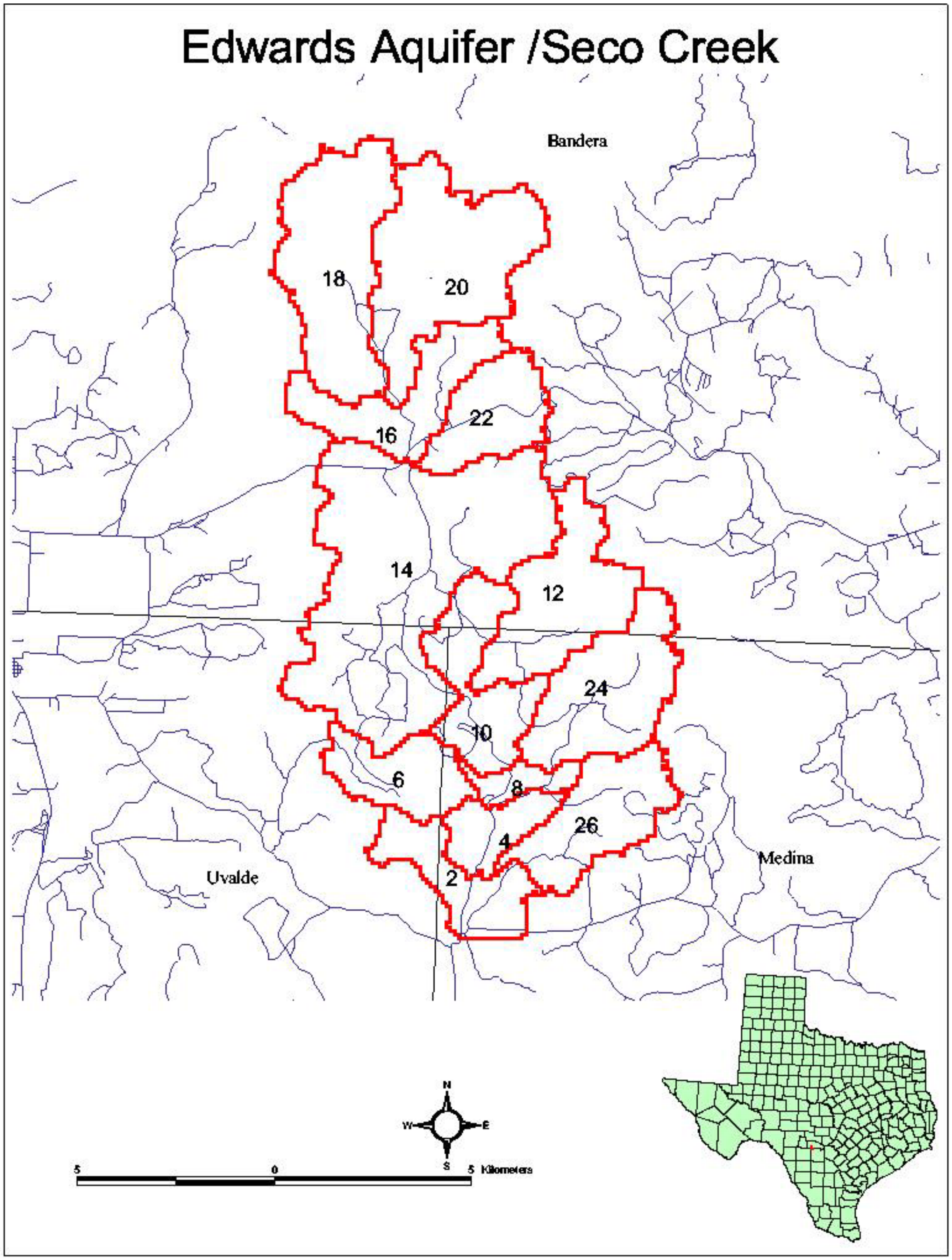



*Figure 6-4. Seco River Basin and Associated Sub-Basin Numbers*

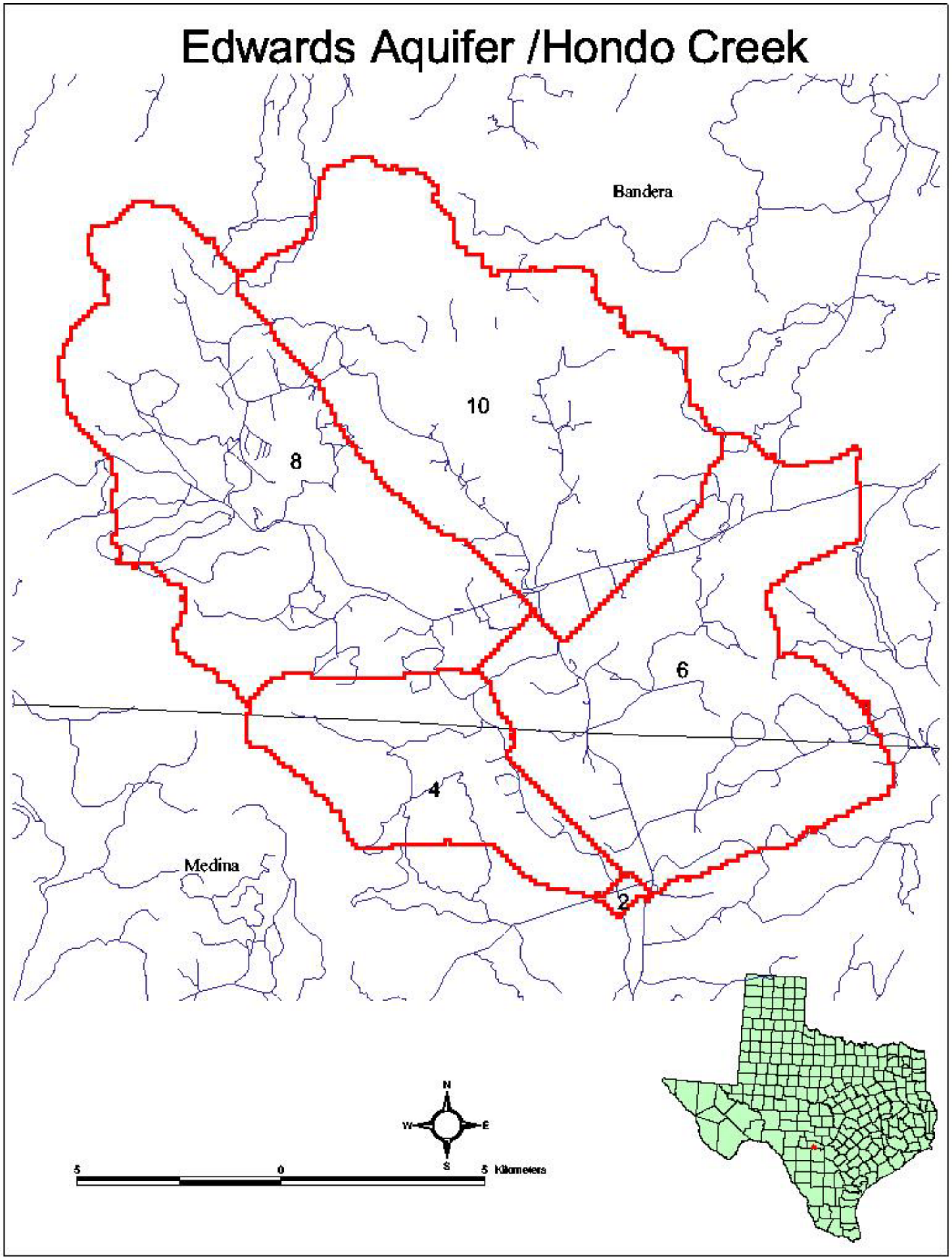



*Figure 6-5. Hondo River Basin and Associated Sub-Basin Numbers*

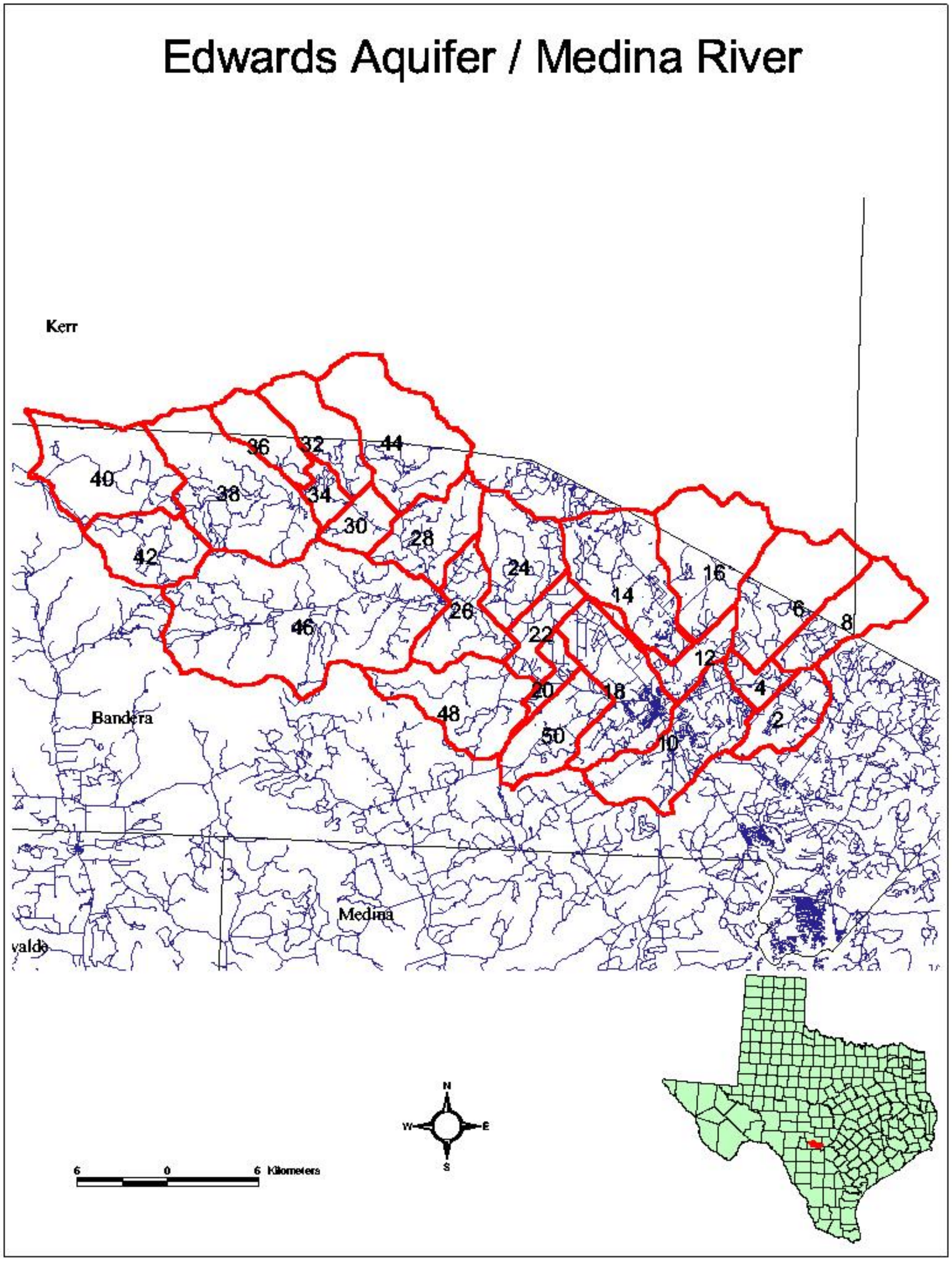



*Figure 6-6. Medina River Basin and Associated Sub-Basin Numbers*

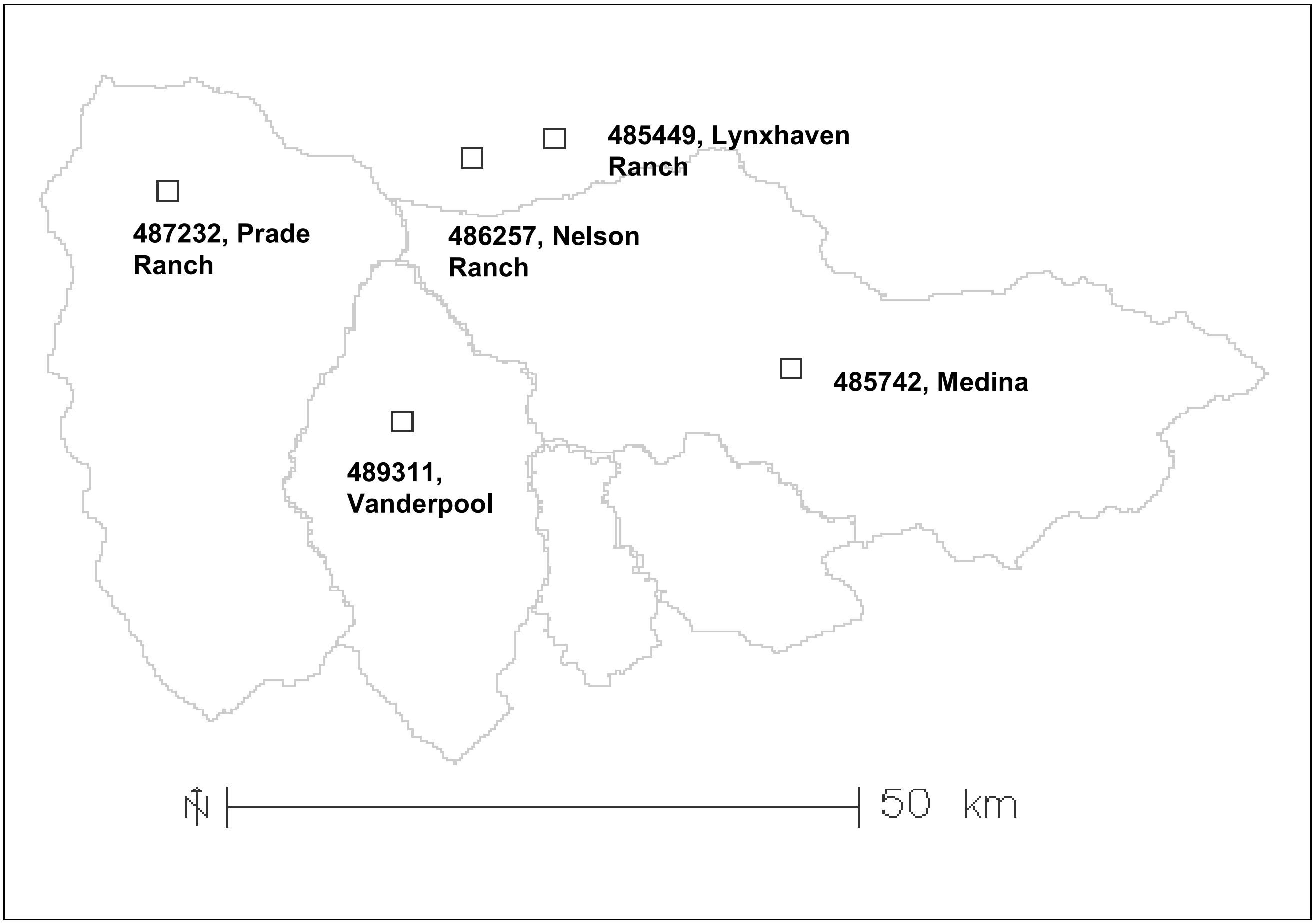



*Figure 6-7. Weather Stations Used for Modeling Hydrology of Edwards Recharge Watersheds*

slopes ranging from 1 to 40 percent. This soil series consisted of 8.13 percent of the Edwards watershed.

#### *6.1.4.4 Speck Series (Thermic Lithic Argiustolls); Clayey, Mixed, Superactive*

The Speck series consists of shallow, well drained, slowly permeable soils formed in residuum and colluvium derived from indurated limestone. These soils are on nearly level to sloping uplands. Slopes range from 0 to 8 percent. The speck soils consisted of 7.7 percent of the Edwards Aquifer Watershed.

#### *6.1.4.5 Krum Series (Thermic Vertic Haplustolls); Fine, Montmorillonitic*

The Krum series consists of very deep, well drained, moderately slowly permeable soils that formed in calcareous clayey sediments. These soils are on nearly level to moderately sloping terraces and lower slopes of valleys. Slopes range from 0 to 8 percent. The Krum soils consisted of 4.16 percent of the Edwards Aquifer Watershed.

### *6.1.5 Land Use/Cover*

Figure 6-8 shows brush areas on which brush control was simulated. The brush areas after removal was assumed converted to open range conditions (grassland). Details of Landsat-7 (ETM+) 1999 image classification is given earlier in the general project description.

### *6.1.6 Ponds & Reservoirs*

The major reservoir in the Edwards Aquifer recharge zone study area was Lake Medina. Since drainage to the U.S. Geological Survey (USGS) gauging points only were considered, Lake Medina and sub-basins draining into Lake Medina were not considered for this project.

### *6.1.7 Model Input Variables*

The important SWAT model parameters and parameter input values before and after calibration are shown in Tables 6-1 through 6-5. The SWAT model calibration was based on matching observed and predicted streamflows at the USGS gauging station. The curve numbers specify runoff rate depending on vegetation cover and soils, and is given for the most common soils in each river basin. West to east there is a general trend for higher transmission losses in the river basins, the curve numbers are reduced compared to default values after the calibration stage except for Frio. The Potential Heat Units (PHUs) which specify maximum canopy maturity as function of cumulated air temperature above a base temperature was obtained from the Climatography of the United States No. 20.[5] The amount of precipitation intercepted by brush canopy was based on field experiments[6] and calibration of SWAT streamflows to USGS measured flows.

[5] NOAA. 1980. Climatography of the United States No. 20, Climatic Summaries for Selected Sites, 1951-1980. National Climatic Data Center, Ashville, North Carolina.
[6] Thurow T.L., and C.A. Taylor. 1995. Juniper effects on the water yield of Central Texas rangeland. Proc. 24th Water for Texas Conference, Texas Water Resources Institute, College Station, Texas. Pp. 657-666.

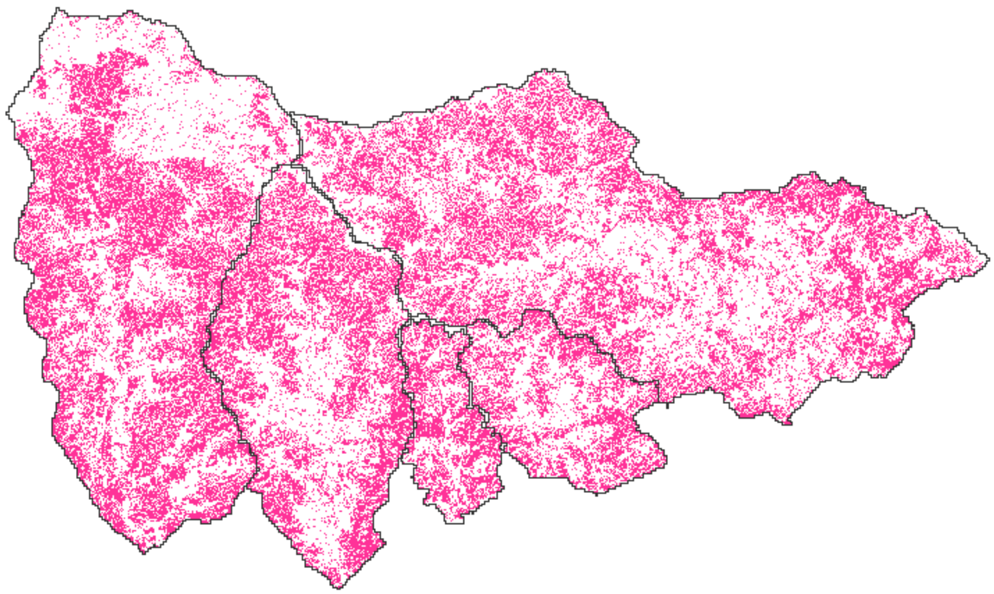


*Figure 6-8. Areas Proposed Controlled for Brush on the Edwards Plateau*

## 6.2 Results

### 6.2.1 Calibration

Figures 6-9 through 6-13 show the SWAT and USGS measured flows for each of the Edwards recharge river basins. The $r^2$ measure was high—over 0.9 for all comparisons.

### 6.2.2 Brush Removal Simulation

The dashed line graph shows cumulative streamflows after brush removal. For the Frio River basin, based on 39 years of simulation it is predicted that there will be an increase in flow at outlet of 20,561 acft/yr due to brush removal; for Sabinal there will be an increased flow at outlet of 15,535 acft/yr due to brush removal; for Hondo there will be an increased flow of 7,665 acft/yr due to brush removal; for Seco SWAT predicts an increased flow of 5,300 acft/yr; and for Medina there will be an increased flow at outlet of river basin of nearly 50,000 acft/yr. Table 6-6 shows the water savings within each sub-basin of the Edwards Plateau recharge watersheds after brush removal. The water savings within sub-basins are much higher than predicted stream flows at outlet of river basins since the streamflows account for all the transmission losses in the

***Table 6-1. The SWAT Input Variable for the Frio River Basin***

| *Parameter* | *Before Calibration* | *After Calibration* | *After Brush Control* |
|---|---|---|---|
| **Curve Number** | | | |
| Heavy Cedar | 77 | 87 | 90 |
| Heavy Oak | 77 | 87 | 87 |
| Open Range/Grass | 85 | 69 | 69 |
| Soil Evaporation Compensation | 0.85 | 0.98 | 0.98 |
| Shallow Aquifer Re-evaporation | 0.40 | 0.30 | 0.10 |
| Heavy Cedar | 4,300 | 4,300 | 4,300 |
| Heavy Oak | 3,750 | 3,750 | 3,750 |
| Open Range/Grass | 2,900 | 2,900 | 2,900 |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range/Grass | 0.0 | N/A | — |
| **Maximum Leaf Area Index ($m^2$ Canopy/$m^2$ Ground)** | | | |
| Heavy Cedar | 8.0 | — | — |
| Heavy Oak | 8.0 | — | — |
| Open Range | 1.0 | — | — |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range | 0.0 | N/A | — |
| **Plant Rooting Depth (feet)** | | | |
| Heavy Cedar | 6.5 | N/A | — |
| Heavy Oak | 6.5 | N/A | — |
| Open Range | 3.3 | 3.3 | — |
| Transmission Loss (in/hr) | 0.04 | 0.04 | — |
| Sub-basin Transmission (in/hr) | 0.02 | 0.02 | — |

***Table 6-2. The SWAT Input Variable for the Sabinal River Basin***

| ***Parameter*** | ***Before Calibration*** | ***After Calibration*** | ***After Brush Control*** |
|---|---|---|---|
| **Curve Number** | | | |
| Heavy Cedar | 77 | 69 | 72 |
| Heavy Oak | 77 | 69 | 69 |
| Open Range/Grass | 85 | 79 | 79 |
| Soil Evaporation Compensation | 0.85 | 0.95 | 0.95 |
| Shallow Aquifer Re-evaporation | 0.40 | 0.15 | 0.10 |
| Heavy Cedar | 4,300 | 4,300 | 4,300 |
| Heavy Oak | 3,750 | 3,705 | 3,705 |
| Open Range/Grass | 2,900 | 2,900 | 2,900 |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range/Grass | 0.0 | N/A | — |
| **Maximum Leaf Area Index ($m^2$ Canopy/$m^2$ Ground)** | | | |
| Heavy Cedar | 8.0 | — | — |
| Heavy Oak | 8.0 | — | — |
| Open Range | 1.0 | — | — |
| Soil Evaporation Compensation Factor (esco) | 0.98 | 0.98 | 0.98 |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range | 0.0 | N/A | — |
| **Plant Rooting Depth (feet)** | | | |
| Heavy Cedar | 6.5 | N/A | — |
| Heavy Oak | 6.5 | N/A | — |
| Open Range | 3.3 | 3.3 | — |
| Transmission Loss (in/hr) | 0.04 | 0.04 | — |
| Sub-basin Transmission (in/hr) | 0.04 | 0.02 | — |

***Table 6-3. The SWAT Input Variable for the Hondo River Basin***

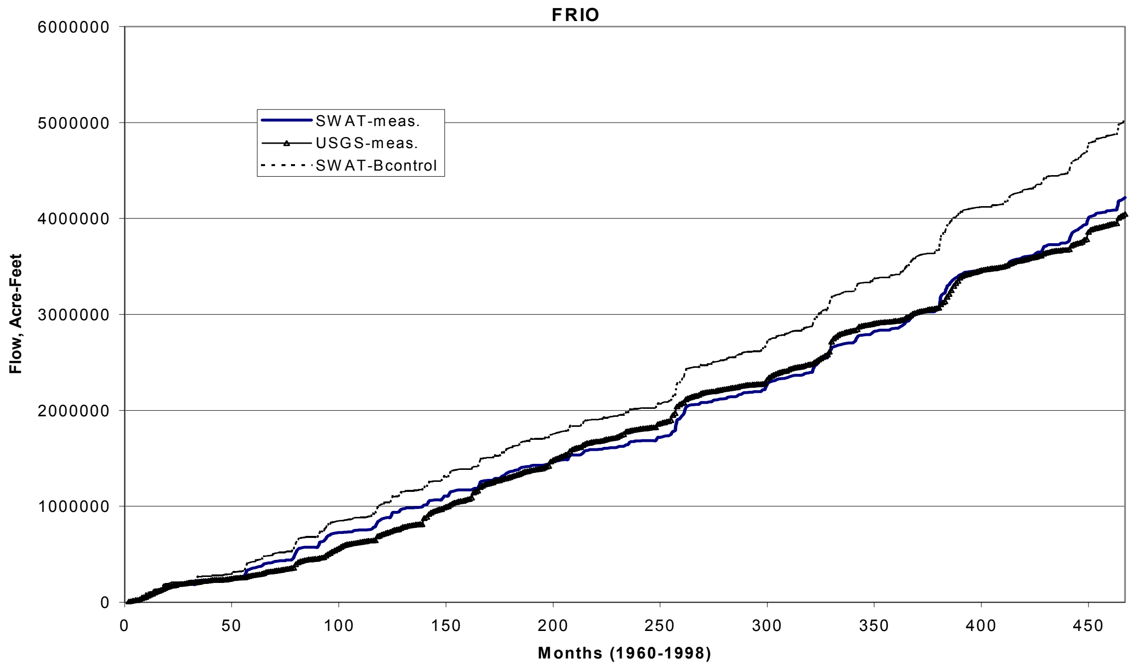
| *Parameter* | *Before Calibration* | *After Calibration* | *After Brush Control* |
|---|---|---|---|
| **Curve Number** | | | |
| Heavy Cedar | 77 | 52 | 56 |
| Heavy Oak | 77 | 59 | 59 |
| Open Range/Grass | 72 | 61 | 61 |
| Soil Evaporation Compensation | 0.85 | 0.95 | 0.95 |
| Shallow Aquifer Re-evaporation | 0.40 | 0.15 | 0.10 |
| Heavy Cedar | 4,300 | 4,300 | 4,300 |
| Heavy Oak | 3,750 | 3,705 | 3,705 |
| Open Range/Grass | 2,900 | 2,900 | 2,900 |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range/Grass | 0.0 | N/A | — |
| **Maximum Leaf Area Index ($m^2$ Canopy/$m^2$ Ground)** | | | |
| Heavy Cedar | 8.0 | — | — |
| Heavy Oak | 8.0 | — | — |
| Open Range | 1.0 | — | — |
| Soil Evaporation Compensation Factor (esco) | 0.98 | 0.98 | 0.98 |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range | 0.0 | N/A | — |
| **Plant Rooting Depth (feet)** | | | |
| Heavy Cedar | 6.5 | N/A | — |
| Heavy Oak | 6.5 | N/A | — |
| Open Range | 3.3 | 3.3 | — |
| Transmission Loss (in/hr) | 0.4 | 0.4 | — |
| Sub-basin Transmission (in/hr) | 0.7 | 0.7 | — |

***Table 6-4. The SWAT Input Variable for the Seco River Basin***

| Parameter | Before Calibration | After Calibration | After Brush Control |
|---|---|---|---|
| **Curve Number** | | | |
| Heavy Cedar | 77 | 63 | 60 |
| Heavy Oak | 77 | 63 | 63 |
| Open Range/Grass | 72 | 65 | 65 |
| Soil Evaporation Compensation | 0.85 | 0.95 | 0.95 |
| Shallow Aquifer Re-evaporation | 0.40 | 0.40 | 0.10 |
| Heavy Cedar | 4,300 | 4,300 | 4,300 |
| Heavy Oak | 3,750 | 3,705 | 3,705 |
| Open Range/Grass | 2,900 | 2,900 | 2,900 |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range/Grass | 0.0 | N/A | — |
| **Maximum Leaf Area Index ($m^2$ Canopy/$m^2$ Ground)** | | | |
| Heavy Cedar | 8.0 | — | — |
| Heavy Oak | 8.0 | — | — |
| Open Range | 1.0 | — | — |
| Soil Evaporation Compensation Factor (esco) | 0.98 | 0.98 | 0.98 |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range | 0.0 | N/A | — |
| **Plant Rooting Depth (feet)** | | | |
| Heavy Cedar | 6.5 | N/A | — |
| Heavy Oak | 6.5 | N/A | — |
| Open Range | 3.3 | 3.3 | — |
| Transmission Loss (in/hr) | 0.2 | 0.2 | — |
| Sub-basin Transmission (in/hr) | 0.2 | 0.2 | — |

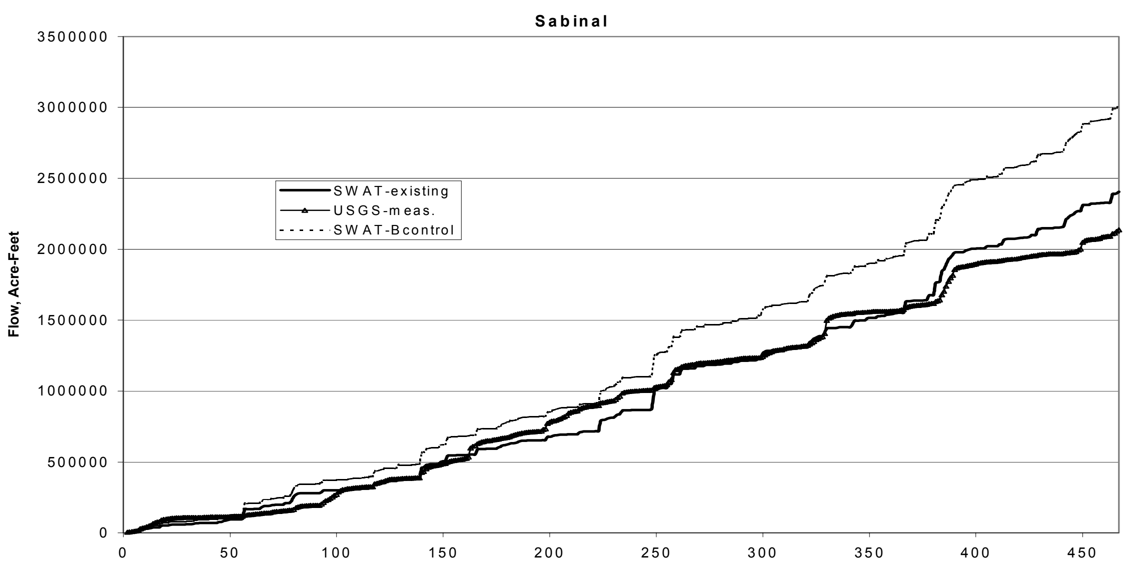
***Table 6-5. The SWAT Input Variable for the Medina River Basin***

| *Parameter* | *Before Calibration* | *After Calibration* | *After Brush Control* |
|---|---|---|---|
| **Curve Number** | | | |
| Heavy Cedar | 77 | 61 | 64 |
| Heavy Oak | 77 | 61 | 61 |
| Open Range/Grass | 72 | 58 | 58 |
| Soil Evaporation Compensation | 0.85 | 0.95 | 0.95 |
| Shallow Aquifer Re-evaporation | 0.40 | 0.40 | 0.10 |
| Heavy Cedar | 4,300 | 4,300 | 4,300 |
| Heavy Oak | 3,750 | 3,705 | 3,705 |
| Open Range/Grass | 2,900 | 2,900 | 2,900 |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range/Grass | 0.0 | N/A | — |
| **Maximum Leaf Area Index ($m^2$ Canopy/$m^2$ Ground)** | | | |
| Heavy Cedar | 8.0 | — | — |
| Heavy Oak | 8.0 | — | — |
| Open Range | 1.0 | — | — |
| Soil Evaporation Compensation Factor (esco) | 0.98 | 0.98 | 0.98 |
| **Canopy Interception (inches)** | | | |
| Heavy Cedar | 0.8 | N/A | — |
| Heavy Oak | 0.8 | N/A | — |
| Open Range | 0.0 | N/A | — |
| **Plant Rooting Depth (feet)** | | | |
| Heavy Cedar | 6.5 | N/A | — |
| Heavy Oak | 6.5 | N/A | — |
| Open Range | 3.3 | 3.3 | — |
| Transmission Loss (in/hr) | 0.78 | 0.78 | — |
| Sub-basin Transmission (in/hr) | 0.98 | 0.98 | — |



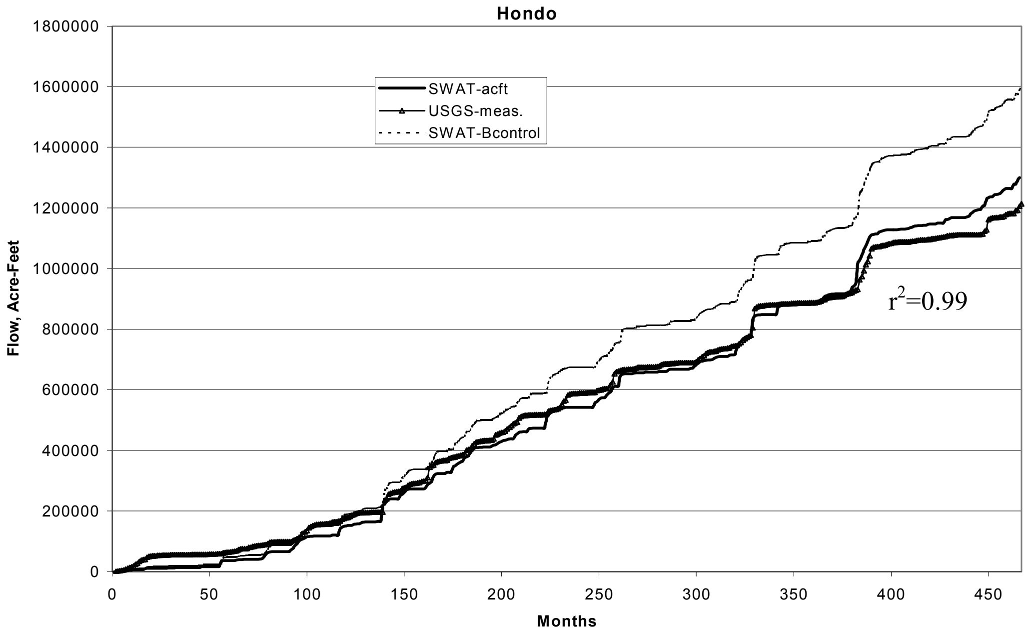

The dotted line above the comparisons is stream flows after brush removal. The USGS estimated drainage area above stream gage was 389 $mi^2$. The SWAT modeled drainage area was 383 $mi^2$ (gage 08195000 at Concan, Texas).

***Figure 6-9. Comparison of SWAT Predicted and USGS Measured Flows, 1960-1998***



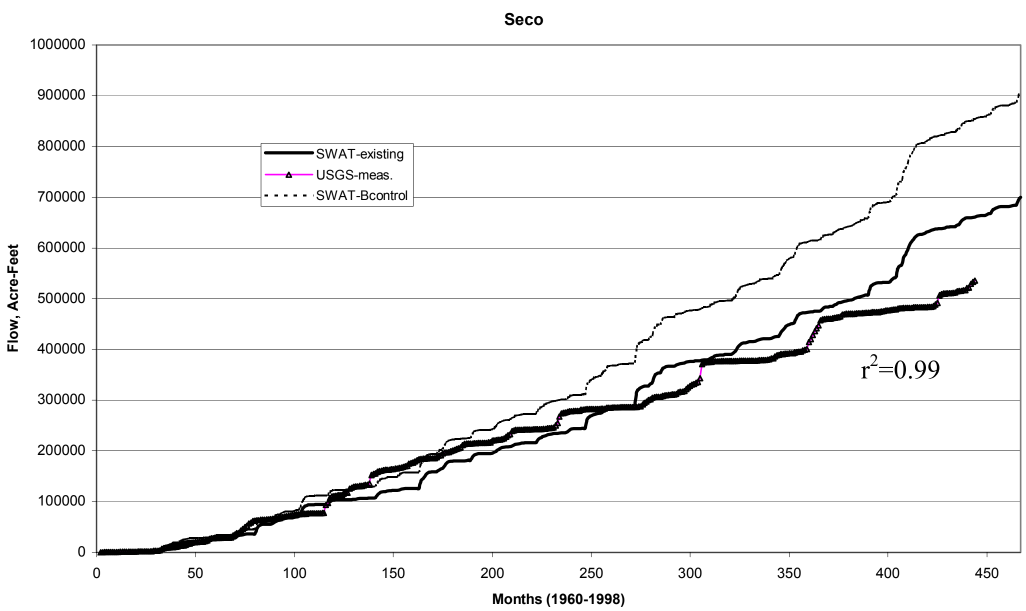

The drainage area above the USGS gage was estimated by USGS to be 206 $mi^2$. The SWAT modeled drainage area was 212 $mi^2$ (gage 08198000 near Sabinal, Texas).

***Figure 6-10. The SWAT Modeled and USGS Measured Flows for Sabinal River Basin***



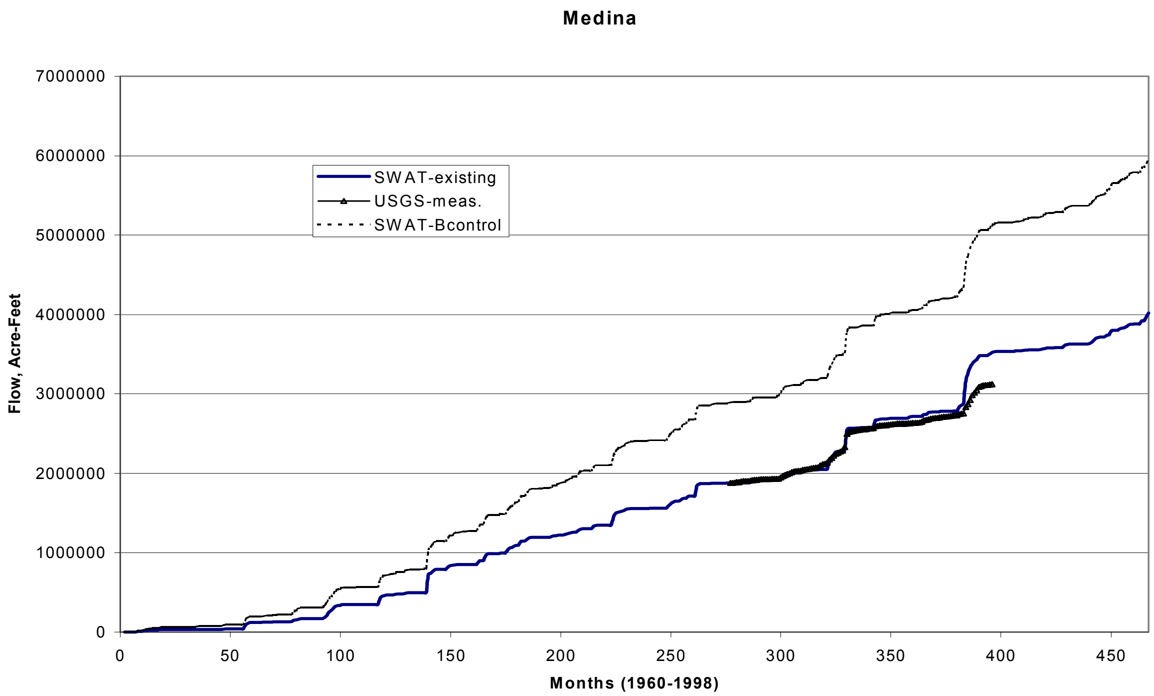

The upper line is for SWAT modeled flows after brush removal and conversion of brush land to open range conditions. The USGS drainage area above the gage was 95.6 $mi^2$. The SWAT modeled drainage area was 90 $mi^2$ (gage 08200000 near Tarpley, Texas).

***Figure 6-11. The SWAT Modeled and USGS Measured Streamflows in Hondo River Basin***




The upper dotted line is streamflows after brush removal. The USGS estimated drainage area above the gage was 45 $mi^2$ and the SWAT modeled drainage area was 51 $mi^2$.

***Figure 6-12. The SWAT Predicted and USGS Measured Flows at Gage 08201500 near Utopia, Texas***




Measurements by USGS were available for a limited time period post-1982. USGS estimated drainage area was 427 $mi^2$, and the SWAT modeled area was 472 $mi^2$

***Figure 6-13. The SWAT Model Predicted and USGS Measured Flows***

**Table 6-6. Water Yield Savings Gallons/Treated Acre/Year for Edwards Aquifer Recharge Sub-Basins**

| *Sub-basin* | *Acres* | *Treated Acres* | *Treated (%)* | *Savings (gal/tr. ac/yr)* | *Savings (gal/yr)* |
|---|---|---|---|---|---|
| Frio | | | | | |
| 2 | 1,678 | 753 | 44.9 | 109,324 | 82,366,931 |
| 4 | 8,183 | 4,108 | 50.2 | 52,967 | 217,585,026 |
| 6 | 6,786 | 2,572 | 37.9 | 112,867 | 290,298,360 |
| 8 | 6,357 | 3,153 | 49.6 | 64,010 | 201,826,587 |
| 10 | 9,903 | 3,704 | 37.4 | 43,320 | 160,450,000 |
| 12 | 12,524 | 4,221 | 33.7 | 54,697 | 230,854,683 |
| 14 | 7,245 | 3,565 | 49.2 | 84,185 | 300,097,619 |
| 16 | 4,565 | 1,055 | 23.1 | 303,675 | 320,257,540 |
| 18 | 8,225 | 8,043 | 37.0 | 123,274 | 375,157,672 |
| 20 | 11,194 | 6,325 | 56.5 | 65,512 | 414,334,709 |
| 22 | 10,765 | 2,928 | 27.2 | 177,901 | 520,884,259 |
| 24 | 12,833 | 3,439 | 26.8 | 22,722 | 78,143,571 |
| 26 | 15,147 | 1,999 | 13.2 | 32,156 | 64,294,788 |
| 28 | 21,536 | 2,843 | 13.2 | 104,121 | 295,995,503 |
| 30 | 8,368 | 3,188 | 38.1 | 124,316 | 396,360,132 |
| 32 | 17,827 | 7,077 | 39.7 | 65,136 | 460,996,825 |
| 34 | 20,675 | 4,590 | 22.2 | 45,335 | 208,081,217 |
| 36 | 8,734 | 594 | 6.8 | 712,718 | 423,272,487 |
| 38 | 6,737 | 916 | 13.6 | 642,870 | 589,018,519 |
| 40 | 7,312 | 3,071 | 42.0 | 63,408 | 194,730,556 |
| 42 | 12,889 | 4,937 | 38.3 | 32,543 | 160,651,323 |
| 44 | 9,146 | 4,820 | 52.7 | 116,848 | 563,170,899 |
| 46 | 16,221 | 8,240 | 50.8 | 28,147 | 232,153,439 |
| Totals | 244,851 | 81,141 | | | 6,780,982,646 |
| Weighted Avg. | | | 33,13874 | 83,571 | |
| Sabinal | | | | | |
| 2 | 14,805 | 7,017 | 47.4 | 94,627 | 664,043,519 |
| 4 | 7,198 | 1,807 | 25.1 | 90,893 | 164,204,153 |
| 6 | 13,603 | 6,026 | 44.3 | 96,152 | 579,418,386 |
| 8 | 3,572 | 786 | 22.0 | 112,311 | 88,248,889 |
| 10 | 7,731 | 2,049 | 26.5 | 107,447 | 220,118,783 |
| 12 | 1,153 | 106 | 9.2 | 115,281 | 12,225,397 |
| 14 | 19,055 | 9,852 | 51.7 | 102,805 | 1,012,788,889 |
| 16 | 24,550 | 6,088 | 24.8 | 118,045 | 718,692,857 |
| 18 | 19,697 | 8,194 | 41.6 | 115,198 | 943,926,720 |
| 20 | 11,169 | 4,680 | 41.9 | 154,459 | 722,837,831 |
| 22 | 13,072 | 4,719 | 36.1 | 16,691 | 550,669,577 |
| Total | 135,603 | 51,323 | | | 5,677,175,000 |
| Weighted Avg. | | | 37.8481 | 110,616 | |

***Table 6-6. Water Yield Savings Gallons/Treated Acre/Year for Edwards Aquifer Recharge Sub-Basins (Continued)***

| *Sub-basin* | *Acres* | *Treated Acres* | *Treated (%)* | *Savings (gal/tr. ac/yr)* | *Savings (gal/yr)* |
|---|---|---|---|---|---|
| Seco | | | | | |
| 2 | 1,514 | 448 | 29.6 | 95,963 | 43,005,185 |
| 4 | 937 | 469 | 50.0 | 98,793 | 46,289,497 |
| 6 | 1,442 | 721 | 50.0 | 106,308 | 76,626,772 |
| 8 | 504 | 252 | 50.0 | 107,113 | 26,992,460 |
| 10 | 2,064 | 586 | 28.4 | 133,991 | 78,534,709 |
| 12 | 2,645 | 1,013 | 38.3 | 198,902 | 201,456,190 |
| 14 | 7,680 | 3,840 | 50.0 | 127,986 | 491,484,656 |
| 16 | 1,968 | 667 | 33.9 | 134,660 | 89,857,011 |
| 18 | 3,477 | 1,739 | 50.0 | 138,385 | 240,610,450 |
| 20 | 3,847 | 1,923 | 50.0 | 137,554 | 264,563,836 |
| 22 | 1,577 | 593 | 37.6 | 138,495 | 82,141,429 |
| 24 | 2,657 | 1,329 | 50.0 | 138,894 | 184,541,984 |
| 26 | 2,094 | 1,047 | 50.0 | 135,662 | 142,024,815 |
| Total | 32,406 | 14,627 | | | 1,968,128,995 |
| Weighted Avg. | | | 45.13504 | 134,558 | |
| Hondo | | | | | |
| 2 | 170 | 51 | 30.0 | 185,882 | 9,496,720 |
| 4 | 6,691 | 2,369 | 35.4 | 134,414 | 318,375,132 |
| 6 | 15,554 | 5,693 | 36.6 | 171,199 | 974,591,534 |
| 8 | 17,459 | 5,901 | 33.8 | 142,441 | 840,581,481 |
| 10 | 17,677 | 5,992 | 33.9 | 149,264 | 894,437,566 |
| Total | 57,551 | 20,006 | | | 3,037,482,434 |
| Weighted Avg. | | | 34.76223 | 151,829 | |
| Medina | | | | | |
| 2 | 6,901 | 2,084 | 30.2 | 168,571 | 351,298,942 |
| 4 | 2,969 | 888 | 29.9 | 159,803 | 141,862,328 |
| 6 | 15,388 | 4,832 | 31.4 | 143,876 | 695,193,651 |
| 8 | 10,161 | 5,080 | 50.0 | 147,483 | 749,280,688 |
| 10 | 15,452 | 3,554 | 23.0 | 169,544 | 602,563,624 |
| 12 | 5,449 | 1,319 | 24.2 | 136,799 | 180,404,153 |
| 14 | 16,314 | 3,540 | 21.7 | 166,424 | 589,154,101 |
| 16 | 16,691 | 5,007 | 30.0 | 138,847 | 695,266,138 |
| 18 | 14,922 | 3,059 | 20.5 | 146,493 | 448,114,550 |
| 20 | 2,981 | 0 | 0 | 0 | 0 |
| 22 | 5,501 | 1,188 | 21.6 | 148,963 | 177,013,254 |
| 24 | 12,029 | 3,152 | 26.2 | 173,678 | 547,375,926 |
| 26 | 9,660 | 2,212 | 22.9 | 172,397 | 381,366,402 |
| 28 | 9,852 | 2,246 | 22.8 | 170,566 | 383,149,339 |
| 30 | 4,519 | 1,487 | 32.9 | 174,737 | 259,784,444 |

**Table 6-6. Water Yield Savings Gallons/Treated Acre/Year for Edwards Aquifer Recharge Sub-Basins (Continued)**

| Sub-basin | Acres | Treated Acres | Treated (%) | Savings (gal/tr. ac/yr) | Savings (gal/yr) |
|---|---|---|---|---|---|
| 32 | 8,818 | 4,409 | 50.0 | 170,107 | 750,028,439 |
| 34 | 2,902 | 1,451 | 50.0 | 181,845 | 263,893,201 |
| 36 | 6,681 | 3,341 | 50 | 170,802 | 570,563,280 |
| 38 | 21,963 | 8,192 | 37.3 | 183,071 | 1,499,760,317 |
| 40 | 17,076 | 4,867 | 28.5 | 183,071 | 792,434,788 |
| 42 | 9,813 | 4,906 | 50.0 | 183,540 | 900,527,910 |
| 44 | 18,681 | 9,340 | 50.0 | 170,016 | 1,588,003,968 |
| 46 | 43,702 | 16,301 | 37.3 | 183,492 | 2,991,050,265 |
| 48 | 14,157 | 4,162 | 29.4 | 174,478 | 726,184,392 |
| 50 | 9,250 | 2,488 | 26.9 | 160,288 | 398,840,344 |
| Total | 301,834 | 99,106 | | | 16,683,114,444 |
| Weighted Avg. | | | 32.83468 | 168,336 | |

stream segments. There is a significant water loss in streams in the Edwards Aquifer river basins. The sub-basin water yields given in gallons/treated ac/yr can be compared against some field measurements. Thruow and Taylor (1995) made water savings estimates of close to 85,000 gallons/treated acre/year in Sonora, Texas. Water savings of nearly 130,000 gallons/treated acre/year in a sub-basin in Seco river basin was observed7.

## 6.3 Upper Nueces River Watershed — Edwards Aquifer

### 6.3.1 Methods

#### 6.3.1.1 Watershed Characteristics

The Upper Nueces watershed covers a large area of South Texas north and east of the Rio Grande River basin. It is within a semiarid climatic region with soils that are primarily Usterts and Ustalfs that generally have large cracks that persist for more than 3 months during the summer. This allows for deep infiltration of any significant rainfall during the summer months. The watershed generally runs northwest to southeast and is above the gauging station at Uvalde. Based on the digital elevation map (DEM), the derived sub-basins are shown in Figure 6-14. Due to the fact that part of the watershed lies over the western part of the Edwards Aquifer recharge zone, the entire Nueces watershed was divided into the upper (Edwards) and lower Nueces. The upper Nueces corresponds to the 8-digit hydrologic response units (HRU) 12110101 and 121102. The streamflow gauge near Uvalde was used to calibrate the flows for the Upper Nueces.

#### 6.3.1.2 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 6-15. 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.

[7] Thurow T.L., and C.A. Taylor. 1995. Juniper effects on the water yield of Central Texas rangeland. Proc. 24th Water for Texas Conference, Texas Water Resources Institute, College Station, Texas. Pp. 657-666.

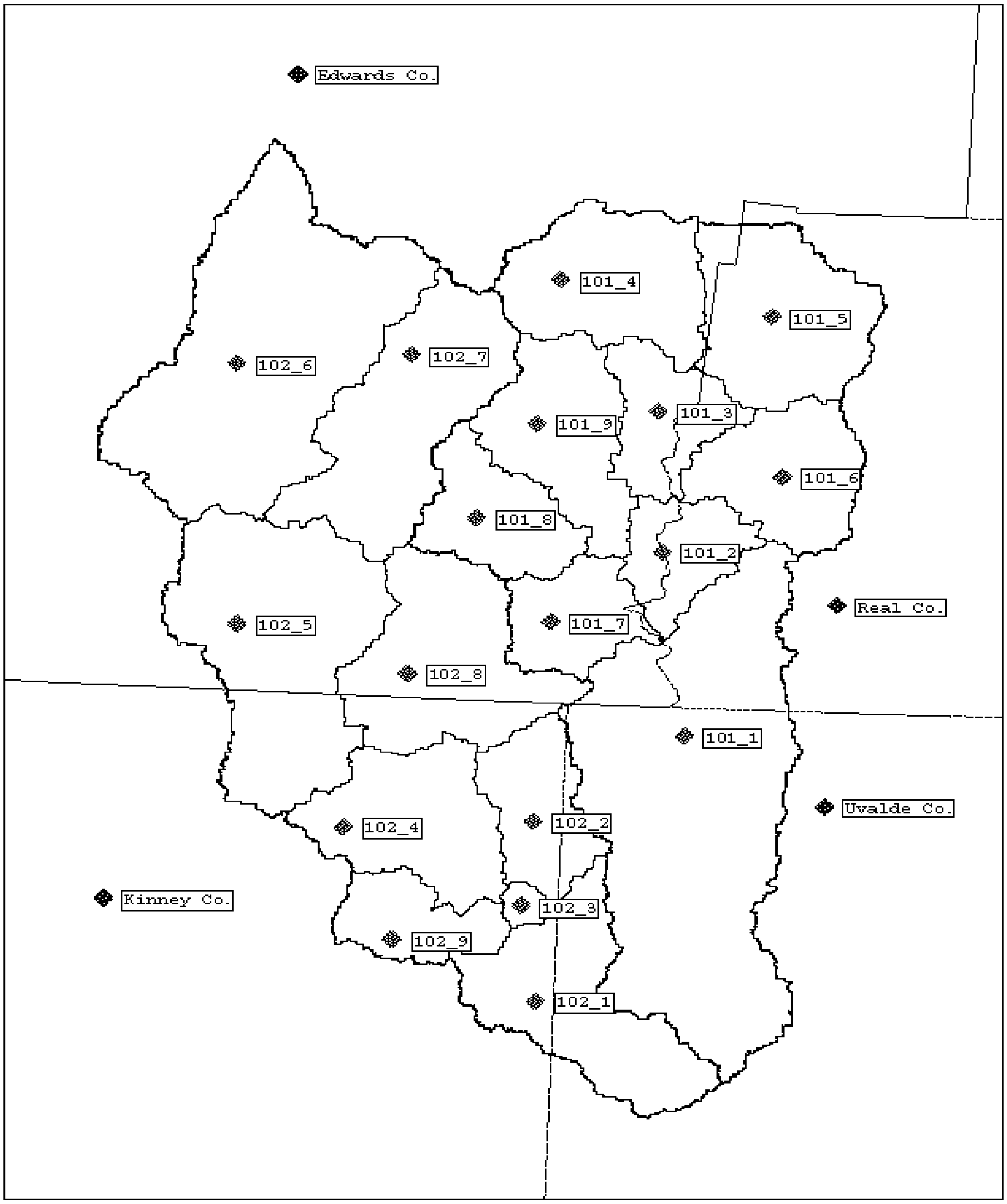



***Figure 6-14. Upper Nueces River Watershed Sub-Basin Map***

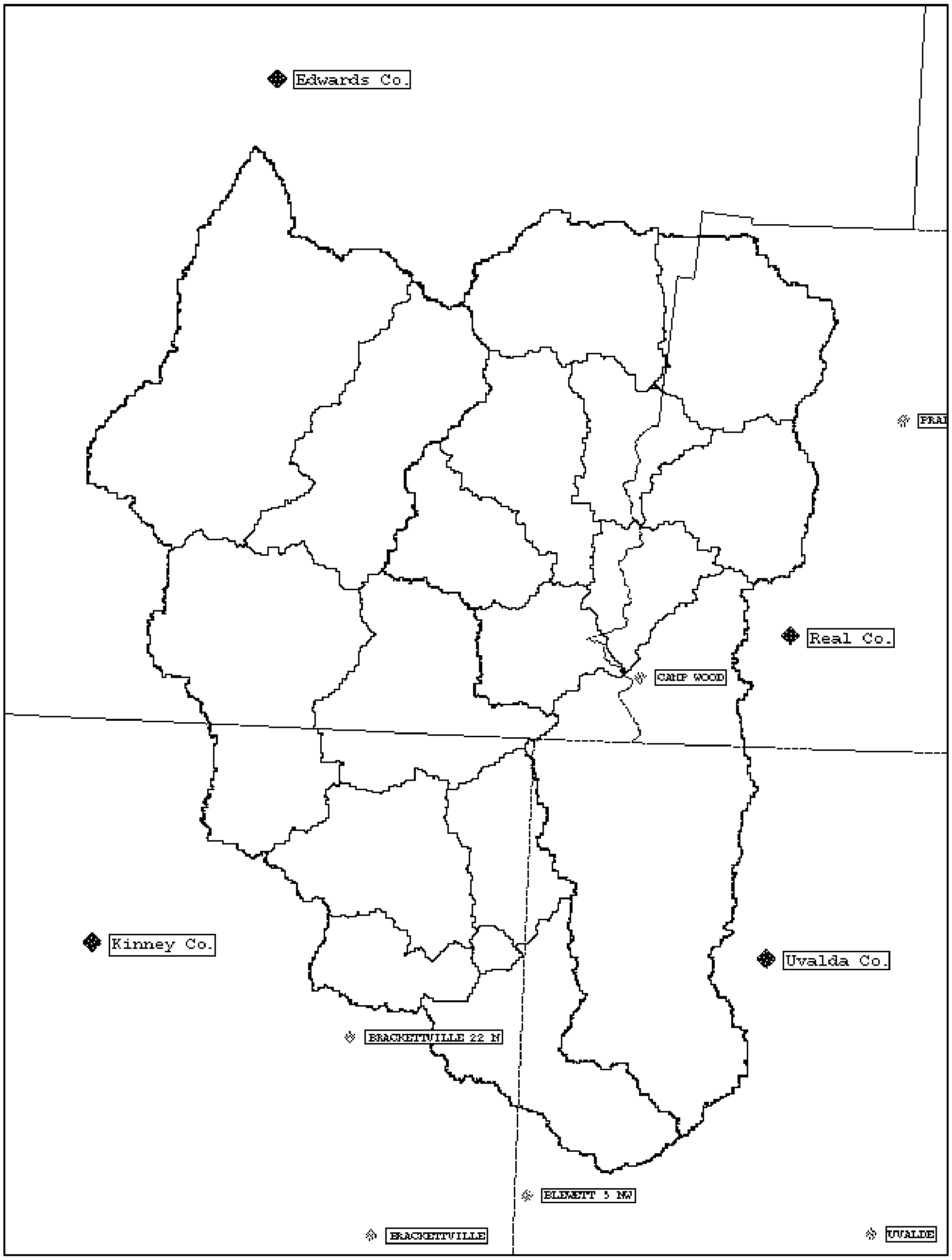



***Figure 6-15. Climate Stations in the Upper Nueces Watershed***

#### *6.3.1.3 Topography*

The outlet or "catchment" for the portion of the upper Nueces River simulated in this study is at Uvalde of sub-basin number 102-1. The sub-basin delineation and numbers are shown in Figure 6-14. Roads (obtained from the Census Bureau) are overlaid in Figure 6-16.

#### *6.3.1.4 Soils*

The dominant soil series in the Nueces River watershed are Uvalde, Aguilares, Duval, Maverick, and Montell. These six 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.
- Aguilares. The Aguilares series consists of deep, well drained moderately permeable soils that formed in calcareous, loamy sediments. These soils are on uplands with slopes ranging from 1 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.
- Maverick. The Maverick series consists of moderately deep, well-drained soils formed in ancient clayey marine sediments. These soils are gently rolling. Slopes range from 0 to 10 percent.
- Montell. The Montell series consists of deep, moderately well-drained, very slowly permeable soils that formed in ancient clayey alluvium. These soils are on nearly level to gently sloping uplands. Slopes range from 0 to about 3 percent.

#### *6.3.1.5 Land Use/Land Cover*

Figure 6-17 show the areas of heavy and moderate brush in the Nueces River Watershed that represent the area of brush removed or treated in the no-brush simulation. This corresponds to 72 percent of the total watershed area.

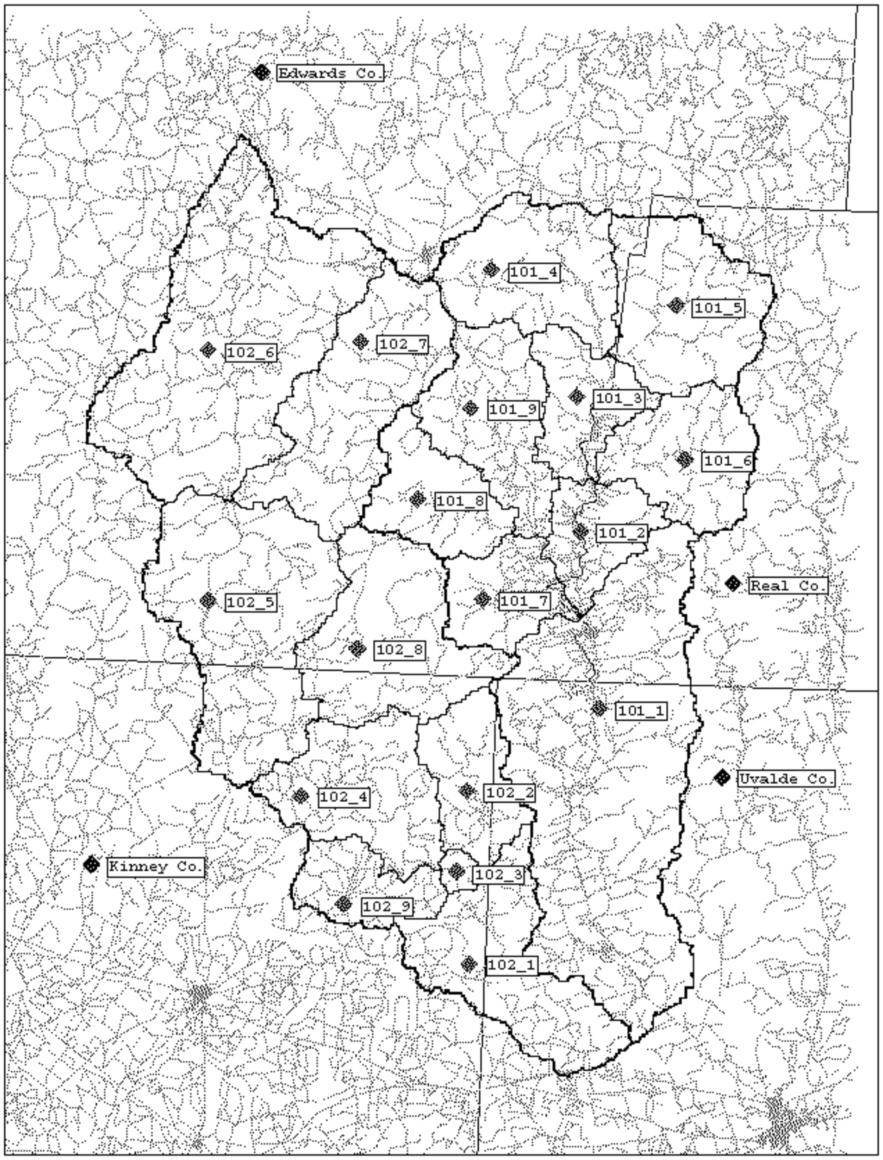



*Figure 6-16. Upper Nueces River Watershed Roads Map*

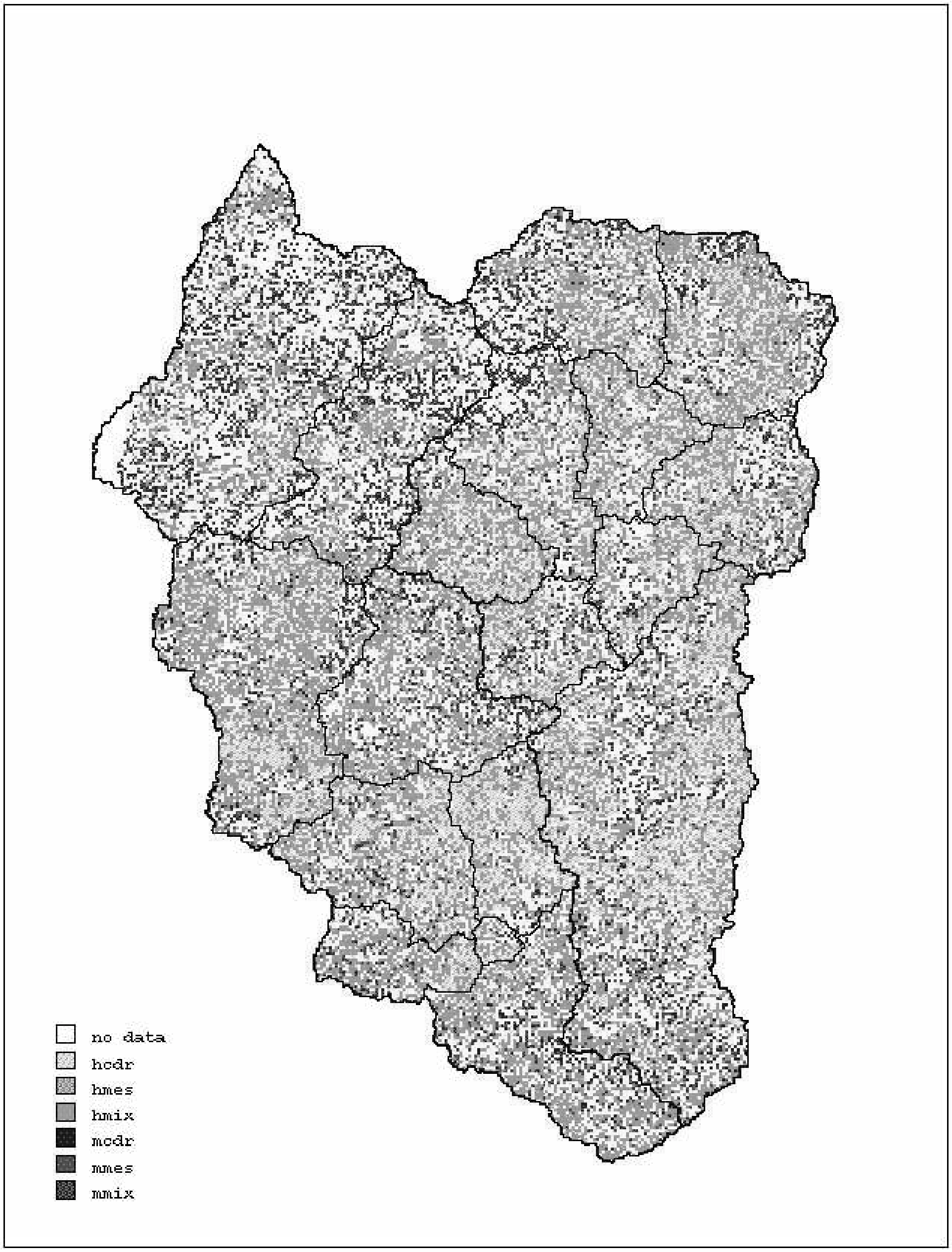



***Figure 6-17. Areas of Heavy and Moderate Brush in the Upper Nueces River Watershed***

#### *6.3.1.6 Model Input Variables*

Significant input variables for the SWAT model for the upper Nueces River Watershed are shown in Table 6-7. Input variables for the no-brush condition were the same as the calibrated condition with one exception:

1. It was 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.

### *6.3.2 Upper Nueces River Watershed Results*

#### *6.3.2.1 Calibration*

SWAT was calibrated for the flow at streamgauges near Uvalde. The results of calibration are shown in Figure 6-18. Measured and predicted average monthly flows compare reasonably well with a 4 percent difference between measured and simulated cumulative flow. At Uvalde, the measured monthly mean is 12,830 acft, and predicted monthly mean is 12,284 acft. The coefficient of determination ($r^2$) was 0.99 between measured and simulated. Average baseflow for the entire watershed is 7 percent of total flow.

#### *6.3.2.2 Brush Removal Simulation*

The average annual rainfall for the Upper Nueces River Watershed is 27.09 inches. Average annual evapotranspiration (ET) in the Upper Nueces is 22.31 inches for the brush condition (calibration) and 19.81 inches for the no-brush condition. This represents 82 percent and 73 percent of precipitation for the brush and no-brush conditions, respectively, in the Upper Nueces.

The increases in water yield by sub-basin for the Upper Nueces River Watersheds are shown in Figure 6-12 and Table 6-8. The amount of annual increase varies among the sub-basins and ranges from 20,130 gallons per acre of brush removed per year in sub-basin number 102-1, to 64,123 gallons per acre in sub-basin number 101-4. 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

## *Table 6-7. SWAT Input Variables for Nueces River Watershed*

| Variable | Brush Condition (Calibration) | No Brush Condition |
|---|---|---|
| Runoff Curve Number Adjustment | -15 | -15 |
| Soil Available Water Capacity Adjustment (%) | 0 | 0 |
| Soil Evaporation Compensation Factor ($in^3\ in^{-3}$) | 0.85 | 0.85 |
| 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) | | |
| Heavy Cedar | 5,399 | 5,399 |
| Heavy Mesquite | 4,697 | 4,697 |
| Heavy mixed Brush | 5,021 | 5,021 |
| Moderate Cedar | 4,697 | 4,697 |
| Moderate Mesquite | 4,157 | 4,157 |
| Moderate Mixed Brush | 4,427 | 4,427 |
| Heavy Oak | 4,697 | 4,697 |
| Moderate Oak | 4,157 | 4,157 |
| Light Brush & Open Range/Pasture | 3,617 | 3,617 |
| Precipitation Interception (inches) | | |
| Heavy Cedar | 0.79 | N/A |
| Heavy Mesquite | 0 | N/A |
| Heavy Mixed Brush | 0.59 | N/A |
| Moderate Cedar | 0.59 | N/A |
| Moderate Mesquite | 0 | N/A |
| Moderate Mixed Brush | 0.39 | 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 |
| Open Range & Pasture | 1 | 1 |
| Channel Transmission Loss (inches/hour) | 0.02 | 0.02 |
| Sub-basin Transmission Loss (inches/hour) | 0.015 | 0.015 |
| Fraction Trans. Loss Returned as Baseflow | 0.07 | 0.07 |

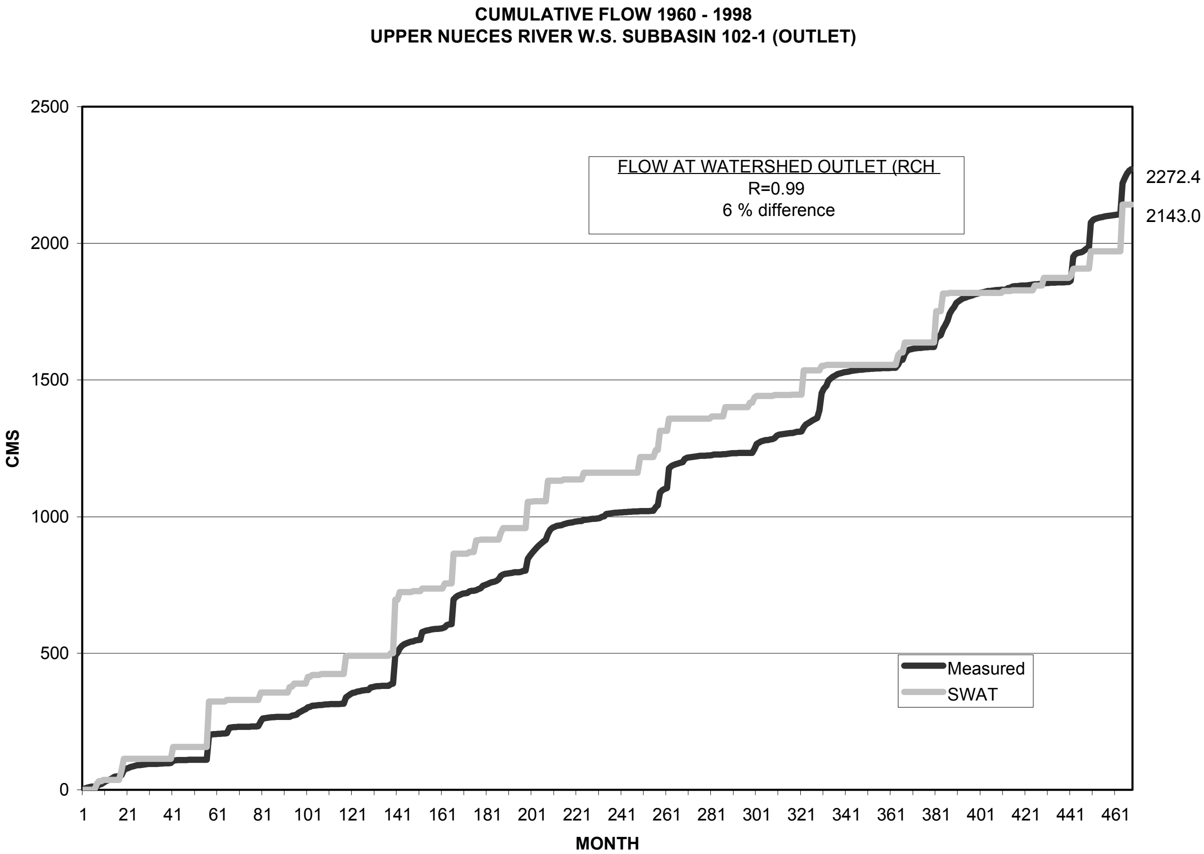



***Figure 6-18. Simulated and Measured Cumulative Flow at the Outlet of the Upper Nueces (Uvalde)***

**Table 6-8. Upper Nueces Areas and Water Yield**

| Sub-basin | Sub-basin Total Area (acres) | Brush Removal Area (acres) | Fraction of Sub-basin Containing Brush | Increase (gal/ac) Water Yield | Ave Ann. Gal. Incr. |
|---|---|---|---|---|---|
| 101-1 | 185288 | 139448 | 0.75 | 43964 | 6130727916 |
| 101-2 | 26787 | 20104 | 0.75 | 47477 | 954472646 |
| 101-3 | 30591 | 25268 | 0.83 | 48458 | 1224429007 |
| 101-4 | 55555 | 33594 | 0.60 | 64123 | 2154144354 |
| 101-5 | 59790 | 45607 | 0.76 | 60097 | 2740863615 |
| 101-6 | 42803 | 31357 | 0.73 | 49777 | 1560845886 |
| 101-7 | 28521 | 22329 | 0.78 | 46209 | 1031808731 |
| 101-8 | 34786 | 28834 | 0.83 | 55885 | 1611377433 |
| 101-9 | 48332 | 33384 | 0.69 | 61662 | 2058534699 |
| 102-1 | 62270 | 46827 | 0.75 | 20130 | 942640759 |
| 102-2 | 33037 | 33037 | 1.00 | 45628 | 1507402078 |
| 102-3 | 3839 | 2879 | 0.75 | 27299 | 78594288 |
| 102-4 | 52055 | 52055 | 1.00 | 30671 | 1596603565 |
| 102-5 | 101325 | 80961 | 0.80 | 41959 | 3397009504 |
| 102-6 | 142026 | 70686 | 0.50 | 62142 | 4392587131 |
| 102-7 | 74993 | 40773 | 0.54 | 62942 | 2566318159 |
| 102-8 | 68093 | 49898 | 0.73 | 47035 | 2346937893 |
| 102-9 | 24961 | 19689 | 0.79 | 24924 | 490735872 |

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 6-7 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 Upper Nueces, the average annual water yield increases by 57 percent or approximately 112,875 acft. The average annual flow at Uvalde could increase by 71,344 acft. The increase in volume of flow is slightly less than the water yield because of stream channel transmission losses that occur after water leaves each sub-basin and the shallow soils that allow for percolation.

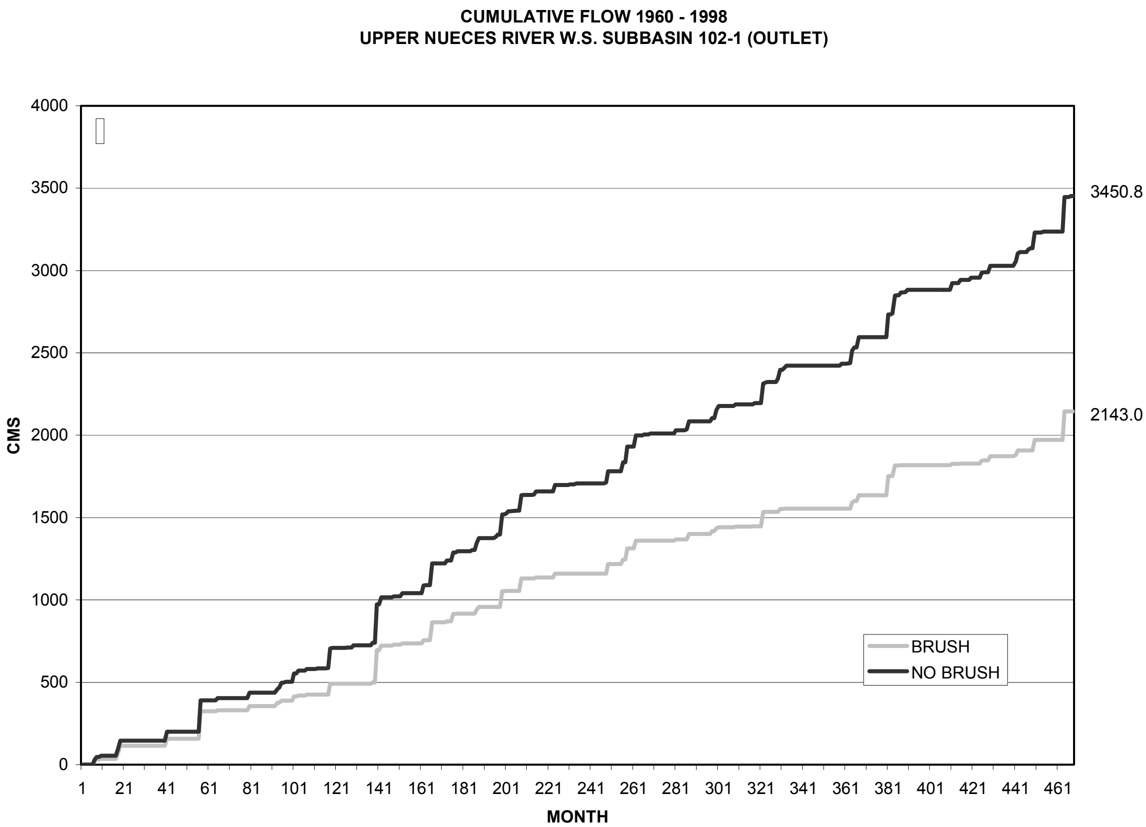



***Figure 6-19. Simulated Cumulative Flow at the Outlet for Brush and No Brush Conditions in the Upper Nueces***

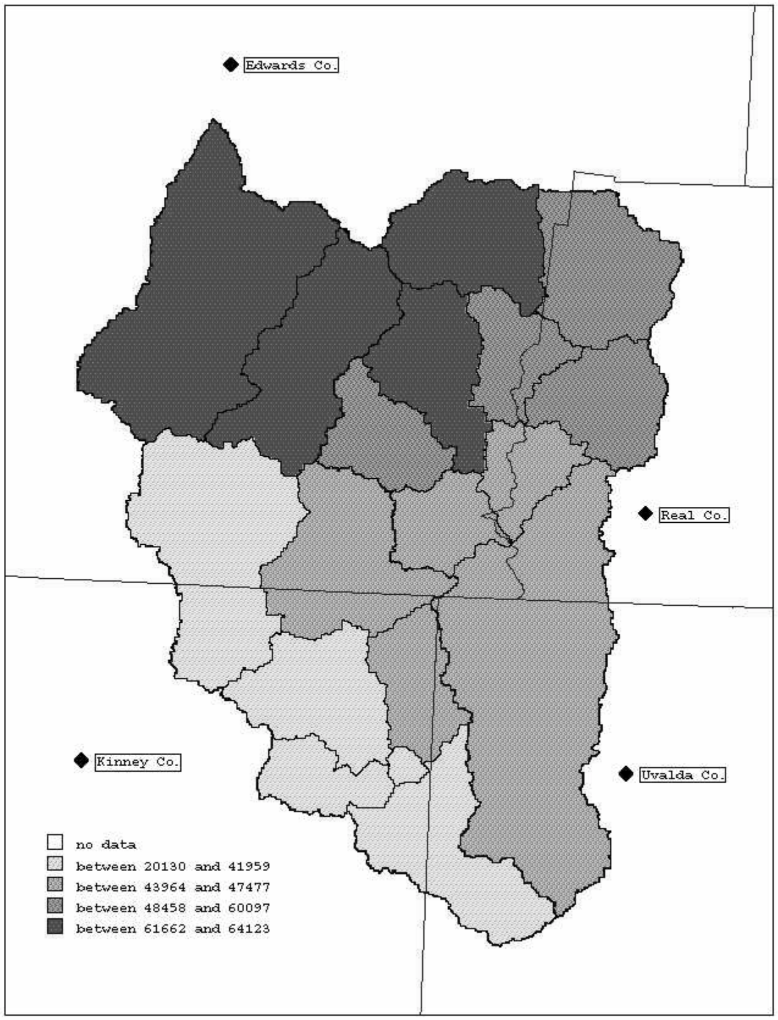



***Figure 6-20. Increase in Water Yield per Treated Acre (gallons/acre) due to Brush Removal from 1960 through 1998***

# Section 7
# Edwards Aquifer Recharge Zone Watershed - Economic Analysis

## 7.1 Introduction

Amounts of the various types and densities of brush cover in the watershed were detailed in the 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 acre-foot costs of a brush control program for water yield for the Edwards Aquifer Recharge Zone 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 the 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. The Recharge Zone is broken into an eastern and western portion. The eastern portion is comprised of the Hondo, Medina, Sabinal and Seco watersheds. Present values of total costs for that region range from $52.02 per acre for moderate mesquite or mixed brush that can be initially controlled with herbicide treatments to $200.76 per acre for root-plowing with pre-dozing for control of heavy mesquite. Costs of treatments, year those treatments are needed, and treatment life for each brush type density category in the eastern portion are detailed in Table 7-1.

***Table 7-1. Cost of Water Yield Brush Control Programs by Type-Density Category (Eastern Portion of Edwards Aquifer Recharge Zone Watershed)***

| *Year* | *Treatment* | *Treatment Cost ($/acre)* | *Present Value ($/acre)* |
|---|---|---|---|
| ***Heavy Cedar — Mechanical[1]*** | | | |
| 0 | Tree Doze | 165.00 | 165.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 182.02 |
| ***Heavy Mesquite — Chemical[2]*** | | | |
| 0 | Aerial Herbicide | 35.00 | 35.00 |
| 4 | Aerial Herbicide | 35.00 | 25.73 |
| 7 | Choice IPT or Burn | 20.00 | 14.59 |
| | | Total | 75.32 |
| ***Heavy Mesquite — Rootplow[3]*** | | | |
| 0 | Rootplow | 160.00 | 160.00 |
| 6 | IPT or Burn | 25.00 | 15.76 |
| | | Total | 175.76 |
| ***Heavy Mesquite — Rootplow with Pre-doze[4]*** | | | |
| 0 | Pre-doze and Rootplow | 185.00 | 185.00 |
| 6 | IPT or Burn | 25.00 | 15.76 |
| | | Total | 200.76 |
| ***Heavy Mixed Brush — Chemical[5]*** | | | |
| 0 | Aerial Herbicide | 35.00 | 35.00 |
| 4 | Aerial Herbicide | 35.00 | 25.73 |
| 7 | Choice IPT or Burn | 20.00 | 14.59 |
| | | Total | 75.32 |
| ***Heavy Mixed Brush — Rootplow[3]*** | | | |
| 0 | Rootplow | 160.00 | 160.00 |
| 6 | IPT or Burn | 25.00 | 15.76 |
| | | Total | 175.76 |
| ***Heavy Mixed Brush — Rootplow with Pre-Doze[4]*** | | | |
| 0 | Pre-Doze and Rootplow | 185.00 | 185.00 |
| 6 | IPT or Burn | 25.00 | 15.76 |
| | | Total | 200.76 |

**Table –7.1. Cost of Water Yield Brush Control Programs by Type-Density Category (Eastern Portion of Edwards Aquifer Recharge Zone Watershed) (Continued)**

| Year | Treatment | Treatment Cost ($/acre) | Present Value ($/acre) |
|---|---|---|---|
| **Moderate Cedar — Mechanical[1]** | | | |
| 0 | Tree Doze | 100.00 | 100.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 117.02 |
| **Moderate Mesquite — Chemical[6]** | | | |
| 0 | Aerial or IPT Herbicide | 35.00 | 35.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 52.02 |
| **Moderate Mesquite — Mechanical Choice[7]** | | | |
| 0 | Choice of Mechanical Method | 60.00 | 60.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 77.02 |
| **Moderate Mixed Brush — Chemical[6]** | | | |
| 0 | Aerial or IPT Herbicide | 35.00 | 35.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 52.02 |
| **Moderate Mixed — Mechanical Choice[7]** | | | |
| 0 | Choice of Mechanical Method | 60.00 | 60.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 77.02 |

[1] Doze of tree shear, stack and burn.
[2] Individual chemical application may also be used.
[3] Rootplow, rake, stack, and burn.
[4] Heavy tree-doze, rootplow, rake, stack, and burn.
[5] Individual chemical application may also be used.
[6] Either aerial or individual chemical applocation may be used.
[7] Choice of tree dozing, stack, & burn, tree shearing, stump spray and later burn, or low power grubbing and burning.

Similar information is presented in Table 7-2 for the western portions of the region, which consists of the upper portions of the Frio and Nueces watersheds. For this portion of the region, present values of total costs range from $52.02 per acre for moderate mesquite or mixed brush that can be initially controlled with herbicide treatments, to $195.76 per acre for root-plowing with pre-dozing for control of heavy mesquite. As in Table 7-1, costs of treatments, year those treatments are needed, and treatment life for each brush type density category for the western region are detailed in Table 7-2.

***Table 7-2. Cost of Water Yield Brush Control Programs by Type-Density Category (Western Portion of Edwards Aquifer Recharge Zone Watershed)***

| *Year* | *Treatment* | *Treatment Cost ($/acre)* | *Present Value ($/acre)* |
|---|---|---|---|
| ***Heavy Cedar —Two Way Chain[1]*** | | | |
| 0 | Two Way Chain | 90.00 | 90.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 107.02 |
| ***Heavy Cedar — Tree-Doze[2]*** | | | |
| 0 | Tree Doze | 145.00 | 145.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 162.02 |
| ***Heavy Cedar – Tree Shear or Flat Cutting[3]*** | | | |
| 0 | Tree Shear/Flat Cutting | 130.00 | 130.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 147.02 |
| ***Heavy Mesquite — Chemical[4]*** | | | |
| 0 | Aerial Herbicide | 35.00 | 35.00 |
| 4 | Aerial Herbicide | 35.00 | 25.73 |
| 7 | Choice IPT or Burn | 20.00 | 14.59 |
| | | Total | 75.32 |
| ***Heavy Mesquite — Rootplow[5]*** | | | |
| 0 | Rootplow | 155.00 | 155.00 |
| 6 | IPT or Burn | 25.00 | 15.76 |
| | | Total | 170.76 |
| ***Heavy Mesquite— Rootplow with Pre-Doze[6]*** | | | |
| 0 | Pre-doze and Rootplow | 180.00 | 180.00 |
| 6 | IPT or Burn | 25.00 | 15.76 |
| | | Total | 195.76 |
| ***Heavy Mixed Brush — Chemical[7]*** | | | |
| 0 | Initial IPT | 60.00 | 60.00 |
| 6 | IPT or Burn | 25.00 | 15.76 |
| | | Total | 75.36 |

***Table 7-2. Cost of Water Yield Brush Control Programs by Type-Density Category (Western Portion of Edwards Aquifer Recharge Zone Watershed) (Continued)***

| ***Year*** | ***Treatment*** | ***Treatment Cost ($/acre)*** | ***Present Value ($/acre)*** |
|---|---|---|---|
| ***Heavy Mixed Brush — Tree Doze[2]*** | | | |
| 0 | Tree Doze | 145.00 | 145.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 162.02 |
| ***Moderate Cedar — Tree Doze[8]*** | | | |
| 0 | Tree Doze | 95.00 | 95.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 112.02 |
| ***Moderate Cedar — Tree Shear or Flat Cutting[9]*** | | | |
| 0 | Tree Shear/Flat Cutting | 75.00 | 75.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 92.02 |
| ***Moderate Mesquite — Chemical[10]*** | | | |
| 0 | Aerial or IPT Herbicide | 35.00 | 35.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 52.02 |
| ***Moderate Mesquite — Mechanical Choice[11]*** | | | |
| 0 | Choice of Mechanical Method | 60.00 | 60.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 77.02 |
| ***Moderate Mixed Brush — Chemical[10]*** | | | |
| 0 | Aerial or IPT Herbicide | 35.00 | 35.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 52.02 |
| ***Moderate Mixed — Mechanical Choice[11]*** | | | |
| 0 | Choice of Mechnical Method | 60.00 | 60.00 |
| 5 | IPT or Burn | 25.00 | 17.02 |
| | | Total | 77.02 |

[1] Two way chain, stack and burn.
[2] Doze, stack and burn.
[3] Tree shear or flat cutting by hand, stack, and burn.
[4] Individual chemical application may also by used.
[5] Rootplow, rake, stack, and burn.
[6] Heavy tree-doze, rootplow, rake, stack, and burn.
[7] Initial IPT for heavy canopies.
[8] Doze, rake, stack, and burn.
[9] Tree shear or flat cutting by hand, stack, and burn.
[10] Either aerial or individual chemical application may be used.
[11] Choice of tree dozing, rake and burn, tree shearing with stump spray and later burn, or grubbing and burning.

## 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 Edwards Recharge Zone watershed are shown in Tables 7-3 (the Hondo, Medina, Sabinal and Seco watersheds), and Table 7-4 (the upper portions of the Frio and Nueces watersheds). Data relating to grazing capacity was entered into the investment analysis model (see Appendix A).

**Table 7-3. Grazing Capacity With and Without Brush Control (Acres/AUY) (Eastern Portion of Edwards Aquifer Recharge Zone Watershed)**

| | | Program Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Brush Type / Category** | **Brush Control** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| Heavy Cedar | Control | 60.0 | 50.0 | 40.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 |
| | No Control | 60.0 | 60.1 | 60.1 | 60.2 | 60.3 | 60.3 | 60.4 | 60.5 | 60.5 | 60.6 |
| Heavy Mesquite | Control | 35.0 | 30.0 | 25.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 |
| | No Control | 35.0 | 35.0 | 35.1 | 35.1 | 35.2 | 35.2 | 35.2 | 35.3 | 35.3 | 35.4 |
| Heavy Mixed Brush | Control | 45.0 | 38.2 | 31.6 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 |
| | No Control | 45.0 | 45.1 | 45.1 | 45.2 | 45.2 | 45.3 | 45.3 | 45.4 | 45.4 | 45.5 |
| Moderate Cedar | Control | 45.0 | 40.0 | 35.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 |
| | No Control | 45.0 | 45.3 | 45.5 | 45.8 | 46.0 | 46.3 | 46.5 | 46.8 | 47.0 | 47.3 |
| Moderate Mesquite | Control | 25.0 | 23.2 | 21.6 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 |
| | No Control | 25.0 | 25.1 | 25.3 | 25.4 | 25.6 | 25.7 | 25.8 | 26.0 | 26.1 | 26.3 |
| Moderate Mixed Brush | Control | 35.0 | 31.6 | 28.3 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 |
| | No Control | 35.0 | 35.2 | 35.4 | 35.6 | 35.8 | 36.0 | 36.2 | 36.4 | 36.6 | 36.8 |

***Table 7-4. Grazing Capacity With and Without Brush Control (Acres/AUY)***
***(Western Portion of Edwards Aquifer Recharge Zone Watershed)***

| | | Program Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Brush Type / Category** | **Brush Control** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| Heavy Cedar | Control | 50.0 | 43.3 | 36.7 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 |
| | No Control | 50.0 | 50.1 | 50.1 | 50.2 | 50.3 | 50.3 | 50.3 | 50.4 | 50.4 | 50.5 |
| Heavy Mesquite | Control | 30.0 | 26.7 | 23.3 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 |
| | No Control | 30.0 | 30.0 | 30.1 | 30.1 | 30.2 | 30.3 | 30.3 | 30.4 | 30.4 | 30.3 |
| Heavy Mixed Brush | Control | 40.0 | 35.0 | 30.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 |
| | No Control | 40.0 | 40.0 | 40.1 | 40.2 | 40.2 | 40.3 | 40.3 | 40.4 | 40.4 | 40.4 |
| Moderate Cedar | Control | 40.0 | 36.7 | 33.3 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 |
| | No Control | 40.0 | 40.2 | 40.3 | 40.3 | 40.4 | 40.4 | 40.5 | 40.6 | 40.6 | 42.0 |
| Moderate Mesquite | Control | 25.0 | 23.3 | 21.6 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 |
| | No Control | 25.0 | 25.1 | 25.2 | 25.3 | 25.3 | 25.4 | 25.4 | 25.5 | 25.5 | 26.3 |
| Moderate Mixed Brush | Control | 35.0 | 31.7 | 28.3 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 |
| | No Control | 35.0 | 35.2 | 35.3 | 35.3 | 35.4 | 35.4 | 35.5 | 35.5 | 35.6 | 36.8 |

As with 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 eastern portion of the watershed, livestock grazing capacities range from about 20 ac/AUY for land on which mesquite is controlled to 60 ac/AUY for land infested with heavy cedar. In the western portion of the watershed, livestock grazing capacities range from about 20 ac/AUY for land on which mesquite is controlled to 50 ac/AUY for land infested with heavy cedar.

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 and goats) in the eastern portion of the project area is shown in Tables 7-5 and 7-6. In the western portion of the project area, the livestock enterprises consist of cattle, sheep, and goats (Tables 7-7, 7-8, and 7-9). It is important to note once again (refer to Appendix A) 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, which was also described in Appendix A.

***Table 7-5. Investment Analysis Budget, Cow-Calf Production (Eastern Portion of Edwards Aquifer Recharge Zone Watershed)***

| ***Revenue Item Description*** | ***Quantity*** | ***Unit*** | ***$ / Unit*** | ***Cost*** |
|---|---|---|---|---|
| **Partial Revenues** | | | | |
| Calves | 405.00 | Pound | .95 | 384.75 |
| Cows | 111.1 | Pound | .40 | 0.00 |
| Bulls | 250.0 | Pound | .50 | 0 |
| | | | Total | 384.75 |
| ***Variable Cost Item Description*** | ***Quantity*** | ***Unit*** | ***$ / Unit*** | ***Cost*** |
| **Partial Variable Costs** | | | | |
| Supplemental Feed | 480.0 | Pound | 0.10 | 48.00 |
| Salt & Minerals | 27.0 | Pound | 0.20 | 5.40 |
| Marketing | 1.0 | Head | 6.32 | 6.32 |
| Veterinary Medicine | 1.0 | Head | 14.00 | 14.00 |
| Miscellaneous | 1.0 | Head | 12.00 | 12.00 |
| Net Replacement Cows | 1.0 | Head | 35.28 | 35.28 |
| Net Replacement Bulls | 1.0 | Head | 3.09 | 6.09 |
| | | | Total | 127.09 |
| Note: This budget is for presentation of the information used in the investment analysis only. Net returns cannot be calculated from this budget, for not all revenues and variable costs have been included. | | | | |

**Table 7-6. Investment Analysis Budget, Meat Goat Production (Eastern Portion of Edwards Aquifer Recharge Zone Watershed)**

| Revenue Item Description | Quantity | Unit | $ / Unit | Cost |
|---|---|---|---|---|
| **Partial Revenues** | | | | |
| Kid Goats | 345.00 | Pound | 0.85 | 293.25 |
| Cull Nannies | 1.0 | Head | 20.00 | 0.00 |
| Cull Bucks | 0.045 | Head | 40.00 | 0.00 |
| | | | Total | 293.25 |
| ***Variable Cost Item Description*** | ***Quantity*** | ***Unit*** | ***$ / Unit*** | ***Cost*** |
| **Partial Variable Costs** | | | | |
| Supplemental Feed | 384.0 | Pound | 0.10 | 38.40 |
| Salt & Minerals | 73.5 | Pound | 0.20 | 14.70 |
| Marketing | 1.0 | Head | 2.55 | 15.31 |
| Veterinary Medicine | 1.0 | Head | 2.50 | 15.00 |
| Miscellaneous | 1.0 | Head | 1.17 | 7.00 |
| Net Replacement Nannies | 1.0 | Head | 6.08 | 36.48 |
| Net Replacement Bucks | 1.0 | Head | 0.79 | 4.74 |
| | | | Total | 131.63 |

Note: This budget is for presentation of the information used in the investment analysis only. Net returns cannot be calculated from this budget, for not all revenues and variable costs have been included.

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 $1.75 per acre (from $9.00 per acre to $10.75 per acre) due principally to the resulting improvement in habitat and accessibility to hunting. Wildlife revenues would not be expected to change with implementation of brush control for the moderate brush type-density categories.

**Table 7-7. Investment Analysis Budget, Cow-Calf Production (Western Portion of Edwards Aquifer Recharge Zone Watershed)**

| Revenue Item Description | Quantity | Unit | $ / Unit | Cost |
|---|---|---|---|---|
| **Partial Revenues** | | | | |
| Calves | 405.00 | Pound | .95 | 384.75 |
| Cows | 111.1 | Pound | .40 | 0 |
| Bulls | 250.0 | Pound | .50 | 0 |
| | | | Total | 384.75 |
| ***Variable Cost Item Description*** | ***Quantity*** | ***Unit*** | ***$ / Unit*** | ***Cost*** |
| **Partial Variable Costs** | | | | |
| Supplemental Feed | 500.0 | Pound | 0.10 | 50.00 |
| Salt & Minerals | 50.0 | Pound | 0.20 | 10.00 |
| Marketing | 1.0 | Head | 6.32 | 6.32 |
| Veterinary Medicine | 1.0 | Head | 14.00 | 14.00 |
| Miscellaneous | 1.0 | Head | 12.00 | 12.00 |
| Net Replacement Cows[3] | 1.0 | Head | 35.28 | 35.28 |
| Net Replacement Bulls[4] | 1.0 | Head | 3.09 | 6.09 |
| | | | Total | 133.69 |

Note: This budget is for presentation of the information used in the investment analysis only. Net returns cannot be calculated from this budget, for not all revenues and variable costs have been included.

***Table 7-8. Investment Analysis Budget Sheep Production (Western Portion of Edwards Aquifer Recharge Zone Watershed)***

| ***Revenue Item Description*** | ***Quantity*** | ***Unit*** | ***$ / Unit*** | ***Cost*** |
|---|---|---|---|---|
| **Partial Revenues** | | | | |
| Lambs | 211.25 | Pound | .85 | 179.56 |
| Cull Ewes | 0.83 | Head | 20.00 | 0 |
| Cull Rams | 0.038 | Head | 40.00 | 0 |
| Wool | 40.00 | Pounds | 1.00 | 40.00 |
| | | | Total | 219.56 |
| ***Variable Cost Item Description*** | ***Quantity*** | ***Unit*** | ***$ / Unit*** | ***Cost*** |
| **Partial Variable Costs** | | | | |
| Supplemental Feed | 300.0 | Pound | 0.10 | 30.00 |
| Salt & Minerals | 60.0 | Pound | 0.30 | 18.00 |
| Marketing | 1.0 | Head | 1.00 | 5.00 |
| Veterinary Medicine | 1.0 | Head | 3.00 | 15.00 |
| Miscellaneous | 1.0 | Head | 1.20 | 6.00 |
| Shearing | 1.0 | Head | 2.40 | 12.00 |
| Net Replacement Ewes | 1.0 | Head | 6.83 | 39.17 |
| Net Replacement Rams | 1.0 | Head | 0.87 | 8.52 |
| | | | Total | 133.69 |

Note: This budget is for presentation of the information used in the investment analysis only. Net returns cannot be calculated from this budget, for not all revenues and variable costs have been included.

**Table 7-9. Investment Analysis Budget, Meat Goat Production (Western Portion of Edwards Aquifer Recharge Zone Watershed)**

| Revenue Item Description | Quantity | Unit | $ / Unit | Cost |
|---|---|---|---|---|
| **Partial Revenues** | | | | |
| Kid Goats | 405.00 | Pound | .85 | 344.25 |
| Cull Nannies | 1.0 | Head | 20.00 | 0.00 |
| Cull Bucks | 0.045 | Head | 40.00 | 0.00 |
| | | | Total | 344.25 |
| ***Variable Cost Item Description*** | ***Quantity*** | ***Unit*** | ***$ / Unit*** | ***Cost*** |
| **Partial Variable Costs** | | | | |
| Supplemental Feed | 350.0 | Pound | 0.10 | 35.00 |
| Salt & Minerals | 73.50 | Pound | 0.20 | 14.70 |
| Marketing | 1.0 | Head | 2.55 | 15.31 |
| Veterinary Medicine | 1.0 | Head | 2.50 | 15.00 |
| Miscellaneous | 1.0 | Head | 1.17 | 7.00 |
| Net Replacement Nannies | 1.0 | Head | 6.83 | 41.00 |
| Net Replacement Bucks | 1.0 | Head | 0.87 | 5.23 |
| | | | Total | 133.24 |

Note: This budget is for presentation of the information used in the investment analysis only. Net returns cannot be calculated from this budget, for not all revenues and variable costs have been included.

With the above information, present values of the benefits to landowners were estimated for each of the brush type-density categories using the procedure described in Section 8. For the eastern part of the region, they range from $52.12 per acre for the control of heavy mesquite to $20.81 per acre for control of moderate mesquite (Table 7-10). For the western portion of the region, present value of landowner benefits range from $33.99 per acre for the control of heavy mesquite to $10.44 per acre for control of moderate cedar (Table 7-11).

**Table 7-10. Landowner / State Cost-Shares of Brush Control (Eastern Portion of Edwards Aquifer Recharge Zone Watershed)**

| Brush Type and Density | Control Practice | PV of Total Cost ($/acre) | Rancher Share ($/acre) | Rancher (%) | State Share ($/acre) | State (%) |
|---|---|---|---|---|---|---|
| Heavy Cedar | Doze or Shear | 182.02 | 43.52 | 0.24 | 138.5 | 0.76 |
| Heavy Mesquite | Chemical | 75.32 | 52.12 | 0.69 | 23.2 | 0.31 |
| | Rootplow | 175.76 | 52.12 | 0.30 | 123.64 | 0.70 |
| | Doze and Plow[1] | 200.76 | 52.12 | 0.26 | 148.64 | 0.74 |
| Heavy Mixed Brush | Chemical | 75.32 | 45.61 | 0.61 | 29.71 | 0.39 |
| | Rootplow | 175.76 | 45.61 | 0.26 | 130.15 | 0.74 |
| | Doze &Plow[1] | 200.76 | 45.61 | 0.23 | 155.15 | 0.77 |
| Moderate Cedar | Doze or Shear | 117.02 | 23.27 | 0.20 | 93.75 | 0.80 |
| Moderate Mesquite | Chemical | 52.02 | 20.81 | 0.40 | 31.21 | 0.60 |
| | Doze or Grub | 77.02 | 20.81 | 0.27 | 56.21 | 0.73 |
| Moderate Mixed Brush | Chemical | 52.02 | 23.88 | 0.46 | 28.14 | 0.54 |
| | Doze or Grub | 77.02 | 23.88 | 0.31 | 53.14 | 0.69 |
| Average | | 121.73 | 37.45 | 0.35 | 84.29 | 0.65 |

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 80% cattle and 20% meat goats. In this region, 20% of typical ranch resources are assigned to wildlife production.

[1]The (pre)doze and plow category is to be applied to extra heavy densities of this brush type (i.e., over 40% canopy cover.)

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. In the eastern part of the region, present values of the state cost share per acre of brush control ranges from $23.20 for control of heavy mesquite with herbicide to $155.15 for mechanical control of heavy mixed brush. For the western portion of the region, present values of the state cost share per acre of brush control range from $36.67 for control of moderate mixed brush with herbicide to $164.96 for mechanical control of heavy mixed brush. Total treatment cost, rancher benefits and state cost share for all brush type-density categories are shown in Tables 7-10 and 7-11.

**Table 7-11. Landowner / State Cost-Shares of Brush Control (Western Portion of Edwards Recharge Zone Watershed)**

| Brush Type and Density | Control Practice | PV of Total Cost ($/acre) | Rancher Share ($/acre) | Rancher (%) | State Share ($/acre) | State (%) |
|---|---|---|---|---|---|---|
| Heavy Cedar | Chain | 107.02 | 30.69 | 0.29 | 76.33 | 0.71 |
| | Doze | 162.02 | 30.69 | 0.19 | 131.33 | 0.81 |
| | Shear or Flat Cut | 147.02 | 30.69 | 0.21 | 116.33 | 0.79 |
| Heavy Mesquite | Chemical | 75.32 | 33.99 | 0.45 | 41.33 | 0.55 |
| | Rootplow | 170.76 | 33.99 | 0.20 | 136.77 | 0.80 |
| | Doze and Plow[1] | 195.76 | 33.99 | 0.17 | 161.77 | 0.83 |
| Heavy Mixed Brush | Chemical | 75.32 | 30.80 | 0.41 | 44.52 | 0.59 |
| | Rootplow | 170.76 | 30.80 | 0.18 | 139.96 | 0.82 |
| | Doze and Plow[1] | 195.76 | 30.80 | 0.16 | 164.96 | 0.84 |
| Moderate Cedar | Doze | 112.02 | 10.44 | 0.09 | 101.58 | 0.91 |
| | Shear or Flat Cut | 92.02 | 10.44 | 0.11 | 81.58 | 0.89 |
| Moderate Mesquite | Chemical | 52.02 | 12.45 | 0.24 | 39.57 | 0.76 |
| | Doze or Grub | 77.02 | 12.45 | 0.16 | 64.57 | 0.84 |
| Moderate Mixed Brush | Chemical | 52.02 | 15.35 | 0.30 | 36.67 | 0.70 |
| | Doze or Grub | 77.02 | 15.35 | 0.20 | 61.67 | 0.80 |
| Average | | 117.46 | 24.19 | 0.22 | 93.26 | 0.78 |

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 mixture of 20% cattle, 30% sheep, and 50% meat goats. In this region, 25% of typical ranch resources are assigned to wildlife production.

[1]The (pre)doze and plow category is for extra heavy density of this brush type (i.e., over 40% canopy cover).

### *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 Chapter).** 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 $29.92 per acre foot for the Hondo Watershed (Table 7-12), $26.68 per acre foot for the Medina Watershed (Table 7-13), $42.04 per acre foot for the Sabinal Watershed (Table 7-14), $35.33 per acre foot for the Seco Watershed (Table 7-15), $51.65 per acre foot for the Upper Frio Watershed (Table 7-16), and $97.51 per acre foot for the upper Nueces Watershed (Table 7-17). Sub-basins range from costs per added acre foot of $4.79 to $241.67. For the entire Edwards Recharge Zone Watershed, the average costs per added acre foot of added water is $67.41.

***Table 7-12. Cost of Added Water from Brush Control by Sub-Basin (acft) (Hondo River Watershed)***

| ***Sub-Basin No.*** | ***Total State Cost ($)*** | ***Average Annual Water Increase (acft)*** | ***10 Year Added Water (acft)*** | ***State Cost for Added Water ($/acft)*** |
|---|---|---|---|---|
| 2 | 5,384.12 | 29.14 | 227.38 | 23.68 |
| 4 | 259,953.00 | 977.06 | 7,623.00 | 34.10 |
| 6 | 630,981.90 | 2,990.91 | 23,335,09 | 27.04 |
| 8 | 631,559.90 | 2,579.65 | 20,126,43 | 31.38 |
| 10 | 647,846.20 | 2,744.93 | 21,415.93 | 30.25 |
| Totals: | $2,175,725.00 | — | 72,727.84 | Average: $29.92 |

**Table 7-13. Cost of Added Water from Brush Control by Sub-Basin (acft) (Medina River Watershed)**

| Sub-Basin No. | Total State Cost ($) | Average Annual Water Increase (acft) | 10 Year Added Water (acft) | State Cost for Added Water ($/acft) |
|---|---|---|---|---|
| 2 | 226,441.20 | 1,078.10 | 8,411.31 | 26.92 |
| 4 | 95,490.56 | 435.36 | 3,396.68 | 28.11 |
| 6 | 535,567.20 | 2,133.47 | 16,645.34 | 32.18 |
| 8 | 568,659.80 | 2,299.46 | 17,940.37 | 31.70 |
| 10 | 366,786.50 | 1,849.20 | 14,427.46 | 25.42 |
| 12 | 138,257.60 | 553.64 | 4,319.50 | 32.01 |
| 14 | 359,552.80 | 1,808.05 | 14,106.39 | 25.49 |
| 16 | 546,827.80 | 2,133.69 | 16,647.08 | 32.85 |
| 18 | 305,680.70 | 1,375.21 | 10,729.41 | 28.49 |
| 20 | 0.00 | 0.00 | 0.00 | 0.00 |
| 22 | 120,691.70 | 543.23 | 4,238.31 | 28.48 |
| 24 | 330,420.20 | 1,679.84 | 13,106.07 | 25.21 |
| 26 | 222,265.90 | 1,170.37 | 9,131.23 | 24.34 |
| 28 | 231,829.80 | 1,175.84 | 9,173.92 | 25.27 |
| 30 | 159,110.80 | 797.25 | 6,220.14 | 25.58 |
| 32 | 486,305.00 | 2,301.75 | 17,958.28 | 27.08 |
| 34 | 160,851.00 | 809.86 | 6,318.52 | 25.46 |
| 36 | 381,194.50 | 1,750.99 | 13,661.26 | 27.90 |
| 38 | 876,745.40 | 4,602.60 | 35,909.45 | 24.42 |
| 40 | 507,575.30 | 2,431.89 | 18,973.63 | 26.75 |
| 42 | 506,360.40 | 2,763.62 | 21,561.75 | 23.48 |
| 44 | 1,055,659.00 | 4,873.41 | 38,022.31 | 27.76 |
| 46 | 1,771,201.00 | 9,179.20 | 71,616.09 | 24.73 |
| 48 | 445,427.80 | 2,228.58 | 17,387.37 | 25.62 |
| 50 | 259,512.40 | 1,224.00 | 9,549.62 | 27.18 |
| Totals: | $10,658,415.00 | — | 399,451.50 | Average: $26.68 |

**Table 7-14. Cost of Added Water from Brush Control by Sub-Basin (acft) (Sabinal River Watershed)**

| Sub-Basin No. | Total State Cost ($) | Average Annual Water Increase (acft) | 10 Year Added Water (acft) | State Cost per acft Added Water ($) |
|---|---|---|---|---|
| 2 | 789,301.05 | 2,037.88 | 15,899.50 | 49.64 |
| 4 | 191,371.13 | 503.92 | 3,931.62 | 48.67 |
| 6 | 671,213.52 | 1,778.17 | 13,873.28 | 48.38 |
| 8 | 80,663.34 | 270.83 | 2,112.98 | 38.18 |
| 10 | 209,190.27 | 675.52 | 5,270.41 | 39.69 |
| 12 | 9,324.73 | 37.52 | 292.72 | 31.86 |
| 14 | 1,134,936.63 | 3,108.14 | 24,249.67 | 46.80 |
| 16 | 634,973.24 | 2,205.59 | 17,207.99 | 36.90 |
| 18 | 926,096.84 | 2,896.81 | 22,600.87 | 40.98 |
| 20 | 544,238.62 | 2,218.31 | 17,307.24 | 31.45 |
| 22 | 523,057.08 | 1,689.94 | 13,184.93 | 39.67 |
| Totals: | $5,714,366.45 | — | 135,931.20 | Average: $42.04 |

***Table 7-15. Cost of Added Water from Brush Control by Sub-Basin (acft) (Seco Creek Watershed***

| Sub-Basin No. | Total State Cost ($) | Average Annual Water Increase (acft) | 10 Year Added Water (acft) | State Cost for Added Water ($/acft) |
|---|---|---|---|---|
| 2 | 49,916.74 | 131.98 | 1,029.69 | 48.48 |
| 4 | 52,445.27 | 142.06 | 1,108.33 | 47.32 |
| 6 | 83,432.24 | 235.16 | 1,834.71 | 45.47 |
| 8 | 28,481.54 | 82.84 | 646.29 | 44.07 |
| 10 | 61,768.17 | 241.01 | 1,880.39 | 32.85 |
| 12 | 119,446.20 | 618.25 | 4,823.56 | 24.76 |
| 14 | 431,926.60 | 1,508.31 | 11,767.84 | 36.70 |
| 16 | 75,782.18 | 275.76 | 2,151.49 | 35.22 |
| 18 | 199,356.70 | 738.41 | 5,761.05 | 34.60 |
| 20 | 220,528.40 | 811.92 | 6,334.57 | 34.81 |
| 22 | 66,386.54 | 252.08 | 1,966.75 | 33.75 |
| 24 | 153,065.80 | 566.34 | 4,418.57 | 34.64 |
| 26 | 122,320.30 | 435.86 | 3,400.57 | 35.97 |
| Totals: | $1,664,857.00 | — | 47,123.82 | Average: $35.33 |

***Table 7-16. Cost of Added Water from Brush Control by Sub-Basin (acft) (Upper Frio River Watershed)***

| Sub-Basin No. | Total State Cost ($) | Average Annual Water Increase (acft) | 10 Year Added Water (acft) | State Cost per acft Added Water ($) |
|---|---|---|---|---|
| 2 | 78,885.85 | 252.77 | 1,972.15 | 40.00 |
| 4 | 431,838.05 | 667.74 | 5,209.74 | 82.89 |
| 6 | 267,148.09 | 890.89 | 6,950.75 | 38.43 |
| 8 | 335,418.12 | 619.38 | 4,832.43 | 69.41 |
| 10 | 381,597.00 | 492.40 | 3,841.73 | 99.33 |
| 12 | 433,077.57 | 708.47 | 5,527.46 | 78.35 |
| 14 | 385,180.51 | 920.97 | 7,185.37 | 53.61 |
| 16 | 107,771.60 | 982.83 | 7,668.07 | 14.05 |
| 18 | 321,190.94 | 1,151.32 | 8,982.57 | 35.76 |
| 20 | 683,386.98 | 1,271.55 | 9,920.61 | 68.89 |
| 22 | 297,984.18 | 1,598.54 | 12,471.77 | 23.89 |
| 24 | 345,686.96 | 239.81 | 1,871.03 | 184.76 |
| 26 | 180,884.86 | 197.31 | 1,539.44 | 117.50 |
| 28 | 254,801.16 | 908.38 | 7,087.16 | 35.95 |
| 30 | 337,833.04 | 1,216.38 | 9,490.23 | 35.60 |
| 32 | 743,995.16 | 1,414.75 | 11,037.86 | 67.40 |
| 34 | 434,452.52 | 638.58 | 4,982.18 | 87.20 |
| 36 | 48,505.48 | 1,298.98 | 10,134.61 | 4.79 |
| 38 | 82,889.31 | 1,807.63 | 14,103.14 | 5.88 |
| 40 | 326,696.18 | 597.61 | 4,662.52 | 70.07 |
| 42 | 516,879.00 | 493.02 | 3,846.55 | 134.37 |
| 44 | 520,780.72 | 1,728.31 | 13,484.26 | 38.62 |
| 46 | 869,668.39 | 712.45 | 5,558.56 | 156.46 |
| Totals: | $8,386,551.66 | — | 162360.18 | Average: $51.65 |

**Table 7-17. Cost of Added Water from Brush Control by Sub-Basin (acft) (Upper Nueces River Watershed)**

| Sub-Basin No. | Total State Cost ($) | Average Annual Water Increase (acft) | 10 Year Added Water (acft) | State Cost for Added Water ($/acft) |
|---|---|---|---|---|
| 101-1 | 16,242,903.00 | 18,814.51 | 146,790.83 | 110.65 |
| 101-2 | 2,297,010.00 | 2,929.17 | 22,853.38 | 100.51 |
| 101-3 | 2,895,235.00 | 3,757.63 | 29,317.07 | 98.76 |
| 101-4 | 3,344,663.00 | 6,610.83 | 51,577.67 | 64.85 |
| 101-5 | 5,312,303.00 | 8,411.40 | 65,625.76 | 80.95 |
| 101-6 | 3,652,463.00 | 4,790.06 | 37,372.05 | 97.73 |
| 101-7 | 2,552,173.00 | 3,166.50 | 24,705.07 | 103.31 |
| 101-8 | 3,303,922.00 | 4,945.14 | 38,581.95 | 85.63 |
| 101-9 | 3,271,623.00 | 6,317.41 | 49,288.44 | 66.38 |
| 102-1 | 5,454,409.00 | 2,892.86 | 22,570.08 | 241.67 |
| 102-2 | 3,694,543.00 | 4,626.05 | 36,092.42 | 102.36 |
| 102-3 | 335,345.90 | 241.20 | 1,881.82 | 178.20 |
| 102-4 | 5,960,334.00 | 4,899.80 | 38,228.21 | 155.91 |
| 102-5 | 9,430,337.00 | 10,425.04 | 81,336.16 | 115.94 |
| 102-6 | 6,355,018.00 | 13,480.35 | 105,173.73 | 60.42 |
| 102-7 | 3,681,164.00 | 7,875.74 | 61,446.53 | 59.91 |
| 102-8 | 5,812,119.00 | 7,202.49 | 56,193.81 | 103.43 |
| 102-9 | 2,293,491.00 | 1,506.01 | 11,749.91 | 195.19 |
| Totals: | $85,889,057.00 | — | 880784.88 | Average: $97.51 |

# 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).

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[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.

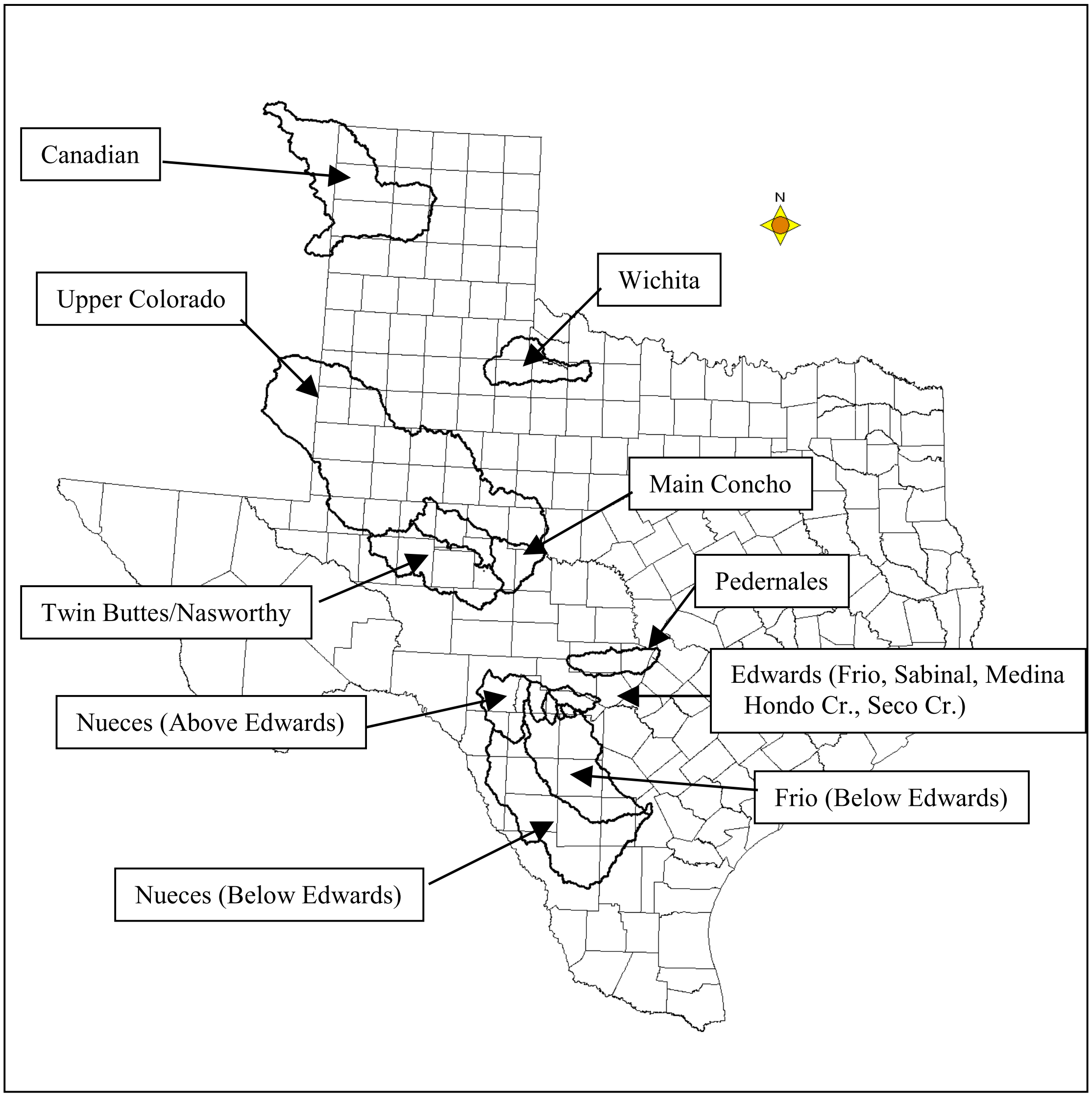


***Figure A-1. Watersheds included in the study area.***

**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):

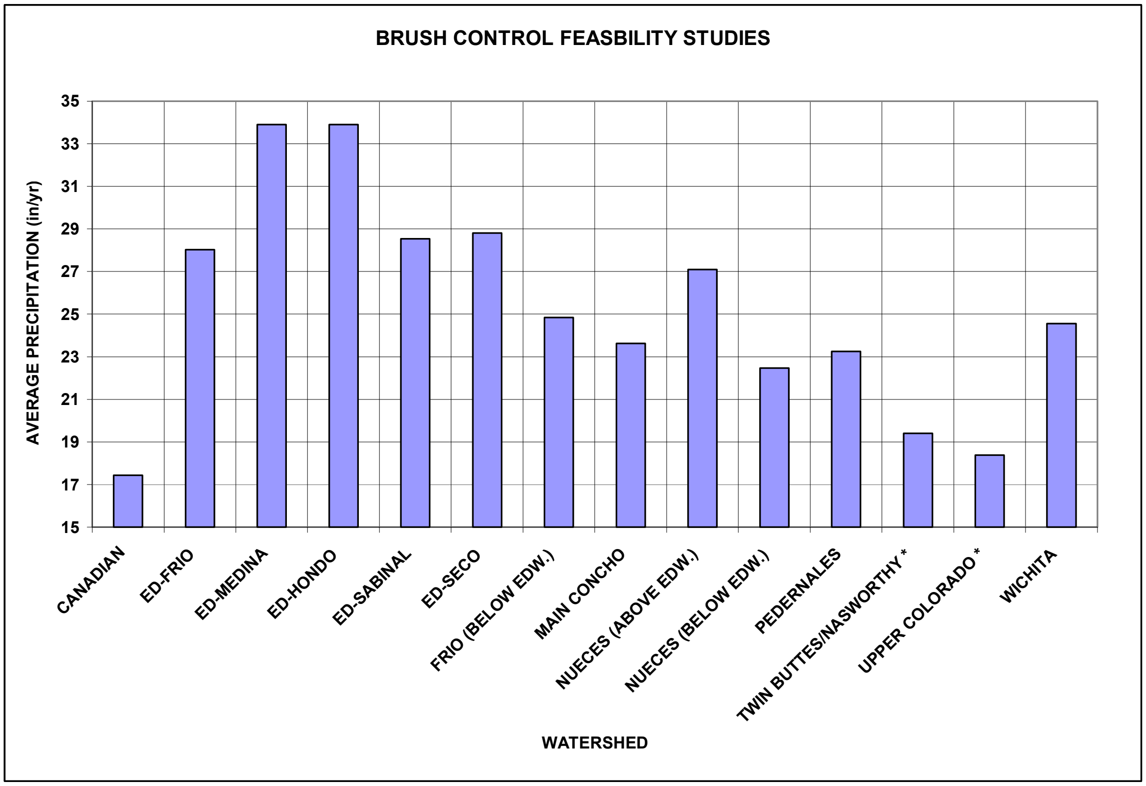


***Figure A-2. Average annual precipitation. Averages are for all climate stations in each watershed.***

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

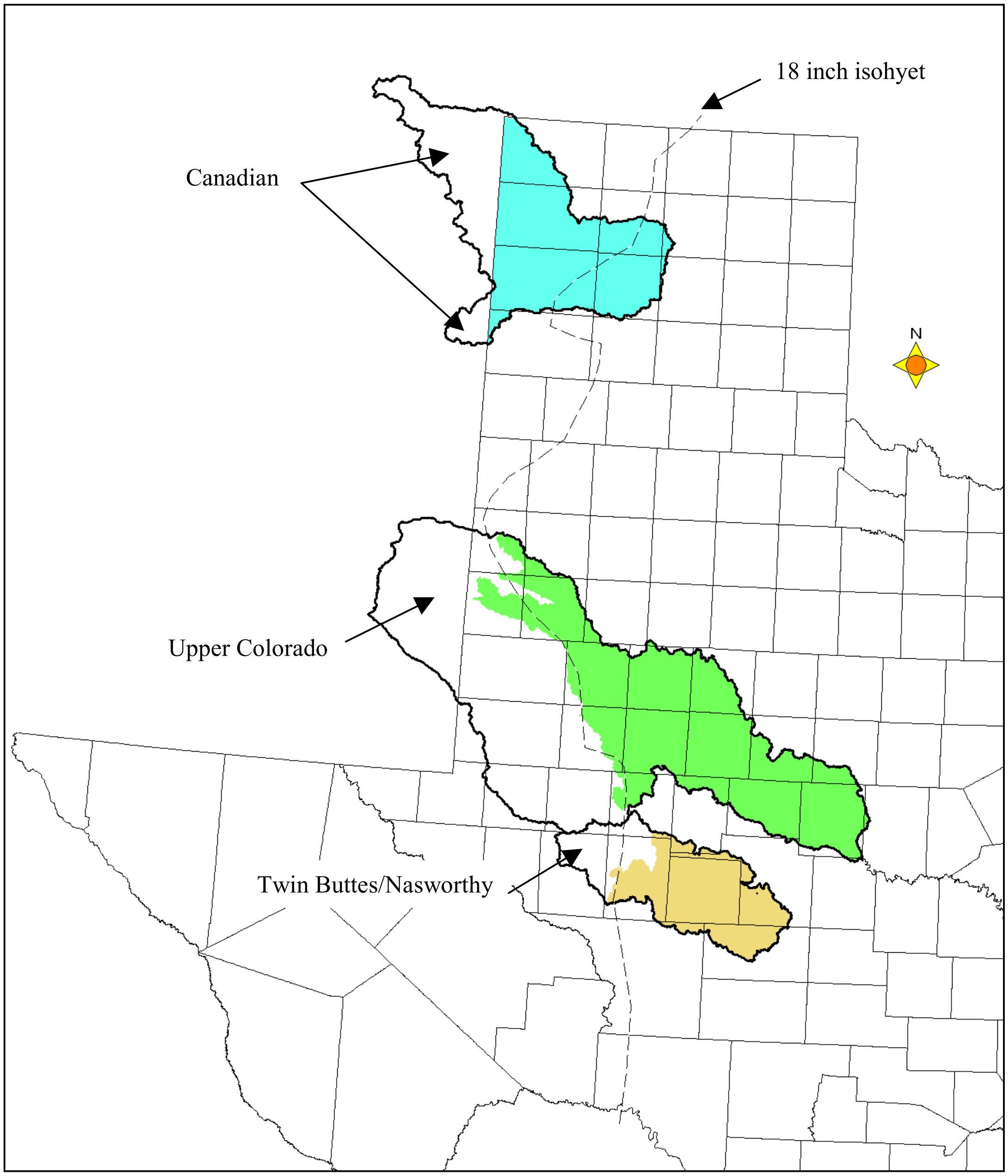


***Figure A-3. Areas where brush treatment was not planned (non-shaded portions of each watershed).***

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.

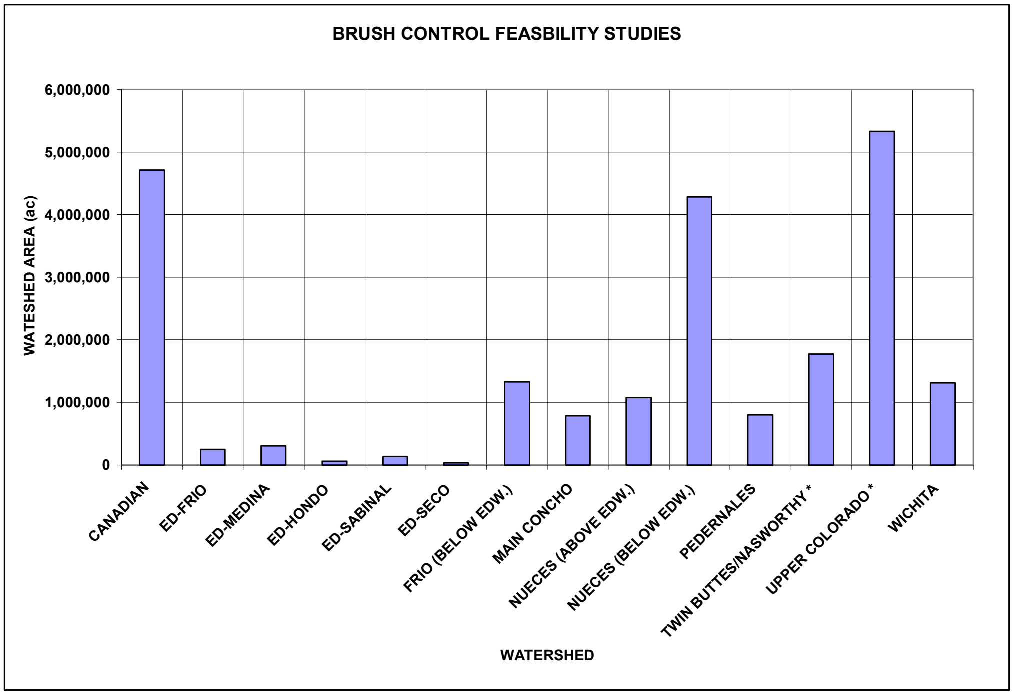


***Figure A-4. Watershed area. For watersheds that lie across the 18 inch isohyet, the area shown represents only the portion of those watersheds where brush treatment was planned and simulated.***

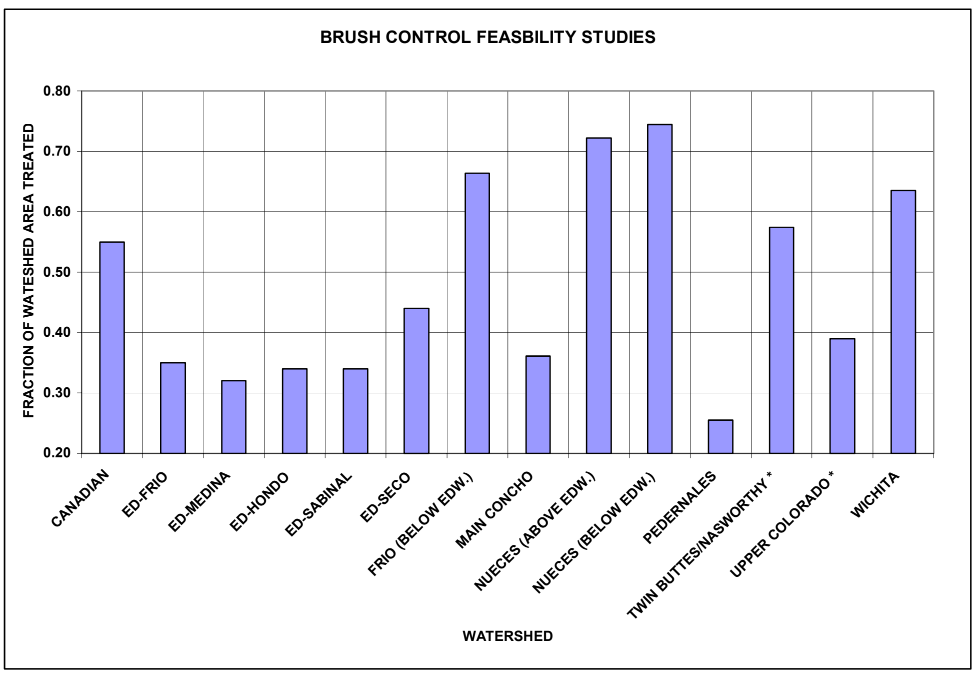


***Figure A-5. Fraction of watershed containing heavy and moderate brush that was treated. For watersheds that lie across the 18 inch isohyet, this is the fraction of the portion of the watershed where brush treatment was planned and simulated.***

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

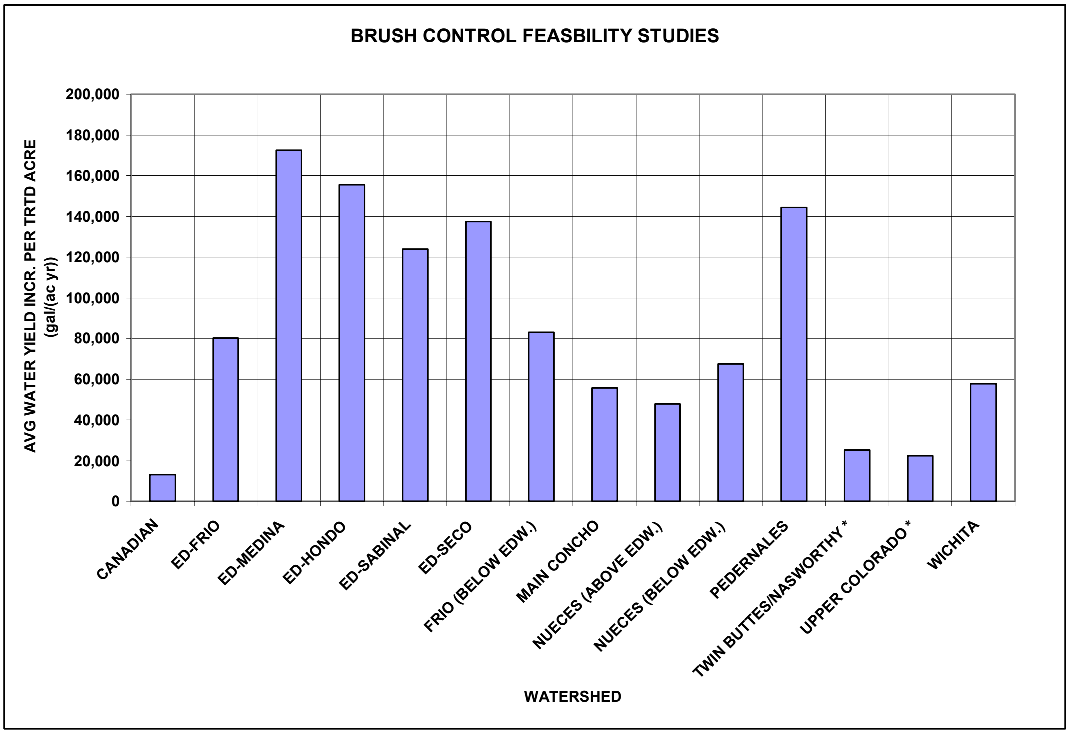


*Figure A-6. Average annual water yield increase, 1960 through 1998.*

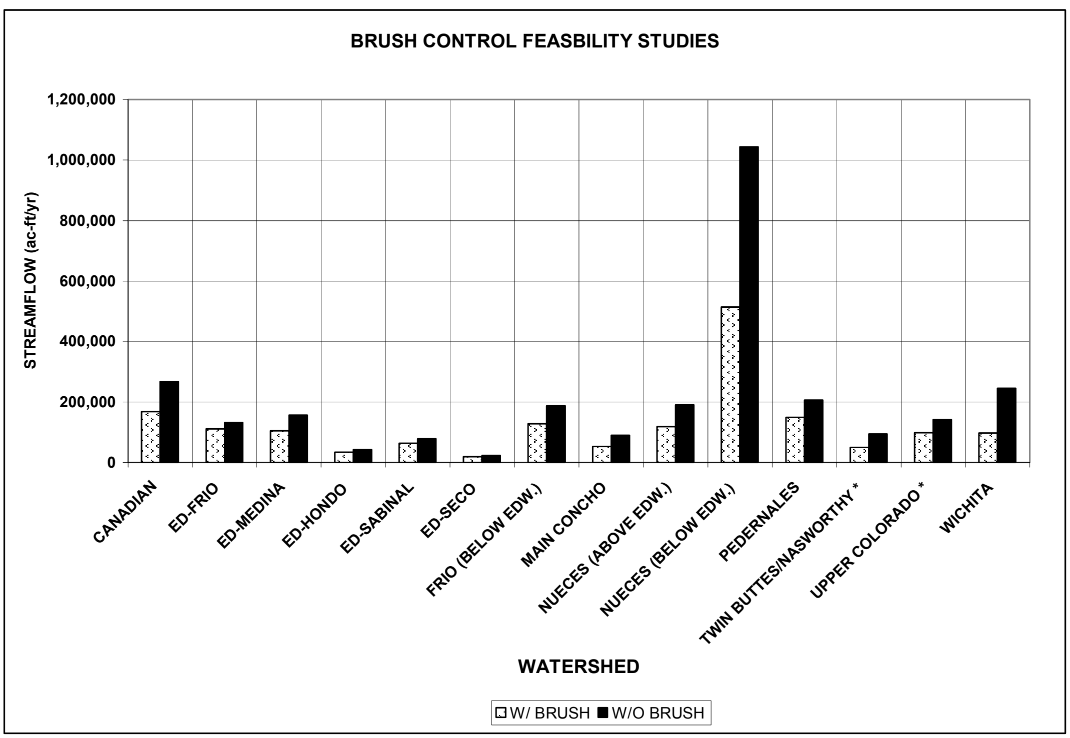


*Figure A-7. Average annual streamflow at watershed outlet, 1960 through 1998.*

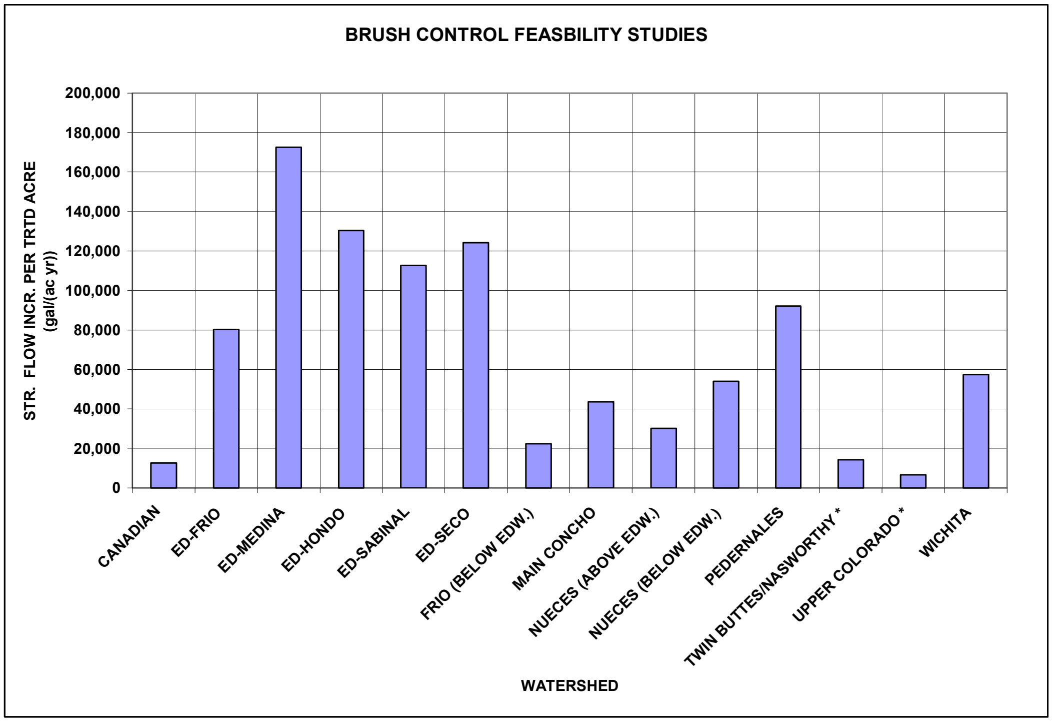


***Figure A-8. Average annual streamflow increase at watershed outlet, 1960 through 1998.***

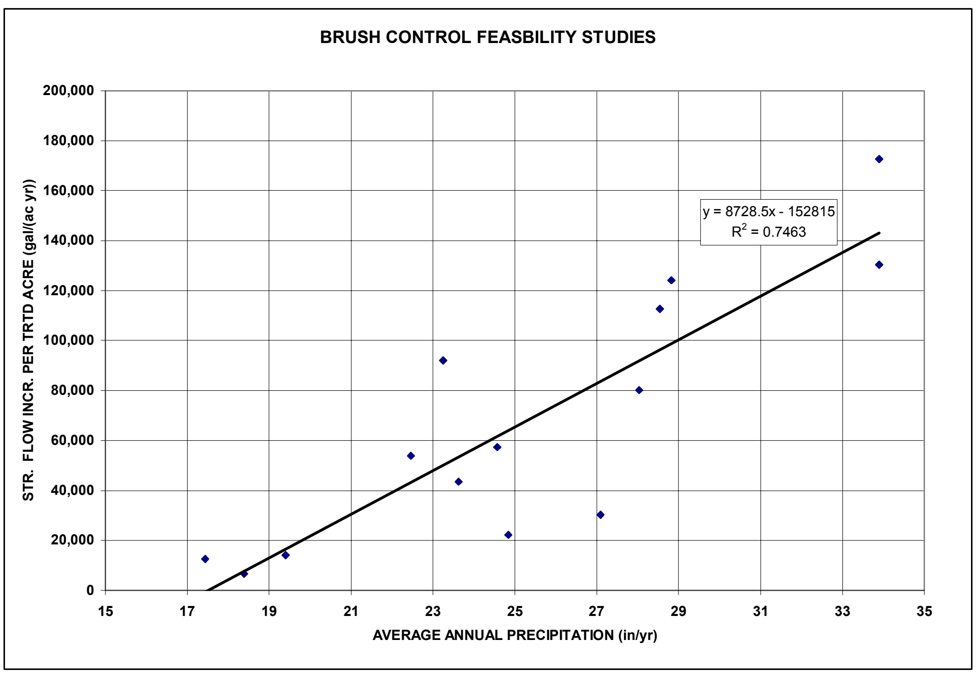


***Figure A-9. Average annual streamflow increase versus average annual precipitation, 1960 through 1998. Each point represents one watershed.***

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.

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# *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).