INFLUENCE OF WOODY PLANTS ON SPRING AND RIPARIAN VEGETATION IN CENTRAL TEXAS

A Dissertation

by

LI SHEN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2007

Major Subject: Rangeland Ecology and Management

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Approved by:
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ABSTRACT

Influence of Woody Plants on Spring and Riparian Vegetation in Central Texas.

(May 2007)

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With the increase in human population, water resources have become more and more precious. A comprehensive study of water yield characteristics is imperative, especially in water-limited semiarid regions. The objective of this study is to examine spring flow and vegetation cover in a first-order watershed and investigate the herbaceous community structure of upland riparian zones. This study consists of two major components: (1) the effects of environmental factors and vegetation cover on spring flow at Pedernales River upland catchments, and (2) the ecological responses of vegetation to altered flow regimes that result from brush management at the upland riparian zones. The study finds that an average of 3.67% of the monthly water budget of first-order catchments in central Texas is made up of spring flow. The influence of woody plant cover on streamflow was evaluated by comparing spring sites with different percentages of woody cover three times during 2003 and 2004. Our findings indicate that changes in woody plant cover had no influence on the amounts of streamflow from these catchments, and the surface catchment area had only a minor influence. This suggests that the real spring catchment area might be different from the surface watershed boundaries that have been delineated by topography. Plant species richness and diversity gradually decreased with increasing lateral distances from the stream bank. Herbaceous richness and diversity declined with increasing Ashe juniper cover in the riparian zone. Ashe juniper canopy cover had a larger effect on the understory composition than the cover of other woody species. Herbaceous diversity and production was greater in areas with sparse tree density than in areas with no trees, but was lowest at high tree densities. The complete removal of Ashe juniper in the riparian zones is not recommended because of the potential loss of grass cover. The recommended management would be to leave a sparse cover of canopy trees to maintain understory plants.

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CHAPTER I

INTRODUCTION

Grasslands represent the most important land type in the world. They are predominated by grasses, forbs, shrubs, and scattered trees (van Auken 2000). The vegetation, in grasslands provides forage production and shelter for wild and domestic animals (Chapin et al. 2002). Most grasslands are found in very dry climates where there are high evapotranspiration rates, variable amounts of precipitation, and shallow soil (van Auken 2000, Wilcox et al. 2003b). Evapotranspiration is the dominant mechanism of water loss because the potential for evapotranspiration is substantially greater than precipitation. Runoff accounts for most of the remaining water loss (Wilcox et al. 2003b), but it generally accounts for less than 10% of the annual water budget (Wilcox 1994, Wilcox and Newman 2005, Wilcox et al. 2005). Surface runoff (overland flow) is usually quickly generated from intense thunderstorms, and often is the only source of streamflow. This occurs only after a substantial recharge by prolonged rains, an indication that subsurface flows are contributing to the streamflow (Gifford 1975, Hibbert 1983, Wilcox et al. 2003b, Wilcox et al. 2005). Therefore, streams are generally characterized as somewhere between ephemeral and intermittent, rarely perennial in a semiarid region (Hibbert 1983). In this region, the hydrological cycle is greatly sensitive to environmental changes because of the limited water resources.

This dissertation follows the style of *Ecology*.

With the increasing human population, water resources have become more and more precious for continued societal use. Therefore, a comprehensive study of water yield characteristics is imperative, especially in the water-limited semiarid regions. Some researchers have shown that land cover changes can be associated with water yield (Walker et al. 1993). Some studies have presented that forests, deciduous hardwood, brush and grass cover all have a decreasing influence on water yield, in that order (Greenwood 1992, Stednick 1996). A 10% removal of the vegetation cover has caused approximately a 40 mm change in the annual water yield for coniferous forests, a 25 mm change for deciduous forests, and a 10 mm change for brush or grass cover (Bosch and Hewlett 1982). The theoretical basis for using vegetation manipulation to increase water yield is founded on the premise that converting vegetation composition from species associated with a high evapotranspiration potential (trees/shrubs) to a species with a lower evapotranspiration potential (grass) will increase the likelihood of water yield (runoff/deep drainage) (Thurow and Hester 1997, Thurow et al. 2000, Wilcox et al. 2003c). In humid landscapes, changes in vegetation cover form woody to herbaceous can also alter the water cycle (Jackson et al. 2000). Some examples present the effects of clearing woody plants, i.e., that there has been a significant increase in runoff or water yield from these study sites (Richardson et al. 1979, Bosch and Hewlett 1982, Troendle 1983, Chang and Watters 1984, Mumeka 1986, Williamson et al. 1987). Contrary to what happened as a result of clearing the vegetation cover, the runoff and water yields decreased in these areas after the vegetation revegetated the humid forests (Swank and Miner 1968, van Lill et al. 1980, Dons 1986, van Wyk 1987). However, relatively few studies have shown that either streamflow or water yield can be increased by clearing the woody vegetation cover (Gifford 1975, Richardson et al. 1979, Carlson et al. 1990, Weltz and Blackburn 1995). There are few observation report (Kelton 1975), modeling studies (Wu et al. 2000), and one chaparral woodland in a Mediterranean climate to support this notion. The link between woody cover and water yield is weak in semiarid environments.

Texas is home to grasslands, and many savannas have converted to woodlands during the past 160 years (Blackburn 1983, Smeins et al. 1997, Knapp and Soule 1998) due to overgrazing and the reduction of naturally occurring fires (Archer 1989, van Auken 2000, Ansley et al. 2001). Ashe Juniper (Juniperus ashei) is a native species and commonly occurs in many steep upland areas with shallow soils over the Edwards Plateau in central Texas (Thurow and Hester 1997, Huxman et al. 2005). However, on naturally open or semi-open landscapes, juniper is truly an invader, and it has recently dramatically increased in abundance and density (Nelle 1997, Smeins et al. 1997). Some people believe that runoff or streamflow can be augmented through aggressive control of juniper in the Edwards Plateau based on the "Rocky Creek Story" (Kelton 1975). Otherwise, the Edwards Plateau is underlain by highly productive karst aquifers, which allows the highly permeable limestone parent material to conduct shallow subsurface flows to support some springs and perennial rivers (Blank et al. 1966, Smith 1993, Maclay 1995, Thurow and Hester 1997, Thurow et al. 2000, Wilcox 2002, Wilcox et al. 2005). The Texas Water Development Board has committed many millions to brush control in Texas in order to increase the quantity of water flowing to the aquifers, springs and streams (TSSWCB 1999, TAES 2004, TSSWCB 2004). However, there have been only a few studies focusing on the relationship between the removal of woody plant cover and spring flows in the upland small catchment. In the Edwards Plateau area, the spring flow is an important indicator for studying and evaluating the relationship between vegetation cover and streamflow (spring flow).

Although brush removal may increase stream flow or water yield, there are some studies which suggest that the density and patterns of woody plants can alter the composition, spatial distribution, and productivity of grasses in semiarid savannahs (Scholes and Archer 1997, Waichler et al. 2001). The species composition under and away from savanna trees is different because of the environmental gradients, which allows the woody canopy to effect the radiant energy regime for the understory, and the root competition to have a greater influence on woody and herbaceous species interactions (Naiman and Decamps 1997, Scholes and Archer 1997). Therefore, when the Ashe juniper was cleared to increase the water yield, the brush removal might have had a significant effect on the vegetation composition or structure of the grasslands. Miller (2000) has found that herbaceous cover and species diversity have declined and bare ground has increased with increasing juniper dominance. There results of various studies have presented that trees have potentially positive effects on grasses, and thereby, herbaceous diversity and production may be greater where there are a few trees than where there are no trees. However, this trend is reversed at high tree densities. Another study about saltcedar (*Tamarisk* spp.) has shown that invading saltcedar has caused the diversity to decline, along with the productivity of the herbaceous understory, and modified the water cycling in the riparian zones (Masters and Sheley 2001).

The riparian zones occupy important landscape positions between upland and aquatic ecosystems and are uniquely productive, physically dynamic, and biologically diverse (Naiman et al. 1993, Dickson et al. 1995, Patten 1998, Masters and Sheley 2001). The understory herbaceous plants are more sensitive to soil moisture in riparian zones where there are steep environmental gradients and abrupt ecotones (Naiman and Decamps 1997, Lamb 2002, Scott et al. 2004). Many studies of riparian plant ecology have been carried out, but they have typically been focused on larger rivers (Wood and Wood 1988, Scholes and Archer 1997, van Coller et al. 2000, Lonard and Judd 2002). There is less information available about the relationship between juniper and herbaceous plants in the riparian zones along the small streams (Wood and Wood 1988). Without a thorough understanding of the changes in community structure and diversity across this ecotone, it is difficult to estimate the benefits of brush management in semiarid landscapes.

RESEARCH QUESTIONS

This study is an exploration of the relationship between the spring flow and the woody plant cover in the first-order watershed in the Edwards Plateau. In addition to vegetation cover, the effects of environmental factors on the water yield will also be examined in small watersheds. Then, the basic data regarding species distribution and abundance will be addresses under different juniper covers and with different amounts of spring flow. Finally, the shift in herbaceous community structures at the upland riparian zones will be investigated. The specific questions to be addressed in this study are:

1. Is the amount of spring related to the environmental factors or the characteristics of the first-order watersheds? The effects of accumulated precipitation, dry/wet seasons, geologic formations, elevation, and the surface area of the small catchment on spring flows will all be evaluated.
2. Is the amount of spring flow influenced by the vegetation cover? The land cover of each catchment will be classified from Landsat imagery into either Ashe juniper cover, other woody plant cover, cropland or grassland. The relationship between the land cover and the spring discharge will be examined.
3. What is the vegetation diversity, and how are these species distributed with respect to the longitudinal and lateral environmental gradients in the riparian zones? The abundance and diversity of data will provide the baseline information necessary for interpreting these results.
4. What changes occur in the riparian zones' plant diversity and herbaceous plant cover under different proportions of woody canopy cover, or with different spring flows? The effects of woody plants cover on herbaceous diversity will be evaluated. The relationship between the amount of spring flow and plant diversity will be investigated.

The introductory sections of this study will present some background information. Then there will be a brief literature review on brush management, water yields, and the ecology of riparian zone plants. This section will be followed by a description of the study area, field sampling methods, and the statistical methodologies used. The core of this study addresses the above questions. Finally, a general discussion is presented.

CHAPTER II
LITERATURE REVIEW

HYDROLOGIC PROCESSES WITH VEGETATION

Increasing water for onsite and offsite uses can be an important objective for management of certain grasslands (Hibbert 1983); therefore, we need to start with understanding the relationship between the hydrologic process and vegetation distribution. The relationship between vegetation and water yield links the atmosphere, hydrology, lithosphere and biosphere together. Within the hydrologic cycle, precipitation driven by gravity reaches the land surface. Some of the precipitation can be intercepted on vegetation or the soil surface; some can infiltrate into the soil or recharge the groundwater and other portion flows over the land surface and ultimately into the streams or rivers. The links between these various components of the water budget can be presented by the following equation (Hornberger et al. 1998):

$$P + R_{si} + R_{gi} - R_{so} - R_{go} - ET - G - \Delta S = 0$$

where: P = precipitation; R_{si} = surface water inflow rate; R_{gi} = groundwater inflow rate; R_{so} = surface water outflow rate; R_{go} = groundwater outflow rate; ET = evapotranspiration; G = groundwater recharge; and ΔS = change in soil water storage. Because the inflows and outflows of groundwater are so small, they will be neglected in this study. The surface water inflows and outflows will be referred to as runoff. Then, we can simplify the equation as follows:

$$P - R - G - \Delta S - ET = 0$$

where: P = precipitation; R = runoff; ET = evapotranspiration; G = groundwater recharge; and ΔS = change in soil water storage. From this equation, we can identify the linkages between different components of the water budget. Then, we can use it to examine the influence of shrub cover on water balance.

In discussing ecohydrological issues in landscapes, the water cycle can be divided into vertical fluxes and horizontal fluxes (Huxman et al. 2005, Wilcox and Newman 2005). The vertical fluxes include precipitation, evapotranspiration, infiltration, and recharge; the horizontal fluxes are related to surface processes of runoff and subsurface runoff. These processes are links between the vegetation distribution and the water cycle; thus, vegetation cover may modify the precipitation and evapotranspiration components of the water budget, runoff, and groundwater recharge, and as a consequence, influence streamflow.

PRECIPITATION

Precipitation is the basic parameter of terrestrial water balance, and it is the major way that water enters a system. The amount, intensity, duration and seasonal distribution of rainfall are all important components of hydrology in a given area. Precipitation would offer a limitation for the vegetation that is already growing and aid in the selection of vegetation species (Patten 1998). However, vegetation cover can interfere in the process of the water cycle. Before reaching the land’s surface, precipitation can be intercepted by vegetation and lost directly into the atmosphere via evaporation. Changing the vegetation distribution or cover can disturb local precipitation patterns. For example, the observation was made by Gat et al. that intensive deforestation has reduced the evaporation and recycling of rainfall in Arizona (Gat et al. 1985). Brooks tried to estimate that if 40% of the forest were cleared for agriculture in the humid tropical Amazon basin, the amount of precipitation would reduce 6% (Brooks 1985). From these pieces of evidence, we can infer that if the vegetation cover was removed to be bare ground, the rainfall would reach the ground without any interception. Then water would infiltrate into the soil or quickly run off into the watershed. The changed hydrologic cycle reduces the amount of water back to the atmosphere onsite attributed to the decreased evapotranspiration from vegetation.

EVAPOTRANSPIRATION

Evapotranspiration is one of the vertical fluxes in the hydrologic cycle, which consists of three separate processes: interception by vegetation, transpiration from plants, and evaporation from the soil (Greenwood 1992, Wilcox et al. 2003b, Huxman et al. 2005).

Interception Loss

Interception loss occurs when precipitation is captured by the vegetation canopy or underlying litter layer and evaporated back into atmosphere, later. During rainfall events, water is held by the vegetation canopy, and later returned to the atmosphere via evaporation without reaching the soil surface. Therefore, the characteristics of vegetation such as branch angle, leaf shape and inclination, leaf area index, canopy density, surface area, the nature and thickness of the bark layer, and evergreen or defoliation will influence the amount of interception. For example, in the Mediterranean climate (annual precipitation around 700-900 mm), pine intercepts a higher percentage of precipitation

(19%) than eucalypt (11%)(Rutter 1963, Smith 1974, Prebble and Stirk 1980, Crockford and Richardson 2000). Juniper captures a higher percentage (46.0%) of precipitation than mesquite (32.0%) and live oak (25.4%) because it, evergreen, had a denser canopy and more surface area onto which precipitation can adhere and then be lost into the atmosphere via evaporation (Eastham et al. 1988, Martinez-Meza and Whitford 1996, Thurow and Hester 1997). In addition to woody species, herbaceous plants can intercept different amounts of precipitation (Clark 1940, Thurow et al. 1987). Tallgrass, such as big bluestem (57.0-84.0%) and bunchgrass, capture higher percentages of precipitation than shortgrass such as sideoat grama (18.0%), as seen in Table 2.1.

From these above studies, we can infer that interception losses can have a significant effect on the water yield. When the vegetation cover is changed, the amount of interception loss is altered. After deforesting, the amount of interception by woody canopies will reduce, and therefore there will be more water to reach the surface ground (Crockford and Richardson 2000). In other words, if the live oak pasture were encroached upon by juniper, there would be more evaporation loss of intercepted water, strongly influencing the amount of water that reaches the soil.

In addition to the vegetation cover, the underlying litter layer also has a high capacity to retain water falling through the tree canopy. From Young's (Young et al. 1984) research, it can be concluded that the litter of juniper captured 43.0% of precipitation, and the litter of live oak captured 20.7% (Table 2.1). The differences between juniper and live oak were attributable to the greater amount of juniper litter build-up (Thurow and Hester 1997). These research results show that the amount of precipitation captured by the litter layer depended upon the species of plants.

TABLE 2.1. Measure of values of interception loss, expressed as a percentage of precipitation, for different species, vegetation cover and litter layers, as gathered from different researches.

Author	Year	Area	Rainfall (mm/yr)	Variables	Interception (%)
Vegetation Species					
Rutter	1963	Berks	723	Pine	32.0
Smith	1974	SE Australia	860	Pine	19.0
				Eucalypt	11.0
Crockford & Richardson	1990	SE Australia (Mediterranean)	679	Pine	18.0
				Eucalypt	11.0
Prebble & Stirk	1980	Australia	719	Eucalypt	11.0
Greenwood et al.	1985	SW Australia (Mediterranean)	770	Eucalypt	16.0-37.0
Young et al.	1984	California, USA	300	Juniper	46.0
Thurow et al.	1987	Texas, USA	609	Live Oak	25.4
Martinez-Meza & Whitford	1996	New Mexico, USA	230	Mesquite	32.0
Lloyd et al.	1988	Amazonas, Brazil.	2402	Mixed Forest	8.9
Clark	1940	Nebraska, USA	—	Big Bluestem	57.0-84.0
				Buffalo grass	17.0-74.0
Thurow et al.	1987	Texas, USA	609	Sideoat grama	18.0
Litter layer					
Young et al.	1984	California, USA	300	Juniper	43.0
Thurow et al.	1987	Texas, USA	609	Live Oak	20.7

Transpiration from plants

Transpiration is the evaporation of water from the plants into the atmosphere, and it is an important component in the hydrologic cycle. In order for water to be taken up by the roots to vaporize and be lost into the atmosphere, solar energy and available water are necessary elements. The water transpired by plants may be drawn from substantially great depths, depending upon the depth and development of plant roots (Hornberger et al. 1998, Wilcox et al. 2003b). For example, woody species can withdraw deeper soil water by a tap root system, but herbaceous species just absorb soil moisture from the uppermost layers of the soil by a shallow root system (Wilcox 2002). In addition, many aridland shrub species have physiological or physical adaptations which allow them to deplete water from much drier soils than can plants such as grasses (Crockford and Richardson 1990, Greenwood 1992, Thurow and Hester 1997). To enhance agriculture, Greenwood et al.(1985) cleared away the woody plants at a more inland and drier (800 mm yr^{-1}) region of the Eucalypt forest. This not only reduced interception but also reduced transpiration to recharge more groundwater (Greenwood 1992). For this study, the amount of recharged groundwater will be increased by reducing interception loss and transpiration.

Other researchers presented the relationship between vegetation cover and evapotranspiration. In the southwestern Australia costal sand plain, total evaporation made up 77% of the annual rainfall. 64% of the evaporation was from the ground flora, the 21% was from the trees. Only 15% was from the shrubs (Farrington et al. 1989). Different types of vegetation cover evapotranspirated various amounts of water back to the atmosphere. Another study cleared the tropical rainforest for 13 months, and the total evaporation decreased to 70% of that of the original mature forest (Greenwood 1992). Changing the vegetation cover can modify the amount of evapotranspiration in the hydrologic process. In Blackland Prairie, where the soil has large water-holding capacities, killing the mesquite brushes reduced evapotranspiration to the extent of about 8 cm per year (Richardson et al. 1979). As has been stated above, a number of studies have shown that evapotranspiration is sensitive to changed vegetation densities and patterns, and further that it influences the water yield in the hydrologic process. This linkage has been better established in forests in mesic climates (Bosch and Hewlett 1982, Stednick 1996, Huxman et al. 2005) than in arid and semiarid landscapes (Crockford and Richardson 2000, Wilcox 2002, Wilcox et al. 2003a). In humid climates (annual precipitation exceeds the annual potential evapotranspiration), woody plants augment both transpiration and interception (Eastham et al. 1988, Greenwood 1992, Crockford and Richardson 2000, Wilcox 2002, Huxman et al. 2005) that leads to lower streamflow and has a significant effect on the water budget. But in arid environments (potential evapotranspiration is many times greater than the precipitation or the ratio of precipitation to potential evapotranspiration is less than 0.65), woody plant cover has a comparatively small effect on the water budget (Blackburn 1983, Hibbert 1983, Wilcox 2002, Huxman et al. 2005). In arid western Australia, a recent study found that the proportion of interception loss by vegetation is similar to that of many humid forests (Dunkerley and Booth 1999). However, the total amount of evapotranspiration and interception loss from dryland plant communities is fewer than from forests because there is a rare plant canopy cover and a lower frequency of rain events (Dunkerley 2000). Most of the water in the dryland landscapes is evaporated regardless of the vegetation cover; therefore, woody plants have a fairly weak effect on the water budget (Crockford and Richardson 2000, Huxman et al. 2005).

Between humid and arid environments, semiarid landscapes represent a transitional zone where woody plant cover can have a significant effect on the water yield. In semiarid environments, some researchers have presented data showing that evapotranspiration and interception losses from vegetation cover are generally between 20-40% of precipitation (Navar and Bryan 1990, Wilcox et al. 2003b). The actual amounts depend upon the character of the vegetation and precipitation. For example, evergreen shrubs can capture more precipitation than defoliation and evapotranspirate the moisture back into the atmosphere. In semiarid landscapes, the total amount of evapotranspiration and interception may be the same as or higher in grasslands than in shrublands because herbaceous vegetation covers more extensively and densely in this environment. Carlson's (1990) study showed that removing all vegetation from the surface could reduce the evapotranspiration loss, but there was no difference between the net evapotranspiration loss of the mesquite and herbaceous sites. Weltz and Blackburn (1995) found similar results in that annual evapotranspiration rates of shrub clusters and grass interspaces were similar, and both were significantly greater than evapotranspiration losses from bare soil. These results imply that water percolated slowly through the clay soil and that water was lost via evapotranspiration before it could percolate below the root zone. There was essentially no net change in evapotranspiration and deep drainage on grasslands where the herbaceous component increased in response to shrub removal in the semiarid areas of Texas. There should be less soil water below the evaporative zone for semiarid or arid systems than for subhumid and humid systems, and hence woody plants produce less transpiration in semiarid or arid systems than in subhumid and humid systems (Huxman et al. 2005). That is why some study results reach different conclusions in Texas and subtropical Australia.

Except the characteristics of vegetation, the total number, seasonal distribution, size, duration, and intensity of storms also influence the proportion of interception loss (Gifford 1975). Streamflow does not come from either redberry or Ashe juniper until the precipitation exceeds 3 mm. Most of the small rainfall events (<5 mm) do not reach the litter layer because of water retention by the foliage (Thurow and Hester 1997, Wilcox et al. 2003b, Wilcox et al. 2003c). A large storm can exceed canopy storage capacity and increase the amount of water to the ground; therefore, the lower proportion of precipitation is intercepted by vegetation during a large storm and a long duration of rainfall.

The value of the evapotranspiration can be modified by changing the vegetation pattern on the surface ground. Dugas and Mayeux (1991) removed mesquite from the ground surface to reduce 40% of the interception loss over and above a non-cut site. Mesquite removal would provide little if any additional water for off-site uses in the short-term, but the effect of brush control can be reduced by covering herbaceous vegetation in semiarid landscapes. After herbaceous plants regrow, the difference made by evapotranspiration and interception between the treated site and the control site was decreased. Removal of brush did not result in decreased evapotranspiration loss due to the increase in herbaceous vegetation (Greenwood 1992).

Evaporation from the soil

Evaporation can only occur when water is available and the humidity of the atmosphere is less than that of the evaporating surface. When the soil dries and its water content decreases, the evaporation rate also progressively decreases. Soil evaporation resistance depends upon soil water potential in the topsoil layer (15 cm). The vegetation cover influences the amount of evaporation from the soil surface. The more vegetation that covers the landscapes, the lower the evaporation is from the soil. In arid and some semiarid areas where much of the soil is bare, the percentage of evaporation may be from 30% to 80% of the water budget (Wilcox et al. 2003b). In the field studies of juniper grasslands, Dugas et al.(1998), Thurow and Hester (1997) found that eradication of juniper leads to an increase in soil moisture. However, we need to consider that eradication of juniper might increase the bare soil as well as increase the amount of evaporation from the soil surface.

INFILTRATION

A portion of the water that infiltrates and percolates downward through the soil profile causes saturation in the soil. The water moves laterally toward a stream channel as a subsurface flow. The partially infiltrated water does not become a subsurface flow. It percolates downward to reach the water table and becomes groundwater. The infiltration rate is dependent upon a variety of vegetation and geographical factors, including the type and amount of vegetation (Williams et al. 1969, 1972, Thurow and Hester 1997). Infiltration rates are often observed to be highest under trees and shrubs, followed in decreasing order by bunchgrass and shortgrass sites, which can be attributed to soil properties under plants such as a lower density, a greater soil aggregate stability, and a greater density of macropores (Blackburn 1983, Carlson et al. 1990, Bergkamp 1998, Wilcox et al. 2003c), and the vegetation canopy cover breaks the erosive force of raindrops (Hester et al. 1997).

RUNOFF

Runoff causes the major horizontal fluxes in the water cycle. There are three paths in the runoff processes: (1) overland flow, (2) subsurface flow and (3) groundwater flow. Overland flow is water that flows across the ground's surface into small rivulets and then into large streams and rivers. Overland flow can occur when the catchment surface is impermeable and the precipitation intensity exceeds the soil infiltration capacity (Wilcox 2002, Wilcox et al. 2003a, Belnap et al. 2005). Overland flow that occurs when the rainfall rate exceeds the ability of the soil to allow water to infiltrate is called infiltration-excess overland flow (Horton overland flow). It is the dominant mechanism of streamflow generation for many grasslands, particularly semiarid ones, and is a major pathway in the transfer of soil, microbes, and plant litter over long distances, connecting otherwise isolated systems.

The water in the soil layer moves laterally toward a stream channel as a subsurface flow. Where a shallow subsurface flow is rapid, plant evapotranspiration rates do not influence runoff amounts, but interception of the water by the plant canopy could (Young et al. 1984, Thurow and Hester 1997). The partially infiltrated water does not become a subsurface flow, and instead percolates downward to reach the water table to become groundwater. Groundwater flow is the slowest of all flow paths that water can take through a catchment. Base flow tends to vary quite slowly over long time periods in response to changing inputs of water through the net recharge system. The groundwater discharge to a stream channel may lag behind the occurrence of precipitation by days, weeks, or even years (Hornberger et al. 1998). If most of the water in a river or stream is generated from groundwater flow, evapotranspiration by vegetation has a potential effect on the streamflow (Wilcox 2002). The presence of spring flow (base flow) is an important indicator of the potential for increasing streamflow by manipulating shrub cover.

Woody vegetation may alter both overland flow and subsurface stream flow generation with a relative abundance of vegetation determining the extent of the alteration (Wu et al. 2000). Woody plants alter overland flow primarily by their influence on soil infiltration, which they can either increase or decrease (Wright et al. 1976, Wilcox 2002). They potentially alter subsurface flow either by intercepting precipitation when subsurface water is available and thus preventing water from reaching the soil, by increasing infiltration via steam flow and preferential root channels, or by transpiring water that would otherwise recharge groundwater and streams (Huxman et al. 2005). Infiltration-excess overland flow is not a significant part of the runoff process in forests, because vegetation cover protects the surface from compaction and the roots of vegetation keep the soil permeable (Burch et al. 1987). But in arid and semiarid regions, infiltration-excess overland flow can be a dominant runoff mechanism in catchments that have sparse vegetative cover (Hornberger et al. 1998).

In humid landscapes, changes in vegetation cover from woody to herbaceous can alter the water cycle (Jackson et al. 2000). When the forests (pine, eucalyptus, and mixed conifer) were removed from areas where the annual average rainfall was over 1000 mm (Chapin et al. 2002), the runoff and the water yield dramatically increased from the study sites, as can be seen in Table 2.2. Forest reduction increased the water yield and reforestation decreased it (Richardson et al. 1979, Chang and Watters 1984). In Australia, Williamson et al. (1987) presented the effects of vegetation clearing on runoff in paired catchments. The storm runoff and the full year runoff from the cleared catchments marked the times of the control catchment. Mumeka (1986) observed the effects of deforestation where the land was cleared for grazing. There was a significant increase in runoff on these agricultural catchments. This indicated that agricultural treatment generates more runoff in humid areas.

Rich and Gottfried (1976) observed from Workman Creek in Arizona that increases in water yield have been achieved by converting vegetation from deep-rooted old growth conifers to shallow-rooted grasses, forbs, brush, or pine seedlings. The increased water yield was significant only after removing significant numbers of trees or clearing areas of significant size. The removal of a small quantity of riparian trees on North Fork did not increase the water yield. In contrast, heavy removals on North Fork and clear-cutting on South Fork significantly increased water yields. The results of Rich’s study indicate that removal of forest vegetation in significant areas and amounts will substantially

TABLE 2.2. The relationship between vegetation cover and water yields.

Author	Year	Area	Rainfall (mm/yr)	Species	Runoff	Water Yield/ Streamflow
Deforestation						
Rothacher	1970	W Oregon, USA	2300	Mixed forest		Increased
Rich & Gottfried	1976	Arizona	830-1550	Mixed conifer		Increased
Troendle	1983	Rocky Mt., USA	6480	Pine		Increased
Williamson et al.	1987	SW Australia	800-1200	Eucalypts		Increased
Mumeka	1986	Zambiz	1400	Tropics forest	Increased	
Gilmour et al.	1987	Nepal	2008	Mixed forest	Increased	
Baker	1984	Arizona, USA	463	Juniper	Increased	
Gifford	1975	S Utah, USA	200-290	Juniper	No increase	
Wright et al.	1976	Texas, USA	660-710	Juniper	No increase	
Dugas et al.	1998	Texas, USA	700	Juniper	No increase	
Richardson et al.	1979	Texas, USA	550	Oak, Juniper, Mesquite	No increase	
Carlson et al.	1990	Texas, USA	650	Mesquite	No increase	No increase
Weltz & Blackburn	1995	Texas, USA	700	Mesquite		No increase
Brown	1965	Utah, USA	483	Juniper		No increase
Collings & Myrick	1966	Arizona, USA	518	Juniper	No increase	
				Pinyon	No increase	
Wilcox et al.	2005	Texas, USA	800	Juniper		No increase
Thurow & Hester	1997	Texas, USA	570	Juniper	No increase	Increased
Baker	1984	Arizona, USA	460	Juniper		Increased
Kelton	1975	Texas, USA	770	Mesquite		Increased
Revegetation						
Swank & Miner	1968	Carolina, USA	1900	Pine	Decreased	
Dons 1986	1986	N New Zealand		Pine	Decreased	
van Wyk	1987	S Africa	1300-2300	Pine		Decreased
van Lill et al.	1980	S Africa	1200	Eucalyptus	Decreased	

increase water yields. Bosch and Hewlett (1982) observed that water yields increase when the vegetation is cleared. The increased water yield depended upon the percentage change in vegetation cover. The responses of water yields were different between the classes of vegetation. Pine and eucalypt types caused an average change of 40 mm per year^{-1} in the water yield per a 10% change in cover, but the deciduous hardwood was only 10-25 mm per year^{-1}. Bosch and Hewlett's study showed that the characteristics of vegetation would influence the effects of brush removal on water yields.

In the Oregon Cascades Mountains, Rothacher (1970) also found that an increase in water yield following a timber harvest roughly conforms to the proportion of the area cleared. Troendle (1983) observed that the water yield could be increased significantly following a timber harvest in the Rocky Mountain region. Because reduced evapotranspiration also reduced soil moisture depletion and left the site more fully charged, any significant precipitation input into the system generated a detectable treatment effect. In Nepal, it has been claimed that local deforestation increased runoff and the highly populated areas downstream were flooded (Gilmour et al. 1987). The increased flooding was due to the decreased infiltration. The deforestation decreased hydraulic conductivity as well as the amount of the infiltration in the areas upstream. These studies demonstrated that changes in vegetation cover can increase water yields through modifying the evapotranspiration and infiltration. They potentially alter subsurface flow either by intercepting precipitation when subsurface water is available and thus preventing water from reaching the soil, by increasing infiltration via steam flow and preferential root channels, or by transpiring water that would otherwise recharge groundwater and streams.

Contrary to clearing the vegetation cover, the runoff and water yields decreased in these areas after the vegetation revegetated in the humid forests (Table 2.2). Swank and Miner (1968) observed that converting a forest from hardwood to white pine reduced water yields in humid subtropical forests in North Carolina. Stream flow steadily declined, and it was 100 mm per year less than from the original hardwood forest. The loss of water yield was caused by the greater interception of the white pine. In New Zealand, Dons (1986) presented the notion that a long-term decline in the flow was due to afforestation of a poor pasture. Between 1964 and 1981 the annual flows were reduced 10.9 $m^3 s^{-1}$, which was attributed to the pines' revegetation. In South Africa, van Wyk (1987) assessed the influence of afforestation on stream flow. Afforestation reduced stream flow, but the afforested region needed to be over 7%. Stream flow decreased 350 mm per year over a period of between 12 and 32 years after afforestation. van Lill et al. (1980) also observed the effects of afforestation on flow in South Africa. After 12 years, eucalyptus planted in the catchment reduced the flow between 300 and 380 mm per year. Maximum reductions in seasonal flows were 200-260 mm per year in summer and 100-130 mm per year in winter.

In semiarid or arid areas where the annual rainfall is below 1000 mm (Chapin et al. 2002), there have been several studies presenting similar results. Kelton (1975) reported one spectacular example in west Texas. The mesquite and other brush that originally had been confined to a few scattered locations, mostly close to the creek, began moving out across the open prairies and up the sides of hills. The Rocky Creek then dried up in the early 1930's. Several ranchmen along Rocky Creek began brush control programs during the 1950's. Eventually the creek bubbled forth enough water that Rocky Creek flowed all the way down to its junction with the Middle Concho after extensive brush removal along its 74,000-acre watershed. The control of brush at least helped bring back creeks and rivers in dry West Texas. In Sonora, Texas, Thurow and Hester (1997) cut down the woody plants and monitored the runoff from each of the treated and untreated watersheds. The results indicated that substantial water yields could be achieved through conversion of grassland vegetation from brush to grass dominance. There was no significantly increased runoff from these treated pastures, but there was an increase in water to infiltrate into the soil. In semiarid Arizona, Baker (1984) also found that an increasing water yield was achieved by killing the overstory trees and leaving them on the sites. Most water yield increases resulting from the herbicide treatment added to the normal spring stream flow. Much of the spring stream flow from these headwater basins is the product of direct flow that consists of overland flow and a substantial interflow. This increase can be expected when precipitation equals or exceeds the winter average. The dispersed upland pinyon-juniper basins could be chemically treated to provide some additional water yield.

However, the linkage between woody cover and water yield is tenuous in semiarid environments. Some studies had tentatively shown that clearing the bushes (juniper and mesquite) resulted in no increase in runoff or water yield (Brown 1965, Collings and Myrick 1966), as can be seen in Table 2-2. Richardson et al. (1979) killed mixed woody plants – live oak, vasey shin oak, ashe juniper, redberry juniper, and honey mesquite – by root plowing in the Edwards Plateau in Texas. After-brush control in this area did not cause a significantly increasing runoff. Gifford (1975) measured runoff between natural woodlands and chained juniper sites in Utah. There was no runoff at all in these sites during two drought years, except during one year. During 1970-71, small amounts of runoff occurred at all study sites, but there was no significant difference between the natural woodlands and the treated sites. Then, Weltz and Blackburn (1995) compared the water yields between the shrub-dominated grasslands and the grass-dominated grasslands in south Texas. Surface runoff and deep drainage of water from the bare soil were both significantly greater than from the grass interspaces and shrub clusters. Yet no net change in the water budget would occur if shrub clusters were replaced with deep-rooted perennial grasses. In Texas, Carlson et al. (1990) also observed that there was no net change in runoff or deep drainage on grasslands where the herbaceous component increased in response to shrub removal. This had no benefit in terms of off-site water yields.

For five years, Dugas et al. (1998) also measured the effects of removing junipers for runoff in Texas. The results showed no significant increase in runoff after removing the junipers because runoff only comprised a small portion (5%) of precipitation in the study sites during those five years. The water yields would not increase by eliminating junipers due to the high evapotranspiration from the herbaceous vegetation that would replace them. These studies presented that the vegetation that would appear after removing the brush would influence the water yield by evapotranspiration, interception and depleting the soil water, resulting in no significant increase in water yields. Wilcox et al. (2005) monitored the streamflow from nine small watersheds over 13 years. They removed shrubs from three of the watersheds and evaluated the influence of woody plant cover on the streamflow by comparing the different stream flows. They observed that changes in woody plant cover had little influence on the streamflow. In addition, Wright et al. (1976) removed the junipers in central Texas by prescribed burning between different slopes. There was no significant difference between the burned sites and the control sites in the moderate slopes.

Although the increased overland flow appeared on the steep slopes, soil erosion and low water quality were problems after burning. As a management alternative, steep slopes might be left alone to preserve the watershed values of the range, but not for water yields.

Results from field studies provide the evidence that changes in vegetation from woody to herbaceous cover can alter the water cycle to increase water yields in humid areas. But in dryland ecosystems, the correlation between woody cover and water yields is weaker (Wilcox 2002). In many semiarid areas, the hydrologic connection between surface and subsurface is quite small, so the changes in woody cover have no significant effect on streamflow or water yields (Wilcox 2002, Wilcox and Newman 2005, Wilcox et al. 2005).

SOIL WATER STORAGE

Soil water storage depends upon the weather pattern and the storage capacity of the soil, and therefore reduced evapotranspiration and soil moisture depletion can leave the soil more fully charged (Troendle 1983). Sharma et al. (1987) presented a study in southwestern Australia (a Mediterranean climate), in which the land was cleared for annual pasture. Within 2 years of the change from forest to pasture, a significant increase in soil water storage occurred in the profiles of the catchments. The results of this study showed that the increases that followed the clearing were greater after a higher rainfall than after a lower rainfall. The increases were greater in the first year after clearing than in the second year. The increased soil water storage was due to the shallow-rooted pasture that extracts water from the top 1 m of soil. However, the original evergreen forest can extract water from depths down to 6 m and beyond. This study showed that reduced soil moisture depletion could leave the soil with more water.

In humid east Texas, USA, Chang et al. (Chang et al. 1983, Chang and Watters 1984) removed the vegetation from the surface of the land by different methods. No matter which method they used, the soil moisture was higher in the cleared cites than in the undisturbed forest with full crown closure. When the rainfall intensity was less than the infiltration rate, much of the rain entered the soil. The risk in this clear-cut procedure is that the bare soil is highly erodible, due to surface runoff.

In northeastern Australia, Eastham and Rose (1988) studied soil water content under different tree densities. Their study showed that soil water was highest under a medium density treatment. The tree canopy produced sufficient shade to reduce the high evaporation that caused low soil water content at low tree densities. However, the highest tree density cover intercepted more rainfall before the water reached the ground, and it also extracted a lot of water from the soil by evapotranspiration.

GROUNDWATER RECHARGE

Groundwater recharge is the downward movement of water across the bottom of the root zone. The groundwater tables or aquifers are recharged from the infiltration of soil water and deep drainage. In humid to mesic environments, deep drainage and groundwater recharge are generally considered equivalent, but this may not be true in arid and semiarid regions, where vadose zones are commonly thick, and thus lag times between deep drainage and groundwater recharge can be long (Seyeried et al. 2005). Where soils have a high storage capacity, the probability of deep drainage greatly decreases (Wilcox et al. 2003b). Where soils are shallow and bedrock is fractured, storage is greatly reduced and the probability of deep drainage is greatly increased. In sloping terrains, deep drainage in fractured rock may not result in direct groundwater recharge but rather in lateral subsurface flow (Seyeried et al. 2005). The replacement vegetation redistributes the root growth and water uptake by these plants. This modifies the vertical flux of deep drainage and recharge, resulting in a general rise in the water table and water logging (Walker et al. 1993).

Peck and Williamson (1987) fully and partially cleared the vegetation from the catchments in their Mediterranean climate. In areas fully cleared for agriculture, the water table moved up by more than 2.6 m. Under partial clearing, the water table rose less rapidly (0.9 m). The deforestation resulted in greatly increased throughfall, surface and subsurface runoff, recharges to the water table, and discharges into streams. In Texas, USA, Thurow and Hester (1997) removed woody plants from the grasslands. The results showed that the eradiation of woody plants (juniper and oak) led to an increase in groundwater recharge to the extent of 3.7 inches of deep drainage per year.

New research suggests that for many arid and semiarid landscapes, downward water fluxes below the root zone are small or even nil and may have been so for thousands of years (Stephenson and Zuzel 1981, Seyeried et al. 2005). Because of the high evaporative demand in these regions, most water stored in the soil will eventually be evaporated or transpired. But in some situations, a high level of deep drainage and groundwater recharge may occur in very dry environments when the permeability of the soil is relatively high, such as in the presence of fractures or very sandy soils (Wilcox et al. 2003b).

In semiarid ecosystems, the water yields respond to many environmental factors by brush control, including the amounts and pattern of precipitation, annual temperature, geology, characteristics of the soil, percent and pattern of vegetation cover, and replacing vegetation types in the watershed area (Blackburn 1983, Chang and Watters 1984, Stednick 1996). Evapotranspiration is the largest component of the water balance equation; the other components are generally quite small, but can be extremely important. Potential evapotranspiration is significantly greater than precipitation in relatively dry climates. In a semiarid environment, most of the incoming precipitation returns to the atmosphere via evapotranspiration. Runoff will account for most of the remaining. Hence, the amount of water moving to groundwater is generally relatively small. For example, a study of climate and evapotranspiration of vegetation types showed that trees and shrubs in the Colorado River Basin receive an annual level of precipitation of over 460 mm and have a potential evapotranspiration rate of over 380 mm (Hibbert 1983).

Therefore, increases in surface runoff and deep drainage of water can both be expected by converting brush to grass at higher precipitation zones of shrubland watersheds (Weltz and Blackburn 1995). However, when shrubs are replaced by grasses and forbs in semiarid grasslands, the herbaceous vegetation depletes the available soil moisture equally well, in which case little or no water yield increases can be expected (Dugas et al. 1998). Increasing water yields from converting shrub-dominated grasslands to grass-dominated grasslands is marginal and limited to those years when the rainfall exceeds the potential evapotranspiration (Weltz and Blackburn 1995).

Sites with less permeable soils and with soils having a larger water-holding capacity make herbaceous plants grow rapidly and vigorously in order to maintain a high level of evapotranspiration after removing the shrubs (Dugas et al. 1998). This increased surface storage capacity allows more time for water infiltration to lead to lower runoff (Wilcox 1994).

Within semiarid areas, vegetation cover and related microtopography have an effect on runoff at fine spatial scales (Bergkamp 1998). For example, on juniper grasslands at a very small scale (1 m^2), runoff accounts for up to 100% of the precipitation from a particular storm, but at the hillslope scale, runoff from the same storm will make up only about 5% of the water budget (Wilcox et al. 2003b). Runoff also has a higher frequency at a fine scale and a lower frequency at broader scales. These phenomena are consequent on the fact that the larger areas increase and provide more opportunities and time for water to infiltrate. Within the procedure of infiltration, soil moisture content and attributes are the major determinants of the amount of runoff (Wilcox 1994).

Water yield includes surface flow, subsurface flow, and groundwater flow. If conversion of shrubs and woody plants to grasses decreases water loss through interception and evapotranspiration, more water would be represented as surface runoff or percolate through the soil to feed streams and ground water. The opportunity to reduce evapotranspiration effectively is limited to certain types of vegetation, climate, and geological conditions. There are four major criteria to be met.

1. Annual precipitation should exceed 450 mm. Maximum efficiency occurs when precipitation is concentrated in the cool season (Bosch and Hewlett 1982, Blackburn 1983, Hibbert 1983, Wilcox 2002).
2. Vegetation must be replaced with a type that depletes less water, such as low biomass species, shallow-rooted species, or deciduous species (Davis and Pase 1977, Hibbert 1983).
3. Significant amounts of vegetation must be removed or significant sizes of area must be cleared (Rich and Gottfried 1976).
4. The groundwater table is within a few meters of the surface, such as is the case with riparian surfaces. If there is no shallow groundwater, there must be deep soil recharge (Wilcox et al. 2006).

From the above review, it can be seen that many researchers have presented that changed vegetation cover does have an effect on increasing or decreasing the water yield, but less evidence can be found for the linkage between woody plant cover and water yields in semiarid environments. Therefore, exploring the linkage between woody plant cover and water yields or spring flow in semiarid Texas is important for relaxing the pressure of water demands in the future.

WOODY AND HERBACEOUS VEGETATION IN A RIPARIAN ZONE

DEFINITION OF A RIPARIAN ZONE

Riparian areas are commonly thought of as narrow strips of land surrounding water bodies such as streams, rivers, pond, lakes, and estuaries (Bren 1993). The spatial extent of riparian areas may be difficult to precisely delineate, but we realize that riparian areas are transitional interfaces between aquatic and terrestrial ecosystems (Dickson et al. 1995, Naiman and Decamps 1997). They encompass those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems. In other words, riparian zones include stream channels between low and high water marks and the portion of the terrestrial ecosystem from the high water mark toward the uplands where surface and subsurface hydrology connect water bodies with their adjacent uplands (Figure 2.1).

Riparian areas include interactions in all three spatial dimensions that include the horizontal distance from the stream channel to the adjacent terrestrial zones (laterally) that stretch along the water course at a variable width (longitudinally), and that extend down into the groundwater and up above the canopy (vertically)(van Coller et al. 2000, Lamb). An important feature of this definition is that riparian areas have gradients in biophysical conditions, ecological processes, and biota as they represent changes with different environmental variables such as geology, flooding, and groundwater levels. Therefore, riparian areas most often form a conspicuous, narrow ribbon that is characterized by distinctive vegetation, soil, and flooding regimes (Naiman and

Decamps 1997). They occupy important landscape positions between upland and aquatic ecosystems and are uniquely productive, physically dynamic, and biologically diverse (Naiman et al. 1993, Patten 1998, Masters and Sheley 2001). Riparian zones provide aesthetic and landscape values, filter sediments and chemicals from water, and potentially benefit a variety of native plants and wildlife (Dickson et al. 1995).

Although hydrology is not inevitably related to all definitions of riparian areas, these statements strongly imply that riparian areas are wetter than adjacent uplands through both above and below-ground interactions. With the exception of hydrology regimes, vegetation and soil characteristics of riparian areas are frequently noted as differing from adjacent uplands in studies and are noted as being adapted to fluctuating ground water levels, dynamic fluvial processes, and relatively high levels of soil moisture (Naiman and Decamps 1997).

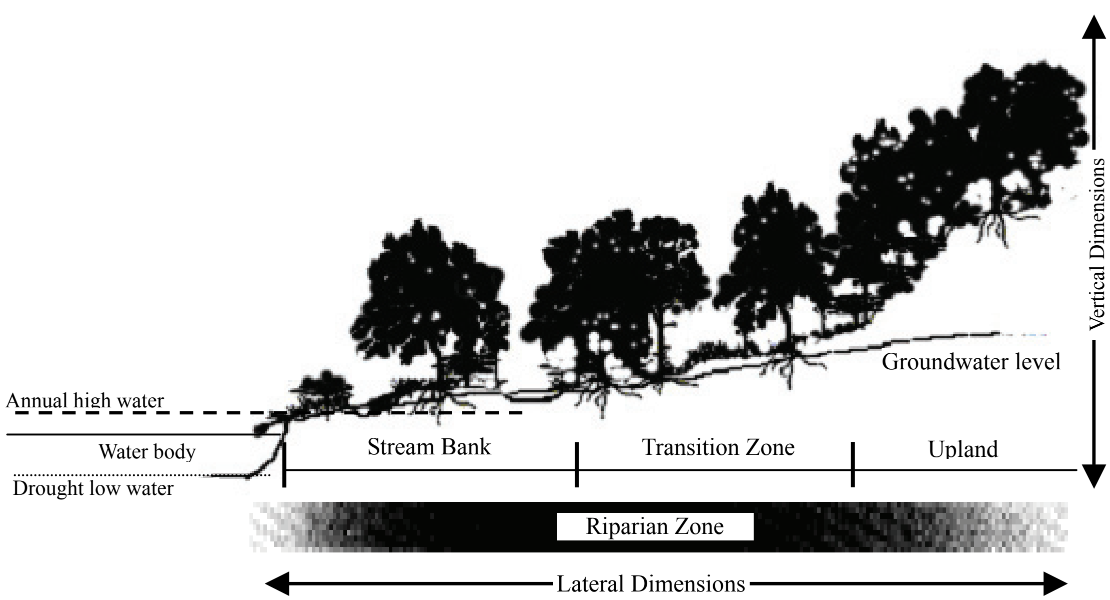

FIG. 2.1. Riparian zones form a narrow interface between aquatic and terrestrial ecosystems and have different dimensional ecotones of interaction.

RIPARIAN VEGETATION PATTERNS

Riparian vegetation patterns are dominated by two major gradients (van Coller et al. 2000). The longitudinal gradient stretches along the watercourse, and the lateral gradient is perpendicular to the stream channel from the banks into the uplands. The longitudinal gradient is characterized by factors such as a variation in current velocity and geomorphology along the length of a stream. Variations in current velocity can cut down or move different amounts of sediment and nutrients, which has a fairly large effect on the distribution patterns of riparian vegetation (Dickson et al. 1995, Naiman and Decamps 1997, Lamb 2002). In addition, the geomorphic template is constantly undergoing changes induced by the discharge regime (Naiman and Decamps 1997). These patterns have received little study (Lamb 2002).

Spatial zonation often exists as a transverse gradient perpendicular to the stream channel. This lateral gradient is primarily related to local variations in topography and soil moisture availability (e.g., depth to the alluvial water table) that influence vegetation distribution. Riparian zone vegetation often includes obligate wetland species such as rush and sedge; thus, the stream-to-upland gradient may be on a continuum from hydric to mesic to xeric species (Kovalchik and Chitwood 1990, Naiman et al. 1993). The steepness of this gradient from emergent aquatic plants to woody trees to scrub/grass vegetation is controlled by valley geomorphology; it may be truncated by a narrow valley or extended across broad alluvial basins (Patten 1998). These plants emerge from shallow water and extend for a short distance onto the shore, typically composed of annual or perennial grasses and herbaceous plants. Among the herbaceous plants, seedlings and small individuals of shrub or tree species can be found (Naiman and Decamps 1997). However, herbaceous species are often more closely associated with a particular level of soil moisture and may act as more sensitive indicators of soil moisture or water table conditions than woody or shrub species (Wood and Wood 1988, Castelli et al. 2000).

Riparian zone ecology research is mostly based on medium to large streams or rivers. There are few studies for riparian zones in very small streams (Lamb 2002). Riparian zones are underrepresented in the numerous headwater streams that are almost completely embedded in the forest. Small streams tend to be missing channel features such as the floodplain bottoms and channel shelves that are common for larger streams or rivers (Hupp and Osterkamp 1985). The lack of certain channel features results in a simpler vegetation structure.

WOODY AND HERBACEOUS PLANT INTERACTION

In semiarid savannahs, there are some studies that found that the density and patterns of woody plants can alter the composition, spatial distribution, and productivity of grasses in savannas (Scholes and Archer 1997, Waichler et al. 2001). These studies presented the notion that saltcedar (*Tamarisk* spp.), after invading into the wetlands and riparian areas in the western United States, led to a decline in the diversity and productivity of the herbaceous understory and modified the water cycling (Masters and Sheley 2001). Another study of western juniper found that herbaceous cover and species diversity declined and bare ground increased with increasing juniper dominance in the mountain big sagebrush/Thurber needlegrass association (Miller et al. 2000).

The species composition under and away from savanna trees is different because of environmental gradients where the woody canopy has an effect on the radiant energy regime for the understory, or the root competition has a greater influence on woody and herbaceous species interaction (Naiman and Decamps 1997, Scholes and Archer 1997). Because of the potentially positive effects of trees on grasses, herbaceous diversity and production may be greater where there are a few trees than where there are no trees, but the trend is reversed at areas with high tree densities.

Riparian zones have long interested plant ecologists because of their high biodiversity, steep environmental gradients, and abrupt ecotones (Naiman and Decamps 1997, Lamb 2002). Many studies of riparian plant ecology have been carried out, but they have typically been focused on larger rivers (Wood and Wood 1988, Scholes and Archer 1997, van Coller et al. 2000, Lonard and Judd 2002). In addition, there are studies focused on the relation between encroached woody plants and the understory herbaceous plants in semiarid landscapes. Even so, the lack of information on composition and structure of small stream riparian communities is especially important in central Texas because of the juniper removal occurring for the purpose of adjusting water yields.

CHAPTER III
METHOD

STUDY AREA

For many semiarid areas the hydrologic connection between surface and subsurface or groundwater recharge is small, and vegetation changes are unlikely in any apparent way to influence the streamflow (Wilcox 2002, Wilcox and Newman 2005). The stream flow in response to vegetation changes will be more obvious in smaller headwater streams, because small changes in water yield can more easily be detected in low-order watersheds than in downstream channels. Therefore, this study tries to demonstrate the responses of increased base flow to the removal brush, and the response of riparian vegetation to brush control must be conducted in first-order watersheds within the headwaters of drainage basins.

Studies have shown that brush management on the Edwards Plateau area has significantly increased water yields (Thurow and Hester 1997, Wu et al. 2001). In the Edwards Plateau, shallow subsurface flow occurs because the soils are shallow with a low water-holding capacity (Dugas et al. 1998) and are underlain by highly permeable parent materials (Maclay 1995). Wilcox (2002) has observed that water which travels a subsurface route allows it to travel rapidly through the subsurface to a stream channel or groundwater body. Where shallow subsurface flow is rapid, juniper evapotranspiration rates will not directly influence runoff amounts, but interception of water by the juniper canopy cover can affect those amounts. Hence, the characteristics of precipitation, geology, soils, and vegetation in the Edwards Plateau are made probable in order to allow water to move quickly beyond the root zone to increase subsurface water to streams under appropriate brush control management. Not only does the Edwards Plateau contain the key features that indicate a potential for increased water yields through brush management, it also was invaded and encroached upon by woody plants—juniper and mesquite—for many years (Taylor and Smeins 1994) which depleted the subsurface and ground water. Therefore, the Edwards Plateau region is a good candidate for this study.

The Edwards Plateau region is in the area that TSSWCB has defined as generally suitable for brush control projects, because this area with infestations of mesquite or juniper is located between the 406.4 mm rainfall belt and the 914.4 mm rainfall belt (TSSWCB 1999). The average annual precipitation in the Pedernales River Watershed is around 820 mm, which also meets Bosch's criteria; annual precipitation should exceed 450 mm. Besides, the Texas Water Development Board has committed U.S. $ 4 million to the Pedernales River Watershed for brush control to enhance the amount of water flowing (TSSWCB 2004). Between 2002-2004, over 55,696 acres of brush were treated in this watershed by using state funds.

Therefore, in the Pedernales River Watershed, there are a number of brush management areas for field study locations and for comparison. The Pedernales River Watershed was selected for studying the responses of spring flow in first-order streams with brush management to estimate the ecological responses of vegetation to the altered flow regimes resulting from such brush management.

PEDERNALES WATERSHED

The Pedernales River watershed was chosen for this study. The watershed is located in the Edwards Plateau region and the Edwards Aquifer Recharge Zone, which is important for supplying much of the water resources used in metropolises in Texas. This watershed is defined by U.S. Geological Survey (USGS) hydrologic unit 12090206, and encompasses approximately 329,800 ha of land in the west-central portion of Texas (30° 7”-30° 17” N; 98° 06”-99° 07” W), mostly within Blanco and Gillespie counties, including small portions of Burnet, Travis, Hays, Kendall, Kerr, and Kimble counties (Figure 3.1). The Pedernales River flows eastward through the watershed and empties into Lake Travis near the river’s confluence with the Colorado River in western Travis County. The Pedernales River’s course is 1,540 km long, of which 630 km have perennial flow. The elevations in this study area increase from about 275 m msl (above mean sea level) at the southeast end of the Pedernales River valley to about 670 m msl at the west end.

Geology

The major geologic structure in this study area is the Llano Uplift, a large dome-shaped structure (LCRA. 2000). This is in the center of the dome area of Precambrian granites, which are overlain by Paleozoic and Cretaceous rocks (marine carbonates and nonmarine clastics). The Precambrian marine sedimentary rocks (limestone, dolomite, sandstone, and shale) were deposited on the eroded surface of the tilted Paleozoic rocks. The Cretaceous strata generally dips gently to the south or southeast (McCampbell 1940). Before the encroachment of the Cretaceous seas, the

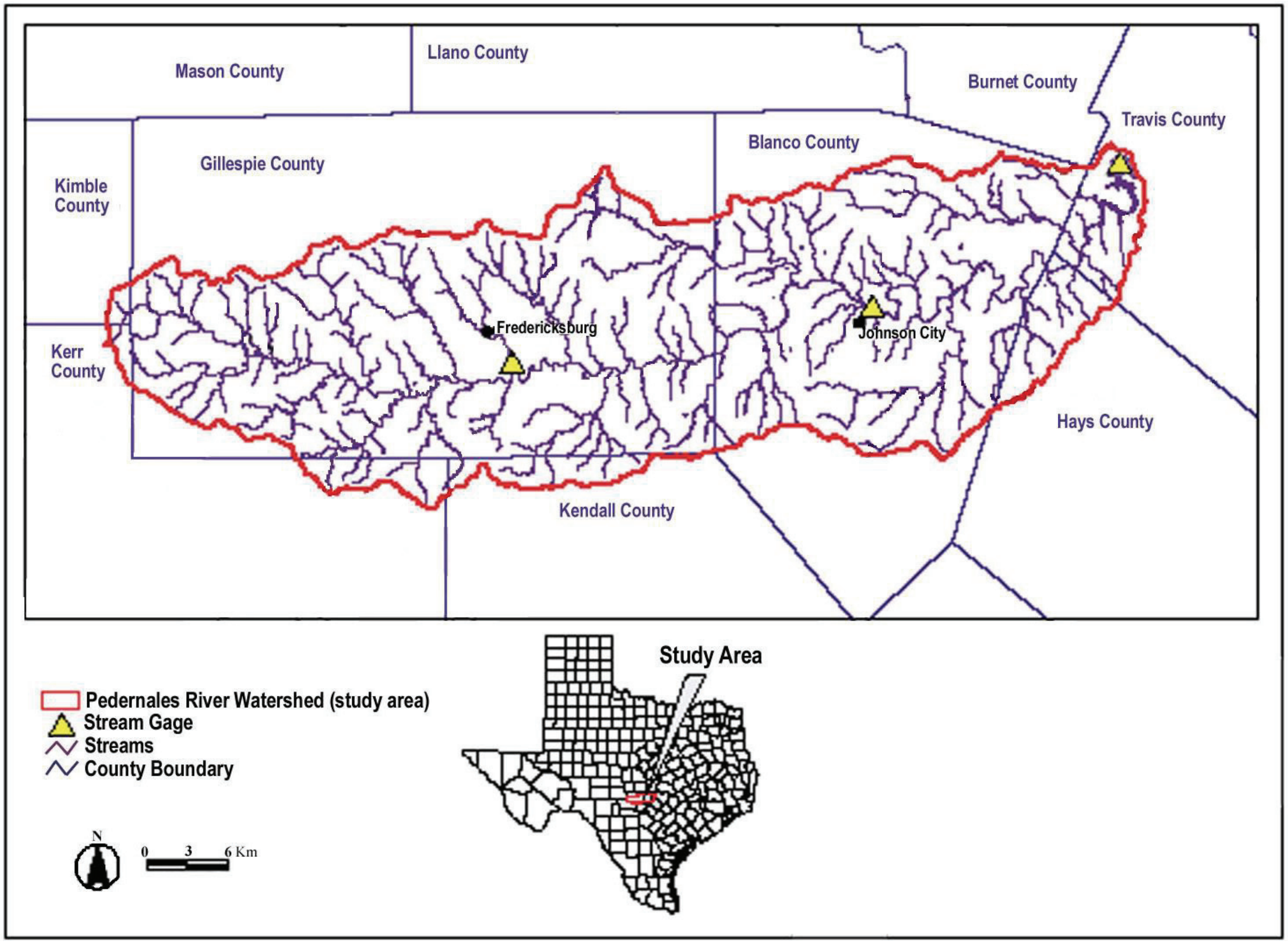

FIG. 3.1. The location of the Pedernales River.

doming and faulting of the Llano region had already been accomplished and the whole region extensively eroded.

As the Comanche ocean advanced from the southeast over the ancient land of this region, basal sands and conglomerates were laid at the edge of the forward-moving seas. The Comanche Peak, where it is recognizable as such, is very sandy in this vicinity. The Edwards formation is represented in its normal facies. In the Pedernales River Basin, the Edwards Plateau and Trinity aquifers are in Cretaceous rock formations and the Ellenburger-San Saba and Hickory aquifers are in Paleozoic rock formations (TAES 2004). Water moves through the aquifers, usually down the dip or slope of the beds. If the aquifer crops out at a lower elevation than the recharge area, water issues from it in the form of springs (Brune 2002). The flow of many springs from these underground reservoirs tends to fluctuate, depending upon the amount of the rainfall, recharge, and water in storage.

The soils in Blanco and Gillespie Counties vary widely. The major soils in this area are the Brackett, Doss, Eckrant, Heatly, Hensley, Luckenbach, Pedernales, Purves, Speak, Tarpley, and Tarrant soils (USDA 1975, 1979). The soils are well drained. Permeability is moderately slow to slow. Some soils are stony and cobbly.

Climate

The Pedernales River watershed has a subtropical climate with typically dry winters and hot, humid summers. Climate data were obtained from the National Climate Data Center (NCDC) for stations at Johnson City (414605) and Fredericksburg (413329). The rainfall distribution in the watershed has two peaks (as seen in Table 3.1). Spring is typically the wettest season, with a peak occurring in May and June. The second peak is usually in September, coinciding with the tropical cyclone season in the late summer/early fall (USDA 1979). Spring rains are typified by convective thunderstorms that produce high intensity, short duration rainfall events and rapid runoff.

TABLE 3.1. Precipitation and temperature in the study area.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec	Year
Johnson City, Texas (1896 – 1996)													
Average Max. Temperature (℃)	15.4	17.3	21.5	25.5	29.1	33.0	35.1	35.5	32.1	27.1	20.7	16.4	25.8
Average Min. Temperature (℃)	1.5	3.1	6.7	11.1	15.8	19.7	21.0	20.7	17.8	12.1	6.4	2.5	11.6
Average Temperature (℃)	8.4	10.2	14.2	18.3	22.5	26.3	28.0	28.1	24.9	19.6	13.6	9.5	18.7
Johnson City, Texas (1931 – 1995)													
Average Total Precipitation (mm)	57.8	62.5	58.2	80.2	107.8	86.8	61.5	53.2	99.8	88.8	57.8	62.8	878.3
Fredericksburg, Texas (1896 – 1996)													
Average Max. Temperature (℃)	15.5	17.8	22.2	26.2	28.8	31.8	33.8	34.0	30.7	26.3	20.7	16.5	25.3
Average Min. Temperature (℃)	1.8	3.7	8.0	12.5	16.3	19.4	20.5	20.1	17.7	12.8	7.5	3.0	12.0
Average Temperature (℃)	8.7	10.7	15.1	19.4	22.6	25.6	27.2	27.0	24.2	19.6	14.1	9.8	18.7
Fredericksburg, Texas (1939 – 1995)													
Average Total Precipitation (mm)	37.1	48.3	42.6	70.2	97.1	88.4	42.9	69.7	87.8	87.2	50.1	45.5	768.0

Note. Temperature and Precipitation data from National Climate Data Center (National Climate Data Center 1996).

Between 1896 and 1996, the mean monthly temperature at Johnson City in Blanco county varied from approximately 8.4℃ to 28.1℃. At Fredericksburg in Gillespie county, mean monthly temperatures varied from approximately 8.7℃ to 27.2℃. Between 1931 and 1995, the average monthly precipitation varied from approximately 53.2 to 107.8 mm at Johnson City in Blanco county, and the mean annual precipitation was 878.3 mm. Between 1939 and 1995, the average monthly precipitation varied from approximately 37.1 to 97.1 mm at Fredericksburg in Gillespie county, and the mean annual precipitation, 768.0 mm, was lower than at Johnson City. Since the flow and the precipitation records are not measured at the same locations within the basin, a statistical analysis was performed to determine the correlation between the precipitations measured at these stations. The nonparametric Spearman method of correlation was used because the data are not normally distributed. The Spearman R value is 0.75, which shows a strong correlation between the stations in Johnson City and Fredericksburg. Therefore, either station could be used in analyzing the flow data.

Hydrology

There are two flow-monitoring stations maintained by USGS within the Pedernales River watershed. One is near Johnson City (08153500) and the other is near Fredericksburg (08152900). The station near Johnson City contains records from 1940 to 2003, and the station near Fredericksburg has records from 1980 to 2003, leaving a gap of six years in the data (as seen in Figure 3.2). From 1940 to 2004, in the Pedernales River watershed, the relationship between the total annual discharge and the total annual precipitation showed an increased discharge with an increased precipitation (as seen in

Figure 3.3). The stream flow data showed that there has been a major drought in almost every decade since 1940. Average monthly flows range from about 9.42 m^3/s in May and June to about 3.2 m^3/s in August.

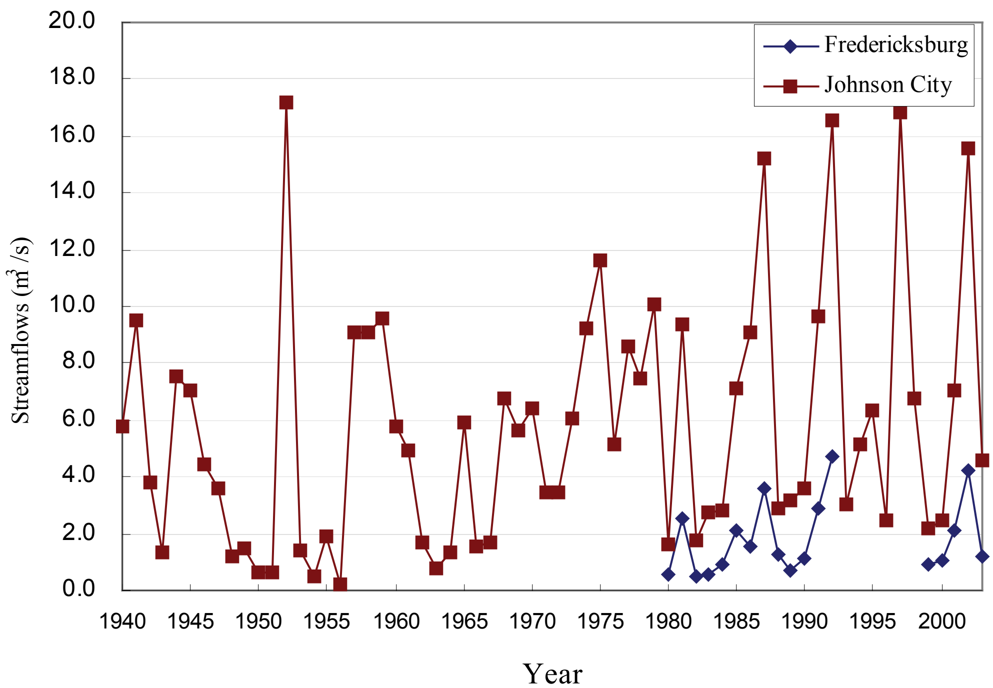

FIG. 3.2. Streamflow diagram for the study area between 1940 and 2003.

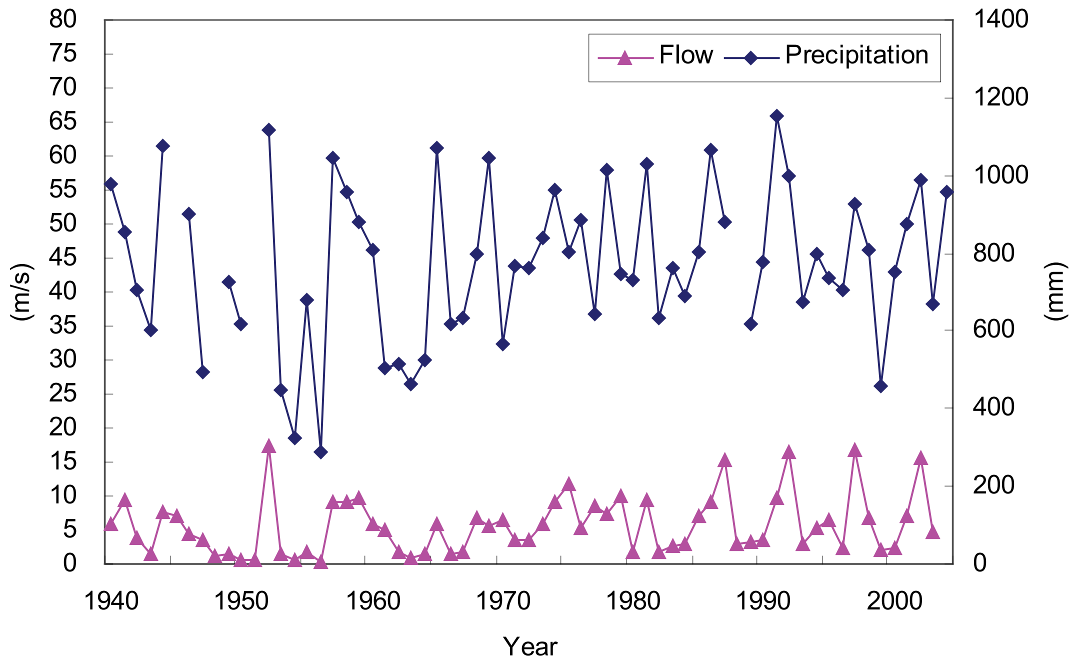

FIG. 3.3. Total annul discharge and precipitation for the study area from 1940 - 2004.

The Pedernales River and its tributaries have generally steep, narrow channels with rocky soils and sparse vegetation cover. During intense rain events, this allows for rapid runoff with high peak discharges and velocities. The river is spring fed and free-flowing. Water in the aquifer within the study area moves from areas of high water level elevations to areas of low water level elevations where ground water is discharged by numerous springs, channel seepage associated with the base flow of effluent streams, subsurface underflow out of the study area, and evapotranspiration along the edge of the Edwards Plateau into the atmosphere (Bluntzer 1992). Although some recharging of the underlying aquifers comes from streams, most streams within the watershed show increases in base flow in the downstream direction, indicating that there is groundwater moving from the aquifer, to the streams. Much of the initial flow in the Pedernales River comes from springs and seeps derived from the dissected Edwards and Trinity (Plateau) aquifers (Preston et al. 1996).

Annual groundwater discharges can vary depending on the amount, frequency, and distribution of precipitation events. Groundwater annual discharge increases during periods of high recharge. During periods of low recharge, groundwater elevations decline, and natural discharge decreases with a reduction in groundwater storage. When groundwater levels intercept the land surface, groundwater can discharge at springs and become surface runoff or stream flow.

Vegetation

The Pedernales River watershed is predominantly comprised of woodland stands of juniper and oak. These communities exist on gentle to steep slopes, shallow soils, and the sites where naturally occurring fires cannot reach (LCRA. 2000). North of the Pedernales River, especially on sandy and granitic soils, oak forests dominate. Prairies and grassy areas are common throughout the region. However, these are limited in their extent to the flat areas of drainage divides and valley floors, deeper soils, and the sites where fire could travel unchecked by topography.

The existing vegetation in Texas derives from land use disturbance. The vegetation data has been classified by the Texas Park and Wildlife Department using Landsat imagery data collected from 1975 to 1981 (McMahan et al. 1984). There are four major plant community types that were categorized by McMahan et al. in the Pedernales River watershed.

Live Oak – Mesquite Parks — This plant community type is chiefly on granitic soils of the Edwards Plateau. The commonly associated woody plants are post oak, blackjack oak, cedar elm, black hickory, agarito, Mexican persimmon, whitebrush, woollybucket bumelia, and elbowbush. The commonly associated grasses and forbs are curly mesquite, buffalograss, Texas grama, sideoats grama, hairy grama, little bluestem, Texas wintergrass, purple three-awn, Indian mallow, Texas bluebonnet, and firewheel. Parks represent the physiognomic class used by McMahan et al. (McMahan et al. 1984) to indicate that the communities support woody plats more than 0.9 m tall that grow as clusters or scatter as individuals throughout the grassland.

Live Oak – Ashe Juniper Parks and Live Oak-Mesquite-Ashe Juniper Parks — These two plant communities are primarily on a single level to gently rolling uplands and ridge tops of the Edwards Plateau. The commonly associated woody plants are Texas oak, shin oak, cedar elm, netleaf hackberry, agarito, Mexican persimmon, kidneywood, saw greenbriar, and flameleaf sumac. The commonly associated grasses and forbs are Texas pricklypear, Texas wintergrass, little bluestem, curly mesquite, Texas grama, Halls panicum, purple three-awn, hairy tridens, cedar sedge, two-leaved senna, and rabbit tobacco.

Live Oak – Ashe Juniper Woods — This plant community is primarily on shallow limestone soils on the hills and escarpment of Edwards Plateau. The commonly associated woody plants are Texas oak, shin oak, cedar elm, evergreen sumac, escarpment cherry, saw greenbriar, mescal bean, poison oak, and elbowbush. The commonly associated grasses and forbs are twistleaf yucca, cedar sedge, little bluestem, Neally grama, Texas grama, meadow dropseed, Texas wintergrass, curly mesquite, mat euphorbia, pellitory, noseburn, spreading sida, and woodsorrel. Woods are described as communities that support wood plants 0.9 to 9 m tall with a relatively close canopy.

STUDY METHOD

SELECTION OF SPRING SITES

Brune (2002) described 12 spring sites in the Pedernales River watershed. This study is aided by local agents of the Texas Cooperative Extension Service. Members of the TAES research team attempted to locate all of the springs in the Pedernales River watershed. The field surveys were performed on ranches that contain springs, with the landowners' permission. We identified those headwater tributaries of the Pedernales River associated with springs, those that fit the geological criteria, and those with access provided by private landowners. Ultimately, thirty-eight springs were accessed for study during the summer of 2003 and spring of 2004 (Appendix A). Those springs were mostly located on the southern side of the Pedernales River (Figure 3.4) and on the interface between the Edwards Plateau and the Upper Glen Rose Formation, or between the Lower Glen Rose and the Hensell Formations (TAES 2004). Also, a wide range of springs with varying amounts of juniper cover was desired. Half of these ranches are treated with brush management, and vice versa. The elevations of spring sites are from around 270 meters msl to 630 meters msl.

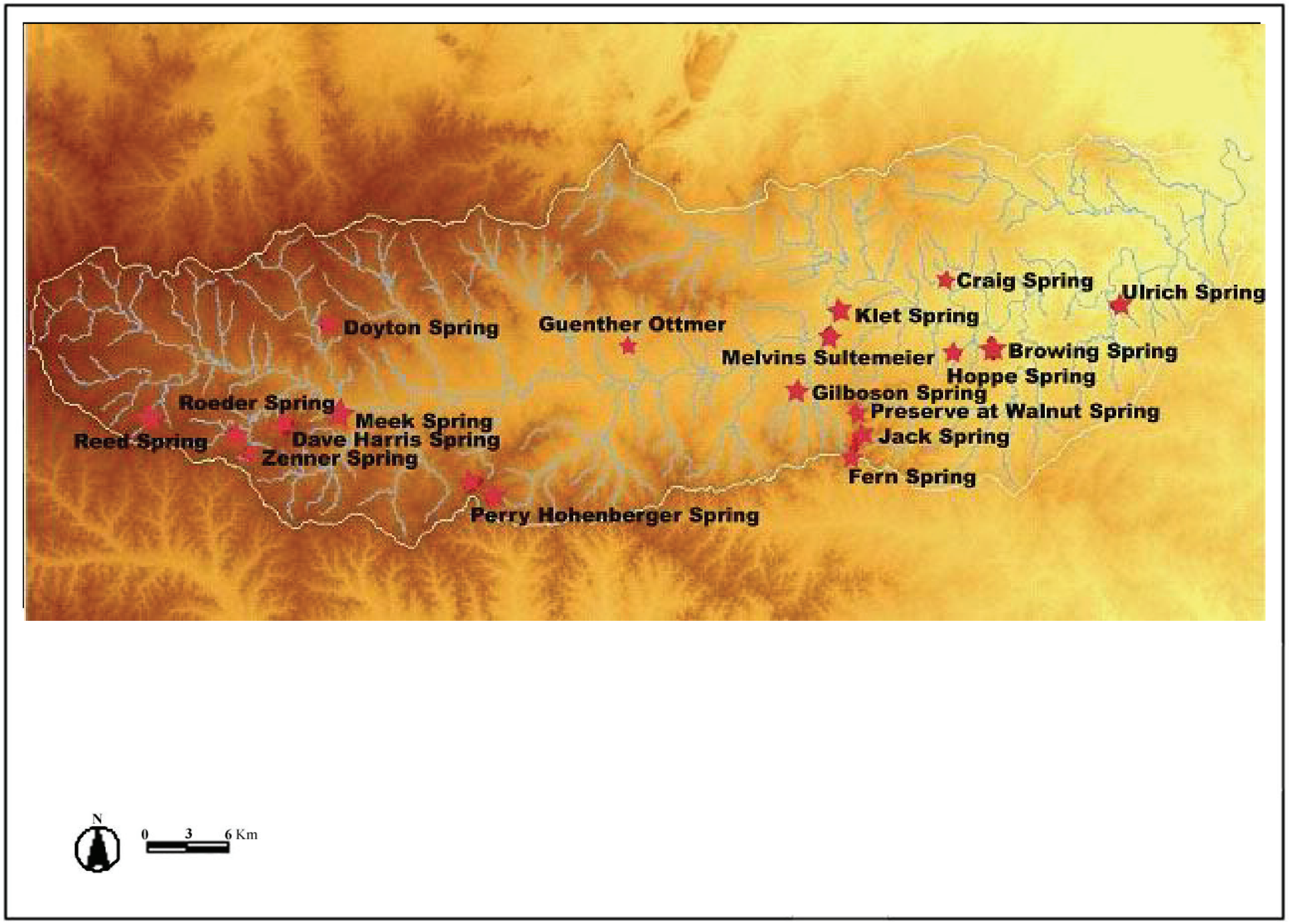

FIG. 3.4. The location of springs in the Pedernales.

The real location of each spring was measured by a global positioning system (GPS) in the field. The geographical coordinates of the springs were pinned on the national elevation dataset (NED) of the Pedernales watershed. The subwatersheds of each spring were delineated with the national elevation dataset and the national hydrography dataset by the EPA's BASIN water quality software package. The areas of subwatersheds could be calculated in accordance with the delineated boundaries of each spring's surface catchment. These surface catchment areas of springs ranged from about 8 hectares to about 820 hectares.

CATCHMENT DELINEATION

The real location of each spring was measured by a global positioning system (GPS) in the field. The geographical coordinates of the springs were pinned on the DEM (Digital Elevation Model) with a 30-meter resolution for the Pedernales watershed. The USGS DEMs contain elevation information that allows for generating digital models of the landscape of the watershed. The National Hydrography Dataset (NHD) containing the stream information was overlayed on top of the DEM file.

BASIN (Version 3) software from the U.S. Environmental Protection Agency (EPA) was used to delineate the surface catchments for each spring with the dataset combined Dem and NHD. The sampling location was used as the outlet of the catchment. The areas of subwatersheds could be calculated in accordance with the delineated boundaries of each spring's surface catchment. These surface catchment areas of the springs are from about 8 hectares to about 820 hectares.

MEASUREMENT OF SPRING FLOW

This study characterized the channel in terms of its dimensions. Dimensions reference the size and shape of the channel using hydraulic geometry such as water surface widths, average channel and water depths, and estimated mean velocity. Discharge was calculated from the information of stream flows in cubic meters per second. These measurements were conducted in the dry season during June, July, August, and September of 2003, and in the wet season during March and April of 2004. Because there was a really large flood event in May of 2004, the spring flow was measured again after this high level of precipitation in order to properly accumulate the data about the changes of spring flow in the study areas. At each sampling location, discharge measurements were conducted in two–five locations, from upstream to downstream using the velocity-area method. At each location, stream velocity was measured in the center of the channel cross section at three depths: on the surface, in the middle, and near the bottom. Flow depth was measured at three horizontal locations: on the left, in the center, and on the right of the stream. Photographs were used to record the morphological conditions along the stream corridor. Theses photographic records also provided the accurate information necessary to conduct the second and third stream channel surveys in the same places. The structure of the stream channel and riparian area at each survey site is illustrated in the Appendix A.

VEGETATION SAMPLING AND MONITORING

Plant compositions were determined for the riparian areas of Pedernales using a line transection and quadrant procedure designed to sample vegetation differences both downstream from the springhead and at different places perpendicular to the stream channel, as depicted in Figure 3.5. In this study we extended the perpendicular transections to 20 meters beyond the stream channel (Transect B). Bare ground, rock, litter, grass, forb or woody vegetation were all recorded along each transection at one meter intervals directly below the side near the watershed, of the tape. Woody plant canopy intercepts were recorded along each transection by species to determine the canopy for each transection. At each one-meter interval, live plants were identified for determining species composition.

At the beginning and the end of the twenty-meter transections, there were two ten-meter transections parallel to the stream channel (Transections A and C). Woody plant canopy intercepts were recorded along each transection by species to determine the canopies for each transection. The vegetation sampling can be seen in Figure 3.5. The vegetation surveys were conducted August 5-7, August 26-27, and Septempter 4, 2003.

Vegetation diversity was determined to be both the number of species and their relative abundance (Magurran 1988). Species density, the number of species per m^2, is the used measure of species richness. Species richness provides an expression of diversity. Vegetation cover was used as an expression of abundance.

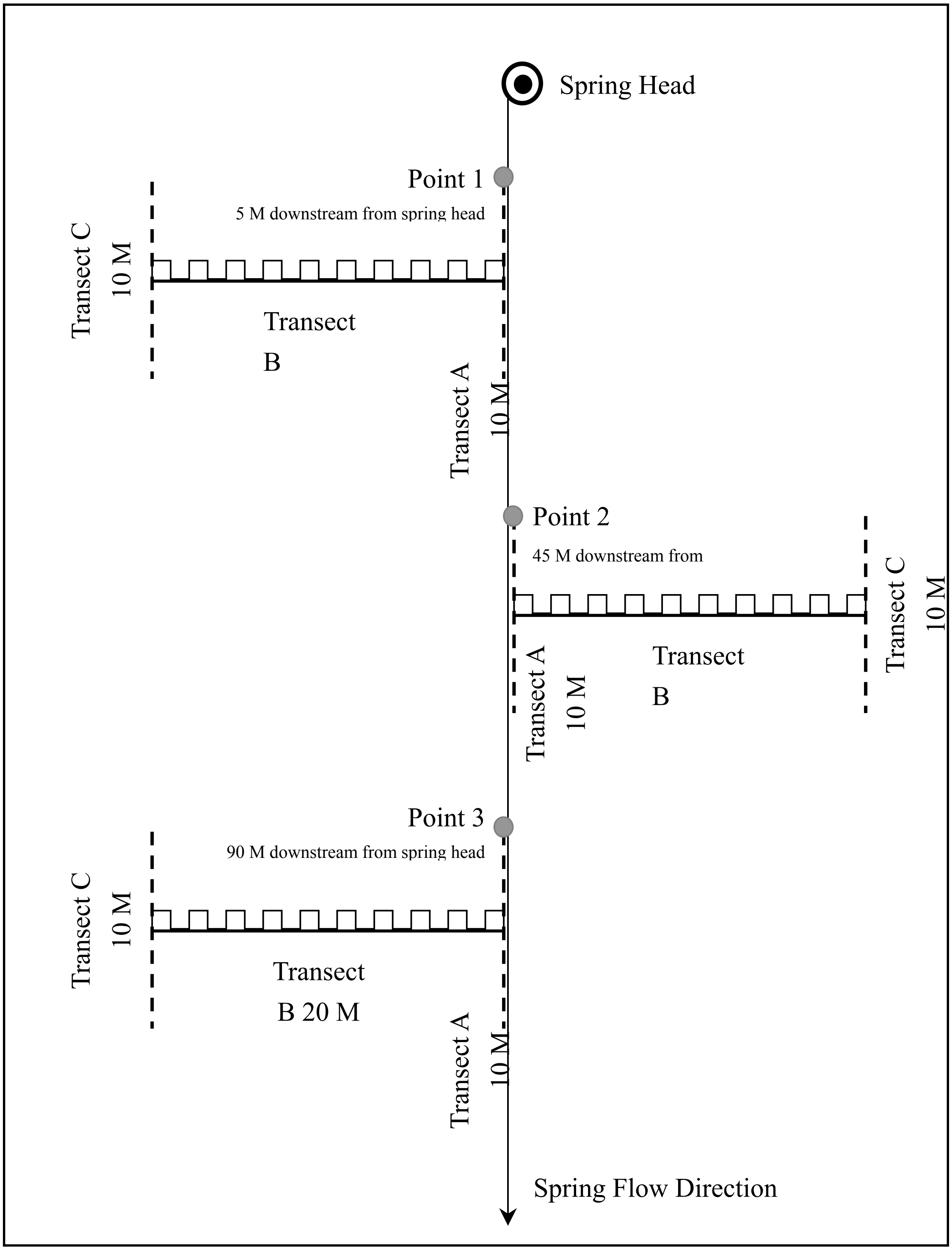

FIG. 3.5. Vegetation sampling scheme.

DATA ANALYSIS

DIVERSITY

Species diversity consists of two major components. The first is species richness, which refers to the number of species in the community. The second component is species evenness, which refers to how the species abundances are distributed among the species. Diversity indices incorporate both species richness and evenness into a single value (Ludwig and Reynolds 1988). To determine species richness and the relative abundance of all the vegetation, three diversity measures were computed separately for all species including the woody and herbaceous vegetations collected for each sampling plot, as described by Hill (Hill 1973). Hill's family of diversity numbers (the 0^{th}, 1^{st}, and 2^{nd} order) are:

$$N_0 = S$$

where S is the total number of species,

$$N_1 = e^{H'} = Exp\left[-\sum_{i=1}^{S}\left(p_i \ln p_i\right)\right]$$

H' is Shannon's index, and P_i is the proportional abundance of the ith species.

$$N_2 = 1/\lambda = 1\Big/\sum_{i=1}^{S} p_i^2$$

where λ is Simpson's index (Simpson 1949), which varies from 0 to 1. If λ closes to 1, indicating that two individuals belong to the same species, then the diversity of the community sample is low.

N_0 is the number of all species in the sample, N_1 is the number of abundant species, and N_2 is the number of very abundant species in the sample. N_1 is always intermediate between N_0 and N_2. However, N_1 and N_2 are increasingly influenced by equitable distribution of cover among the species in the sample such that they become more insensitive to relatively rare species (Wilkins 1992). Simply stated, Hill's family of diversity indices is a measure of the number of species in the sample where each species is weighted by its abundance.

For each sampling plot, herbaceous diversity (Herb N_0, Herb N_1, Herb N_2), woody diversity (Woody N_0, Woody N_1, Woody N_2), and whole vegetation diversity (Species N_0, Species N_1, Species N_2) were all tested for environmental gradients along the stream bank by an analysis of ANOVA.

SIMILARITY

Estimates of dominance, frequency, and simple presence or absence of various species could all provide the information necessary for making comparisons of plant resemblance functions betweens samples (Taylor 1973). Resemblance functions quantify the similarity or dissimilarity between two objects based on observations (Ludwig and Reynolds 1988). Similarity coefficients reflect the mathematical degree of similarity between two or more plant communities in relation to species composition or other structural qualities such as density, biomass, or dominance. These indices are based solely on the presence or absence data from the field samples, and present a degree of similarity in species composition between each pair of sample units. There are more common species shared by two sample units, and there is a greater ecological similarity between this pair of sample units.

To determine the similarity between the sample units, Jaccard's index was used. Jaccard's index was based on presence-absence data that were originally used to measure the degree of association between the different species. Jaccard's index (Ludwig and Reynolds 1988, Krebs 1999) is :

$$JI = \frac{a}{a+b+c}$$

where

a = the number of species which simultaneously occur in both sample units.

b = the number of species which just occur in one sample unit.

c = the number of species which just occur in the other sample units.

Jaccard's index is equal to 0 at total dissimilarity and 1 at maximum similarity. This index measures the number of joint occurrences of the species compared to the total occurrences of the species in the pair of sample units. Jaccard's index was found to be generally unbiased, even at a small sample size (Ludwig and Reynolds 1988).

Along the sampling transect from the stream bank to the upland, each sampling plot was paired with the first plot adjacent to the stream bank to measure the degree of similarity between those pairs of sampling plots. In addition, each sampling plot was also paired with the last plot to compute the similarity. Then, the changing degree of the similarity was tested along the horizontal environment gradient by an analysis of ANOVA. The changing degrees of similarity present the changes of species composition and community structure. Dominance-diversity curves (Preston 1948, Whittaker 1965) were used to graphically represent changes in species-abundance relationships associated with treatment rates.

CHAPTER IV

RESULTS

INFLUENCES OF ENVIRONMENTAL FACTORS ON SPRING FLOWS IN UPLAND SMALL CATCHMENTS

ENVIRONMENTAL FACTORS WITH SPRING FLOWS

Rainfall Records

Rainfall records were collected from the Blanco County Extension Office, Texas Cooperative Extension. Daily rainfall values from a weather station in Johnson City (approximately 98° 24' W, 30°16' N) were available from January of 2002 to May of 2004. A statistical analysis was performed to determine the correlation between precipitations at the Blanco County Extension Office and the local weather stations. The precipitation pattern from the stations in the Blanco County Extension Office was correlated with the one from the Johnson City weather station (Spearman $r_s = .94$, n=28, $p < .01$). In addition, there was also a strong correlation between the precipitation pattern from the Blanco County Extension Office and the Fredericksburg weather station (Spearman $r_s = .80$, n=28, $p < .01$). Therefore, the weather data from the Blanco County Extension Office could be used in analyzing the flow data.

During 2002, the rainfall distribution in the watershed had two peaks. The wettest season was in the early summer with a relative high peak occurring in July (as seen in Figure 4.1). The second peak was in October. The total annual precipitation in 2002 (1118.36 mm) was obviously higher than in 2003 (706.88 mm). In 2003, there were two dry periods. The potential evapotranspiration was larger than the amount of precipitation from April to May and November to December. From January to May in 2004 there was a moist period that was adequate for plant growth. From the annual rainfall amount, the 2003 year could be considered a relatively drier year than the 2002 year. The precipitation record showed that the spring season (March-May) in 2004 was wetter than in the 2003 summer period (Figure 4.1). Finally, the spring flow was recorded using both the dry season samples (2002-summer) and the wet season samples (2003-spring).

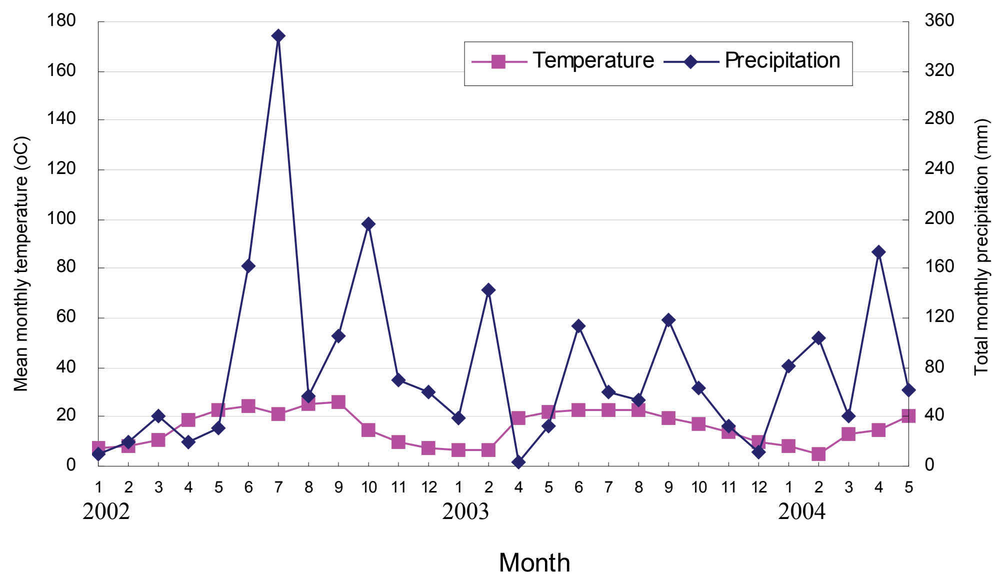

FIG. 4.1. The climate diagram of the Pedernales River watershed from 2002-2004.

Spring Flow Records

A total of 33 out of 38 of the spring sampling locations were close to a geology interface between the Edwards and the Upper Glen Rose Formation or between the lower Glen-Rose and the Hensell Formation. The six spring sites were not located on these two geologic interfaces, which were on the Craig, Reed and Guenther Ottmer ranches. Therefore, three spring data sets from both ranches were excluded from this analysis. In the summer of 2003, the spring flows were recorded from June to September (Appendix B). The total precipitation was 346.71 mm during the dry season survey period (June-August). Then in spring of 2004, the spring flows were recorded first during March and April. After the big flood event in May of 2004, all spring flows were recorded in June. The total precipitation was 430.02 mm during the wet season survey period (March-June). The precipitation record showed that spring (March-June) of 2004 was wetter than the summer of 2003 (Figure 4.1). However, 11 out of 33 springs showed more spring flows in the summer of 2003 than in the spring of 2004 (as seen in Figure 4.2).

Each spring offers very different amounts of discharge. The spring flows at Hoppe Ranch ranged from about 15.36 to 39.12 L/s during the 2004 spring season (Appendix B). The spring flows at the Perry Hohenberger Ranch were about 20.28 L/s during the 2003 summer season. The others were smaller than 10 L/s during the summer of 2003 and the spring of 2004. Figure 4.2 shows that the spring discharge patterns were different between the spring and summer seasons. The spring flow over the entire study period made up a relatively small part of the water budget, about 4% for most of the spring catchments. Spring flow from springs 17 and 18 during the summer of 2003 was much higher than from the other watershed (Appendix B).

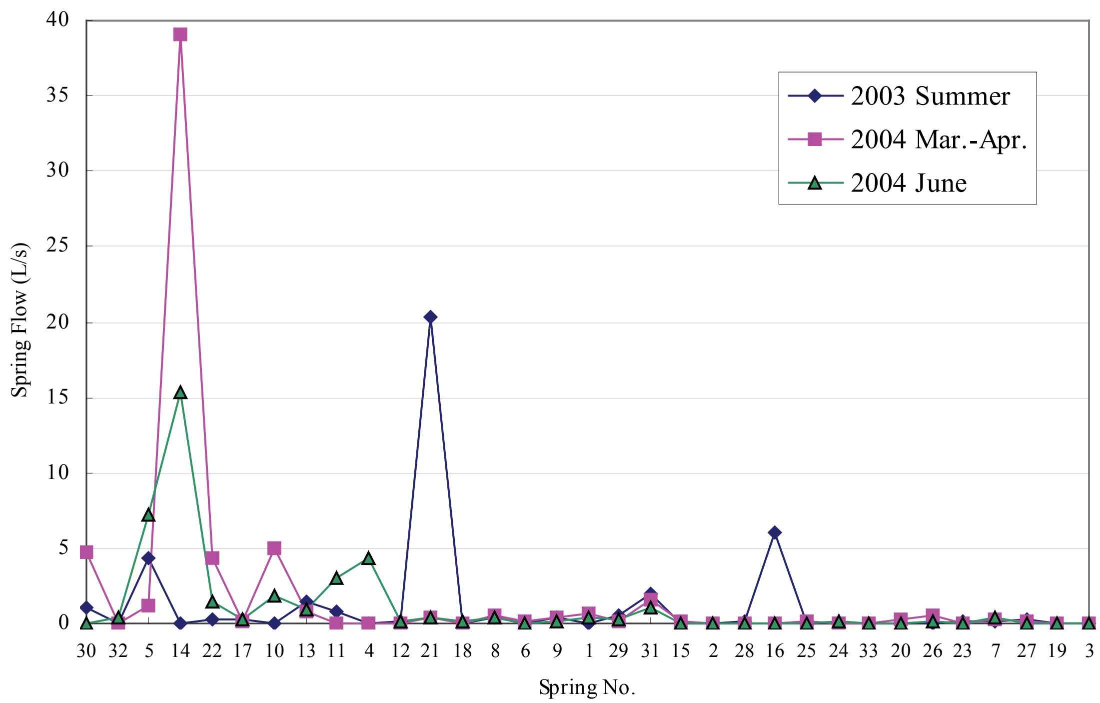

FIG. 4.2. The ranked (by surface area) spring flows for each spring site.

The relationship between the spring flow and the amount of precipitation was examined via a Spearman correlation analysis. The results showed that there was no correlation between the amount of monthly precipitation and the amount of spring flows (Spearman $r_s = 0.002$, $n = 99$, $p = 0.98$). Because the larger surface area of the catchment could collect more rainfall, the total amount of spring flow was divided by each surface area of spring catchment. The relationship between the monthly precipitation and the depth of the spring was examined again. The results presented that there was no correlation between the amount of monthly precipitation and the depth of the spring

(Spearman r_s = - 0.027, n = 99, p = 0.79).

Besides, the amounts of the spring flow of each spring site were recorded at different days during the dry and wet seasons. The different accumulated amounts of daily rainfall were calculated for each spring site, and the relationship between the accumulated amounts of precipitation and the depth of the spring (spring flow divided by watershed area) was examined. However, after a thorough analysis, it was found that the discharge of the spring did not significantly correlate with the 7-day, 2-week, 1-month, 1.5-month, and 2-month accumulated amounts of precipitation (Table 4.1 and Figure 4.3).

TABLE 4.1. Spearman correlation coefficients between the depth of spring discharge and accumulated amounts of precipitation.

Accumulated Period	Spring Discharge	
	Coefficient	*p*
1 week	0.061	0.549
2 weeks	0.077	0.450
4 weeks	0.076	0.457
6 weeks	0.040	0.693
8 weeks	0.069	0.499

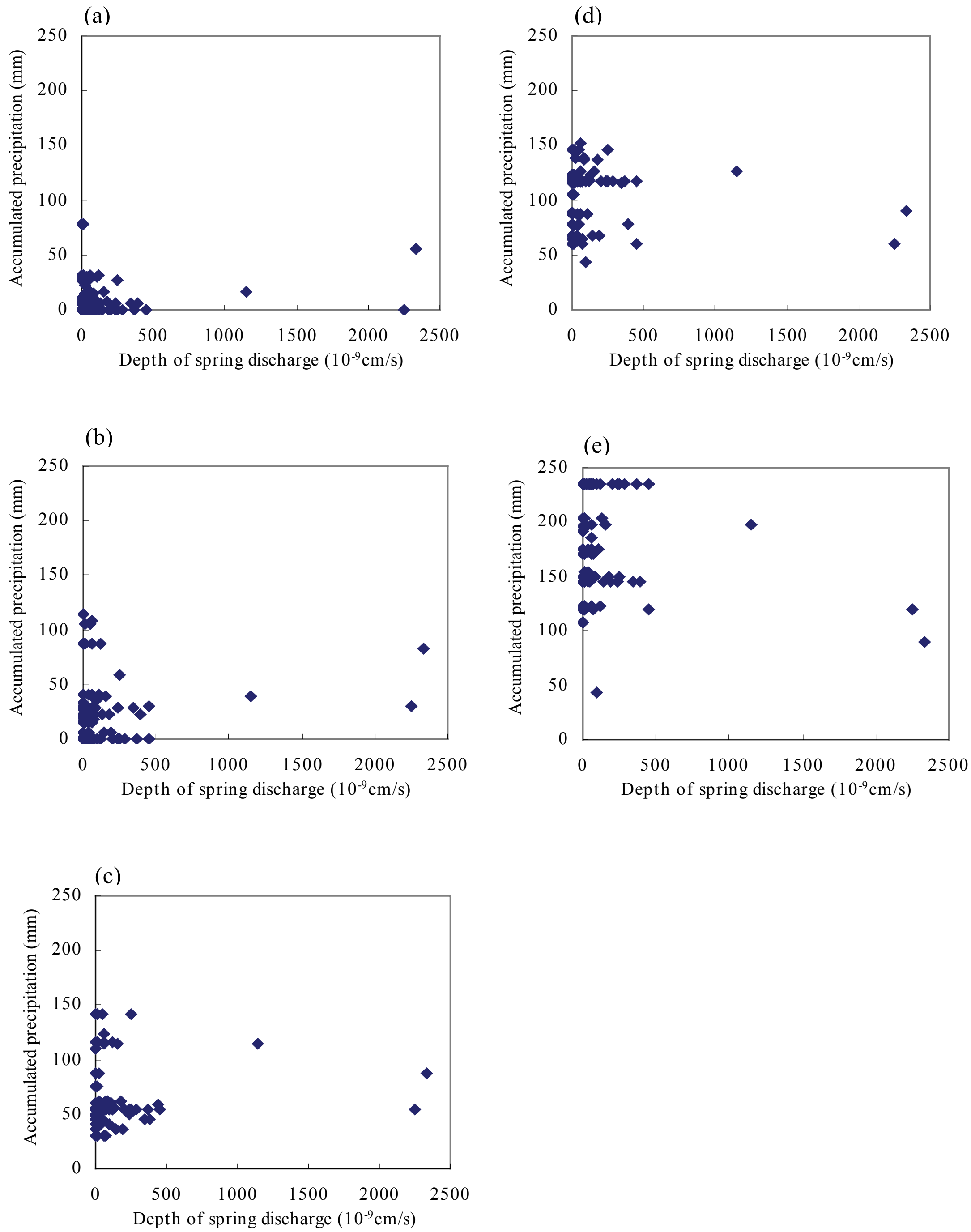

FIG. 4.3. Plot of accumulated precipitation versus depth of spring discharge. (a) 1 week accumulated precipitation; (b) 2 weeks accumulated precipitation; (c) 4 weeks accumulated precipitation; (d) 6 weeks accumulated precipitation; (e) 8 weeks accumulated precipitation.

Surface Area

The source of water in a spring catchment is the precipitation on the surface of the land. If the catchment area is larger, there has been more precipitation captured by the surface land. The precipitation infiltrates into the soil and discharges as spring flow after dropping from the sky. There should be a relationship between the catchment surface area and the spring discharge. Otherwise, there should be a relationship between the catchment subsurface area and the spring discharge.

For the spring sites in the Pedernales River basin, the average surface catchment area was 115.52 ha (*SD* = 158.75). In addition, the average subsurface area was 82.48 ha (*SD* = 141.12). The relationship between the surface and subsurface areas is shown in Figure 4.4. There was an obvious relationship between the surface area and the subsurface area of the spring sites, r (33) = 0.83, $p < 0.05$. Because of the high correlation between the surface and subsurface areas, the relationship between the catchment subsurface area and the spring discharge was confirmed in a regression analysis with the average spring discharge as the dependent measure and the surface catchment area as the predictor. Regression analysis revealed that the model significantly predicted that the average spring flow, F (1,31) = 10.87, $p < 0.01$. R^2 for the model was 0.26 (Table 4.2), and adjusted was 0.24. The results show the positive relationship between the surface catchment area and the spring discharge (Figure 4.5).

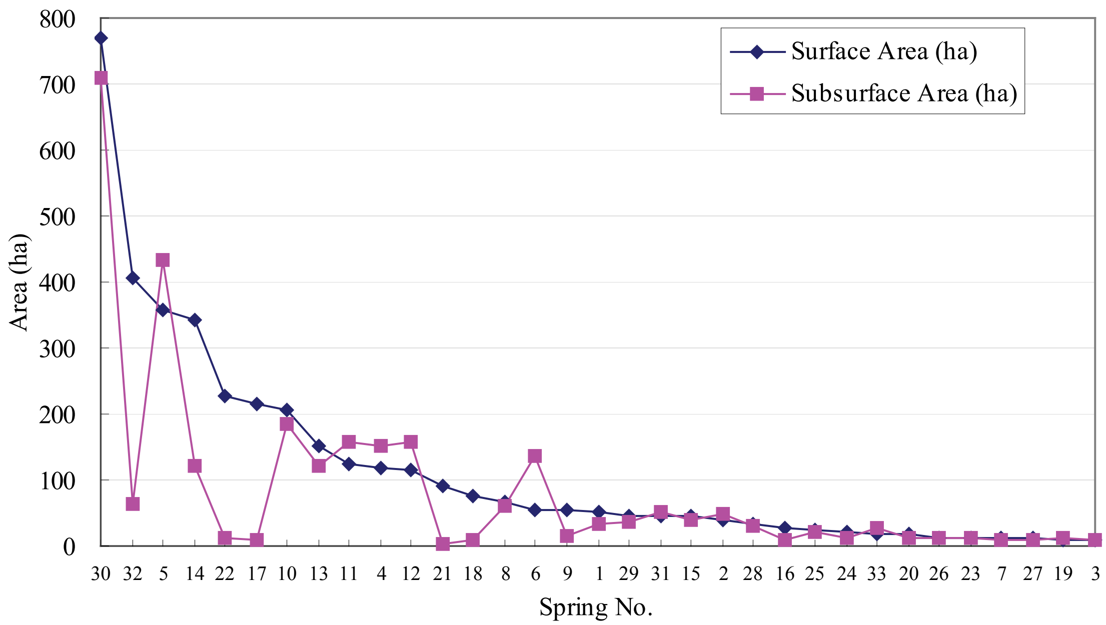

FIG. 4.4. The ranked surface area and subsurface area for each spring catchment.

TABLE 4.2. The relationship between the surface catchment area and the spring discharge. The independent variable was the surface area. The dependent variable is the average spring flow. The dependent variable was transformed as e^x.

Variables in Model	B	SE B	β	R^2	F
				0.26	10.87 **
Constant	-2.158 ***	0.378			
Surface Area	0.006 **	0.002	0.509		

Note. ** p <0.01, *** p <0.001.

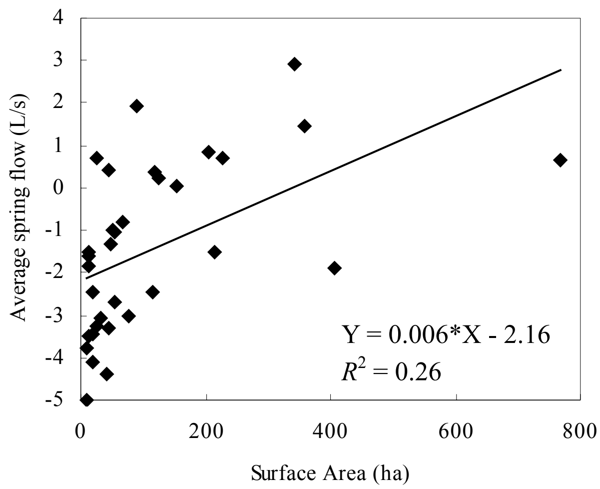

FIG. 4.5. Linear regression of the surface catchment area versus the average spring discharge (Y was transformed as ex).

Geology

There were 33 springs in the Pedernales River watershed located at the geological interface between the Edwards and the Upper Glen Rose formations or between the lower Glen-Rose and the Hensell formations. The contact geological formation between the Edwards and the Upper Glen Rose formation was found along the watershed perimeter and the basin slopes (Appendix A). However, the interface between the two was found in the basin valley (TAES 2004). At the contact geological formation between the Edwards and the Upper Glen Rose formations (E-URG formation in Figure 4.6), the spring elevations range form 530 to 620 meters. Most of the spring sites at the geological interface between the lower Glen-Rose and the Hensell formations (GR-H Formation) range from 270 to 540 meters of elevation, and there is only one site located at over 500 meters.

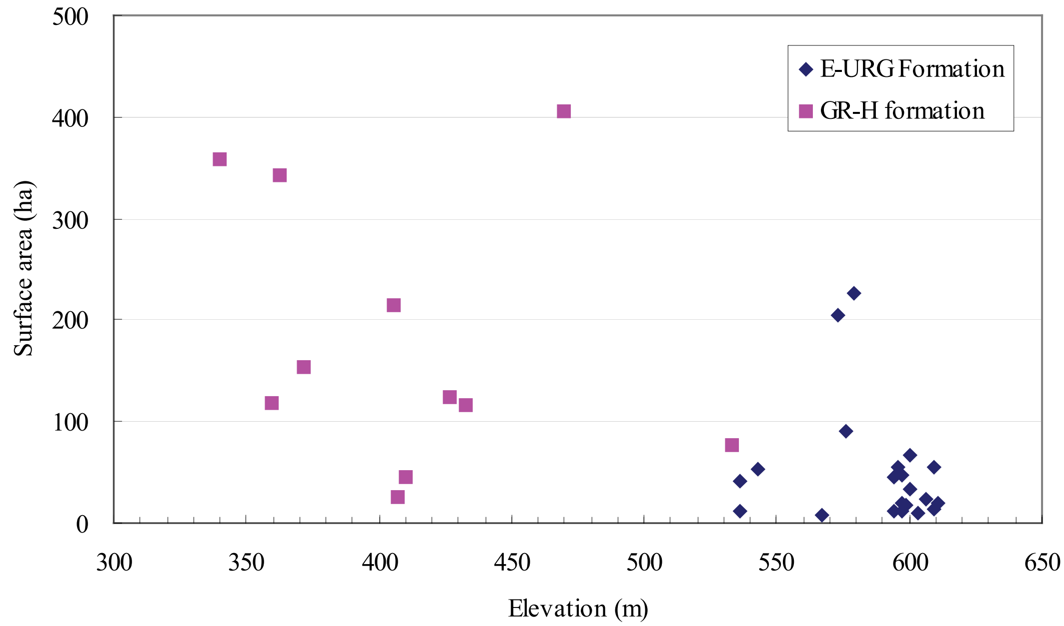

FIG. 4.6. Elevation and surface area for each spring site.

The range of the surface area of the spring catchments was large, from 8.10 to 769.23 ha. Figure 4.6 presents that there were different distributions of the surface area of the spring catchments between these two geological formations. A *t* test was used to test the relationship between the environmental characters, geological character and the surface area of the spring sites. The results of this analysis revealed a significantly different size of spring catchment between the different geologies, t (31) = -2.85, $p < 0.05$. On average, the spring catchments at the interface between the Glen-Rose and the Hensell formations were larger than at the interface between the Edwards and the Upper Glen Rose formations (at GR-H Formation: M = 228.98 ha, SD = 211.79; at E-UGR Formation: M = 50.68 ha, SD = 59.26). Since the surface area of the spring sites was relatively different between these two geological formations, when the relationship between the geological formation and the spring flow was examined, the size of the catchment needed to be controlled.

The average spring flow at the interface between the Edwards and the Upper Glen Rose formations during the summer of 2003 was 1.17 L/s (*SD* = 4.40), 0.69 (*SD* = 1.36) during the spring of 2004, and .31 (*SD* = 0.51) after several large flood events in May. Furthermore, the average spring flow at the interface between the lower Glen-Rose and Hensell formations during the summer of 2003 was 1.17 L/s (*SD* = 1.97), 3.84 (*SD* = 11.19) during the spring of 2004, and 2.65 (*SD* = 4.60) after May. As discussed above, the amounts of spring flow were significantly influenced by the surface area of the spring catchment. When the relationship between the geological formation and the spring flow was examined, the size of the catchment needed to be controlled. In this study, the spring flow was converted to the spring depth, which was measured as the total amount of spring flow divided by the surface area of the spring catchment. A *t* test was used to test the relationship between the geological formations and the spring depth during the three survey periods. The results of this analysis did not reveal a significantly different spring depth between the E-UGR Formation and GR-H Formation, t (97) = -0.58, $p > 0.05$. On average, the spring depth at the interface between the Edwards and the Upper Glen Rose formations was slightly smaller than at the interface between the Glen-Rose and Hensell formations (at the E-UGR Formation: $M = 1.06\times10^{-7}$ cm; at the GR-H Formation: $M = 1.48\times10^{-7}$ cm). The difference in the spring flow was not due to the different geological formations in the Pedernales watershed.

Furthermore, the relationship between the elevation and the spring flow was examined. A correlation analysis was used to test the relationship between the geological formations and the spring depth, which is measured as the spring flow divided by the surface area, during the three survey periods. The results of this analysis did not reveal a significantly correlated relationship between the spring depth and the elevation for springs located at r (99) = 0.05, $p > 0.05$. There was no clear relationship between the spring discharges with regards to the elevation of the spring sites.

LAND COVER

The estimates of land cover were taken from classified 2003 Landsat imagery. The non-canopy occupied areas were converted into grasslands and croplands for each basin. The other woody and shrub canopy occupied areas were transformed into two categories, Ashe juniper and other woody cover, for each catchment. Since the 30 meter image resolution of the Landsat imagery did not allow us to distinguish oak from other species, the best interpretation of cover by oak is via the total "other" woody cover in each catchment.

The estimates of the canopy cover by Ashe juniper (*Juniperus ashei*) in these spring sites were from 0.1 to 168.49 ha (Table 4.3), with a mean of 18.20 ha (SD = 36.34). The percentages of juniper canopy cover for each catchment ranged from 0.88 to 40.63 %, with a mean of 11.66 % (SD = 11.60). Approximately one-third of the spring catchments had total juniper canopy cover of less than 4%, and only one-third had a juniper canopy cover of over 10% (Figure 4.7). The estimates of canopy cover by other woody species in these spring sites ranged from 0.005 to 92.73 ha, with a mean of 11.76 ha (SD =

17.74). The percentages of other woody canopy cover for each catchment ranged from 0.04 to 41.67%, with a mean of 16.44% (*SD* = 14.09). About one-third of the spring catchments had a total woody canopy cover (without juniper) of less than 10 %, and one-third had a canopy cover of over 20% (Figure 4.7).

TABLE 4.3. The average land cover types of each spring catchment in the Pedernales River watershed.

	N = 33			
	Area (ha)		Land cover (%)	
	Mean	*S.D.*	Mean	*S.D.*
Juniper	18.20	36.34	11.66	11.60
Other Woody Plants	11.76	17.74	16.44	14.09
Cropland	0.68	2.07	0.55	0.94
Grassland	8.56	19.62	5.39	5.82

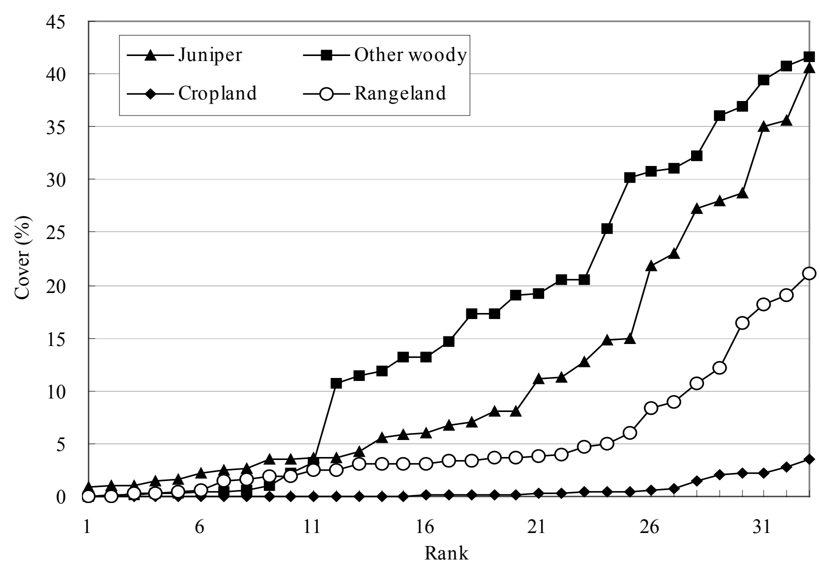

FIG. 4.7. The ranked land cover by each type for the spring catchments.

Croplandscovered only a few areas in the Pedernales watershed, and only about half of the spring basins had cropland. The average area covered by cropland was 0.68 ha (*SD* = 2.07). The mean percentage of cropland for each catchment was 0.55% (*SD* = 0.94). For those classified land types listed in this study, cropland covered the fewest areas. However, two of the 33 spring sites did not contain grassland area void of any woody species in its catchments. The largest range area covered 93.78 ha, and the smallest grassland was 0.09 ha. The average area of grassland was 8.56 ha (*SD* = 19.62). The mean percentage of grassland for each spring catchment was 5.39% (*SD* = 5.82).

The estimates of vegetation cover derived from the classified Landsat imagery were used to interpret the association between the grassland management alternatives and the spring discharge. Brush control management decreased water loss through both interception and evapotranspiration by replacing vegetation with a type that depleted less water, lowered biomass species, and shallow-rooted species (Davis and Pase 1977).

Hence, these classes of Ashe juniper and other woody species were combined to present the total woody canopy cover for each spring catchment. The total canopy cover stood for the vegetation cover, which depleted more water than grasses or grasslands. Furthermore, high water-use plants should be thinned or eradicated for brush management (Hibbert 1983). Although there were few juniper or other woody plants in the cropland, the crops depleted more water than the grasses. In this study, the brush control area was presented by the class of grassland for each spring catchment.The relationship between the spring discharges with the types of vegetation cover in the Pedernales watershed was tested by the partial correlation technique, which is controlled by the surface area of the spring catchments. The percentages of Ashe juniper cover significantly negatively as related to the percent of other woody cover, *r* (95) = -0.70 ($p < 0.001$). Both Ashe juniper and other woody plant percent coverage significantly correlated tp the total woody canopy percent cover, Ashe juniper: *r* (95) = 0.23 ($p < 0.05$) and other woody plants: *r* (95) = 0.58 ($p < 0.001$). Finally, the juniper percent cover and the cropland percent cover showed a strong negative correlation of *r* (95) = -0.34 ($p < 0.001$). In the spring sites there were fewer percentages of juniper cover and more percentages of cropland (Table 4.4). That could be because the landowners moved the juniper brushes and converted those lands into croplands. In addition, the other woody species' percent cover also significantly positively correlated with the cropland percent cover, *r* (95) = 0.45 ($p < 0.05$). However, the percentages of other woody species cover were significantly negatively correlated to the percentages of grassland area, *r* (95) = -0.31 ($p < 0.05$). Furthermore, there was a strongly correlated relationship between the whole woody plants' percent cover and the grassland percent cover, *r* (95) = -0.60 ($p < 0.001$). This means that there were more open areas such as grasslands after the removal of woody brushes.

In this study, the relationship between the level of brush control and the spring discharge was discussed. There was no correlation in the data set between the spring discharge and either the juniper percent cover or the other woody species percent cover ($r = 0.04$ and –0.10, respectively, $n = 98$). The relationship between the spring discharge and percentages of cropland area was not in obvious correlation ($r = - 0.12$, $n = 98$). However, the spring discharge correlated to the percentages of grassland cover, *r* (95) =

0.23 ($p < 0.05$). The results of this analysis mean that thereare more spring discharges when there are more open range area, upon which the all woody shrubs are removed and the surface of soil is covered by grasses.

TABLE 4.4. Partial correlation coefficients among land cover and spring discharge.

	Spring flow	% Juniper	% Other woody cover	% Total woody cover	% Cropland	% Grassland
Spring flow	1.00					
% Juniper	0.04	1.00				
% Other woody cover	-0.10	-0.70 ***	1.00			
% Total woody cover	-0.10	0.23 *	0.58 ***	1.00		
% Cropland	-0.12	-0.34 ***	0.45 *	0.22 *	1.00	
% Grassland	0.23 *	-0.18	-0.31 *	-0.60 ***	-0.18	1.00

Note. * Correlation is significant at the 0.05 level (2-tailed), *** Correlation is significant at the 0.001 level (2-tailed).

In the Pedernales watershed, the springs were mainly located at two geological interfaces, the interface between the Edwards and the Upper Glen Rose formations and the interface between the lower Glen-Rose and Hensell formations. Between those two geological formations, the average amount of spring flow was not significantly different. Also, the average amounts of spring flow and the elevation of the spring sites were not obviously correlated to one another. The environmental factors that had a relationship to the amount of spring discharges were surface area and land cover. There was an obviously positive relationship between the percentages of the brush control area (free-shrub grassland) and spring discharge. Brush control management might increase the spring flow in the Pedernales watershed on the Edward Plateau.

DISCUSSION

Environmental Factors

On Texas grasslands, springs are commonly associated with limestone or karst geology. The Pedernales River watershed is located on the Edwards Plateau which lies on the aquifer and underground reservoir (Brune 2002). Water moves through the aquifer and issues from the interface between two different geologicsl formations as springs or seeps (Williams et al. 1972). In this study, the springs in the Pedernales River watershed are located at the two geological interfaces, one between the Edwards and the Upper Glen Rose formations and the other between the lower Glen-Rose and Hensell formations. No matter on what geological interfaces or elevations the spring sites were located, there was no significant difference in the spring depth. The different amounts of spring flow from the 33 spring catchments were not due to the different geological formations or elevation locations in the Pedernales watershed.

For first-order catchments in the Pedernales watershed in central Texas, spring flows made up an average of 3.67% of the of the monthly water budget. The percentage of water yield from precipitation in the Pedernales watershed shows a similarity to an earlier study by Wilcox et al. (Wilcox et al. 2005) on the Annandale Ranch that had no springs from the western Edwards Plateau. Runoff at the Annandale Ranch accounted for about 4% of the precipitation. However, the results from this study show a much lower rate than another earlier body of research by Huang, on the Honey Creek watershed with springs on the eastern Edwards Plateau (Huang 2006, Huang et al. 2006). Runoff from the Honey Creek watershed accounted for about 22% of the precipitation.

During the survey periods, the accumulated amount of precipitation was slightly higher in the wet spring season of 2004 (430.02 mm), than in the dry summer season of 2003 (346.71 mm). Although there was more total precipitation in the spring of 2004, one-third of the spring sites showed a declining average amount of spring flow. The relationship between the amount of spring flow and precipitation was examined by a Spearman correlation analysis. The results showed that there was no correlation between them. Furthermore, the spring was generated from subsurface flows and base flows. The groundwater might have come from pre-event water already on the sites (Buttle 1994), and hence the different accumulated amounts of daily rainfall were calculated for each spring site from the spring recording day. However, after each was analyzed, the depth of the spring discharge did not significantly correlate with the accumulated precipitation from within those two months. From these results, it can be seen that the amount of spring flow might be influenced by other environmental factors (Chang and Watters 1984). Ultimately, we need more research to focus on the process of the generation of spring discharge from precipitation.

The source of water in a spring catchment is the precipitation falling on the surface of the land (Hornberger et al. 1998). According to this concept, the catchment area becomes larger; more water is delivered to the spring outlet via precipitation, runoff, and groundwater inflow. The results of this study show that there were weak relationship between the surface catchment area and the spring discharge. This might be that plant root channels and natural karst fractures provide pathways for subsurface flow in the Edwards plateau (Taucer et al. 2005, Dasgupta et al. 2006a). The real spring catchment might be not alike the surface watershed delineated by topography (Dasgupta et al. 2006b). Not all areas in the catchment contributed to the spring (Taucer et al. 2005).

Land Cover

In this study, the estimates of land cover were taken from classified 2003 Landsat imagery. The vegetation cover of the first-order catchments with springs in the Pedernales River watershed were classified into four types—grassland, cropland, Ashe juniper cover, and other woody plant cover. The highest vegetation cover was other woody plant cover with an average of 16.44% of the spring catchments. The second highest vegetation cover was Ashe juniper cover with a mean of 11.66% of the spring catchments. The grasslands occupied an average of about 5.39%, and the croplands covered a fairly small portion of the catchment, averaging 0.55%. The estimates of vegetation cover were used to interpret the association between the grassland management alternatives and the spring discharge.

The relationship between the spring discharge and the type of vegetation cover in the Pedernales watershed was tested by the partial correlation technique, which is controlled by the surface areas of the spring catchment. The results from this study present that the juniper percent cover and the cropland percent cover are in a negative correlation. That could be because the landowners moved the juniper brushes and converted those lands into croplands. Furthermore, there was a correlated relationship between the whole woody plant percent cover and the grassland percent cover. This might mean that there were more open areas for grassland, after the woody brushes were removed.

This study's results have shown that there was no significant relationship between the amount of spring discharge to the Ashe juniper or other woody plants percent cover in the Pedernales River watershed. Moreover, there was no significant relationship to the amount of spring discharge to the whole woody plants percent cover. This result showed difference from an earlier study by Huang (2006), in Honey Creek, that streamflow in first-order catchments can be augmented through woody plant removal. But, this result here showed similarity to another earlier study by Wilcox et al. (Wilcox et al. 2005), in the western part of the Edwards Plateau, that changes in woody plant cover had no influence on the streamflow.

However, there was very weak correlated relationship between the amounts of spring discharge with the percentage of grassland cover in the first-order catchments. The results of this analysis mean that there was little more of a spring discharge when there are more open range areas on which woody shrubs have been removed for more open space, and the surface of the soil covered by grasses. Removal brush decreased water loss through interception and evapotranspiration by replacing woody vegetation with a type that depletes less water, low biomass species, and shallow-rooted species (Davis and Pase 1977, Hibbert 1983). However, if the woody plants were removed for cropland, the spring discharge would not increase. This result might be from the fact that the crop depleted much of the water from the soil, and hence the vegetation cover converted from woody plants cover into cropland could not increase the spring discharge. To increase the water yield via changing vegetation cover, one needs to follow the major criteria and exceed 450 mm in annual precipitation (Bosch and Hewlett 1982, Blackburn

1983, Wilcox 2002), clear a significantly sized area (Rich and Gottfried 1976), have the groundwater table be within a few meters of the surface (Wilcox et al. 2006), and replace woody plants with a type that depletes less of the water species (Davis and Pase 1977).

VEGETATION PATTERNS IN THE RIPARIAN ZONES OF SMALL SPRING STREAMS

SPECIES REPONSE IN RIPARIAN ZONES

The riparian area of vegetation along the first-order spring streams in the Pedernales watershed was highly diverse. In this study, a total of 132 vascular plant species from 95 genera were encountered in the sampling process in the riparian area (Appendix C). The majority of herbaceous species belonged to forbs (50 species) and grasses (42 species). The remainder was just two vine species and one fern species. The most common botanical families of herbaceous plant were *Poaceae*, *Asteraceae*, and *Verbenacea*. The scattered woody overstory consisted of 21 families with 36 species in the riparian area. The most substantially represented botanical family was *Fagaceae* (11 species) with the most common genus being *Quercus*.

The mean number of herbaceous species was approximately 19 and the mean number of woody species was approximately 4 per spring site, while the average number of species per quadrat was 12. The riparian area vegetation was dominated by a relatively small number of species (Table 4.5). The most abundant herbaceous species included the sedge *Carex planostachys Kunze*, the grasses *Bothriochloa ischaemum*, *Stipa leucotricha*, *Schizachyrium scoparium*, *Aristida oligantha Michx*, and *Bouteloua* *curtipendula,* the forbs *Sida albutifolia*, and *Salvia farinacea*. In addition to woody species, the most abundant shrubs were *Quercus virginiana*, *Juglans microcarpa*, *Juniperus ashei*, and *Quercus buckleyi*.

TABLE 4.5. Common riparian area species in the Pedernales watershed.

Species		Frequency	Mean % cover	Mean % cover when present	IV
Herbaceous					
King Ranch Bluestem	*Bothriochloa ischaemum*	221	9.09	37.00	17.64
Little Bluestem	*Schizachyrium scoparium*	179	5.59	28.12	11.41
Texas Wintergrass	*Stipa leucotricha*	207	4.62	20.09	10.19
Oldfield Threeawn	*Aristida oligantha Michx.*	147	2.43	14.90	5.86
Cedar Sedge	*Carex planostachys Kunze*	234	1.53	5.88	5.51
Mealy Sage	*Salvia farinacea*	99	1.52	13.84	3.76
Bermudagrass	*Cynodon dactylon*	34	1.90	50.40	3.54
Sideoats Grama	*Bouteloua curtipendula*	93	1.32	12.81	3.35
Meadow dropseed	*Sporobolus compositus*	56	1.47	23.63	3.12
Seep Muhly	*Muhlenbergia reverchonii*	58	1.35	20.90	2.94
Sida	*Sida albutifolia*	126	0.25	1.80	2.04
Woody					
Greenbriar	*Smilax rotundifolia*	106	0.65	5.48	32.45
Ashe Juniper	*Juniperus ashei*	108	6.65	66.54	23.30
Live Oak	*Quercus virginiana*	118	8.71	79.69	6.80
Cedar Elm	*Ulmus crassifolia*	43	2.71	68.12	5.91
Persimmon	*Diospyros virginiana*	17	0.79	49.88	5.76
Texas Persimmon	*Diospyros texana*	10	0.31	33.80	4.33
Gum Bumelia	*Bumelia lanuginosa*	6	0.12	17.33	4.17
Spanish oak	*Quercus buckleyi*	89	6.48	78.63	4.16
Twistleaf Yucca	*Yucca rupicola*	5	0.09	15.60	3.19
Lacey Oak	*Quercus laceyi*	16	1.27	86.00	2.84
Agarita	*Berberis trifoliolata*	14	0.72	55.64	1.55
Tasajillo	*Opuntia leptocaulis DC.*	3	0.03	10.00	1.36
Hackberry	*Celtis occidentalis*	16	1.15	77.94	1.31

Note. IV is the importance value.

Approximately 12 herbaceous species could be considered to be relatively important foliar cover on these riparian zones of the spring watershed. These species appeared as dominant and accounted for 69.35% of the important values (as seen in Table 4.5). These herbaceous species were King Ranch Bluestem (*Bothriochloa ischaemum*), Little Bluestem (*Schizachyrium scoparium*), Texas Wintergrass (*Stipa leucotricha*), Oldfield Threeawn (*Aristida oligantha Michx.*), Cedar Sedge (*Carex planostachys Kunze*), Mealy Sage (*Salvia farinacea*), Bermudagrass (*Cynodon dactylon*), Sideoats Grama (*Bouteloua curtipendula*), Meadow dropseed (*Sporobolus compositus*), Seep Muhly (*Muhlenbergia reverchonii*), and Sida (*Sida albutifolia*). All other woody species had important values less than 2%. In addition to the herbaceous species, on these riparian zones of the spring watershed, 5 species appeared as dominant and accounted for 74.21% of the important values (as seen in Table 4.5). These woody species were Greenbriar (*Smilax rotundifolia*), Ashe Juniper (*Juniperus ashei*), Live Oak (*Quercus virginiana*), Cedar Elm (*Ulmus crassifolia*), and Persimmon (*Diospyros virginiana*). All other woody species had important values less than 3%.

All vegetation species were classified after growth form into grasses (i.e., *Poaceae*, *Cyperaceae*, and *Juncaceae*), forbs, and woody species, following Dynesius (Dynesius et al. 2004). Grasses were the major component of the riparian areas where the average coverage was 35.12% (*SD* = 27.91). The percent cover of grasses was relatively constant from the stream bank to the upland that made up at least one-third of the sampling area (Table 4.6). The woody plant cover made up the smallest component in the riparian area. The average coverage percentage was 2.195 (*SD* = 7.50).

TABLE 4.6. The distribution of ground components coverage from the stream bank to the upland.

Distance (m)	Rock (%)	Bare Ground (%)	Litter (%)	Grass (%)	Forb (%)		Woody (%)
1	14.69	7.87	32.00	35.92	8.29	a	1.34
3	15.27	9.22	29.62	36.74	7.46	a, c	1.67
5	17.11	7.79	29.57	35.24	7.84	a, b	2.48
7	17.23	8.63	29.06	36.06	5.89	a, b, c	3.12
9	17.40	8.19	31.18	34.66	5.58	a, b, c	3.00
11	17.84	7.70	31.72	34.67	5.29	a, b, c	2.78
13	16.41	10.01	30.86	35.41	4.72	a, b, c	2.59
15	19.18	9.88	32.00	32.48	4.30	a, b, c	2.17
17	20.10	9.49	30.02	35.89	3.11	c	1.33
19	21.86	12.08	27.09	34.10	3.44	b, c	1.41
Average	17.71	9.09	30.31	35.12	5.59		2.19
F	0.79	0.96	0.32	0.17	2.82	**	0.78

Note. ** $p < 0.01$.

In addition, the presence of woody vegetation significantly related to the distribution of rocks on the ground, r (900) = -0.13 (p<0.001). On the rocky sites, there were fewer vegetation covers, so there were fewer woody and herbaceous plants.

In addition, the woody canopy was also relatively smaller on those rocky spring sites, r (900) = -0.12 (p<0.001). Furthermore, the relationship between the percentages of woody canopy and percentages of litter cover was significantly positive, r (900) = 0.48 (p<0.001). The dropped leaves and branches were the sources of litter on the ground, and hence more woody cover produced more litter cover. The higher woody species coverage was in the transition zone, which was between the stream bank and the upland, around 6-12 meters away from the stream bank (as seen in Figure 4.8). However, there was no significant difference in the woody plant coverage between the transition zone and the stream bank or the transition zone and the uplands.

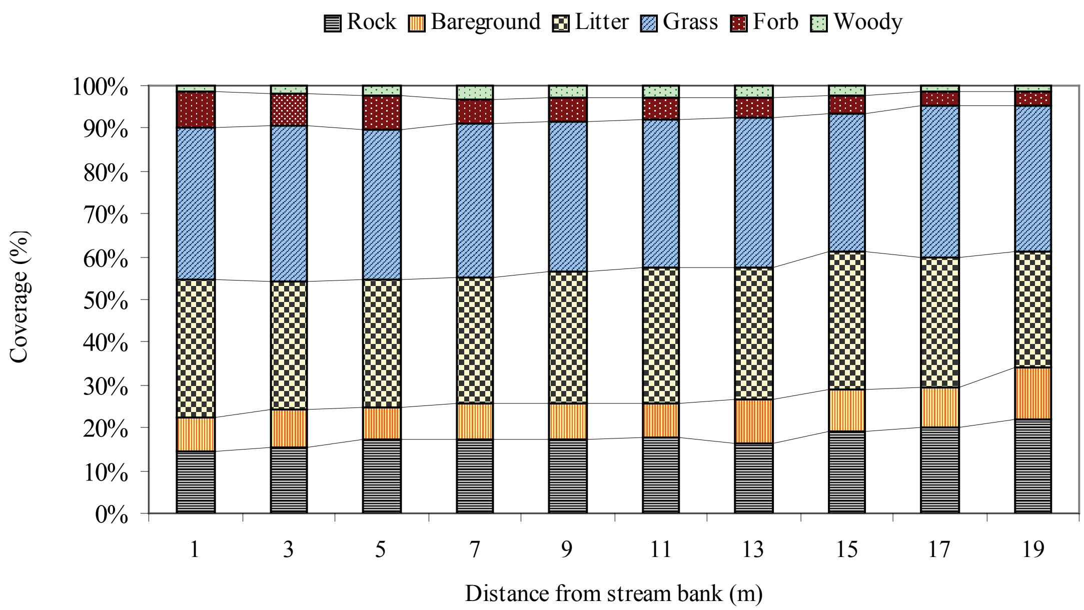

FIG. 4.8. Horizontal trends of ground components for the Pedernales watershed.

In addition to the grasses and woody plants, forbs were also distributed over the Pedernales riparian area. Although the ratio of the forbs coverage was small, there was a clear trend of distribution from the stream bank to the uplands. The average coverage of forbs was 2.82% (*SD* =10.26). There was a higher level of coverage along the stream bank (8.29%). The percent cover of forbs decreased with the sampling plots further away from the stream bank. A one-way ANOVA indicated significant differences in percent cover of forbs across the ten different distances from the stream bank, F (9, 890) = 2.82, $p < 0.01$, $\eta^2 = 0.03$. Table 4-6 summarizes the ANOVA results. To assess pairwise differences among the ten levels for distances away from the stream bank, an LSD follow-up procedure ($p = 0.05$) was performed. The results indicate that the percent cover of forbs along the stream bank (0-5 m) was significantly higher than in both the transition zone (6-15 m) and the uplands (16-19 m). The percent of forbs in the uplands was significantly lower than in the transition zone.

Besides horizontal environment gradients from the stream bank to the uplands, there was a longitudinal environment gradient from the springhead to the downstream. In the abiotic components, the average percent cover of rock decreased slightly from the springhead (18.85%, *SD* = 19.88) to the downstream (16.61%, *SD* = 18.03), 90 meters away from the springhead (as seen in Figure 4.9). The major component, litter, had a higher coverage around the downstream (30.09 %, *SD* = 18.84) than in the springhead (27.61%, *SD* = 22.42). The percent cover of bare ground slightly decreased from the springhead (10.20%, *SD* = 10.04) to the downstream (8.77%, *SD* = 8.93). The coverage of those abiotics did not significantly affect the three distances from the springhead (5 m, 45 m, and 90 m).

For the longitudinal gradient, the vegetation species were also classified into different growth forms—grasses, forbs, and woody plants. For each growth form, there was no significant difference in the percent cover among those three distances from the springhead (Figure 4.9). The primary growth form, grasses, had a slightly higher coverage in the downstream (37.29%, *SD* = 21.36) than in the upstream area. This trend of grass distribution might be significantly related to the coverage of woody plants. The percent cover of woody species slightly decreased from the springhead (2.73%, *SD* = 6.09) to the downstream (1.76%, *SD* = 3.52). The percent cover of forbs was relatively similar to those three distances from the springhead. The average coverage of forbs in the springhead was 5.63% (*SD* = 6.83), and was 5.50% (*SD* = 6.72) in the downstream.

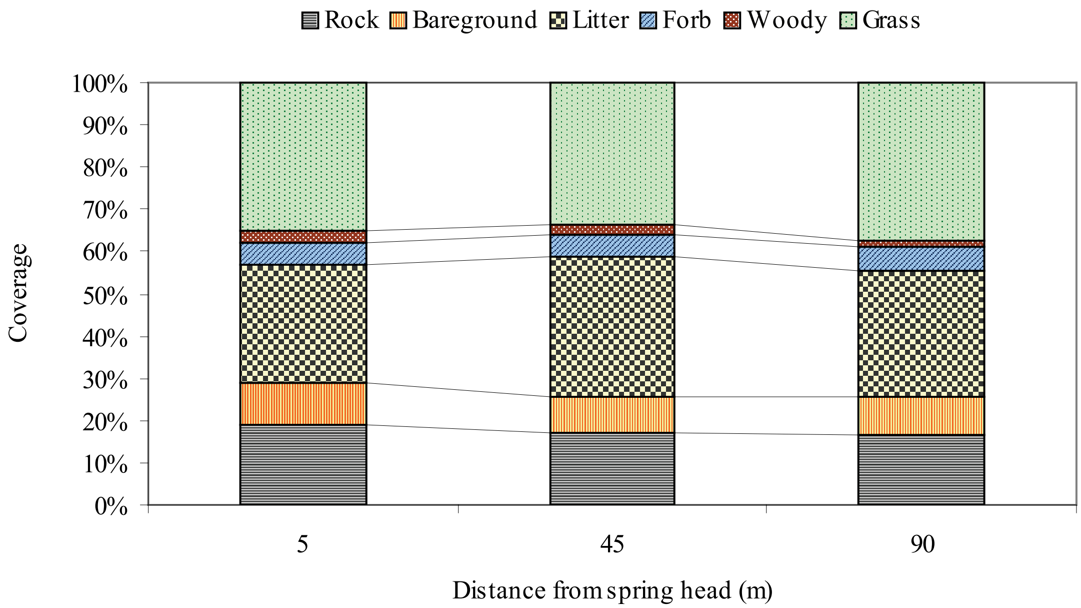

FIG. 4.9. Longitudinal trends of ground components for the Pedernales watershed.

PLANT DIVERSITY

From the sampling results, in can be concluded that the average number of woody species was 3.37 (*SD* = 2.61) for spring sites in the Pedernales watershed. The most sites (90%) had woody plant cover, with many sites (40%) having 1-2 species. Almost half of the sites (47%) had 3-8 woody species in the riparian areas along the stream channels (Figure 4.10). Only one site had more than 10 species of woody plants. There were three spring sites whose owners cleared all the woody plants in the riparian areas on both sides of the stream banks.

No matter how much woody plant cover there was in the riparian area, more than 10 species of herbaceous plants were encountered in the samples taken from each spring site. Over 50% of the sites had 13-20 species of herbaceous plants (Figure 4.10). There were 10 spring sites that had more than 20 species of herbaceous plants in the riparian areas. There were just 3 spring sites that had only 11-12 species of herbaceous plants. The average number of herbaceous species was 18.70 (*SD* = 4.71) for spring sites in the Pedernales watershed. In the riparian areas of both stream banks along the stream channel, the number of herbaceous plants was much more than the number of woody plants. However, there was no correlation in the number of species between the woody plants and the herbaceous plants in the riparian area (r = -0.16, n = 30, *ns*) along the stream channel.

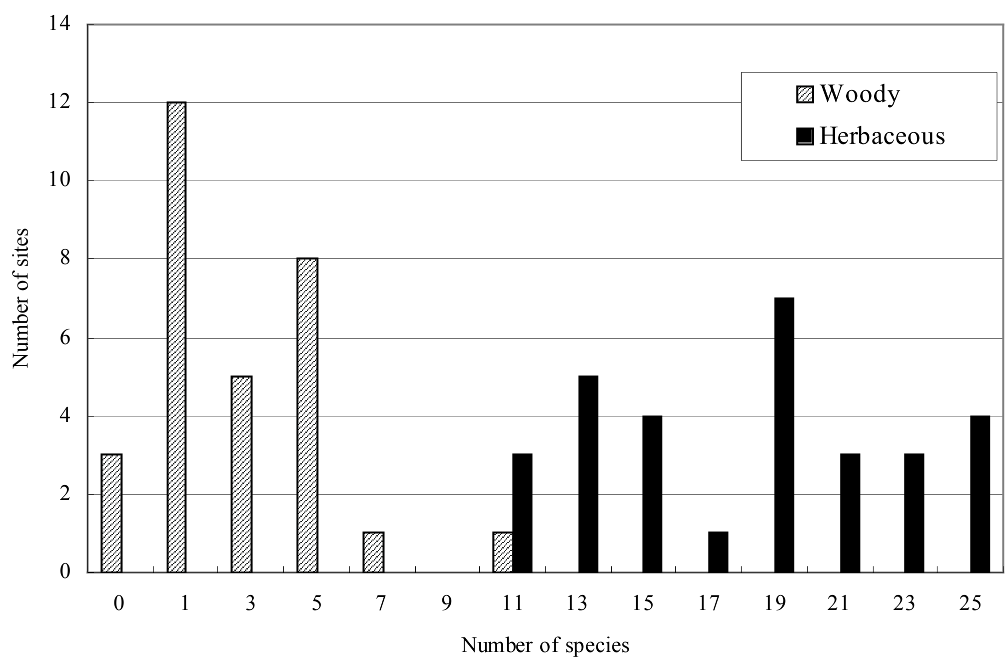

FIG. 4.10. Number of species for woody and herbaceous plants across 30 headwater spring sites in the Pedernales watershed.

All vegetation species richness (N_0) measures showed a decreasing trend with increasing distances from the stream banks. The richness number for the whole vegetation did not respond to the horizontal environmental gradient with a significant linear decrease in the riparian area. From the stream bank adjacent to the stream channel 3 meters away, the average value of the richness (N_0) was the highest (N_0 = 3.42, *SD* = 1.43) along the sampling transections (Table 4.7). The average values of richness decreased with increasing distances away from the stream bank, but the average values of richness increased in the transition zone (6 – 10 m away from the stream bank). Then the average richness dropped again at the upland area (N_0 = 2.96, *SD* = 1.29). However, it was a failure to demonstrate a statistical significance in the obvious downward trend in the richness of all the plants across the horizontal environmental gradient from the stream bank to the upland.

As described by Hill (1973), the higher order diversity indices (N_1 and N_2) might better represent the number of effective species, as N_1 and N_2 are interpreted as representing the number of abundant and very abundant species in a sample, respectively. When Hill's diversity indices (N_1 and N_2) stand for the whole vegetation in the horizontal environmental gradient from the stream bank to the upland, the ranges are from 2.11 to 2.44 for N_1 and between 1.83 and 2.11 for N_2 (Table 4.7). The values of N_1 and N_2 followed a similar trend to the values of N_0. The highest average values of N_1 and N_2 were presented respectively on the stream bank. Then, the average values of N_1 and N_2 decreased from the stream bank through the transition zone, especially at the point between the transition zone and the upland, in which the lowest values presented

TABLE 4.7. Means for total species diversity along the horizontal and longitudinal environmental gradients.

Environmental Gradient	Total diversity (*N* = 810)			Plant cover (%)
	N_0	N_1	N_2	
Horizontal from stream bank				
0 – 3	3.42± 1.43	2.44± 1.06	2.11± 0.92	45.75± 23.08
2 – 5	3.39± 1.28	2.43± 0.94	2.11± 0.81	45.63± 22.57
4 – 7	3.29± 1.32	2.38± 1.01	2.08± 0.87	45.94± 23.20
6 – 9	3.21± 1.34	2.27± 0.95	1.98± 0.76	45.19± 26.25
8 – 11	3.23± 1.36	2.24± 0.95	1.93± 0.81	43.83± 27.27
10 – 13	3.22± 1.35	2.19± 0.89	1.89± 0.75	43.43± 25.41
12 – 15	3.06± 1.37	2.11± 0.94	1.83± 0.79	41.28± 25.11
14 – 17	3.02± 1.33	2.14± 0.90	1.88± 0.78	40.07± 25.67
16 – 19	2.96± 1.29	2.16± 0.95	1.91± 0.85	40.23± 27.82
F	1.28	1.54	1.54	0.81
Longitudinal from spring head				
5	3.12± 1.35	2.20± 0.90	1.92± 0.76	43.22± 25.51
45	3.16± 1.33	2.27± 0.96	1.99± 0.83	41.56± 24.84
90	3.32± 1.34	2.32± 1.01	2.00± 0.86	45.67± 25.15
F	1.64	1.18	0.84	1.82

between 12-15 meters away from the stream bank (N_1 = 2.96, *SD* = 1.29; N_2 = 2.96, *SD* = 1.29). After the turning point (12-15 m away from the stream bank), the trend of the average N_1 and N_2 values increased at the upland. The average values of N_1 and N_2, presented between 16-19 meters away from the stream bank, respectively, were 2.16 (*SD* = 0.95) and 1.91 (*SD* = 0.85). However, the increasing rate of N_1 and N_2 in the uplands was lower than the decreasing rate from the stream bank through the transition zone. Ultimately, the results failed to demonstrate that the statistical significance of all species diversity differed between the different areas – the stream bank, transition zone, and uplands – along the horizontal environmental gradient.

For the longitudinal environmental gradient, the whole vegetation species richness (N_0) measures showed an increasing trend from the springhead (5 m) to the downstream (90 m). The highest value of richness presented in the downstream (90 meters away from the spring head) vegetation community, N_0 = 3.32, *SD* = 1.34 (Table 4.7). The lowest vegetation richness presented at the springhead, N_0 = 3.12, *SD* = 1.35. The average values of N_0 did not respond to the longitudinal environmental gradient with any statistical significance of an increasing trend in the riparian area. Then, the values of N_1 and N_2 followed a similar trend to the values of N_0 through the longitudinal environmental gradient. Both the average values of N_1 and N_2 were lowest at the springhead (N_1 = 2.20, *SD* = 0.90; N_2 = 1.92, *SD* = 0.72) and were highest in the downstream (N_1 = 2.20, *SD* = 1.01; N_2 = 1.92, *SD* = 0.86). The average values of N_1 and N_2 did not respond to the longitudinal environmental gradient from the springhead to the downstream with statistical significance.

The total herbaceous cover at the stream bank (44.24%) adjacent to the stream channel was slightly higher than at the upland (38.45%). There was no statistically significant difference between those sampling plots in the riparian zone. Furthermore, the lowest herbaceous cover did not present at the furthest sampling plot (16-19 m) from the stream bank. Between 14-17 meters away from the stream channel, the ground was covered with the fewest herbaceous plants, 37.99% (Table 4.8).

TABLE 4.8. Means for herbaceous species diversity along the horizontal and longitudinal environmental gradients.

Environmental Gradient	Total diversity (*N* = 810)			Plant cover (%)
	N_0	N_1	N_2	
Horizontal from stream bank				
0 – 3	3.14± 1.50	2.25± 1.11 [a]	1.96± 0.95 [a]	44.24± 23.94
2 – 5	3.09± 1.40	2.25± 1.02 [a]	1.97± 0.87 [a]	43.59± 23.18
4 – 7	2.96± 1.33	2.17± 1.00 [a, b]	1.92± 0.85 [a, b]	42.78± 24.04
6 – 9	2.85± 1.24	2.06± 0.86 [a, b]	1.82± 0.73 [a, b, c]	41.52± 25.71
8 – 11	2.90± 1.34	2.05± 0.90 [a, b]	1.79± 0.77 [a, b, c]	40.42± 26.41
10 – 13	2.90± 1.38	1.97± 0.85 [a, b]	1.70± 0.72 [a, b, c]	40.64± 25.34
12 – 15	2.73± 1.40	1.89± 0.90 [b]	1.64± 0.75 [b, c]	38.87± 26.12
14 – 17	2.67± 1.34	1.91± 0.88 [b]	1.69± 0.75 [b, c]	37.99± 26.49
16 – 19	2.62± 1.27	1.91± 0.89 [b]	1.70± 0.79 [c]	38.45± 28.24
F	1.53	2.13 *	2.23 *	0.71
Linear	11.30 ***	15.78 ***	15.41 ***	5.45 *
Quadratic	0.01	0.47	0.77	0.40
Longitudinal from spring head				
5	2.79± 1.35	1.98± 0.90	1.75± 0.77	40.79± 25.82
45	2.85± 1.43	2.06± 0.98	1.81± 0.85	39.13± 25.89
90	2.98± 1.30	2.11± 0.94	1.84± 0.80	42.91± 24.75
F	1.43	1.28	0.90	1.50

Note. * $p \leqq 0.05$, *** $p \leqq 0.001$.

All three measures of herbaceous diversity decreased with increasing distances from the stream bank to the upland, with a significant linear trend. Mean numbers of herbaceous species per plot (N_0) were slightly higher at the bank of the stream channel (N_0 = 3.14, *SD* = 1.50) than at the upland (N_0 = 2.62, *SD* = 1.67). However, it was a failure to demonstrate a statistical significance in the obvious downward trend of the richness of the herbaceous vegetation across the horizontal environmental gradient from the stream bank to the upland.

Along the horizontal environmental gradient, the Hill's diversity indices (N_1 and N_2) for herbaceous vegetation responded with a significant decrease to the increased distances from the stream bank to the uplands. The highest average values of N_1 and N_2 were represented on the stream bank, respectively (Table 4.8). The values of N_1 and N_2 were lower at the transition zone and at the upland, especially at 12-15 meters away from the stream bank, which presented the lowest values, respectively (N_1 = 1.89, *SD* = 0.90; N_2 = 1.64, *SD* = 0.75). After the turning point (12-15 m away from the stream bank), the trend of the average N_1 and N_2 values mildly increased at the upland. The one-way ANOVA analysis indicated a significant difference of N_1 across the riparian zone from the stream bank to the upland, in addition to significant linear decreases, F (8, 801) = 2.13, $p < 0.05$, $\eta^2 = 0.02$. The values of N_2 were also significantly different between those plots across the riparian zone, F (8, 801) = 2.23, $p < 0.05$, $\eta^2 = 0.02$, and had a trend similar to that of N_1 (Table 4.8). To assess pairwise differences among the nine levels for distances away from the stream bank, an L-S-D follow-up procedure ($p = 0.05$) was performed. The results indicate that the values of N_1 along the stream bank (0-6 m) differed significantly from both the transition zone (6-12 m) and the uplands (12-19 m). In addition to N_1, The values of N_2 along the stream bank (0-6 m) also differed significantly from both the transition zone (6-10 m) and the uplands (10-19 m).

For the longitudinal environmental gradient, the herbaceous vegetation species richness (N_0) measures increased from the springhead (5 m) to the downstream (90 m). The highest value of richness presented themselves in the downstream (90 meters away from the spring head) vegetation community, $N_0 = 2.98$, *SD* = 1.30 (Table 4.8). The lowest vegetation richness presented itself at the springhead, $N_0 = 2.79$, *SD* = 1.35. There was no statistically significant difference in herbaceous vegetation species richness between those sampling plots along the longitudinal environmental gradient in the riparian zone. Then, the values of N_1 and N_2 of the herbaceous vegetation followed a similar trend to the values of N_0 through the longitudinal environmental gradient. Both the average values of N_1 and N_2 were lowest at the springhead ($N_1 = 1.98$, *SD* = 0.90; $N_2 = 1.75$, *SD* = 0.77) and were highest in the downstream ($N_1 = 2.11$, *SD* = 0.94; $N_2 = 1.84$, *SD* = 0.80). There was no statistically significant difference in the herbaceous vegetation species diversity index between those sampling plots along the longitudinal environmental gradients from the springhead to the downstream in the riparian zone.

However, the trend of woody species cover was not similar to the herbaceous plant cover. There were lower woody plant covers along the stream banks and at the uplands, but there was a higher level of woody plant cover in the transition zone. At approximately 6-9 m away from the stream bank, there was the highest average woody plant cover, 3.68% (*SD* = 8.86). There was more woody cover from the transition zone to the uplands than the area of stream bank adjacent to the stream channel (Table 4.9).

TABLE 4.9. Means for woody species diversity along the horizontal and longitudinal environmental gradients.

Environmental Gradient	Total diversity (*N* = 810)			Plant cover (%)
	N_0	N_1	N_2	
Horizontal from stream bank				
0 – 3	0.28± 0.52	0.25± 0.45	0.25± 0.43	1.51± 4.08
2 – 5	0.31± 0.51	0.28± 0.47	0.28± 0.45	2.04± 6.09
4 – 7	0.33± 0.54	0.31± 0.49	0.30± 0.47	3.17± 8.10
6 – 9	0.36± 0.59	0.34± 0.53	0.33± 0.51	3.68± 8.86
8 – 11	0.33± 0.51	0.31± 0.47	0.30± 0.45	3.41± 8.89
10 – 13	0.32± 0.54	0.30± 0.49	0.29± 0.46	2.79± 6.98
12 – 15	0.32± 0.50	0.31± 0.47	0.30± 0.47	2.41± 5.51
14 – 17	0.35± 0.53	0.33± 0.49	0.33± 0.48	2.08± 5.50
16 – 19	0.34± 0.59	0.32± 0.54	0.31± 0.51	1.78± 4.52
F	0.18	0.25	0.25	1.15
Longitudinal from spring head				
5	0.33± 0.56	0.31± 0.51	0.29± 0.49	2.42± 6.96
45	0.31± 0.49	0.30± 0.45	0.29± 0.43	2.44± 6.16
90	0.34± 0.55	0.32± 0.51	0.31± 0.49	2.76± 7.04
F	0.13	0.12	0.11	0.22

In this study, some spring sites were under brush control management and were free of woody plant cover. Therefore, in three spring sites there were no woody species encountered in the riparian zone. The richness number for woody plants did not respond to the horizontal environmental gradient with a significant trend in the riparian area. There were two high peaks of richness, among 6-9 m (N_0 = 0.36, *SD* = 0.59) and 14-17 m (N_0 = 0.35, *SD* = 0.53), respectively. Because there was a higher level of woody plant cover at the transition zone and at the uplands, the woody species richness (N_0) was also higher at the transition zone and the uplands than at the stream bank. Although it was lower at the uplands than at the transition zone, there was as higher richness at the uplands than at the transition zone (Table 4.9). Between those sampling plots, there was no statistically significant difference along the horizontal environmental gradient in the riparian zone.

From the stream bank adjacent to the stream channel to the transition zone in the riparian area, the measures of woody diversity increased with increasing distances from the stream bank (Table 4.9). Along the horizontal environmental gradient, the lowest average score on Hill's diversity indices for woody plants presented at 0 - 3 meters from the stream channel ($N_1 = 0.25$, $SD = 0.45$; $N_2 = 0.25$, $SD = 0.43$). The mean number of woody species diversity indices (N_1 and N_2), measured between 6 - 9 meters away from the stream bank, was highest, respectively ($N_1 = 0.34$, $SD = 0.53$; $N_2 = 0.33$, $SD = 0.51$). After the highest peak diversity, the average N_1 and N_2 values decreased slightly at the interface between the transition zone and the upland area. In addition, the mean number of woody species diversity indices increased again at the uplands. The trend of the average N_1 and N_2 values presented an inverted U-shape at the uplands, which was similar to the trends at the transition zone. Around 14-17 m, there was a second turning point at which the average values of N_1 and N_2 both were 0.33. However, the results failed to demonstrate that the statistical significance of woody species diversity differed between the different areas — the stream bank, transition zone, and the uplands — along the horizontal environmental gradient.

For the longitudinal environmental gradient, there were lower woody plant covers at the springhead, 2.42% (*SD* = 6.96). Additionally, the woody cover slightly increased with an increase in distance from the springhead. The mean of the woody plant cover was slightly higher down stream, 2.76% (*SD* = 7.04). However, there was no statistical significance in the woody plant cover between the levels at the springhead and the downstream (Table 4.9).

Although there was a slight increase in the trend of woody vegetation cover from the springhead to the downstream, the average number of woody species richness (N_0) did not follow the same trend (Table 4.9). The mean numbers of woody species richness (N_0) were slightly higher at the upstream (5 m from the springhead) and the downstream area (90 m from the springhead) than in the middle area (45 m from the springhead). The average values of N_0 did not respond to the longitudinal environmental gradient with the statistical significance of an increasing trend in the riparian area.

The average Hill's diversity indices of woody plants along the longitudinal environmental gradient followed a trend similar to that of the richness index. The lowest values of N_1 and N_2 were aaround 45 meters away from the springhead area (N_1 = 0.30, *SD* = 0.45; N_2 = 0.29, *SD* = 0.43). The average values of N_1 and N_2 did not respond to the longitudinal environmental gradient from the springhead to the downstream with statistical significance.

In this study, the scores on the Hill's diversity indices (N_1 and N_2) for woody species were between 0 and 1.10 for N_1 and from 0 to 1.05, respectively. For woody species, N_1 and N_2 diversity scores had a substantially smaller range due to fewer numbers of species and more uneven distribution of individuals among the various species. In other words, there was a greater disparity between the very abundant species of woody plants and those that were only rarely encountered in the spring sites.

COMMUNITY RESPONSE ACROSS A GRADIENT

The changing vegetation patterns in the riparian zone were examined by the degree of similarity between the first plot and other plots along the same sampling transection line. The degree of similarity was based upon a comparison of the presence or absence of the species in each pair of the sampling plots. The calculated similarity coefficients provide a means of relating each pair of the sampling plots.

In this study, the sampling plot just adjacent to the stream channel was the first origin for calculating the Jaccard's similarity index. The results were illustrated in the Figure 4.11 where the similarity index was present for the whole body of data from the 30 spring sites. The average similarity declined with a distance reflecting the fact that the further away from the first plot it was, the less similar it was, with a significantly linear trend. The mean number of similarities was highest at the plot one meter away from the initial plot (M = 0.39, SD =0.24). The lowest value of similarity was at the furthest plot from the stream bank along the transection line, M = 0.13, SD =0.20 (Table 4.10). The one-way ANOVA analysis indicated a significant difference of similarity across the riparian zone from the stream bank to the uplands, with a significant linear decrease, F (8, 800) = 12.33, $p < 0.001$, $\eta^2 = 0.11$.

To assess pairwise the different levels of similarity among the nine levels of distances away from the stream bank, an LSD follow-up procedure (p = 0.05) was performed. The composition of vegetation communities changed gradually along the horizontal environmental gradients in the riparian zone. Depending upon the levels of similarity, the plant communities could be separated into four groups, but those vegetation groups overlapped. The results also presented that there was a relatively high similarity in the coefficients between the adjacent plant sampling plots.

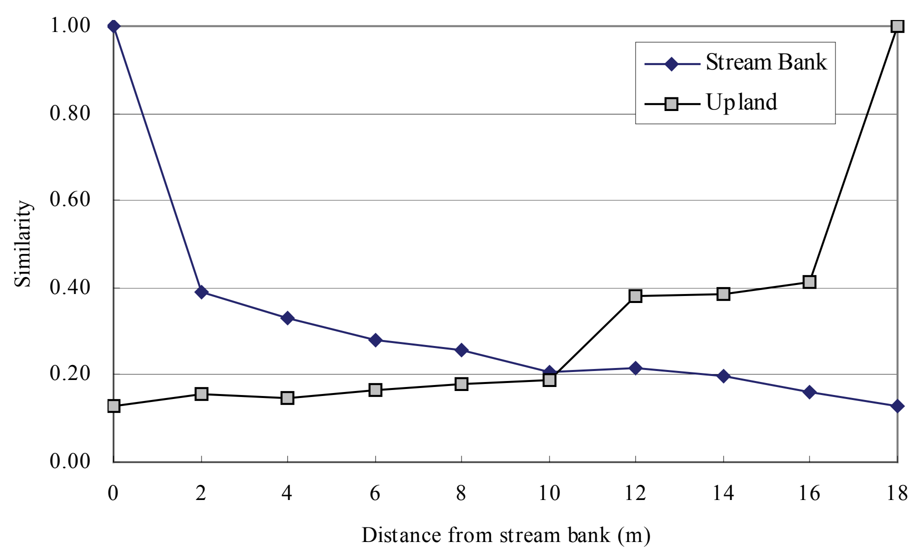

FIG. 4.11. The similarity coefficient as it changed along the horizontal environmental gradients.

Furthermore, Jaccard's similarity index was applied by calculating the origin at the uplands which was the furthest sampling plot from the stream bank. The similarity coefficients decreased with distance from the origin, with a significant quadratic trend along the horizontal environmental gradient. The highest average values of similarity in the coefficients presented themselves at the upland (Table 4.10), especially the sampling plot adjacent to the origin (M = 0.41, SD =0.25). The lowest mean value of the similarity coefficient was at the plot furthest from the upland along the transection line, $M = 0.13$, $SD = 0.20$ (Table 4.10). The one-way ANOVA analysis indicated a significant difference of similarity across the riparian zone from the stream bank to the upland, with a significant quadratic decrease, $F\ (8, 719) = 21.77$, $p < 0.001$, $\eta^2 = 0.20$.

TABLE 4.10. Means for vegetation similarity along the horizontal environmental gradients.

Environmental gradient	**Similarity**			
	Origin at stream bank		Origin at upland	
Horizontal distance from stream bank (M)				
0	1.00		0.13± 0.20	a
2	0.39± 0.24	a	0.16± 0.20	a
4	0.33± 0.25	a, b	0.15± 0.19	a
6	0.28± 0.24	b, c	0.16± 0.20	a
8	0.26± 0.23	b, c	0.18± 0.21	a
10	0.21± 0.21	c, d	0.19± 0.21	a
12	0.22± 0.21	c, d	0.38± 0.26	b
14	0.20± 0.21	c, d	0.39± 0.26	b
16	0.16± 0.21	d	0.41± 0.25	b
18	0.13± 0.20	d	1.00	
F	12.33 ***		21.77 ***	

Note. *** $p \leqq 0.001$.

To assess pairwise the different levels of similarity among the nine levels of distances away from the stream bank, an LSD follow-up procedure ($p = 0.05$) was performed. The composition of vegetation communities changed gradually along the horizontal environmental gradients in the riparian zone. Depending upon the levels of similarity, the plant communities could be separated into two very different groups without any significant overlap. There was a substantial increase in of the similarity coefficient from between 10-12 m away from the stream bank. The plant communities among 12-17 m away were relatively more similar to the origin than the other plant communities among 0-11 m along the sampling transection lines in the riparian zone.

DISCUSSION

Riparian areas are some of the most productive range sites in the West and have a greater diversity of plant and wildlife species than adjoining uplands (Naiman and Decamps 1997, Masters and Sheley 2001). The riparian area of vegetation along the first-order spring streams in Pedernales watershed is highly diverse. According to the earlier Pedernales River watershed research report from the LCRA (LCRA. 2000), the vegetation is dominated by woodlands and forests with grasslands, including live oak, Ashe juniper, Texas oak, honey mesquite, black cherry, Cedar elm, sugarberry, and netleaf hackberry. A distinct understory may be present, and it is likely to be dominated by yaupon, American beautyberry, hoptree, and Mexican buckeye. Several species on the Edwards Plateau are limited in distribution to central or south-central Texas, including Texas persimmon (*Diospyros texana*), Ashe juniper (*Juniperus ashei*), and cedar elm (*Ulmus crassifolia*) are all examples (van Auken et al. 1980). Texas persimmon, Ashe juniper, and cedar elm were encountered during this investigation and were the most dominant woody species in the riparian zone. However, we encountered different understory woody plants than the LCRA's report (2000). All of above-mentioned understory species—yaupon, American beautyberry, hoptree, and

Mexican buckeye—were absent in the riparian zones along the smaller streams. Instead, we found greenbriar (*Smilax rotundifolia*) and twistleaf yucca (*Yucca rupicola*) to be the most common understory woody species in the riparian zones.

Some consider most of the Edwards Plateau to be a southern extension of the Mixedgrass Prairie (Chapin et al. 2002). This land type supports midgrasses, and is dominated by little bluestem (*Schizachryium scoparium*), Texas wintergrass (*Stipa leucotricha*), silver bluestem (*Bothriochloa saccharoides*), and sideoats grama (*Bouteloua curtipendula*) (LCRA. 2000). We encountered all of these species during this investigation. Little bluestem and Texas wintergrass were the most dominant herbaceous species in the riparian zones. We also found old-field three-awn, a common herbaceous species in these areas because it increases with overgrazing. Cedar sedge (*Carex planostachys Kunze*) was encountered with a relatively high frequency, especially near the stream bank, because of the accessible water (Wood and Wood 1988).

Herbaceous plants made up the largest portion of the land cover. Woody plant litter was the second largest contributor to cover, and it increased with woody plant cover. In contrast, the relationship between the woody plants and rock cover was significantly negative. The proportion of rock cover had substantial effect on woody vegetation distribution, but not on herbaceous vegetation distribution. This might be that herbaceous plants are able to initially establish themselves in chinks in the rocks, relying on the sparse and shallow soil. However, it is hard for woody plant roots to penetrate through the rock layer. This study’s result is somewhat different from that of Waichler et al. (2001), who conducted a study on the western juniper community and found there was not clear relationship between tree and understory composition with the rock cover.

The abundance of plant species along the longitudinal gradient was weakly correlated with land cover. This suggests that the abiotic factors did not change rapidly enough in the small watershed to elicit change. For example, there was both a small volume and a low velocity of stream flow, and therefore, the water cannot erode soil or carry a substantial amount of the sediment downstream. A similar hydraulic regime within 100 meters could result in a similar land cover distribution. Thus, an environmental gradient with a horizontal distance away from the channel is a primary factor influencing diversity (van Coller et al. 2000).

In the riparian zones, herbaceous vegetation cover made up the largest proportion of the surface land cover. Herbaceous species are often closely associated with a particular level of soil moisture and may be a more sensitive to water conditions than woody or shrub species (Castelli et al. 2000). This is supported by our results; we found no clear relationship between woody plant distribution and the environmental gradients. The herbaceous vegetation, however, responded to increasing lateral distances from the stream bank with declining percentages of cover. Species richness also decreased with an increase in the lateral distance from the stream bank. In contrast, herbaceous diversity gradually decreased with increasing distances along the lateral gradients from the stream bank. The highest herbaceous diversity (N_1 and N_2) was found on the stream bank, respectively. The upland supported the lowest herbaceous diversity. Furthermore, herbaceous diversity decreased from the stream bank to the uplands. This herbaceous vegetation pattern was similar to that of other research that found a greater diversity of plants near the stream channel than that of the adjoining uplands (Patten 1998, Masters and Sheley 2001).

The use of specific individual species to delineate the boundaries of a riparian zone may lead to incorrect placement (Lamb 2002). To avoid this, we calculated a similarity index between the first plot (channel bank) and the last plot (upland) with other sampling plots along the transection line. This will help us uncover changes in the vegetation in the riparian zone. The gradually changing similarity of vegetation will act as an index to explore the vegetation pattern responses to the average spring flow and Ashe juniper cover.

A COMPARISON OF THE EFFECTS OF SPRING FLOW AND JUNIPER COVER ON PLANT DIVERSITY

RELATIONSHIP BETWEEN PLANT DIVERSITY WITH SPRING FLOW

Woody Vegetation Patterns

Total woody canopy cover increased in response to the increasing average amounts of spring discharge, in a significantly linear fashion (Table 4.11). The one-way ANOVA analysis indicated a significant difference of woody species dominance among the three levels of spring discharge, F (2, 544) = 7.33, $p \leqq 0.001$, $\eta^2 = 0.03$. To assess pairwise differences of the woody plant canopy cover among the three levels of spring discharge, an LSD follow-up procedure (p = 0.05) was performed. The results presented that there were obviously different levels of woody canopy cover between the spring sites with low amounts of spring discharge (<0.05 L/s) and high amounts of spring flow (>1.00 L/s).

TABLE 4.11. Mean levels for woody species diversity at different spring discharges.

Average Spring Flow (L/s)	Woody Diversity			Woody cover (%)
	N_0	N_1	N_2	
< 0.05	1.29± 0.60	1.22± 0.46 [a]	1.19± 0.41 [a]	86.77± 44.68 [a]
0.05 – 1.00	1.33± 0.69	1.27± 0.56 [a,b]	1.25± 0.52 [a,b]	96.65± 52.00 [a,b]
> 1.0	1.44± 0.67	1.35± 0.54 [b]	1.31± 0.50 [b]	100.00± 45.44 [b]
F	2.85	3.24 *	3.42 *	7.33 ***
Linear	5.26 *	6.41 *	6.83 **	14.65 ***
Quadratic	0.37	0.04	0.00	0.03

Note. * $p \leqq 0.05$, ** $p \leqq 0.01$, *** $p \leqq 0.001$.

All three woody diversity measures increased with an increase in the average amounts of spring discharge (Table 4.11). Diversity numbers for woody plants responded to increased average amounts of spring flow with significantly linear increases. The one-way ANOVA analysis indicated no significant difference in species richness (N_0) among the three levels of spring discharge, F (2, 544) = 2.85, $p > 0.05$, $\eta^2 = 0.01$. The woody species richness was not influenced by the amount of spring discharge. Values of N_1 and N_2 increased with increasing average amounts of spring discharge, along with the lower values on the spring sites with the smaller spring discharge. The one-way ANOVA analysis indicated a significant difference of N_1 among the three levels of spring discharge, F (2, 544) = 3.24, $p < 0.05$, $\eta^2 = 0.01$. The values of N_2 were also significantly different between these levels of spring flow, F (2, 544) = 3.42, $p < 0.05$, $\eta^2 = 0.01$, and had a similar trend of N_1 (Table 4.11). To assess a pairwise difference of N_1 and N_2 among the different levels of spring discharge, an LSD follow-up procedure

($p = 0.05$) was performed. The results indicated that the number of abundant species and the number of very abundant species for the average spring flow >1.0 L/s differed significantly from the average spring flow <0.05 L/s. There was an increase in the dominance of fewer species in those sites with a lower average spring flow (<0.05 L/s).

Spring sites with a <0.05 L/s average spring flow in the contributing basin had a cumulative total of 24 species, and the spring sites with >1.00 L/s average spring flow had a cumulative total of 26 species. The spring sites with 0.05-1.00 L/s average spring flow in the contributing basin had the fewest cumulative total at 21 species. This was illustrated in the comparisons of dominance-diversity curves in Figure 4.12. The spring <0.05 L/s plots had fewer woody species in common among themselves than did the spring 0.05-1.00 L/s plots, resulting in a higher combined species richness (as can be seen in the longer right tail in Figure 4.12).

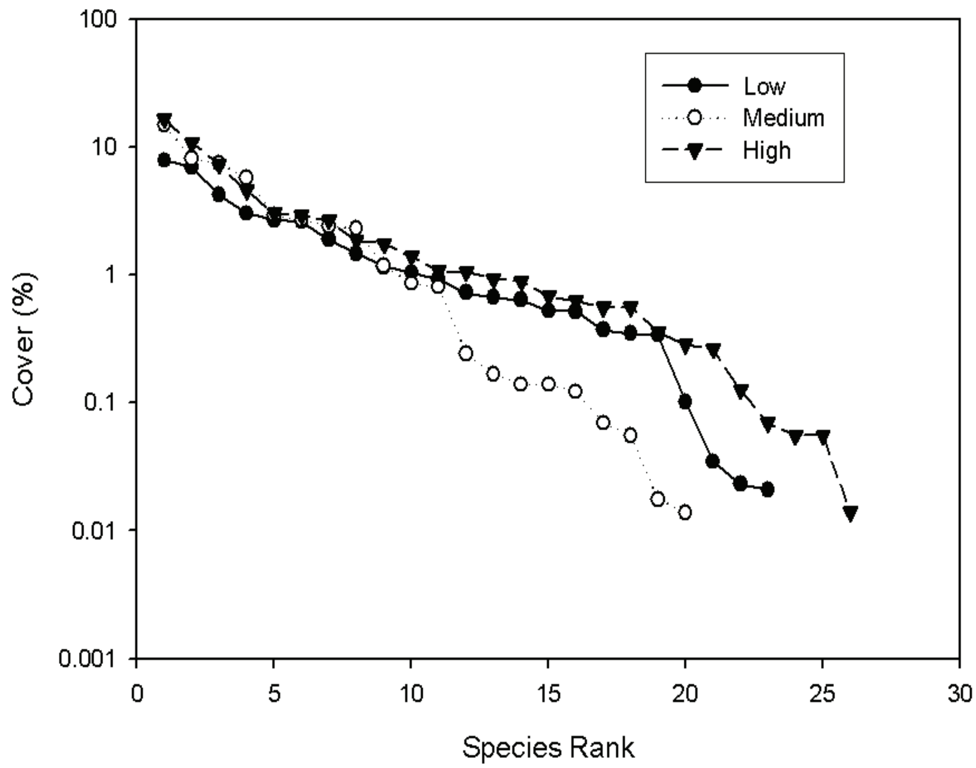

FIG. 4.12. Dominance-diversity curves for woody plant species in headwater springs with contributing basins under low (<0.05 L/s), medium (0.05-1.00 L/s), and high (>1.00 L/s) average spring flows.

Herbaceous Vegetation Patterns

The total herbaceous cover percentages were significantly different between the three levels of average spring discharge, F (2, 871) = 9.33, $p \leqq 0.001$, $\eta^2 = 0.02$. A significant quadratic tern was reflected in the extreme susceptibility of the herbaceous cover to 0.05-1.00 L/s. To assess pairwise differences in the percentages of canopy cover among the different levels of spring discharge, an LSD follow-up procedure (p = 0.05) was performed. The results presented that the percentages of herbaceous cover for sites with an average spring flow of 0.05-1.00 L/s were significantly lower than the sites with an average spring flow of <0.05 L/s or >1.00 L/s (Table 4.12). Additionally, there was no significant difference in the percent of herbaceous plant cover between the sites with spring flow <0.05 L/s and >1.00 L/s.

TABLE 4.12. Means of herbaceous species diversity at different spring discharges.

Average Spring Flow (L/s)	Herbaceous Diversity			Herb cover (%)
	N_0	N_1	N_2	
< 0.05	2.94± 1.35	2.14± 0.99 [a,b]	1.88± 0.87 [a]	44.49± 25.15 [a]
0.05 – 1.00	3.01± 1.43	2.28± 1.05 [a]	2.00± 0.94 [a]	35.38± 25.49 [b]
> 1.0	2.94± 1.70	2.03± 1.04 [b]	1.71± 0.95 [b]	44.50± 30.71 [a]
F	0.22	3.74 *	6.56 ***	9.33 ***
Linear	0.00	1.91	5.69 *	0.05
Quadratic	0.44	5.91 *	8.10 **	18.60 ***

Note. * $p \leqq 0.05$, ** $p \leqq 0.01$, *** $p \leqq 0.001$.

The herbaceous species richness (N_0) was not influenced by the amount of spring discharge. It was a failure to demonstrate a statistical significance in herbaceous cover among the different levels of spring discharge, F (2, 871) = 0.22, $p > 0.05$, $\eta^2 = 0.00$. No matter how much the springs discharged, there were only about three different herbaceous species found in this sample. The values of N_1 and N_2 were lower on the spring sites with smaller spring discharges (Table 4.12). The one-way ANOVA analysis indicated a significant difference of N_1 among the three levels of spring discharge, F (2, 871) = 3.74, $p < 0.05$, $\eta^2 = 0.01$. The values of N_2 were also significantly different between these levels of spring flow, F (2, 871) = 6.56, $p \leqq 0.001$, $\eta^2 = 0.02$, and had a trend similar to N_1 (Table 4.12). A significant quadratic tern was reflective of the extreme susceptibility of the herbaceous community to 0.05-1.00 L/s. To assess a pairwise difference between N_1 and N_2 among the different levels of spring discharge, an LSD follow-up procedure (p = 0.05) was performed. The results indicated that the number of abundant herbaceous species for sites with an average spring flow of >1.0 L/s differed significantly from the sites with an average spring flow 0.05-1.00 L/s, and the numbers of very abundant herbaceous species for sites with an average spring flow of >1.0 L/s differed significantly from other sites with an average spring flow of <1.0 L/s. There was an increase in dominance of fewer species in those sites with a lower average spring flow (<0.05 L/s).

Spring sites with a <0.05 L/s average spring flow in the contributing basin had a cumulative total of 72 herbaceous species, and the spring sites with a >1.00 L/s average spring flow had a cumulative total 70 herbaceous species. The spring sites with 0.05-1.00 L/s average spring flow in the contributing basin had the fewest cumulative total at 57 species. This was illustrated in the comparisons of dominance-diversity curves in Figure 4.13. The spring <0.05 L/s and >1.00 L/s plots had dominant herbaceous species, but they also had fewer herbaceous woody species in common among themselves than the spring 0.05-1.00 L/s.

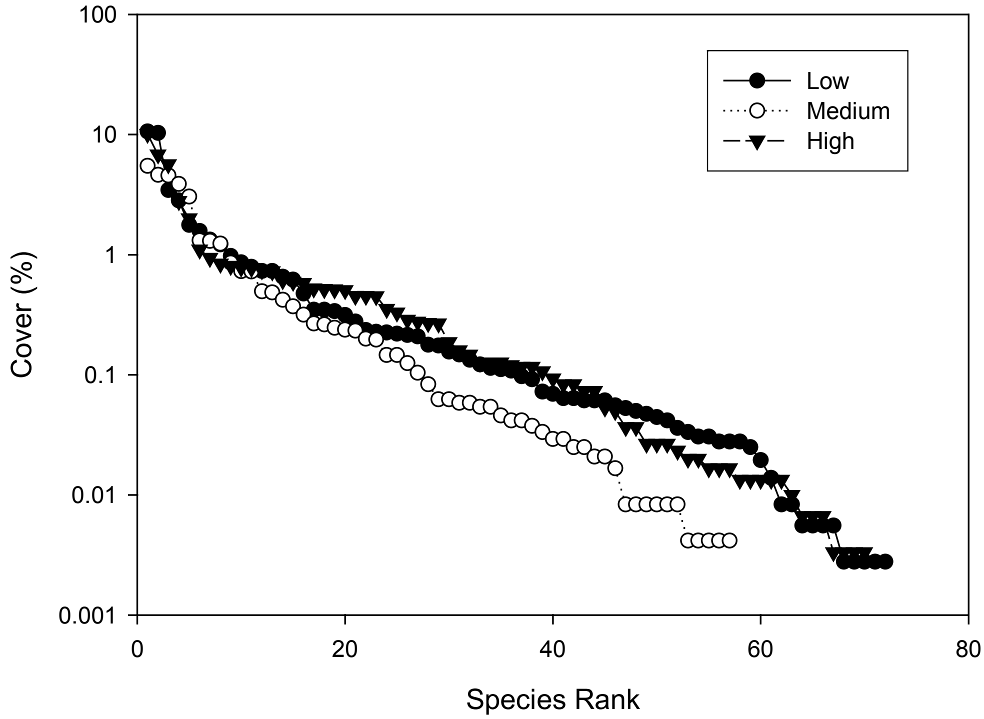

FIG. 4.13. Dominance-diversity curves for herbaceous plant species in headwater springs with contributing basins under low (<0.05 L/s), medium (0.05-1.00 L/s), and high (>1.00 L/s) average spring flows.

RELATIONSHIP BETWEEN PLANT DIVERSITY WITH WOODY CANOPY COVER

Woody Vegetation Diversity with Ashe Juniper Cover

The estimates of vegetation cover in the riparian zone derived from the 20-meter-transection along the stream channel were the most clearly interpretable for associating the juniper cover management alternatives to a potential response of the riparian flora. The estimates of canopy cover made up of Ashe juniper in the 30 basins ranged from 0 to 58.5%, with a mean of 6.65%. Almost half of the spring watersheds had 0% juniper cover in the riparian zone; approximately one-third of the spring watersheds had juniper cover of 0.4 - 2.0 % in the riparian zone; and the last third had a juniper cover of 3.0 – 58.5 % in the riparian zone. Percent juniper cover was positively correlated to percent total woody cover.

The total woody canopy cover increased in response to increasing average amounts of juniper canopy cover, which was significantly linear (Table 4.13). The one-way ANOVA analysis indicated a significant difference of woody species dominance among the three levels of juniper canopy cover, F (2, 544) = 11.67, $p < 0.001$, $\eta^2 = 0.04$. To assess a pairwise difference of the woody plant canopy cover among the three levels of juniper percent cover, an LSD follow-up procedure (p = 0.05) was performed. The results presented that there were obviously different levels of woody canopy cover between the spring sites with Ashe juniper cover (0.1-2.0 %, >2.0 %) and the spring sites without Ashe juniper cover (0.0 %). Juniper removal decreased the total woody canopy cover in the riparian zone in the spring sites. Therefore, there were lower percentages of woody canopy cover in the spring sites without Ashe juniper than in other sites with juniper brushes.

TABLE 4.13. Means for woody species diversity at different levels of juniper canopy cover.

Average Juniper Cover (%)	Woody Diversity			Woody cover (%)
	N_0	N_1	N_2	
0.0	1.22± 0.49 [a]	1.18± 0.40 [a]	1.15± 0.37 [a]	84.10± 42.79 [a]
0.1 – 2.0	1.45± 0.73 [b]	1.36± 0.57 [b]	1.32± 0.52 [b]	108.36± 51.22 [b]
> 2.0	1.39± 0.69 [b]	1.31± 0.56 [b]	1.28± 0.51 [b]	96.62± 45.92 [b]
F	5.64 **	5.76 **	5.57 **	11.67 ***
Linear	6.33 *	6.58 *	6.38 *	6.69 **
Quadratic	5.42 *	5.40 *	5.22 *	17.48 ***

Note. * $p \leqq 0.05$, ** $p \leqq 0.01$, *** $p \leqq 0.001$.

All three woody diversity measures were lower in those spring sites without Ashe juniper than in other sites with juniper brushes (Table 4.13). Diversity numbers for woody plants responded to the increased average amounts of juniper canopy cover. Woody species richness (N_0) showed fewer woody species on those spring sites without juniper cover. In the spring sites with juniper cover, there were more woody species. The one-way ANOVA analysis indicated significant differences of species richness (N_0) among the three levels of juniper canopy cover, F (2, 544) = 5.64, $p < 0.01$, $\eta^2 = 0.02$. The average woody species richness was slightly higher in the sites with 0.1-10.0% juniper covers than in the sites with over 10% juniper covers. However, there was no significant difference between these two levels of Ashe juniper cover. Values of N_1 and N_2 were also lower on the spring sites where there is no juniper cover. The one-way ANOVA analysis indicated a significant difference of N_1 among the three levels of Ashe juniper canopy cover, F (2, 544) = 5.76, $p \leqq 0.01$, $\eta^2 = 0.02$. The values of N_2 were also significantly different between these levels of juniper canopy cover, F (2, 544) = 5.57, $p < 0.01$, $\eta^2 = 0.02$, and had a similar trend of N_1 (Table 4.13). To assess the pairwise differences of N_1 and N_2 among the different levels of juniper canopy cover, an LSD follow-up procedure ($p = 0.05$) was performed.

The results indicated that the number of abundant species and the number of very abundant species for the spring sites with Ashe juniper cover differed significantly from the sites without juniper cover. Furthermore, the average values of N_1 and N_2 were slightly higher in the sites with 0.1-10.0% juniper cover than in the sites with over 10% juniper cover.

Spring sites with over a 2.0% average juniper cover in the contributing basin had a cumulative total of 23 species, and the spring sites with 0.0% average juniper canopy cover had a cumulative total of 22 species. The spring sites with a 0.1-2.0 % average Ashe juniper cover in the contributing basin had the smallest cumulative total at 20 species. This was illustrated in the comparison of a dominance-diversity curve, as shown in Figure 4.13. The spring sites with 0.1-2.0% Ashe juniper canopy cover had fewer woody species in common among themselves than sites with a juniper cover over 2.00%, resulting in a higher combined species richness (as seen by the longer right tail in Figure 4.14.)

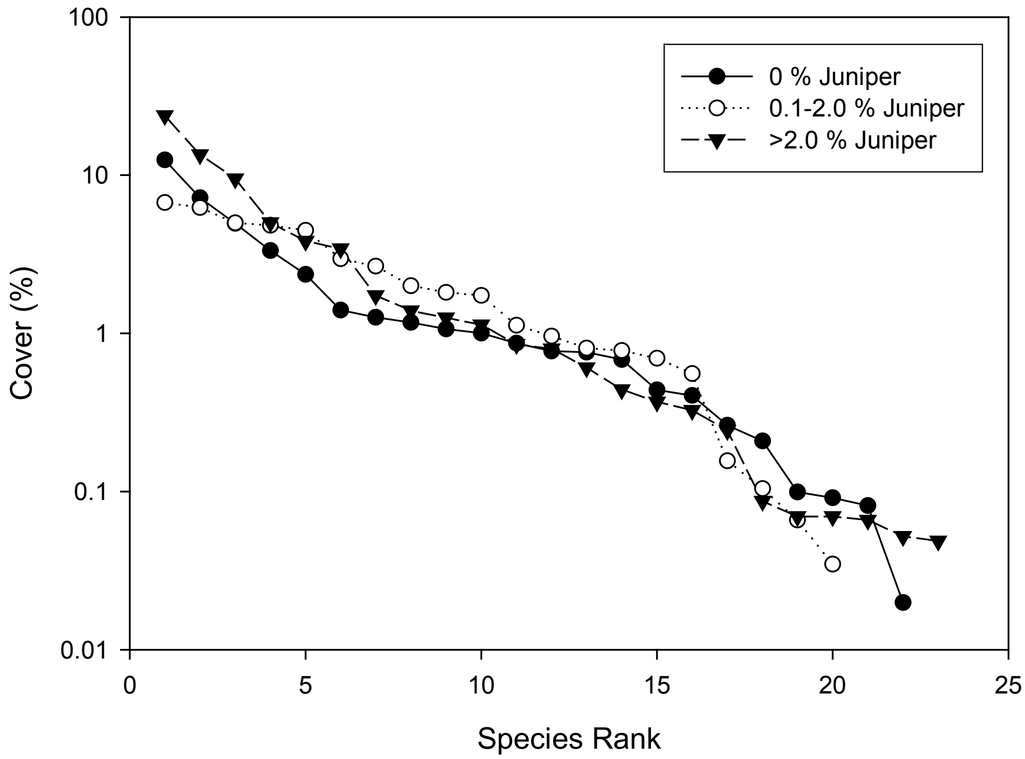

FIG 4.14. Dominance-diversity curves for woody plant species in headwater springs with contributing basins under 0.0% juniper cover, 0.1-2.0% juniper cover, and >2.0% juniper cover.

Herbaceous Vegetation Diversity with Ashe Juniper Cover

Total herbaceous cover decreased in response to increasing average amounts of juniper canopy cover, with a significantly linear trend (Table 4.14). The one-way ANOVA analysis indicated a significant difference of herbaceous species dominance among the three levels of juniper canopy cover, F (2, 871) = 14.44, $p < 0.001$, $\eta^2 =$ 0.03. To assess the pairwise differences in the herbaceous plant canopy cover among the three levels of juniper percent cover, an LSD follow-up procedure ($p = 0.05$) was performed. The results presented that there were obviously different levels of herbaceous cover between the spring sites with a high juniper canopy cover (>2.0 %) and the sites with a lower juniper cover (0.0 % and 0.1-2.0 %). The herbaceous percent cover increased when the Ashe juniper canopy cover decreased.

TABLE 4.14. Means for herbaceous species diversity at different levels of juniper canopy cover.

Average Juniper Cover (%)	Herbaceous Diversity			Herb cover (%)
	N_0	N_1	N_2	
0.0	3.32± 1.50 [a]	2.35± 1.09 [a]	2.04± 0.97 [a]	45.80± 26.61 [a]
0.1 – 2.0	2.61± 1.25 [b]	1.86± 0.82 [b]	1.64± 0.72 [b]	43.90± 27.52 [a]
> 2.0	2.68± 1.57 [b]	2.05± 1.02 [b]	1.76± 0.97 [b]	34.12± 27.37 [b]
F	23.73 ***	18.90 ***	15.60 ***	14.44 ***
Linear	28.88 ***	12.82 ***	13.40 ***	27.53 ***
Quadratic	12.22 ***	19.66 ***	13.33 ***	3.61

Note. *** $p \leqq 0.001$.

All three woody diversity measures were lower in the spring sites with a low Ashe juniper canopy cover (0.1-2.0 %) than in other sites with a higher juniper percent cover (>2.0%) or without juniper (0.0%). The one-way ANOVA analysis indicated a significant difference in the herbaceous species richness (N_0) among the three levels of juniper canopy cover, F (2, 871) = 23.73, $p < 0.001$, $\eta^2 = 0.05$. The average herbaceous species richness was significantly higher in the sites without juniper canopy covers (0.0 %) than in the sites with Ashe juniper covers (0.1-2.0 5 and >2.0 %). However, there was no significant difference in the herbaceous species richness between these two levels of Ashe juniper cover (Table 4.14). Values of N_1 and N_2 were also higher in the spring sites where there was no juniper cover. The one-way ANOVA analysis indicated a significant difference of N_1 among the three levels of Ashe juniper canopy cover, $F\,(2, 871) = 18.90$, $p < 0.001$, $\eta^2 = 0.04$. The values of N_2 were also significantly different between these levels of juniper canopy cover, $F\,(2, 871) = 15.60$, $p < 0.001$, $\eta^2 = 0.04$, and had a trend similar to that of N_1 (Table 4.14). To assess the pairwise difference between N_1 and N_2 among the different levels of juniper canopy cover, an LSD follow-up procedure (p = 0.05) was performed.

The results indicated that the number of abundant species and the number of very abundant species for the spring sites with Ashe juniper cover differed significantly from the sites without juniper cover. The results presented an increase in dominance of fewer herbaceous species in the spring sites with more juniper canopy cover.

Spring sites with a 0.0% average of juniper canopy cover had a high cumulative total of 78 herbaceous species, and the spring sites with 0.1-2.0% average juniper cover in the contributing basin had a cumulative total of 59 species. The spring sites with over a 2.0% average Ashe juniper cover in the contributing basin had the lowest cumulative total at 55 herbaceous species. This was illustrated in the comparisons of dominance-diversity curves in Figure 4.15. The spring sites with Ashe juniper canopy cover had more dominant herbaceous species.

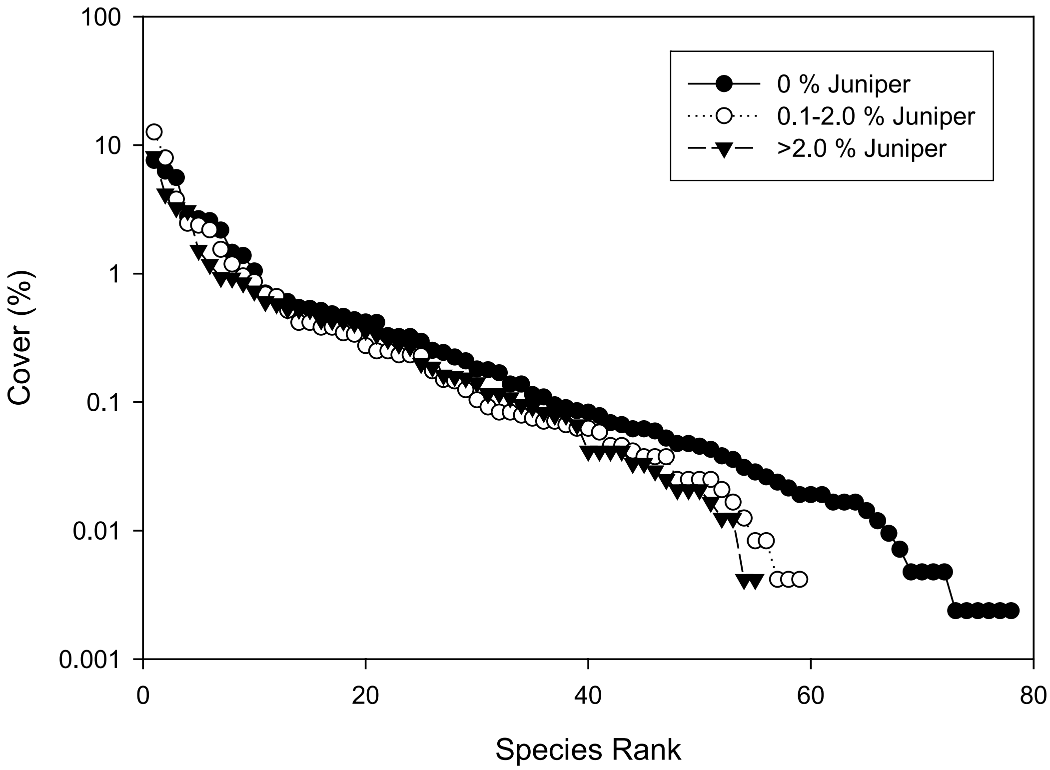

FIG. 4.15. Dominance-diversity curves for herbaceous species in headwater springs with contributing basins under 0.0% juniper cover, 0.1-2.0% juniper cover, and >2.0% juniper cover.

Herbaceous Vegetation Diversity with Other Woody Canopy Cover

In the Pedernales watershed, some ranches removed the Ashe juniper, but they left the other woody vegetation on the spring watersheds. Those woody canopy covers also provided shade for herbaceous vegetation in the riparian zone along the stream channel. The estimates of woody canopy cover excluded the Ashe juniper in the 30 basins, ranging from 0.96 to 96.31%, with a mean of 41.91%. About one-third of the spring sites had 0.96 – 30.0% woody plant cover in the riparian zone; and one-third of the spring watersheds had over 50% woody canopy cover without the Ashe juniper (Table 4.15). There was a significantly positive correlation between the percentages of juniper canopy cover and the percentages of other woody vegetation cover, r (874) = 0.24, p<0.001.

TABLE 4.15. Means for herbaceous species diversity at different levels of juniper canopy cover and other woody plant canopy covers.

Other Woody Cover (%)	Average Juniper Cover (%)	Herbaceous Diversity			Herb cover (%)
		N_0	N_1	N_2	
<30	0.0	3.72± 1.53	2.50± 1.10	2.14± 0.96	50.69± 24.59
	0.1 – 2.0	2.49± 1.21	1.77± 0.79	1.58± 0.67	49.24± 28.92
	> 2.0	2.53± 1.26	1.97± 0.89	1.77± 0.80	40.34± 26.58
	Average	3.06± 1.50	2.16± 1.02	1.89± 0.87	47.44± 26.65
30-51	0.0	3.16± 1.32	2.32± 1.02	2.04± 0.89	41.09± 23.05
	0.1 – 2.0	2.73± 1.26	1.84± 0.82	1.62± 0.70	56.63± 20.03
	> 2.0	3.03± 1.86	2.29± 1.27	1.93± 1.22	39.32± 30.88
	Average	3.03± 1.45	2.20± 1.06	1.92± 0.95	44.29± 25.28
>51	0.0	3.00± 1.57	2.19± 1.14	1.90± 1.05	45.25± 31.79
	0.1 – 2.0	2.64± 1.27	1.97± 0.86	1.73± 0.78	30.20± 24.60
	> 2.0	2.58± 1.63	1.98± 0.94	1.64± 0.94	23.79± 22.36
	Average	2.77± 1.51	2.06± 1.00	1.77± 0.95	34.33± 28.57

The ANOVA analysis on these herbaceous covers in the riparian zone revealed a main effect on the percentages of other woody plant covers, F (2, 865) = 23.88, p<0.001, with high woody canopy covers (> 51%) reporting fewer herbaceous vegetation covers (M = 34.33) than did low woody canopy covers (M = 47.44 and 44.29). There was another significant main effect for the percentages of juniper cover, F (2, 865) = 14.97,

$p<0.001$. The influence of juniper canopy cover on the coverage of herbaceous plants was similar to other woody species cover. An interaction between the percentages of juniper cover and the percentages of other woody plant covers, F (4, 865) = 8.63, $p<0.001$, also was found (Table 4.16). An analysis of the effects of other woody species covers revealed that the herbaceous coverage decreased with an increasing Ashe juniper cover when the riparian zone was highly covered by other woody plants, whereas the herbaceous coverage increased with a decreasing Ashe juniper cover when highly covered by other woody plants (Table 4.15).

The herbaceous diversity measures were influenced by a juniper canopy cover more than by cover provided by other woody species. An ANOVA analysis of the herbaceous richness (N_0) in the riparian zone revealed only a single main effect for the percentages of juniper cover, F (2, 865) = 20.32, $p<0.001$, without juniper canopy covers (0 %) reporting a higher herbaceous richness (M = 3.32) than with a juniper cover (M = 2.61 and 2.68). An interaction between the percentages of juniper cover and the percentages of other woody plant cover, F (4, 865) = 4.99, p = 0.001, was found (Table 4.16). An analysis of the effects of other woody species covers revealed that the herbaceous richness (N_0) increased without the Ashe juniper cover when the riparian zone was highly covered by other woody plants, whereas the herbaceous richness decreased with an increasing Ashe juniper cover when highly covered by other woody plants (Table 4.15).

TABLE 4.16. Analysis of the variance of riparian herbaceous vegetation diversity associated with woody canopy covers in basins contributing to headwater springs.

Source of Variation	Sum of Squares	*d.f.*	Mean Square	F	Sig. of *F*
Coverage					
Main effects	1625203.97	9	180578.22	265.70	<0.001
Juniper cover	20348.37	2	10174.18	14.97	<0.001
Other woody cover	32464.90	2	16232.45	23.88	<0.001
Two-way interactions	23456.42	4	5864.11	8.63	<0.001
Residual	587890.03	865	679.64		
Total	2213094.00	874			
N_0					
Main effects	7792.04	9	865.78	416.53	<0.001
Juniper cover	84.46	2	42.23	20.32	<0.001
Other woody cover	7.76	2	3.88	1.87	0.155
Two-way interactions	41.47	4	10.37	4.99	0.001
Residual	1797.96	865	2.08		
Total	9590.00	874			
N_1					
Main effects	4046.84	9	449.65	448.23	<0.001
Juniper cover	34.92	2	17.46	17.40	<0.001
Other woody cover	1.36	2	0.68	0.68	0.508
Two-way interactions	11.20	4	2.80	2.79	0.025
Residual	867.74	865	1.00		
Total	4914.58	874			
N_2					
Main effects	3045.81	9	338.42	413.13	<0.001
Juniper cover	23.38	2	11.69	14.27	<0.001
Other woody cover	1.69	2	0.85	1.03	0.357
Two-way interactions	6.10	4	1.53	1.86	0.115
Residual	708.58	865	0.82		
Total	3754.39	874			

Values of N_1 and N_2 were also higher in the spring sites where there was no juniper cover. An ANOVA analysis of the herbaceous diversity (N_1) in the riparian zone revealed only a single main effect for the percentages of juniper cover, F (2, 865) = 17.40, p<0.001, without juniper canopy covers (0%) reporting a higher herbaceous diversity (M = 2.35) than with juniper covers (M = 1.86 and 2.05). An interaction between the percentages of juniper cover and the percentages of other woody plant cover can be represented by F (4, 865) = 2.80, p = 0.025 (Table 4.16).

An analysis of the effects of other woody species covers revealed that the values of N_1 for herbaceous vegetation increased with no Ashe juniper cover when the riparian zone was highly covered by other woody plants, whereas the values of N_1 decreased with increasing Ashe juniper cover when highly covered by other woody plants (Table 4.15). An ANOVA analysis of the herbaceous diversity (N_2) in the riparian zone revealed only a single main effect on the percentages of juniper cover, F (2, 865) = 14.27, p<0.001, without juniper canopy covers (0%) reporting higher herbaceous diversity (M = 2.04) than with juniper covers (M = 1.65 and 1.76). There was no other main effect or interaction between the percentages of juniper cover and the percentages of other woody plant cover (Table 4.16).

Both the Ashe juniper canopy cover and other woody species canopy covers influenced the percentages of herbaceous vegetation cover in the riparian zone in the Pedernales watershed. However, the herbaceous diversity was dominantly influenced by the juniper canopy coverage. When the Ashe juniper presented itself in the spring sites, the herbaceous diversity significantly decreased. There was a higher level of diverse herbaceous species in the riparian zone without any Ashe juniper, and vice versa.

HERBACEOUS VEGETATION SIMILARITY WITH WOODY CANOPY COVERS

Herbaceous Plant Patterns with Different Levels of Ashe Juniper Cover

The changing vegetation pattern in the riparian zone was examined by the degree of similarity under the different levels of juniper cover. The spring watersheds were separated into three levels of juniper cover. The first group of spring sites was without any juniper in the riparian zone; the second group of spring sites was covered by Ashe juniper at a level under 2%; and there was an average juniper canopy cover of more than 2% in the riparian zone in the third group of spring watersheds. In this study, the Jaccard's similarity index presented the similarity of vegetation communities between the two sampling plots.

As can be seen by comparing the vegetation communities with the first sampling plot adjoining the stream channel, the average values of the similarity declined with the increasing distance from the stream channel, with a significantly linear trend (Table 4.17). The one-way ANOVA analysis indicated a significant difference in similarity between the stream channel in the uplands and spring sites without juniper. The mean number of similarities was at its highest percent at the plot that was one meter away from the first sampling plot (M = 0.43, SD =0.21). The lowest value of similarity was at the furthest plot from the stream bank along the transect line, M = 0.13, SD =0.22 (Table 4.17). The one-way ANOVA analysis indicated a significant difference of similarity across the riparian zone from the stream bank to the uplands, with a significant linear decrease, F (8, 368) = 8.20, $p < 0.001$, $\eta^2 = 0.15$.

TABLE 4.17. Means for vegetation similarity along the horizontal environmental gradients under different percentages of juniper canopy cover.

Gradient	Similarity					
	Origin at stream bank			Origin at upland		
	0 % Juniper	0.1-2.0%juniper	>2.0 % Juniper	0 % Juniper	0.1-2.0%juniper	>2.0 % Juniper
Horizontal distance from stream bank (M)						
0	1.00	1.00	1.00	0.13± 0.22 [a]	0.17± 0.21 [a]	0.08± 0.16 [a]
2	0.43± 0.21 [a]	0.42± 0.27 [a]	0.28± 0.24 [a]	0.12± 0.15 [a]	0.22± 0.22 [a]	0.16± 0.24 [a,b]
4	0.38± 0.25 [a]	0.32± 0.20 [a,b]	0.26± 0.30 [a,b]	0.13± 0.20 [a]	0.21± 0.17 [a]	0.11± 0.16 [a,c],
6	0.36± 0.26 [a,b]	0.26± 0.23 [b,c]	0.17± 0.18 [a,c]	0.14± 0.19 [a]	0.21± 0.21 [a]	0.16± 0.21 [a,b]
8	0.26± 0.22 [b,c]	0.28± 0.22 [b,c]	0.23± 0.27 [a,d]	0.19± 0.24 [a,b]	0.21± 0.17 [a]	0.12± 0.18 [a,b]
10	0.23± 0.22 [c]	0.25± 0.23 [b,c]	0.13± 0.13 [c,d]	0.15± 0.18 [a]	0.26± 0.25 [a,b]	0.16± 0.17 [a,b]
12	0.22± 0.20 [c,d]	0.25± 0.25 [b,c]	0.17± 0.19 [b,c,d]	0.20± 0.27 [a,d]	0.29± 0.29 [a,b]	0.24± 0.26 [b,d]
14	0.22± 0.20 [c,d]	0.22± 0.24 [b,c]	0.14± 0.18 [c,d]	0.28± 0.29 [b,c,d]	0.39± 0.31 [b,c]	0.20± 0.21 [b,c ,d]
16	0.19± 0.21 [c,d]	0.22± 0.25 [b,c]	0.06± 0.09 [c]	0.37± 0.29 [c]	0.39± 0.26 [b,c,]	0.28± 0.25 [d]
18	0.13± 0.22 [d]	0.17± 0.21 [c]	0.08± 0.16 [c]	1.00	1.00	1.00
F	8.20 ***	2.30 *	3.51 ***	5.25 ***	2.71 **	2.25 *
Linear	61.46 ***	14.71 ***	23.59 ***	31.54 ***	18.07 ***	13.14 ***
Quadratic	1.58	1.29	0.07	8.25 **	2.01	0.68
Cubic	0.50	1.82	0.19	1.19	0.03	0.48

Note. * $p \leqq 0.05$, ** $p \leqq 0.01$, *** $p \leqq 0.001$.

The one-way ANOVA analysis indicated a significant difference of similarity along the sampling transect from the stream channel to the uplands in the spring sites with low (< 2%) juniper covers, F (8, 207) = 2.30, p < 0.05, η^2 = 0.08. The values of the similarity were also significantly different along the sampling transect in the spring sites with more (> 2%) juniper cover, F (2, 207) = 3.51, p < 0.05, η^2 = 0.12 (Table 4.17). No matter what level was the percentage of juniper canopy cover, there were similar trends in the vegetation patterns in the riparian zone. The composition of vegetation communities changed gradually along the horizontal environmental gradients.

Furthermore, the Jaccard's similarity index was also calculated by being based on the origin at the upland, which was the furthest sampling plot from the stream bank. The similarity coefficients decreased with increasing distances from the origin, and with a significantly linear trend along the horizontal environmental gradient. In the spring watersheds without any Ashe juniper, the highest average values of similarity coefficients presented at the upland (Table 4.17), especially the adjacent sampling plot to the origin (M = 0.37, SD =0.29). The lowest mean value of the similarity coefficient was at the furthest plot from the upland along the transec line, M = 0.13, SD =0.22. The one-way ANOVA analysis indicated a significant difference of similarity across the riparian zone from the stream bank to the upland, with a significantly linear decrease, F (8, 360) = 5.25, $p < 0.001$, $\eta^2 = 0.10$.

The one-way ANOVA analysis indicated a significant difference of similarity along the sampling transection from the stream channel to the upland in the spring sites with a low (< 2%) juniper cover, F (8, 207) = 2.71, $p < 0.01$, $\eta^2 = 0.10$. The values of similarity were also significantly different along the sampling transec in those spring sites with more (> 2%) juniper cover, F (2, 206) = 2.25, $p < 0.05$, $\eta^2 = 0.08$ (Table 4.17). No matter what the level of percentage of juniper canopy cover was, there were similar trends of vegetation pattern changes in the riparian zone. The composition of vegetation communities changed gradually along the horizontal environmental gradients. The results presented that there was a relatively high similarity coefficient between the adjacent plant sampling plots, but there were significant differences in vegetation composition between the sampling plots adjoined to the stream channel and at the uplands.

The composition of vegetation communities changed gradually along the horizontal environmental gradients from stream bank to the uplands in the riparian zone. In the 20 m riparian zone, the vegetation pattern changed less than in the spring watersheds with a lower Ashe juniper cover (< 2 %) than in the sites with a higher juniper cover (>2 %). In the low juniper canopy cover spring sites (0% and 0.1-2.0%), the average value of the similarity index between the first and the last sampling plots on the transect line were both over 0.10 (Table 4.17), but the average value of the similarity index was lower than 0.10 in the spring sites with a higher juniper canopy cover (> 2.0 %). In the spring watersheds without Ashe juniper, the vegetation communities that were away from the stream bank about 12-13 meters had the same similarity to the stream bank and the uplands (Figure 4.16). In the Pedernales watershed, the average width of the riparian zone was 12-13 m in the spring sites without Ashe juniper. When there were fewer juniper covers (<2 %), the average width of the riparian zone decreased to about 9-10 m (Figure 4.17). In the juniper cover (> 2%) sites, the average width of the riparian zone decreased to about 6 m (Figure 4.18) due to the rapid vegetation pattern changes. These results from this study presented that the increasing juniper canopy cover decreased the width of the riparian zone.

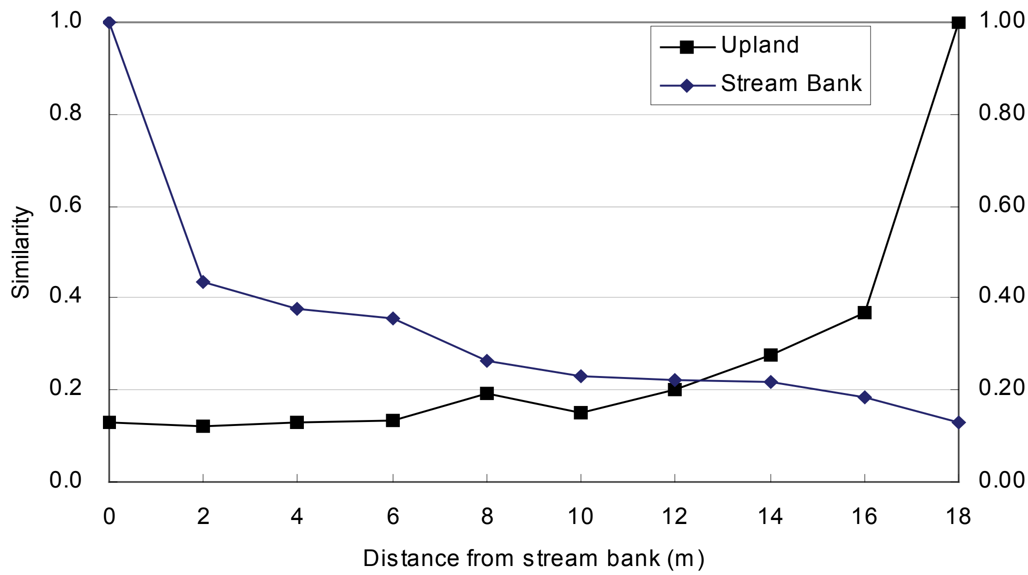

FIG. 4.16. The similarity coefficient changed along the horizontal environmental gradients with 0 % juniper canopy cover.

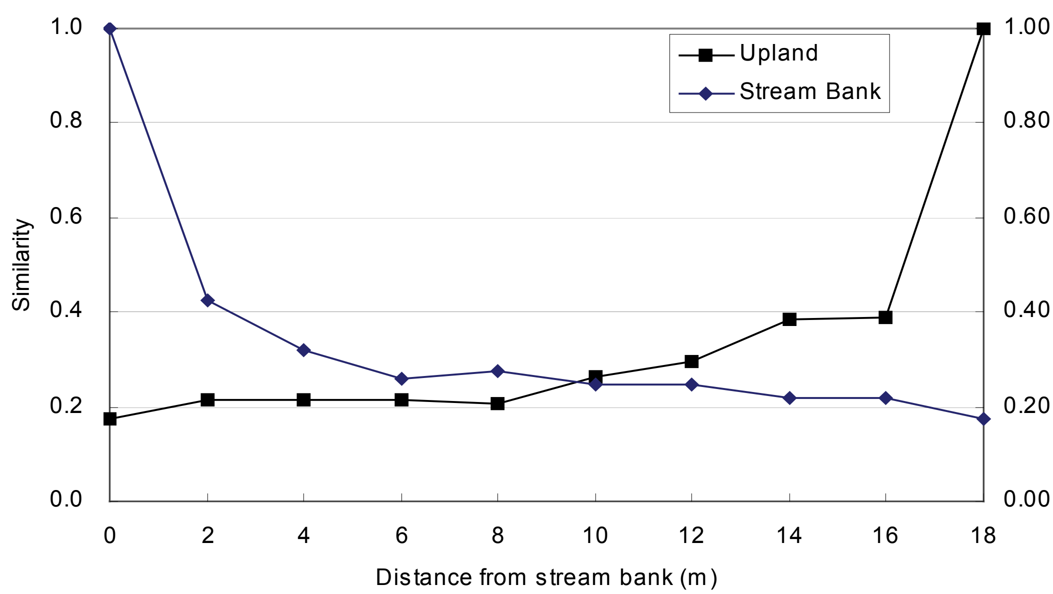

FIG. 4.17. The similarity coefficient changed along the horizontal environmental gradients with a < 2% juniper canopy cover.

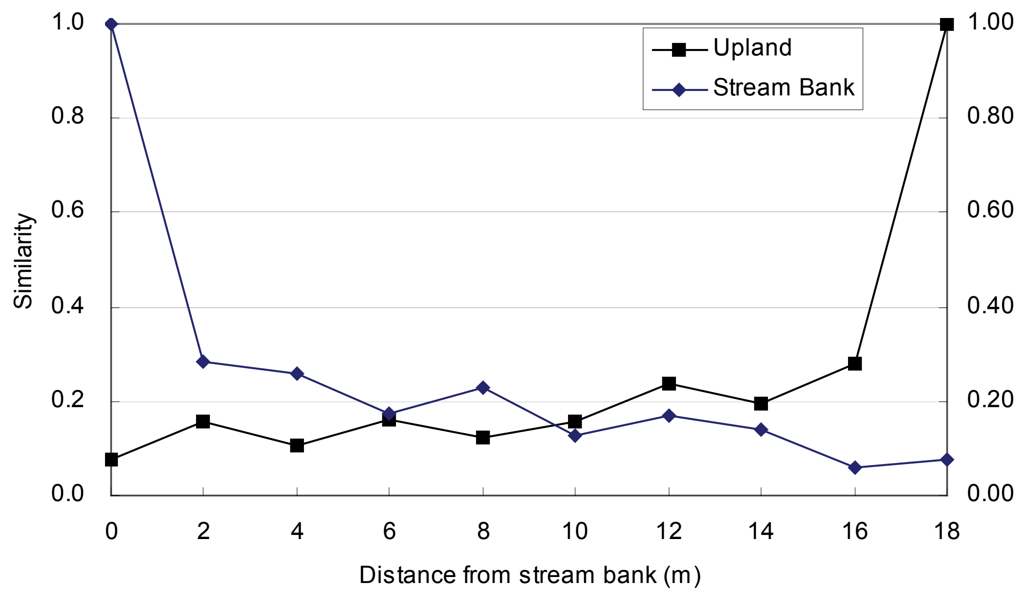

FIG. 4.18. The similarity coefficient changed along the horizontal environmental gradients with > 2 % juniper canopy cover.

Herbaceous Plant Pattern with Different Levels of Other Woody Plant Cover

The changing vegetation pattern in the riparian zone was examined by the degree of similarity under different levels of woody canopy cover except under that of Ashe juniper. The spring watersheds were separated into three levels of woody canopy cover in the riparian zone. The first group of spring sites was covered by sparse woody vegetation (≦ 30 %); the second group of spring sites was covered by woody plants to the extent of 31-51 %; and there was an average juniper canopy cover of more than 51% in the riparian zone in the third group of the spring watersheds. In this study, the Jaccard's similarity index presented the similarity of vegetation communities between the two sampling plots. To compare the vegetation communities with the first sampling plot adjoining the stream channel, the average values of similarity declined with the increasing distance from the stream channel, to a significantly linear extent (Table 4.18). The one-way ANOVA analysis indicated a significant difference in the similarity between the stream channel and the uplands in the spring sites with an insubstantial woody canopy cover ($\leqq$ 30 %). The mean number of the similarity was highest at the plot, which was one meter away from the first sampling plot (M = 0.42, SD =0.26). The lowest value of similarity was at the furthest plot from the stream bank along the transect line, M = 0.12, SD =0.21. The one-way ANOVA analysis indicated a significant difference in similarity across the riparian zone from the stream bank to the uplands, with a significant linear decrease, F (8, 288) = 5.42, $p < 0.001$, $\eta^2 = 0.13$.

The one-way ANOVA analysis indicated a significant difference in similarity along the sampling transect from the stream channel to the uplands in the spring sites with medium (31-51%) woody plant covers, F (8, 234) = 4.34, $p < 0.05$, $\eta^2 = 0.13$. The values of similarity were also significantly different along the sampling transect in the spring sites with high (> 51 %) woody vegetation covers, F (2, 260) = 3.88, $p < 0.001$, $\eta^2 = 0.11$ (Table 4.18). No matter how high the percentage of woody canopy cover, there were similar trends of vegetation pattern changes in the riparian zone. The composition of vegetation communities gradually changed along the horizontal environmental gradients.

TABLE 4.18. Mean for vegetation similarity along the horizontal environmental gradients under different percentages of woody canopy cover.

Gradient	**Similarity**					
	Origin at stream bank			Origin at upland		
	≦30 % woody	31-51 % woody	>51 % woody	≦30 % woody	31-51 % woody	>51 % woody
Horizontal distance from stream bank (M)						
0	1.00	1.00	1.00	0.12± 0.21 [a]	0.15± 0.21 [a]	0.12± 0.19 [a]
2	0.42± 0.26 [a]	0.44± 0.22 [a]	0.31± 0.22 [a]	0.14± 0.21 [a]	0.16± 0.20 [a,b]	0.17± 0.19 [a,b]
4	0.33± 0.26 [a,b]	0.35± 0.23 [a,b]	0.31± 0.27 [a]	0.13± 0.16 [a]	0.15± 0.18 [a]	0.16± 0.22 [a,b]
6	0.34± 0.26 [a,b]	0.30± 0.26 [b,c]	0.20± 0.18 [b]	0.14± 0.20 [a]	0.19± 0.20 [a,b]	0.16± 0.19 [a,b]
8	0.33± 0.23 [a,b]	0.29± 0.28 [b,c]	0.15± 0.15 [b]	0.14± 0.20 [a]	0.19± 0.19 [a,b]	0.20± 0.23 [a,b]
10	0.23± 0.23 [b,c]	0.24± 0.24 [b,c,d]	0.15± 0.15 [b]	0.12± 0.16 [a]	0.26± 0.23 [a,c]	0.19± 0.22 [a,b]
12	0.21± 0.25 [c,d]	0.25± 0.19 [b,c,d]	0.19± 0.18 [b]	0.22± 0.26 [a,b]	0.28± 0.31 [b,c]	0.22± 0.26 [a,b]
14	0.24± 0.26 [b,d]	0.20± 0.19 [c,d]	0.15± 0.17 [b]	0.28± 0.31 [b]	0.33± 0.29 [c]	0.26± 0.26 [b]
16	0.15± 0.24 [c,d]	0.19± 0.17 [c,d]	0.15± 0.20 [b]	0.33± 0.27 [b]	0.32± 0.22 [c]	0.41± 0.31 [c]
18	0.12± 0.21 [c]	0.15± 0.21 [d]	0.12± 0.19 [b]	1.00	1.00	1.00
F	5.42 ***	4.34 ***	3.88 ***	3.87 ***	2.49 *	3.80 ***
Linear	39.85 ***	32.28 ***	22.47 ***	21.78 ***	18.35 ***	22.05 ***
Quadratic	0.04	1.01	3.15	6.38 *	0.49	4.47 *
Cubic	0.24	0.85	1.26	0.63	0.60	3.59

Note. * $p \leqq 0.05$, *** $p \leqq 0.001$.

Furthermore, the Jaccard's similarity index was also calculated by basing it on the origin at the upland, which was the furthest sampling plot from the stream bank. The similarity coefficients decreased with increasing distances from the origin, with a significant linear trend along the horizontal environmental gradient. In the spring watersheds with little woody canopy cover (≦ 30 %), the highest average value of the similarity coefficient presented at the upland (Table 4.18), especially the sampling plot adjacent to the origin (*M* = 0.33, *SD* =0.27). The lowest mean value of the similarity coefficient was at the furthest plot from the upland along the transect line, *M* = 0.12, *SD* =0.21. The one-way ANOVA analysis indicated a significant difference of similarity across the riparian zone from the stream bank to the upland, with significantly linear decreases, F (8, 288) = 3.87, $p < 0.001$, $\eta^2 = 0.10$.

The one-way ANOVA analysis indicated a significant difference of similarity along the sampling transect from the stream channel to the upland in those spring sites with a medium level of woody plant cover (31-51%), F (8, 207) = 2.49, $p < 0.05$, $\eta^2 = 0.08$. The values of the similarity were also significantly different along the sampling transect in the spring sites with high (> 51 %) woody vegetation covers, F (2, 258) = 3.80, $p <$ 0.001, $\eta^2 = 0.11$ (Table 4.18). No matter how many percentages of woody canopy covers were taken, there were similar trends in vegetation pattern changes in the riparian zone. The composition of vegetation communities gradually changed along the horizontal environmental gradients. The results presented that there was a relatively high similarity coefficient between the adjacent plant sampling plots, but there were significant differences of vegetation composition between the sampling plots adjoined to the stream channel at the upland.

The composition of vegetation communities gradually changed along the horizontal environmental gradients from the stream bank to the uplands in the riparian zone. In the 20 m riparian zone, the trend of vegetation patterns changed similarly, no matter how many percentages of woody canopy cover were recorded. The average values of the similarity index between the first and the last sampling plots on the transect line were all between 0.12-0.15 (Table 4.18). In the spring watersheds with a low woody canopy cover, the vegetation communities approximately 12 meters away from the stream bank had the same similarity to the stream bank and the upland (Figure 4.19). In the Pedernales watershed, the average width of the riparian zone was 12 m in those spring sites with a low woody canopy cover (≦30 %). When there was a medium level of woody plant cover (31-51 %), the average width of the riparian zone decreased to about 10 m (Figure 4.20). In the high woody plant cover (>51 %) sites, the average width of the riparian zone decreased to about 7 m (Figure 4.21) due to the rapid vegetation pattern changes. The results from this study presented that the increasing woody canopy cover decreased the width of the riparian zone.

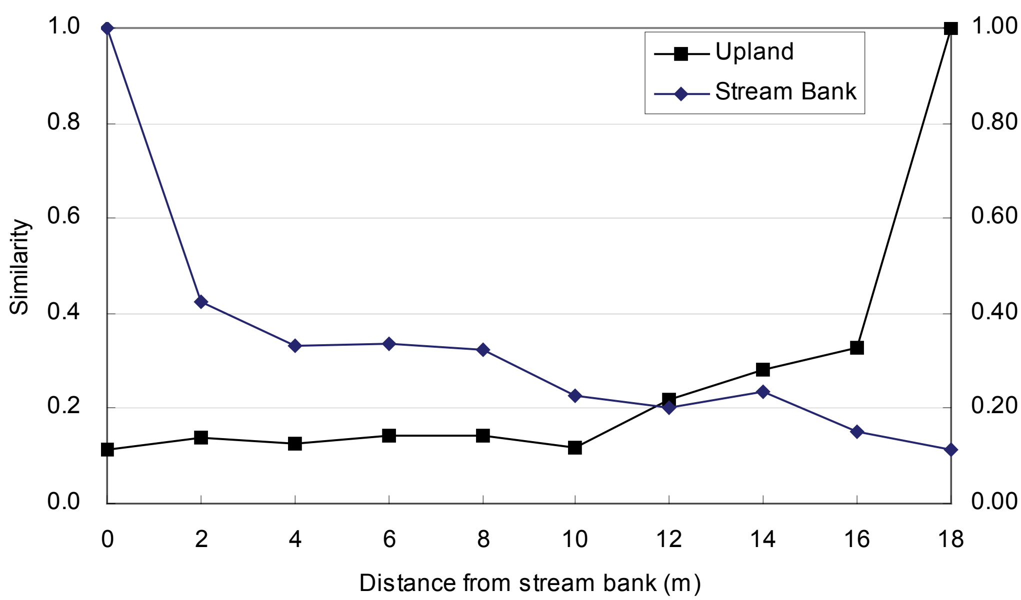

FIG. 4.19. The similarity coefficient changed along the horizontal environmental gradients with ≦ 30 % woody canopy cover (except Ashe juniper).

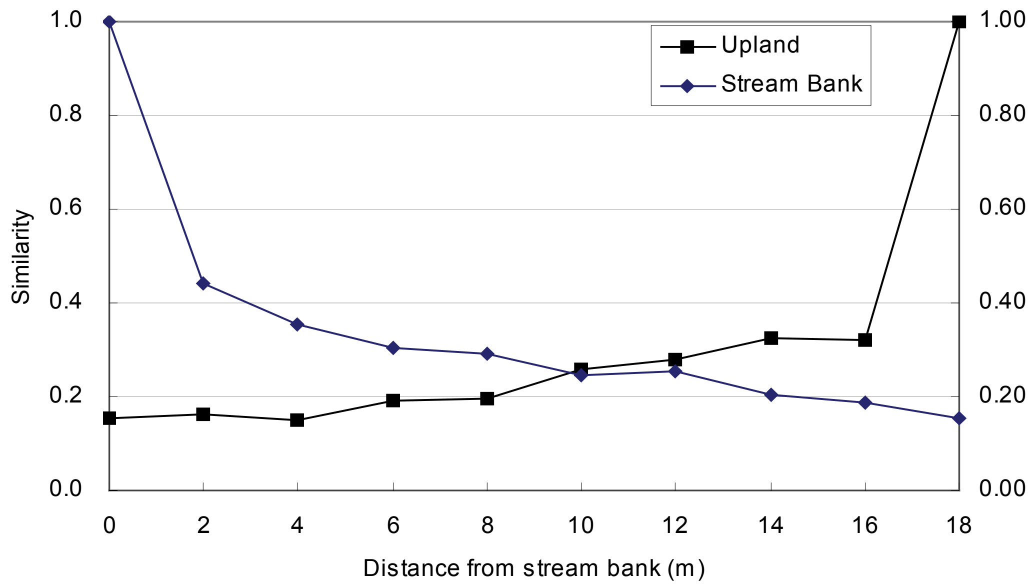

FIG. 4.20. The similarity coefficient changed along the horizontal environmental gradients with 31-51 % woody canopy cover (except Ashe juniper).

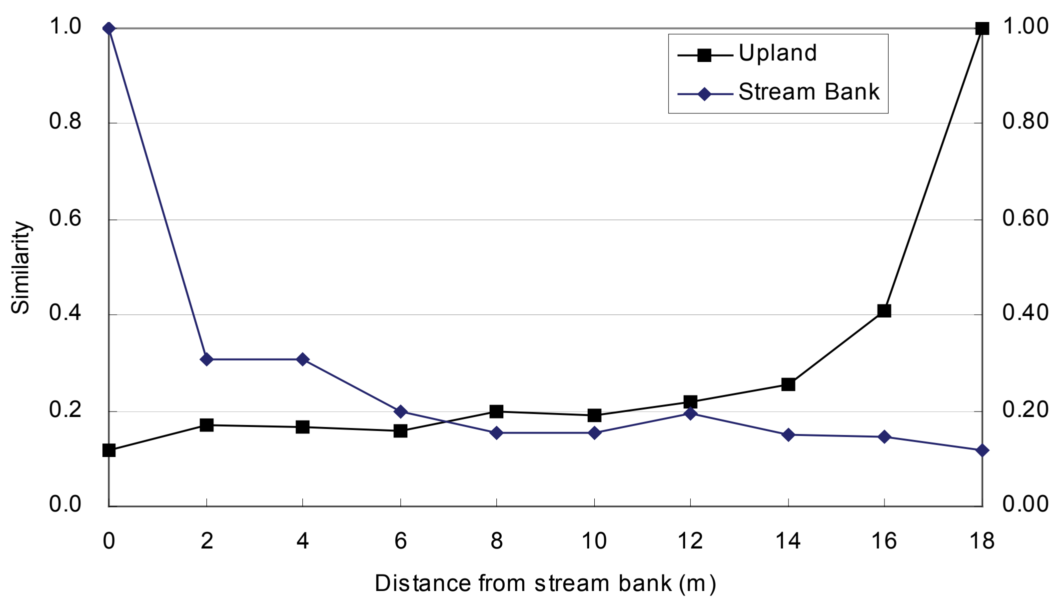

FIG. 4.21. The similarity coefficient changed along the horizontal environmental gradients with > 51 % woody canopy cover (except Ashe juniper).

DISCUSSION

Plant Diversity with Spring Flow

The larger amounts of spring flow in the stream channel can provide more water for riparian vegetation, including woody and herbaceous plants (Wood and Wood 1988). The responses of vegetation diversity to the accessible water source were examined by this study. We found that the riparian zones with higher spring flows had more woody canopy cover and had a higher woody species richness. The woody species diversity increased linerally with increased spring flow and was significantly higher in the sites with spring flows over 1.0 L/s than those with spring flows lower than 0.05 L/s. Therefore, greater stream flow supports woody plants in the riparian zones, and greater woody diversity.

Herbaceous species are more sensitive to soil moisture than are woody or shrub species (Castelli et al. 2000). However, in this study we found herbaceous cover in sites with an average spring flow of 0.05 to 1.00 L/s was significantly lower than those sites with an average spring flow of less than 0.05 L/s or greater than 1.00 L/s. The herbaceous percent cover might be influenced by other abiotic factors, such as the rock cover.

In the riparian zones, there were no significant differences of herbaceous species richness between the different levels of the spring flow. However, there was a significant difference in herbaceous species diversity between those sites with a spring flow greater than 1.0 L/s and sites with less than 1.0 L/s of spring flow. Herbaceous species diversity was lower in those sites with a higher spring flow. This result differed from other studies that found that species richness and diversity were greatest in the riparian zones on the channel edge where water was easily available (Wood and Wood 1988, Patten 1998). Here, streamflow supported a larger woody canopy cover.

Diversity with Woody Canopy Cover

This study can separate spring sites into two different groups depending upon the presence or absence of Ashe juniper. Woody cover was significantly higher in sites with some Ashe juniper than those with none. Woody species diversity also responded to the increased average juniper canopy cover in the riparian zones. Woody species richness was less in riparian zones with no Ashe juniper cover. The diversity of woody vegetation also increased in accordance with the increasing percent cover and richness of woody plants. There was a significantly greater woody canopy diversity in areas with some Ashe juniper than those sites with none.

Waichler (2001) found that soils were more important than tree parameters in determining herbaceous cover and composition. However, this study departs from Waichler (2001). In the Pedernales River riparian zones, the herbaceous vegetation cover was lower in areas with larger than 2% Ashe juniper canopy cover. There was a higher level of herbaceous plant cover when the spring sites with less than 2% average Ashe juniper percent cover or were without any Ashe juniper. This result is similar to Miller et al. (2000), which finds that herbaceous cover declined with an increase in juniper dominance (Miller et al. 2000). Another study suggests that increasing redberry juniper encroachment decreased the frequency and density of grasses (Ansley et al. 1995).

Herbaceous species' richness and diversity were significantly lower in those sites with Ashe juniper cover than in other sites with no Ashe juniper. These results support those of other studies which find that the diversity of the herbaceous understory is reduced by salt cedar (*Tamarix* L.), which has invaded riparian streams throughout the western United States (Masters and Sheley 2001). Also, in western Texas increasing juniper cover let to a decline in grasses (Ueckert et al. 2001).

Therefore, the mechanism for herbaceous plant density was shade by woody cover. The whole woody canopy cover provided shade for the herbaceous vegetation in the riparian zone along the stream channel. The high coverage of live oak can have the same effects on herbaceous coverage as Ashe juniper. Herbaceous cover decreased with an increasing woody canopy cover, no matter what woody species is present. Furthermore, there was a significantly positive correlation between the percentages of Ashe juniper canopy cover and the percentages of other woody vegetation cover.

In contrast, herbaceous species richness and diversity were directly influenced by Ashe juniper cover. The cover of other woody vegetation did not present any clear effects on herbaceous richness and diversity. Therefore, Ashe juniper has an effect on the composition and structure of the herbaceous understory (Masters and Sheley 2001).

Similarity with Woody Canopy Covers

We used the similarity index to demonstrate the gradually changing herbaceous understory. In the 20 m riparian zone, the levels of Ashe juniper were important for vegetation change. The vegetation pattern changed less in those watersheds with a lower Ashe juniper cover (< 2 %) than sites with higher cover (>2 %). In those spring watersheds with no Ashe juniper, the vegetation communities 12-13 meters away from the stream bank had the same similarity to the stream bank and the upland.

We used the intersection point of these two changing lines to determine the width of the riparian zones of the small streams in the Pedernales watershed. We found that under less juniper cover (<2 %), the average width of the riparian zone decreased to about 9-10 m. Finally, under a higher number of juniper cover (> 2%) sites, the average width of the riparian zone decreased to about 6 m, because of abrupt changes in vegetation pattern. This study finds that the increasing juniper canopy cover decreased the width of both the riparian and buffer zones.

In addition to the Ashe juniper, the similarity index finds gradually changing herbaceous understory under the different levels of other woody plant cover in the 20 m riparian zone. Under lower other woody covers (≦30 %), the average width of the riparian zone was 12 m in the spring sites. In areas with medium woody plant cover (31-51 %), the average width of the riparian zone decreased to about 10-12 m. In the high woody plant cover sites (>51 %), the average width of the riparian zone was 7-12 m. The results from this study suggest that increasing woody canopy cover decreases the width of the riparian zone.

PLANT COMMUNITY DYNAMICS FOLLOWING DIFFERENT ENVIRONMENTAL FACTORS WITH A HORIZONTAL GRADIENT IN THE RIPARIAN ZONE

In the Pedernales spring head watersheds, the riparian zones were dominated by species from the *Poaceae* (such as king ranch bluestem, little bluestem, Texas wintergrass, and bermudagrass), *Cyperaceae* (cedar sedge and spike rush), *Asteraceae* (such as Frostweed, Prairie Coneflower, and Sumpweed), *Lamiaceae* (Mealy Sage and Henbit), and other species from 21 families, each of which represented less than one percent of the total basal area (Figure 4.22).

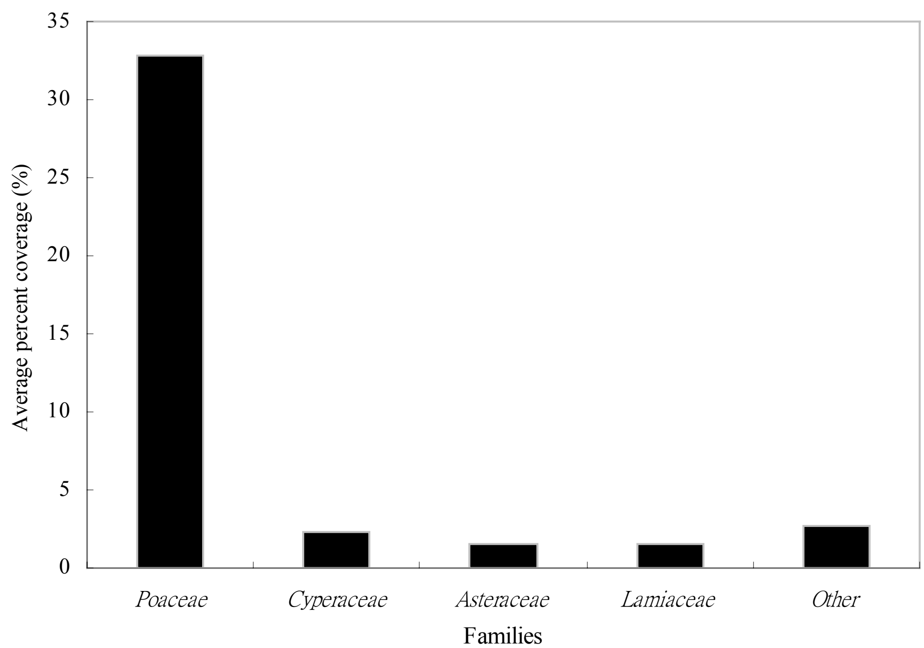

FIG. 4.22. Dominant understory families in the riparian zone.

Within 10 meters from the stream bank, the herbaceous plants from the *Lamiaceae* presented in 4.6% of the sampling plots. Beyond 10 meters, the herbaceous plants from the *Lamiaceae* presented in 1.9% of the sampling plots (Table 4.19). The relationship between the distribution of *Lamiaceae* and the distance from the stream bank was significant, χ^2 (1, N=106) = 10.57, p≦0.001. In addition, the herbaceous plants from the *Fabaceae* presented in 14.6% of the sampling plots within 10 meters from the stream bank. Beyond 10 meters, the herbaceous plants from the *Fabaceae* presented in 7.5% of the sampling plots. The relationship between the distribution of *Fabaceae* and the distance from the stream bank was significant, χ^2 (1, N=32) = 4.54, p≦0.05. The presented ratios of vegetation from *Lamiaceae* and *Fabaceae* were both higher than average within 10 meters from the stream banks.

TABLE 4.19. Present herbaceous plant families according to different distances from the stream bank.

	Distance from the Stream Bank							
	<10 M (N=540)			>10 M (N=360)				
Families	Count	% [a]	Adjusted Residual	Count	% [a]	Adjusted Residual	Overall (%)	χ^2 (df=1)
Fabaceae (N=32)	25	**4.60**	2.10	7	1.90	-2.10	3.60	4.54 *
Lamiaceae (N=106)	79	**14.60**	3.30	27	7.50	-3.30	11.80	10.57 ***

Note. [a] The presented ratio in each environmental category.

HERBACEOUS VEGETATION DISTRIBUTION WITH THE AMOUNT OF AVERAGE SPRING DISCHARGE

The correspondence analysis (CA) made it possible to visually present the relationship between the distributions of herbaceous species and the average spring flows. The herbaceous species were selected for the CA via criteria in which the frequency of each species was larger than 1%. There were 47 herbaceous species selected for the CA. In a correspondence analysis, the maximum number of dimensions that can be estimated is one less than the smaller number of rows or columns (Ludwig and Reynolds 1988, Clausen 1998, Meulman and Heiser 2001). In this study, the maximum number of dimensions must be two, because there were only three categories of environmental variables—average spring flow, juniper canopy cover, and other woody canopy covers. However, a dimension will only be accepted if it has singular values greater than 0.20 (Joseph F. Hair et al. 2006). In this study, these two dimensions produced by the correspondence analysis each had a singular value grater than 0.02 (Table 4.20). The first dimension explained 67.0% of the variance and the second dimension explained 33.0% of the variance. The principle coordinates of the average spring flows by the herbaceous species profile points (Appendix D) from the correspondence analysis in the two-dimensional solution were plotted in Figure 4.23.

TABLE 4.20. The dimensionality of herbaceous species and average spring flows.

Dimension	Singular Value	Inertia (Eigenvalue)	Proportion of Inertia	Chi Square df=92	
1	0.447	0.199	0.670		
2	0.313	0.098	0.330		
Total		0.297	1.000	722.199	***

Note. *** $p \leq 0.001$.

The joint display revealed (Figure 4.23) that single-seed croton, red lovegrass, poison ivy, green sprangletop, downy brome, and musk were closest to the lowest average spring flow (<0.05 L/s). The dallisgrass, ceder sedge, prairie coneflower, Texas verbena, bermudagrass, broomweed, violet wild petunia, and false ragweed were closest to the highest average spring flow (>0.1 L/s).

The above results reveal a relationship between the distributions of herbaceous species and the average spring flow. In addition, the herbaceous vegetations were classified by grass families. The relationship between the distribution of grass families and the average spring flow was examined using the chi-square test. In the spring watershed with the lower average spring discharge (<0.1 L/s), the herbaceous plants from *Cactaceae* and *Poaceae* presented 3.60% and 91.20% in the sampling plots, respectively (Table 4.21 and Appendix E). And the herbaceous plants from *Cactaceae* and *Poaceae* presented in the lower ratio of sampling plots within the higher spring flow sites, 0.80% and 80.20%, respectively. The relationship between the distribution of *Cactaceae* and the average amount of spring flow was significant, $\chi^2(1, N=19) = 8.13$, $p \leq 0.01$. Finally, the relationship between the distribution of *Poaceae* and the average

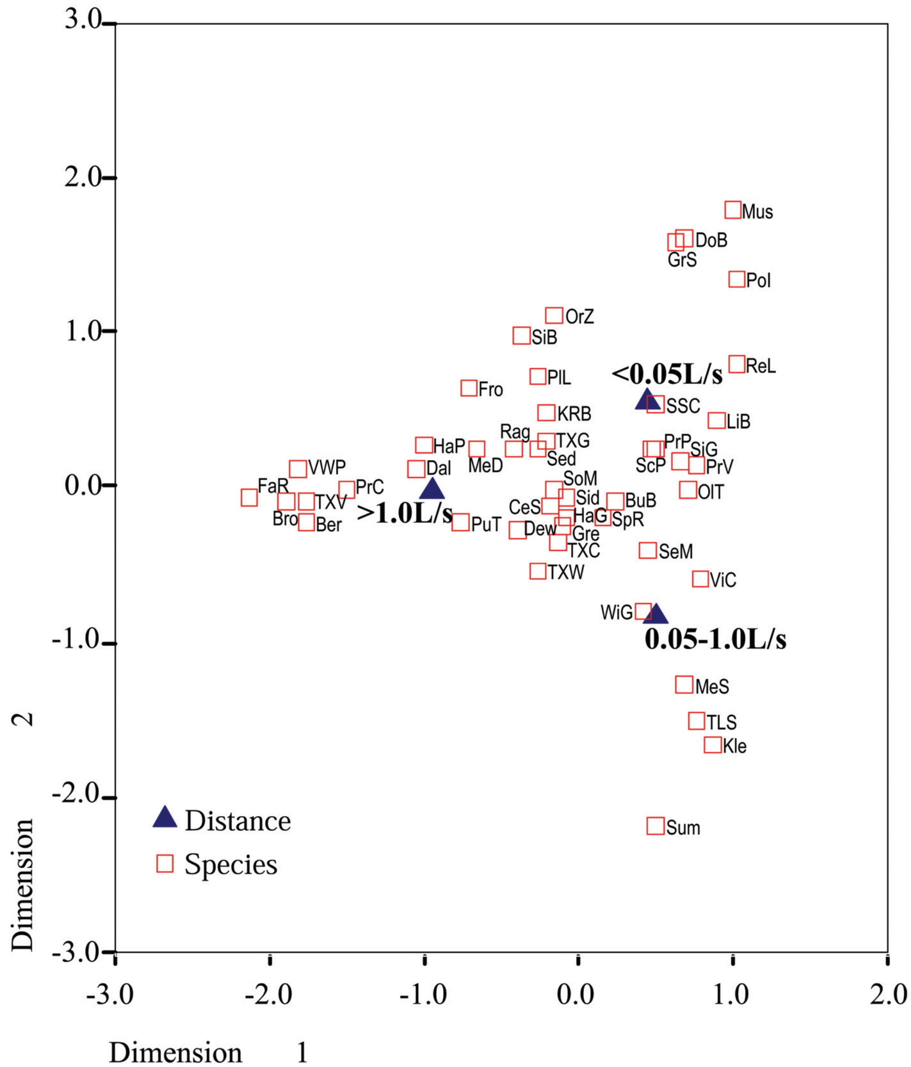

FIG. 4.23. Two-dimensional correspondence analysis of herbaceous species by average spring flow.

Note: *Ber= Bermudagrass, Bro= broomweed, BuB= bushy bluestem, CeS= cedar sedge, Dal= dallisgrass, Dew= dewberry, DoB= downy brome, FaR= false ragweed, Fro= frostweed, GrS= green sprangletop, Gre= greenbriar, HaG= hairy grama, HaP= halls panicum, KRB= king ranch bluestem, Kle= kleingrass, LiB= little bluestem, MeD= meadow dropseed, MeS= mealy sage, Mus= Musk, OlT= oldfield threeawn , OrZ= orange zexmania, PlL= plains lovegrass, PoI= poison ivy, PrC= prairie coneflower, PrV= prairie verbena, PrP= prickly-pear cactus, PuT= purple threeawn, Rag= Ragweed, ReL= red lovegrass, ScP= scribner's panicum, Sed= sedge, SeM= seep muhly, Sid= sida, SiG= sideoats grama, SiB= Silver Bluestem, SSC= single-seed croton, SoM= snow-on-the-mountain, SpR= spike rush, Sum= sumpweed, TXC= Texas croton, TXG= Texas grama, TXV= Texas verbena, TXW= Texas wintergrass, TLS= two-leaved senna, VWP= violet wild petunia, ViC= virginia creeper, WiG= wild grape.*

TABLE 4.21. Presented herbaceous plant families by different average spring flows.

Families	Average Spring Flow: <0.1 L/s (N=420) Count	% [a]	Adjusted Residual	Average Spring Flow: >0.1 L/s (N=480) Count	% [a]	Adjusted Residual	Overall (%)	χ^2 (df=1)
Asteraceae (N=159)	63	15.00	-2.00	96	**20.00**	2.00	17.70	3.85 *
Cactaceae (N=19)	15	**3.60**	2.90	4	0.80	-2.90	2.10	8.13 **
Cyperaceae (N=280)	110	26.20	-3.00	170	**35.40**	3.00	31.10	8.90 **
Poaceae (N=768)	383	**91.20**	4.60	385	80.20	-4.60	85.30	21.59 ***
Smilacaceae (N=106)	40	9.50	-2.00	66	**13.80**	2.00	11.80	3.85 *

Note. [a] The presented ratio in each environmental category.

* $p \leqq 0.05$, ** $p \leqq 0.01$, *** $p \leqq 0.001$.

amount of spring flow was also significant, χ^2 (1, N=768)= 21.59, p≦0.001. However, the herbaceous plants from *Asteraceae, Cyperaceae* and *Smilacaceae* each presented higher ratios with 20.00%, 35.40% and 13.80% in the higher spring flow sites, respectively, than in the lower spring discharge sites. The relationship between the distribution of *Asteraceae* and the average amount of spring flow was significant, χ^2 (1, N=159) = 3.85, p≦0.05; the relationship between the distribution of *Cyperaceae* and the average amount of spring flow was significant, χ^2 (1, N=280) = 31.10, p≦0.01; and the relationship between the distribution of *Smilacaceae* and the average amount of spring flow was also significant, χ^2 (1, N=106) = 3.85, p≦0.05. The result show that the herbaceous vegetation from *Cactaceae* and *Poaceae* presented more in the lower amounts of spring discharge sites, but the herbaceous vegetation from *Asteraceae, Cyperaceae* and *Smilacaceae* presented more in the higher amounts of spring discharge sites.

HERBACEOUS VEGETATION DISTRIBUTION WITH AMOUNT OF JUNIPER CANOPY COVER

The relationship between the distributions of the herbaceous species and the juniper canopy cover was revealed by the CA. There were 47 herbaceous species in which the frequency of each species was larger than 1%, selected for the CA. In this study, the maximum number of dimensions was required to be two because of the only three categories of juniper cover variables — no juniper, a juniper canopy cover of < 2%, and a juniper cover >2%. In this analysis, both of these two dimensions produced by the correspondence analysis had a singular value grater than 0.02 (Table 4.22). The first dimension explained 59.7% of the variance and the second dimension explained 40.3% of the variance. The principal coordinates of the juniper canopy cover by the herbaceous species profile points (Appendix D) from the correspondence analysis in the two-dimensional solution were plotted in Figure 4.24. The configuration revealed that mealy sage, sida, Texas croton, and Texas verbena were closest to the no juniper canopy cover (0%). The cedar sedge and sedge were closer to 0-2 % and >2% juniper cover than to no juniper. Besides, greenbriar was closest to a >2% juniper cover (Figure 4.24).

TABLE 4.22. The dimensionality of herbaceous species and juniper canopy cover.

Dimension	Singular Value	Inertia (Eigenvalue)	Proportion of Inertia	Chi Square df=92	
1	0.369	0.136	0.597		
2	0.303	0.092	0.403		
Total		0.228	1.000	554.385	***

Note. *** $p \leqq 0.001$.

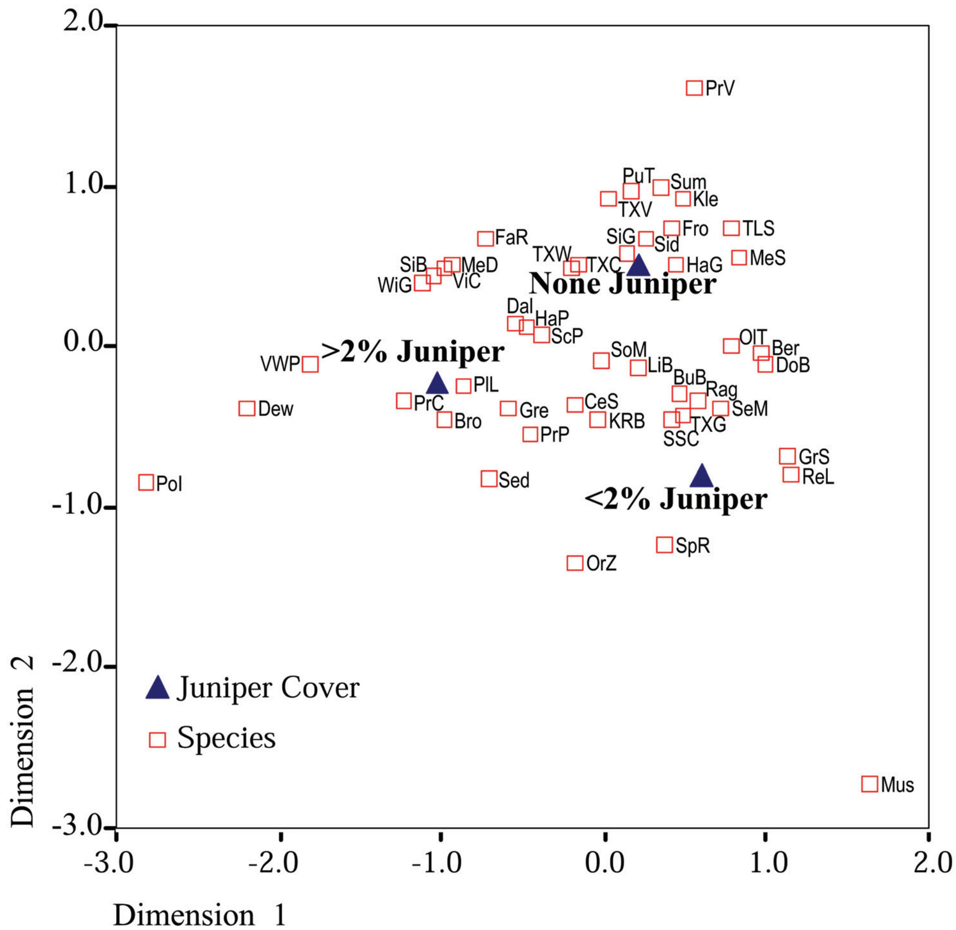

FIG. 4.24. Two-dimensional correspondence analysis of herbaceous species by juniper canopy cover.

Note: *Ber= Bermudagrass, Bro= broomweed, BuB= bushy bluestem, CeS= cedar sedge, Dal= dallisgrass, Dew= dewberry, DoB= downy brome, FaR= false ragweed, Fro= frostweed, GrS= green sprangletop, Gre= greenbriar, HaG= hairy grama, HaP= halls panicum, KRB= king ranch bluestem, Kle= kleingrass, LiB= little bluestem, MeD= meadow dropseed, MeS= mealy sage, Mus= Musk, OlT= oldfield threeawn , OrZ= orange zexmania, PlL= plains lovegrass, PoI= poison ivy, PrC= prairie coneflower, PrV= prairie verbena, PrP= prickly-pear cactus, PuT= purple threeawn, Rag= Ragweed, ReL= red lovegrass, ScP= scribner's panicum, Sed= sedge, SeM= seep muhly, Sid= sida, SiG= sideoats grama, SiB= Silver Bluestem, SSC= single-seed croton, SoM= snow-on-the-mountain, SpR= spike rush, Sum= sumpweed, TXC= Texas croton, TXG= Texas grama, TXV= Texas verbena, TXW= Texas wintergrass, TLS= two-leaved senna, VWP= violet wild petunia, ViC= virginia creeper, WiG= wild grape.*

The above results revealed some relationship between the distribution of herbaceous species and the juniper canopy cover. Then, the herbaceous vegetations was classified by grass families. The relationship between the distribution of grass families and the juniper canopy cover was examined with the chi-square test. In the spring watershed with the juniper cover, the herbaceous plants from *Cyperaceae* and *Smilacaceae* presented in the 36.00% and 14.20% sampling plots, respectively (Table 4.23 and Appendix E). In addition, the herbaceous plants from *Cyperaceae* and *Smilacaceae* presented lower ratios in the spring sites without juniper canopy cover, 25.50 and 9.00%, respectively. The relationship between the distribution of *Cyperaceae* and the juniper canopy cover was significant, χ^2 (1, N=280) = 11.67, $p \leqq 0.001$. And, the relationship between the distribution of *Smilacaceae* and the juniper canopy cover was also significant, χ^2 (1, N=106) = 5.65, $p \leqq 0.05$. However, the herbaceous plants from *Euphorbiaceae, Lamiaceae, Malvaceae, Poaceae* and *Verbenaceae* presented higher ratios with 18.10%, 18.80%, 21.70%, 90.20% and 6.70%, respectively, in the spring flow sites without juniper than in the spring sites with some juniper canopy covers.

The relationship between the distribution of *Euphorbiaceae* and the juniper canopy cover was significant, χ^2 (1, N=135) = 5.92, $p \leqq 0.05$; the relationship between the distribution of *Lamiaceae* and the juniper canopy cover was significant, χ^2 (1, N=106) = 11.80, $p \leqq 0.001$; the relationship between the distribution of *Malvaceae* and the juniper canopy cover also was significant, χ^2 (1, N=126) = 38.45, $p \leqq 0.001$. Furthermore, the relationship between the distribution of *Poaceae* and the juniper canopy cover was also significant, χ^2 (1, *N*=768) = 15.14, p ≦ 0.001; and the relationship between the distribution of *Verbenaceae* and the juniper canopy cover was also significant, χ^2 (1, *N*=37) = 13.05, p ≦ 0.001. These results show that the herbaceous vegetation from *Cyperaceae* and *Smilacaceae* both presented more in the spring watersheds with a juniper canopy cover, but the herbaceous vegetation from *Euphorbiaceae, Lamiaceae, Malvaceae, Poaceae* and *Verbenaceae* presented more in the spring sites without juniper.

TABLE 4.23. Presented herbaceous plant families by different average juniper canopy covers.

	Average Juniper Canopy Cover							
	None Juniper Cover (N=420)			With Juniper Cover (N=480)				
Families	Count	% *	Adjusted Residual	Count	% *	Adjusted Residual	Overall (%)	χ^2 (df=1)
Cyperaceae (N=280)	107	25.50	-3.40	173	**36.00**	3.40	31.10	11.67 ***
Euphorbiaceae (N=135)	76	**18.10**	2.40	59	12.30	-2.40	15.00	5.92 *
Lamiaceae (N=106)	79	**18.80**	6.10	27	5.60	-6.10	11.80	37.47 ***
Malvaceae (N=126)	91	**21.70**	6.20	35	7.30	-6.20	14.00	38.45 ***
Poaceae (N=768)	379	**90.20**	3.90	389	81.00	-3.90	85.30	15.14 ***
Smilacaceae (N=106)	38	9.00	-2.40	68	**14.20**	2.40	11.80	5.65 *
Verbenaceae (N=37)	28	**6.70**	3.60	9	1.90	-3.60	4.10	13.05 ***

Note. [a] The presented ratio in each environmental category.

* $p \leqq 0.05$, *** $p \leqq 0.001$.

HERBACEOUS VEGETATION DISTRIBUTION WITH AMOUNT OF OTHER WOODY CANOPY COVER

The relationship between the distributions of the herbaceous species and woody canopy (except Ashe juniper) cover was revealed by the CA. There were 47 herbaceous species in which the frequency of each species was larger than 1%, selected for the CA. In this study, the maximum number of dimensions must be two because there are only three categories of woody canopy cover — <30% woody cover, 31-51% woody cover, and >51% woody cover. In this analysis, both of these dimensions produced by the correspondence analysis had a singular value grater than 0.02 (Table 4.24). The first dimension explained 63.3% of the variance and the second dimension explained 36.7% of the variance. The principal coordinates of the woody canopy cover by the herbaceous species profile points (Appendix D) from the correspondence analysis in the two-dimensional solution were plotted in Figure 4.25.

TABLE 4.24. The dimensionality of herbaceous species and juniper canopy cover.

Dimension	Singular Value	Inertia (Eigenvalue)	Proportion of Inertia	Chi Square df=92	
1	0.427	0.183	0.633		
2	0.325	0.106	0.367		
Total		0.288	1.000	699.688	***

Note. *** ≦ 0.001.

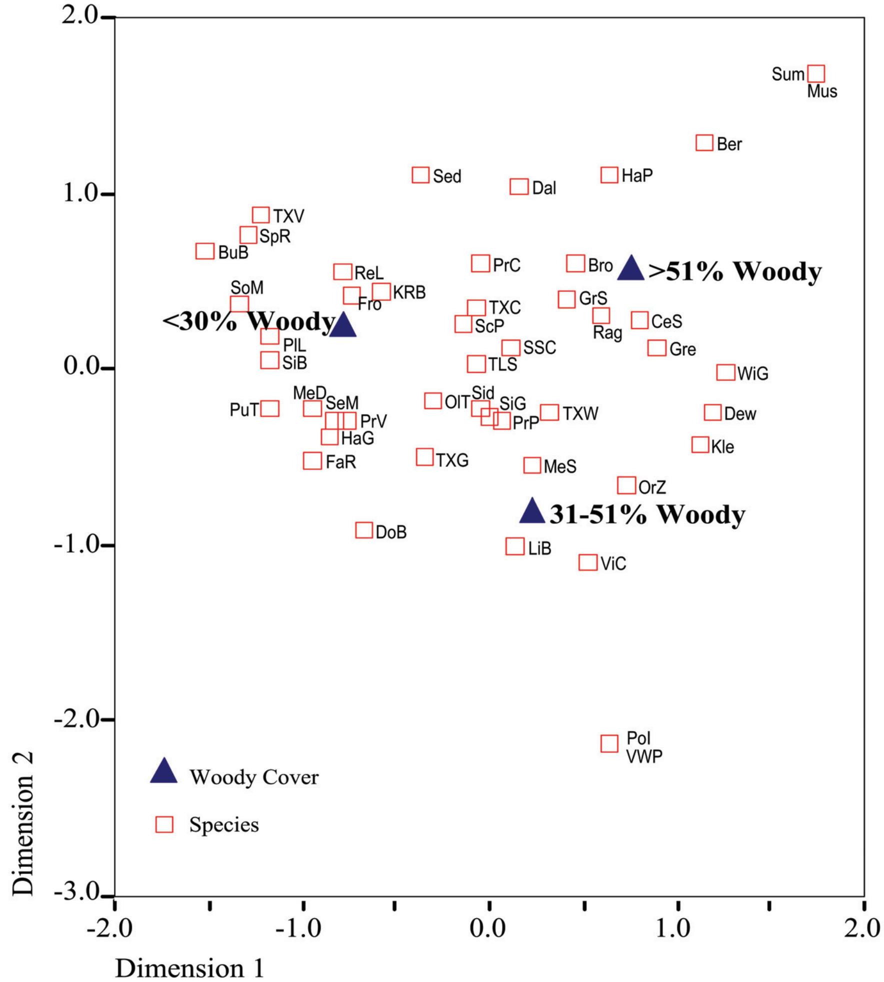

FIG. 4.25. Two-dimensional correspondence analysis of herbaceous species by other woody canopy cover.

Note: *Ber= Bermudagrass, Bro= broomweed, BuB= bushy bluestem, CeS= cedar sedge, Dal= dallisgrass, Dew= dewberry, DoB= downy brome, FaR= false ragweed, Fro= frostweed, GrS= green sprangletop, Gre= greenbriar, HaG= hairy grama, HaP= halls panicum, KRB= king ranch bluestem, Kle= kleingrass, LiB= little bluestem, MeD= meadow dropseed, MeS= mealy sage, Mus= Musk, OlT= oldfield threeawn , OrZ= orange zexmania, PlL= plains lovegrass, PoI= poison ivy, PrC= prairie coneflower, PrV= prairie verbena, PrP= prickly-pear cactus, PuT= purple threeawn, Rag= Ragweed, ReL= red lovegrass, ScP= scribner's panicum, Sed= sedge, SeM= seep muhly, Sid= sida, SiG= sideoats grama, SiB= Silver Bluestem, SSC= single-seed croton, SoM= snow-on-the-mountain, SpR= spike rush, Sum= sumpweed, TXC= Texas croton, TXG= Texas grama, TXV= Texas verbena, TXW= Texas wintergrass, TLS= two-leaved senna, VWP= violet wild petunia, ViC= virginia creeper, WiG= wild grape.*

The joint display revealed that king ranch bluestem, red lovegrass, prairie verbena, snow-on-the-mountain, and Texas verbena were closest to the lower woody canopy cover (<30%). The cedar sedge, greenbriar, and wild grape were closest to the higher woody canopy cover (>51%).

In the spring watershed with a high woody canopy cover (except Ashe juniper), the herbaceous plants from *Cyperaceae*, *Lamiaceae*, *Smilacaceae* and *Vitaceae* presented in 36.50%, 13.70%, 16.50% and 6.10% of the sampling plots, respectively (Table 4.25 and Appendix E). And the herbaceous plants from *Cyperaceae*, *Lamiaceae*, *Smilacaceae* and *Vitaceae* presented lower ratios in the spring sites with lower woody canopy cover (<40%), 24.10%, 9.20%, 5.60% and 0.80%, respectively. The relationship between the distribution of *Cyperaceae* and the woody canopy cover was significant, χ^2 (1, N=280) = 15.77, $p \leqq 0.001$; the relationship between the distribution of *Lamiaceae* and the woody canopy cover was also significant, χ^2 (1, N=106) = 4.30, $p \leqq 0.05$. Furthermore, the relationship between the distribution of *Smilacaceae* and the woody canopy cover was significant, χ^2 (1, N=106) = 24.94, $p \leqq 0.001$; and the relationship between the distribution of *Vitaceae* and the woody canopy cover was also significant, χ^2 (1, N=34) = 17.14, $p \leqq 0.001$.

However, the herbaceous plants from *Euphorbiaceae, Poaceae* and *Verbenaceae* presented higher ratios with 19.00%, 91.30% and 7.20%, respectively, in the spring flow sites with a lower woody canopy cover (<40 %) than with a higher woody cover (>40 %). The relationship between the distribution of *Euphorbiaceae* and the woody canopy cover was significant, χ^2 (1, N=135) = 8.53, $p \leqq 0.01$; the relationship between the distribution of *Poaceae* and the woody canopy cover was significant, $\chi^2(1, N=768) = 19.46, p \leqq 0.001$; and the relationship between the distribution of *Verbenaceae* and the woody canopy cover was also significant, $\chi 2$ (1, N=37) = 16.44, p≦0.001. The results showed that the herbaceous vegetation from *Cyperaceae*, *Lamiaceae*, *Smilacaceae* and *Vitaceae* presented more in the spring watersheds with a high woody canopy cover, but the herbaceous vegetation from *Euphorbiaceae, Poaceae* and *Verbenaceae* presented more in the spring sites with a low woody canopy cover.

TABLE 4.25. Presented herbaceous plant families by different averages of other woody canopy covers.

Families	Average Other Woody Canopy Cover: <40 % (N=390) Count	% *	Adjusted Residual	> 40% (N=510) Count	% *	Adjusted Residual	Overall (%)	χ^2 (df=1)
Cyperaceae (N=280)	94	24.10	-4.00	186	**36.50**	4.00	31.10	15.77 ***
Euphorbiaceae (N=135)	74	**19.00**	2.90	61	12.00	-2.90	15.00	8.53 **
Lamiaceae (N=106)	36	9.20	-2.10	70	**13.70**	2.10	11.80	4.30 *
Poaceae (N=768)	356	**91.30**	4.40	412	80.80	-4.40	85.30	19.46 ***
Smilacaceae (N=106)	22	5.60	-5.00	84	**16.50**	5.00	11.80	24.94 ***
Verbenaceae (N=37)	28	**7.20**	4.10	9	1.80	-4.10	4.10	16.44 ***
Vitaceae (N=34)	3	0.80	-4.10	31	**6.10**	4.10	3.80	17.14 ***

Note. * The presented ratio in each environmental category.

The herbaceous vegetation from *Euphorbiaceae, Poaceae* and *Verbenaceae* presented more in the spring sites without juniper or with low levels of other woody species cover. These herbaceous plants might not tolerate the heavy shaded environment. However, the herbaceous vegetation from *Cyperaceae* and *Smilacaceae* presented more in the spring watersheds with a high woody canopy cover, no matter what kind of woody species provided the cover. These herbaceous plants tolerate shade cover.

DISCUSSION

The ecotone between the stream bank and the upland vegetations change on the lateral gradient. The correspondence analysis (CA) visually presents the relationship between the herbaceous species composition and average spring flows. In the spring watersheds with a lower average spring discharge (<0.1 L/s), there were more herbaceous plants from *Cactaceae* and *Poaceae*. However, the herbaceous plants from *Asteraceae, Cyperaceae* and *Smilacaceae* were at greater ratios in the higher spring flow sites (>0.1 L/s) than in the lower spring discharge sites, respectively. Herbaceous members of the *Lamiaceae* and *Fabaceae* families clustered near stream channel, within 10 meters from the stream bank.

The distribution of herbaceous understory was also influenced by the Ashe juniper cover. Herbaceous plants from *Cyperaceae* and *Smilacaceae* were in the riparian zones, dominated by Ashe juniper cover. However, the herbaceous plants from *Euphorbiaceae, Lamiaceae, Malvaceae, Poaceae* and *Verbenaceae* were at higher ratios in the spring sites with no juniper canopy.

In addition to Ashe juniper cover, herbaceous plants from *Cyperaceae*, *Lamiaceae*, *Smilacaceae* and *Vitaceae* were also influenced by the higher woody canopy covers (>40%) of the riparian zones. However, the herbaceous plants from *Euphorbiaceae, Poaceae* and *Verbenaceae* were at higher ratios in the riparian zones with lower woody canopy covers (<40 %). The result showed that the herbaceous vegetation from

Cyperaceae, *Lamiaceae*, *Smilacaceae* and *Vitaceae* presented more in the spring watersheds with high woody canopy covers, but the herbaceous vegetation from *Euphorbiaceae, Poaceae* and *Verbenaceae* were greater in the spring sites with low woody canopy covers.

Finally, the herbaceous vegetation from *Euphorbiaceae, Poaceae* and *Verbenaceae* were greater in the spring sites with no juniper and with low levels of other woody species cover (Table 4.26). These herbaceous plants might be able to tolerate the heavily shaded environment. In contrast, herbaceous vegetation from *Cyperaceae* and *Smilacaceae* was greater in the spring watersheds with a high woody canopy cover, no matter what kind of woody species were present. These herbaceous plants tolerate shade cover and need more moist environments. If the grassland managers want to increase forage, they need more open areas for grasses, which require high light. Therefore, not only the cover of Ashe juniper needs attention, but the cover of other woody species must also be considered.

TABLE 4.26. Present herbaceous plant families by different environmental factors.

Family	**Ashe Juniper Cover(%)**	**Other Woody Cover(%)**	**Spring Flow (L/s)**
Euphorbiaceae	None	<40	
Poaceae	None	<40	<0.1
Verbenaceae	None	<40	
Lamiaceae	None	>40	
Cyperaceae	Yes	>40	>0.1
Smilacaceae	Yes	>40	>0.1

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

In the water-limited semiarid regions with increasing water demands one potential management solution for providing an increasing supply of water resources is to reduce the amount of water consumed by the land cover (Thurow et al. 2000). Some research has shown that land cover changes have been associated with water yield (Walker et al. 1993), but most of this research was performed in humid or Mediterranean climates (Richardson et al. 1979, Bosch and Hewlett 1982, Troendle 1983, Chang and Watters 1984, Mumeka 1986, Williamson et al. 1987, Jackson et al. 2000). Therefore, a comprehensive study of water yield characteristics is imperative, especially in the semiarid regions.

The research of Wilcox et al. (2006), the shrub-streamflow framework of the Edwards Plateau, which has a shallow soil layer (Dugas et al. 1998) and the underlaying, highly permeable parent material (Maclay 1995, Brune 2002). Both qualities have the potential to act as opportunities for increasing water yields through brush management, especially in the upland areas where conditions allow for some deep drainage. In this study, we selected first-order catchments within the Pedernales River watershed. These streams are hydrologically sensitive to changes in woody plant cover, and therefore would have the greatest spring flow responses to brush management. In addition to the relationship between the water yield and the removal of brush, this study also focused on the ecological responses of vegetation to the altered flow regimes resulting from brush management.

For first-order catchments in the Pedernales watershed in central Texas, spring flows made up an average of 3.67% of the of the monthly water budget. The small percentage of water yield from precipitation in Pedernales watershed is similar to other earlier studies in the semiarid regions (Wilcox et al. 2005). In addition, there is no clear relationship between accumulated precipitation in the two studied seasons and the amount of spring discharge. The observed spring flow is the baseflow in the first-order catchments. Therefore, it can be concluded that the quantity amount of the spring flow might be influenced by other environmental factors, such as surface area of catchment. The total amount of spring discharge was only slightly influenced by the surface catchment areas, as the real spring catchment might not be the same as the surface watershed delineated by topography (Dasgupta et al. 2006b).

In this study, we used classified Landsat imagery to estimate land cover. The vegetation cover of the first-order catchments with springs in Pedernales River watershed was classified into four types—grassland, cropland, Ashe juniper cover, and other woody plant cover. The highest vegetation cover was made up of the other woody plant cover category with an average of 16.44% in the spring catchment. The second highest level of vegetation cover was Ashe juniper cover with a mean of 11.66% of the spring catchment. The grasslands and croplands occupied only a small portion of the catchment. This study’s results show that there was no relationship between the amount of spring discharge to the Ashe juniper or other woody plants percent cover in the Pedernales River watershed. Moreover, there was also no relationship to the amount of spring discharge to the whole woody plants percent cover. Therefore, changes woody cover had no influence on the baseflow in the first-order catchments.

However, there was a very weak correlated relationship between the amounts of spring discharge with the percentages of grassland cover in the first-order catchments. The results of this analysis showed that there was slightly more spring discharge when there were open areas with no woody shrubs. However, this relationship needs long-term monitoring to determine the relationship between these factors.

No matter whether the Ashe juniper encroached into the grasslands from the steep slopes or was removed from these grasslands, changes in the woody plant cover affected the distribution of the herbaceous understory. Ashe juniper (*Juniperus ashei*), live oak (*Quercus virginiana*), cedar elm (*Ulmus crassifolia*) and greenbriar (*Smilax rotundifolia*) are the most important woody species presented in the riparian zones. King ranch bluestem (*Bothriochloa ischaemum*), little bluestem (*Schizachryium scoparium*), Texas wintergrass (*Stipa leucotricha*), and old-field three-awn (*Aristida oligantha Michx.*) are the most important herbaceous species in the riparian zones.

There was a weak link between the distribution of land cover and the abundance of plant species along the longitudinal gradient. However, herbaceous vegetation cover responded to the increasing lateral distances from the stream bank with a declining percentage of cover. The species richness and diversity responded to increasing distances along the lateral gradient from the stream bank. The herbaceous vegetation pattern was similar to other research that find areas near the stream channel have a greater plant diversity than those adjoining uplands (Wood and Wood 1988, Patten 1998, van Coller et al. 2000, Masters and Sheley 2001). In contrast, there was no clear relationship between the woody plant distribution and environmental gradients, which suggests that the herbaceous species are more sensitive to water conditions than woody species (Castelli et al. 2000).

Other studies have found that Ashe juniper has an obvious effect on the composition and structure of the herbaceous understory (Masters and Sheley 2001), and this study supports this. Herbaceous richness and diversity were influenced by Ashe juniper cover. In contrast, other woody plant cover had no impact on the herbaceous diversity or richness.

We used the similarity index to characterize the gradually changing herbaceous understory. In the 20 m riparian zone, the vegetation pattern changed less in the spring watersheds with lower Ashe juniper cover (< 2 %) than in those sites with higher juniper cover (>2 %). In the spring watersheds with no Ashe juniper, the vegetation communities slowly changed 12-13 meters away from the stream bank. When the Ashe juniper cover percent increased, this distance decreased to 6 meters. This suggests that increasing juniper canopy cover decreases the width of the riparian and buffer zones. When the cover of other woody plant species increased in the 20 meters riparian zone, it gradually decreased the herbaceous understory. However, the rate of change was smaller in areas with Ashe juniper. This suggests that the Ashe juniper canopy had a greater effect on understory composition than the other woody species.

The ecotone between the stream bank and the upland vegetation changes along the lateral gradient. The herbaceous vegetation from *Euphorbiaceae, Poaceae* and *Verbenaceae* families were greater in the spring sites with no Ashe juniper and with low cover of other woody species. These herbaceous plants do not tolerate the low light of the heavily shaded environment. In contrast, plants from the *Cyperaceae* and *Smilacaceae* families were greater in the spring watersheds with a high woody canopy cover, regardless of canopy species. These herbaceous plants tolerate shade and require a moister environment. If grassland managers want to increase forage, then increasing open areas is necessary. Not only the percentage of Ashe juniper cover, but also other woody canopy cover proportions need to be reduced, but not eliminated completely. Therefore, the removal of all Ashe juniper from the riparian zones is not the best management practice because of the potentially positive effects of trees on grasses (Naiman and Decamps 1997, Scholes and Archer 1997). Herbaceous diversity and production may be greater where there are a few trees than where there are no trees, but the trend is reversed at high tree densities.

The removal of Ashe juniper from grasslands does not only affect the water supply, but it also affects the ecological function of the riparian zones along small streams. It is imperative that future studies pay more attention to the relationship between herbaceous plants and woody cover; including finding an appropriate balance between increasing water yields in semiarid regions and stabilizing ecological functions in the riparian zone. Future studies should also incorporate the temporal scale, including frequent observations over a long period of time. The process from precipitation to spring flow and its duration can be elucidated by daily streamflow records. Furthermore, future studies should clearly delineate the boundary of the riparian zones in small catchments. This would be valuable for future riparian management of water yields and ecological systems through brush management.

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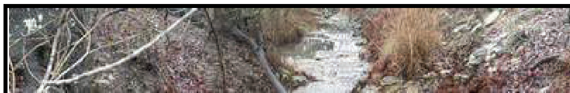
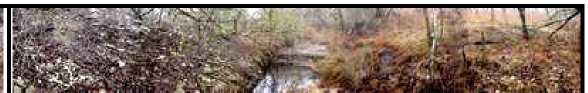
APPENDIX A

Photo 1. The structure of stream channel and riparian zone in each spring site



No.01 Bamberger Ranch -Fern spring

Location	30°10’10.2’’N, 98°28’40.3’’W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	542.54
Surface Area (ha)	52.20
Slope	0.11
Woody Cover (%)	27.41

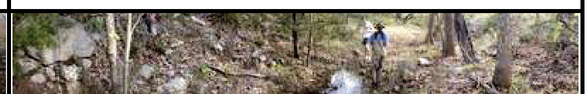


No.02 Bamberger Ranch-Jack spring

Location	30°10’37.1’’N, 98°28’27.7’’W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	536.45
Surface Area (ha)	40.86
Slope	0.06
Woody Cover (%)	23.24

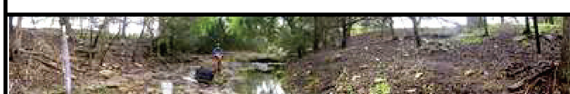
No.03 Bamberger Ranch – Lowest Spring

Location	30°10’51.5’’N, 98°28’26.7’’W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	566.93
Surface Area (ha)	8.10
Slope	0.05
Woody Cover (%)	15.33



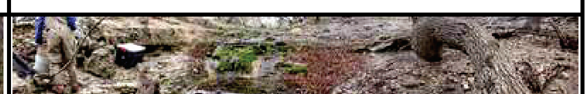
No.04 Browning Ranch -Upstream spring

Location	30°15’12.8’’N, 98°19’55.3’’W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	359.66
Surface Area (ha)	118.08
Slope	0.07
Woody Cover (%)	41.14



No.05 Browning Ranch - Downstream spring

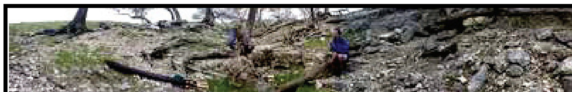
Location	30°15’59.2’’N, 98°20’ 0.2’’W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	339.85
Surface Area (ha)	358.20
Slope	0.09
Woody Cover (%)	35.53



No.06 Dave Harris Ranch- Left Mental Goat spring

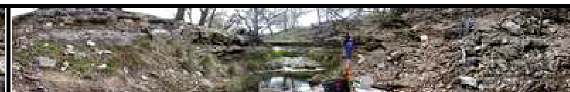
Location	30°11’14.7’’N, 99° 4’ 19.7’’W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	609.6
Surface Area (ha)	55.17
Slope	0.11
Woody Cover (%)	24.26

Photo 1. (Continued).



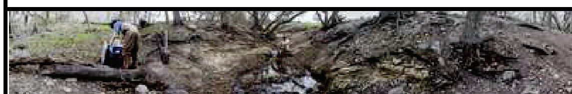
No.07 Dave Harris Ranch –Right Cross Country spring

Location	30°11'37.7"N, 99° 4'11.6" W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	594.36
Surface Area (ha)	11.79
Slope	0.09
Woody Cover (%)	7.67



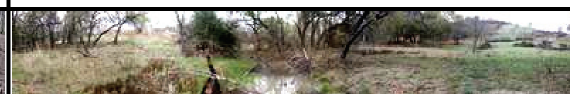
No.08 Dave Harris Ranch –Left Cross Country spring

Location	30°11'39.1"N, 99° 4' 7.7" W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	600.46
Surface Area (ha)	65.97
Slope	0.07
Woody Cover (%)	22.70



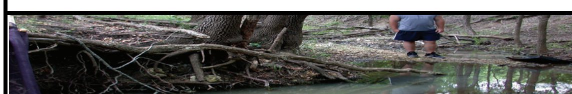
No.09 Dave Harris Ranch- Right Mental Goat spring

Location	30°11'18.1"N, 99° 4'23.7" W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	595.88
Surface Area (ha)	55.17
Slope	0.13
Woody Cover	24.26



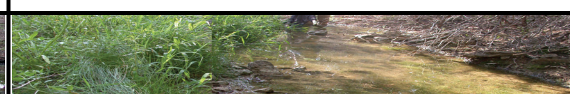
No.10 Dayton Weidenfeller Ranch spring

Location	30°16'53.0"N, 99° 1'54.8" W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	573.02
Surface Area (ha)	205.11
Slope	0.07
Woody Cover	23.23



No.11 Gibson Ranch – Eastern spring

Location	30°13'20.7"N, 98°32' 6.7" W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	426.72
Surface Area (ha)	124.20
Slope	0.03
Woody Cover	41.12



No.12 Gibson Ranch – Western spring

Location	30°13'21.6"N, 98°32'14.0" W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	432.82
Surface Area (ha)	115.56
Slope	0.03
Woody Cover	41.93

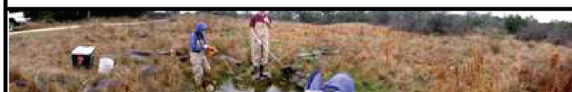
Photo 1. (Continued).

No.13 Hoppe Ranch- Northern spring

Location	30°15’20.5”N, 98°22’23.3” W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	371.86
Surface Area (ha)	152.91
Slope	0.06
Woody Cover	9.03

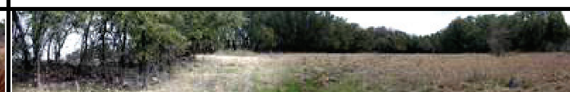
No.14 Hoppe Ranch- Southern spring

Location	30°15’16.4”N, 98°22’15.2” W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	362.71
Surface Area (ha)	342.00
Slope	0.10
Woody Cover	15.22



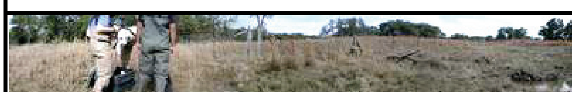
No.15 Klet Ranch spring

Location	30°17’32.6”N, 98°29’29.2” W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	409.96
Surface Area (ha)	44.55
Slope	0.04
Woody Cover	23.15



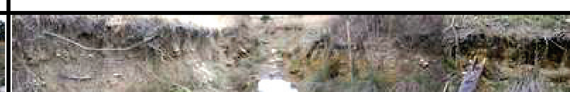
No.16 Margie & Melvin Sultemeier –Grass spring

Location	30°16’25.2”N, 98°30’ 1.8” W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	406.91
Surface Area (ha)	25.83
Slope	0.02
Woody Cover	28.47



No.17 Margie & Melvin Sultemeier –Creek spring

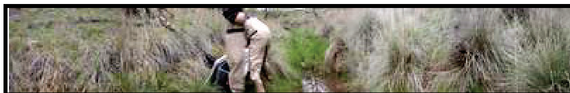
Location	30°16’18.9”N, 98°30’ 9.8” W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	405.38
Surface Area (ha)	214.83
Slope	0.03
Woody Cover	19.50



No.18 Meek Ranch spring

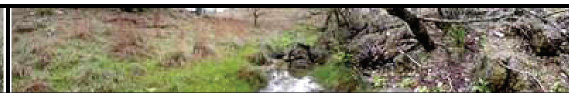
Location	30°12’14.4”N, 99° 0’ 59.6” W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	533.40
Surface Area (ha)	76.32
Slope	0.04
Woody Cover	16.69

Photo 1. (Continued).



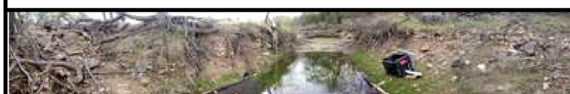
No.19 Perry Hohenberger Ranch IV –Upstream spring

Location	30° 8’28.9”N, 98°52’16.2”W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	603.50
Surface Area (ha)	9.81
Slope	0.14
Woody Cover	40.46



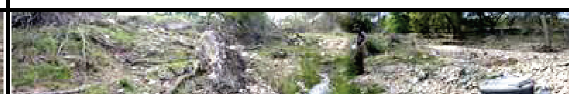
No.20 Perry Hohenberger Ranch IV–Downstream spring

Location	30° 8’28.5”N, 98°52’17.7”W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	598.93
Surface Area (ha)	17.64
Slope	0.14
Woody Cover	37.68



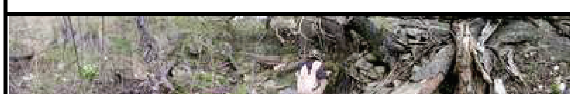
No.21 Perry Hohenberger Ranch II spring

Location	30° 7’46.7”N, 98°51’19.3”W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	576.07
Surface Area (ha)	90.27
Slope	0.08
Woody Cover	28.87



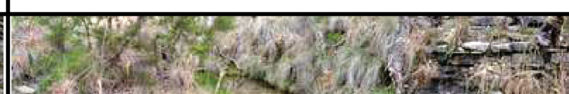
No.22 Perry Hohenberger Ranch III spring

Location	30° 7’33.1”N, 98°51’36.8”W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	579.12
Surface Area (ha)	226.71
Slope	0.07
Woody Cover	38.51



No.23 Perry Hohenberger Ranch I spring

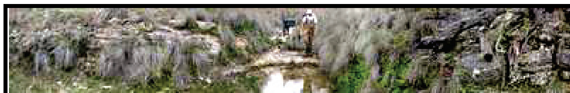
Location	30° 8’12.3”N, 98°52’33.1”W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	597.41
Surface Area (ha)	11.97
Slope	0.09
Woody Cover	41.73



No.24 Perry Hohenberger Ranch V–Upstream spring

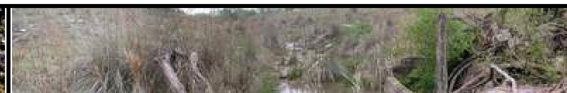
Location	30° 8’ 8.5”N, 98°52’51.1”W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	611.12
Surface Area (ha)	20.25
Slope	0.09
Woody Cover	33.27

Photo 1. (Continued).



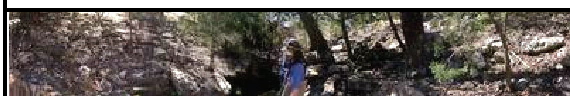
No.25 Perry Hohenberger Ranch V–Downstream spring

Location	30° 8' 9.5"N, 98°52'48.7"W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	606.55
Surface Area (ha)	24.30
Slope	0.10
Woody Cover	33.27



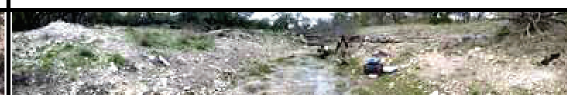
No.26 Perry Hohenberger Ranch VI spring

Location	30° 8' 13.5"N, 98°52'34.3"W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	609.60
Surface Area (ha)	13.23
Slope	0.13
Woody Cover	42.55



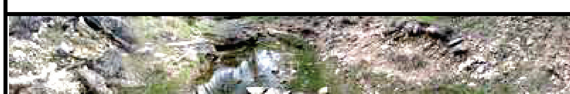
No.27 Preserve at Walnut Spring

Location	30°12'18.6"N, 98°28'33.4"W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	536.45
Surface Area (ha)	11.79
Slope	0.17
Woody Cover	12.75



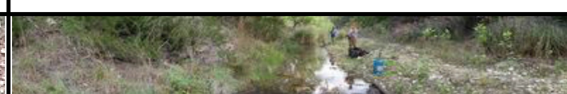
No.28 Roeder Ranch -Upstream spring

Location	30°11' 3.7"N, 99° 7'44.2"W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	600.46
Surface Area (ha)	33.30
Slope	0.07
Woody Cover	34.88



No.29 Roeder Ranch -Downstream spring

Location	30°11' 8.5"N, 99° 7'43.8"W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	597.41
Surface Area (ha)	46.44
Slope	0.06
Woody Cover	34.58



No.30 Ulrich Ranch Spring

Location	30°17' 51.0"N, 98°12' 12.5"W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	274.32
Surface Area (ha)	769.23
Slope	0.20
Woody Cover	22.16

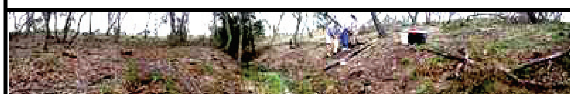
Photo 1. (Continued).

No.31 Zenner Ranch spring

Location	30˚10’ 4.5’’N, 99˚ 6’51.3’’W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	594.36
Surface Area (ha)	45.00
Slope	0.04
Woody Cover	25.83

No.32 Whitten Ranch spring

Location	30˚13’ 7.4’’N, 98˚31’ 5.1’’W
Geology (Formation)	Low Glen Rose-Hensel
Elevation (m)	469.39
Surface Area (ha)	406.08
Slope	0.05
Woody Cover	21.75



No.33 Basis Ranch spring

Location	30˚19’ 42.2’’N, 98˚59’10.0’’W
Geology (Formation)	Edwards-Upper Glen Rose
Elevation (m)	597.41
Surface Area (ha)	19.26
Slope	0.07
Woody Cover	38.87

APPENDIX B

TABLE B-1. The total precipitation, amount of spring flows, and percentage of discharge from precipitation for different evaluation periods, 2003.

	June-August, 2003
Total Precipitation (mm)	346.71

Ranch	Spring No.	Site	Spring Flow (Liter/s)	Flow / Rain (%)
Bamberger	1	1	0.06	0.34
	2	2	0.00	0.00
	3	3	0.04	1.51
Browning	4	4	0.00	0.00
	5	5	4.38	3.66
Craig	—	6	102.46	—
Dave Harris	6	7	0.05	0.24
	7	8	0.08	1.90
	8	9	0.36	1.63
	9	34	0.42	2.26
Doyton Weinderfellar	10	10	0.00	0.00
Gibson	11	11	0.75	1.80
	12	12	0.12	0.31
Guenther Ottmer	—	13	0.00	—
	—	36	0.00	—
Hoppe	13	14	1.40	2.74
	14	15	0.00	—

TABLE B-1. (Continued).

Ranch	Spring No.	Site	Spring Flow (Liter/s)	Flow / Rain (%)
Klett	15	16	0.01	0.08
Margie & Melvin	16	17	6.03	69.76
	17	18	0.31	0.43
Meek	18	19	0.00	0.00
Perry Hohenberger	19	20	0.00	0.00
	20	21	0.00	0.00
	21	22	20.28	67.16
	22	23	0.32	0.43
	23	24	0.09	2.25
	24	25	0.00	0.00
	25	26	0.00	0.00
	26	38	0.00	0.00
Preserve at Walnut	27	27	0.30	7.61
Reed	—	28	1.98	—
	—	29	0.00	—
Roeder	28	30	0.12	1.09
	29	31	0.51	3.28
Ulrich	30	32	1.05	0.41
Zenner	31	33	2.00	13.30
Witten	32	35	0.00	0.00
Basis	33	37	0.00	0.00

TABLE B-2. The total precipitation, amount of spring flows, and percentage of discharge from precipitation for different evaluation periods, 2004.

	March-June, 2004
Total Precipitation (mm)	430.02

Ranch	**Spring No.**	**Site**	**Spring Flow (Liter/s)**		**Flow / Rain**
			March-April	**June**	**(%)**
Bamberger	1	1	0.68	0.35	2.41
	2	2	0.02	0.02	0.11
	3	3	0.01	0.02	0.44
Browning	4	4	0.00	4.32	4.46
	5	5	1.19	7.17	2.85
Craig	—	6	41.20	56.25	—
Dave Harris	6	7	0.16	0.00	0.35
	7	8	0.21	0.33	5.55
	8	9	0.51	0.45	1.78
	9	34	0.45	0.17	1.38
Doyton Weinderfellar	10	10	4.95	1.87	4.06
Gibson	11	11	0.00	3.04	2.99
	12	12	0.00	0.00	0.15
Guenther Ottmer	—	13	0.00	0.08	—
	—	36	0.04	0.00	—
Hoppe	13	14	0.83	0.96	1.42
	14	15	39.12	15.36	—

TABLE B-2. (Continued).

Ranch	Spring No.	Site	Spring Flow (Liter/s)		Flow / Rain
			March-April	June	(%)
Klett	15	16	0.08	0.02	0.27
Margie & Melvin	16	17	0.00	0.00	0.00
	17	18	0.10	0.26	0.21
Meek	18	19	0.06	0.08	0.23
Perry Hohenberger	19	20	0.00	0.00	0.02
	20	21	0.26	0.00	1.81
	21	22	0.42	0.39	1.10
	22	23	4.30	1.42	3.08
	23	24	0.00	0.00	0.02
	24	25	0.02	0.08	0.57
	25	26	0.10	0.01	0.57
	26	38	0.51	0.16	6.20
Preserve at Walnut	27	27	0.18	0.00	1.88
Reed	—	28	0.00	0.00	—
	—	29	0.00	0.00	—
Roeder	28	30	0.01	0.01	0.07
	29	31	0.08	0.21	0.75
Ulrich	30	32	4.69	0.00	0.74
Zenner	31	33	1.55	1.05	7.06
Witten	32	35	0.06	0.40	0.14
Basis	33	37	0.05	0.00	0.31

APPENDIX C

TABLE C-1. Woody species list.

Species	***Science Name***	***Family***
Agarita	*Berberis trifoliolata*	*Berberidaceae*
Ashe Juniper	*Juniperus ashei*	*Cupressaceae*
Black Cherry	*Prunus serotina*	*Rosaceae*
Black Walnut	*Juglans nigra*	*Juglandaceae*
Blackjack Oak	*Quercus marilandica*	*Fagaceae*
Buckeye	*Aesculus arguta*	*Hippocastanaceae*
Cedar Elm	*Ulmus crassifolia*	*Ulmaceae*
Chinquapin Oak/Chinkapin Oak	*Quercus muhlenbergii*	*Fagaceae*
Cottonwood	*Populus deltoides*	*Salicaceae*
Deciduous Yaupon	*Ilex decidua*	*Aouifolieaceae*
Elbow Bush	*Forestiera ligustrina*	*Oleaceae*
Flameleaf Sumac	*Rhus copallina*	*Anacardiaceae*
Greenbriar	*Smilax rotundifolia*	*Smilacaceae*
Gum Bumelia	*Bumelia lanuginosa*	*Sapotaceae*
Hackberry	*Celtis occidentalis*	*Ulmaceae*
Lacey Oak	*Quercus laceyi*	*Fagaceae*
Live Oak	*Quercus virginiana*	*Fagaceae*
Mesquite	*Prosopis glandulosa*	*Fabaceae*
Mulberry	*Morus alba*	*Moraceae*
Mustang grape	*Vitis mustangensis*	*Vitaceae*
Pecan	*Carya illinoensis*	*Juglandaceae*
Persimmon	*Diospyros virginiana*	*Ebenaceae*
Pin Oak	*Quercus palustris*	*Fabaceae*
Post Oak	*Quercus stellata*	*Fabaceae*
Prickly-Pear	*Opuntia strigil*	*Cactaceae*
Redbud	*Cercis canadensis*	*Fabaceae*
Sandpaper Tree	*Ehretia anacua*	*Boraginaceae*
Shin Oak	*Quercus mohriana*	*Fabaceae*
Spanish oak / Texas oak	*Quercus buckleyi*	*Fabaceae*
Sycamore	*Platanus occidentalis*	*Platanaceae*

TABLE C-1. (Continued).

Species	***Science Name***	***Family***
Tasajillo	*Opuntia leptocaulis DC.*	*Cactaceae*
Texas Persimmon	*Diospyros texana*	*Ebenaceae*
Texas Walnut	*Juglans microcarpa*	*Juglandaceae*
Twistleaf Yucca	*Yucca rupicola*	*Liliaceae*
White Oak	*Quercus alba*	*Fagaceae*
Wild Grape	*Vitis rotundifolia*	*Vitaceae*

TABLE C-2. Herbaceous species list.

Species	*Science Name*	*Family*
Aparejograss	*Muhlenbergia utilis*	*Poaceae*
Barrel Cactus	*Ferocactus wislizwni*	*Cactaceae*
Bee Balm	*Monarda didyma*	*Lamiaceae*
Bermudagrass	*Cynodon dactylon*	*Poaceae*
Big Bluestem	*Andropogon gerardii*	*Poaceae*
Big Muhly	*Muhlenbergia lindheimeri*	*Poaceae*
Big Threeawn / Piedmont Threeawn	*Aristida condensata Chapm.*	*Poaceae*
Broomsedge Bulestem	*Andropogon virginicus L.*	*Poaceae*
Broomweed	*Amphiachyris dracunculoides*	*Asteraceae*
Buckeye	*Aesculus arguta*	*Hippocastanaceae*
Buffalograss	*Buchloe dactyloides*	*Poaceae*
Bull Thistle	*Cirsium vulgare*	*Asteraceae*
Bur-Clover	*Medicago polymorpha*	*Fabaceae*
Bushy Bluestem	*Andropogon glomeratus*	*Poaceae*
Butterfly weed	*Asclepias tuberosa*	*Asclepiadaceae*
Canada wildrye	*Elymus canadensis L.*	*Poaceae*
Cedar Sedge	*Carex planostachys Kunze*	*Cyperaceae*
Dallisgrass	*Paspalum dilatatum Poir.*	*Poaceae*
Dewberry	*Rubus tricialis*	*Rosaceae*
Downy Brome	*Bromus tectarum*	*Poaceae*
Fall Witchgrass	*Digitaria cognata*	*Poaceae*
False Ragweed	*Parthenium hysterophorus*	*Asteraceae*
Frostweed	*Verbesina virginica*	*Asteraceae*
Gerardia	*Agalinis tenuifolia*	*Scrophulariaceae*
Green Sprangletop	*Leptochloa dubia*	*Poaceae*
Greenbriar	*Smilax rotundifolia*	*Smilacaceae*
Gum Bumelia	*Bumelia lanuginosa (Michx. Pers.)*	*Sapotaceae*
Hairy Grama	*Bouteloua hirsuta Lag.*	*Poaceae*
Halls Panicum	*Panicum hallii Vasey var. hallii*	*Poaceae*
Henbit	*Lamium amplexicaule*	*Lamiaceae*
Indian Grass	*Sorghastrum nutans*	*Poaceae*

TABLE C-2. (Continued).

Species	*Science Name*	*Family*
Indian Paintbrush	*Castilleja coccinea*	*Scrophulariaceae*
King Ranch Bluestem	*Bothriochloa ischaemum*	*Poaceae*
Kleingrass	*Panicum coloratum L.*	*Poaceae*
Little Bluestem	*Schizachyrium scoparium*	*Poaceae*
Little Muhly / Gravelbar Muhly	*Muhlenbergia eludens*	*Poaceae*
Maidenhair Fern	*Adiantum raddianum*	*Pteridaceae*
Meadow dropseed	*Sporobolus compositus*	*Poaceae*
Mealy Sage	*Salvia farinacea*	*Lamiaceae*
Milkpea	*Galactia heterophylla*	*Lauraceae*
Milkweed	*Asclepias syriaca*	*Asclepiadaceae*
Monkey/Mondo Grass	*Ophiopogan japonicus*	*Liliaceae*
Mule's Ear	*Wyethia mollis*	*Asteraceae*
Musk (or Nodding) Thistle	*Carduus nutans*	*Asteraceae*
New Mexican verbena	*Verbena macdougalii*	*Verbenaceae*
Nightshade	*Solanum dulcamara*	*Solanaceae*
Oldfield Threeawn	*Aristida oligantha Michx.*	*Poaceae*
Orange Zexmania	*Zexmenia hispida*	*Asteraceae*
Peppergrass	*Lepidium montanum*	*Brassicaceae*
Plains Lovegrass	*Eragrostis intermedia Hitchc.*	*Poaceae*
Plantain	*Plantago major*	*Plantaginaceae*
Poison ivy	*Rhus radicans*	*Acacardiaceae*
Prairie Coneflower	*Ratibida pinnata*	*Asteraceae*
Prairie Parsley	*Polytaenia nuttallii*	*Apiaceae*
Prairie Verbena	*Verbena bipinnatifida*	*Verbenaceae*
Prickly-Pear	*Opuntia strigil*	*Cactaceae*
Purple Threeawn	*Aristida purpurea Nutt.*	*Poaceae*
Purple Verbena	*Verbena bonariensis*	*Verbenaceae*
Queen Anne's Lace	*Daucus carota*	*Apiaceae*
Ragweed	*Ambrosia artemisiifolia*	*Asteraceae*
Red Lovegrass	*Eragrostis secundiflora Presl.*	*Poaceae*

TABLE C-2. (Continued).

Species	*Science Name*	*Family*
Rescuegrass	*Bromus unioloides*	*Poaceae*
Scribner's Panicum	*Dichanthium oligosanthes*	*Poaceae*
Sedge	*Carex sp.*	*Cyperaceae*
Seep Muhly	*Muhlenbergia reverchonii*	*Poaceae*
Sharp-pod morning glory	*Ipomoea trichocarpa*	*Convolvulaceae*
Sida	*Sida albutifolia*	*Malvaceae*
Sideoats Grama	*Bouteloua curtipendula*	*Poaceae*
Silky bluestem	*Dichanthium sericeum*	*Poaceae*
Silver Bluestem	*Bothriochloa saccharoides*	*Poaceae*
Silver-Leaf Nightshade	*Solanum elaeagnifolium*	*Solanaceae*
Single-seed Croton	*Croton monanthogynus*	*Euphorbiaceae*
Small-Headed Sneezeweed	*Helenium microcephalum*	*Asteraceae*
Sneezeweed	*Helenium outumnale*	*Asteraceae*
Snow-on-the-Mountain	*Euphorbia marginata*	*Euphorbiaceae*
Spike Rush	*Eleacharis calva*	*Cyperaceae*
St. Augustinegrass	*Stenotaphrum secundatum*	*Poaceae*
Sumpweed	*Iva annua*	*Asteraceae*
Tasajillo	*Opuntia leptocaulis*	*Opuntiaceae*
Texas Croton	*Croton texensis*	*Euphorbiaceae*
Texas Cupgrass	*Eriochloa sericea*	*Poaceae*
Texas Frog Fruit	*Phyla incisa*	*Verbenaceae*
Texas Grama	*Bouteloua rigidiseta*	*Poaceae*
Texas Verbena	*Verbena X Hybrida*	*Verbenaceae*
Texas Wintergrass	*Stipa leucotricha*	*Poaceae*
Threeawn	*Aristida intermedia*	*Poaceae*
Tumblegrass	*Schedonnardus paniculatus*	*Poaceae*
Two-Leaved Senna	*Cassia roemeriana*	*Fabaceae*
Velvet Bean	*Mucuna utilis*	*Fabaceae*
Vinemesquite	*Panicum obtusum H.B. K.*	*Poaceae*
Violet Wild Petunia	*Ruellia nudiflora*	*Acanthaceae*

TABLE C-2. (Continued).

Species	*Science Name*	*Family*
Virginia Creeper	*Parthenocissus quinquefolia*	*Vitaceae*
White Tridens	*Tridens albescens*	*Poaceae*
Wild bean	*Strophostyles helvola*	*Fabaceae*
Wild Grape	*Vitis rotundifolia*	*Vitaceae*
Yellow Sweet Clover	*Melilotus officinalis*	*Fabaceae*

APPENDIX D

TABLE D-1. Herbaceous species and average spring flow loadings from CA.

Objects	Score in Dimension 1	Score in Dimension 2	Inertia
Average spring flow			
<0.05 L/s	0.451	0.561	0.077
0.05-0.10 L/s	0.489	-0.834	0.086
>0.10 L/s	-0.957	-0.019	0.134
Herbaceous species			
Bermudagrass (Ber)	-1.766	-0.235	0.020
Broomweed (Bro)	-1.907	-0.087	0.018
Bushy Bluestem (BuB)	0.249	-0.103	0.000
Cedar Sedge (CeS)	-0.180	-0.120	0.002
Dallisgrass (Dal)	-1.056	0.105	0.008
Dewberry (Dew)	-0.400	-0.265	0.000
Downy Brome (DoB)	0.694	1.606	0.004
False Ragweed (FaR)	-2.144	-0.059	0.018
Frostweed (Fro)	-0.708	0.647	0.005
Green Sprangletop (GrS)	0.639	1.573	0.007
Greenbriar (Gre)	-0.094	-0.259	0.001
Hairy Grama (HaG)	-0.068	-0.193	0.000
Halls Panicum (HaP)	-1.012	0.283	0.003
King Ranch Bluestem (KRB)	-0.206	0.487	0.008
Kleingrass (Kle)	0.877	-1.666	0.008
Little Bluestem (LiB)	0.893	0.439	0.031
Meadow Dropseed (MeD)	-0.669	0.243	0.005
Mealy Sage (MeS)	0.682	-1.268	0.029
Musk (Mus)	1.010	1.791	0.010
Oldfield Threeawn (OlT)	0.698	-0.016	0.013

TABLE D-1. (Continued).

Objects	Score in 1	Dimension 2	Inertia
Orange Zexmania (OrZ)	-0.152	1.109	0.003
Plains Lovegrass (PlL)	-0.275	0.730	0.004
Poison ivy (PoI)	1.018	1.346	0.004
Prairie Coneflower (PrC)	-1.507	-0.023	0.017
Prairie Verbena (PrV)	0.776	0.152	0.001
Prickly-Pear Cactus (PrP)	0.508	0.245	0.001
Purple Threeawn (PuT)	-0.774	-0.221	0.002
Ragweed Rag()	-0.433	0.252	0.001
Red Lovegrass (ReL)	1.029	0.801	0.002
Scribner's Panicum (ScP)	0.467	0.260	0.004
Sedge (Sed)	-0.274	0.243	0.000
Seep Muhly (SeM)	0.447	-0.403	0.003
Sida (Sid)	-0.068	-0.057	0.000
Sideoats Grama (SiG)	0.664	0.183	0.008
Silver Bluestem (SiB)	-0.362	0.987	0.003
Single-seed Croton (SsC)	0.503	0.528	0.003
Snow-on-the-Mountain (SoM)	-0.151	-0.016	0.000
Spike Rush (SpR)	0.162	-0.208	0.000
Sumpweed (Sum)	0.507	-2.190	0.007
Texas Croton (TXC)	-0.120	-0.354	0.001
Texas Grama (TXG)	-0.206	0.308	0.001
Texas Verbena (TXV)	-1.768	-0.104	0.010
Texas Wintergrass (TXW)	-0.271	-0.527	0.010
Two-Leaved Senna (TLS)	0.755	-1.512	0.008
Violet Wild Petunia (VWP)	-1.829	0.126	0.006
Virginia Creeper (ViC)	0.790	-0.591	0.004
Wild Grape (WiG)	0.422	-0.806	0.001
Total			0.297

TABLE D-2. Herbaceous species and average juniper cover loadings from CA.

Objects	Score in Dimension 1	Score in Dimension 2	Inertia
Average spring flow			
None Juniper	0.208	0.491	0.047
<2.0% Juniper	0.605	-0.828	0.081
>2.0% Juniper	-1.037	-0.256	0.101
Herbaceous species			
Bermudagrass (Ber)	0.975	-0.043	0.005
Broomweed (Bro)	-0.986	-0.464	0.005
Bushy Bluestem (BuB)	0.466	-0.286	0.001
Cedar Sedge (CeS)	-0.171	-0.365	0.005
Dallisgrass (Dal)	-0.537	0.139	0.002
Dewberry (Dew)	-2.195	-0.397	0.008
Downy Brome (DoB)	0.994	-0.120	0.002
False Ragweed (FaR)	-0.721	0.681	0.003
Frostweed (Fro)	0.420	0.737	0.003
Green Sprangletop (GrS)	1.133	-0.683	0.004
Greenbriar (Gre)	-0.593	-0.388	0.008
Hairy Grama (HaG)	0.442	0.503	0.001
Halls Panicum (HaP)	-0.487	0.118	0.001
King Ranch Bluestem (KRB)	-0.042	-0.449	0.006
Kleingrass (Kle)	0.488	0.922	0.002
Little Bluestem (LiB)	0.217	-0.126	0.002
Meadow Dropseed (MeD)	-0.942	0.520	0.009
Mealy Sage (MeS)	0.825	0.565	0.014
Musk (Mus)	1.639	-2.730	0.023
Oldfield Threeawn (OlT)	0.776	-0.007	0.013

TABLE D-2. (Continued).

Objects	Score in Dimension 1	Score in Dimension 2	Inertia
Orange Zexmania (OrZ)	-0.169	-1.349	0.004
Plains Lovegrass (PlL)	-0.875	-0.248	0.005
Poison ivy (PoI)	-2.809	-0.845	0.013
Prairie Coneflower (PrC)	-1.241	-0.341	0.010
Prairie Verbena (PrV)	0.564	1.620	0.005
Prickly-Pear Cactus (PrP)	-0.449	-0.547	0.001
Purple Threeawn (PuT)	0.159	0.957	0.002
Ragweed Rag()	0.588	-0.338	0.002
Red Lovegrass (ReL)	1.161	-0.797	0.003
Scribner's Panicum (ScP)	-0.381	0.073	0.002
Sedge (Sed)	-0.707	-0.819	0.003
Seep Muhly (SeM)	0.718	-0.393	0.006
Sida (Sid)	0.263	0.666	0.008
Sideoats Grama (SiG)	0.134	0.588	0.004
Silver Bluestem (SiB)	-1.049	0.441	0.004
Single-seed Croton (SsC)	0.411	-0.448	0.002
Snow-on-the-Mountain (SoM)	-0.010	-0.084	0.000
Spike Rush (SpR)	0.382	-1.224	0.008
Sumpweed (Sum)	0.355	1.000	0.002
Texas Croton (TXC)	-0.167	0.500	0.003
Texas Grama (TXG)	0.490	-0.438	0.002
Texas Verbena (TXV)	0.032	0.929	0.002
Texas Wintergrass (TXW)	-0.213	0.482	0.007
Two-Leaved Senna (TLS)	0.779	0.750	0.003
Violet Wild Petunia (VWP)	-1.797	-0.105	0.005
Virginia Creeper (ViC)	-0.982	0.490	0.004
Wild Grape (WiG)	-1.122	0.388	0.002
Total			0.228

TABLE D-3. Herbaceous species and average woody cover (except juniper) loadings from CA.

Objects	Score in Dimension 1	Score in Dimension 2	Inertia
Average spring flow			
<30% Woody Cover	-0.790	0.231	0.108
31-51% Woody Cover	0.222	-0.830	0.076
>51% Woody Cover	0.749	0.544	0.104
Herbaceous species			
Bermudagrass (Ber)	1.151	1.283	0.015
Broomweed (Bro)	0.458	0.605	0.002
Bushy Bluestem (BuB)	-1.507	0.662	0.013
Cedar Sedge (CeS)	0.805	0.270	0.029
Dallisgrass (Dal)	0.172	1.045	0.006
Dewberry (Dew)	1.193	-0.248	0.003
Downy Brome (DoB)	-0.665	-0.923	0.002
False Ragweed (FaR)	-0.947	-0.534	0.004
Frostweed (Fro)	-0.726	0.419	0.004
Green Sprangletop (GrS)	0.404	0.395	0.001
Greenbriar (Gre)	0.893	0.119	0.015
Hairy Grama (HaG)	-0.840	-0.385	0.003
Halls Panicum (HaP)	0.636	1.096	0.003
King Ranch Bluestem (KRB)	-0.572	0.451	0.019
Kleingrass (Kle)	1.137	-0.441	0.004
Little Bluestem (LiB)	0.138	-1.002	0.025
Meadow Dropseed (MeD)	-0.937	-0.230	0.009
Mealy Sage (MeS)	0.234	-0.544	0.005
Musk (Mus)	1.754	1.674	0.016
Oldfield Threeawn (OlT)	-0.300	-0.175	0.003

TABLE D-3. (Continued).

Objects	Score in Dimension 1	2	Inertia
Orange Zexmania (OrZ)	0.725	-0.653	0.003
Plains Lovegrass (PlL)	-1.173	0.181	0.011
Poison ivy (PoI)	0.644	-2.132	0.007
Prairie Coneflower (PrC)	-0.053	0.605	0.002
Prairie Verbena (PrV)	-0.759	-0.298	0.001
Prickly-Pear Cactus (PrP)	0.073	-0.292	0
Purple Threeawn (PuT)	-1.172	-0.223	0.003
Ragweed Rag()	0.590	0.313	0.002
Red Lovegrass (ReL)	-0.785	0.561	0.001
Scribner's Panicum (ScP)	-0.148	0.265	0.001
Sedge (Sed)	-0.366	1.106	0.003
Seep Muhly (SeM)	-0.825	-0.294	0.008
Sida (Sid)	-0.041	-0.230	0.001
Sideoats Grama (SiG)	0.011	-0.260	0.001
Silver Bluestem (SiB)	-1.178	0.042	0.006
Single-seed Croton (SsC)	0.114	0.121	0.000
Snow-on-the-Mountain (SoM)	-1.328	0.361	0.005
Spike Rush (SpR)	-1.283	0.752	0.013
Sumpweed (Sum)	1.754	1.674	0.010
Texas Croton (TXC)	-0.062	0.349	0.001
Texas Grama (TXG)	-0.340	-0.503	0.002
Texas Verbena (TXV)	-1.214	0.879	0.006
Texas Wintergrass (TXW)	0.314	-0.237	0.005
Two-Leaved Senna (TLS)	-0.058	0.019	0.000
Violet Wild Petunia (VWP)	0.644	-2.132	0.007
Virginia Creeper (ViC)	0.532	-1.090	0.005
Wild Grape (WiG)	1.260	-0.018	0.003
Total			0.288

APPENDIX E

TABLE E-1. Presented herbaceous plant families by different distances from the stream bank.

Families		Distance from the Stream Bank <10 M Count	% [a]	Adjusted Residual	>10 M Count	% [a]	Adjusted Residual	Total % [a]	χ^2
Acacardiaceae	(N= 10)	7	1.30	0.60	3	0.80	-0.60	1.10	0.42
Acanthaceae	(N= 10)	7	1.30	0.60	3	0.80	-0.60	1.10	0.42
Apiaceae	(N= 11)	10	1.90	2.10	1	0.30	-2.10	1.20	4.43
Asclepiadaceae	(N= 7)	4	0.70	-0.20	3	0.80	0.10	0.80	0.02
Asteraceae	(N=159)	102	18.90	1.20	57	15.80	-1.20	17.70	1.39
Brassicaceae	(N= 1)	1	0.20	0.80	0	0.00	-0.80	0.10	0.67
Cactaceae	(N= 19)	15	2.80	1.70	4	1.10	-1.70	2.10	2.90
Convolvulaceae	(N= 1)	1	0.20	0.80	0	0.00	-0.80	0.10	0.67
Cyperaceae	(N=280)	159	29.40	-1.30	121	33.60	1.30	31.10	1.75
Euphorbiaceae	(N=135)	90	16.70	1.70	45	12.50	-1.70	15.00	2.94
Fabaceae	(N= 32)	25	4.60	2.10	7	1.90	-2.10	3.60	4.54 *
Hippocastanaceae	(N= 1)	0	0.00	-1.20	1	0.30	1.20	0.10	1.50
Lamiaceae	(N=106)	79	14.60	3.30	27	7.50	-3.30	11.80	10.57 ***
Lauraceae	(N= 4)	2	0.40	-0.40	2	0.60	0.40	0.40	0.17
Liliaceae	(N= 1)	1	0.20	0.80	0	0.00	-0.80	0.10	0.67
Malvaceae	(N=126)	80	14.80	0.90	46	12.80	-0.90	14.00	0.74
Plantaginaceae	(N= 3)	1	0.20	-0.90	2	0.60	0.90	0.30	0.89
Poaceae	(N=768)	470	87.00	1.80	298	82.80	-1.80	85.30	3.13
Pteridacea	(N= 2)	0	0.00	-1.70	2	0.60	1.70	0.20	3.01
Rosaceae	(N= 11)	8	1.50	0.90	3	0.80	-0.90	1.20	0.75
Scrophulariaceae	(N= 3)	3	0.60	1.40	0	0.00	-1.40	0.30	2.01
Smilacaceae	(N=106)	64	11.90	0.10	42	11.70	-0.10	11.80	0.01
Solanaceae	(N= 5)	3	0.60	0.00	2	0.60	0.00	0.60	0.00
Verbenaceae	(N= 37)	26	4.80	1.30	11	3.10	-1.30	4.10	1.70
Vitaceae	(N= 34)	18	3.30	-0.90	16	4.40	0.90	3.80	0.73
Total	(N= 900)	540			360				

Note. [a] The percent within distance.

* $p \leqq 0.05$, *** $p \leqq 0.001$.

TABLE E-2. Presented herbaceous plant families by different levels of average spring flow.

Families		Average Spring Flow <0.1 L/s Count	% [a]	Adjusted Residual	Average Spring Flow >0.1 L/s Count	% [a]	Adjusted Residual	Total % [a]	χ^2
Acacardiaceae	(N= 10)	9	2.10	2.80	1	0.20	-2.80	1.10	7.63
Acanthaceae	(N= 10)	1	0.20	-2.30	9	1.90	2.30	1.10	5.46
Apiaceae	(N= 11)	5	1.20	-0.10	6	1.30	0.10	1.20	0.01
Asclepiadaceae	(N= 7)	4	1.00	0.60	3	0.60	-0.60	0.80	0.31
Asteraceae	(N=159)	63	15.00	-2.00	96	20.00	2.00	17.70	3.85 *
Brassicaceae	(N= 1)	1	0.20	1.10	0	0.00	-1.10	0.10	1.14
Cactaceae	(N= 19)	15	3.60	2.90	4	0.80	-2.90	2.10	8.13 **
Convolvulaceae	(N= 1)	1	0.20	1.10	0	0.00	-1.10	0.10	1.14
Cyperaceae	(N=280)	110	26.20	-3.00	170	35.40	3.00	31.10	8.90 **
Euphorbiaceae	(N=135)	65	15.50	0.40	70	14.60	-0.40	15.00	0.14
Fabaceae	(N= 32)	14	3.30	-0.30	18	3.80	0.30	3.60	0.11
Hippocastanaceae	(N= 1)	1	0.20	1.10	0	0.00	-1.10	0.10	1.14
Lamiaceae	(N=106)	41	9.80	-1.80	65	13.50	1.80	11.80	3.08
Lauraceae	(N= 4)	2	0.50	0.10	2	0.40	-0.10	0.40	0.02
Liliaceae	(N= 1)	1	0.20	1.10	0	0.00	-1.10	0.10	1.14
Malvaceae	(N=126)	58	13.80	-0.20	68	14.20	0.20	14.00	0.02
Plantaginaceae	(N= 3)	1	0.20	-0.50	2	0.40	0.50	0.30	0.22
Poaceae	(N=768)	383	91.20	4.60	385	80.20	-4.60	85.30	21.59 ***
Pteridacea	(N= 2)	0	0.00	-1.30	2	0.40	1.30	0.20	1.75
Rosaceae	(N= 11)	3	0.70	-1.30	8	1.70	1.30	1.20	1.68
Scrophulariaceae	(N= 3)	2	0.50	0.70	1	0.20	-0.70	0.30	0.48
Smilacaceae	(N=106)	40	9.50	-2.00	66	13.80	2.00	11.80	3.85 *
Solanaceae	(N= 5)	0	0.00	-2.10	5	1.00	2.10	0.60	4.40
Verbenaceae	(N= 37)	12	2.90	-1.80	25	5.20	1.80	4.10	3.14
Vitaceae	(N= 34)	20	4.80	1.40	14	2.90	-1.40	3.80	2.10
Total	(N= 900)	420			480				

Note. [a] The percent within distance.

* $p \leqq 0.05$, ** $p \leqq 0.01$, *** $p \leqq 0.001$.

TABLE E-3. Presented herbaceous plant families by different levels of juniper cover.

Families		Juniper Canopy Cover 0.0 % Count	% [a]	Adjusted Residual	>0.1 L/s Count	% [a]	Adjusted Residual	Total % [a]	χ^2
Acacardiaceae	(N= 10)	0	0.00	-3.00	10	2.10	3.00	1.10	8.85
Acanthaceae	(N= 10)	3	0.70	-1.10	7	1.50	1.10	1.10	1.13
Apiaceae	(N= 11)	6	1.40	0.50	5	1.00	-0.50	1.20	0.28
Asclepiadaceae	(N= 7)	4	1.00	0.60	3	0.60	-0.60	0.80	0.31
Asteraceae	(N=159)	70	16.70	-0.70	89	18.50	0.70	17.70	0.54
Brassicaceae	(N= 1)	1	0.50	1.10	0	0.00	-1.10	0.10	1.14
Cactaceae	(N= 19)	6	1.40	-1.30	13	2.70	1.30	2.10	1.78
Convolvulaceae	(N= 1)	1	0.20	1.10	0	0.00	-1.10	0.10	1.14
Cyperaceae	(N=280)	107	25.50	-3.40	173	36.00	3.40	31.10	11.67 ***
Euphorbiaceae	(N=135)	76	18.10	2.40	59	12.30	-2.40	15.00	5.92 *
Fabaceae	(N= 32)	18	4.30	1.10	14	2.90	-1.10	3.60	1.22
Hippocastanaceae	(N= 1)	1	0.20	1.10	0	0.00	-1.10	0.10	1.14
Lamiaceae	(N=106)	79	18.80	6.10	27	5.60	-6.10	11.80	37.47 ***
Lauraceae	(N= 4)	2	0.50	0.10	2	0.40	0.10	0.40	0.02
Liliaceae	(N= 1)	1	0.20	1.10	0	0.00	-1.10	0.10	1.14
Malvaceae	(N=126)	91	21.70	6.20	35	7.30	-6.20	14.00	38.45 ***
Plantaginaceae	(N= 3)	1	0.20	-0.50	2	0.40	0.50	0.30	0.22
Poaceae	(N=768)	379	90.20	3.90	389	81.00	-3.90	85.30	15.14 ***
Pteridacea	(N= 2)	1	0.20	0.10	1	0.20	0.10	0.20	0.01
Rosaceae	(N= 11)	2	0.50	-1.90	9	1.90	1.90	1.20	3.63
Scrophulariaceae	(N= 3)	1	0.20	-0.50	2	0.40	0.50	0.30	0.22
Smilacaceae	(N=106)	38	9.00	-2.40	68	14.20	2.40	11.80	5.65 *
Solanaceae	(N= 5)	5	1.20	2.40	0	0.00	-2.40	0.60	5.75
Verbenaceae	(N= 37)	28	6.70	3.60	9	1.90	-3.60	4.10	13.05 ***
Vitaceae	(N= 34)	18	4.30	0.70	16	3.30	-0.70	3.80	0.56
Total	(N= 900)	420			480				

Note. [a] The percent within distance.

* $p \leqq 0.05$, *** $p \leqq 0.001$.

TABLE E-4. Presented herbaceous plant families by different levels of woody canopy cover (excepted juniper).

		Other Woody Canopy Cover							
		<40.0 %			>40.0 %				
Families		Count	% [a]	Adjusted Residual	Count	% [a]	Adjusted Residual	Total % [a]	χ^2
Acacardiaceae	(N= 10)	0	0.00	-2.80	10	2.00	2.80	1.10	7.73
Acanthaceae	(N= 10)	6	1.50	1.10	4	0.80	-1.10	1.10	1.14
Apiaceae	(N= 11)	7	1.80	1.40	4	0.80	-1.40	1.20	1.87
Asclepiadaceae	(N= 7)	4	1.00	0.70	3	0.60	-0.70	0.80	0.55
Asteraceae	(N=159)	62	15.90	-1.20	97	19.00	1.20	17.70	1.48
Brassicaceae	(N= 1)	0	0.00	-0.90	1	0.20	0.90	0.10	0.77
Cactaceae	(N= 19)	7	1.80	-0.60	12	2.40	0.60	2.10	0.33
Convolvulaceae	(N= 1)	0	0.00	-0.90	1	0.20	0.90	0.10	0.77
Cyperaceae	(N=280)	94	24.10	-4.00	186	36.50	4.00	31.10	15.77 ***
Euphorbiaceae	(N=135)	74	19.00	2.90	61	12.00	-2.90	15.00	8.53 **
Fabaceae	(N= 32)	13	3.30	-0.30	19	3.70	0.30	3.60	0.10
Hippocastanaceae	(N= 1)	0	0.00	-0.90	1	0.20	0.90	0.10	0.77
Lamiaceae	(N=106)	36	9.20	-2.10	70	13.70	2.10	11.80	4.30 *
Lauraceae	(N= 4)	0	0.00	-1.80	4	0.80	1.80	0.40	3.07
Liliaceae	(N= 1)	1	0.30	1.10	0	0.00	-1.10	0.10	1.31
Malvaceae	(N=126)	60	15.40	1.00	66	12.90	-1.00	14.00	1.10
Plantaginaceae	(N= 3)	2	0.50	0.80	1	0.20	-0.80	0.30	0.67
Poaceae	(N=768)	356	91.30	4.40	412	80.80	-4.40	85.30	19.46 ***
Pteridacea	(N= 2)	0	0.00	-1.20	2	0.40	1.20	0.20	1.53
Rosaceae	(N= 11)	2	0.50	-1.70	9	1.80	1.70	1.20	2.87
Scrophulariaceae	(N= 3)	1	0.30	-0.40	2	0.40	0.40	0.30	0.12
Smilacaceae	(N=106)	22	5.60	-5.00	84	16.50	5.00	11.80	24.94 ***
Solanaceae	(N= 5)	5	1.30	2.60	0	0.00	-2.60	0.60	6.58
Verbenaceae	(N= 37)	28	7.20	4.10	9	1.80	-4.10	4.10	16.44 ***
Vitaceae	(N= 34)	3	0.80	-4.10	31	6.10	4.10	3.80	17.14 ***
Total	(N= 900)	390			510				

Note. [a] The percent within distance.

* $p \leqq 0.05$, ** $p \leqq 0.01$, *** $p \leqq 0.001$.

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