RISK ASSESSMENT OF RUNOFF AND EROSION ON A RANGE WATERSHED IN BRAZOS COUNTY, TEXAS

A Thesis

by

TRACY MARIE GWALTNEY

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

MASTER OF SCIENCE

December 2003

Major Subject: Rangeland Ecology and Management

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ABSTRACT

Risk Assessment of Runoff and Erosion on a

Range Watershed in Brazos County, Texas. (December 2003)

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A drip type rainfall simulator and an existing watershed study were used to assess relationships between runoff, infiltration, erosion and associated risk thresholds on a range watershed in Brazos County, Texas. The focus of the research was determining erosion risk associated with seasonal variations in precipitation and vegetation. The objectives were to (1) develop a climatic profile for Brazos County, Texas, (2) evaluate relationships between vegetative cover, infiltration, runoff, and climatic events, (3) quantify erosion/ runoff risk associated with measured vegetation, soil moisture, and climatic events, and (4) identify potential managerial thresholds for erosion risk management on similar range watersheds.

The current year climatic profile showed the wettest season was summer with thirty-two percent of the precipitation coming from one rainfall event. Also, October through December was higher than the long-term rainfall average.

Pair wise correlations identified season, initial time to runoff, percent litter, annual as the dominant species, soil moisture, amount to runoff and amount to storage as

significant ($p<0.05$) variables affecting runoff and infiltration. Percent saturation and annuals as the dominant species were significant variables affecting sediment yield.

During the current study, seasonal variations in precipitation patterns influenced runoff, infiltration, and sediment yield. Spring and summer had the highest infiltration rates while the largest runoff events were in fall and winter. The highest percent of soil saturation coincided with the largest runoff and sediment losses.

Minimums of two centimeters (winter and fall) and three centimeters (spring and summer) initiated runoff. This rainfall threshold would be exceeded 20 percent of the time based on the climatic profile developed for Brazos County.

Peak biomass production for the watershed site was 170.61 g/m^2. This was above the recommended biomass threshold of 134.5 to 168.1 grams/m^2 to minimize sediment loss for tallgrass rangeland. Annual sediment loss was 10.8 grams/m^2, which is negligible. Additional research across a wider array of site variation is needed to identify appropriate thresholds for the Post Oak Savanna ecosystem.

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My family's support has always been valuable to me. I would especially like to thank my parents, Kay and Steven Fischer, and my Nana and Papa (Mr. and Mrs. Clyde P. Donahoe) for their constant love and support. Their guidance and encouragement has always been an inspiration and appreciated. I would also like to thank Nathan Olday for his patience and love while I completed this thesis.

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INTRODUCTION

The continued degradation of rangeland systems indicates past management decisions have not provided for sustainability. A contributing factor to continued degradation is inadequate risk assessment strategies and a low priority on sustainability.

Byrd and Cothern (2000) define risk as the “probability of future loss.” Ecosystem risk management is a continual process of manipulating a biophysical system and human interactions by making decisions that hold the overall risk to an acceptable level at a minimum cost (Cleaves and Haynes 1999). Since risk involves future implications, the natural resource manager must address both financial and ecological risks associated with management decisions to better predict the potential impacts and influence on the future sustainability of the biophysical system.

Many past management decisions have focused on the concept of short-term maximum sustainable yield and not long-term sustainability. Therefore, financial risk has received higher priority than ecological risk. Drucker (1974) suggested that long-term viability of an enterprise must not be jeopardized for short-term economic gains if sustainability is a goal. Financial returns from rangeland enterprises depend on renewable resources as the basis for production. Thus, sustainable financial management is directly related to sustaining the resource and ecological function.

Thesis follows style and format of the Journal of Range Management.

Rangeland risk literature is generally lacking except in general terms. If resource sustainability is an important goal, then long-term ecological risk must be acknowledged, analyzed and detrimental risk situations avoided. Development of tools that managers can apply for identifying long-term ecological risk is vital for improved decision-making.

The “state and transition” model (Archer 1989, Westoby et al. 1989, Friedel 1991) describes the concept of ecological states and the thresholds that separate them. This concept suggests that vegetation and soils may exist as one of several ‘states” on a given site and can be extremely variable (i.e. species composition, productivity, and ground cover). In many cases, it is the interaction between human management decisions and natural disturbance that affect a shift in ‘state’ and viability. Shift is often perceived as a loss of productivity, ecological function, or a decline in health. Laycock (1991) stressed the importance of thresholds because “once a threshold is crossed towards increased degradation, improvement cannot be attained on a practical time-scale without a much greater intervention, input, and management effort.” Avoidance of an undesirable state/transition change requires development and recognition of critical thresholds and use of calculated probabilities of risk associated with crossing the threshold.

Threshold information from an ecological risk perspective has often been overlooked. Risk probabilities and the outcome of most decisions have not been evaluated. Defining thresholds and calculating risk probabilities for critical processes and resource components is needed to improve the decision-making process.

The objectives of this study are:

- Develop a climatic profile for Brazos County, Texas to identify seasonal variations in precipitation patterns. Specifically, identifying the frequency of different rainfall events for different seasons used in conjunction with seasonal vegetation/ soil cover characteristics;
- Evaluate relationships between vegetative cover, infiltration, runoff, and climatic events on an existing range watershed;
- Quantify erosion/runoff risk associated with measured vegetation, soil moisture, and climatic events; and
- Identify potential managerial thresholds for erosion risk management on similar range watersheds.

LITERATURE REVIEW

Several studies have addressed function and processes of a rangeland watershed (Meeuwig 1970, Dixon 1985, Thurow 1985, 1991, 2000, Franklin 1987, Heathcote 1998, and Flenniken et al. 2001). Rangeland watersheds are unique because they generally fall at one extreme or another on the hydrologic yield scale (i.e. low rainfall or low water yield) (Branson et al. 1972). Major concerns of rangeland hydrology are 1) runoff or water yield, 2) erosion and sediment yield, 3) and water quality (Branson et al. 1972). Risk associated with watershed degradation has not been adequately addressed. Most rangeland risk research focuses on financial, short-term goals (Society for Range Management 1983, Meppen and Johnston 1990, Smith 1994, White 1994). This focus often underemphasizes the importance of long-term sustainability of watershed health. Therefore, degradation has continued to occur on many rangeland ecosystems across the world (Whisenant 1999). The following literature review summarizes prior research and the interrelationships of watershed characteristics and climatic influences within the context of an ecological risk analysis approach.

Watershed Studies

Significant research has been conducted on multiple aspects of rangeland watersheds (Harrington et al. 1984, Hart 1984, Thurow 1985, Hays et al. 2000). However, many of the variables affecting watershed health has been studied independently (Blackburn et al. 1986), although many of these variables interact together. Their relationships need to be addressed together to develop predictive capabilities for risk analysis, leading to improved management strategies.

Climatic influences, soil maintenance and water capture/loss are important concepts in the rangeland/watershed ecosystem. Therefore it is necessary to review these aspects and their interrelationships with other watershed characteristics. Sediment yield, runoff, and infiltration relationships for several watershed components are summarized in Table 1, adapted from Thurow (1985) and McGinty et al. (1995).

The importance of soil erosion has been documented in literature since the 1900's. It has been estimated that the United States loses 4.4 billion tons of soil every year (Giodanego et al. 2003). Sustaining existing soil resources is essential. Soil should be considered as an irreplaceable natural resource (Arnalds et al. 2001); therefore, it is necessary to understand and predict the risks associated with soil loss as related to management decisions.

Table 1: Summary of hydrologic relationships between sediment yield and runoff to selected watershed characteristics. Adapted from Thurow (1985) and McGinty et. al. (1995). (+): Increase or (-): Decrease

Watershed component	**Sediment Yield/Runoff**	**Infiltration**
As intensity of storm increases	+	-
As soil moisture increases	+	-
As infiltration increases	-	
As vegetative cover increases	-	+
As litter increases	-	+

Climate Influences

Climate, in particular precipitation, influences productivity and is the major factor determining hydrology on a rangeland watershed (Rowan et al. 1994, Tate1996a, Heathcote 1998). Houerou et al. (1988) considers variability of rainfall amount, distribution and primary production of vegetation directly related to degree of aridity.

Three storm types control the way precipitation occurs; frontal, convective, and orographic (Tate 1996a, Ward and Elliot 1995), with frontal and convective being the most prevalent in Texas. Warm or cold fronts cause frontal precipitation. High intensity rainfall in narrow bands is created with a cold front, while warm fronts produce low precipitation intensities over large land areas (Tate 1996a). Convective storms are caused by air being heated and expanded by solar energy, and then becoming lighter and rising by convection (Ward and Elliot 1995). These storms are generally small in size, but create intense showers, hail, or tornados (Tate 1996a), and are common in the summer in the central United States (Ward and Elliot 1995).

Soil loss and rainwater retention during storm events are affected by rainfall characteristics such as intensity, duration, and amount (Blackburn et al. 1986, Kang et al. 2001, Mills et al. 1992, Toy et al. 2002). Ward and Elliot (1995) explained that storms with a longer duration can have a greater amount of precipitation, but shorter duration storms can have greater intensities, thereby producing the same total amounts of precipitation. The duration of the storm has to be sufficiently long to exceed the soil's storage capacity or infiltration rate in order to initiate runoff (Branson et al. 1972). Thunderstorms often begin with relatively high intensities followed by periods of decreasing intensities. The delayed pattern can then increase runoff because it increases the soil moisture (Ward and Elliot 1995). Dunne et al. (1982) reported a non-linear change in infiltration rate as rainfall intensity increases. Cheruiyot (1984) reported that high intensity rainfall led to higher rates of runoff especially if the soil is already wet.

Often long-term weather data is only available as daily, monthly, or annual averages or totals. However, as Branson et al. (1972) explains, total and average data "are not sufficient to form generalized hydrologic conclusions since the water yield to be expected for individual storm events in a watershed is extremely variable and is affected by many variables."

Hydrologic frequency analysis describes the return period of different storm events. Specifically, it is "the evaluation of hydrologic records to estimate how often (frequent) events of a given magnitude will occur or be exceeded" (Tate 1996b). Rainfall frequency analysis allows a certain degree of uncertainty and risk assessment . Return periods are the average period of time in years expected between either high intensity storms or between dry years. Appendix Table A1 summarizes precipitation return periods for Brazos County, Texas obtained by hydrologic frequency analysis. Probability of storm occurrence can be determined from the frequency analysis. Appendix Table A2 describes the minimum probability of precipitation in College Station, Texas.

Branson et al. (1972) described storm behavior in the southwestern United States as: "1) most convective storms in the region are of short duration, low volume, and limited aerial extent, 2) comparatively few storms produce channel flow, 3) runoff producing storms (defined as those producing channel flow) are of relatively higher intensity, 4) approximately 65-70% of annual precipitation falls in the summer time." In Texas, warm, moist air masses from the Gulf Coast are the predominant air masses that influence the precipitation patterns (Ward and Elliot 1995).

High intensity, short duration storms allow less time for infiltration before runoff begins. Kang et al. (2001) concluded that the most runoff and erosion occurred during the more intense summer rainstorms. It becomes more difficult to predict these rainstorms in more arid climates because variation in rainfall increases as annual rainfall decreases (Harrington et al. 1984, Houerou et al. 1988).

Precipitation/Soil Moisture

Rapid changes occur in the relationship between runoff and natural precipitation as the soil moisture content increases (Hartmen et al. 1960). For example, greater antecedent soil moisture significantly increased the time to runoff in a study completed by Giordanengo (2001). A strong positive correlation between total runoff and increased soil moisture was reported by Toy et al. (2002) and Meyles et al. (2003). Tromble et al. (1974) found that infiltration on pre-wetted plots was less than on dry plots. At different moisture regimes different variables became more or less important. Weltz et al. (2000) reported that "biomass was more important in reducing surface runoff for dry soils than it was for wet soils" in a short grass prairie ecosystem.

The most limiting factor for plant production and biological activity on most rangelands is water availability (Harrington et al. 1984, Holecheck et al. 1998, Bhark and Small 2003). Plants are unable to grow and production is reduced when adequate moisture is unavailable (Fuhlendorf 1996). Semiarid regions have particularly high rainfall variability making them more susceptible to extreme water availability and events such as severe storms, floods and droughts (Mannaerts and Gabriels 2000). These extreme events have the potential to have a significant impact on the hydrologic structures and processes of a landscape.

Infiltration/ Runoff and Erosion

Infiltration is the process by which water enters the soil profile (Thurow 1985, Ward and Elliot 1995, Heathcote 1998). The infiltration rate is the quantity of water absorbed by soil per unit of time; a higher infiltration rate results in reduced runoff and erosion (Branson et al. 1972). Many factors including, particle size distribution (texture), soil structure, degree of compaction, chemical composition, organic matter, bulk density, soil moisture, permeability, type and quantity of plant and litter cover, season of year, bare ground, and slope affect infiltration (Meeuwig 1970, Blackburn 1975, Ward and Elliot 1995, Heathcote 1998). Toy et al. (2002) added that the infiltration rate is a "function of the size and connections among soil pore spaces (soil permeability), as well as the extent to which the pores are already filled with water (antecedent soil moisture)."

Runoff occurs when the amount of precipitation exceeds the infiltration and storage capacity of the soil, and begins as soon as infiltration is less than the application rate of water and surface depressions are filled (Ward and Elliot 1995, Holecheck et al. 1998). In a given storm, differences occur from site to site due to soil types, plant types, and range condition. Runoff will vary with differences in types of vegetation as well as quantity of vegetation (Branson et al. 1972). Rainfall amount and intensities are the most significant factors in producing runoff (Branson et al. 1972). According to Dunne and

Leopold (1978), the most important variables affecting the runoff hydrograph are rainfall characteristics, soil properties, vegetation and land use. Runoff from rangeland is one of the primary forces in initiating soil movement (Branson et al. 1972).

Erosion is the process of soil particles becoming detached and transported away from the site either by wind or water (Thurow 1985, Whisenant 1999). Erosion is one of the world's greatest problems because eroded sediments remove organic matter, degrade soil structure, and reduce fertility, soil depth, and water storage capacity (Thurow 1985, Ward and Elliot 1995). Major variables affecting erosion are climate, soil conditions, vegetation, and topography (Branson et al. 1972, Ward and Elliot 1995). Boers et al. (1992) described the erosion process in four steps; 1) raindrops strike soil surface, 2) raindrop impact destroys aggregates and detaches soil particles, 3) soil crust potentially forms, and 4) surface flow with detached particles is increased and infiltration rate is reduced. Soil erosion also leads to decreased rangeland productivity through the loss of organic matter and plant nutrients (Giordanengo et al. 2003). Once soil leaves a site, it is unavailable for future production on that site (Thurow 1991, Pellant 2000). Reduction in the soil profile depth reduces the amount of water that can be stored in the soil profile, which shortens the time plants have to utilize the stored water (Wilcox et al. 1988, Mc Ginty et al. 1995). The length of the growing season is dramatically reduced if the storage capacity is decreased, thus, reducing productivity of the site.

"Rainfall versus runoff and flood forecasting, based on statistical frequency analysis has long been described" (ECAFE 1966). However, probability techniques in soil erosion studies are limited (Mannaerts and Gabriels 2000). The traditional method of predicting soil loss has been the Universal Soil Loss Equation (USLE), which provided long term averages and is not adequate for assessing risk within a given season, year or storm event (Mills et al. 1992). As discussed earlier, semiarid regions have high variability in rainfall amounts. Due to these variations, using the USLE can overestimate soil loss in dry years, while underestimating during wet years (Simanton 1980, Hart, 1984, Manaerts and Gabriels 2000, Spaeth et al. 2003,). Blackburn (1975) and Thurow (1985) found that the USLE grossly underestimated soil loss on rangeland sites. Although the use of the USLE is limited in natural systems [and from a risk management perspective], the factors within its equation can provide a degree of measure for a risk assessment such as, 1) increased cover of vegetation and litter, 2) increased soil surface roughness, and 3) reduced unobstructed length (fetch) of exposed soil (Mills et al. 1992).

Influence of Cover

Vegetation characteristics have been shown to directly influence runoff, infiltration, soil erosion, and rain drop impact (Manoucher and Gifford 1980, Thurow 1985, McGinty et al. 1995, Holecheck et al. 1998). Surface conditions are closely related to the ability of rainfall to infiltrate, so modification of vegetation and soil can also affect the hydrologic cycle and have a significant impact on the water yield (Newson 1994, Holecheck et al. 1998).

Adequate plant cover is necessary to maintain a healthy watershed, decrease sedimentation, and increase infiltration (Holecheck et al. 1998). Good plant cover reduces soil temperature, protects against erosion, and increases soils’ ability to absorb precipitation (Hays et al. 2000). However, the different types of cover (litter, tree/shrub canopy, herbaceous standing crop) have different effects on the watershed functions and processes. Seasonality of cover influences the denseness of plant canopy, controls the rate at which precipitation reaches the soil, and controls the impact on the ground (Ward and Elliot 1995). Soils under shrub or woody canopy have higher infiltration rates than interspaces (Wood et al. 1998, Bhark and Small 2003).

As raindrops reach the surface they can 1) be intercepted by vegetation and be returned to the atmosphere as water vapor, 2) follow the stem to the soil surfaces as stem flow, or 3) proceed through the foliage to the soil surface as throughfall (Branson et al 1972). Rainfall builds kinetic energy as it moves towards the earth's surface and creates the potential for detachment of soil particles resulting in degradation of the soil surface and is referred to as raindrop impact (Osborn 1954a). Cover intercepts and dissipates the kinetic energy of raindrops (Osborn 1954b, Cheruiyot 1984, Eldridge and Koen 1993, Thurow 2000). Reduced cover increases the effects of raindrop impact on the soil surface such as, increased soil crusting, runoff, soil and nutrient loss (Thurow 2000). The height of vegetation also plays a role in protecting bare soils from raindrop impact. Pearce et al. (1998a,b) reported that vegetation height was important in regression models for sediment particles of 10-30 nanometers. Frasier et al. (1998) found that an organic layer on soil surfaces exhibited signs of water repellency. The water repellency decreased the infiltration rates during initial-stages of rainfall simulation.

Soil crusts created by raindrop impact are thin surface layers that cause the soil surface to seal and absorb less water (Pellant 2000). This can cause a break down of surface aggregates through slacking and dispersing into individual parts (Eldridge and

Koen, 1993). Slaking occurs when the aggregates are not strong enough to withstand pressures of entrapped air in capillaries or the pressure due to swelling (Tisdale and Oades 1982). Separated aggregates clog or seal pores between the aggregates, which causes a rapid decrease in the infiltration rate (Tisdale and Oades 1982, Harrington et al. 1984, Thurow 2000, Mc Dowel and Sharpley 2002).

Runoff declines as cover increases due to the cover's ability to slow the movement of runoff, thereby increasing time for infiltration (Holecheck et al. 1998, Aguilera et al. 2003). Aguilera et al. (2003) found that tall grasses in semi-arid Argentina lost forty percent as runoff, while short grass lost sixty percent and bare ground lost sixty-five percent. Similarly, the tall grasses had negligible soil loss, while short grasses had 15 g/m^2 and the bare ground lost 110 g/m^2.

Eldridge and Koen (1993) further described the importance of cover and emphasized its importance as soil conditions decline. Plants maintain the porosity of the soil through biospheres and root channels, which enhance infiltration and reduce runoff. Even the smallest increase in cover on degraded sites can produce additional pores to increase water transport to the subsurface (Eldridge and Koen 1993).

Table 2 illustrates vegetation's ability to protect rainfall from runoff and sediment production. Higher levels of herbaceous vegetation produce less runoff and sediment loss and more infiltration (Franklin 1987, Mc Ginty 1995). Residue left from these plants can also provide protection from raindrop impact and provide a more consistent temperature and moisture microenvironment (Thurow 2000, Pellant 2000). According to Linse (2001), raindrops striking the surface had little impact when cover was greater than seventy percent because litter protected the soil surface. Mc Ginty et al. (1995) and Pellant (2000) described decomposing plant material's (litter) ability to add to the stability and maintenance of soil structure, which allow water to flow more readily into the soil profile. Giodanengo et al. (2003) reported that litter had effects similar to live vegetation on rainfall infiltration.

Table 2: Runoff and sediment production rates compared to different vegetation groups. From McGinty et al. (1995).

Vegetation Group	Runoff	Sediment Production (lbs/ ac)
Herbaceous	1.6%	222
Herbaceous/ Mesquite	4.6%	1,248
Bare Ground	14.0%	20, 811

Soil Influences

Soils are a vital part of the hydrological process in rangeland ecosystems. "Rangelands in poor condition tend to lose existing material resources, fail to capture incident rainfall, and are unable to garner replacement materials" (Tongway 1994). The role of soil for pasture plants is to absorb and store rainfall, store and cycle nutrient elements, and remain stable (i.e. resist erosion) (Tongway 1994).

Low macroporosity can result in decreased infiltration and decreased aggregate stability (Mills et al. 1992). Macroporosity status of a soil is caused by differences in cover, particularly perennial cover (Eldridge and Koen 1993). Perennial grasses enhance infiltration by maintaining active flow paths along root channels and enhance aggregate stability (Mills et al. 1992, Pellant 2000). Perennials also tend to produce more foliage thereby protecting the soil surface to a greater extent. Mid grasses have a greater capability of stabilizing the soil when compared to short grasses (Blackburn et al. 1986). Perennials also have stronger root systems, and thus provide more soil stability. Stronger root system plants were able to stabilize soil better and increase infiltration capabilities (Mills et al. 1992).

The most important soil property affecting soil erosion is soil texture (Spaeth et al. 1996 and Toy et al. 2002). Soils are classified by particle size; clay soil particles are the smallest, silt particles are intermediate, and sand has the largest particles (Ward and Elliot 1995). Table 3 describes the soil classification by particle size as described by the International Society of Soil Science. Mixtures of these soil particles make up a soil type. The USDA categorized the soil types by percentage of clay, sand, and silt (Figure 1). Soil types with more clay particles are less erosive because they are resistant to detachment (Ward and Elliot 1995 and Toy et al. 2002). Sand particles are larger and have larger spaces between the particles. Therefore, water can move more quickly through sand, which allows less runoff for detachment and transport (Ward and Elliot 1995, Toy et al. 2002). The medium textured soils (silt) tend to be the most easily detachable and susceptible to transport by increased runoff (Toy et al. 2002).

Table 3: Classification of soil based on particle size (mm) according to International Society of Soil Science. Adapted from Ward and Elliot (1995) and Toy et al. (2002).

Error!

Soil Particle	Particle size (mm)
Clay	0.0002 to 0.001
Silt	0.002 to 0.01
Fine Sand	0.02 to 1.9
Coarse Sand	2.0+

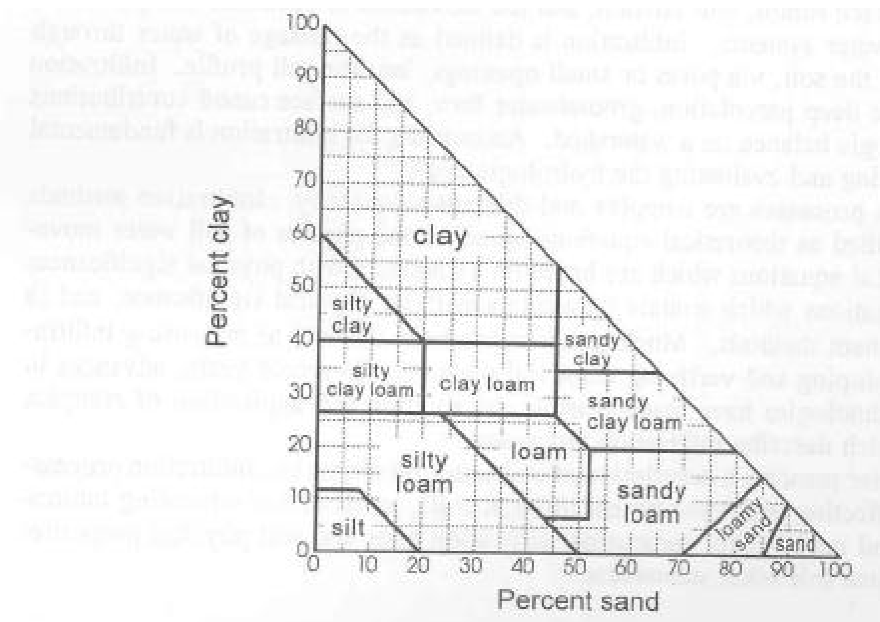


Figure 1: USDA categorization of soil types by percentage of clay, sand, and silt (Ward and Elliot 1995).

Stable aggregates provide a range of pore sizes for storage of water, transmission of water and air, and root growth. Unstable aggregates slake into smaller aggregates and particles when wet (Tisdale and Oades 1982). Aggregates should be porous to remain aerobic, and yet possess smaller pores to retain water for plant growth (Tisdale and Oades 1982). Reduction in aggregate size reduces infiltration, increases erosion, and creates unfavorable physical soil conditions for biological activity (Tisdale and Oades 1982, Jastow 1987).

Watershed Degradation Cycle

Many relationships interact together to create a hydrologic response (Meyles et al. 2003). Weltz et al. (2000) stated, “Rangeland ecosystems are complex and many of the interacting abiotic and biotic processes are not clearly defined with regards to their resistance and resilience to stress.” Watershed degradation continues to occur because the ecosystem’s resistance and resiliency boundaries are exceeded (Figure 2).

Whisenant (1999) described how removing vegetation and litter initiates a positive feedback system that continually accelerates degradation. Prolonged loss of vegetation results in decreased infiltration and runoff, then decreased production, reduced fertility, deteriorated soil structure, increased erosion, and the cycle continues until management is addressed. Drought effects can also be used as an example of the positive feedback degradation cycle. Fuhlendorf (1996) found that prolonged drought in the Edwards Plateau of Texas results in lower basal area, which results in decreased soil moisture. Different plant species moved in that were more adapted to a different moisture regime. The site had changed its original characteristics and productivity.

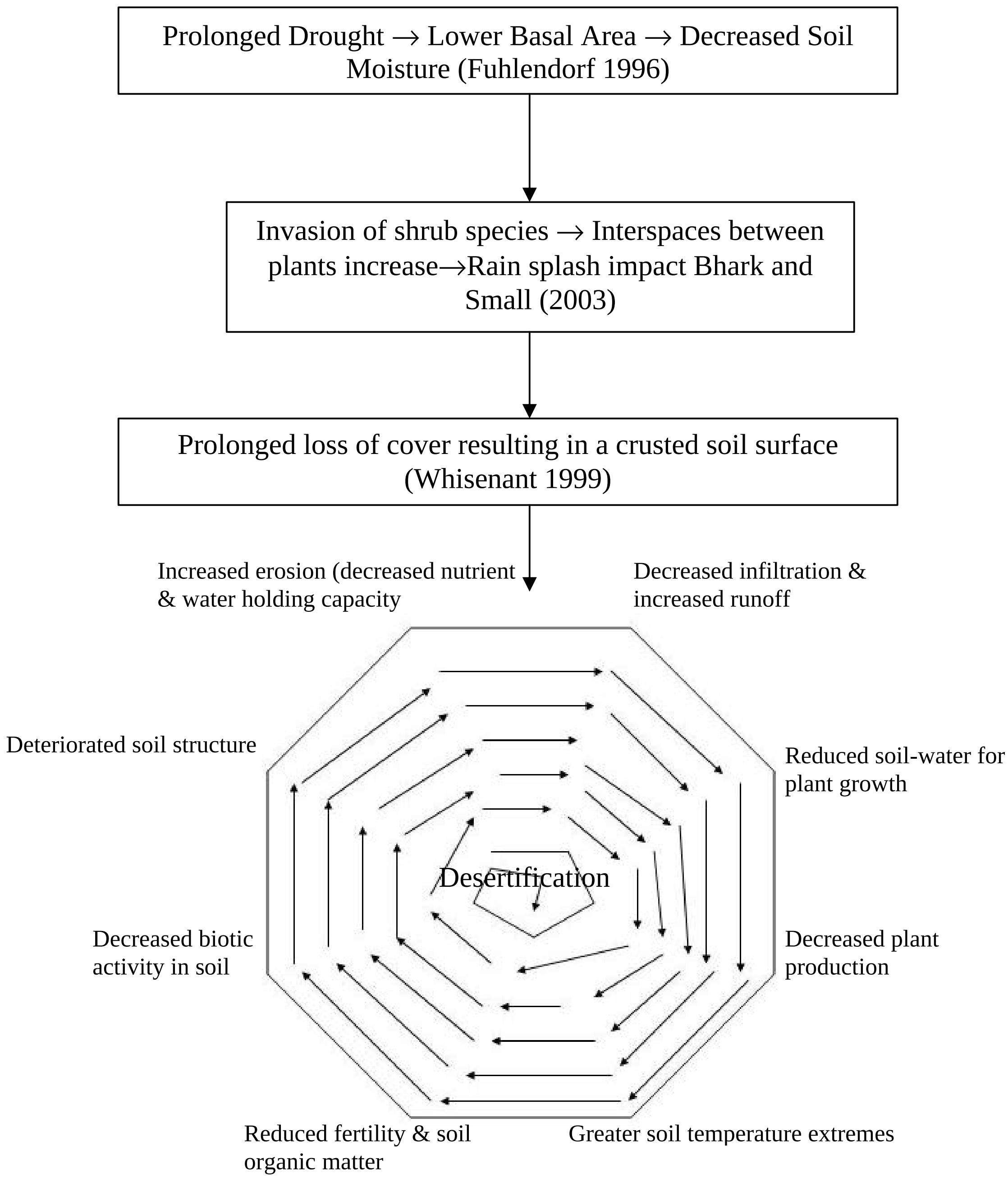


Figure 2: An example of the cycle of degradation in a rangeland watershed ecosystem. Adapted from Fuhlendorf (1996), Whisenant (1999), Bhark and Small (2003).

Bhark and Small (2003) continued the example from Fuhlendorf (1996) with the invasion of shrub species. With the invasion of the shrub species, the interspaces between plants increased. The increased interspaces were more susceptible to rain splash and runoff impact, which feeds back to the Whisenant (1999) example of deteriorated soils and reduced infiltration and plant productivity.

These studies discuss the processes of degradation, but fail to discuss the increased risks as the degradation occurs. Management needs to become more pro-active and reverse the degradation cycle, instead of reacting and being one step behind the cycle.

Risk Management

Understanding risk concepts will allow for a better understanding of soil losses, factors that affect infiltration and runoff, and when management changes are needed. “Knowledge of risks facilitates better planning and management decisions” (Mills et al.1992). Most rangeland literature focuses on financial aspects of risk while the importance of ecological risk is underemphasized. In 1993, the “United States Environmental Protection Agency had no agency guidance for ecological risk assessments in large part due to the absence of formal ecological risk assessment methods for which to provide guidance” (Suter 1993). Ecological risk management can be defined as a continual process of manipulating a system of risks to the biophysical and human components by managing to hold overall risk to an acceptable level at a minimal cost (Cleaves and Haynes 1999).

Many management strategies developed by humans have been some form of command and control. In this style of management, a problem is perceived and then a solution for its control is developed and implemented. This produced a reactionary management system and a loss of long-term sustainability (Holling and Meffe 1996). However, an ecological risk assessment [analysis] can be used as a proactive tool to estimate the probability of adverse change in natural systems (Vogt et al. 1997).

Risk Theory

Risk has been defined as the “probability of future loss” by Byrd and Cothern (2000), but risk assessment is made by humans to facilitate better decisions (Haynes and Cleaves 1999). Risk is discussed in probabilistic terms because there is an uncertainty in the final outcome (Haynes and Cleaves 1999). Possible sources of uncertainty can be identified in risk assessments as 1) inherent randomness (variability) of the world, 2) imperfect or incomplete knowledge, 3) mistakes in execution of assessment activities (error), 4) statistical variation, poor scientific background, disagreement among experts, and model uncertainty (Suter 1993, Haynes and Cleaves 1999, Byrd and Cothern 2000). According to Haynes and Cleaves (1999) uncertainty is a condition of not knowing, which is part of human judgment. Risk assessments formalize information for improved decision-making and also include uncertainty analysis (Vogt et al. 1997).

Successional Theory

Knowingly or unknowingly risk is incorporated into management decisions. Rangeland management decisions have been incorporated into successional theory since Clements (1916) and Dyksterhuis (1949) described early successional models as individualistic and on a single continuum (Noss and Cooperrider 1994, Holechek et al. 1998). This model predicted that a degraded site could return to the previous (climax) condition with removal of the disturbance causing degradation. This model has been found inadequate for understanding complex successional pathways. Decisions based on early successional models severely underestimated the risk of degradation to the ecosystem and the ability of a system to recover. The latest paradigm in explaining successional pathways has been the “state and transition” model, which emphasizes the risk of crossing biological thresholds that cause recovery to be limited or proceed to a new state not identified in the Clements’ approach (Archer 1989, Westoby et al. 1989, Friedel 1991).

Recent developments in ecological theory suggest that vegetation and soils can exist in one of several “states” on a given site (Archer 1989, Westoby et al. 1989, Friedel 1991). Stringham et al. (2003) defined states as “climate/ soil/ vegetation domains that encompass a large amount of variation in species composition.” The state of a rangeland ecosystem can be extremely variable (i.e. species composition, productivity, ground cover, etc.). In many cases, it is the interaction between human management decisions (i.e. continued grazing during drought) and natural disturbance (i.e. flood and drought) or some combination of the two that affect the shift in a state (Archer 1989, Westoby et al. 1989, Friedel 1991, Tongway 1994). The change in a state requires a change in the integrity of the site’s primary ecological processes, including hydrology, energy capture, and nutrient cycling.

The system's resistance and resiliency affect the rate of change and the end result. Stringham et al. (2003) defined resistance as "the ability of the system to remain the same under external change" and resiliency as "the ability of the system to recover after it has been disturbed." Bestelmeyer et al. (2003) defined resiliency as the "magnitude of disturbance that can be absorbed or accommodated before the system changes its structure by changing the variables that control the system's behavior." Resilience may also be defined as the ability to respond to outside pressures, but with a strong tendency to return to the original state once the pressure is lifted (Harrington et al. 1984).

After the system's resiliency has been surpassed, the system crosses a threshold to a new state with different ecological processes and functions (Laycock 1991, Noss and Cooperrider 1994). The state and transition model as described by Archer (1989), Laycock (1991), and Noss and Cooperrider (1994) can be used to identify areas at risk of surpassing the resiliency of the state and crossing the ecological threshold. Noss and Cooperrider (1994) describe how a grass-dominated rangeland invaded by juniper can revert back to grassland, if grazing pressure is relaxed and fire not suppressed. However, once the threshold is crossed the juniper is able to out-compete the grasses and remain a "stable" system. Therefore, the transition phase is critical because the recovery becomes more difficult if degradation continues during this phase (Jones 1992). Archer and Stokes (2000) indicate that the existence of a new steady state indicates the existence of critical thresholds. At or beyond a threshold, changes to the new state become rapid and potentially irreversible over reasonable time frames (Archer and Smeins 1991). Laycock

(1991) stresses the importance of thresholds because “once a threshold is crossed towards increased degradation, improvement cannot be attained on a practical time-scale without a much greater intervention, input, and management effort.” Avoidance of an undesirable state/transition change requires recognition of critical thresholds and use of calculated probabilities of risk associated with crossing the threshold. The goal and direction of management should be to not cross these ecological thresholds (Archer and Stokes 2000). The ability to identify these critical thresholds will allow managers to predict the risk of crossing these thresholds and identify the at-risk areas. However, Archer and Stokes (2000) believe that application of the state and transition model is limited by the understanding of the rate of movement across the threshold and what triggers the irreversible shift in state across the threshold.

Management thresholds are a tool that rangeland managers could use to rank competing values (risks) and improve their decision-making capabilities, thus improving success and sustainability (Vogt et al. 1997). Threshold concepts from the state and transition model can serve as a potential pathway to characterize and estimate risk. However, threshold literature (Archer 1989, Westoby et al. 1989, Friedel 1991, Laycock 1991) has not been considered in a probabilistic risk assessment approach.

Hanselka et al. (2001) described two types of thresholds, ecological and management. An ecological threshold is “the point that an irreversible change in health and sustainability of a rangeland may occur” (Hanselka et al. 2001). For example, natural erosion is increased to accelerated erosion due to increased degradation. On the other hand, a management threshold is the point where “management must be changed to avoid crossing an ecological threshold" (Hanselka et al. 2001). Management thresholds for minimal residual standing crops have been estimated at 134.5 to 168.1g/m^2 for tall grass vegetation (White and Richardson 1995, Hanselka et al. 2001). They concluded that this level would need to be left on the site to maintain healthy plants and protect the soil surface from excessive runoff and erosion. Utilizing additional biomass past this threshold has the potential to greatly increase runoff and erosion by reducing the infiltration capabilities of the site.

Risk Analysis Model

Prevention of crossing a threshold will require a proactive management strategy. Developing a risk analysis model can guide proactive planning and management decisions. Current risk models have been designed to assess human health, hazardous waste, and technological risk (Louvar and Louvar 1999, Suter 1993, Smith et al. 1994). These models all use different terminology, but consist of similar elements. Understanding these models can provide a basis for implementing an ecological risk assessment for rangeland management.

Louvar and Louvar's (1999) risk analysis model is used primarily for human health studies and was adapted from chemical hazard evaluation procedures. Their risk analysis model had four steps: 1) hazard identification, 2) source identification, 3) risk management, and 4) risk communication. The hazard identification step identified the hazards that had the potential to cause human or environmental health. The exposure assessment and the dose-response assessment identified the frequency and duration of the hazard and the effects of the exposure. Risk characterization was the next step, and it involved estimated risk probabilities and determined the risk significance. During the risk management stage, management alternatives were evaluated, decided upon, implemented, and monitored. Risk communication is the final step in Louvar and Louvar's (1999) risk analysis model and involved communicating the risk to stakeholders for improved decision-making.

Another model described by Cleaves and Haynes (1999) was designed as a risk model for ecosystems, and outlined six steps: 1) hazard identification, 2) risk assessment, 3) risk evaluation, 4) risk adjustment, 5) implementation, and 6) monitoring. Hazard identification identifies the human actions or natural events that could produce adverse effects, and the parts of the ecosystem that could bear these adverse effects. Risk assessment characterizes the risks by estimating the magnitudes of loss to the endpoints and the likelihood of occurrence. The next stage is the risk evaluation, which assesses the relative acceptability of the risk to existing policies, standards, and other human values. The risk adjustment stage examines and chooses a strategy for dealing with the risk. The implementation step is simply putting the risk management plan in action. Finally, monitoring is the final stage that evaluates the effectiveness of the risk adjustment strategy.

Each of these plans has similar and important concepts and could be combined into a five step plan that includes: 1) hazard identification, 2) exposure identification, 3) risk assessment/ characterization, 4) risk management, and 5) monitoring. The Hazard Identification step identifies the stressors and part of the ecosystem that will be affected. All potential adverse conditions (human actions or natural event) that could cause possible losses and the parts of the ecosystem that would bear them are identified. Next, the exposure identification phase will accomplish three things: 1) identify the endpoints that are to be maintained to prevent risk, 2) identify the exposure pathway and results if endpoints are not maintained, and 3) identify the frequency and duration of the risk. The numerical estimates of risk losses, frequencies of occurrence (thresholds), and the significance of the risk losses are determined during the risk evaluation step. Risk Management requires an evaluation of the management alternatives, determination of amount of acceptable risk, best options and guidelines to reduce or eliminate risk, and execution of the plan. Finally, Monitoring of the plan requires evaluation of the plan effectiveness, and readjustment of the strategy if necessary.

Managing for Rangeland Risk

An ecological risk assessment is a process that evaluates the likelihood that diverse ecological effects may occur or are occurring as a result to exposure to one or more stressors (Byrd and Cothern 2000). The purpose of a risk assessment is to provide better information for making decisions about managing risks and how to address them (Haynes and Cleaves 1999). “An ecological risk assessment can be seen as an effort to estimate the probability of moving from a desired system to a less desired or unacceptable state (Vogt et al. 1997). When estimating risks, it is imperative to not reduce the biological variability of a system because that will reduce its resilience and increase the probability of rare events previously “absorbed” by a system causing dramatic changes (Hetschmidt and Stuth 1991).

Summary

Ecological risk can be defined as the probability of future loss to an ecosystem process or function. For example, watershed risks include loss of rainfall to runoff and erosion. Past risk literature has focused primarily on the financial aspects of ecosystem risk. This focus has promoted reactive management and continuation of a degradation cycle on rangeland watersheds.

There are many important watershed characteristics and functions that are interrelated that must be addressed when making management decisions on a watershed. Climate, vegetation, soil and soil moisture all interact to create a hydrologic relationship that affects infiltration, runoff, and erosion.

An ecological risk model can aid in increased proactive management. The five steps include: 1) hazard identification, 2) exposure identification, 3) risk assessment/ characterization, 4) risk management, and 5) monitoring. Using concepts from the state and transition model and initiating risk management decisions into a proactive plan will support future sustainability.

STUDY AREA

The research was conducted near the Cooperative Wildlife Nature Trail at Texas A&M University in College Station, Texas (N 29^{o} 23’ 53.7” W100^{o} 00’ 1.8’), located in Brazos County, Texas (Figure 3).

The historic uses of the area included corn/ cotton farming and raising beef cattle (Dering and Mason, 2001). The study area has been removed from these disturbances/ uses for approximately fifty years (Dr. Fred Smiens, pers. comm.-October 7, 2003).

Vegetation

The site is located within and has typical secondary successional vegetation of the Post Oak Savannah. Typical climax grasses that characterized this vegetation area include little bluestem (*Schizachyrium scoparium)*, yellow Indiangrass (*Sorghastrum nutans)*, and beaked panicum (*Panicum anceps*). Brownseed paspalum (*Paspalum plicatulum)*, threeawns (*Aristida* spp.), rosette grasses (*Dichanthelium* spp.), and several lovegrasses (*Eragrostis* spp.) are some of the lower successional species (NRCS 2001). Dominant tree species included post, water, and live oaks (*Quercus stellata, nigra,* and *virginica*, respectively*)*, Eastern red cedar (*Juniperus virginiana*), and hackberry (*Celtis pallida)*. Additional understory vegetation included yaupon (*Illex vomitoria),* American beautyberry (*Callicarpa americana)*, greenbriar (*Smilax bona-nox),* and dewberry (*Rubus* spp.).

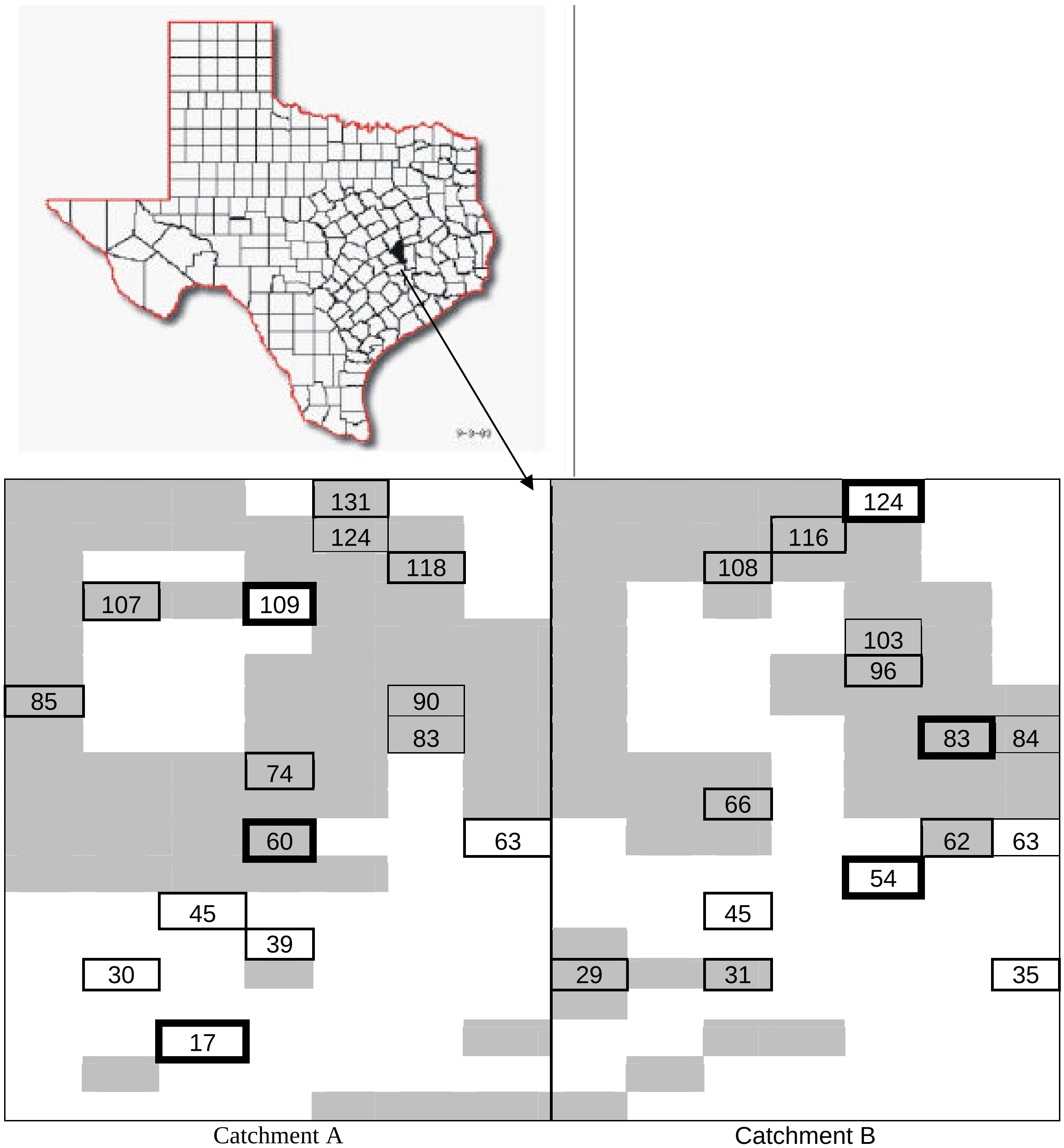
Climate

May and September are the peak months for precipitation, which gives the area a bimodal precipitation pattern (White et al. 2001). The mean annual precipitation is 76.2

to 114.3 centimeters. Both long and short-term droughts are common and frequent in this area. More discussion on climate analysis can be found in the Climatic section in the Results.

Soils

Soils were mapped at the study site as a transition zone between the Zachary (ZaC2) and Tabor soil series (TaA) (NRCS 2001). The top15.24 centimeters of the Tabor series consisted of a fine sandy loam and the remaining horizons were predominately clay. The Zachary series' top 17.78 centimeters was a fine sandy loam with the remaining layers consisting of clay. The upper horizons were moderately well drained, and the clay horizons had very slow permeability. Both series are in the thermic family of Udertic Paleustalfs (Appendix B).



Legend

= 0.5 m^2 plots observed monthly

= Plots that were sampled for the soil textural analysis

= Area that was cover with woody canopy

Figure 3: Map of Texas counties showing the location of the study site in Brazos County, Texas shown in bold (top) and layout of study plots (bottom).

METHODS

The research consisted of three major parts:

1. Climatic Analysis:

- Created and assessed a climatic profile of seasonal variation in precipitation patterns for Brazos County, Texas based on long-term data from Somerville, Texas.
- Analyzed rainfall for 2002-2003 from the Brazos County, Texas watershed study site.

2. Rainfall Simulation Study:

- Conducted ten rainfall simulations (randomly selected) for each of five dates during 2002-2003 to measure soil moisture, cover, biomass, runoff and sediment loss adjacent to the Brazos Watershed Study site.

3. Paired Watershed Study:

- Utilized an existing paired watershed study in Brazos County, Texas
- Determined soil moisture, cover, and biomass monthly on fifteen randomly selected permanent plots in each of the paired watersheds.
- Monitored runoff and sediment yield by event during 2002-2003 on the paired watersheds

Climatic Profiles

Climate data was analyzed to determine the characteristics of rainfall events for Brazos County, Texas. The National Climatic Data Center reported rainfall in fifteen-minute intervals was used (http://www.ncdc.noaa.gov/oa/ncdc.html). Burleson County was selected to create a climatic profile because Brazos County did not have a listing. Somerville dam (in Burleson County) and Wheelock (in Brazos County) were the two weather stations listed within this file. Wheelock is approximately twenty miles north of the study site and Somerville dam is approximately twenty-five miles southwest.

After evaluation of the Somerville and Wheelock data sets, Somerville was used exclusively because it had the most complete record of information from 1975 to 1993. The Somerville dam data was analyzed through a program written by Dr. David Cairns, Associate Professor at Texas A&M University (Geography Department). The program determined the number of storms for the nineteen-year period, start and end time, year of storm occurrence, storm duration, maximum and average intensity, and total amount of precipitation for each storm. Storms were considered separate events when separated by 10-hour or more (if no precipitation occurred within the 10-hour period, it was considered a separate event).

Precipitation was totaled for each month and year. These values were then crosschecked with NOAA, Data in Texas. These data were analyzed by Rainfall Analysis software http://rangeweb.tamu.edu/trm/ rainfall/rainfall.htm developed by Dr. Larry D. White.

To compare the 2002 rainfall events to this long-term data set, the 2002 monthly totals of precipitation were retrieved from the NCDC website. However, April and May precipitation totals were missing. Monthly totals were retrievable from Easterwood Airport in College Station. A correlation between existing Somerville data and the College Station data was developed. The resulting equation, $y=0.9246x+0.4503$ (r^2 =

0.99) was used to predict the missing values for the Somerville data. After the 2002 data set was added, the Rainfall Analysis software was used to characterize the historic monthly and annual rainfall of the Brazos Valley area.

Each storm was broken into four quintiles by storm duration, which would represent the four quarters in a storm event. The quintiles were developed to determine which part of the storm event produced the most rainfall. The quintiles were divided by duration and separated into average amount (cm) and percent of total rainfall season.

The probability of a given storm amount was calculated in two ways. First, the probability of a given storm event was calculated solely on the rain gauge data during the year of study (April 2002 to May 2003). Secondly, probabilities of a given storm amount were calculated based on the long-term data set from Somerville, Texas.

Rainfall Simulation

The rainfall simulation study was conducted near the watershed study on the southwestern side of the paired catchments. The rainfall simulation aspect of the research project had similar sampling methodology to the paired watershed study. However, this part of the study was conducted bimonthly for one year (April 2002 to April 2003) and consisted of destructive sampling. A total of fifty simulations, ten per date, were completed throughout the year. Rainfall simulation methodology was adapted from Thurow (1985).

Each individual plot was constructed with metal flashing and a metal triangle trough (flume) (Figure 4). The flashing and flume were mapped on a grid to determine the actual total runoff area. Each plot was measured for biomass, cover, dominant species, soil moisture (antecedent soil moisture and percent saturation), amount to runoff, initial time to runoff, and amount to storage capacity. Amount to runoff was

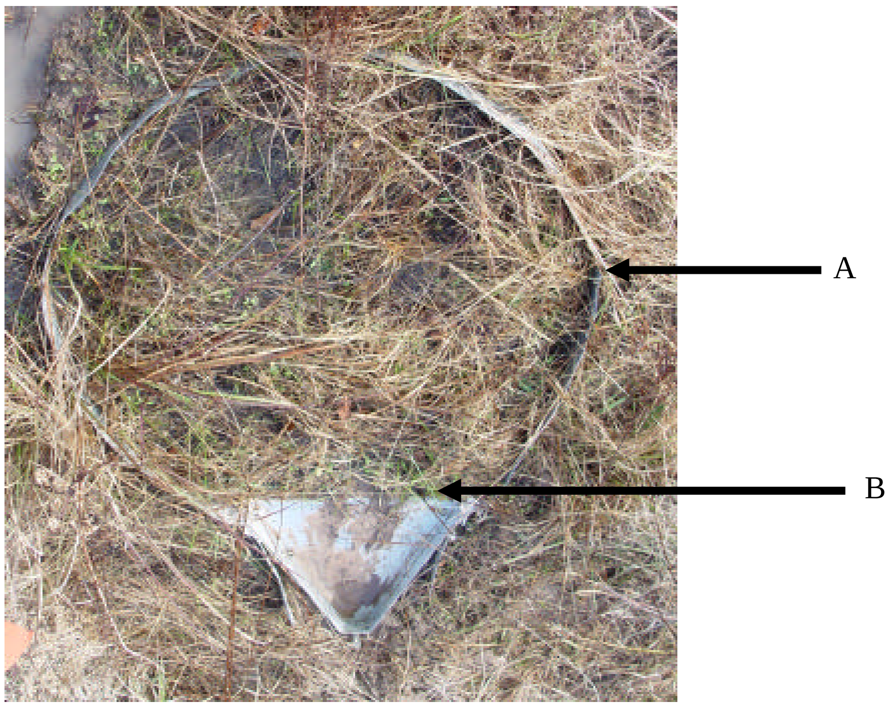


Figure 4: Rainfall simulation runoff plot setup includes flashing (A) that surrounded each plot and the exit flume (B).

calculated by taking the cumulative amount of “rain” that had fallen before runoff began. Amount to “storage” was assumed when runoff was equal or excededprecipitation for a five-minute period. Area and cover were mapped for the entire 0.5 m^2 and inside the flashing. A drip type rainfall simulator similar to the one described by Blackburn et al. (1974) was placed over the plot. The metal flume was covered with Plexiglass to ensure only runoff was collected in the trough. Runoff was captured from a hose that was connected to the trough and pumped into a collection bucket. A scale was then used to weigh the runoff at five-minute intervals. A soil moisture reading and a soil sample were taken for each simulation plot. The simulator was set to “rain” at a rate of 15.24 cm/hour. A stopwatch was started when rainfall was initiated. Initial time of runoff and runoff in five-minute intervals thereafter was recorded. The simulation was allowed to continue for one hour. Total runoff was collected and agitated. Then, a one-liter (1L) subsample was taken from the total runoff. Plots were clipped, separating vegetation from inside the runoff area and outside within the 0.5 m^2 plot.

The accuracy of the simulators to produce a 15.24 centimeter per hour storm as described by Robert Knight (pers. comm., May 2001) was investigated after the simulation study was completed. The simulators were set up exactly like they were in the simulation study. However, during this test a Davis Instruments tipping bucket rain gauge with a Hobo event logger was used to measure total rainfall for one hour.

The scales used to weigh the runoff from the rainfall simulation plot were also checked for accuracy. One gallon of water was weighed on each of the two scales. A gallon of water should weigh 3.78 kilograms; however, each scale read 3.63 kilograms. No corrections were made for this inaccuracy in the rainfall simulation calculations.

Sample Size

Sample size was determined by previous research and the number expected to be done in a day (Thurow 1985). Ten different 0.5m2 plots were sampled bimonthly. The simulations were conducted within a 7 x 19 meter area adjacent to the paired watersheds (it had similar vegetation and soil characteristics). All possible simulation plots (0.5 m2 were identified and numbered. A random number generator on a calculator was used to determine the location of bimonthly simulation plots.

Vegetation

As in the watershed study, ocular estimates of cover and biomass were made on the $0.5m^2$ rainfall simulation plots before the simulations occurred. Vegetation within the runoff area was also characterized. Bare ground, litter, and basal cover were estimated on a 100% basis. The basal estimations were divided into form (woody, herbaceous, or forb). Biomass was estimated in grams per $0.5m^2$ plot.

Basal herbaceous cover was also mapped. A sixty-four square grid was placed over the simulator plot. Then, on a corresponding paper grid, vegetation was recorded by marking bare ground (B), litter (L), grass (G), forb (F), or woody (S). Determination of basal cover type was made by marking the type of cover that was under the bottom right hand corner of each grid square. Percent cover was calculated for the whole plot as well as the area inside the flashing. Vegetation was then clipped inside and outside of the runoff area, dried at 60^oC for 48 hours, and weighed to determine actual biomass. Mapping and clipping the vegetation provided a double sample technique to correct visual estimations on the watershed study (National Academy of Sciences 1962).

A linear relationship between personal estimations and actual observations was created to correct all estimates made on the watersheds. These relationships were created for each rainfall simulation sampling period (S) and used for corresponding watershed sampling periods (W).

Soil Moisture

An Aquameter Instrument's TEMP 200 soil moisture probe was used to determine percent soil saturation outside each plot. The probe was adjusted to 100% moisture reading with a saturated soil sample before, during and after its use in the field. Soil samples were taken at the same location as the probe readings to determine antecedent soil moisture. The antecedent soil moisture sample was taken from the top three inches of the soil profile. Percent water on a dry weight basis was determined by the gravimetric procedure described by Gardner (1985). Samples were dried for forty-eight hours at fifty-five degrees Celsius. After forty-eight hours, the samples were weighed and percent water on a dry weight basis was determined.

Rainfall, Runoff and Sedimentation

Rainfall was applied by a drip type rainfall simulator (Figure 5) similar to the one described by Blackburn et al. (1974), set to rain at a rate of 15.24 cm. per hour for one hour. This rate was chosen because it would guarantee a runoff event that would exceed a 1-hour, 100-year storm event (Robert Knight, personal communication May 2001). However, after testing the equipment it was determined that one simulator was raining at a rate of 22.3 cmper hour and the other was raining at 15.8 cm per hur. The average of the two rates, 19.05 cm, was used in the calculations because it was unknown, which simulator was used on each simulation plot.

Figure 5: Rainfall simulators and equipment used during the rainfall simulation study.

Runoff and sediment accumulation was weighed at five-minute intervals during the hour of study, which produced a hydrograph for each simulated rainfall event. Initial time to runoff was also recorded for each simulation.

Sedimentation amounts and total soil loss for each event were determined through a filtration process. First, the total collected runoff/ soil sample was thoroughly mixed, and a one-liter subsample was removed. The subsample was filtered through Whatman's number one filter paper by vacuum pressure, dried at fifty-five degrees Celsius for twenty-four hours and weighed to determine grams of soil per liter of runoff. Total amount of sediment load was determined by multiplying the total runoff by grams per liter.

The following formulas were used to calculate infiltration rate and runoff:

- Cumulative Infiltration Rate (cm/hour) = [{Rain applied (19.05cm)/ Time (60 mins.)} - {cumulative amount of runoff(cm) /Time (60 mins.)}]* 60

- Percent of runoff lost to rainfall = [Cumulative runoff (cm)/ Total rainfall applied (19.05 cm)] *100

Monthly vegetation variables were analyzed with ANOVA (analysis of variance) using Tukey's test to separate significant differences at the 95% confidence level with SPSS (Statistical Package for the Social Sciences) ver.11.0 (Ott and Longnecker 2001). Infiltration, runoff, and sediment yield were treated as dependent variables in separate models. Multivariate analysis was conducted in Stata (http://www.stata.com) to compare the variables to runoff, infiltration, and sediment yield. Specifically pair wise correlations and ordinary least squares (OLS) multiple regressions were conducted.

Diagnostics were run for heteroskedasticity and omitted variables with the Cook-Weisberg Test and Ramsey Reset Test, respectively. The Ramsey Reset Test concluded there were no omitted variables. The Cook-Weisberg Test found moderate heteroskedasticity, but significance was still found among the variables. The regression was re-analyzed with the robust standard errors. However, this did not result in significant change in direction or levels of significance among the variables.

Paired Watershed Study

Texas Cooperative Extension (TCE) installed the paired watershed catchments in December 2000. Measurements have been collected on vegetation and soil each May and October on permanent transects by TCE. Watershed catchment A is 158.56m^2 and B is 135.40m^2. Natural rainfall and associated runoff exits through a one-foot H flume (Figure 6). The H flume uses a Global Water Logger weir stick to determine water flow from runoff at two-minute increments. A composite water sample was collected from each flume for sediment determination after each rainfall event, if there was sufficient runoff. The ratings for the H flume (Brakenseik et al. 1979) were entered into Excel to create a polynomial equation with an R^2 of 1.00 (Figure 7). This was then used to calculate cm^3/m^2 of runoff from water level readings.

Site characteristics were measured monthly to compare vegetation/ soil/ cover effects on runoff and sediment production from natural rainfall events from April 2002 through April 2003. Information collected from the TCE study allowed for additional interpretation.

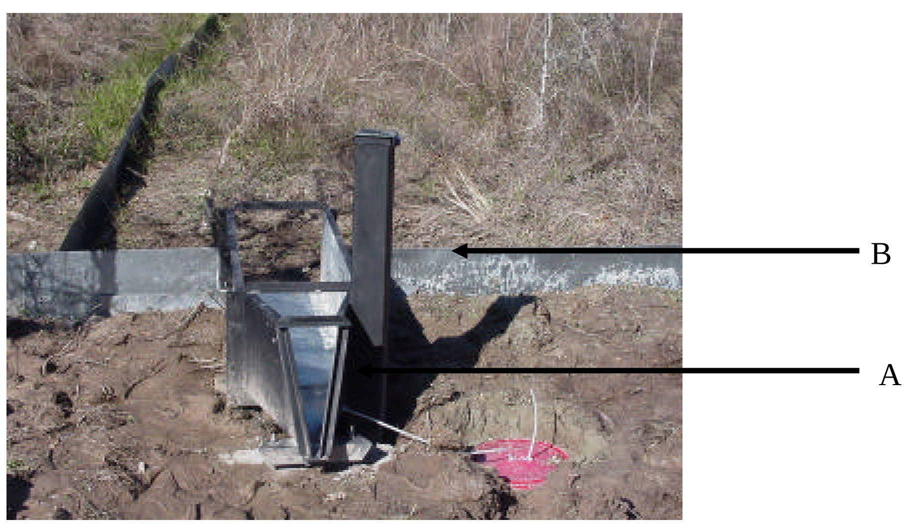


Figure 6: Runoff exits through a one foot H-flume (A) and the black box houses the water logger (weir stick) (B), which measures the height of water flowing through the flume at two-minute intervals.

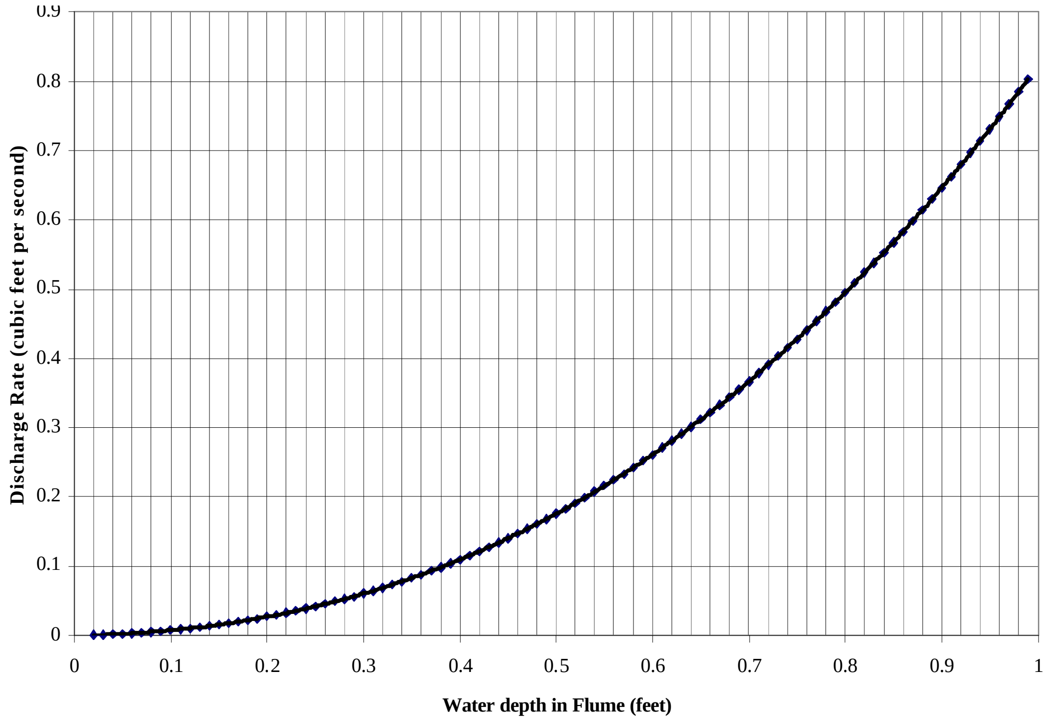


Figure 7: Relationship of water depth to cubic feet per second of flow through a one foot HS flume (Based on rating table in Brakenseik et al. 1979). The equation for cfs = -0.0008x5-0.0481x4+.361x3+0.4816x2+0.0268x-0.0004, r^2 =1.00.

Sample Size

To determine an adequate sample size for the paired watershed study, ten estimates of bare ground, litter, and biomass in a 0.5 m^2 quadrat were made along a permanent transect in each watershed by two observers. Estimates were averaged, the range between the maximum and minimum estimates was determined, and a ratio was created by dividing the average by the range. This ratio was then used to determine the appropriate sample size from a chart prepared by White and Richardson (1995). This procedure resulted in fifteen samples to be estimated per sample date per watershed.

All potential quadrats in the watersheds were identified and numbered (Figure 3). A random number generator on a calculator was used to determine which plots were to be sampled. The same fifteen randomly selected $0.5m^2$ plots were non-destructively monitored monthly for one year for changes in vegetation (biomass and cover) and soil moisture (percent saturation using the moisture probe discussed in the soil moisture section).

Soil Analysis

Soil analysis was conducted to compare the textures from the study site to those described by NRCS (1991) for the site. Soil samples were taken in June 2003 after all measurements had been made.

Three plots in each watershed were selected to represent the vegetative community. One sample was taken in each watershed near the front (open canopy), middle (dense canopy), and back (mixed canopy cover). Plots 17, 60, and 109 in watershed A and plots 54, 83, and 124 in watershed B were sampled for textural analysis (Figure 3). The samples were collected in June 2003 after all study measurements were completed. In June, the soil was dry and hard so an infiltrometer ring was inserted into the ground and wetted for one week in the morning, afternoon and in the evening to moisten the soil, so a sample could be taken. Approximately three gallons were applied into each infiltrometer ring and allowed to soak into the soil at each wetting time.

A sixteen-inch sharp shooter was used to extract the soil profile. On average, ten inches were extracted for observations. The profile was photographed and observations were made on appearance, distinctions in horizons, and abundance of rocks. Three samples were extracted from each profile for textural analysis.

The samples were then allowed to air dry for eighteen days. Then the soils were ground to less than two millimeter in size. Fifty grams of the sample were used to conduct the textural analysis. The soil textural analysis was determined by the hydrometer method (Bouyoucos 1962). An ANOVA in SPSS was used to determine if there were significant differences in sand, silt and clay percentages between plots.

Vegetation

Monthly ocular observations of cover and biomass were made on the fifteen selected quadrats in each of the paired watersheds. Bare ground, litter, and basal cover were estimated on a 100% basis. The basal estimations were divided into form (shrub, herbaceous, or forb). Biomass was estimated in grams per $0.5m^2$.

Soil Moisture

An Aquameter Instrument’s Temp 200 soil moisture probe was used to determine percent soil saturation outside each quadrat at monthly intervals. It was necessary to calibrate the soil moisture probe prior to and during its use in the field.

The probe was calibrated by taking a soil sample from the site and mixing it together to create a uniform sample. Small nail holes were punched into three one pound coffee cans. Filter paper was then inserted in the bottom of each can to allow for drainage without losing soil. The cans were then weighed for reference. Then soil was evenly distributed among the cans. The soil cans were then oven dried for seventy-two hours at 55^0 C. Higher temperatures might result in destruction of organic matter and soil particles (Gardner 1986). After the seventy-two hour drying period, a probe reading was taken and the soil and can weighed again. The samples were then saturated by placing the cans in a water bath. Water was brought to the same level as the soil in the cans, but not over the can. The cans were allowed to sit in the water bath for twenty-four hours to ensure water moved throughout the soil sample. A thin film of water was on the soil surface when the sample was saturated (Figure 8). Another probe reading was taken and adjusted to read 100%. One sample was capped and maintained at saturation. The remaining samples sat for an additional twenty-four hours to reach field capacity. A probe reading was taken at field capacity; then, the samples were placed in the dryer for three hours. After three hours, the samples were taken out, cooled for one hour, a probe reading taken, and weighed. The samples were cooled for one hour to ensure equal distribution of water within the sample. As the soil samples began to dry, they became hard and crusted. The drying, weighing, and probe measurements were continued for three days due to the samples becoming hard, crusted and indentions remaining from the probe, which influenced the measurements.

Figure 8: Saturated soil sample used in the field for calibration. A thin layer of water on top of soil sample indicates that the soil is at saturation.

A regression equation was used to correct probe readings to actual percent of soil saturation during the watershed and rainfall simulation study (Figure 9). The resulting equation (y = 1.004 (probe reading) – 18.961, r^2 = 0.90) was used to estimate actual percent of soil saturation at each simulation and catchment plot sample date.

Rainfall, Runoff, and Sediment Production

A Davis Instruments' Rain Collector recorded the amount of rainfall at the paired watershed study. The rain collector uses a self-emptying tipping bucket that measures in 0.0254-centimeter increments. A Hobo event logger was used in conjunction with the rain collector and recorded rainfall intensity throughout the study. The data was downloaded bi-annually and entered into the existing "Water for Texans" database.

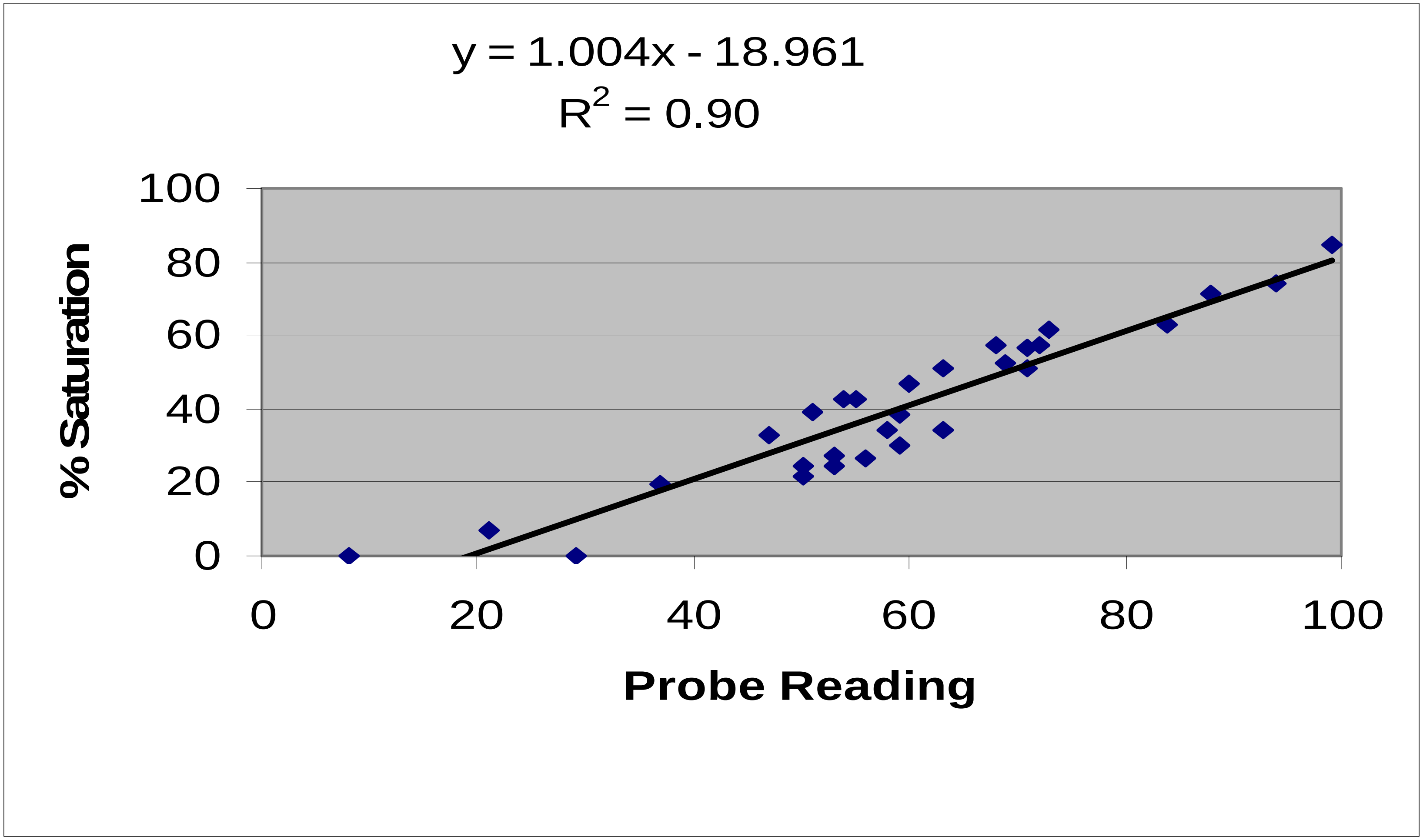


Figure 9: Probe reading relationship to actual percent saturation soil moisture in the soil. Equation was used to correct probe readings to actual percent of soil saturation during the watershed and rainfall simulation studies.

Runoff flow depth was measured with a weir stick (water logger) at two-minute intervals during the study. Data was downloaded monthly and inserted into the existing “Water for Texans” database. Flashing surrounded each catchment to ensure runoff from only the plot was being measured. All runoff exited through a one foot H-flume.

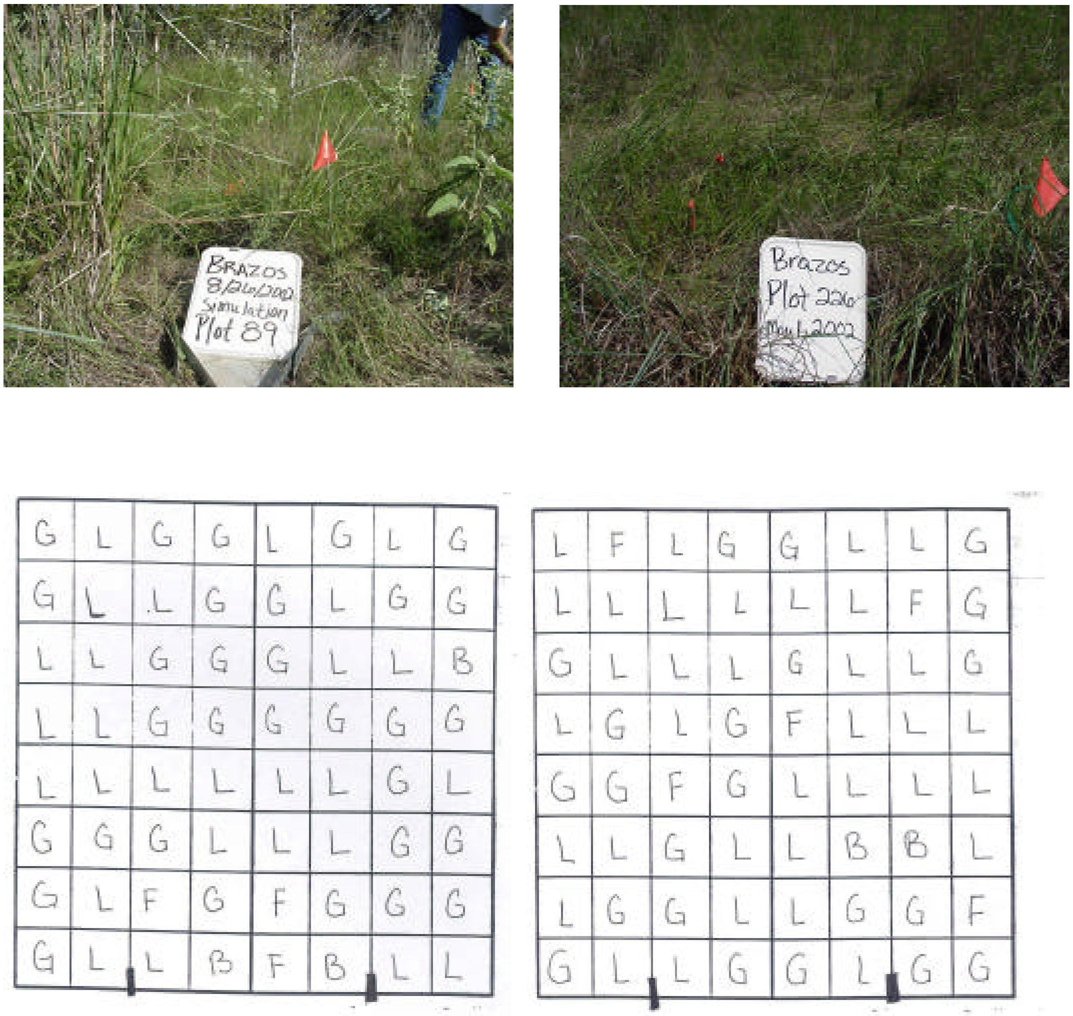
The water logger weir sticks began malfunctioning in May of 2001. The problem went undetected until the recorded data was compared to the precipitation data. It was then discovered that the results from the logger recordings were impossible. It appeared the loggers were reading extreme low and high end values, continually recording for days at a time, and recording values when there was not rainfall. Therefore, runoff events were only used in the analysis if runoff values were significant (greater than 0) and plausible (less runoff than precipitation).

Sediment production was measured by taking a composite sample at the tiem of downloading prior to the research study and soon after each rain event during the current study. Each sample was agitated, and then analyzed through filtration, drying, and weighing to determine sediment yield per unit volume of water flow.

Validity Threats

Watershed function and processes are the result of many different variables. Not all factors could be analyzed in the scope of this study. Some factors not included in the analysis were surface roughness and slope of individual plots. The Brazos County, Texas site had little variability in percent cover for extrapolation to other areas. Low variability can underestimate the effects of the study variables. The spatial patterns of the vegetation had the potential to affect the study’s dependent variables. If all the bare ground for the plot was located in front of the simulator exit flume, there could have been more runoff as compared to a plot with little bluestem (*Schizachyrium scoparium*) being directly in front of the exit flume (Figure 10). The same rate of simulated rainfall was used for all simulation plots, so the effects of different intensities were not tested in the simulation analysis. Soil texture analysis for the paired watershed was conducted, but soil samples were not collected at each individual simulator site. However, the differences should be minimal between the simulation site and the watershed catchments. Differences in textures between the plots can affect runoff and infiltration rates. Effects of soil aggregation and percent organic matter were not tested. Some soil disturbance is inevitable when installing the flashing on the simulation plots. Great care was taken to minimize disturbance on these plots.

Malfunctioning equipment also had the potential to skew data. The rainfall simulations and the rain gauges had missing or false data that had to be adjusted.



G	L	G	G	L	G	L	G
G	L	L	G	G	L	G	G
L	L	G	G	G	L	L	B
L	L	G	G	G	G	G	G
L	L	L	L	L	L	G	L
G	G	G	L	L	L	G	G
G	L	F	G	F	G	G	G
G	L	L	B	F	B	L	L

L	F	L	G	G	L	L	G
L	L	L	L	L	L	F	G
G	L	L	L	G	L	L	G
L	G	L	G	F	L	L	L
G	G	F	G	L	L	L	L
L	L	G	L	L	B	B	L
L	G	G	L	L	G	G	F
G	L	L	G	G	L	G	G

Figure 10: Example of two plots with similar percentages of cover with different spatial patterns of vegetation. The plot on the left produced more runoff than the plot on the right.

RESULTS

Climatic Profile

A climatic profile was created for the Brazos County, Texas site to identify seasonal variations in precipitation patterns. A rain gauge on the study site and a long-term data set from Somerville, Texas was used to assess the precipitation patterns.

Total annual rainfall for April 2002 through March 2003 was 115.57 cm at Somerville, Texas and 136.93 cm at the Brazos County, Texas study site. Both Brazos County and Somerville had higher annual precipitation than the average annual precipitation (Figure 11). The Brazos County site was 48.66 centimeters higher than the annual average precipitation. The highest monthly precipitation was recorded in July, which was much higher than the long-term average. August, October, November, December, and February also had higher than average precipitation.

Number of storms and the average storm duration, amount and intensity per event from April 2002 to April 2003 are summarized in Table 4. A total number of storms, 140, was recorded for the year. An average storm lasted 756.21 minutes, produced 1.64 cm of rainfall, and had an intensity of 0.43 cm/hour. Summer storms had the highest average intensity at 0.65 cm/hour. The storms with the longest duration and lowest intensity were recorded during the winter season.

Spring is historically the wettest season of the year (Figure 11). During the time of this study only 8.25% of the annual precipitation fell in the spring. The most rain fell in summer, and was followed by a wet fall and winter. However, 32% of

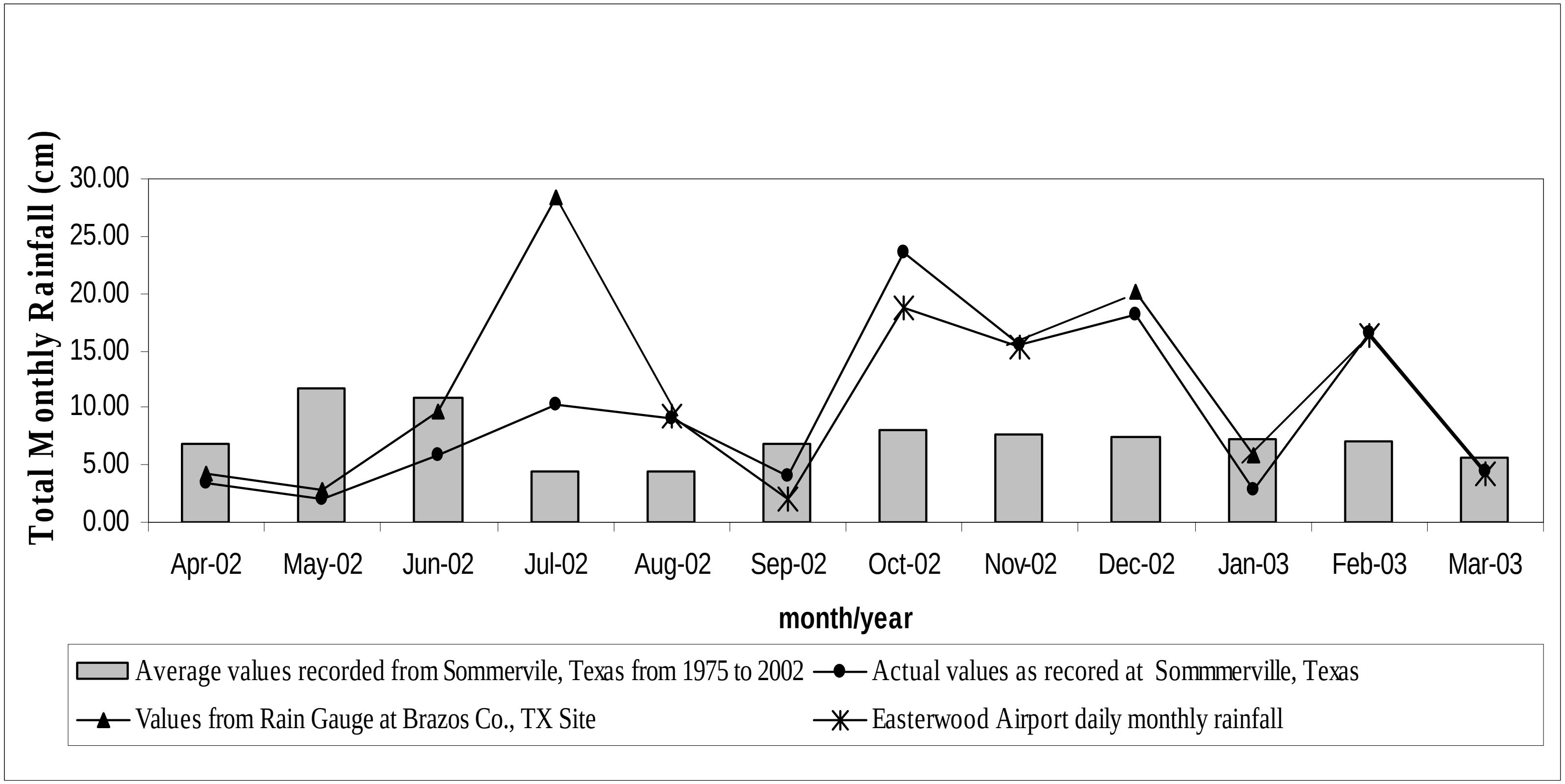


Figure 11: Average monthly precipitation for Somerville, Texas from 1975 to 1993 compared to 2002-2003 Somerville, Texas and 2002-2003 Brazos County, Texas. Values for Somerville were obtained from NOAA precipitation data at http://www.noaa.gov/ , and Brazos County were retrieved from a rain gauge on-site. Missing values for the rain gauge at the Brazos County study site were obtained from the Easterwood Airport rain gauge, which is located approximately 20 miles for the study site.

Table 4: Storm characteristics based on 2001 and 2002 storm events from the Brazos County, Texas study site.

	Number storms	Avg. Duration mins.	Total Avg. Rainfall Amount per storm (cm)	Intensity cm/hour
Winter	27	934.46	1.99	0.30
Spring	28	653.97	1.59	0.41
Summer*	34	745.76	2.29	0.65
Fall*	51	690.64	1.47	0.35

*Missing storm event data was replaced with daily totals from Easterwood Airport-College Station, Texas (10 events in summer and 37 events in fall).

Table 5: Amount and percent of rainfall in four time quintiles based on duration of each storm event in minutes from the Brazos County, Texas study site.

	Average Percent				Average amount (cm)			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Winter	40.12	16.77	22.16	20.96	0.67	0.28	0.37	0.35
Spring	33.96	26.42	24.53	15.09	0.54	0.42	0.39	0.24
Summer*	45.20	23.49	19.22	21.12	1.27	0.66	0.54	0.34
Fall**	43.21	38.21	8.57	10.00	1.21	1.07	0.24	0.28

*Missing storm event data was replaced with daily totals from Easterwood Airport-College Station, Texas (10 events in summer and 37 events in fall).

the summer precipitation came from one storm in July. This storm was the largest storm recorded during the time of the study and totaled 15.24 centimeters.

Storm events were divided into four time quintiles or quarters of a storm event (Table 5). The first and second quarters of the average storm produced the largest amount of rainfall. Summer storms typically had a large surge at the beginning of the storm and tapered off towards the end of the storm. Fall storm quintiles were similar to the typical summer event with the largest proportion of rainfall falling within the first quarter of the storm. Spring and winter quintiles were similar throughout the quintiles.

Frequency and probabilities of precipitation in Brazos County, Texas are located in Appendix A. Table A1 summarizes the duration and frequency by return periods. The smallest storm recorded by Hershfield (1961) was a one year, thirty minute storm that produced 3.68 cm of rainfall. The average rainfall from a single storm at the Brazos County site was 1.84 cm (Table 4). Eighty percent of the long-term Somerville data set and 80.81% of the storms recorded at the Brazos site produced less than 2.00 centimeters of rainfall (Table 7). One percent of the storms were greater than 15.00 centimeters.

Average, standard deviation, maximum, minimum, and median monthly totals for the Somerville, Texas long-term rainfall data are outlined in Appendix Table A5. Several months had a zero minimum storm event, while the maximum values ranged from 7 to 28 cm in a month. The annual average for any given month was 7.28 centimeters.

Table 6: Total precipitation and percent of precipitation during 2002-2003 from the Brazos County, Texas study site.

	Total Precipitation (cm)	% Total Precipitation
March 2003	4.32	3.16
April 2002	4.24	3.10
May 2002	2.74	2.00
Spring	11.3	8.25
June 2002	9.75	7.12
July 2002	28.37	20.72
August 2002	9.19	6.71
Summer	47.31	34.56
September 2002	1.96	1.43
October 2002	18.80	13.73
November 2002	15.24	11.13
Fall	36.00	26.29
December 2002	20.04	14.64
January 2003	5.89	4.30
February 2003	16.37	11.96
Winter	42.21	30.83
Total	136.91	100

Table 7: Frequency of storm events as a percentage by storm event amount for the long-term data set (Somerville, Texas) and the Brazos County, Texas study site.

Rainfall Amounts per Storm Event	Somerville Frequency (%)*	Cumulative Frequency (%)	Brazos Frequency (%)**	Cumulative Frequency (%)
0-0.99 cm	0.05	0.05	65.66	65.66
1.00 to 1.99 cm	80.08	80.13	15.15	80.81
2.00 to 2.99 cm	11.92	92.05	9.09	89.90
3.00 to 3.99 cm	3.91	95.96	2.02	91.92
4.00 to 4.99 cm	1.46	97.41	4.04	95.96
5.00 to 5.99 cm	1.13	98.54	1.01	96.97
6.00 to 6.99 cm	0.46	99.00	0.00	96.97
7.00 to 7.99 cm	0.38	99.38	0.00	96.97
8.00 to 8.99 cm	0.30	99.68	1.01	97.98
9.00 to 9.99 cm	0.08	99.76	0.00	97.98
10.00 to 10.99 cm	0.05	99.81	0.00	97.98
11.00 to 11.99 cm	0.03	99.84	1.01	98.99
12.00 to 12.99 cm	0.05	99.89	0.00	98.99
13.00 to 13.99 cm	0.05	99.95	0.00	98.99
14.00 to 14.99 cm	0.03	99.97	0.00	98.99
>15 cm	0.03	100.00	1.01	100.00

*Based on long-term rainfall data obtained from NOAA at the Somerville, TX weather station from 1974 to 1995.

****Based on the rain gauge data at the Brazos County, Texas study site for April 2002 to March 2003.**

Soil Analysis

A textural analysis was constructed to determine change due to previous erosion since the NRCS (1991) soil survey and for better interpretation of the study site characteristics. Figure 3 is a map illustrating the layout of the watershed catchments and the location of the plots that were sampled for soil textural analysis in relation to canopy cover.

NRCS (1991) mapped the soils at the Brazos County study site as a Tabor fine sandy loam (TaA) and Zachary fine sandy loam (ZaC2). These soils are classified as either a sandy loam or loamy sand (Table 8). The Tabor series description was more similar to soil samples from the Brazos County site. Both the Zachary and Tabor series have a top horizon (0-15.24 centimeters) of fine sandy loam. The textural analysis showed catchment A to be a loamy sand and catchment B a sandy loam in the first 15.24 centimeters. The second horizon (15.24 -30.48 centimeters) became sandier in catchment A. Catchment B remained a sandy loam in the second horizon. The Zachary series classified the second horizon (17.78-45.72 centimeters) as clay. The percent of clay in both catchments ranged from 8 to 14 percent. Forty percent of the soil makeup must be clay particles to be texturally classified as a clay soil (Figure 1). In catchment A, plots near the front (near the exit flume) were loamy sands and the samples taken with more canopy cover were sandy loam. All of B was a sandy loam except for one sample’s third horizon, which was a loamy sand.

Sand made up the largest portion of the soil texture classes; silt percentages followed sand and the smallest contribution came from clay. Some of the pedons at approximately 20 to 25 centimeters in depth from Watershed B, plot 54 (B54) had distinct mottling. B54 also had numerous rocks and pebbles throughout the profile. Digging became arduous at 25.4 centimeters because of larger rocks in B54. Few pebbles were observed in any of Watershed A plots.

Table 8: Comparison of texture descriptions from NRCS (1991) soil series descriptions of the study area and textural analysis on watershed study site soils at Brazos County, Texas.

TaA		ZaC2	
Tabor fine sandy loam		Zachary fine sandy loam	
Profile Depth	Texture	Profile Depth	Texture
Ap 0-15.24 cm	fine sandy loam	Ap 0-17.78 cm	very fine sandy loam
E1.24-35.56 cm	fine sandy loam	Bt1 17.78-45.72 cm	clay
Bt1 35.56-58.42 cm	clay	Bt2 45.72 -60.96 cm	clay
Bt2 58.42-106.68 cm	clay	2BCk 60.96-91.44 cm	sandy clay loam
Bt3 106.68-144.78 cm	clay loam	2Ck 91.44 -152.40 cm	loam
Btg 144.78-170.18 cm	sandy clay loam		
BCtg1 170.18-182.88 cm	sandy clay loam		
BCtg2 182.88 -203.20	sandy clay loam		
Plot A		Plot B	
Brazos Watershed		Brazos Watershed	
Sample/ Depth	Texture	Sample/ Depth	Texture
A17-1: 0-5.08 cm	loamy sand	B54-1: 0-5.08 cm	sandy loam
A17-2: 5.08-15.24 cm	loamy sand	B54-2: 5.08-15.24 cm	sandy loam
A17-3: 15.24-21.59 cm	loamy sand	B54-3: 15.24 -25.4 cm	loamy sand
A60-2: 5.08-15.24 cm	loamy sand	B83-1: 0-5.08 cm	sandy loam
A60-3: 15.24 -25.4 cm	sandy loam	B83-2: 5.08-20.32 cm	sandy loam
A109-2: 5.08-15.24 cm	sandy loam	B124-1: 0-5.08 cm	sandy loam
A109-3: 15.24-27.94 cm	sandy loam	B124-2: 5.08-15.24 cm	sandy loam
A109-1+A60-1: 0-5.08 cm	sandy loam	B124-3: 15.24 -30.48 cm	sandy loam

Rainfall Simulations

Variables measured as part of the rainfall simulation study included vegetation (biomass and percentages of bare ground, grass, forbs, and litter cover), soil moisture, initial time to runoff, amount of rainfall to runoff, and amount to "storage capacity" (amount to storage). Soil moisture was measured in two ways. The first method was gravimetric soil moisture on a dry weight basis, and the second method was derived from a probe reading that measured antecedent soil moisture on a saturated basis (percent saturation). Variables were observed to determine their seasonal relationship to infiltration rate and percent of runoff.

Little difference between vegetation variables was detected by an ANOVA (Table 9). There were no significant ($p< 0.05$) differences between percent bare ground, percent forb, and biomass. Highest average percent bare ground (10.4%) was observed during the fourth simulation. Average bare ground for all simulations was less than 6%. Very little variation in percent forb cover was recorded between simulations. The average percent of forbs was 10.8% and ranged from 8.3% to14.6%. Biomass averaged from 92.2 grams/m^2 to 151.3 grams/m^2. The percent of grass generally increased throughout the study, while percent of litter decreased. Grass was the lowest during the first (spring) simulation and highest during the fifth (winter) simulation. The predominant grass on the study site was little bluestem (*Shizachyrium scoparium*), which is a warm season grass that starts growth in spring and matures during the fall. Litter was the lowest in the fourth (fall) and fifth (winter) simulations when grass was at maturity and rainfall was the highest, and highest in the first (spring) simulation when the warm season grasses start growth.

Table 9: Average vegetation parameters for the five rainfall simulations conducted near the Brazos County, Texas watersheds.

	Biomass g/m^2	% Bare Ground	% Grass	% Forb	% Litter
S1 Avg. Spring	92.2 a	3.3 a	24.6 a	14.6 a	57.4 a
S2 Avg. Summer	135.6 a	1.5 a	43.2 ab	11.0 a	45.6 a
S3 Avg. Summer	151.3 a	7.2 a	49.3 b	8.3 a	36.0 a
S4 Avg. Fall	107.7 a	10.4 a	45.7 b	11.6 a	35.9 ab
S5 Avg. Winter	127.5 a	6.1 a	52.1 b	8.8 a	33.0 b
Total Avg.	122.9	5.7		10.8	

Means in the same column with the same letter are not significantly different from each other ($p<0.05$).

Differences were found among the soil moisture variables (Table 10). Antecedent soil moisture samples were taken from the surface of the soil, and percent saturation measured soil moisture over a deeper profile. Both soil moisture readings increased throughout the simulation study with the exception of the third simulation gravimetric antecedent soil moisture reading. The average third simulation gravimetric antecedent soil moisture reading was 0.5%. The highest gravimetric antecedent soil moisture averages were 16.7% and 18.8%, which corresponded with the highest percent of saturation at 74.5% and 72.8%, fourth and fifth simulation respectively. The first and second simulation percent saturation recordings were significantly different from all other simulations, which indicated that the last simulations were significantly wetter than the first three simulations.

Table 10: Average soil moisture parameters (percent) from the five rainfall simulations conducted near the Brazos County, Texas site.

	Antecedent soil moisture*		**Percent Saturation****	
S1 Avg. Spring	5.7	a	24.0	a
S2 Avg. Summer	7.8	a	44.6	b
S3 Avg. Summer	0.5	b	61.3	c
S4 Avg. Fall	16.7	c	74.5	c
S5 Avg. Winter	18.8	c	72.8	c
Annual	9.9		55.4	

Means in the same column with the same letter are not significantly different from each other ($p<0.05$).* Based on gravimetric dry weight basis. **Converted probe readings to percent saturation using a regression equation.

Runoff calculations were separated into four categories: 1) initial time to runoff, 2) amount to “storage”, 3) percent of rainfall as runoff, and 4) total infiltration rate (cm/ hour) (Table 12). Initial times to runoff averaged 3.43 and 3.89 minutes in winter and fall respectively, and ranged from 8.32 to 12.01 minutes in the drier spring and summer months. The amount to storage was reached when runoff for that interval met or exceeded the amount of precipitation for that interval. Storage was met only five out of fifty times. Storage was not met in any of first two simulations. In the third simulation two plots reached storage after 15.88 centimeters of rainfall. During the fourth simulation, it was reached after 15.88 and 6.35 centimeters. Storage was only met once after 15.88 centimeters of rainfall in the fifth simulation. The most rainfall was lost to runoff in the last two simulations. The least amount of rainfall was lost to runoff during the first two simulations. Conversely, infiltration rate was highest in the first simulation and lowest in the last simulation.

No significant differences in sediment production between simulations were observed, but the average sediment values ranged from 2.1 g/ m^2 to 22.3 g/m^2 (Table 11). The two highest average soil losses were in the fourth and fifth simulation, which corresponded with the highest percent of saturation.

Table 11: Average runoff and infiltration rate variables for the five rainfall simulations conducted near the Brazos County, Texas watersheds.

Simulation	Initial time to Runoff	Amount to Runoff (cm)	Amount to Storage	%Rainfall lost to Runoff	Infiltration Rate (cm/hr)	Sediment Production (g/m2)
S1 Avg. Spring	10.77 [b]	3.35 [ab]	0.00 [a]	16.83 [a]	13.95 [abc]	2.1 [a]
S2 Avg. Summer	8.32 [ab]	3.71 [ab]	0.00 [a]	8.98 [a]	17.34 [c]	2.3 [a]
S3 Avg. Summer	12.01 [b]	4.76 [ab]	3.53 [a]	23.21 [a]	14.63 [bc]	11.6 [a]
S4 Avg. Fall	3.89 [a]	1.94 [a]	1.99 [a]	48.23 [b]	9.86 [a]	22.3 [a]
S5 Avg. Winter	3.43 [a]	2.07 [a]	1.59 [a]	40.77 [b]	11.28 [ab]	12.1 [a]
Annual Avg.	7.68	3.17	1.42	27.60	13.41	10.08

Means in the same column with the same letter are not significantly different from each other ($p<0.05$).

A minimum average of 1.94 centimeters of rainfall was needed to initiate runoff (Table 11). In the warmer months when the soil was drier, 3.35 centimeters of rainfall was applied before runoff was initiated.

Statistical Analysis

Two phases of the statistical analysis was constructed to aid in the quantification of erosion and runoff risk. The two phases consisted of a correlation analysis and a regression analysis. The correlation analysis was constructed to evaluate the relationships of the measured study variables. The regression analysis was completed to increase the explanatory validity of the research study. The regression analyses created a model that explains the effects of selected variables when controlling for the selected variables. The regression analysis was also divided into two steps. First, a regression equation was created based on significant relationships. The second equation selected variables based on previous research to test the ability of selected variables to use as management thresholds.

The correlation analysis results showed that season, initial time to runoff, percent litter, annuals as the dominant species, percent of saturation, amount to runoff, and amount to “storage” were significantly ($p < 0.05$) related to infiltration rate and percent of precipitation lost to runoff (Table 12). Variables that significantly ($p<0.05$) decreased infiltration rate and increased percent runoff were increased soil moisture (percent saturation and gravimetric antecedent soil moisture), and amount to storage. Runoff decreased as infiltration increased. Variables with a significant ($p<0.05$) and positive

Table 12: Correlation coefficients (r) of variables used in the rainfall simulations study near the Brazos County, Texas watershed study site.

	Infiltration rate	% Runoff	Sediment m2	Winter	Spring	Summer	Fall	Initial time to runoff	Antecedent soil moisture
% Runoff	1.00 **								
Sediment	-0.35 *	0.35 *							
Winter	-0.44 **	0.44 **	0.04						
Spring	0.28	-0.28	-0.18	-0.25					
Summer	0.49 **	-0.49 **	-0.18	-0.41 **	-0.41 **				
Fall	-0.44 **	0.44 **	0.32 *	-0.25	-0.25	-0.41 **			
Initial time to runoff	0.56 **	-0.56 **	-0.23	-0.32 *	0.15	0.35 **	-0.26		
Antecedent soil moist.	-0.56	0.56	0.18	-0.47 **	-0.04	-0.25	0.81 **	-0.16	
% Bare ground	-0.28	0.28	0.05	0.01	-0.16	-0.15	0.33 **	-0.19	0.15
% Grass	-0.23	0.23	0.05	0.30 *	-0.51 **	0.07	0.11	-0.15	-0.14
% Forb	-0.05	0.05	0.00	-0.13	0.27	-0.15	0.05	0.15	0.21
% Litter	0.39 **	-0.39 **	-0.09	-0.29 *	0.53 **	-0.04	-0.19	0.15	0.03
Annual as dom. spcs.	-0.40 **	0.40 **	0.32 *	0.22	-0.22	-0.23	0.29 *	-0.24	0.11
Forb as dom. spcs.	0.25	-0.25	0.10	-0.25	0.41	0.04	-0.22	0.06	0.10
% saturation	-0.47 **	0.47 **	0.29 *	0.38 **	-0.70 **	-0.14	0.42 **	-0.37 **	0.12
Amt. to runoff	0.50 **	-0.50 **	-0.29	-0.27	0.22	0.29 *	-0.29 *	0.62 **	-0.36 **
Amt. to "storage"	-0.41 **	0.41 **	-0.03	0.00	-0.17	0.05	0.10	-0.04	-0.03
Biomass	0.14	-0.14	-0.12	0.03	-0.19	0.21	-0.09	0.05	-0.16

* = p < 0.05, ** = p < 0.01

Table 12: continued.

	% Bare ground	% Grass	% Forb	% Litter	Annual as dominant species	Forb as dominant species	Percent saturation	Amount to runoff	Amount to storage
% Forb	-0.03	-0.40 **							
% Litter	-0.34	-0.61 **	0.08						
Annual as dominant species	-0.05	0.16	-0.04	-0.16					
Forb as dominant species	-0.16	-0.58 **	0.35 **	0.48 **	-0.05				
Percent saturation	0.16	0.44 **	-0.24	-0.40 **	0.33 **	-0.37 **			
Amount to runoff	-0.19	-0.07	0.12	0.07	-0.19	0.15	-0.23		
Amount to "storage"	0.27	0.09	-0.07	-0.20	0.28	-0.15	0.15	-0.09	
Biomass	-0.28	0.55	-0.16	-0.36 **	-0.11	-0.38 **	-0.05	0.16	-0.04

* = p < 0.01, ** = p < 0.05

relationship with infiltration included initial time to runoff, percent litter, amount to runoff, and biomass.

Other variables were correlated as expected to infiltration rate and percent runoff although the relationships were not significant ($p<0.05$) (Table 12). As infiltration rate increased, sediment yield and percent runoff decreased. Variables that had a negative relationship with infiltration rate and a positive relationship with percent runoff but were not significant included increased percent forb cover and percent bare ground. Winter and fall also had a negative relationship with infiltration and positive relationship with percent runoff.

Fall, percent saturation, and annuals as the dominant species were the variables that were significantly correlated with sediment yield per plot ($p<0.05$), but had weak relationships ($r = 0.44$, 0.32, and 0.29, respectively). Other variables in the correlation analysis were not strongly significant, but followed expected trends (Table 12). As soil moisture, percent bare ground, percent forb cover, forb as the dominant species, and initial time to runoff increased, the amount of sediment production also increased. As percent litter, biomass, amount to storage, and amount to runoff increased, sediment production decreased. Correlation analysis generally showed as initial time to runoff increased, infiltration rate increased and runoff decreased because rainfall had more time to infiltrate into the soil profile. Percent of saturation strongly ($p<0.01$) influenced the initial time to runoff (Table 12). As percent of saturation increased, available pore space in the soil profile became limited and infiltration decreased and rainfall lost to runoff (percent runoff) increased. Therefore, as the amount to storage increases (more infiltration), the initial time to runoff decreases. As the antecedent soil moisture increased, the initial time to runoff decreased.

Significant trends ($p<0.05$) were observed among the different seasons (Table 12). Winter had the shortest time to runoff with higher percent of saturation and summer had the longest time to infiltrate with the lowest percent of saturation. Also, percent grass was higher in winter when most of the grass species present on the site was at maturity and lower during the spring when growth was initiated. The opposite relationship was observed in percent litter. A higher percent of litter was recorded in spring and a lower percent in winter.

The second part of the statistical analysis consisted of OLS regression analysis. The regression equations created for percent runoff, infiltration rate and sediment yield are listed in Table 13. Variables in the A equation were selected first by their significance level, and then by the r-coefficient. Infiltration rate and percent runoff variables were selected as the dependent variables. The independent variables were selected if the p-value was less than 0.01 and the r-coefficient was greater than or equal to 0.44 in relation to the dependent variables. All values that had a 95% significance level to sediment yield were used in the sediment yield regression equation. In B equation, variables were selected by expected effects on the dependent variables from past research.

The variables used in the percent runoff and infiltration rate equations were season, initial time to runoff, percent saturation, and amount of precipitation required to produce runoff (Table 13-Section A). Fifty-five percent of the variability was explained using these variables. The variables selected for sediment yield were fall, annuals as the dominant species and initial time to runoff. Only sixteen percent of the variability was explained with the equation created for sediment yield.

Summer was the only significant predictor variable in the percent runoff and infiltration rate equations in Table 13a (Appendix C, p105). When controlling for all other variables in the equation there was a change in the direction of the trend with winter. This was due to the driving factor in seasonal effects is climate pattern. The climate pattern controls the amount of moisture in the soil. Controlling for the variables, percent saturation, initial time to runoff, and amount to runoff negates the effects of season. Therefore, the moisture variables negate the effect of season. There were no significant predictor variables in the sediment yield prediction equation.

Equations in Table 13-Section B were constructed using percent saturation, amount of precipitation to runoff, percent litter, and biomass. Forty percent of the variability was explained with these variables. However, these variables only explained five percent of the variability in the sediment yield regression equation.

The infiltration predictor variables used in equation B1 with a positive trend were amount to runoff, biomass, and litter. The significant variables ($p<0.05$) in the infiltration rate and percent runoff regression equations were amount to runoff and litter. Increased percent saturation decreased infiltration because the soil pores were already be filled with water. Amount to runoff had a negative relationship with infiltration because the more water that is needed to initiate runoff the more water the soil is able to capture. Biomass and litter also increased infiltration due to slowing runoff.

Table 13: Predictive equations generated from multiple regression analysis with percent runoff, infiltration rate, and sediment production as the dependent variables for data collected from the rainfall simulation study near the Brazos County, Texas watershed study.

A Equations	Regression equations based on current study statistics.	d.f.	r^2
1. Percent Runoff[1] =	42.36 -2.04(x1) -14.89(x2) -20.93(x3) -0.58(x5) +0.15(x6) -1.68(x7)	41	0.47
2. Infiltration Rate[1] =	10.97+0.39(x1)+2.84(x2)+3.99(x3) + 0.11(x5) - 0.03(x6) +0.32(x7)	41	0.47
3. Sediment Yield[2] =	10.57 +10.27(x4) +11.79(x8) -0.46(x5)	40	0.16

B Equations	Regression equations based on previously recognized factors affecting the dependent variables.		
1. Percent Runoff[1] =	49.70 +0.25(x6) -3.48(x7) -0.42(x9) -0.05(x10)	41	0.40
2. Infiltration Rate[1] =	9.58 -0.05(x6) +0.66(x7) +0.08(x9) +0.009(x10)	41	0.40
3. Sediment Yield[3] =	12.77 +.20(x6) -3.36(x7) -0.50(x9) -0.005(x10)	40	0.05

[1]F(prob)<0.001 [2]F(prob)<0.05 [3]F(prob)<0.20

x1=winter, x2=spring, x3=summer, x4=fall, x5=initial time to runoff, x6=percent saturation, x7=amount of precipitation to runoff, x8= annual as the dominant species, x9= percent litter, x10= biomass(g/m2).

Paired Watershed Study

Vegetation and soil moisture variables were measured monthly for a year to evaluate seasonal trends and the relationships to infiltration and runoff on an existing paired watershed. The paired watersheds were used as repetitions and were designed to be similar in composition and function.

Vegetation

Many of the variables during this research demonstrated wide ranges of values and showed significant differences ($p<0.05$) between months and seasons (Table 14 and 15). Percent litter cover in fall and winter was significantly different as compared to spring and summer litter cover in both catchments. The annual average of percent litter cover was 47.67%, while bare ground averaged 2.6% for the year in both catchments. No significant differences ($p<0.05$) were observed in percent bare ground in catchment A. In catchment B, percent bare ground cover in spring and winter were significantly different from summer and fall; seasonal averages ranged from 1.04 to 4.97% bare ground

Percent grass cover generally increased throughout the study from spring to winter (Table 14). Annual percent grass averaged 47.8% in catchment A and 43.55% in

Table 14: Seasonal averages of percent bare ground and litter for the Brazos County, Texas study.

Catchment A					Catchment Cover B			
		Average	Average				Average	Average
Season	Month	% Bare ground	% Litter		Season	Month	% Bare ground	% Litter
Spring	March 2003	5.07[a]	46.59[b]		Spring	March 2003	4.41[bcd]	44.15[ab]
	April 2002	4.36[a]	45.59[bc]			April 2002	6.79[cd]	46.05[ab]
	May 2002	1.60[a]	60.44[d]			May 2002	1.45[ab]	64.52[c]
Spring Average		**3.67[a]**	**50.87[b]**		**Spring Average**		**4.24[a]**	**51.57[a]**
Summer	June 2002	1.49[a]	64.01[d]		Summer	June 2002	1.49[ab]	67.55[c]
	July 2002	0.75[a]	46.22[c]			July 2002	1.12[ab]	48.55[b]
	August 2002	0.87[a]	48.59[c]			August 2002	1.00[ab]	48.75[b]
Summer Average		**1.04[a]**	**52.94[b]**		**Summer Average**		**1.20[b]**	**54.95[b]**
Fall	September 2002	4.16[a]	40.04[ab]		Fall	September 2002	1.38[ab]	41.45[ab]
	October 2002	0.00[a]	45.16[bc]			October 2002	0.69[ab]	42.46[ab]
	November 2002	6.56[a]	44.76[bc]			November 2002	----------	----------
Fall Average		**3.05[a]**	**43.32[a]**		**Fall Average**		**1.04[b]**	**41.96[a]**
Winter	December 2002	2.88[a]	37.13[a]		Winter	December 2002	3.83[abc]	36.79[a]
	January 2003	4.14[a]	43.67[bc]			January 2003	7.99[d]	46.30[b]
	February 2003	1.62[a]	4.18[bc]			February 2003	2.93[abc]	43.47[ab]
Winter Average		**2.88[a]**	**41.66[a]**		**Winter Average**		**4.97[a]**	**42.18[a]**

Means of the same letter are not significant from each other ($p < 0.05$). Months and seasons are compared separately.

Table 15: Average seasonal percent basal cover and biomass recorded for the watershed study (Catchments A and B) at Brazos County, Texas.

A	Season	Month	Average % Grass	Average % Forb	Average % Shrub	Average Biomass (g/m2)
	Spring	March 2003	66.24^{d}	6.92^{a}	1.87^{a}	166.10^{cd}
		April 2002	41.31^{c}	13.54^{bc}	2.40^{a}	198.63^{cd}
		May 2002	27.27^{a}	16.40^{cd}	1.27^{a}	.
	Spring Average		**44.94^{b}**	**12.29**	**1.84^{a}**	**182.37^{ab}**
	Summer	June 2002	28.02^{ab}	18.06^{d}	2.87^{a}	100.41^{b}
		July 2002	41.15^{bc}	12.82^{bc}	1.60^{a}	167.62^{cd}
		August 2002	41.12^{bc}	10.90^{bc}	1.93^{a}	209.64^{cd}
	Summer Average		**36.76^{b}**	**13.93**	**2.13^{a}**	**159.22^{ab}**
	Fall	September 2002	45.62^{cd}	7.97^{ab}	1.87^{a}	212.25^{d}
		October 2002	46.15^{cd}	7.23^{a}	2.12^{a}	156.79^{bc}
		November 2002	69.26^{d}	11.20^{bc}	1.87^{a}	81.40^{a}
	Fall Average		**53.68^{a}**	**8.87**	**1.95^{a}**	**150.15^{a}**
	Winter	December 2002	43.65^{c}	7.96^{ab}	1.47^{a}	160.28^{cd}
		January 2003	57.31d	8.06^{ab}	1.73^{a}	196.25^{cd}
		February 2003	64.11^{d}	7.10^{a}	1.73^{a}	202.84^{cd}
	Winter Average		**55.02^{a}**	**7.71**	**1.64^{a}**	**186.45^{b}**
	Annual Average		**47.8**	**10.7**	**1.89**	**169.55**

Means of the same letter are not significant from each other ($p < 0.05$). Months and seasons are compared separately.

Table 15 continued

B	Season	Month	Average % Grass	Average % Forb	Average % Shrub	Average Biomass (g/m2)
	Spring	March 2003	55.53[cd]	7.93[ab]	0.53[a]	180.80[b]
		April 2002	36.71[ab]	15.63[cd]	0.20[a]	192.45[b]
		May 2002	27.09[a]	17.06[d]	0.47[a]	----------
	Spring Average		**39.78[ab]**	**13.54[b]**	**0.40[a]**	**186.62[a]**
	Summer	June 2002	26.09[a]	17.23[d]	0.40[a]	89.23[a]
		July 2002	38.77[ab]	12.90[c]	0.47[a]	151.85[ab]
		August 2002	41.15[abc]	11.04[b]	0.53[a]	190.93[b]
	Summer Average		**35.33[a]**	**13.72[b]**	**0.47[a]**	**143.93[a]**
	Fall	September 2002	44.93[bcd]	8.03[ab]	0.13[a]	209.87[b]
		October 2002	45.93[bcd]	7.73[a]	0.40[a]	144.25[ab]
		November 2002	----------	----------	----------	----------
	Fall Average		**45.43[a]**	**7.88[a]**	**0.27[a]**	**177.06[a]**
	Winter	December 2002	44.13[bcd]	8.18[ab]	0.40[a]	156.48[ab]
		January 2003	57.52[d]	8.73[ab]	0.53[a]	183.58[ab]
		February 2003	59.30[d]	7.60[a]	0.53[a]	197.26[b]
	Winter Average		**53.65[b]**	**8.17[a]**	**0.49[a]**	**179.11[a]**
	Annual Average		**43.55**	**10.8**	**0.41**	**171.68**

Means of the same letter are not significant from each other ($p < 0.05$). Months and seasons are compared separately.

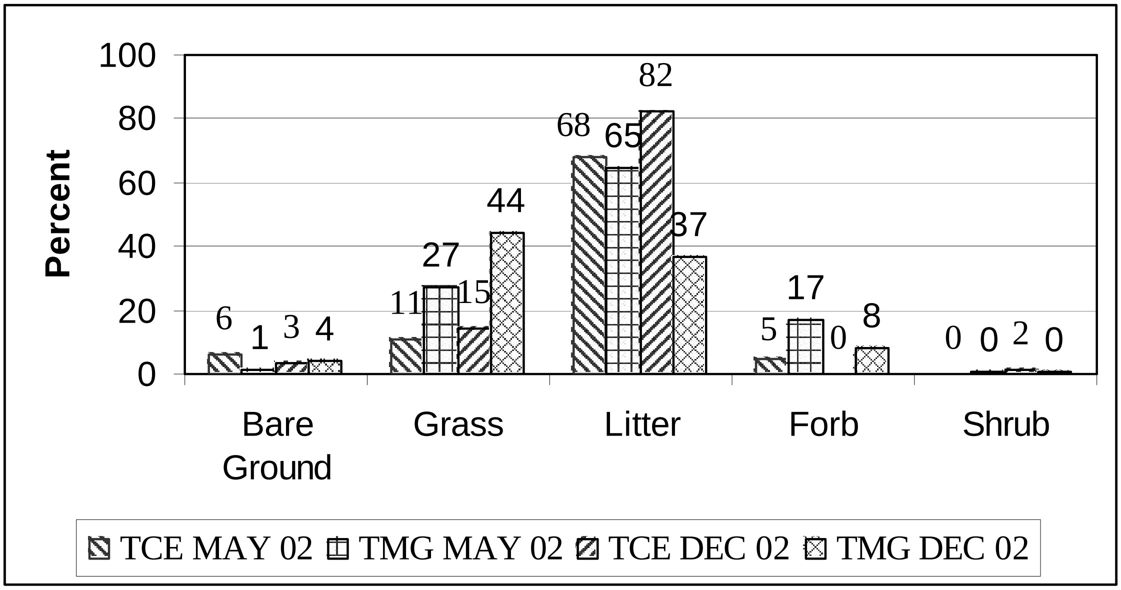
catchment B. In catchment A, spring and summer percent grass cover was significantly ($p<0.05$) different from winter and fall. The range was similar in both catchments. There were no significant differences in percent woody cover between catchments; however, catchment A had higher percentages of shrub/woody vegetation (1.89%) than catchment B (0.41%). Average biomass also did not significantly change seasonally in catchment A. Annual averages for catchments A and B were 169.55 g/m^2 and 171.68 g/m^2, respectively. Biomass in both catchments was highest in winter and spring.

The TCE study had similar results, but the differences in the way the studies were conducted yielded different summary results. Table 16 summarizes the total percentages of cover for the two catchments from 2000 to 2003. The TCE study also averaged less than five percent bare ground regardless of time of collection. However, the TCE study resulted in a higher percent of litter and lower percentages of grass and forbs.

The sampling methodologies for the two studies were different, which resulted in slightly different observations. Figure 12 illustrates these differences by comparing the summary results of the TCE study and the current research study (TMG) by sampling date. The percentages of the different cover types were different, but they follow similar trends. Percent grass was less in spring and summer as compared to winter and fall in both catchments. The opposite trend was observed for percent forbs; they were higher in the spring and summer and lower in the winter and fall.

Table 16: Vegetation parameters measured along a permanent transect on each catchment on the Brazos County, Texas study site by the Texas Cooperative Extension (TCE).

Catchment	% Bare Ground	% Grass	% Litter	% Forb	% Grasslike	% Shrub	% Canopy Cover
	Dec.-00	**Dec.-00**	**Dec.-00**	**Dec.-00**	**Dec.-00**	**Dec.-00**	**Dec.-00**
A	4.2	7.0	88.7	0.0	0.0	0.0	52.18
B	1.6	1.6	96.8	0.0	0.0	0.0	92.38
	Jul.-01	**Jul.-01**	**Jul.-01**	**Jul.-01**	**Jul.-01**	**Jul.-01**	**Jul.-01**
A	3.0	7.6	81.8	1.5	4.5	1.5	54.1
B	3.1	20.3	64.1	3.1	9.4	0.0	39.4
	Nov.-01	**Nov.-01**	**Nov.-01**	**Nov.-01**	**Nov.-01**	**Nov.-01**	**Nov.-01**
A	2.8	2.8	94.4	0.0	0.0	0.0	87.0
B	0.0	6.3	0.0	0.0	93.7	0.0	91.0
	May-02	**May-02**	**May-02**	**May-02**	**May-02**	**May-02**	**May-02**
A	0	0	93.2	2.7	0	0	82.2
B	6.3	11.1	68.3	4.8	0	0	93.5
	Dec.-02	**Dec.-02**	**Dec.-02**	**Dec.-02**	**Dec.-02**	**Dec.-02**	**Dec.-02**
A	0	16.9	81.69	0	0	1.41	55.77
B	3.23	14.52	82.26	0	0	0	100.97
	May-03	**May-03**	**May-03**	**May-03**	**May-03**	**May-03**	**May-03**
A	5.71	4.29	90	0	0	0	55
B	1.59	1.59	95.24	0	0	1.59	71.75



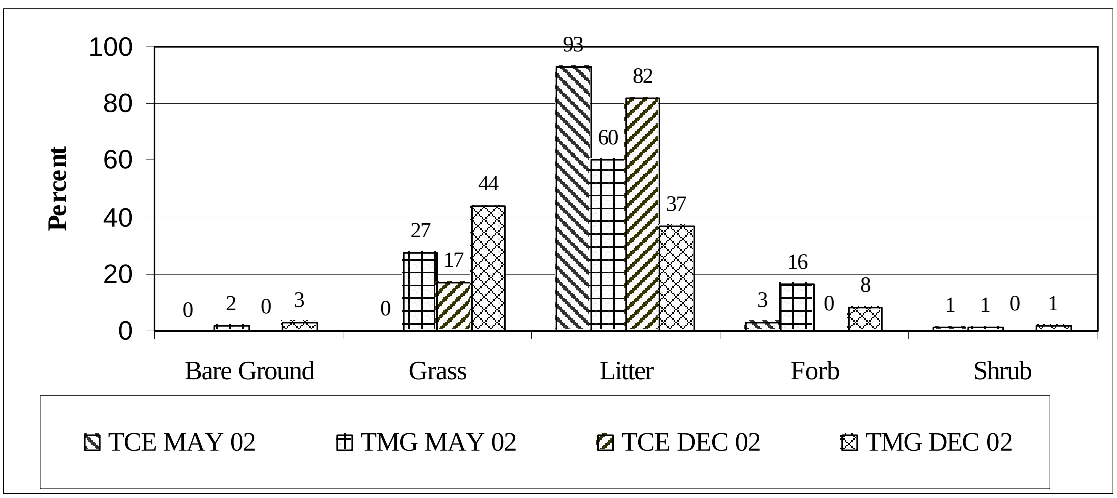


Figure 12: Differences observed by the current research study (TMG) and the study conducted by the Texas Cooperative Extension (TCE) during 2002 on the Brazos County study site- Catchment A (top) & B (bottom).

Soil Moisture

Soil moisture was measured on the same fifteen randomly selected vegetation plots in the paired watershed catchments at monthly intervals. Soil moisture was measured on a percent saturation basis with a soil moisture probe. The soil moisture probe readings on the watershed catchements were adjusted to percent saturation using the following equation: percent saturation (%) =1.004(probe)-18.961, r^2=0.90.

Percent saturation in winter was significantly ($p<0.05$) greater than the rest of the seasons in both catchments (Table 17). May 2002 had significantly ($p<0.05$) lower soil saturation compared to other months. May was the first month measurements were made. These readings were not calibrated to a saturated sample prior to its use in the field. Measurements were made at the beginning of each month. The next lowest two months that were significantly different were June and October. The months of April and September preceding the low recordings had lowest monthly precipitation totals (Figure 10). Soil moisture began to increase in November and continued into March, which corresponded with increased precipitation beginning in October. Although January had low monthly precipitation, October, November, and December had above normal precipitation (Figure 10). The soil was very wet throughout the winter months and into spring. Soil averaged 81% saturation in November 2002, December 2002 and March 2003.

Table 17: **Annual and seasonal percent saturation recorded at the Brazos County, Texas study site (Cathment A, left and B, right).**

A. Season	Month	Average % Saturation*
Spring	March 2003	81.44 [f]
	April 2003	66.64 [cde]
	May 2002**	2.7 [a]
Spring Average		**42.07** [**b**]
Summer	June 2002	18.82 [b]
	July 2002	63.43 [cd]
	August 2002	67.32 [cde]
Summer Average		**49.86** [**b**]
Fall	September 2002	63.16 [cd]
	October 2002	27.62 [b]
	November 2002	81.44 [f]
Fall Average		**57.41** [**b**]
Winter	December 2002	81.44 [f]
	January 2003	74.41 [def]
	February 2003	77.61 [ef]
Winter Average		**77.82** [**a**]
Annual Average		**56.79**

B. Season	Month	Average % Saturation*
Spring	March 2003	81.44 [f]
	April 2003	65.91 [cd]
	May 2002**	6.55 [a]
Spring Average		**44.00** [**b**]
Summer	June 2002	13.88 [ab]
	July 2002	70.80 [cde]
	August 2002	68.39 [cde]
Summer Average		**51.02** [**b**]
Fall	September 2002	64.97 [c]
	October 2002	24.35 [b]
	November 2002	81.44 [f]
Fall Average		**56.92** [**b**]
Winter	December 2002	81.44 [f]
	January 2003	74.98 [def]
	February 2003	77.42 [ef]
Winter Average		**77.95** [**a**]
Annual Average		**57.47**

Means of the same letter are not significantly different from each other($p<0.05$). Months and seasons are compared separately.
*Percent saturation was derived from a soil moisture probe that was converted to percent saturation with a regression equation.
**May 2002 probe readings were not calibrated with a saturated soil sample prior to its use in the field.

Runoff, Infiltration and Sediment Production

The weir sticks used in the Brazos County study began malfunctioning in 2001. The problem was not detected until data was compared to rainfall data after the completion of the study. The sediment collection system also had similar problems. Data were collected, but the accuracy of the sample is unknown. The sediment data was also unusable because there was no runoff data for computing total sediment production. Runoff, infiltration, and sediment calculations were not reported and used, since the validity of the data is questionable.

DISCUSSION/CONCLUSIONS

The hydrological condition of a site is the result of complex interrelationships of soil, vegetation, and climate. Reducing erosion and maintaining or improving infiltration are imperative for long-term sustainability and productivity. This research provided the first step to understanding risk by identification of potential managerial thresholds for a recovering Post Oak Savannah vegetation area with minimal bare ground and disturbance.

The infiltration and runoff regression equations based on current statistics solely indicated that infiltration and runoff were mostly influenced by season, percent of saturation, and initial time to runoff (Table 13-section A). A second regression equation was constructed based on previously recognized factors from the literature (Table 13-section B). For these equations, percent saturation, amount to runoff, percent litter, and biomass were compared to runoff, infiltration, and sediment yield.

Climatic Influences

Climatic (rainfall) influences by season played a large role in the infiltration and runoff processes. The rainfall/storm profile created during the current research was different from the long-term average. Half of the year was much wetter than average. Late fall and winter months were especially wetter (Figure 10). This corresponded with increased soil moisture on the rainfall simulation plots (Table 11) and the watershed catchments (Table 18). The average amount of sediment loss and percent of rainfall lost to runoff were the highest and infiltration on the rainfall simulation plots was the lowest during the winter and fall simulations (Table 12).

During the winter and fall, less precipitation was required before runoff initiation because of the increased soil saturation (%). Several studies have reported increased runoff with increased soil moisture (Giordanengo 2001, Hartmen et al. 1960, Meyles et al. 2003). With a similar climatic profile, different management strategies should be implemented during different seasons. During the current research, the watershed was more susceptible to erosion and runoff during the fall and winter due to increased saturation of the soil.

According to White et al. (2001), peak months for rainfall are May and September; July and October were the peak months for precipitation during the current study (Figure 15). Spring was drier than average and fall and winter were wetter than average. October through December were much wetter than average.

Annual precipitation during the time of this study was higher than the 1975-1993 average from Somerville, Texas. However, the frequency and return periods discussed in Hershfield (1961) reported storms with greater precipitation amounts. The durations were often longer than the durations discussed in (Hershfield 1961). The climatic results from this study indicated that this 2002-2003 study was drier or producing less intense storms as compared to storm events in the Hersfiled (1961) study.

Winter storms, on average, had the longest duration and the smallest intensity (Table 5). Spring and summer, on average, consisted of more intense storms, which coincides with less intense frontal storms in the fall and winter and more intense summer storms as discussed by Ward and Elliot (1995) and Tate (1996b). The longer duration of the winter storms indicates that the site has the potential to stay wetter longer and reach its storage capacity. Therefore, when it rains again the initial time to runoff is quicker and more rainfall is lost to runoff. Slower frontal storms are also longer in duration. Therefore, when it rains again the initial time to runoff is quicker and more rainfall is lost to runoff. Slower frontal storms are also longer in duration. Therefore, more of the soil pores are filled, which increases the potential to reach the soil's storage capacity and reduces infiltration rate. The fall and winter simulations had the quickest initial times to runoff and were the only simulations that reached "storage" capacity (Table 12).

All seasons on average had the most precipitation during the first quintile when the infiltration rate is the highest (Table 6). However, the differences between the winter quintiles were not as large as the differences from the summer storms. The season with the largest amount of rainfall in the fourth quintile was winter. Winter also had the highest soil moisture and also had steady rainfall till the end of the storm event when infiltration was the lowest.

The amount of precipitation before runoff initiation was used to create a precipitation amount threshold. In the cooler seasons (fall and winter) runoff occurred with less rainfall than the warmer seasons (summer and spring). The rainfall threshold for runoff initiation was two centimeters in the cooler seasons and three centimeters in the warmer seasons on the rainfall simulation plots. Wilcox et al. (2003) found a threshold value of 1.5 cm of precipitation for a storm event was necessary to produce runoff. Similarly, 1.9 cm was found to produce runoff in an Edwards Plateau study (Thurow 1985). Eighty percent of the storm events from the long-term and current studies were less than two inches (Table 8). With a similar climatic profile and site characteristics, 20% of storms will cause a runoff event. Most of the storms in the Wilcox et al. (2003) study were produced in the summer months and were convective in nature. In the current study, 30.83% of the total precipitation fell in the winter and 34.56% of the total precipitation fell in the summer (Table 7).

Based on the climatic profile created during the current research, the risk of runoff and sediment loss is the highest in fall and winter. Therefore, management should maintain higher levels of biomass and ground cover during the cooler seasons to protect the soil from erosion and promote infiltration.

Vegetation Cover and Seasonal Influences

The relationships illustrated in the correlation analysis were consistent with past literature (Table 13). Percent litter and biomass had a significant and positive relationship with infiltration rate, while percents of forbs and bare ground had a negative relationship with infiltration. Past watershed hydrological studies quote bare ground, litter, and/or grass cover as significant factors affecting infiltration rate, runoff rate, and sediment production (Mings 1993, Pluhar 1984, Cheruiyot 1984, Thurow 1985). Although the correlation analysis agreed with the direction of these relationships, percent litter and biomass were the only significant variables increasing infiltration and decreasing runoff and sediment production. Many studies have more variability in bare ground and ground cover percentages than this study site. This research study averaged 5.7% bare ground, while most studies have at least 30% bare ground. No significant differences were found in bare ground, biomass, or forb cover. The significant differences in grass and litter cover were during the summer simulations. The variables that had more variability had the potential to more significantly affect infiltration and runoff in the correlation and regression analyses. The statistical analysis showed percent of saturation as one of the most significant variables. In the ANOVA analysis, percent saturation had high variability between months and seasons. The statistical analysis was then able to measure the differences between the different levels of moisture and affects of the different levels on the dependent variables.

Soil moisture and rainfall characteristics were two variables that changed significantly over the seasons. The highest amount of rainfall and soil moisture was observed in the cooler months of fall and winter. Lower temperatures increase soil moisture because there is less evapotranspiration, and more biological activity occurs in the summer months (Toy et al. 2002).

Management Implications

Management strategies need to account for seasonal and annual variations in climate and vegetation. These climate and vegetation factors should be addressed in assessing the acceptable level of risk for the management area. Determining threshold levels can aid in proactive planning.

Several thresholds have been identified in past studies (Thurow 1985, Hanselka et al. 2001, and Wilcox et al. 2003). Wilcox et al. (2003) and Thurow (1985) found that exceeding a level of precipitation caused runoff. This study resulted in two threshold levels of precipitation. On the current study site, three (summer and spring) or two centimeters (fall and winter) of precipitation would cause runoff from simulated rainfall plots. In this study 80% of the rainfall events resulted in less than two centimeters of rainfall. Therefore, 20% of the storms could be expected to cause runoff even with the high levels of vegetation and low levels of bare ground. Exposing the soil to these potential storms during construction especially under high soil moisture conditions would accelerate runoff and erosion. Construction during the summer months when storage capacity was seldom reached would probably have lower runoff and sediment losses compared to winter. Also leaving native buffers such as the study area would be beneficial for absorbing the increased runoff and sediment within development areas.

White and Richardson (1995) and Hanselka et al. (2001) proposed a threshold of 134.5-168.1 g/m^2 oven dry weight of residual forage to promote healthy plants and protection for the site on a tall grass prairie. The annual biomass production on an oak-scub shrubland climax community with Tabor fine sandy loam soils should be 151.31 g/m^2 based on NRCS technical guidelines. The current research study averaged 170.61 g/$m^2$of biomass, which is higher than the two recommended rates from the literature. This indicates that there is room for additional use, such as grazing, on this site. However, with increased use, percent of runoff and sediment will increase. The amount of use on the site will depend on the amount of risk assumed. Prescribed fire is another use that could further improve the site. Fire can increase the dominance and palability of some species, such as little bluestem. A cool season burn would be less intense and maintain higher amounts of litter to protect the soil surface. A hotter summer burn would kill more of the woody species, but would increase the risk of soil loss due to increased bareground.

Grazing and prescribed burning are two management practices that could be applied to the study area. The annual total biomass for the watershed study was 170.61 g/m^2, which is above the management threshold estimated by White and Richardson (1995) and Hanselka et al. (2001). Therefore there is room for grazing. However, as biomass, grass and litter decrease, runoff and sediment loss can be expected to increase. At this time sediment loss is very low and some increase would not be detrimental. Fire can increase the palability and basal area on species such as little bluestem. A cool season burn would be less intense and maintain higher amounts of litter protection. A hotter more intense summer burn would reduce more of the woody species, but could increase the risk of runoff from an intense summer storm. Fire can increase the palability and basal area on species such as little bluestem. A cool season burn would be less intense and maintain higher amounts higher amounts of litter protection of the soil surface. A hotter more intense summer burn would reduce more of the woody species, but could increase the risk of runoff from an intense summer storm.

Future Research Needed

The current study is a first step in calculating risk probabilities for the Brazos County, Texas watershed study site. More research is needed to identify climatic profiles and the vegetation thresholds affecting runoff and sediment production under different conditions and land management situations. Current rainfall records for most weather reporting stations are inadequate. More long-term data that records the exact time of storm events throughout their duration is needed to adequately determine long-term duration averages and frequencies. Exact time intervals of storm events would allow for an improved intensity analysis. In addition, different intensities need to be studied with rainfall simulation to better address the relationships between soil moisture, vegetation and intensity to the dependent variables. Then, climate intensities and storm events could be evaluated for better prediction capabilities in a risk analysis.

Rainfall simulations with more variability in cover and bare ground need to be assessed to determine the threshold level of biomass and/or percent of basal vegetation coverage. Different treatments could also be applied to watersheds to adequately determine the threshold level of residual forage for the study site.

A complete set of runoff data on the study watersheds is needed for a better analysis of runoff and sediment relationships to natural rainfall and vegetative characteristics.

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APPENDIX A

CLIMATIC ANALYSIS

A1: Summary Table for Return Periods in College Station, Texas

Return Period	Duration minutes	Duration hour	Precipitation inch	Precipitation cm
1 YR	30	0.5	1.45	3.683
	60	1	1.8	4.572
	120	2	2.1	5.334
	180	3	2.3	5.842
	360	6	2.7	6.858
	720	12	3.2	8.128
	1540	24	3.4	8.636
2 YR	30	0.5	unav.	
	60	1	2.2	5.588
	120	2	2.6	6.604
	180	3	2.75	6.985
	360	6	3.25	8.255
	720	12	3.75	9.525
	1540	24	4.5	11.43
5 YR	30	0.5	2.2	5.588
	60	1	2.7	6.858
	120	2	3.4	8.636
	180	3	3.7	9.398
	360	6	4.3	10.922
	720	12	5.25	13.335
	1540	24	6.0	15.24
10 YR	30	0.5	2.5	6.35
	60	1	3.1	7.874
	120	2	3.8	9.652
	180	3	4.3	10.922
	360	6	5.25	13.335
	720	12	6.25	15.875
	1540	24	7.1	18.034

Summarized from Hershfield (1961).

Return Period	Duration minutes	Duration hour	Precipitation inch	Precipitation cm
25 YR	30	0.5	2.9	7.366
	60	1	3.6	9.144
	120	2	4.5	11.43
	180	3	5.0	12.7
	360	6	6.25	15.875
	720	12	7.5	19.05
	1540	24	8.5	21.59
50 YR	30	0.5	3.25	8.255
	60	1	4.1	10.414
	120	2	5	12.7
	180	3	5.6	14.224
	360	6	6.75	17.145
	720	12	8.5	21.59
	1540	24	9.5	24.13
100 YR	30	0.5	3.5	8.89
	60	1	4.5	11.43
	120	2	5.5	13.97
	180	3	6.3	16.002
	360	6	7.75	19.685
	720	12	93.5	237.49
	1540	24	11.0	27.94

A2: Monthly Precipitation (cm) Probabilities and Quintiles, 1971-2000[1]

Quin	Prob	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANN
Q0	MIN	0.56	0.25	0.74	0.20	1.60	0.23	0.00	0.20	1.27	0.89	2.18	0.58	
	0.1	1.52	1.24	2.41	1.60	3.71	2.06	0.25	0.76	2.29	2.31	3.18	2.18	69.90
Q1	0.2	2.69	2.11	3.45	2.74	5.59	3.43	0.94	1.57	3.73	3.84	4.34	3.38	79.02
Q2	0.4	5.13	11.46	5.33	5.08	9.04	6.17	2.46	3.51	9.07	6.91	6.30	5.64	92.43
	0.5	6.55	4.83	6.32	6.43	10.92	7.75	3.40	4.70	8.10	8.64	7.29	6.88	98.65
Q3	0.6	8.23	5.97	7.42	8.00	13.06	9.53	4.55	6.17	9.91	10.64	8.41	8.28	105.13
Q4	0.8	13.16	9.30	10.46	12.57	19.00	14.73	7.98	10.72	15.11	16.43	11.38	12.27	121.29
	0.9	17.86	12.45	13.21	16.92	24.43	19.63	11.35	15.24	19.94	21.89	14.02	15.95	134.39
Q5	MAX	39.62	24.94	15.42	19.46	28.91	28.24	17.86	27.00	26.09	32.79	23.60	27.23	

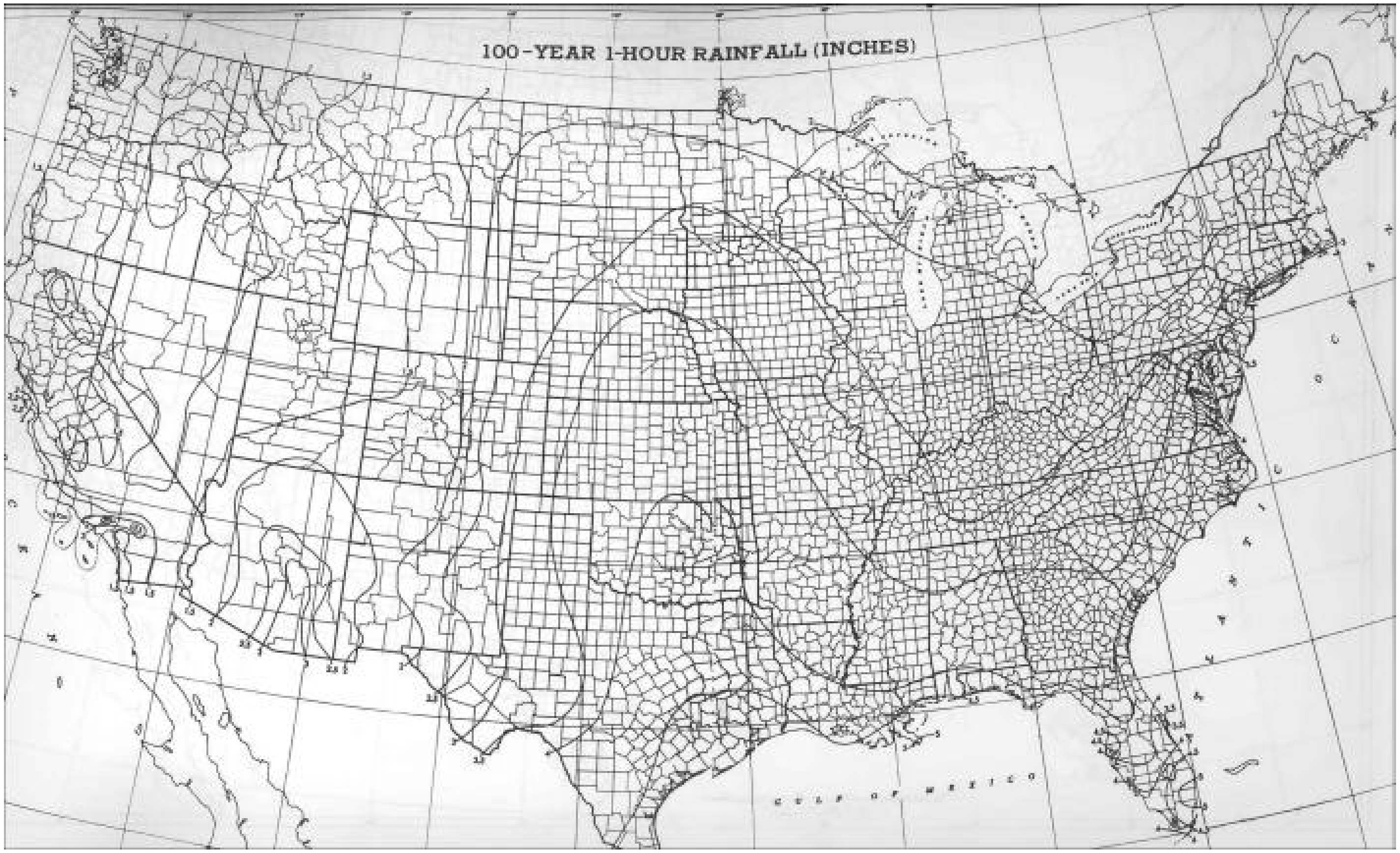
From: NOAA et al. (2002).

Procedures and Explanations for Table A2

The following description explains the computational procedures of the Appendix Table 2 on the previous page from NOAA et al. (2002):

> The precipitation probabilities are the monthly precipitation totals that correspond to the indicated probability levels. The historical precipitation data are based on the 1971-2000 historical sequential monthly precipitation. The historical precipitation data are the adjusted values form the monthly normals as presented in *Climatology of the United States* No. 81.
>
> Computational Procedures: When historical climate dataare accumulated, they generally follow a certain pattern called a statistical distribution. While temperature usually follows a Gaussian or bell-shaped distribution, precipitation does not because it is zero-bounded. Precipitation generally follows a Gamma distribution, where most values are near zero with rapidly diminishing higher values. Thus, the gamma distribution was used to estimate the precipitation probability and quintile statistics. Probabilities are computed for the amount of precipitation expected at fifteen probability levels (0.005, 0.01, 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 0.95, 0.99, and 0.995) for each month of the year and for the annual total. For example, if 1.77 inches corresponds with the 0.20 probability level, that means that on average, 2 out of every 10 years will have 1.77 inches or less of precipitation in that month. It also means that, on average, 8 out of every 10 years will have more than 1.77 inches of precipitation in that month.
>
> The precipitation quintiles show the expected precipitation values at the five quintile levels shown for each of the twelve months: 1. First Quintile (0-20%); 2. Second Quintile (20-40%); 3. Third Quintile (40-60%); 4. Fourth Quintile (60-80%); 5. Fifth Quintile (8-100%). For example, if 2.91 and 4.07 inches would be classified as a second quintile precipitation amount and that month would be considered relatively dry. The firt lone (Q0) shows the precipitation value derived from the historical record. This would be used if a future precipitation observation is less than the 1971-2000 minimum. At the opposite end, Quintile level 5 (indicated with Q5) would be observed if the observed value is more than the 1971-2000 maximum

A3: Example of Hydrologic Frequency Analysis Map, From Hershfield (1961)



APPENDIX B

SOIL PROFILE DESCRIPTIONS

B1: Tabor Soil Series Description

The Tabor series is a member of the fine sandy loam, montmorillontic, thermic family of Udertic Paleustalfs in the order Alfisols. They are very deep, moderately well drained, very slowly permeable soil on nearly level stream terraces and terrace remnants in uplands. Runoff is slow to medium. The soil was formed in clayey and loamy sediments. Slopes range from 0 to 5 percent.

A typical profile of the Tabor series is described as (colors moist unless otherwise stated):

Ap- - 0 to 6 inches; brown (10YR 4/3); fine sandy loam, pale brown (10 YR 6/3) dry; common medium prominent strong brown (7.5 YR 4/6) mottles; moderate medium and fine subangular blocky structure; hard, friable; many fine roots; 5 percent siliceous pebbles; strongly acid; clear smooth boundary.

E- - 6 to 14 inches; brown (10 YR 5/3) fine sandy loam, pale brown (10YR 6/3) dry; common fine distinct dark yellowish brown (10YR 3/4) mottles; moderate medium and fine subangular blocky structure; hard, friable; many fine roots; 6 percent siliceous pebbles; strongly acid, clear wavy boundary. (combined boundaries of Ap and E is 10 to 18 inches).

Bt1- - 14 to 23 inches; brown(10YR 4/3) clay, brown (10YR 5/3) dry; common medium prominent dark red (2.5YR 3/6) and common coarse prominent structure; very hard, very firm; common fine roots; few fine pores; common distinct pressure faces; common pale brown (10YR 6/3) coats on ped faces; few siliceous pebbles; strongly acid; gradual wavy boundary.

Bt2- - 23 to 42 inches; grayish brown (10YR 4/3) clay; many coarse prominent yellowish brown (10YR 5/6) and few fine prominent dark red (2.5 YR 3/6) mottles; weak coarse angular blocky structure; very hard, very firm; few fine roots; common distinct slickensides; many distinct pressure faces; few dark grayish brown (10YR 4/2) clay films on vertical ped faces; 2 percent siliceous pebbles; medium acid clear smooth boundary.

Bt3- - 42 to 57 inches; yellowish brown (10YR 5/6) clay loam, common medium distinct strong brown (7.5YR 4/6) and few fine grayish brown (10YR 5/2) mottles; weak coarse prismatic structure parting to moderate medium angular blocky; very hard, very firm; few fine roots; few fine pores; many continuous very dark grayish brown (10YR 3/2) clay films on ped surfaces and in pores; common distinct pressure faces; few siliceous pebbles; neutral; gradual smooth boundary. (Combined thickness of the Bt horizons is 30-50 inches).

Btg- - 57 to 67 inches; light brownish gray (10YR 6/2) sandy clay loam; many medium prominent yellowish brown (10YR 5/6) and common medium distinct red (2.5YR 4/6) mottles; weak coarse prismatic structure parting to weak medium angular blocky; very hard, very firm; few fine roots; few fine pores; few calcium carbonate concretions; common continuous very dark grayish brown (10YR 3/2) clay films on vertical ped faces; 2 percent siliceous pebbles; neutral; gradual smooth boundary. (0-20 inches).

BCtg1- - 67 to 72 inches; light gray (10YR 7/2) sandy clay loam; common coarse prominent red (10YR 4/6) and common medium prominent brownish yellow (10YR 6/6) mottles; weak coarse angular blocky structure; hard firm; few fine roots; few fine pores; few patchy very dark grayish brown (10YR 3/2) clay films; few distinct brown (10YR 4/3) sand coats; few distinct grayish brown (10YR 5/2) clay films on vertical ped faces; 8 percent siliceous pebbles; neutral; gradual smooth boundary.

BCtg2- - 72 to 80 inches; light gray (10YR 7/1) sandy clay loam; many coarse prominent yellowish red (5YR 5/8) and common medium prominent red (10 YR 4/6) mottles; weak coarse angular blocky structure; hard, friable; few fine roots; few fine pores; few patchy dark grayish brown (10YR 4/2) clay films on vertical ped faces; thick continuous prominent (10YR 6/4) coats on vertical ped faces; few siliceous pebbles; neutral; gradual smooth boundary. (Combined thickness of BC horizons is 0 to 30 inches).

B2: Zachary Soil Series Description

The Zachary series is a member of the fine, montmorillontic thermic family of Udic Paleustalfs in the order Alfisols. They are very deep, moderately well drained, very slowly permeable soils on dissected uplands. The soil formed in neutral to alkaline clayey and loamy sediments. Runoff is slow to rapid and permeability is very slow. A perched water table in the A and upper Bt horizons occurs for a few days to about two weeks after heavy rains. Slopes are mostly 1 to 5 percent, but range from 1 to 8 percent.

A typical profile of the Zachary series is described as (colors are dry unless otherwise stated):

Ap- - 0 to 7 inches; dark brown (10YR 4/3) very fine sandy loam, dark brown (10YR 3/3) moist; weak medium subangular blocky structure; hard, very friable; common fine roots; few fine siliceous pebbles; strongly acid; abrupt smooth boundary. (4 to 10 inches thick).

Bt1- - 7 to 18 inches; mottled dark grayish brown (10YR 4/2) dark reddish brown (5YR 3/3) and dark red (2.5YR 3/6) clay; moderate medium blocky structure; very hard, very firm; common fine roots; continuous clay films on ped faces; slightly acid; clear wavy boundary. (4 to 12 inches thick).

Bt2- -18 to 24 inches; dark brown (7.5YR 4/4) clay, dark brown (7.5YR 3/4) moist; moderate coarse angular blocky structure; very hard, very firm; common fine roots; continuous clay films on ped faces; neutral; clear smooth boundary. (4 to 14 inches thick).

2BCk- - 24 to 36 inches; mottled light yellowish brown (10YR 6/4) and very dark grayish brown (10YR 3/2) sandy clay loam; weak medium subangular blocky structure; slightly hard, firm; few fine roots; common creations of calcium carbonate; moderately alkaline; abrupt irregular boundary. (0 to 23 inches thick).

2Ck- - 36 to 60 inches; thinly bedded light brownish gray (10YR 6/2), dark reddish brown (5 YR 3/3), and light red (2.5YR 6/8) loam; massive; extremely hard, extremely firm; common calcium carbonate concretions; moderately alkaline.

APPENDIX C

STATISTICAL ANALYSIS

A1. Percent Runoff = 42.36 -2.04(x1) -14.89(x2) -20.93(x3) -0.58(x5) +0.15(x6) -1.68(x7)

Source	SS	df	MS
Model	10197.2703	6	1699.54505
Residual	8341.51833	35	238.329095
Total	18538.7887	41	452.165577

Number of obs =	42
F(6, 35) =	7.13
Prob > F =	0.0001
R-squared =	0.5501
Adj R-squared =	0.4729
Root MSE =	15.438

	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
X1	-2.042707	7.449893	-0.27	0.786	-17.16679	13.08138
X2	-14.89128	15.12037	-0.98	0.331	-45.58726	15.80469
X3	-20.92811	9.768131	-2.14	0.039	-40.75847	-0.097745
X4	(dropped)					
X5	-.5802375	.7414125	-0.78	0.439	-2.085385	0.9249098
X6	.1521367	.2098009	0.73	0.473	-.2737817	.5780552
X7	-1.67569	1.265268	-1.32	0.194	-4.244321	.8929407
cons	42.36483	16.76305	2.53	0.016	8.334031	76.39562

A2. Infiltration Rate = 10.97+0.39(x1)+2.84(x2)+3.99(x3) + 0.11(x5) - 0.03(x6) +0.32(x7)

Source	SS	df	MS
Model	369.905499	6	61.6509165
Residual	302.529355	35	8.64369585
Total	672.434853	41	16.4008501

Number of obs =	42
F(6, 35) =	7.13
Prob > F =	0.0001
R-squared =	0.5501
Adj R-squared =	0.4730
Root MSE =	2.94

	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
X1	.3882399	1.418768	0.27	0.786	-2.492011	3.268491
X2	2.838527	2.879542	0.99	0.331	-3.007255	8.684309
X3	3.985455	1.860256	2.14	0.039	.2089347	7.761975
X4	(dropped)					
X5	.110668	.1411956	0.78	0.438	-.1759742	.3973103
X7	-.0289014	.0399548	-0.72	0.474	-.1100139	.052211
X7	.319238	.2409594	1.32	0.194	-.1699355	.8084115
cons	10.97436	3.192377	3.44	0.002	4.493489	17.45523

A3. Sediment Yield = 10.57 +10.27(x4) +11.79(x8) -0.46(x5)

Source	SS	df	MS
Model	2776.75593	3	925.58531
Residual	12863.862	39	329.842616
Total	15640.618	42	372.395666

Number of obs	=	43
F(3, 39)	=	2.81
Prob > F	=	0.0522
R-squared	=	0.1775
Adj R-squared	=	0.1143
Root MSE	=	18.162

	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
X4	10.26593	7.60722	1.35	0.185	-5.121129	25.65298
X8	11.79354	7.923543	1.49	0.145	-4.233341	27.82041
X5	-0.4602155	.4784867	-0.96	0.342	-1.428046	.5076152
cons	10.56835	5.479914	1.93	0.061	-.5158179	21.65253

B1. Percent runoff = 49.70 +0.25(x6) -3.48(x7) -0.42(x9) -0.05(x10)

	SS	df	MS
Model	8560.62763	4	2140.15691
Residual	9978.16103	37	269.680028
Total	18538.7887	41	452.165577

Number of obs	=	42
F(4, 37)	=	7.94
Prob > F	=	0.0001
R-squared	=	0.4618
Adj R-squared	=	0.4036
Root MSE	=	16.422

	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
x7	-3.483422	1.107411	-3.15	0.003	-5.72725	-1.239595
x9	-.4193809	.2023004	-2.07	0.045	-.8292804	-.0094814
x10	-.0460621	.0326399	-1.41	0.167	-.1121968	.0200727
x6	.2499808	.1323182	1.89	0.067	-.0181214	.518083
cons	49.70322	16.03962	3.10	0.004	17.20387	82.20258

regress 9.58 -0.05(x6) +0.66(x7) +0.08(x9) +0.009(x10)

Source	SS	df	MS
Model	310.558956	4	77.6397389
Residual	361.875898	37	9.78042967
Total	672.434853	41	16.4008501

Number of obs	=	42
F(4, 37)	=	7.94
Prob > F	=	0.0001
R-squared	=	0.4618
Adj R-squared	=	0.4037
Root MSE	=	3.1274

	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
x7	.6636976	.2108936	3.15	0.003	.2363867	1.091009
x9	.079906	.0385258	2.07	0.045	.0018454	.1579666
x10	.0087765	.0062159	1.41	0.166	-.0038181	.0213711
x6	-.0475673	.0251985	-1.89	0.067	-.0986242	.0034897
cons	9.577409	3.05456	3.14	0.003	3.388283	15.76653

```
Sediment Yield = 12.77 +.20(x6) -3.36(x7) -0.50(x9) -0.005(x10)
Source |       SS       df       MS              Number of obs =     41
-------------+------------------------------     F(  4,    36) =   1.56
Model    2374.04944     4  593.512361            Prob > F      = 0.2063
Residual 13708.7393    36  380.798315            R-squared     = 0.1476
-------------+------------------------------     Adj R-squared = 0.0529
Total    16082.7888    40   402.06972            Root MSE      = 19.514

----------------------------------------------------------------------
            Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+--------------------------------------------------------
x7    |  -3.364756   2.063419    -1.63   0.112    -7.549563    .8200522
x9    |  -.0506642   .2432845    -0.21   0.836     -.544068    .4427396
x10   |  -.0052307   .0415993    -0.13   0.901     -.089598    .0791366
x6    |   .2030248   .1678888     1.21   0.234    -.1374694    .5435191
cons  |   12.77221   19.81195     0.64   0.523    -27.40827     52.9527
```

C1. Cook-Weisberg test for heteroskedasticity using fitted values

Ho: Costanst variance

Chi2(1)=2.97

Prob>2=0.0849

APPENDIX D

SPECIES LIST

C1: List of dominant species observed in the rainfall simulation plots.

Common Name	Scientific Name
Dotted gayfeather	*L. punctata* Hook
Fall whichgrass	*Digitaria cognata* (Schult.) Pilger
Little bluestem	*Schizacyrium scoparium (Michx.) Nash*
Oldfield threeawn	*Aristida oligantha* Michx
Paspalum	*Paspalum* spp.
Ratail smutgrass	*Sporobolus indicus* (L.) R. Br.
Scibner's rosettegrass	*Dichanthelium oligosanthes* (Schult.) Gould
Silverleaf nightshade	*Solanum elaeagnifolium* Cav.
Switchgrass	*Panicum virgatum* L.
Texas croton	*Croton texensis* (Klotzch) Muell. Arg

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