THE EFFECTS OF JUNIPER REMOVAL ON RAINFALL PARTITIONING IN THE EDWARDS AQUIFER REGION: LARGE-SCALE RAINFALL SIMULATION EXPERIMENTS

A Thesis

by

PHILIP ISAIAH TAUCER

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

May 2006

Major Subject: Biological and Agricultural Engineering

THE EFFECTS OF JUNIPER REMOVAL ON RAINFALL PARTITIONING IN THE EDWARDS AQUIFER REGION: LARGE-SCALE RAINFALL SIMULATION EXPERIMENTS

A Thesis

by

PHILIP ISAIAH TAUCER

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

Approved by:

Chair of Committee, Clyde Munster

Committee Members, Ann Kenimer
Binayak Mohanty
Bradford Wilcox

Head of Department, Gerald Riskowski

May 2006

Major Subject: Biological and Agricultural Engineering

ABSTRACT

The Effects of Juniper Removal on Rainfall Partitioning
in the Edwards Aquifer Region: Large-Scale Rainfall
Simulation Experiments. (May 2006)

Philip Isaiah Taucer, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Clyde Munster

Two experimental rainfall simulation plots in the Edwards Aquifer region of Texas were established to measure the effects of brush clearing on surface and subsurface water movement pathways. Multi-stage rainfall simulations were carried out at a site with *Juniperus ashei* (ashe juniper) cover both before and after brush removal, with three replications of a particular rainfall event for each vegetation condition. Similar simulations were carried out on a plot with a longstanding grass cover. Both plots included trenches at their downhill ends for observation of shallow lateral subsurface flow. Canopy interception was found to represent a major water loss, with interception of 32.7 mm for an average 166 mm, 5.25 hr rainfall event. Brush clearing had little impact on surface runoff, with no overland flow occurring at the juniper plot for either vegetation condition, while 31.9 percent of applied rainfall moved as overland flow at the grass plot. This difference was attributed to differences in the structure and permeability of the epikarst. Brush removal caused significant (90 percent confidence level) reduction in shallow lateral subsurface flow into the trench after brush removal, with 56.7 percent of water reaching the surface entering the trench for the pre-cut condition and only 43.4 percent for the post-cut condition. However, subsurface water movement through other pathways increased from 31.0 to 54.1 percent after brush removal. This additional water, due to removal of canopy interception, could either move off-site through conduit and fracture flow or remain on site as storage in conduits, unconsolidated caliche/marl layers, or in soil pockets.

Two tracer tests with fluorescent dyes were also conducted using simulated

rainfall to assess discrete flow paths discharging into the trench at the downhill end of the juniper plot. Analysis of samples from sixteen outlet locations revealed that not all areas of the plot were connected hydraulically to the trench. Additionally, subsurface flow paths were found to have a high degree of interconnection, linking conduit flow outlets with multiple inlet locations on the plot surface. Conduits showed strong connection with an area surrounding juniper vegetation, with rapid water flow (up to 2.4 m/h) from this area.

ACKNOWLEDGEMENTS

I am deeply indebted to the members of my advisory committee for their help over the past two years. I would like to thank Dr. Clyde Munster and Dr. Brad Wilcox for proposing and developing the rainfall simulator project and for serving as advisors for my graduate research. Their technical guidance and assistance played a very important role in the development of this thesis. Special thanks are also due to Dr. Binayak Mohanty and Dr. Ann Kenimer.

Dr. M. Keith Owens provided and installed a great deal of the equipment used during the study. His continued technical assistance and instruction throughout the course of the study has been greatly appreciated. I would also like to thank the many co-workers who have assisted with data collection and reduction during the course of this project. Much of this study builds on the recent work of my predecessors, particularly Josh Sorenson, Shane Porter, Surajit Dasgupta, and Yuli Surhanoto. I would also like to express my gratitude to all of the people that worked long hours on this project in the field, especially Luke Gregory, Bobby Bazan, Ryan Hill, Gary Nolan, David Bass, and Andrew Weichert.

A number of people provided assistance for the dye tracer portion of this study. Geary Schindel, Stephen Worthington, and Evelynn Mitchell helped in determining dye amounts and analyzing samples. Bev Shade did a remarkable job in data reduction for dye concentrations. Thanks are also due to all of the agencies that supplied the resources and funding that made this study possible. Financial backing was provided by the National Science Foundation, the Edwards Aquifer Authority, San Antonio Water Systems, and the Texas Water Resources Institute. The Texas Parks and Wildlife Department hosted the project site, while BexarMet Water District provided numerous truckloads of water for simulations.

I owe a great deal to my family for the support and advice they have given me throughout my education. I am especially grateful to my wife Anne, who has been a constant source of help and reassurance during my graduate studies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I
INTRODUCTION AND LITERATURE REVIEW

Synopsis

The topic of groundwater quality and supply has long been of interest to both researchers and agricultural industries, and the use of groundwater has been a key factor in allowing high levels of both urban and agricultural development throughout the world. However, aquifers do not offer limitless water supplies, nor are they immune to depletion from overpumping and contamination by pollutants. While these problems often draw the greatest amount of attention in terms of sustainable groundwater supply, humans impact the water cycle and ultimately groundwater supply in a number of other ways. One potential anthropogenic factor drawing increasing interest from hydrogeologists, ecologists, and resource managers is large-scale human alteration of plant cover.

It is a well-known principle in landscape ecology that the type and density of vegetation directly influences the amount of evapotranspiration and plant canopy interception in an area. This, in turn, impacts soil moisture, surface runoff, lateral subsurface water movement, and deep drainage to groundwater. These factors, when combined with properties such as soil composition, geology, rainfall patterns, and topography, play important roles in determining the distribution of water within local and regional water budgets. In arid and semi-arid regions where maintaining reliable water supplies is extremely important, determining the impacts of vegetation on water availability is essential.

Over the course of the past two centuries, extensive areas of semi-arid landscapes that were once dominated by herbaceous grasslands have gradually been converted to shrublands (or mixed grassland/shrubland vegetation) through a process commonly called "woody plant encroachment." This extensive change has been largely attributed to human influence by a number of sources for well over half a century. An early

---

This thesis follows the guidelines of *Hydrological Processes*.

historical review of brush encroachment by Humphrey cited research as early as the 1930s indicating largely anthropogenic causes. Overgrazing was generally considered by early investigators to be the primary factor in shrub encroachment, with heavy livestock grazing pressure reducing much of the natural grass cover and removing competitors to woody plants. Early research also implicated aggressive fire suppression, noting that fires have long been known as a tool to maintain prairie ecosystems and as an agent capable of killing woody plants (Humphrey 1958). The findings of more recent studies (Archer 1994, Van Auken 2000) continue to support these suggestions.

Unfortunately, the effects of extensive woody plant encroachment on regional water budgets are complex and are not yet thoroughly understood. Much evidence, both anecdotal and scientific, suggests that removal of brush species may increase availability of groundwater for streamflow and aquifer recharge. Work by Dugas and Mayeux (1991) and Dugas et al (1998) on honey mesquite (*Prosopis glandulosa*) and ashe juniper (*Juniperus ashei*) found some impact of brush cover on evapotranspiration, but with only small increases in water availability occurring for short durations. However, computer-based modeling studies such as those by Bednarz et al (2000) and Wu et al (2001) indicate the potential for large water yield increases under a properly designed brush management program. Most recently, a modeling study by Afinowicz (2004) has shown increased surface runoff, baseflow, and deep aquifer recharge in response to clearing heavy brush. In spite of the lack of consensus on the subject and limited knowledge from field studies, the State of Texas has established brush control programs to counteract woody plant encroachment and increase water supplies. The implications of this program are significant when considering that over $30 million has been appropriated for brush control projects in Texas in recent years (TSSWCB 2004).

Brush and water yield

The basic concept behind using brush removal as a method for increasing water yield is that converting vegetation cover with high evaporation and transpiration rates to species that use less water may increase water yield (Thurow et al 2000), such as by replacing deeply-rooted species with shallow rooted species (Carlson et al 1990). For humid landscapes, vegetation alteration may cause significant changes in the water cycle (Wilcox 2002). However, because the efficiency of this vegetation alteration process increases with annual precipitation, drier landscapes may not be as effective as other areas for increasing water yield (Graf 1988). In some drylands, such as southwestern chaparral rangelands, woody plant control is linked to increases in streamflow (Wilcox 2002). In others, such as pinyon-juniper communities in Arizona and Utah, brush removal typically does not impact water yield (Wright et al 1976). In general, the potential for increasing water yield through brush control exists for areas with annual precipitation of approximately 450 mm or greater (Hibbert 1983, Thurow et al 1987). Vegetation management for increased water yield may be a viable option on less than 1 percent of western rangelands (Hibbert 1983). There has been some suggestion that honey mesquite removal could increase water yields (Dugas and Mayeux 1991, Weltz and Blackburn 1995) and that increased ashe juniper populations have reduced recharge and stream flow (Dugas and Mayeux 1991); these assertions continue to be hotly debated and are far from universally accepted as reliable water management strategies for Texas rangelands. Several factors may influence the likelihood of increased water yield from brush control in Texas, including average precipitation, shrub density, runoff and streamflow generation characteristics, and canopy interception (Wilcox 2002). Brush control is unlikely to impact water yields in areas with low subsurface water movement (TAES 2005). There is some potential for increased water yield on juniper rangelands in Texas due to their high interception capacity and tendency to be found in areas with shallow soils and permeable parent materials creating the possibility of subsurface flow (Wilcox 2002). One such area is the Edwards Plateau, where some studies have documented increased water yield following brush removal (Kreuter et al 2004). However, even for this highly permeable landscape, which contains the karst Edwards Aquifer, one must consider the impacts of local geology and soil conditions, brush clearing method, extent of clearing, and scale of observation on water yields.

Brush encroachment history

The replacement of grassland vegetation by encroaching brush species in rangelands is occurring in a number or locations worldwide, with widespread changes in southeast Asia, Africa, Australia, and North and South America during the past century (Archer 1994, Archer et al 2001). This is particularly important due to the potential for woody plant encroachment to adversely impact approximately 20 percent of the world's population (Archer et al 2001). In North America, alteration of native vegetation has been documented for numerous locations throughout the southwestern United States. Unfortunately, the amount of data to constrain the history of this vegetation change is limited (Bhark and Small 2003) and in many cases may be based on location-specific personal accounts of travelers and early settlers. Although some of the vegetation types taking over grasslands represent introduced species (including members of the genus *Tamarix*, also known as salt cedar), many are native species from preexisting adjacent communities (Van Auken 2000). Many of the brush species extending in range are members of the genus *Juniperus,* whose increasing range and density have impacted roughly 16.6 million ha in the Intermountain West and an additional 8.9 million ha in Texas. Overall, approximately 40 million ha of Texas rangeland is dominated by woody shrubs and tree growth (Carlson et al 1990). Many of these species, including ashe juniper (*Juniperus ashei*), were originally confined to steep slopes and rocky outcrops (Owens 1996, Van Auken 2000, Miller et al 2000) but have spread downslope into grasslands (Van Auken 2000). In Texas, this increase has been especially pronounced for the last 50 to 80 years for mesquite (*Prosopis glandulosa*), redberry juniper (*Juniperus pinchotii*), and ashe juniper (Wilcox 2002, Olenick et al 2004).

A number of factors have been cited as potential causes of woody plant encroachment, many of which are attributable to human influence. An early historical review of brush encroachment by Humphrey (1958) cited research as early as the 1930s indicating largely anthropogenic causes. In many cases, there seems to be a strong linkage between woody plant encroachment and the development of the livestock industry in the Southwest (Archer 1994, Van Auken 2000). While large herbivores such as bison inhabited rangelands prior to European settlement and the development of the cattle industry, the ability to roam freely meant that destructive and long-lasting impacts on vegetation composition were rare and locally isolated. The confinement of livestock led to destructive grazing on many rangeland areas. In some parts of the southwestern United States livestock densities increased to a level where drought conditions or severe winters could lead to mortality rates of nearly 85 % (Smeins et al 1997).

Alteration of fire frequency and suppression of natural fires is also commonly cited as a cause of brush encroachment (Humphrey 1958, Van Auken 2000). Fire frequency, intensity, and timing are among a number of factors controlling the relative proportion of the landscape vegetated with ashe juniper (Fuhlendorf et al 1997), and it has been suggested that in the absence of periodic disturbances such as fire much of the Edwards Plateau could succeed to nearly closed canopy brush stands (Smeins et al 1997). The timing of woody plant encroachment in some southern areas appears to be associated with fire suppression in addition to the aforementioned increase in cattle ranching (Van Auken 2000). Fire suppression has been especially active since World War II, and heavy grazing by domestic livestock has reduced fine fuel loads (Miller et al 2000). Prior to European settlement, fires ignited by lightning as well as those intentionally set by Native Americans minimized woody plant presence in southwestern grasslands (Burkhardt and Tisdale 1976). Although Native American use of fire as a tool for vegetation and wildlife management has not been explicitly proven for the Edwards Plateau, it is well documented in other areas and there seems to be little reason to doubt its occurrence for the Plateau as well (Smeins et al 1997).

Rangland water cycle

Before understanding how brush encroachment alters the partitioning of rainfall, one must understand the basic movement pathways in the rangeland water cycle. Rangeland basins contribute most of the surface flow and recharge in the southwestern United States (Carlson et al 1990). Runoff, most of which occurs as flood flow, typically makes up less than ten percent of rangeland water budgets (Wilcox et al 2003), although overland flow is the predominant contributor to storm channel runoff in arid and semi-arid areas (Yair and Lavee1985). Runoff in rangelands may take several forms, moving as Horton overland flow, saturation overland flow, groundwater flow, or shallow subsurface flow (Yair and Lavee 1985, Wilcox 2002). Horton overland flow results from rainfall rates greater than soil infiltration capacities (Kirby 1985) and dominates runoff processes in drylands (Graf 1988). Saturation excess overland flow is caused by rainfall on saturated soil (Kirby 1985), which is relatively rare in semi-arid settings (Wilcox et al 1997) but may occur due to rising groundwater levels or a perched zone above an impermeable layer (Wilcox et al 2003, Wilcox et al 1997).

Shallow lateral subsurface flow is lateral movement of water through near-surface soil or rock horizons and can be generated by matrix or macropore flow paths. Macropores may result in direct lateral flow or may cause lateral flow by contributing to saturated zones above low-permeability bedrock (Newman et al 1998). Subsurface preferential flow pathways may also impact water movement. However, the presence of macropores is not a guarantee that preferential flow will occur (Helling and Gish 1991). Macropore-associated preferential flow is governed by a number of factors, including pore continuity and density and water fluxes (Devitt and Smith 2002), and macropore flow is typically greater in structured, fine-grained soils than in coarse sediments (Scanlon et al 1997).

Deep drainage is the movement of water downward past the bottom of the root zone and due to thick vadose zones in arid and semi-arid environments may not always be equated with recharge (Seyfried et al 2005). For semi-arid rangelands recharge is generally low (Wilcox et al 2003, Wilcox 2002) and in many arid and semi-arid landscapes may not occur (Seyfried et al 2005). However, the probability of deep water movement is increased in areas with soils conducive to permeability or with fractured bedrock (Seyfried et al 2005, Wilcox 2003).

Evapotranspiration (ET) consists of water transpired from vegetation and evaporation from both the soil and plant surfaces (Ward and Trimble 2004), and represents the largest single water loss from rangelands (Dugas and Mayeux 1991). For arid and semi-arid environments it roughly equals precipitation over multi-seasonal periods (Kurc and Small 2004). In semi-arid rangelands, it can account for as much as 80 to 95 percent of the water budget (Wu et al 2001). Because potential evapotranspiration exceeds precipitation in these landscapes, true ET in drylands is often limited by soil moisture availability (Kurc and Small 2004). This makes storage of large amounts of water in arid and semi-arid regions unlikely (Seyfried et al 2005).

Vegetation, whether brush or herbaceous matter, also plays a direct role in the partitioning of rainfall in rangelands. Rainfall striking vegetation may be intercepted, or captured by the plant canopy or litter, and evaporated. For rangeland systems, this water loss is generally between 20 and 40 percent of precipitation but may vary between 1 and 80 percent (Wilcox et al 2003). In addition causing evaporative losses, interception reduces the impact of raindrops on the ground surface, reducing the dislodging of soil particles which can clog soil pores (Weltz and Blackburn 1995). Some of the water intercepted by the plant canopy may also flow down the plant as stemflow. Stemflow results in rapid concentration of high water volumes at the base of vegetation and could provide an important source of moisture in semi-arid landscapes (Martinez-Meza and Whitford 1996). This flow may also be nutrient enriched (Thurow and Hester 1997). Stemflow depends on vegetation type, morphology, and the distribution of cover (Martinez-Meza and Whitford 1996).

Vegetation patches in rangelands also act as reserves for moisture and nutrients (Ludwig and Tongway 1997), obstructing and trapping runoff, sediments, and nutrients from flow generated in canopy interspaces. These inputs may create added growth within the vegetation cluster, increasing the capacity to trap nutrients (Ludwig et al 2005). This focusing of water into vegetation clusters may be necessary for growth in arid and semi-arid areas, as soil moisture would be insufficient for biological requirements if rainfall were spread evenly over such areas (Ludwig and Tongway 1997).

Impacts of brush on range

Due to the intimate connection between vegetation and water movement on rangelands, alteration of plant cover may have a number of impacts on the hydrologic cycle; Scanlon et al (1997) asserts that vegetation may be the most significant control on desert soil water movement. Because overland flow is such an important part of the rangeland water budget, studies of brush encroachment often examine how brush species influence surface runoff. The primary mechanism by which brush species impact surface runoff is through alteration of soil infiltration, which may be increased or decreased (Huxman et al 2005). In shrubland systems, infiltration rates are typically highest under shrubs and trees and lowest for bare ground (Thurow et al 1988), although this is not true for all situations (Bhark and Small 2003). Shrubs may alter infiltration capacity through the addition of leaf litter, which improves soil structure and maintains large pores (Thurow and Hester 1997) as well as through root action (Wilcox 2002). In addition, litter dissipates rainfall energy and shields the ground surface from soil detachment (Hester et al 1997), which might otherwise clog surface pores and increase runoff (Weltz and Blackburn 1995). Although infiltration may increase under shrub canopies, shrublands are often associated with more overland flow than grasslands (Bhark and Small 2003). In many cases this high runoff is generated not within the canopy but in the bare interspaces between plants (Schlesinger et al 1999, Reynolds et al 1999). In some situations shrub litter may obstruct interspace runoff and act as a sink for overland flow (Thurow and Hester 1997, Bhark and Small 2003). However, in some cases the conversion of grasslands to shrub growth reduces the efficiency of vegetation patches as runon sinks (Wilcox et al 2003), with runoff generated in interspaces tending to travel through other interspaces and bypassing vegetated areas (Seyfried and Wilcox 1995, Wilcox et al 2003).

Woody vegetation also influences the evapotranspiration component of the rangeland water budget. Woody cover can alter evapotranspiration due to higher interception and transpiration in woody vegetation than in grassland (Wu et al 2001). Woody plants tend to have longer active seasons than herbaceous plants and impact soil water year round (Huxman et al 2005, Wu et al 2001). The deeper roots of shrubs enable them to continue transpiration under low soil moisture conditions (Kurc and Small 2004). Additionally, bare soils, which provide a surface for direct evaporative losses, generally occupy a greater proportion of shrublands than grasslands (Kurc and Small 2004).

Juniper vegetation in particular has great potential for impacting evaporative water losses. Juniper can transpire throughout the year, is capable of withdrawing water from drier soils than grasses, and provides a greater surface area for water evaporation from its vegetation surfaces and litter (Thurow and Hester 1997). Compared to live oak, another tree species common on the Edwards Plateau area, ashe juniper has a leaf area index three times greater than that of the oak and transpires much more water on a daily basis; a mature ashe juniper may transpire up to 125 liters per day, while a mature oak of similar size uses 72 liters per day (Owens and Ansley 1997). On an annual basis a mature ashe juniper can transpire 305 to 432 mm of water per year (TAES 2005). This heavy water use may not harm the competitive ability of ashe juniper, as it is able to maintain active gas exchange under water-limited conditions (Owens 1996).

The process of canopy interception is closely related to evapotranspiration, as water captured by vegetation canopies can later be directly evaporated from leaf and stem surfaces. Both grass and shrubs intercept a significant portion of ambient rainfall (Weltz and Blackburn1995). In some cases with heavy herbaceous cover interception losses may match or exceed those of brush, but in many cases evergreen shrubs such as juniper display higher interception due to their evergreen nature and high leaf area (Wilcox et al 2003). Work by Thurow et al (1987) at Sonora, TX on herbaceous plant interception found that sideoats grama may intercept 18.1 percent of the annual water budget, while curlymesquite intercepts 10.8 percent of annual rainfall. Interception by tree canopies is species dependent and may be influenced by rainfall intensity (Owens and Lyons 2004). Domingo et al (1998), in an analysis of desert shrubs, found interception losses of 21 percent for *Retama sphaerocarpa* and 40 percent for *Anthyllis cytisoides*. Návar and Bryan (1990) documented interception losses of 27.2 percent for

Acacia farnesiana / *Prosopis laevigata* vegetation in northeastern Mexico. For live oak (*Quercus virginiana*) on the Edwards Plateau, interception losses as high as 45 percent have been documented, with 25.4 percent of rainfall intercepted by the canopy and an additional 20.7 percent lost to litter (Thurow et al 1987). Ashe juniper intercepts a large fraction of annual precipitation; Thurow and Hester (1997) found 36.7 percent of gross precipitation lost to ashe juniper. Owens and Lyons (2004) found similar behavior, with 40 percent of annual precipitation intercepted and lost to evaporation.

Stemflow focuses water application to the bases of trees or shrubs, resulting in rapid concentration of large volumes of water (Martinez-Meza and Whitford 1996). The amount of water moving as stemflow is dependent on precipitation characteristics, vegetation type, leaf type and position, bark roughness, stem area and angle, and tree size (Martinez-Meza and Whitford 1996). Stemflow in arid and semi-arid landscapes varies widely by species. A stemflow value of 0.6 percent of bulk preceipitation has been documented for *Acacia farnesiana* and *Prosopis laevigata* associations in northeastern Mexico, with *Diospyrus texana* in the same area having 5.6 percent stemflow. Skau found stemflow in Utah and alligator juniper in Arizona to be between 1 and 2 percent of precipitation (1964). For live oak on the Edwards Plateau, stemflow has been observed to focus as much as 222 percent of annual precipitation near the base of trees (Thurow et al 1987). The stemflow contribution may be even more pronounced for ashe juniper. One study of ashe juniper on the Edwards Aquifer found stemflow accounting for 2 percent of rainfall moving as stemflow at the 10 mm precipitation level and 4 percent at high rainfall levels (Owens an Lyons 2004). Another study on ashe juniper found 5.1 percent of precipitation moving as stemflow, leading to concentration of 462 percent of annual precipitation at the base of the trunk (Thurow and Hester 1997).

Shrubs can also alter subsurface water movement. Shrub-linked preferential flow is known to occur in some arid and semi-arid landscapes (Seyfried et al 2005); preferential flow paths under brush include root systems and animal burrows (Devitt and Smith 2002). This channeling of water to deeper roots by brush may provide the shrubs with a means of functioning during drought conditions (Seyfried et al 2005). In some situations the redistributed water reaches great depths. For example, water moving along the soil-root interface of Australian mallee vegetation may be stored as deep as 28 m (Nulsen et al 1986). The depth of water movement under shrubs is a function of shrub canopy and root distribution (Martinez-Meza and Whitford 1996) and has been documented to be generally greater for higher rainfall application rate, large shrub size, wet antecedent conditions, and concentration of rainfall into a single large event (Devitt and Smith 2002).

Impacts of brush on other species

The encroachment of woody plants into grasslands by its nature causes significant decreases in herbaceous production. This process is particularly well-known for juniper species. Increasing juniper cover tends to correspond with a decrease in herbaceous cover (Thurow et al 1997), and in some circumstances juniper may virtually eliminate understory growth (Davenport et al 1998). Grazing capacities in central Texas have been reduced from 1 animal unit / 6 ha to 1 animal unit / 20 ha due to ashe juniper encroachment (Wright et al 1982). This decline in herbaceous understory has been associated with a number of factors, including canopy shading, water interception, litter accumulation, and allelopathic effects (Schott and Pieper 1985). Shading and deep litter accumulation appear to be the primary constraints on herbaceous growth (Smeins et al 1997) Under unbrowsed trees, the hydrophobic litter layer can limit germination of herbaceous species (Fuhlendorf et al 1997) because moisture can run off or dry quickly (Smeins et al 1997). Fortunately, it appears that at least to some extent brush removal reverses the effects of brush on herbaceous production; an increase in herbaceous production from nearly 0 to 1,400 kg/ha following chemical brush treatment has been observed for western juniper (Thurow et al 1997).

Juniper vegetation possesses a number of other attributes which enable it to out-compete other species once established. Juniper shrubs maintain deep and lateral roots as well as a dense root mat near the soil surface, enabling them to compete for water in canopy and interspace areas and use water inaccessible to herbaceous competitors

(Thurow and Hester 1997). In at least one case ashe juniper has been documented to receive nearly a quarter of the water for growing season transpiration from a depth of greater than 7 m (Jackson et al 2000). Some brush species also have exceptionally low pressure limits for extraction of soil water (Seyfired et al 2005), enabling them to gather moisture under low soil moisture conditions. Although sometimes overlooked, juniper has considerable reproductive advantages as well. While the seed bank of ashe juniper displays low viability and germinability (Owens and Schliesing 1995), a large ashe juniper may, under favorable conditions, produce between 100,000 and 250,000 berries per year (Smeins et al 1997). Successful longterm juniper management requires consideration of seed input and reduction of existing seed stock (Owens and Schliesing 1995).

Texas brush studies

Several field studies in Texas have examined the effects of upland brush vegetation and brush clearing on local hydrologic cycles. A number of studies have focused on the effects of brush treatment methods on sediment yields and surface runoff. Wright et al (1976) performed six paired watershed studies on the effects of prescribed burning after tree dozing on sediment, water yield, and water quality in the north end of the Edwards Plateau. Level areas did not experience adverse effects, but moderate and steep slopes showed increased erosion losses, runoff changes, or decreased water quality. These effects lasted 9 to 15 months on moderate slopes and up to 30 or more months on steep slopes (Wright et al 1976). A subsequent study found that herbaceous seeding of steep slopes reduced soil losses by 78 to 93 percent and decreased the time required to stabilize soil loss and overland flow and restore water quality (Wright et al 1980). More recently, Hester et al (1997) examined the hydrologic effects of fire on juniper, oak, bunchgrass, and shortgrass vegetation. Prior to burning, terminal infiltration rates were highest for oak and juniper, with infiltration rates significantly reduced after burning for oak, shortgrass, and bunchgrass vegetation. Improved soil structure under the juniper prevented a significant decrease in terminal infiltration rate.

After burning, erosion increased significantly for all four vegetation types (Hester et al 1997).

Other water budget components and relationships have also been examined. Richardson et al (1979) established two small (3.5 to 4.1 ha) plots near Sonora, TX in areas with mixed live oak, shin oak, ashe juniper, redberry juniper, and honey mesquite cover. The plots also included a herbaceous cover of forbs, shortgrasses, and midgrasses. Woody plants were removed from one of the plots by root plowing. The researchers determined that removal of the brush vegetation resulted in a 20 percent reduction in surface runoff, due to surface storage in large depressions created by the root plowing process. Interestingly, for the plots examined antecedent moisture played little role in determining the amount of runoff from a given rainfall event. A similar study in the Blackland Prairie examined plots originally vegetated with honey mesquite and herbaceous growth, with the woody growth killed on one plot using a chemical treatment. Evapotranspiration was measured for both plots before and after brush treatment, with similar ET from both plots prior to brush treatment. Subsequent to chemical application, evapotranspiration from the treated site decreased approximately 8 cm per year (Richardson et al 1979).

Another study by Carlson et al (1990) focused on the effects of honey mesquite on the Rolling Plains of Texas. Nine tree-scale plots (15.0 to 26.7 m^2) were monitored using nonweighable lysimeters, with honey mesquite left intact on three plots, mesquite removed from three plots, and both mesquite and herbaceous cover removed from the remaining plots. Average soil moisture in the upper two meters of the soil profile was greatest in the bare ground plots. Runoff was also greatest on bare ground, with little difference between the mesquite and mesquite-herbaceous plots. Evapotranspirative losses from both mesquite and mesquite-herbaceous covers were similar, with approximately 12 percent greater losses than bare ground evaporation except in a low rainfall year. Rangeland brush removal was concluded to have no effective net change on deep drainage, evapotranspiration, or runoff when followed by an increase in herbaceous cover (Carlson et al 1990).

Dugas and Mayeux (1991) focused on the evapotranspiration component of the mesquite rangeland water budget near Throckmorton, Texas. Bowen ratio / energy balance ET measurements were taken for two adjacent 4 hectare areas, one with herbaceous cover after mequite treatment with diesel and another with mixed herbaceous and honey mesquite cover. Honey mesquite provided 15 percent of the cover and 38 percent of total ET for the untreated plot. Differences in evapotranspiration between the untreated and treated plots were greatest during dry conditions, with little difference immediately following precipitation. Overall, evapotranspiration from the untreated plot was only slightly greater than for the treated area due to an increase in herbaceous cover on the treated plot subsequent to mesquite control. The authors concluded that the site's low potential for runoff and recharge made increased water yields through mesquite control unlikely, but suggested that changes might occur for other sites or for treatment followed by herbaceous crop management (Dugas and Mayeux 1991).

Dugas, Hicks, and Wright (1998) studied evapotranspiration and runoff in ashe juniper vegetation in the Edwards Aquifer area using Bowen ratio / energy balance methods. ET readings were monitored for a five year period at two 15 hectare sites, one with juniper vegetation cut after nearly two years and the other with juniper vegetation left untreated. Due to limited runoff data, comparison of runoff for the treated and untreated plots was inconclusive. For the post-treatment period, removal of juniper resulted in an average decrease in ET of 0.07 mm/d, with the difference peaking after two years and water yields decreasing after three years. The study did note that for areas with less permeable soils and more moisture storage an increased herbaceous response after clearing would likely result in less change in evapotranspiration. Interestingly, for this study area ET accounted for only 65 percent of precipitation (Dugas et al 1998); this value is quite low for a semi-arid rangeland system.

Owens and Lyons (2004) monitored ashe juniper canopy and litter water interception for 2700 rainfall events across ten locations on the Edwards Plateau during a three year period. Overall, juniper canopies intercepted 35 percent of precipitation, with another five percent intercepted by the litter layer. Interception losses varied with rainfall amount and intensity, with very high interception for smaller events (60 percent of rainfall for a 12.5 mm, 19 hr storm) and lower interception for larger events (20 percent for a 71 mm, 15 hr storm). The relationship between rainfall amount and percentage of interception was modeled as an exponentially decreasing function. Storms of less than approximately 25 mm were found to be ineffective for increasing soil moisture, with nearly 83% of rainfall events falling below 0.5 inches. The study notes significant differences in interception losses among the ten sites, with differences in tree morphology suggested as a probable cause for variability in losses (Owens and Lyons 2004).

Wu et al (2001) modeled the effects of various brush control strategies on the water yield of the Cusenbary Draw basin on the Edwards Plateau using the SPUR-91 hydrologic model. A complete lack of brush management resulted in a 35 percent decrease in water yield. A simulation of a hypothetical cost-share clearing program with least-cover areas on 40 percent of range sites reduced to 3 percent cover resulted in a 43 percent increase in water yields. Location and soil properties played a significant role in results, with a similar cost share program potentially increasing yield 50 percent on sites with deep soil and high forage value and 100 percent on sites with shallow soils and high water yield potentials. Modeling results suggested that brush removal must reduce cover below a threshold value of 20 percent to effectively alter water yields (Wu et al 2001).

Another modeling study prepared for the Texas State Soil and Water Conservation Board used the SWAT model to simulate the hydrology of the Edwards Aquifer area to determine relationships between changes brush cover and shifts in the proportion of rainfall taking the form of runoff. None of the sub-basins studied exhibited decreasing runoff as a percentage of precipitation. While three of the sub-basins were suggested for further analysis, none were found to be promising areas for increased water yield through brush management (HDR 2000). Another study on brush control in the Edwards Aquifer area using the SWAT model found considerable increases in water yield for a hypothetical brush control program, with increases of from approximately 80 to 170,000 gal/treated acre/year for 26 to 45 percent brush removal for the sub-basins examined (Bednarz et al 2001).

More recently, Afinowicz (2004) investigated the effects of brush clearing on the North Fork of the Upper Guadalupe River basin (NFUGR) using a modified SWAT model. For the simulation period, removal of heavy brush caused the greatest decreases in ET and resulted in increased surface runoff, baseflow, and deep recharge. Evapotranspiration was reduced by an average of 46.6 mm/y for complete removal of heavy and moderate brush covers.

The Edwards Aquifer

The Edwards Plateau region of Texas, a broad, gently rolling upland region, is one of the largest continuous karst landscapes in the United States (Smith and Veni 1994). Its eastern portion contains the Edwards Aquifer, which extends from north of Uvalde to near the Austin area in a band approximately 250 km long and from 8 to 50 km wide (Dugas et al 1998). The aquifer contains several major functional zones, including a contributing catchment on the Edwards Plateau, a recharge area in the Balcones fault zone, and a confined area of both fresh and saline water zones. The Edwards Aquifer is also one of the most productive carbonate aquifers in the United States, with large porosity and high permeability due to limestone dissolution and the formation of a cavernous network (Maclay 1995). Karst landscapes are derived primarily through chemical erosion and are often characterized by sinkholes, caves, and sinking streams; permeability may span orders of magnitude and include subsurface conduits / streams. While the amount of water stored in conduits is relatively small, 94 to 99.7 percent of water in karst systems moves through conduits over time (Veni 2004). Dye tracer testing in the Barton Springs segment of the aquifer has documented flow velocities of approximately 6.4 to over 11 km/day under moderate and high groundwater flow conditions (BS/EACD 2003).

In spite of such rapid water movement, the Edwards Aquifer is not immune from overuse. It provides the primary source of water for San Antonio, Austin and many other cities (Wu et al 2001) and has been designated as a "sole source" water supply for San Antonio by the U.S. Environmental Protection Agency (Maclay 1995). Populations in the area are increasing, with a 25.2 percent population growth in San Antonio between 1990 and 1998 and a 47.7 percent growth in Austin and San Marcos from 1990 to 2000; the population of the Edwards Plateau is projected to increase 88 percent from 1995 to 2030 (Kreuter et al 2004). In recent years, spring flow and pumping discharge has exceeded aquifer recharge several times (Dugas et al 1998). The number of new wells constructed each year is increasing due to irrigation of more land in Uvalde, Medina, and Bexar counties (Maclay 1995).

Scope and objectives

In the Edwards Aquifer region of Texas, which includes the rapidly-expanding city of San Antonio, the potential for increased water yield through brush management is unknown. While some field investigations of plant-water cycle interactions have been carried out in the area, the rangeland water budget of the region includes a number of components that have not yet been studied in great detail. For that reason, this study has sought to take a comprehensive approach to the analysis of brush control by simultaneously examining many potential water movement pathways, with the major goal of improving scientific understanding of the effects of juniper clearing on the hydrology of the Edwards Aquifer region. In order to meet this goal, the project was designed to address the following objectives:

(1) Determination of which components of the rangeland water budget (canopy and litter interception, runoff, evapotranspiration, throughfall, stemflow, lateral subsurface flow, soil moisture, deep recharge, etc.) are active during precipitation events at a large plot scale in a juniper landscape.

(2) Quantification of how rainfall is proportioned among these different components and how the proportion responds to rainfall amount for both undisturbed and cleared conditions.

(3) Characterization of shallow subsurface flow pathways for the project plot.
(4) Analysis of the interactions between brush vegetation and subsurface flow paths.
(5) Assessment of the potential for increasing human-accessible water yield through juniper removal in the Edwards region based on collected data.

Support for brush control programs is based on the assertion that invasive brush species result in an overall reduction of human-available water (runoff, streamflow, and aquifer recharge) in comparison to natural grassland/savanna vegetation. Earlier studies of brush control in the Edwards Aquifer region have focused primarily on canopy interception and evapotranspiration (ET), which constitute a considerable portion of the water budget in arid and semiarid landscapes. However, brush species alter other factors such as topography, infiltration capacity, and spatial distribution of moisture which play a role in the partitioning of water within local and regional water budgets. Additionally, for the Edwards Aquifer region, studies have shown surprisingly low ET (≈ 65% of precipitation) values for a semiarid landscape (Dugas et al 1998). As such, examination of only a few factors of the water budget leaves a great deal of uncertainty in terms of potential enhancement of water yield. Thus, this project has sought to address this uncertainty by monitoring multiple hydrologic factors during natural and artificial rainfall events to develop detailed water budgets for a representative large plot scale simulation site. Water budgets have been determined for the site both with and without juniper cover, with a comparison of the two conditions revealing impacts of woody plant removal. It is hoped that the results from this study, along with those from a new companion site, will encourage similar studies throughout the Edwards Aquifer region. Furthermore, it provides a potential framework on which to base similar studies in other semi-arid brush landscapes which have traditionally been examined only in terms of evapotranspiration.

CHAPTER II
EFFECTS OF BRUSH REMOVAL

Overview

Conversion of grassland vegetation to shrublands by encroaching species is occurring in a number of locations worldwide (Archer 1994, Archer 2001). This alteration includes both introduced species and native species from adjacent communities (Van Auken 2000). Brush encroachment in the southwestern United States is often associated with anthropogenic causes, including development of the livestock industry and active suppression of rangeland fires (Humphrey 1958, Archer 1994, Van Auken 2000). The issue of brush encroachment is well known in Texas, where brush and tree growth dominates approximately 40 million ha of Texas rangelands, including 8.9 million ha impacted by members of the genus *Juniperus* (Carlson et al 1990). The effects of this vegetation on the hydrologic cycle of Texas rangelands are not known. Some brush species are known to use large amounts of water. For example, mature *Juniperus ashei* (ashe juniper) have been documented to transpire up to 125 liters of water per day (Owens and Ansley 1997). Brush species can also alter other aspects of rainfall partitioning as well. Soil infiltration capacities may be altered by the addition of leaf litter (Thurow and Hester 1997) and by root action (Wilcox 2002). These changes in infiltration capacity are also the primary mechanism by which brush impacts runoff (Huxman et al 2005). Some evergreen shrubs may also intercept a higher percentage of precipitation than herbaceous species (Wilcox et al 2003). Some of this intercepted water may also become stemflow, which focuses large volumes of water at the base of trees and shrubs (Matinez-Meza and Whitford 1996). One study documented application of 4.6 times the annual rainfall total at the base of ashe juniper vegetation due to stemflow (Thurow and Hester 1997). Shrub-linked preferential flow processes are also known to occur in some arid and semi-arid landscapes (Seyfried et al 2005).

Brush control (through chemical treatment, cutting, chaining, or prescribed burning) is commonly considered to be a viable method to increase water yields. The basic concept behind this is that replacement of deep-rooted species that use large amounts of water with shallow-rooting herbaceous plants may result in a higher net water yield (Thurow et al 2000). However, due to the complex nature of rangeland hydrology, one cannot automatically equate lower transpiration with long-term increases in human-accessible water yields. Factors influencing the potential for increased yields include annual precipitation, shrub cover density, runoff and groundwater flow characteristics, and rainfall interception characteristics of vegetation (Wilcox 2002).

Several recent modeling studies indicate potentially large water yield increases under various brush management scenarios (Bednarz et al 2000, Wu et al 2001, Afinowicz 2004). However, the field studies carried out to date have not shown such dramatic results. For example, Carlson et al (1990) found no effective net change on evapotranspiration, runoff, or deep drainage after mesquite treatment, partially due to increased herbaceous growth after treatment. Another study by Dugas et al (1998) on ashe juniper found only slight short term decreases in evapotranspiration after treatment. There may be some potential for increased water yields from juniper rangelands due to the high interception capacity of juniper canopies and the tendency of juniper to grow in areas with shallow soils and permeable parent materials (Wilcox 2002). The karst Edwards Aquifer region of the Edwards Plateau is one such area. Unfortunately, as with other areas of the state, only a limited number of studies have examined the effects of juniper removal on the Edwards Aquifer; these studies have historically focused on only a few components of the rangeland water budget, with the primary focus on evapotranspiration and surface runoff. This study attempts to address the existing limitations in knowledge by monitoring the effects of juniper brush removal on partitioning of rainfall for multiple surface and subsurface flow routes.

Methods

Study area

The study area is located in the Edwards Aquifer region of Texas approximately 40 km north of downtown San Antonio within the confines of the Honey Creek State Natural Area (29° 50' N, 98° 29' W). Honey Creek is situated in western Comal County (see Figure 2.1 on the following page) within the drainage area of the Edwards Aquifer. Water falling within the drainage area travels through spring-fed streams to the Edwards Aquifer recharge zone (Maclay 1995). The natural area is located within the Upper Guadalupe River basin in close proximity to the river itself. The topography of the area is typical of the Central Texas Hill Country, characterized by numerous "stairstep" hills caused by alternating hard and soft limestone beds within the underlying Glen Rose Formation (Woodruff et al 1992). Although the project site is located on the lower member of the Glen Rose formation rather than on Edwards limestone, the local geology represents a highly karstified limestone subsurface, with fractures and solutional conduits within this limestone acting as preferential flow paths for water movement. Surface recharge features such as sinkholes are common within the natural area, with several located within 100 m of the research site. Smith and Veni (1994) describe the lower Glen Rose Formation as a "thick-bedded to massive fossiliferous limestone that contains many of the longer caves in Texas." Soils at the study site are typically shallow, gravelly clays and loams, with extensive presence of small surface rocks and larger rock outcrops. Several soil series are present within the Honey Creek preserve, with large extents of the Comfort-Rock Outcrop and Real-Comfort-Doss groups as well as some Eckrant-Rock Outcrop soils located along the creek itself (SCS 1984). Although soils in the area are often viewed as having minimal infiltration capacity, work at and near the study site has revealed localized areas with remarkably rapid infiltration capacity. Vegetation in the Honey Creek area consists of mixed grassland and brushland growth. Woody growth includes scrub live oak (*Quercus virginiana* Mill.) and the more dominant ashe juniper. Intercanopy spaces are typically occupied by grasses such as little bluestem, sideoats grama, and Texas wintergrass. Pricklypear is common in intercanopy areas and appears to be able to compete even within areas of dense grass growth (Andrew Weichert 2005, personal communication).

Average annual precipitation is approximately 737 mm/year. Precipitation in the area comes primarily from intense thunderstorms during the summer months (Maclay 1995). The average growing season for the area is 250 days (Porter 2005).

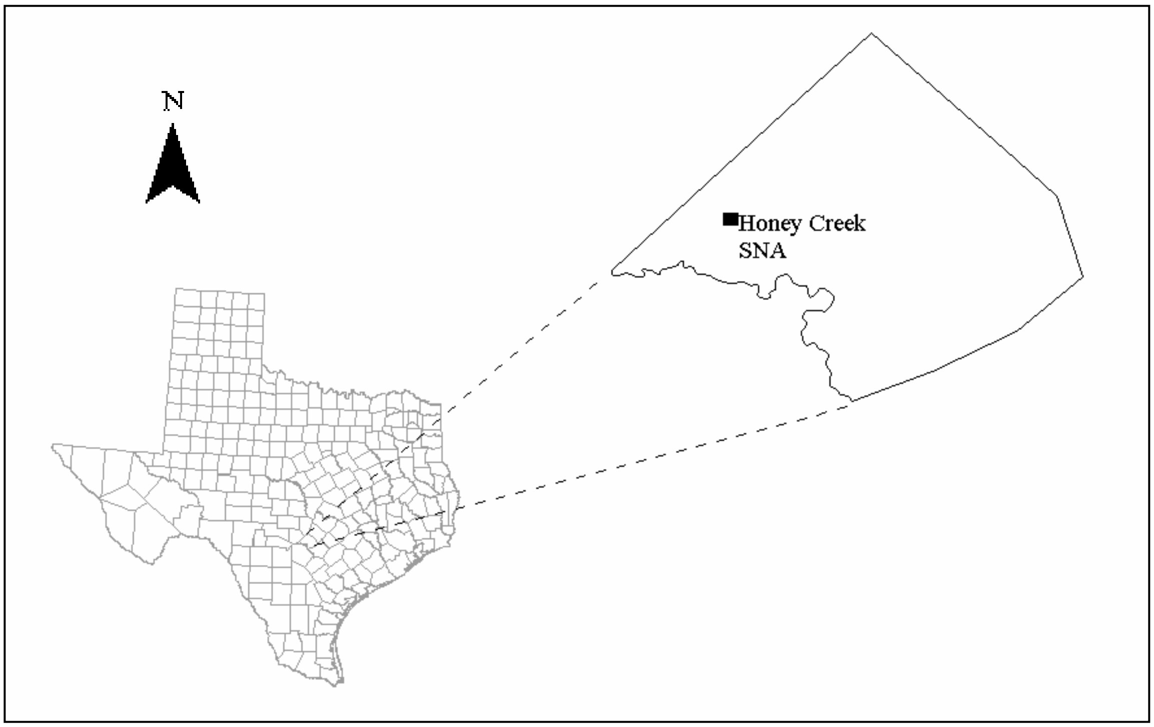

Figure 2.1. Location of Honey Creek State Natural Area, Comal County, Texas.

Plot characteristics

The study used two plots for an analysis of the effects of brush clearing on rainfall partitioning. The main project plot was established in juniper woodland, while a companion plot was established in a nearby area historically free of brush vegetation. Soils at both plots are members of the Real-Comfort-Doss group.

The main project plot occupies 98 m^2 (7 x 14 m) at the edge of a dense juniper forest. Under the pre-cut condition, tree growth dominated the plot, with woody vegetation in the plot consisting solely of juniper at nearly 100 percent canopy coverage. Ground cover was characterized almost entirely by a 2.5 to 5 cm deep layer of juniper leaf litter or "duff" as well as numerous surface rocks, with minimal presence of short grasses, prickly pear, and agarita. After brush clearing, cedar litter and rock matter continued to dominate surface cover, although grass vegetation expanded to approximately ten percent of surface coverage. Coarse, granular sandy clay loam soils ranging from 0 to 30 cm in depth underlie the litter layer. Rather than forming a continuous layer from the surface to bedrock, the soil profile is broken into numerous veins and pockets by the large number of limestone plates incorporated into the soil, with the only continuous region of the profile being the upper 7.5 cm. In some locations soil may extend deeper into the bedrock profile through vegetation influence or filling of inactive karst features. Average plot slope is two percent, although surface rocks and vegetation structures create a highly irregular surface topography. The subsurface, which has been exposed only at the downhill end of the plot, consists primarily of limestone, with approximately 1 m of highly fractured limestone directly beneath the upper 30 cm of soil and rock. A heavily-weathered marl layer of approximately 1m thickness occurs below this level, separated from the fractured layer by a clay lens varying from 2 to 45 cm in thickness. Open fractures and solutional conduits are present, primarily in the fractured limestone layer.

The companion plot is approximately 100 m southwest of the main plot and occupies 98 m^2 (7 x 14m) in a grass-vegetated area showing no indications of prior brush growth. Herbaceous cover of the plot includes moderate to heavy growth of little bluestem, sideoats grama, and Texas wintergrass. Mature prickly pear are common in the vicinity, with several inside the plot boundary. Like the main plot, the companion plot displays coarse, granular soils. Soil depth varies from approximately 7.5 to 15 cm within the plot boundary. Average plot slope is two percent, with minimal presence of microtopographic features. Exposure of the subsurface at the downhill end of the plot suggests a massive limestone subsurface with closed fractures present in limited numbers, with some possibility for the existence of solutional conduits.

Juniper plot layout

The main project plot initially located in juniper vegetation was 14 m long and 7 m wide. A perimeter wall consisting of 16-gauge galvanized metal sheeting extended 5 cm into the soil, with 15 cm projecting above the soil. This wall hydrologically isolated the upper portion of the soil profile from the surrounding area, preventing any water falling outside the plot from traveling through the soil layer and into the plot area. Additional isolation was provided by a 3.66 m wide border of polyethylene sheeting on the sides and upper end of the plot.

Two techniques were used to estimate throughfall. The primary technique consisted of an array of 140 mm capacity plastic rain gauges. Gauges were arranged in a grid within the plot with a 1 m by 1.7 m gauge spacing to collect throughfall readings, allowing researchers to determine both approximate throughfall amount and spatial distribution of throughfall near the plot surface. For all standard simulations, gauge depths were recorded after each run, with the average reading used to represent throughfall over the plot surface. An additional array of rain gauges located outside of the plot (with a coarser 2 m x 2 m spacing) was used for estimation of wind losses during simulations and for measurement of natural rainfall events between simulations.

Two trees in the plot were also equipped for stemflow measurement using apparatus similar to that described by Owens and Lyons (2004). Water flowing down the stem was collected in a set of scoop-shaped plastic funnels attached to each major branch and conveyed to a tipping bucket gauge system with a resolution of 1 L. Measurements were scaled to the whole plot using a ratio of tree basal areas.

A 15.25 cm H-flume at the downhill end of the plot was used to measure surface runoff. The water level in the flume was detected using a float and potentiometer system located in an adjacent stilling well. Depth measurements could be converted to volumetric flow rates through a known relationship based on the dimensions of the flume. A pipe then conveyed surface runoff away from the plot area.

Change in soil moisture storage was measured using ten ECH_2O 10 (Decagon 2005) dielectric soil moisture sensors located randomly throughout the plot. Due to the shallow nature of the upper soil layer the sensors were installed at shallow angles to ensure complete coverage of the probe surface. All sensors were calibrated to measure gravimetric moisture content.

A trench (2 m wide, 2.5 m deep, and 10 m long) was installed at the downhill end of the plot to monitor lateral shallow subsurface flow. The trench floor sloped downward and drained to a sump located at one end. Subsurface flow collected in the sump, from which a float-activated pump conveyed it to a tipping bucket gauge array with a one-liter data resolution (that is, each liter of flow resulted in a signal to the datalogger). In addition to the automatically-logged flow data, information was also collected for each simulation about how long each subsurface flow path contributing to the trench required to begin producing flow. A lightweight roof over the trench isolated it from simulator overspray.

Ambient precipitation was measured using a rain gauge located outside the plot. Measurement resolution for this device was 0.25 mm.

Surface runoff, soil moisture, lateral subsurface flow, and precipitation were recorded on a CR21X datalogger, while throughfall and stemflow were recorded on a CR10X datalogger. For both dataloggers sensor readings were averaged (or summed) and stored at one minute intervals during simulations and at fifteen minute intervals otherwise. More detailed descriptions of equipment and data analysis procedures for both plots can be found in Appendix A. An illustration of the juniper plot layout is shown in Figure 2.2 on the following page (with manual rain gauges omitted).

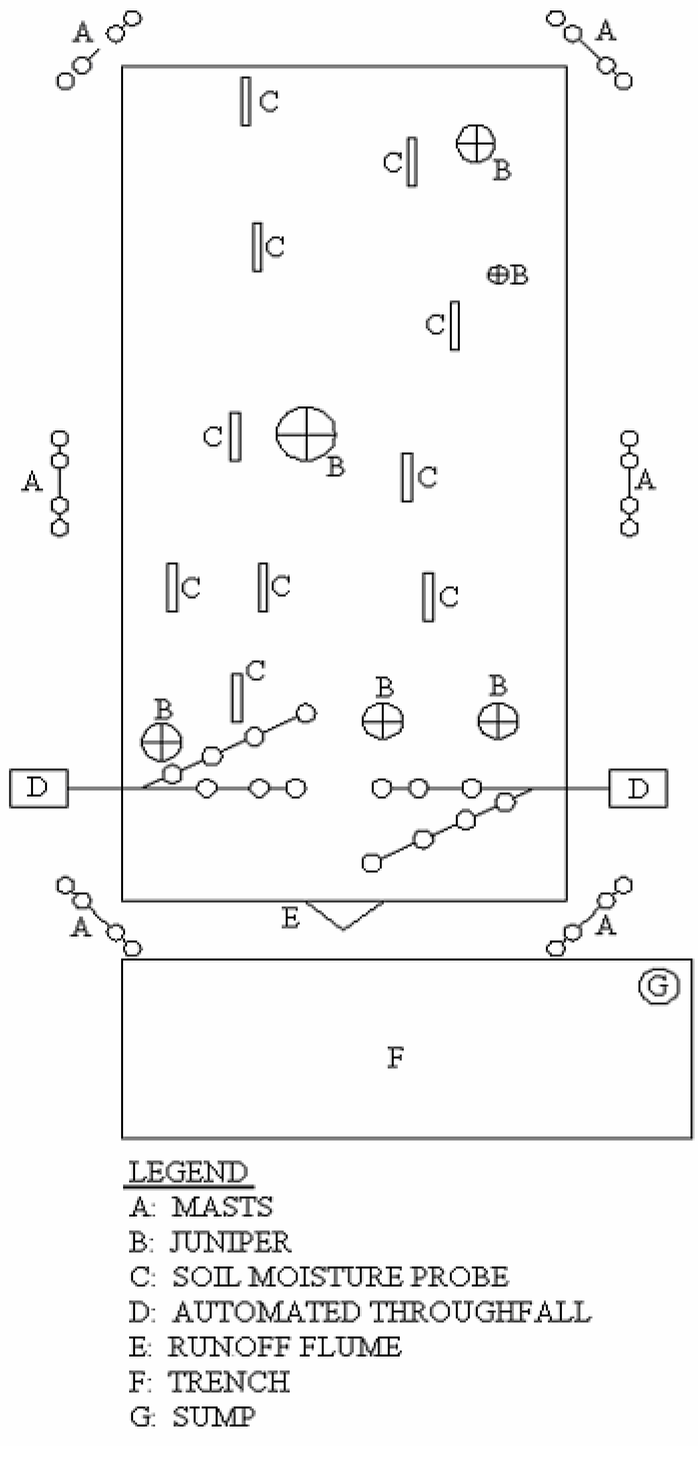

Figure 2.2. Layout of components at Honey Creek juniper plot.

Grass plot layout

The grass plot occupied 98 m^2 (7 m wide and 14 m long) in an area dominated by midgrass vegetation. Like the juniper plot, the grass plot was isolated using metal sheeting and a 3.66 m wide polyethylene border.

At the grass plot, throughfall data were collected exclusively using an array of 140 mm capacity rain gauges. As with the juniper plot, gauge spacing was at a 1m by 1.7 m grid. Surface runoff was measured with a 15.25 cm H-flume system identical to the one used at the juniper plot. Manual depth readings were also collected from the flume during simulations. Due to problems with automatically recorded data, water budget calculations for the grass plot relied on the manual readings. Soil moisture was recorded using ten randomly-located Echo 10 dielectric soil moisture probes.

A narrow trench (1 m wide, 2.5 m deep, and 9 m long) at the downhill end of the plot enabled researchers to observe shallow lateral subsurface flow. Like the juniper plot trench, the floor sloped to a sump at one end. However, for the grass plot, water flowing into the sump was measured manually using a holding vessel. Water was conveyed from the sump to the vessel via a switch-operated pump.

Ambient precipitation between simulations was measured using a tipping bucket rain gauge located in the center of the plot. Measurements of surface runoff, soil moisture, and precipitation were stored on a CR10X datalogger with a recording interval of one minute during simulations and fifteen minutes otherwise.

Rainfall simulation

Although equipment in place at the plot monitored water movement on a continuous basis, the highly variable nature of natural rainfall precluded the possibility of observing near-identical rainfall events for both pre- and post-cut conditions. While the hydrologic impacts of brush removal could conceivably be revealed by monitoring plot behavior during natural events, doing so would have required a prohibitively long study period. Simulation also allowed for observation by key personnel during rainfall events (Porter 2005). For this reason, the study relied primarily on an artificial rainfall system that consistently recreated a certain set of rainfall conditions during both phases of the project.

This project used an elevated manifold rainfall simulator very similar to those used by Sorenson (2004) and Porter (2005) in prior studies. The rainfall simulator apparatus used in this study, while similar in concept to traditional small rainfall simulators often used at the small plot scale, serves to apply water over a large area and at a broad variety of flow rates. While this study attempted to limit the application area to the 98 m^2 plot, a similar simulator for a companion study routinely produces wetted areas of approximately 500 m^2 (Gregory 2006). The simulator configuration at the project site allowed sustained application of rainfall at rates ranging from 2.5 to 25 cm/h; below a rate of 2.5 cm/h, the equipment cannot apply water in droplet form. The simulator array consists of six telescoping masts (with maximum extension of 11 m) located along the sides of the plots and topped with manifolds feeding four sprinkler heads each. Each sprinkler head is equipped with an independent valve, allowing the amount of water applied to be controlled by turning the sprinkler heads on or off. During simulation, water is pumped through collapsible vinyl hose from permanent storage tanks through a filter apparatus, flow meter, and pressure gauge. A set of flow splitters located after the pressure gauge divides the flow, distributing an equal amount of water to each of the six masts. Although flow rates are controlled primarily with the manifold valves, even small changes in hose positioning can alter flow rates from expected values. For this reason, pump speed is adjusted at the beginning of each water application to achieve the desired flow rate. While some components of the rainfall simulator system are portable (the pump, filter, conveyance lines, and pressure and flow meters), the masts are designed to be a semi-permanent feature and are not moved except for repairs.

Simulation parameters

Three replications of a standard simulation were carried out both before and after brush clearing at the juniper plot and over the natural vegetation cover at the grass plot.

The standard simulation consisted of three distinct "runs" or intensity-duration pairs. An initial "pre-wetting" run applied water at a rate of 102 mm/h for one hour to create similar initial moisture conditions among simulations for the subsequent applications. The second run applied water at a rate of 25 mm/h for two hours, while the final run applied 152 mm/h for 0.75 hours. After each run, lateral subsurface flow was allowed to stop before beginning the next run. Pre-cut simulations were carried out on 10/26/2004, 6/1/2005, and 6/9/2005. Post-cut simulations were carried out on 6/14/2005, 6/15/2005, and 6/28/2005. For the grass plot, simulations were carried out on 7/6/2004, 8/10/2004, and 8/11/2004.

Water budgeting

As stated earlier, the effects of brush clearing on the hydrology of the study site were determined using a comparison of pre- and post-clearing water budgets. For this study, the relationship can be stated in its most simple form as:

$$P = M_{SURF} + M_{SUB} + M_{DEEP} + \Delta S \qquad [1]$$

where P is applied rainfall, M_{SURF} is a composite term for all movement of water off of the plot at or above the surface, M_{SUB} is a composite term for subsurface water movement off of the plot area, M_{DEEP} represents water movement from the plot to deeper horizons (recharge), and ΔS is a composite term for change in water storage within the plot volume. Each of these terms can be subdivided into a number of other components or combinations of components which have been measured throughout the course of the study. M_{SURF} includes surface runoff, losses to wind and simulator overspray above the plant canopy, as well as interception of rainfall by the plant canopy itself. M_{SUB} includes shallow lateral subsurface flow through conduit, fracture, and soil matrix flow paths, while M_{DEEP} accounts for movement of water to deeper geologic horizons. The storage term ΔS represents change in water storage in the litter layer and soil as well as in subsurface conduits and fractures. This study focuses on water movement at relatively short timescales, with the period of observation extending from the beginning of water application to the end of lateral subsurface flow. Because evapotranspiration during this period is assumed to be negligible, it is not included directly in the water budget. Over longer periods of time water from the subsurface components mentioned below, particularly on-site storage, may be taken up by vegetation and converted to evapotranspiration losses.

Results

Water budgets

Water budgets for the juniper plot for pre- and post-cut conditions and for the grass plot are shown in Table 2.1. All values given are percentages of water reaching the plot surface (the sum of throughfall and stemflow) rather than of bulk rainfall. Detailed water budgets for each standard simulation are given in Appendix B. The column entitled Grass Plot (Estimated) gives a revised estimate of the grass plot water budget based on 30 percent by volume soil moisture storage change. Individual components of the water budgets will be discussed in the following sections.

Table 2.1. Water budgets for Honey Creek juniper and grass plots. Values are given as a percentage of water applied to plot surface.

Budget Component	Pre-Cut Juniper	Post-Cut Juniper	Grass Plot	Grass Plot (Estimated)
Stemflow	16.8	0.0	0.0	0.0
Throughfall	83.2	100.0	100.0	100.0
Surface Runoff	0.0	0.0	31.9	31.9
Δ Soil Storage	5.1	2.5	?	23.3[1]
Trench Flow	56.7	43.4	5.0	5.0
Other Sub. Flow	38.1	54.1	?	39.8

[1] *Assuming 30 percent volumetric soil storage change.*

Throughfall

Throughfall accounted for 83.2 percent of the water reaching the surface of the juniper plot prior to brush removal and accounted for all water reaching the surface after brush removal and in the grass plot. Subsequent to brush removal, average throughfall totals were significantly higher ($\alpha = 0.1$) for standard simulations. Throughfall averaged 112 mm for pre-cut simulations and 167.7 mm for post-cut simulations. Uniformities of rainfall were calculated using the Christiansen Uniformity (CU) method (Tarjuelo et al 1999). For standard simulations at the juniper plot, pre- and post-cut uniformities were nearly identical, with an average CU of 58.9 percent with brush in place and 60.0 percent after brush removal. On a per-run basis only run 2 shows a statistically significant ($\alpha = 0.1$) difference in uniformity between vegetation conditions, with slightly higher uniformity after brush removal. Standard simulation uniformity for the grass plot was 58.4 percent, which was not significantly different ($\alpha = 0.1$) from either vegetation condition at the juniper plot.

Results of an analysis of natural rainfall data contrast sharply with those from the standard simulations. Comparing natural rainfall data from the juniper plot in the pre-cut condition to the limited natural data for the post-cut condition and to natural data from the grass plot it appears that the uniformity of rainfall under the juniper canopy is significantly lower than for open conditions locally ($\alpha = 0.1$). Under precut conditions, average uniformity was 71 percent. Post-cut, only two natural rainfall events were recorded, one with 87 percent uniformity and the other with 67 percent uniformity (very low rainfall). For the grass plot, average uniformity was 91 percent but has been observed to be as high as 96 percent.

Stemflow

Stemflow (shown in Figure 2.3) accounted for 16.8 percent of water reaching the juniper plot surface for the pre-cut condition, ranging from 14.3 to 19.1 percent of water reaching the surface on a per-simulation basis. On a per-run basis, the percentage of water reaching the surface in the form of stemflow showed no clear relationship to either application rate or total amount of water reaching the surface. The lag time between the start of water application and the initiation of stemflow varied from 3 to 12 minutes, with an average and median delay of seven minutes. There was a weak linear relationship ($r^2 = 0.56$) between the intensity of above-canopy water application (pumping) rate and time required for stemflow initiation, suggesting that the lag time for initiation of stemflow may decrease as application intensity increases. After the end of water application, stemflow persisted for three to six minutes, with an average and median residual flow time of five minutes.

An examination of stemflow hydrographs shows that for all of the runs with the exception of run 1 on 10/26/2004, stemflow begins rapidly and increases to a peak level, then remains at steady state until the end of water application, after which it rapidly returns to zero during the aforementioned post-application lag time. The peak rate of stemflow varied from 0.07 to 0.35 mm/min and showed clear linear relationship to both pumping rate ($r^2 = 0.88$) and total per-run stemflow amount ($r^2 = 0.89$).

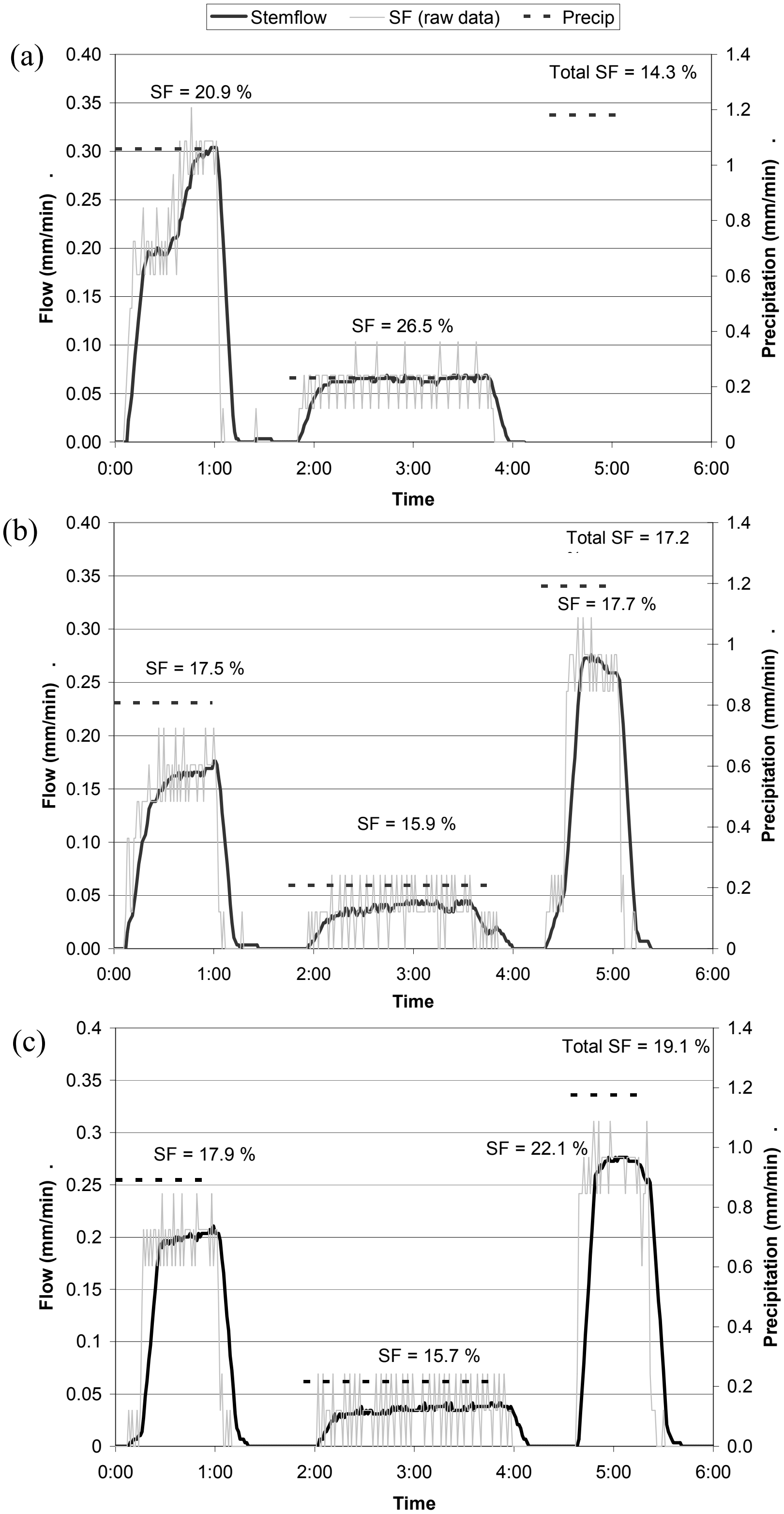

Figure 2.3. Stemflow for standard simulations at Honey Creek Juniper plot for (a) 10/26/2004, (b) 6/1/2005, and (c) 6/9/2005. Per-run stemflow is abbreviated as SF.

Surface runoff

No surface runoff occurred for the juniper plot for any standard simulation, nor for any simulations conducted at the project plot prior to the beginning of this study; this includes a simulated event with a nominal rainfall intensity of 250 mm/hr and duration of one hour. However, ponding of water in the juniper plot was observed for all runs of the standard simulations. The majority of ponded water was located on the uphill side of trees at the end of the plot near the trench, with smaller reservoirs behind other trees and in various locations throughout the plot. Ponding of water occurred more quickly for runs 1 and 3 due to higher application rates, but even for the lower application rate for run 2, water began ponding within approximately 10 minutes.

Surface runoff behavior for the grass plot is illustrated in Figure 2.4. Surface runoff was the dominant observed outflow component for the grass plot, with surface runoff on a per-simulation basis varying from 19.5 to 54.0 percent of water reaching the surface and on a per-run basis varying from 7.1 to 75.5 percent of water reaching the surface. Runoff for the grass plot began approximately 30 minutes after the beginning of water application for runs 1 and 2 under dry conditions, while for wet conditions the lag time for surface runoff was less than 20 minutes. For standard simulations with dry antecedent conditions surface runoff for run 3 lagged water application by approximately 15 minutes, while under wet conditions the surface runoff started within three minutes. Once surface runoff began, it rapidly increased to a peak rate. After the end of water application, surface runoff decreased rapidly, although trace flow continued for up to 20 minutes. The amount of water moving as surface runoff (both in terms of total volume and as a percentage of water applied to the plot surface) appeared closely related to antecedent conditions. For the standard simulation on 8/10/2004, which was carried out under the driest conditions, surface runoff accounted for only 19.5 percent of applied water; most of this water flowed during run 3. In contrast, the simulation on 8/11/2004, which began under wet antecedent conditions, produced significant surface runoff for all runs, with overland flow accounting for more than 50 percent of applied rainfall.

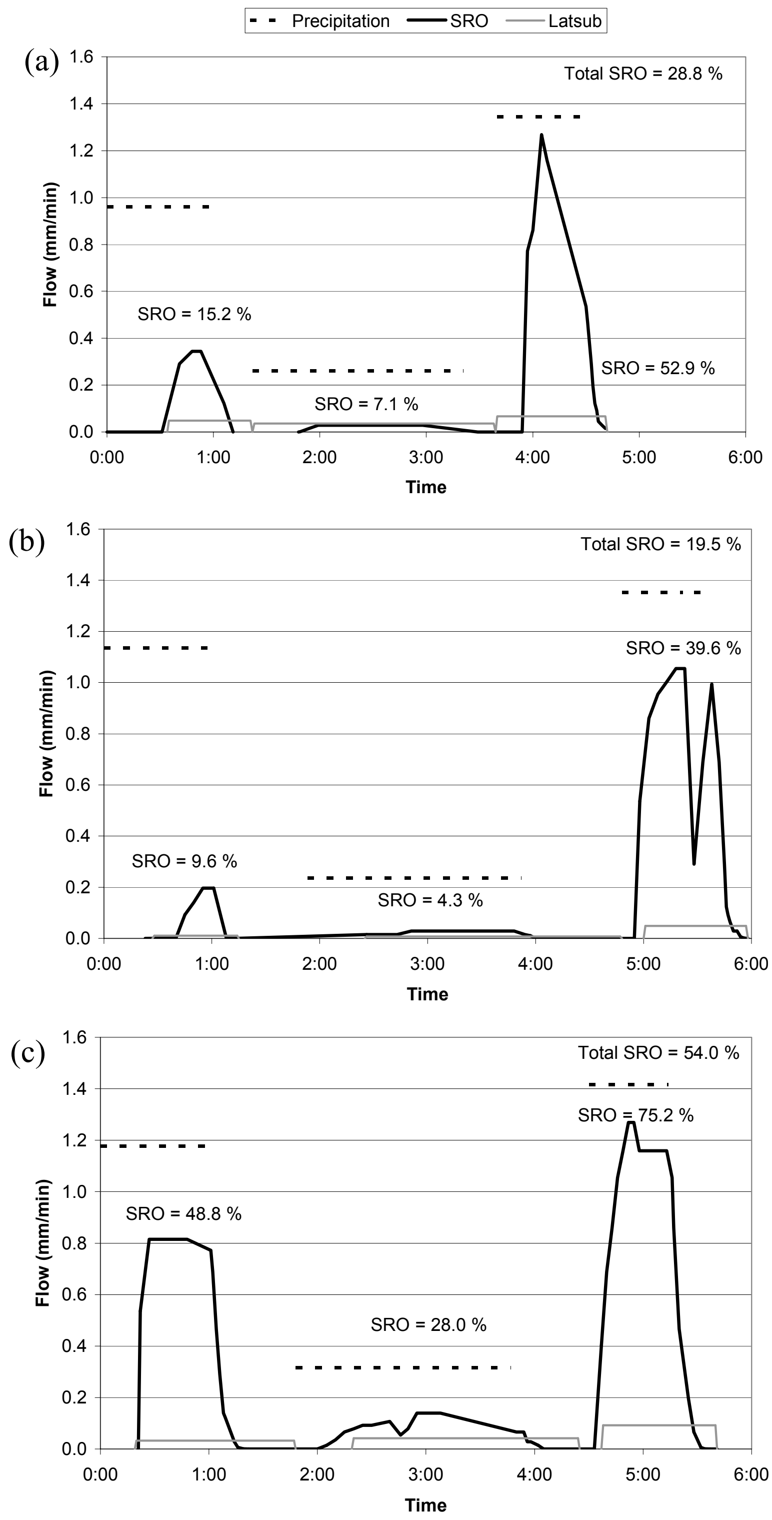

Figure 2.4. Surface runoff for standard simulations at Honey Creek grass plot for (a) 7/6/2004, (b) 8/10/2004, and (c) 8/11/2004.
Note: Multiple peaks for run 3 on 8/10/2004 are due to a gap in rainfall application

Soil moisture storage change

For the juniper plot, change in soil moisture storage constituted a small portion of the standard simulation water budgets, with 5.1 percent of surface applied water stored for pre-cut conditions and 2.5 percent for post-cut conditions. Due to the influence of antecedent conditions, the small total amount of soil moisture storage, and the inherent variability (± 2 percent) in the soil moisture sensors (Decagon 2005), the difference between pre- and post-clearing soil moisture storage change was not found to be important.

Soil moisture responded rapidly to rainfall application, with moisture content sharply increasing and quickly reaching steady state shortly after rainfall initiation; moisture levels rapidly decreased after rainfall. Overall behavior resembled a flow hydrograph, with the timing and pattern of soil moisture fluctuation resembling the hydrographs for stemflow and lateral subsurface flow (see Figure 2.5). For some of the runs, average soil moisture content readings approached 70 percent volumetric water content, with readings from some individual probes of over 80 percent. There was a great deal of variability in readings among individual soil moisture probes during the simulations; however, the gauges followed general patterns across the simulations. The three gauges which tended to have the highest readings and sharpest changes in moisture for most of the simulations were located in areas near ponded water. Thus, while drift from initial calibration may partially explain the anomalously high water content readings, it is likely that a true physical process is also responsible. Volumetric soil moisture was also measured in a grid in the juniper plot (adjacent to the rain gauge grid) before and after rainfall application for one precut and one post-cut standard simulation. Average antecedent moisture was similar for both simulations but antecedent uniformity was higher for the post-cut simulation. After simulation, the post-cut condition had a larger soil moisture storage change and higher uniformity.

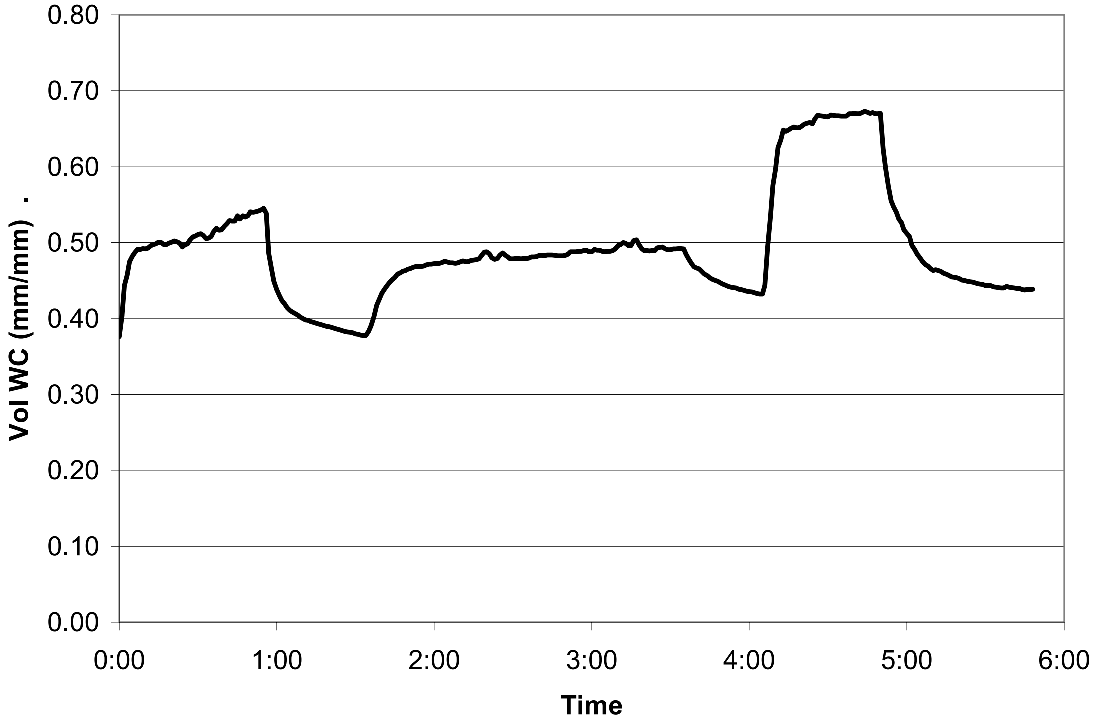

Figure 2.5. Soil moisture response for Honey Creek juniper plot for the standard rainfall simulation on 6/28/2005.

Lateral subsurface flow to trench (trench flow)

For the grass plot, lateral subsurface flow to the trench represented only a small amount of the water budget, with 5.0 percent of water reaching the plot surface emerging as shallow subsurface flow. As with surface runoff, trench flow at the grass plot showed a clear relationship to antecedent moisture, with the least flow (2.7 percent of throughfall) for the driest conditions and the highest flow (8.1 percent of throughfall) for very wet conditions. Subsurface flow into the trench occurred exclusively at the soil-rock interface, with flow beginning in discrete locations along the interface but rapidly transitioning to flow along the entire soil-rock margin. Although this area was the first to become wet, lateral subsurface flow started after surface runoff for most of the runs.

Shallow lateral subsurface flow to the trench was the dominant outflow component observed at the juniper plot, as shown in Figure 2.6. The majority of this flow enters the trench through discrete conduit and fracture features, although a small amount enters as matrix flow through dense clay pockets in the trench face. Flow from preferential paths is rapid, with flow rates as high as 0.62 mm/min observed during standard simulations, although rates as high as 0.78 mm/min have been observed for other simulations.

Trench flow accounted for 56.7 percent of water reaching the plot surface for the pre-cut condition, with totals for individual simulations ranging from 41.3 to 70.9 percent. On a per-run basis the amount of surface applied water emerging as lateral subsurface flow in the trench ranged from 8.2 to 95.0 percent. For post-cut conditions, 43.4 percent of surface applied water moved to the trench, ranging from 40.4 to 47.4 percent on a per-simulation basis and 19.2 to 82.3 percent on a per-run basis. The percentage of surface-applied water moving to the trench was significantly lower (α = 0.1) for the post-cut standard simulations. On a per-run basis, only run 3 showed a significant difference, with a higher amount of observed lateral subsurface flow for the pre-cut condition.

Due to limitations on the maximum flow rate of the trench sump pump, the subsurface flow hydrographs from most of the standard simulations are somewhat distorted, with flow entering the trench more quickly than it could be pumped for runs 1 and 3. While this did not result in losses of measured water, it did mute flow peaks and create artificially long falling limbs on the hydrographs. However, an examination of data collected at the plot from a previous pumping system reveals trends in the flow hydrographs for the pre-cut condition. For this data, as application intensity increases, the relationship between application intensity and peak lateral subsurface flow rate to the trench becomes weaker. That is, for events of approximately 50 mm/h surface application intensity (similar to run 1), maximum lateral subsurface flow rate was much higher than that for events of approximately 10 mm/h intensity (similar to run 2). However, when comparing a 50 mm/h event to one of 60mm/h (similar to run 3) or higher intensity, there was very little difference in maximum flow rate. Both older data and data from the standard simulations show that while flow increased to a sharp peak

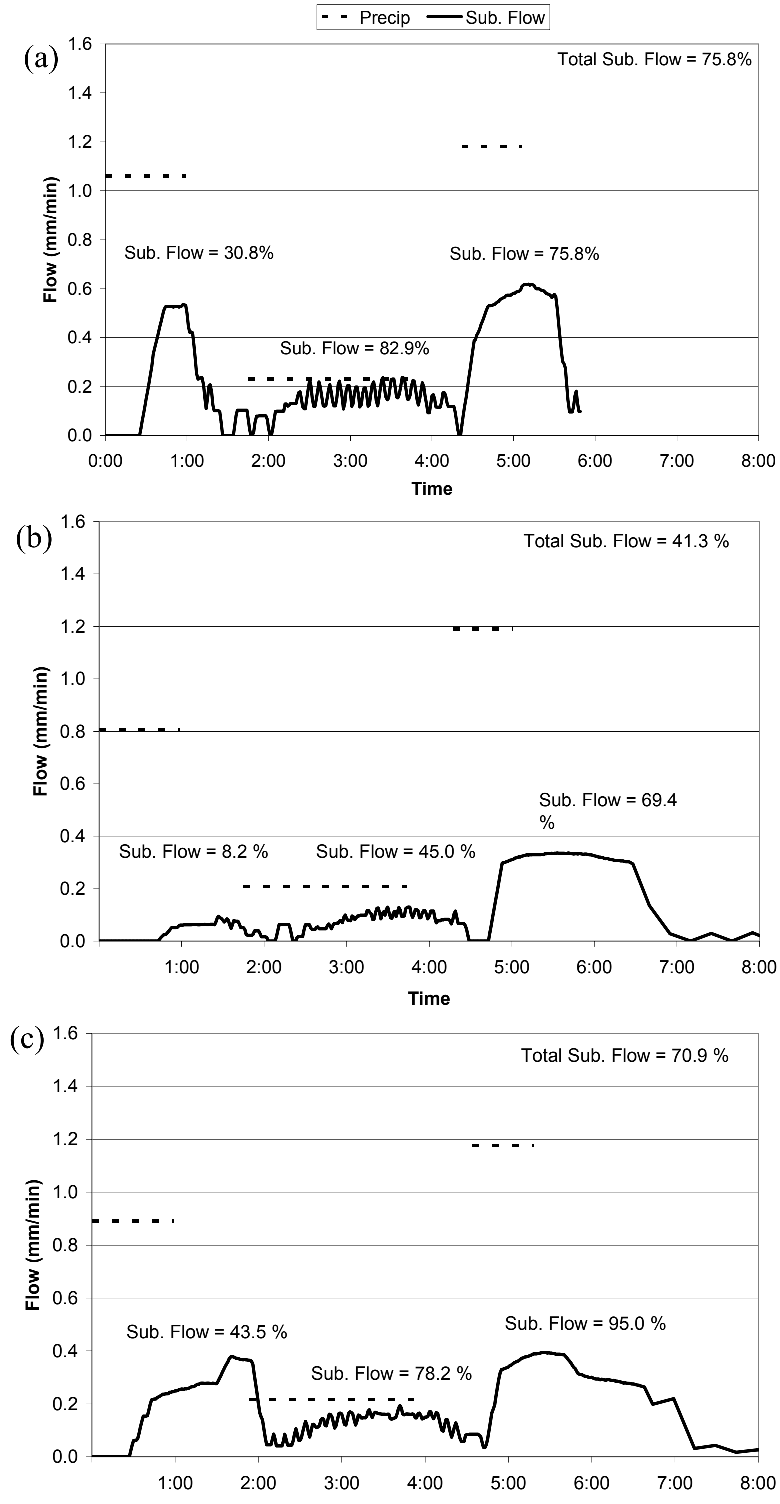

Figure 2.6. Lateral subsurface flow for standard simulations at Honey Creek juniper plot on (a) 10/26/2004, (b) 6/1/2005, and (c) 6/9/2005.

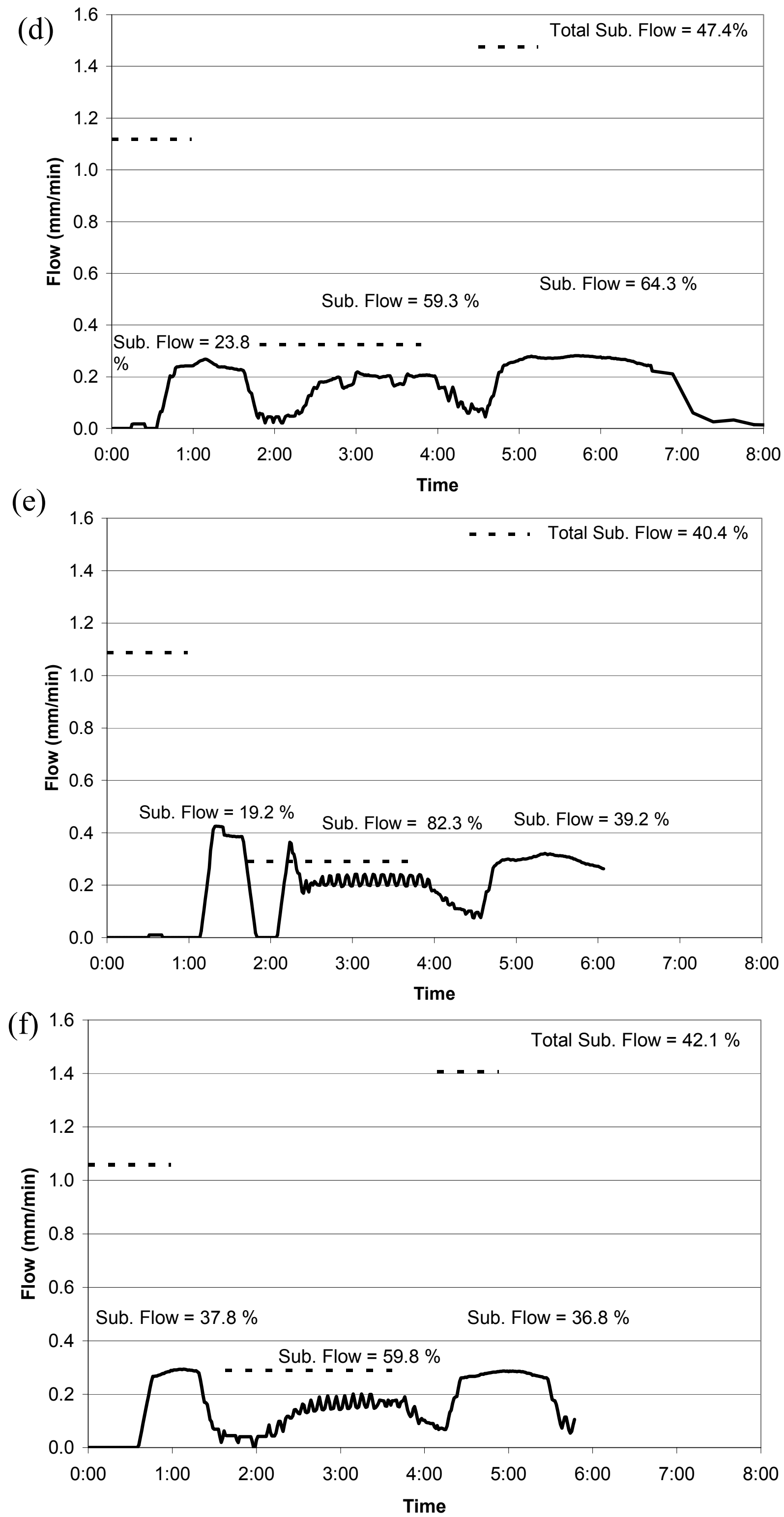

Figure 2.6 continued. (d) 6/14/2005, (e) 6/15/2005, and (f) 6/28/2005

.

for the higher intensity runs, for run 2 the flow quickly reached a steady state and remained at this level until the end of water application.

While individual activation times for the major subsurface flow paths varied considerably among standard simulations, average activation times were similar for the two vegetation conditions; thus, no significant ($\alpha = 0.1$) change in activation time for the subsurface flow paths was observed subsequent to brush removal. Antecedent moisture conditions appeared to impact the lag time between water application and lateral subsurface flow to the trench; for both pre-cut and post-cut vegetation conditions conduit activation times were lowest for very wet antecedent conditions.

It is important to note that the lateral subsurface flow measured and reported in this study represents only the portion of flow moving in the direction of the surface slope and within the upper 2.5 m of the subsurface. For both the juniper and grass plots water likely moves laterally through a number of flow paths which do not intersect the trench and thus are not measured.

Canopy interception

Canopy interception (loss) cannot be measured directly, but is calculated as the difference between precipitation above the canopy layer and the amount of water reaching the top of the litter layer. However, due to difficulty in estimating wind losses and the high out-of-plot overspray losses of the simulator, this method could not be reliably used for the current study. One possible method to estimate interception is the interception relationship developed by Owens and Lyons (2004) for juniper on the Edwards Plateau. In addition to problems in determining true rainfall rate, the structure of the simulation, with several large rainfall events in rapid succession, makes using this method unreliable. While the standard simulations do not represent a single large storm due to the pauses between runs, the assumption that the canopy completely empties between runs is not plausible. Additionally, the ashe juniper at Honey Creek have a multi-stemmed structure, while most ashe juniper monitored on the Edwards Plateau have a single-stemmed physiology.

For the standard simulations, average canopy interception was determined by examining the difference in total water reaching the surface for the pre-cut and post-cut simulations. Because wind and overspray losses take place before simulated rainfall reaches the plant canopy, any differences in water applied to the surface of the litter layer should be caused solely by canopy losses. Using this method, average canopy interception for the pre-cut condition was 32.7 mm per simulation. This value would account for 19.5 percent of water reaching the top of the plant canopy. This study did not examine interception by the herbaceous vegetation in the grass plot or by leaf litter.

Discussion

Throughfall

Due to removal of canopy interception losses, throughfall increased considerably for post-cut conditions. While this is not surprising, it is somewhat unusual that for standard simulations the juniper plot under pre-cut conditions generated uniformities similar to the post-cut condition and the grass plot. This is probably a function of the simulator apparatus itself, which produces uniformities between 58 and 73 percent (depending on flow rate) for very low wind conditions. The standard simulations for the study plots were carried out under a variety of conditions, with the size of the simulator and the length of the simulations preventing control of wind conditions. This also explains the greater difference in juniper and open plot uniformities for natural rainfall events, which are typically more even at the large plot scale.

Another interesting question is why natural rainfall, though more evenly distributed than that from the simulator, averages only 91 percent uniformity. This seems partially a function of rainfall event size; for example, a total variation of 10 mm across the plot for a 30 mm event would result in a much lower uniformity than a 10 mm variation for a 50 mm event. Additional variability may also result from small variations in accuracy among the rain gauges. Results for the grass plot show high uniformities (> 93 percent) for events of approximately 50 mm or greater and less even distributions for smaller events. One large event in August 2005 was observed to apply approximately

140 mm of rainfall with a total variation of less than 4 mm across the plot; this equates to an estimated application uniformity of over 99 percent.

Stemflow

The fraction of applied water taking the form of stemflow for this study is considerably different from other studies of ashe juniper on the Edwards Plateau. For the study of interception by Owens and Lyons (2004), at the highest rainfall levels 90 percent of rainfall reached the top of the litter layer (although 5.6 percent was intercepted by the litter), with 4 percent of rainfall moving as stemflow (Owens and Lyons 2004). This is equivalent to 4.4 percent of water reaching the surface, considerably lower than the 16.8 percent found for this study. However, while both the Owens study and this project examine large rainfall events, it is important to note that the Owens study examined individual natural rainfall events of a variety of sizes and intensities, while the standard simulation for this project actually consists of several large rainfall events in rapid succession. Several other rainfall simulator studies have been carried out at various locations throughout the Edwards Plateau region. Comparing to other rainfall simulator research on the Plateau, the stemflow was higher than that reported by Sorenson (2004) at Sornora, Texas but lower than previous results at the Honey Creek plot by Porter (2005). For the comparison to the Sorenson study, it is possible that some of the differences are due to simulation intensity and duration, plot scale, and number of trees. It also seems quite likely that the multi-stemmed form of the trees at the Honey Creek area and the presence of branches down to the top of the litter layer may partially explain the greater amount of stemflow; this may explain differences from the Owens and Lyons (2004) study as well. This does not, however, explain why Porter (2005) calculated a much higher proportion of applied water taking the form of stemflow, especially since the scaling factor for the trees was actually slightly smaller than that used for this study. The most likely explanation seems to be a linkage between stemflow and ambient conditions. While the data for the Porter study was collected in December, two of the three pre-cut simulations for this study took place in June under rather warm conditions when the bark was probably dry prior to the beginning of simulation. The rainfall simulation on 10/26/04, which was carried out under cooler conditions, showed greater per-run percentages of stemflow and higher peak stemflow rates. Although seasonal variation in stemflow for ashe juniper has not yet been documented, the data from this study suggest that seasonal fluctuations in temperature and other ambient conditions may impact the stemflow component.

Surface runoff

As stated earlier, for standard simulations at the juniper plot, no surface runoff was detected for either vegetation condition, while surface runoff played a significant role in the water budgets for standard simulations at the grass plot. There are several surface and subsurface differences in the plots which could be responsible for these different behaviors. Based on early data from the project plot prior to brush removal, Porter (2005) suggested that ponding in juniper-related microtopographic features, combined with focused water application from the large stemflow component of the water budget, promoted infiltration and prevented surface runoff. However, the lack of surface runoff after brush removal rules out stemflow as a controlling factor in this process. Although microtopographic ponding may play some role, it is important to keep in mind that these features do not hold a large volume of water at any particular time.

Based on observations made at both plots, differences in local runoff processes appear to be influenced by both soil and limestone subsurface characteristics. While infiltration through grass plot soils is relatively rapid, especially at the beginning of rainfall simulation, soils at the grass plot are much less granular than those at the juniper plot; rock content for the grass plot soil layer was low as well. Additionally, the solid bedrock observed in the grass plot trench, although not necessarily representative of the entire plot, may limit infiltration in some portions of the plot.

Unlike the grass plot, subsurface water movement at the juniper plot appears to be dominated by macropore flow in both the soil and limestone bed. Soils at the juniper plot appear to have been heavily impacted by the ashe juniper vegetation, with the upper portion of the soil layer including a considerable amount of partially decomposed litter incorporated into the soil structure. The coarse, highly organic soils at the juniper plot display high infiltration capacities, with some locations in the plot with capacities of at least 6.8 mm/min (determined through concentrated water application directly to the top of the litter/soil). Post-simulation excavations by Porter (2005) revealed that only the upper portions of the leaf litter and soil layers were wet, suggesting that almost all water movement to through these layers occurred via macropore flow. Highly non-uniform soil moisture was also observed during manual testing with a TDR probe; during this testing, many locations in the plot remained too dry for probe insertion even after a standard rainfall simulation. Below the soil layer, the highly fractured subsurface provides open flow pathways for rapid drainage.

This raises the question of how, if the coarse soils and fractured subsurface provide little resistance to water movement, ponding still occurs at the juniper plot. It is likely that even though the juniper plot subsurface is highly fractured, some locations within the plot may have a locally solid subsurface. Since water encountering this restriction must move laterally before encountering a nearby inlet, a nearby perched zone could be created. This would be especially noticeable in locations with concentrated water application, such as the aforementioned stemflow into microtopographic features.

Soil moisture storage change

Soil moisture storage change for the juniper plot for both pre- and post-cut conditions appears to be a relatively minor part of the total water budget. Because the difference in calculated pre- and post-cut moisture change was less than the range of error for the probes, it appears that brush removal had no noticeable impact on the volume of water stored as soil moisture. In fact, the values calculated for storage change may be an overestimate. Values calculated for the water budget assumed an equivalent soil depth of 76 mm (305 mm with 75 percent rock content) based on excavations at the plot perimeter; average soil moisture change from the moisture proves was applied to this entire layer. However, for excavations subsequent to simulations by Porter (2005), the litter layer was observed to remain largely dry below a thin wet surface layer. Similar results were obtained using a small needle-type rainfall simulator on undisturbed litter samples in a laboratory setting. Similar observations have been made for the soil layer as well, suggesting that very little of the soil layer truly stores significant moisture. There may be localized exceptions to this in the portions of the juniper plot where ponding occurs.

As noted in the results section, soil moisture response resembled a hydrograph, with volumetric water contents greater than realistic soil porosity values. Due to the large amount of partially decomposed litter in the upper soil layer and the documented presence of preferential flow in both the litter and soil layers, macropore flow directly across the measuring surface of the probes seems likely. This would explain both the unusually high volumetric water contents and the rapid increases and decreases in soil moisture.

The comparison of pre- and post-cut soil moisture uniformities is inconclusive. Although the greater total water input for the cleared condition may have influenced post-simulation moisture uniformity, throughfall uniformity is unlikely to have played any role due to similar application values for the two simulations. Due to the potential effects of antecedent conditions, more data would be necessary to identify significant changes and contributing factors.

While soil moisture content was not recorded for the grass plot due to equipment problems, total storage change likely accounted for a considerable portion of applied water. Although the soil was unlikely to reach complete saturation, the presence of a restrictive horizon, gradual bottom-up wetting of the soil layer observed at the trench, and high application volume for the standard simulation suggest that a large amount of available pore space was filled. An estimated change in soil moisture from 20 to 50 percent during a standard simulation would result in total soil storage of 45 mm of moisture, or about 23 percent of water applied to the plot surface. While this scenario represents the extreme estimate of change in soil moisture, storage change from the grass plot is clearly higher than that from the juniper plot and likely several times as large.

Lateral subsurface flow to trench (trench flow)

Specific discussion of the individual lateral subsurface flow paths, contributing areas, and linkages to vegetation are discussed in detail in Chapter III. It has been noted that for the grass plot lateral subsurface flow to the trench accounted for very little of the water budget and tended to occur after the beginning of surface runoff in spite of coming from the first portion of the soil layer to become wet at the trench exposure. One possibility is that even though the soil stores a considerable amount of water, gravity drainage of water from the soils is still slow except in soil macropores. Thus, the lateral subsurface flow component of the grass plot may represent gravity drainage of the macropore fraction of the soil. Another possibility is that while the plot surface slopes in the direction of the trench, the subsurface may, at least for some portions of the plot, slope in a different direction; thus, true lateral subsurface flow may be greater than the amount observed at the project trench.

As noted in the results section, trench flow as a percentage of water reaching the surface for the juniper plot was higher for pre-cut conditions. While some of the difference may be due to truncation of the run 3 data record for one of the post-cut simulations, field observations suggest that the majority of water for this run was accounted for. Greater lateral subsurface flow into the trench prior to brush removal is likely due to the presence of the stemflow component, which accounted for nearly 17 percent of water reaching the plot surface. This considerable fraction of the water budget was focused in a very small area at the base of the juniper vegetation; dye tracer testing, discussed in greater detail in Chapter III, has shown the presence of connections between conduit flow paths and the basal area of a large juniper near the plot center. However, the numbers given reflect only lateral subsurface flow in the direction of the surface slope and in the upper few meters of subsurface; removal of stemflow contributions may simply allow water to move through lateral flow paths under the trench or in a different direction. Downward movement of water or on-site storage is also possible. Observations of preferential flow through soil and litter layers and the rapid disappearance of ponded water suggest that water moves rapidly through the subsurface at the plot for either vegetation condition.

Because the trench is a large, artificial feature, one must consider the possibility that the presence of the trench itself impacts shallow subsurface flow. Observations of fractures on the trench face suggest that they were not created during trench installation but rather are pre-existing subsurface features and were hydraulically active prior to trench installation. Many of the fractures and conduits on the trench face show signs of weathering, discoloration, soil deposits, and the presence of fine roots. However, it is highly likely that the trench has altered subsurface flow in some way. For a similar rainfall simulation study at Sonora, Texas, plot hydrology was observed to change as a trench near the plot was enlarged (Sorenson 2004). During natural rainfall events at the Honey Creek juniper plot, water has been observed to rapidly enter the trench from all sides rather than from the plot alone; for a number of intense summer thunderstorms, this flow has completely filled the trench. After such events, water drains from the trench slowly and in some cases may persist for a week or more. These observations suggest that (1) the trench serves as an artificial sink for local subsurface water movement and (2) the lateral subsurface flow paths intersected by the trench may have originally shown less dramatic flow response.

While it seems likely that subsurface flow has changed to some degree after trench installation, the net effect of this alteration on plot hydrology is unknown. A shift in the direction of flow or dominance of particular flow paths does not necessarily equate to alterations of infiltration capacity or total volume of subsurface flow. Without the influence of the trench at the juniper plot, water may have rapidly filled many subsurface flow paths, spilling over onto the surface and resulting in surface runoff. It is also possible that subsurface flow would simply have moved through pathways other than those currently feeding the trench. While it is not possible to determine which of these scenarios is representative of the juniper plot, several observations suggest that runoff from the plot would be unlikely. In addition to the high soil and litter permeability of the plot and the fractured nature of the subsurface, it is important to note that roughly half of the water reaching the plot surface moves through paths not intersecting the trench. Also, additional testing at the plot has shown that not all areas of the plot contribute to the trench; some of these areas accept sustained inputs of approximately 380 mm/h with no surface runoff. For these reasons, it seems probable that the net infiltration capacity of the plot has not been altered by trench installation.

Interception

The value estimated for interception was considerably higher than expected. Although ashe juniper has been documented to intercept a large portion of annual precipitation, sixty percent of the storms in the area are less than 2.5 mm, for which interception is roughly 96 percent; the proportion of interception decreases with increasing storm size (Owens and Lyons 1996). Using the exponential relationship developed by Owens and Lyons (1996) and assuming a 167 mm rainfall event estimated from post-cut throughfall, interception was estimated approximating the standard simulation as a single large event (since the canopy at the juniper plot has been observed to remain wet between runs). Approximating as a single event resulted in interception of 21.1 mm of moisture. While there may be some error in this estimate as the size of the rainfall event falls slightly outside the range used to develop the interception equation, it is clear that the interception observed at the Honey Creek juniper plot is much higher than would be expected for ashe juniper on the Edwards Plateau. However, the 32.7 mm estimate is not unreasonable, as the only changes to the plot between vegetation conditions were brush removal and lowering of the masts to 5 m. Alteration of mast height is likely not a factor, since the travel distance from the manifolds to the ground was actually greater than from the manifolds to the plant canopy. Thus, any difference in water reaching the plot surface is attributed to canopy losses. Additionally, the original vegetation cover of the plot possessed characteristics conducive to high interception, including a closed canopy with considerable overlap and a multi-stemmed physiology with dense branches beginning at the top of the litter layer.

Other subsurface flow

Of the water applied to the juniper plot surface for standard simulations, 38.1 percent for pre-cut conditions and 54.1 percent for post-cut conditions was unaccounted for. Although the destination of this water cannot be clearly determined, there are a number of possible pathways that could account for unmeasured outflows and storage. Results from dye tracer testing, discussed in greater detail in Chapter III, indicate that not all areas in the plot contribute to outflows at the trench. Water entering the subsurface may have moved downward as recharge or through lateral subsurface flow paths bypassing the trench from below or to the side. Lateral flow may also have traveled in pathways not parallel to the surface slope (that is, exiting through the sides of the plot).

Due to the complex nature of the subsurface flow paths and the lag time between water application and flow into the trench, the conduits and fractures themselves probably store a considerable amount of water on site. Additional storage could also occur in the caliche and marl layers in the plot subsurface. Exchange of water between fractures and the subsurface matrix has been documented at the juniper plot (Dasgupta 2005).

Revised budgets

Table 2.2 presents revised water budgets, with values reported as a percentage of water applied to the top of the plant canopy (juniper or grass). Interestingly, after accounting for interception, the percentages of rainfall observed as lateral subsurface flow to the trench are nearly identical for the pre-cut and post-cut conditions. At the same time, the percentage of water moving through other subsurface paths remains much higher for the post-cut condition. Thus, while both the volume and percentage of bulk canopy-level rainfall entering the trench was not impacted by brush removal, one can conclude that removal of ashe juniper from the plot increased movement and storage through other subsurface pathways. The primary mechanism of this alteration was likely increased total input after brush removal coupled with a lack of focused stemflow routing.

The revised budget for the grass plot also reveals interesting plot behavior. The estimate of soil moisture storage change, which represents a hypothetical 30 percent volumetric storage increase, accounts for 23.3 percent of applied rainfall. While this is nearly a quarter of the water budget, it leaves 39.8 percent of applied water unaccounted for. There are a number of possible explanations for this large volume of unmeasured flow. Soils in the uphill region of the plot may be deeper than expected, resulting in greater storage than estimated. It is also possible that the bedrock slope does not closely match the surface slope, allowing water to flow away from the trench along the soil - bedrock interface. The possibility exists that some slow movement of water to deeper horizons occurs at the grass plot. Finally, viewed at longer timescales, water moving through these pathways may be taken up by plants and become lost through ET.

Table 2.2. Revised water budgets for Honey Creek juniper and grass plots. Values are given as a percentage of precipitation at canopy level.

Budget Component	Pre-Cut Juniper	Post-Cut Juniper	Grass Plot	Grass Plot (Estimated)
Stemflow	13.5	0.0	0.0	0.0
Throughfall	67.0	100.0	100.0	100.0
Canopy Int.	19.5	0.0	0.0	0.0
Surface Runoff	0.0	0.0	31.9	31.9
Δ Soil Storage	4.1	2.5	?	23.3
Trench Flow	45.7	43.4	5.0	5.0
Other Sub. Flow	30.7	54.1	?	39.8

Conclusions

This study revealed a number of impacts of brush removal on the partitioning and distribution of rainfall among multiple water budget components. The volume of water reaching the plot surface as throughfall increased considerably after brush removal for the juniper plot, with an analysis of natural rainfall data suggesting that this increased input volume also reaches the surface with a much more uniform distribution. The post-clearing increase in throughfall and total surface input are primarily attributed to high canopy interception, which accounted for over 18 percent of water reaching the top of the plant canopy. This interception was much higher than expected and may represent high canopy storage capacity resulting from a multi-stemmed tree physiology with dense branches along the entire length of the tree stems.

Stemflow represented a large input to the juniper plot for the pre-cut condition, with 16.8 percent of water reaching the surface moving as stemflow. The majority of stemflow infiltrated quickly and some of this water was stored in surface depressions behind the juniper but disappeared quickly after the end of rainfall. Interestingly, the results of the stemflow analysis suggest seasonal variation in stemflow capacity of juniper vegetation. However, this behavior has not previously been documented for ashe juniper.

For the two project sites studied, surface runoff appears to be controlled by both soil and subsurface permeability, with juniper vegetation likely playing an important role in altering soil infiltration characteristics. The high infiltration capacities of litter, soil, and the fractured limestone subsurface for the juniper plot precluded surface water movement beyond localized ponding. In contrast, the less permeable soils and seemingly solid subsurface of the grass plot limited infiltration and allowed overland flow. The presence of such drastically different responses for locations in close proximity highlights the high complexity of the Edwards Aquifer landscape.

Perhaps the most interesting conclusions of the study relate to subsurface water movement at the juniper plot. The percentage of surface-applied water entering the trench as lateral subsurface flow was significantly higher for pre-cut conditions, possibly due to focused application of large amounts of water through stemflow; connections between juniper vegetation and conduit outlets in the trench were established through dye tracer testing. The average percentage of bulk rainfall (rainfall at canopy level) entering the trench was similar for both vegetation conditions, due to greater inputs after removal of the juniper canopy and its associated high interception. Although lateral flow to the trench (as a percentage of estimated above-canopy rainfall) remained unchanged, total water movement to the subsurface through other paths did increase substantially. While this is an encouraging sign for improved water yield, one must not automatically equate increased subsurface flow with increased recharge. Considerable amounts of water may be stored on site in near-surface conduits, fractures, and soil pockets, or in porous or unconsolidated caliche and marl layers in the subsurface. While this water could become available for herbaceous growth, it is unclear how much additional water might eventually contribute to groundwater recharge.

CHAPTER III
DYE TRACER TESTING*

Overview

Although shallow lateral subsurface flow is generally not viewed as a major component of most rangeland water budgets, it can be a significant flow pathway in some landscapes. In the karst landscape of the Edwards Plateau in central Texas, rapid shallow subsurface flow has been observed to occur at far greater rates under juniper cover than for grassland vegetation. The rapid subsurface flow at juniper sites has been observed through root macropores and in root mat layers at rock layer interfaces (Sorenson 2004) in addition to the more commonly witnessed flow through solutional conduits. Similar results have been observed for ongoing studies on the southeastern Edwards Plateau north of San Antonio (at the Honey Creek State Natural Area), with significant subsurface macropore flow (through fractures and conduits) under juniper vegetation. However, the relationship between macropore and solutional conduit flow and juniper vegetation has not yet been explicitly established.

In this study, a conceptual model for hydrologic changes due to juniper encroachment into grass rangeland has been developed based on observations of large-plot scale study sites on the Edwards Plateau. Juniper is conceptualized as altering local hydrology in a number of ways, including decreased surface runoff and ground surface evaporation and increased transpiration, canopy interception, and subsurface water movement. The conceptual model also describes juniper as creating a shift from a uniform system with locally uniform vegetation cover, rainfall application, and evapotranspiration to a system with spatially non-uniform rainfall application, soil wetting, soil moisture, and evapotranspiration. For this model, the preferential

---

*Modified with permission from ASCE from "Large plot tracing of subsurface flow in the Edwards Aquifer epikarst" by Taucer PI, Munster CL, Wilcox BP, Shade B, Owens MK, Mohanty B. 2005. In *Sinkholes and the Engineering and Environmental Impacts of Karst*. ASCE: Reston, VA; 207 - 215.

movement of water begins at the plant canopy level, with a portion of the water captured by the plant canopy moving to the base of the tree as stemflow and reaching the surface in a highly non-uniform pattern. This water is further focused through ponding in microtopographic features created by juniper roots and leaf litter. Post-rainfall excavations in the research plot have shown that water infiltrates into the subsurface through preferential flow paths (likely created by juniper roots), leaving most of the littler layer dry. Under-canopy areas in the research plot produce no surface runoff, even with simulated rainfall rates as high as 25 cm/hr. This suggests that the entire under-canopy area contributes to subsurface flow through preferential infiltration channels. Below the surface, flow occurs in three primary domains as described at the project plot by Dasgupta (2005), with the majority of flow moving rapidly through open limestone conduits and fractures, a smaller amount moving through narrower fractures, and the smallest amount of subsurface flow moving through matrix flow. A fourth classification of movement along bedding planes has been suggested for the plot as well, based on high seepage rates observed at a clay lens/bedrock interface. Since water enters the trench at a small number of discrete and isolated locations rather than through all of the large fracture networks in the trench face, the conceptual model describes subsurface flow paths under juniper cover at the research site as discrete flow paths, with minimal interconnection at the large plot scale (5 - 10 meters). The conceptual model also asserts that the conduit and fracture flow domains are related largely to vegetation-associated surface areas, while seepage outlets are fed by flow over a broader surface area. Vegetation may influence the larger flow paths in a number or ways, including juniper root insertion, canopy interception, throughfall and stemflow routing, movement through the hydrophobic litter layer, and detention in micro-reservoirs created by the juniper trees.

The subsurface flow components of the conceptual model are of particular interest, given the importance of subsurface water movement to aquifer recharge and the potential for brush vegetation to interact with flow paths at a larger scale (reaching into the fractured rock) than native grassland vegetation due to greater rooting depths. As such, the primary objective of this research was to use surface-applied fluorescent tracers to evaluate the source, flow paths, and travel times of the lateral subsurface flow on juniper covered hillslopes on the Edwards Plateau to test several subsurface flow components of the conceptual model.

Methods

Project site

The research site is located in Honey Creek State Natural Area, located in the southeastern section of the Edwards Plateau, approximately 40 km north of downtown San Antonio, Texas. The Honey Creek area consists of a hilly landscape with highly terraced "stairstep" topography. The geology is also typical of the Edwards Plateau, with shallow, coarse soils underlain by the highly permeable karstified lower member of the Glen Rose Formation. This karstified limestone has fractures and conduits that facilitate preferential flow paths below ground, as well as surface recharge features such as sinkholes. Vegetation in the Honey Creek area consists of mixed grassland and brushland with woody growth dominated by ashe juniper (*Juniperus ashei*) and occasional oak trees. Intercanopy spaces are typically occupied by grasses, primarily little bluestem, sideoats grama, and Texas wintergrass.

The research site is 7 x 14 m (98 m^2) in a dense juniper forest and is hydrologically isolated from the surrounding area by a metal border extending to a depth of 5 cm below the soil surface. Tree cover within the plot consists entirely of ashe juniper, with a canopy cover of nearly 100 percent. Ground cover is characterized primarily by a 2.5 to 5 cm thick layer of juniper leaf litter, with minimal understory growth consisting of sparse grass clusters as well as immature agarita and prickly pear. The soil in the research plot is a granular sandy clay loam ranging from 2.5 to 15 cm in depth. The average plot slope is 2%, although surface rock cover and juniper trunks and surface roots create highly irregular microtopography. A 152 mm H-flume is installed at the down-slope end of the site to quantify surface runoff.

To simulate rainfall above the plot's juniper canopy, water is pumped from storage tanks to manifolds located at the top of six masts installed around the plot. Each manifold includes four irrigation sprinklers with 90° spray patterns, which can be opened or closed independently using valves to control rainfall application rate. Possible simulated rainfall rates vary from 2.5 to 25 cm/hr.

The research site also includes a 10 m long by 2.5 m deep trench located at the downhill end of the plot to capture lateral subsurface flow. Water flowing into the trench from outlets in the trench face moves to a collecting sump. Lateral subsurface flow collected in the sump is pumped to a tipping-bucket measuring system that is used to determine the flow volume as a function of time. Sixteen locations on the trench face have produced flow under simulated rainfall conditions since establishment of the trench. However, not all locations produce flow for every rainfall event, with locations characterized by low flow or seepage requiring significant rainfall for activation. Prior to tracer testing, flow locations were grouped into four regions based on outlet type and relative amount of flow. Region A displays moderate flow through small conduits and fractures, while Region B exhibits high flows, primarily through larger conduits and fractures. Regions C and D are seepage locations in at the top of clay lenses at the clay/limestone interface, with locations in Region D becoming active only after extended rainfall simulation. The sampling sites are shown in Figure 3.1.

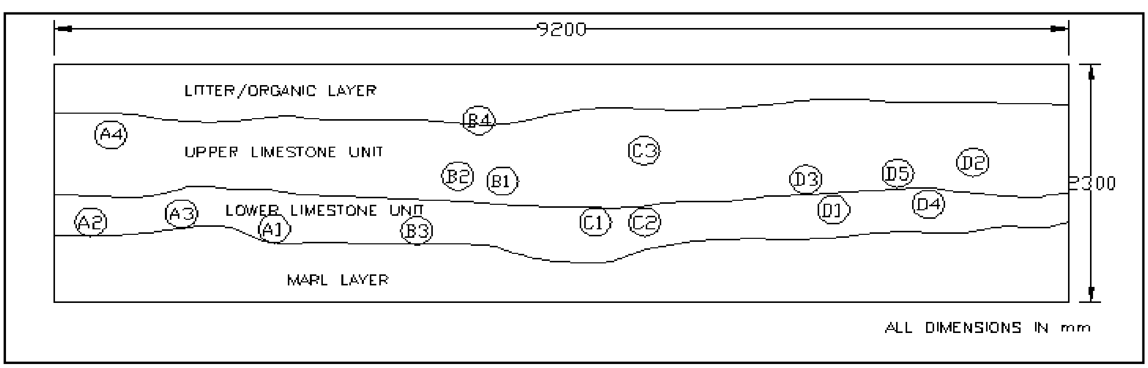

Figure 3.1. Location of sampling points for dye tracer testing (Honey Creek juniper plot). Modified from an original illustration provided by Surajit Dasgupta.

Dye application

Two tracer tests were conducted at the research site. For both tests, Phloxine B, eosine, and uranine dyes were applied to the same locations within the plot. Each dye was mixed with approximately 3.8 L of water and applied to the litter layer using a handheld garden sprayer. Phloxine B was applied in a 0.3 m wide band at the downhill end of the plot, eosine was applied in a 0.3 m wide circular band around the base of a large juniper near the center of the plot, and uranine was applied in a 0.3 m wide band with its center 2.2 m from the uphill edge of the plot (see Figure 3.2). For the first test, conducted on January 30, 2004, the masses of dye applied were 160 mg of Phloxine B, 140 mg of eosine, and 40 mg of uranine. These masses were chosen in accordance with concentrations that have provided positive dye detections in direct sinkhole dye injections. Because the samples from the first test contained few clear dye signatures, dye masses for the second test (May 13, 2004) were increased by approximately 10 times for Phloxine B and eosine and 25 times for uranine (since no uranine was detected

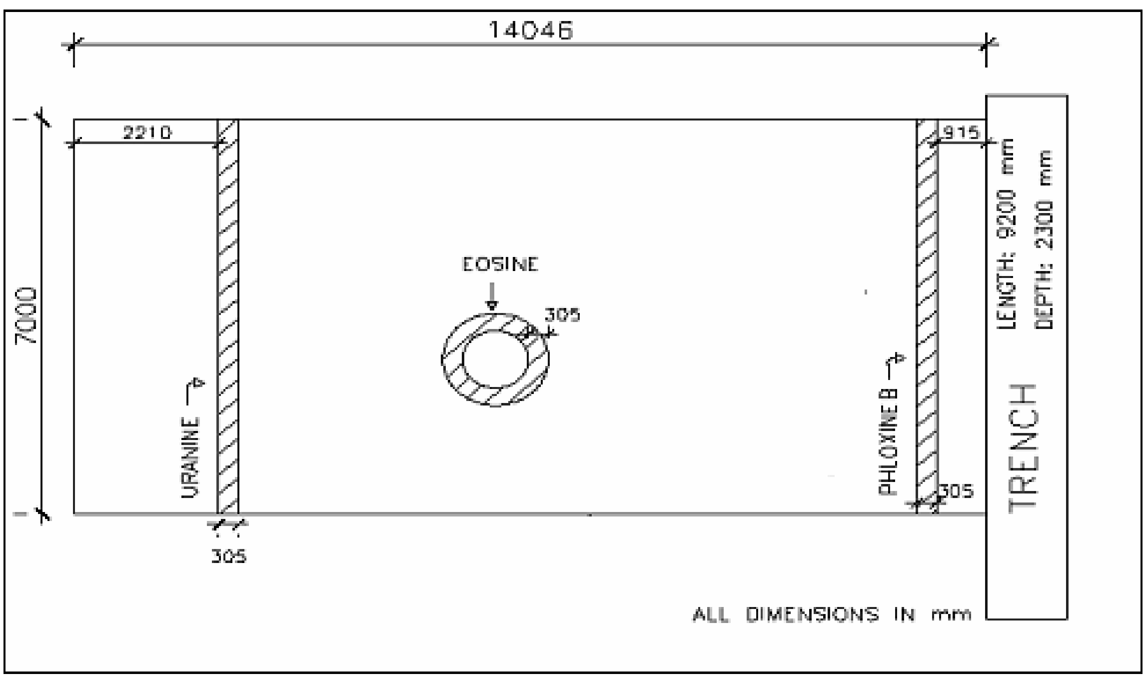

Figure 3.2. Dye application areas. Modified from an original illustration provided by Surajit Dasgupta.

in the first test). Masses of dye for the second test were 1665 mg of Phloxine B, 1500 mg of eosine, and 1000 mg of uranine.

Rainfall simulation

For each test, rainfall was simulated in two stages, with the first stage consisting of a 2.5 cm/hr event lasting for four hours. After the end of the first stage, lateral subsurface flow in the trench was allowed to stop before beginning the second stage simulation with an intensity of 15.2 cm/hr and duration of one hour. The second stage of rainfall application began as soon as subsurface flow had decreased to a level that no longer allowed sampling (with essentially no lateral subsurface flow).

Sampling procedure

For both tracer tests, water samples were collected from every location on the trench face which produced flow, with the first sample from each location collected at initiation of flow. Succeeding samples were taken at regular intervals until the end of flow. The time interval between samples depended on relative flow amount at each location. The shortest intervals were used at high flow conduits and the longest time intervals were at the seepage locations. For the first tracer test, major spring locations (B_1 and B_2) were sampled every two minutes, with remaining locations sampled every five minutes. For the second test, sampling intervals were initially set at five minutes for high and medium flow locations and fifteen minutes for seepage locations. For the period of decreasing flow at the end of the test, all locations were sampled at ten-minute intervals. In order to prevent cross-contamination of samples, latex gloves were changed between sampling locations. Water samples were collected in clean, unused vials and some seepage locations required pipettes for sample collection. Fresh pipettes were used for each sample. Samples were stored in a sealed, insulated container to prevent photodegradation of the dye contained in the samples.

Fluorescence analysis

Samples were scanned individually for fluorescence signatures using regular light wavelength intervals in a luminescence spectrometer. Relative intensity values were generated for each wavelength increment and stored in tabular form. A graphical display of relative intensity for each sample was used to determine dye signature peak height and central wavelength. Due to the significant level of noise present in the intensity data and the possibility of overlapping dye peaks, raw sample data were analyzed with nonlinear curve fitting software using a Pearson Type VII Area function which fit a smoothed curve to the raw values. The software also divided each intensity curve into component peaks representing background and dye signals. Dye presence was confirmed by the application of a limit of detection set at five times the standard error of fitted to raw data (averaged over all samples for each location). For samples exceeding the limit of detection an additional limit of quantification (the level above which dye intensity can be accurately quantified) of ten times the standard error was applied. Intensity values were converted into concentrations through a linear relationship developed from spectrometer calibration standards of known concentration. The resultant concentrations were then arranged into time series by sampling location and time, with samples below the limit of quantification omitted.

Results

Test I

For the first tracer test, dye concentrations in all samples were generally very low, with only a small proportion of the samples collected exhibiting eosine and phloxine dye intensities above the limit of quantification. Uranine was not detected in any sample from any location. Location A_1 produced samples with low quantities of eosine for approximately 2.75 hours. Concentrations for this location averaged 0.62 ppb with a maximum eosine concentration of 0.96 ppb. Locations A_2 and A_3 exhibited traces of eosine as well, although the eosine signatures at these locations were sporadic and all fell below the limit of quantification. The results for sampling location B_1 indicated the presence of both eosine and phloxine in small concentrations, with eosine present shortly after flow and phloxine delayed until near the end of the test. Eosine was present for 2.83 hours, with the few quantifiable samples giving an average concentration of 0.54 ppb. Although phloxine appeared later, it demonstrated slightly higher concentrations (average of 1.1 ppb) for 1.03 hours. B_2 and B_3 also produced small quantities of eosine shortly after the beginning of flow. Locations B_4, C_1, C_2, and C_3 all had breakthrough curves for phloxine. Almost no dye was detected for region D, with D_1, D_2, D_3, and D_5 showing no detectable dye and location D_4 showing two samples with confirmed phloxine presence.

Test II

Overall, dye concentrations were much higher for the second tracer test, although once again no uranine was detected in any samples. All of the conduit outlets (A_1 and B_2) and several of the fracture outlets (A_2, A_3, B_2, and B_3) produced samples with quantifiable amounts of both eosine and phloxine. Location A_1 produced breakthrough curves for both dyes, with eosine and phloxine present for almost the full duration of flow. However, the two dyes were observed in nearly opposite patterns, with high eosine concentrations during the first stage of the simulation and high phloxine concentrations during the second stage. For A_2, no clear pattern could be found in the breakthrough curve, possibly due to gaps in the sampling interval. At location A_3, both dyes persisted for the full duration of flow, with eosine peaking after three minutes and then decreasing rapidly and phloxine steadily increasing to a peak at the 33-minute mark. At locations B_1 and B_3 concentrations of phloxine and eosine both followed a pattern of increasing concentration during the first stage of rainfall simulation. However, for the second stage phloxine and eosine displayed different patterns, with peaks for eosine lagging behind those for phloxine. This behavior was typical of the fracture outlets in the trench. Behavior of the two tracers at B_2 was very similar to one another, with concentrations of phloxine above those of eosine for most of the test. The remaining fracture locations (A_4 and B_4) produced high concentrations of phloxine (400

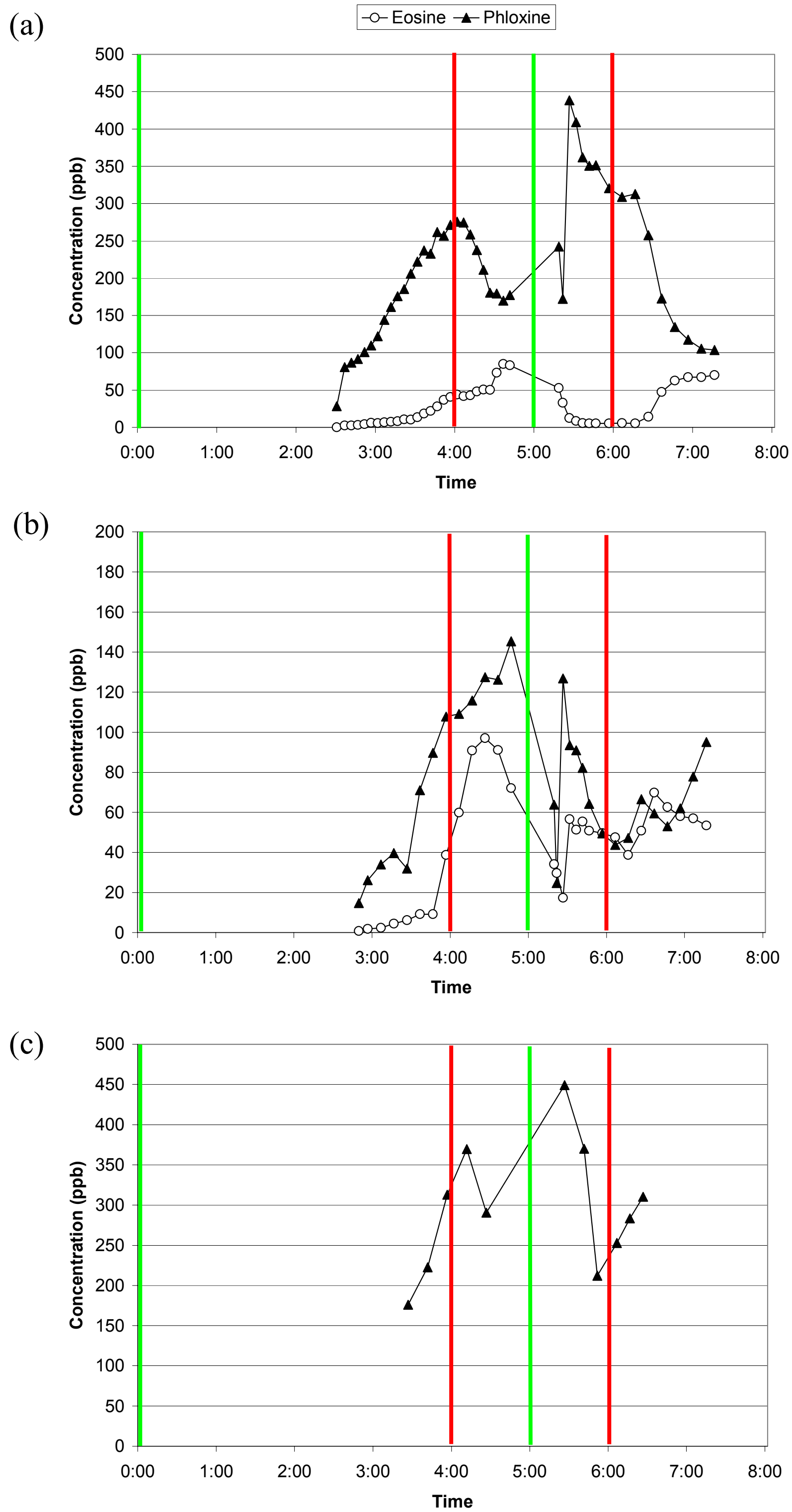

Figure 3.3. Dye behavior at locations (a) B_1, (b) B_2, and (c) C_2 for the second dye tracer test at the Honey Creek juniper plot.

to 700 ppb), although the short duration of flow from these locations prevented the formation of a clear breakthrough curve.

The seepage locations in regions C and D also produced short time series of dye concentrations dominated almost entirely by phloxine, with only locations C_1 and D_4 producing eosine signatures. The dyes in samples at C_1 had a similar pattern to those in B_1 and B_3, but with phloxine concentrations exceeding those of eosine by a greater amount. For D_4, eosine was detected at 2.40 ppb in a single sample. For illustration of flow for each domain type see Figure 3.3, where the green and red lines represent run starts and stops respectively. Results for all sampling locations producing dye signatures for test II are given in Appendix C.

Discussion

Tracer effectiveness

Before interpreting the results of the dye tracer test in relationship to the conceptual model, the effectiveness of the testing method itself must be evaluated. As shown in the results of the second test, quantifiable dye concentrations were found for every sampling location and for a majority of samples. In addition, at locations with long time series of dye concentrations reasonably smooth and coherent breakthrough curves were obtained. The detection of dye concentrations in trench samples demonstrates the potential for the successful use of surface applied fluorescent tracers, and the breakthrough curves are excellent for flow studies in shallow epikarst.

However, the two tracer tests performed at Honey Creek reveal limitations to the use of surface applied dyes as well. While sinkhole injection traces may encounter some problems with dilution, surface application appears to suffer to a much greater extent from dye loss through binding with organic leaf litter as well as subsurface clays. Currently there is no clear relationship which has been developed to predict the amount of dye required for tracer studies utilizing surface application. One can clearly see this in the amounts of dye applied for the two tracer tests, which differed by orders of magnitude.

Contributing area

An examination of the results of the dye tracer tests suggests that not all under-canopy areas contributed shallow lateral subsurface flow into the trench. As noted earlier in the results section, the uranine dye applied at the rear portion of the plot was not detected in any sample for either test. The rear portion of the research site does differs significantly in appearance from the forward portion, with a more level surface, lighter juniper cover, and more rock presence on the surface. Because water is not observed to pond on the rear portion of the plot, nor to move through surface runoff to other plot sections (no uranine was detected in ponded water within the plot), it must be entering the subsurface at locations close to the dye application area. There are a number of possible explanations for the lack of dye detections between the rear portion of the plot and the monitoring trench. The simplest scenario is that the water entering the subsurface through the rear of the plot may simply move through flow paths which do not intersect the trench, moving around or under the excavation rather than following the slope of the ground surface. As well, the rear portion of the plot may drain away from the trench. With bedrock exposed at the ground surface, water in this area may have intersected some subsurface karst feature such as a solutionally enlarged vertical fracture, which allowed the water to travel down instead of laterally. Another possibility is that hydraulic travel time from the rear portion of the plot greatly exceeded the rainfall simulation time so that flow did not persist long enough for dye to reach the front of the plot. It is also possible that water from the rear portion of the plot did in fact reach outlets in the trench but arrived without retaining detectable levels of the uranine tracer, with the combination of loss of dye to the litter layer and through binding with flow path surfaces and clays resulting in complete capture of the applied uranine. Since this distance is farther from the trench, there are correspondingly more opportunities for loss due to adsorption. This issue requires additional research. However, the lack of any uranine dye in the trench samples serves as a reminder of the high geologic variability which occurs even over small distances in karst.

Discrete flow paths

For discrete flow paths with little or no interconnection, each outlet would be associated with the signature of a single dye, with each conduit outlet associated with a well-defined contributing area on the plot surface. The differences in hydraulic response times for the each outlet in the trench and the discrete spatial locations of the outlets in the trench face suggest that the subsurface flow paths intersecting the trench operate independently of one another. However, the results of the tracer tests indicate that the flow paths are linked to multiple contributing zones within the plot. Combining these two sets of observations suggests that the flow paths are highly connected, but also that all portions of the flow networks do not respond uniformly; they respond as the flow in each section changes, which is why we can see overall connectedness, but hydraulic individuality. While only one location for the first test (B_1) included both phloxine and eosine (probably due to low applied concentrations), the second test had eight of the sixteen sampling locations with strong signatures for both phloxine and eosine. With half of the active sampling locations linked to multiple inlet locations, one must reject the conceptual model's assertion that flow paths under the plot's juniper canopy cover have minimal interconnection. Therefore, there is high flow path interconnection, even over short (10 m) distances. Subsequent testing using smoke injected into outlet A_1 as a visible tracer confirmed flow path interconnection, with smoke emerging from locations A_2, A_3, B_1, and B_2 in the trench face. Smoke was only observed to exit the trench face through cracks and fissures which have been observed to produce water flow. It is also important to note that while there are clear connections between various flow paths, these connections are not uniform, due to the highly variable nature of this multiple-scale permeability system.

Inlet-outlet linkages

For the conceptual model, specific contributing area types are associated with the different flow domains, which corresponds partially to the findings of the dye tracer tests. Matrix or slow flow through clay lenses was dominated almost entirely by water from the forward portion of the plot, with only two of the eight seepage locations (C_1 and C_4) sampled in the trench producing samples with eosine. Only one of these locations (C_1) produced a clear breakthrough curve. The other location (C_4) showed only a single sample with eosine. This may be because these flow systems were moving too slowly to produce water from the rest of the plot during the trial period of approximately seven hours, because of dye loss from other parts of the plot to adsorption, or because the seepage locations are not as extensively connected, so only produced water from a very local flow network. However, the conduit and fracture flow sampling locations in the trench contained high concentrations of eosine from the central tree area as predicted by the conceptual model. However, as discussed in the analysis of flow path interconnection, samples from locations in regions A and B where conduit and fracture flow were observed contained both eosine and phloxine signatures. Interestingly, seven of the locations which produced breakthrough curves for multiple dyes are either conduits or open fractures. Therefore, the conduit outlets in the trench face received water primarily from the surface in the plot where the central juniper tree was located. Several trends in the data suggest that the central portion of the plot did contribute the majority of water to these outlets. The strongest evidence is the closely timed appearance of both phloxine and eosine in samples from conduit and fracture outlets, with A_2 and A_3 displaying concurrent appearance and the others having eosine appearance lagging phloxine by 13 to 25 minutes. In order for the eosine to travel laterally 7 m in the same or nearly the same time that phloxine traveled 1m laterally, flow from the central area of the plot must have been much more rapid, such as through conduits. Such closely timed dye emergence could also come from the movement of eosine to the forward portion of the plot through ponding or localized overland flow. However, samples from ponded water between the central and forward portions of the plot showed no indications of any dye, making overland transport of eosine unlikely. Additionally, four of the seven major conduits and open fractures showed eosine concentrations peaking prior to phloxine. This also suggests that eosine was transported rapidly through conduits, while phloxine had to infiltrate through the soil without the aid of root-enlarged macropores before reaching the fractures or conduits in the underlying limestone.

Travel times

Travel times for both water and dyes were clearly related to outlet type, with conduit and large fracture outlets responding relatively quickly (producing flow in 2.5 to 3.5 hours), with most of the smaller fractures taking slightly longer and most of the seepage locations responding only after five to six hours. This was expected, since the larger conduits have frequently been observed to produce rapid flow of large volumes of water. Lateral dye movement rates of eosine were higher for conduits and large fractures (up to 2.4 m/hr for at B_1) than for smaller fractures (2.2 m/hr at B_3) and seepage locations (1.9 m/hr). Interestingly, locations C_1 and C_2, although operating in the seepage flow domain, became active shortly after location B_2 began to produce flow. Their close proximity to the main outlet suggests that this may be due to linkage between the two regions. Figure 3.1 shows cross-cutting stratigraphy at the trench scale. This cross-cutting feature is probably a karst feature that has been filled. The area surrounding this feature could be expected to have higher permeability and/or connectivity, due to the solutional activity that created the karst feature. As such, it appears that flow path interconnections at the research site may, in addition to linking conduit flow paths, create linkages across flow domains, creating flow rates far in excess of those expected for the seepage domain. This, combined with the fracture-like dye breakthrough response of C_1, suggest that movement through bedding planes indeed forms an active flow domain under the plot. Flow in karst aquifers in the phreatic zone is known to be able to integrate flow from conduits, fractures, and the matrix, and this study demonstrates similar effects in the epikarst.

Conclusions

The results of the dye content analysis lead to a number of important conclusions about the subsurface hydrology of the project site, including: (1) surface applied fluorescent dyes are useful tracers for studies of water movement in shallow karst at the large plot scale, (2) flow direction at this scale is not predictable from topography, (3) high flow path interconnection exists even at short scales, (4) outlets with high flow rates are hydraulically connected to juniper land cover. Based on these conclusions, the original suggestions of the conceptual model for discrete flow paths are rejected in favor of significant interconnection among flow paths, even over short distances. However, the fourth major conclusion supports the conceptual model's assertion of a relationship between juniper vegetation and the outlets with high rates of lateral subsurface flow. Given the complex nature of subsurface flow paths in the area and the demonstrated potential for juniper to interact with the dominant flow domain, future studies must endeavor to gain a better understanding of these interactions and their effects on potential water yields from brush clearing.

CHAPTER IV
CONCLUSIONS

Analysis of the results of standard simulation testing at the juniper and grass plots revealed a great deal about local hydrologic processes and the effects of brush removal. As with other studies of ashe juniper, stemflow was observed to route large volumes of water directly to the base of trees. However, stemflow totals from this study were much higher then values previously reported in the literature for ashe juniper on the Edwards Plateau. While data was limited by the relatively small number of simulations at the plot, it also appears that stemflow may exhibit a seasonal variability not previously documented for ashe juniper. An examination of runoff data reveals other interesting behavior. Brush vegetation, including juniper, is often observed to play a major role in determining surface runoff behavior. For this area surface runoff is controlled by both soil and subsurface structure, both of which vary considerably over short distances. Juniper appears to create major alterations in local soil structure and improved infiltration capacity.

Brush removal was shown to decrease the proportion of surface-applied water moving as shallow lateral subsurface flow to the trench. However, the total amount of water reaching subsurface layers and possibly (although not certainly) traveling off-site through other pathways was increased after removal of juniper vegetation. The increased water input is a direct result of brush removal, as interception accounted for the loss of an estimated 19.5 percent of standard simulation precipitation. This loss is much higher than previous estimates of interception for a rainfall event of this size for Edwards Aquifer juniper vegetation. While the additional water may not necessarily travel beyond the plot boundaries, it could provide on-site benefits including increased moisture availability for herbaceous growth.

The dye tracer experiments carried out at the juniper plot highlight the complexity of the karst geology of the Edwards Aquifer, even at small scales. Subsurface flow paths were highly interconnected, resulting in outlet linkages to multiple contributing areas within the plot surface. Test results also show the ability of surface and subsurface flow paths to move in different directions even at small scales, as demonstrated by the subsurface flow disconnect found between the middle and top of the plot. Finally, a strong connection between juniper vegetation and conduit flow paths was discovered. While the implications of this association are unclear, future standard simulations at the Honey Creek project site and at other locations on the Edwards Plateau may reveal more information on the impacts of brush removal over time on water yields.

REFERENCES

Afinowicz J. 2004. Evaluation of shrub encroachment and brush control on water availability in the Upper Guadalupe River watershed. MS Thesis. Texas A&M University: College Station, TX.

Archer S. 1994. Woody plant encorachment into southwestern grasslands and savannas: rates, patterns, and proximate causes. In *Ecological Implications of Livestock Herbivory in the West*, Varva M (ed.). Society for Range Management: Denver; 13-63.

Archer S, Boutton TW, Hibbard KA. 2001. Trees in grasslands: biogeochemical consequences of woody plant expansion. In *Global Biogeochemical Cycles in the Climate System*, Schulze ED (ed.). Academic Press: San Diego; 115-137.

Bednarz ST, Dybala T,. Muttiah RS, Rosenthal W, Dugas WA. 2000. Brush management/water yield feasibility studies from eight watersheds in Texas. Blackland Research Center: Temple, TX.

Bhark EW, Small EE. 2003. Association between plant canopies and the spatial patterns of infiltration in shrubland and grassland of the Chihuahuan Desert, New Mexico. *Ecosystems* **6**(2): 185-196.

BS/EACD (Barton Springs / Edwards Aquifer Conservation District). 2003. Summary of groundwater dye tracing studies (1996-2002), Barton Springs segment of the Edwards Aquifer, Texas. BS/EACD: Austin, TX.

Burkardt JW, Tisdale EW. 1976. Causes of juniper invasion in southwestern Idaho. *Ecology* **57**(3): 472-484.

Carlson D, Thurow T, Knight R, Heitschmidt R. 1990. Effect of honey mesquite on the water balance of Texas Rolling Plains rangeland. *Journal of Range Management* **43**(6): 491-496.

Dasgupta S. 2005. Infiltration under two contrasting hydrologic scenarios in Texas. MS Thesis, Texas A&M Univeristy: College Station, TX.

Davenport DW, Breshears DD, Wilcox BP, Allen CD. 1998. Viewpoint: sustainability of pinon-juniper ecosystems - a unifying perspective of soil erosion thresholds. *Journal of Range Management* **51**(2): 231-240.

Decagon. 2005. ECH_2O soil moisture sensor operator's manual version 2.1. Decagon Devices: Pullman, WA.

Devitt DA, Smith SD. 2002. Root channel macropores enhance downward movement of water in a Mojave Desert ecosystem. *Journal of Arid Environments* **50**(1): 99-108.

Domingo F, Sánchez G, Moro MJ, Brenner AJ, Puigdefábregas J. 1998. Measurement and modeling of rainfall interception by three semi-arid canopies. Agricultural and Forest Meteorology **91**(4): 275-292.

Dugas WA, Mayeux HS. 1991. Evaporation from rangeland with and without honey mesquite. *Journal of Range Management* **44**(2): 161-170.

Dugas WA, Hicks RA, Wright P. 1998. Effect of removal of Juniperus ashei on evapotranspiration and runoff in the Seco Creek watershed. *Water Resources Research* **34**(6): 1499-1506.

Fuhlendorf SD, Smeins FE, Taylor CA. 1997. Browsing and tree size influences on ashe juniper understory. *Journal of Range Management* **50**(5): 507-512.

Graf WL (editor). 1988. Vegetation and dryland rivers. In *Fluvial Processes in Dryland Rivers*. Springer-Verlag: Berlin, Germany; 233-258.

Gregory LF. 2006. Water budgets and cave recharge on juniper rangelands in the Edwards Plateau. MS Thesis, Texas A&M University: College Station ,TX.

HDR Engineering, Inc. 2000. Edwards Aquifer watershed: brush control planning, assessment, and feasibility study. HDR: Omaha, NE.

Helling CS, Gish TJ. 1991. Physical and chemical processes affecting preferential flow. In *Preferential Flow: Proceedings of the National Symposium*. Americal Society of Agricultural Engineers: St. Niles, Mi; 77-86.

Hester JW, Thurow TL, Taylor CA. 1997. Hydrologic characteristics of vegetation types as affected by prescribed burning. *Journal of Range Management* **50**(2): 199-204.

Hibbert AR. 1983. Water yield improvement potential by vegetation management on western rangelands. *Water Resources Bulletin* **19**(3): 375-381.

Humphrey RR. 1958. The desert grassland: a history of vegetational change and an analysis of causes. *The Botanical Review* **24**(4): 193-252.

Huxman TE, Wilcox BP, Breshears DD, Scott RL, Snyder KA, Small EE, Hultine K, Pockman WT, Jackson RB. 2005. Ecohydrological implications of woody plant encroachment. *Ecology* **86**(2): 308-319.

Jackson RB, Sperry JS, Watson TE. 2000. Root water uptake and transport: using physiological processes in global predictions. *Tends in Plant Science* **5**(11): 482 - 488.

Kirby MJ. 1985. Hillslope hydrology. In *Hydrological Forecasting*. John Wiley and Sons: New York, NY; 37-76.

Kreuter UP, Tays MR, Conner JR. 2004. Landowner willingness to participate in a Texas brush reduction program. *Journal of Range Management* **57**(3): 230-237.

Kurc SA, Small EE. 2004. Dynamics of evapotranspiration in semiarid grassland and shrubland ecosystems during the summer monsoon season, central New Mexico. *Water Resources Research* **40**(9): W090305.

Ludwig, J.A., and D.J. Tongway. 1997. Viewing rangelands as landscape systems. In *Landscape Ecology, Function and Management: Principles from Australia's Rangelands*. CSIRO: Melbourne, Australia; 1-12.

Ludwig JA, Wilcox BP, Breshears DD, Tongway DJ, Imeson AC. 2005. Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes. Ecology 86(2): 288-297.

Maclay RW. 1995. Geology and Hydrology of the Edwards Aquifer in the San Antonio Area, Texas. *USGS Water Resources Investigations Report 95-4186*. USGS Library Call Number (200) WRi no.95-4186. Available online at http://pubs.er.usgs.gov/usgspubs/wri/wri954186. Last accessed 4/18/2006.

Martinez-Meza E, Whitford WG. 1996. Stemflow, throughfall and channelization of stemflow by roots in three Chihuahuan Desert shrubs. *Journal of Arid Environments* **32**(2): 271-287.

Miller RF, Svejcar TJ, Rose JA. 2000. Impacts of western juniper on plant community composition and structure. *Journal of Range Management* **53**(6): 574-585.

Návar J, Bryan RB. 1990. Interception loss and rainfall redistribution by three semi-arid growing shrubs in northeastern Mexico. *Journal of Hydrology* **115**: 51–63.

Newman BD, Campbell AR, Wilcox BP. 1998. Lateral subsurface flow pathways in a semiarid ponderosa pine hillslope. *Water Resources Research* **34**(12): 3485-3496.

Nulsen RA, Bligh KJ, Baxter IN, Solin EJ, Imrei DH. 1986. The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia. *Australian Journal of Ecology* **11**(4): 361-371.

Olenick KL, Wilkins RN, Conner JR. 2004. Increasing off-site water yield and grassland bird habitat in Texas through brush treatment practices. *Ecological Economics* **49**(4): 469-484.

Owens K, Ansley J. 1997. Ecophysiology and growth of ashe and redberry juniper. In *Juniper Symposium 1997 Proceedings, Texas Agricultrual Experiment Station Technical Report 97-1*. Texas Agricultural Experiment Station: San Angelo; 3.19-3.32.

Owens MK. 1996. The role of leaf and canopy level gas exchange in the replacement of *Quercus virginiana* (Fagacea) by *Juniperus ashei* (Cupressaceae) in semiarid savannas. *American Journal of Botany* **83**(5): 617-623.

Owens MK, Lyons RK. 2004. Evaporation and interception water loss from juniper communities on the Edwards Aquifer Recharge Zone, Final Report. Texas A&M University: College Station, TX

Owens MK, Schliesing TG. 1995. Invasive potential of ashe juniper after mechanical disturbance. *Journal of Range Management* **48**(6): 503-507.

Porter SC. 2005. The use of a rainfall simulator for brush control research on the Edwards Plateau region of Texas. MS Thesis, Texas A&M University: College Station, TX.

Reynolds JF, Virginia RA, Kemp PR, de Soyza AG, Tremmel DC. 1999. Impact of drought on desert shrubs: effects of seasonality and degree of resource island development. *Ecological Monographs* **69**(1): 69-106.

Richardson CW, Burnett E, Bovey RW. 1979. Hydrologic effects of brush control on Texas rangelands. *Transactions of the ASAE* **22**(2): 315-319.

Scanlon BR, Tyler SW, Wierenga PJ. 1997. Hydrologic issues in arid, unsaturated systems and implications for contaminant transport. *Reviews of Geophysics* **35**(4): 461-490.

Schlesinger WH, Abrahams, Parsons AJ, Wainwright J. 1999. Nutrient losses in runoff from grassland and shrubland habitats in southern New Mexico: I. rainfall simulation experiments. *Biogeochemistry* **45**(1): 21-34.

Schott MR, Pieper RD. 1985. Influence of canopy characteristics of one-seed juniper on understory grasses. *Journal of Range Management* **38**(4): 328-331.

SCS (Soil Conservation Service). 1984. Soil survey of Comal and Hays Counties, Texas. SCS: College Station, TX.

Seyfried MS, Schwinning S, Walvoord MA, Pockman WT, Newman BD, Jackson RB, Phillips FM. 2005. Ecohydrological control of deep drainage in arid and semiarid regions. *Ecology* **86**(2): 277-287.

Seyfried MS, Wilcox BP. 1995. Scale and the nature of spatial variability: field examples having implications for hydrologic modeling. *Water Resources Research* **31**(1): 173-184.

Skau CM. 1964. Interception, throughfall, and stemflow in Utah and alligator juniper cover types of northern Arizona. *Forest Science* **10**(3): 283-287.

Smeins F, Fuhlendorf S, Taylor C. 1997. Environmental and land use changes: a long-term perspective. In *Juniper Symposium 1997 Proceedings, Texas Agricultrual Experiment Station Technical Report 97-1*. Texas Agricultural Experiment Station: San Angelo; 1.3-1.21.

Smith RA, Veni G. 1994. Karst Regions of Texas. In *The Caves and Karst of Texas: a guidebook for the 1994 conventions of the National Speleological Society with emphasis on the southwestern Edwards Plateau, Brackettville, Texas, June 19-24, 1994*. National Speleological Society: Huntsville, AL; 7-12.

Sorenson JR. 2004. The use of large plot rainfall simulation to investigate runoff generation on the Edwards Plateau, Texas. MS Thesis, Texas A&M University: College Station, TX.

TAES (Texas Agricultural Experiment Station). 2005. Shrub control and water yield on Texas rangelands: current state of knowledge, Research Report 05-1. Texas Agricultural Experiment Station: College Station, TX

Tarjuelo JM, Montero J, Carrion PA, Honrubia FT, Calvo MA. 1999. Irrigation uniformity with medium sized sprinklers part II: influence of wind and other factors on water distribution. *Transactions of the ASAE* **42**(3): 677-689.

Thurow TL, Hester JW. 1997. How an increase or reduction in juniper cover alters rangeland hydrology. In *Juniper Symposium 1997 Proceedings, Texas Agricultrual Experiment Station Technical Report 97-1*. Texas Agricultural Experiment Station: San Angelo, TX; 4.9-4.22

Thurow TL, Thurow AP, Garriga MD. 2000. Policy prospects for brush control to increase off-site water yield. *Journal of Range Management* **53**(1): 23-31.

Thurow TL, Thurow AP, Taylor CA, Conner R, Garriga M. 1997. Environmental and economic tradeoffs associated with vegetation management on the Edwards Plateau. In *Juniper Symposium 1997 Proceedings, Texas Agricultrual Experiment Station Technical Report 97-1*. Texas Agricultural Experiment Station: San Angelo, TX; 2.3-2.10.

Thurow TL, Blackburn WH, Taylor CA. 1988. Infiltration and interrill erosion responses to selected livestock grazing strategies, Edwards Plateau, Texas. *Journal of Range Management* **41**(4): 296-302.

Thurow TL, Blackburn WH, Warren SD, Taylor CA. 1987. Rainfall interception by midgrass, shortgrass, and live oak mottes. *Journal of Range Management* **40**(5): 455-460.

TSSWCB (Texas State Soil & Water Conservation Board). 2004. Brush Control Program 2004 Annual Report. TSSWCB: Temple, TX.

Van Auken OW. 2000. Shrub invasions of North American semiarid grasslands. *Annual Review of Ecological Systems* **31**: 197-215.

Veni G. 2004. Karst research in Texas and the Edwards Aquifer: past, present and future. Pre-print of paper submitted to STGS/AGS Edwards water resources symposium. San Antonio, TX. May 21-22, 2004.

Ward AD, Trimble SW. 2004. *Environmental Hydrology*. Lewis Publishers: Boca Raton, FL; 434.

Weltz Ma, Blackburn WH. 1995. Water budget for south Texas rangelands. *Journal of Range Management* **48**(1): 45-52.

Wilcox BP. 2002. Shrub control and streamflow on rangelands: a process based viewpoint. *Journal of Range Management* **55**(4): 318-326.

Wilcox BP, Breshears DD, Allen CD. 2003. Ecohydrology of a resource-conserving semiarid woodland: effects of scale and disturbance. *Ecological Monographs* **73**(2): 223-239.

Wilcox BP, Newman BD, Brandes D, Davenport DW, Reid K. 1997. Runoff from a semiarid ponderosa pine hillslope in New Mexico. *Water Resources Research* **33**(10): 2301-2314.

Woodruff CM, Marsh WM, Wilding LP. 1992. Research overview: multidisciplinary approach to terrain analysis with implications for environmental management. In *Soils, Landforms, Hydrologic Processes, and Land-use Issues: Glen Rose Limestone Terrains, Barton Creek Watershed, Travis Count, Texas*. Society of Independent Professional Earth Scientists Central Texas Chapter: Austin, TX.; 1.1 - 1.6.

Wright H, Churchill FM, Stevens WC. 1982. Soil loss, runoff, and water quality on seeded and unseeded steep watersheds following prescribed burning. *Journal of Range Management* **35**(3), 382 - 385.

Wright HA, Chruchill FM, Stevens WC. 1980. Soil loss, runoff, and water quality of seeded and unseeded steep watersheds following prescribed burning. *Journal of Range management* **35**(3): 382-385.

Wright HA, Chruchill FM, Stevens WC. 1976. Effect of prescribed burning on sediment, water yield, and water quality from dozed juniper lands in central Texas. *Journal of Range Management* **29**(4): 294-298.

Wu XB, Redeker EC, Thurow TL. 2001. Vegetation and water yield dynamics in an Edwards Plateau watershed. *Journal of Range Management* **54**(2): 98-105.

Yair A, Lavee H. 1985. Runoff generation in arid and semi-arid zones. In *Hydrological Forecasting*. John Wiley and Sons: New York, NY; 183-220.

APPENDIX A

Stemflow

Stemflow was measured directly on two of the six mature juniper trees located within the juniper plot. Due to the multi-stemmed physiology of the trees and dense branches, the stemflow measurement system differed slightly from the basic stemflow collars used by Owens and Lyons (2004), Sorenson (2004), and Gregory (2006) in similar studies. For this study, scoop-shaped funnels were attached to the undersides of major limbs and sub-stems. Water flowing along these limbs was captured by the funnels and routed through tubing to a collar around the dominant stem. Water captured directly by this collar and by the smaller contributing funnels then moved through a hose to an enclosed tipping bucket meter. The bucket had a 1 L capacity, with each liter of flow causing the bucket to tip and send a signal to a datalogger. The total number of tips was stored at one-minute intervals for standard simulations and at 15 minute intervals otherwise. Drainage holes in the bottom of the tipping bucket enclosure allowed measured water to reach the base of the tree in an effort to minimize the impact of the measurement system.

Because only two of the six mature trees in the plot were instrumented, the values stored by the datalogger were scaled to represent the entire plot. Note that while this study used a stemflow scaling factor of 3.38, similar to the value of 3.33 used by Porter (2005) at the plot for a previous study, the factors were determined in different ways. Porter (2005) used a canopy cover ratio to derive a scaling factor, with the 100 percent canopy cover for the plot divided by the 30 percent cover for the instrumented trees generating the scaling multiplier. For this study, the stemflow scaling factor was based on trunk size. Tree circumference was measured at ground level, with trunk cross-sectional area approximated as a circle with a circumference equal to that measured. The scaling factor was calculated as the ratio of total tree basal area for the entire plot to the basal area of the two instrumented trees.

To determine total stemflow for a standard simulation run, stemflow values for both trees were added for the time interval of the run. This value was multiplied by 3.38 to represent the entire plot. This value, in liters, was divided by 1000 for conversion into

m^3 and then divided by the plot area of 98 m^2 to give an equivalent depth in m. To generate a final depth in mm, the depth was multiplied by 1000. It is important to note that because stemflow represents a scaled value, uncertainty in the scaling factor may impact the stemflow estimate itself as well as estimates of total water reaching the plot surface.

An example of stemflow calculation from formatted datalogger output is shown below:

(1) *Formatted datalogger output*

Time (min)	Bucket #1 (L)	Bucket #2 (L)	Total (L)
0:00	0	0	0
0:01	0	1	1
0:02	1	2	3
0:03	1	2	3
0:04	0	1	1
0:05	1	0	1
		Total (L):	9

(2) Scaling

9 L * 3.38 = 30.42 L

(3) *Conversion to* m^3

30.42 L * (1 m^3 / 1000 L) = 0.03042 m^3

(4) Conversion to depth in mm

(0.03042 m^3 / 98 m^2) * (1000 mm / 1 m) = **0.31 mm**

Throughfall

As noted in Chapter II, throughfall was measured using both automated and manual systems. The automated system, similar to that used by Owens and Lyons (2004), Sorenson (2004), and Gregory (2006), consisted of two sets of branched funnel arrays. The photograph below shows a portion of the automated system used at the plot.

Throughfall funnels and piping system.

Water captured by the funnels traveled through PVC piping to an enclosed tipping bucket gauge system similar to that used to measure stemflow. Throughfall resolution was finer than that for stemflow, with throughfall measured with 0.1 L (100 mL) tipping bucket gauges. Values recorded on the datalogger were summed and then scaled to represent the entire plot by multiplying by a scaling factor. This factor was the ratio of total plot area to the throughfall funnel area. Conversion of this total from L to mm followed the same procedure as stemflow, with the only difference being the value of the scaling factor. Due to maintenance errors on the part of the author, the automated system failed to operate properly for most simulations; however, for simulations immediately following equipment lubrication, values from the automated system closely matched those from the manual system. During brush clearing, the automated system was removed from the juniper plot and was not re-installed.

Throughfall was also measured using an array of rain gauges located throughout the plot on a 1 by 1.7 m grid. These gauges were of the type commonly encountered in garden supply stores and had a maximum capacity of 140 mm. Depths readings for the gauges were recorded after every run, with the gauges emptied after reading. An estimated throughfall depth for the plot was generated by averaging the readings from the gauges in the array, with gauges falling over during simulations omitted from the calculation.

The manual gauge array was also used to calculate application uniformity using the Christiansen method, which is commonly used to assess the performance of irrigation sprinklers. The Christiansen Coefficient of Uniformity (CU) can vary from 0 to 100 percent (perfectly uniform) and is calculated using the equation

$$CU = 100 * \left(1 - \frac{\sum_{i=1}^{n} \left| x_i - \bar{x} \right|}{n * \bar{x}} \right)$$

where x_i is the depth for a particular gauge, $\bar{x}$ is the average gauge reading, and n is the total number of gauges (Tarjuelo et al 1999).

Out of plot losses

The methodology section of Chapter II briefly mentions a rain gauge array surrounding the juniper plot, with gauges spaced at 2 m by 2 m for use in measuring wind and overspray losses. Gauges were of the same type used for the manual array within the juniper and grass plots. This out-of-plot array was originally intended to allow for interception estimation for individual pre-cut standard simulations. Averaging of these gauges would give total out-of-plot losses, which when subtracted from pumped volume would reveal canopy-level precipitation. The difference between this precipitation and water reaching the surface (throughfall + stemflow) would represent interception.

However, testing of this method under post-cut conditions revealed severe under-estimation of overspray losses. For post-cut conditions, the average out-of-plot gauge value should have represented the difference between pumped and throughfall depths but only showed about half of the actual loss. This poor performance was likely due to the coarse 2 m by 2 m grid spacing and the fact that most overspray was observed to fall in the two meters between the plot border and the first row of out-of-plot gauges. Due to the low reliability of the wind and overspray loss estimate, this technique was abandoned as a method of estimating canopy interception.

Interception

As noted in the body of the thesis, canopy interception for the pre-cut standard simulations was estimated to be 32.7 mm. This estimate came from a comparison of total inputs to the juniper plot surface for pre- and post-cut conditions. Because similar volumes were pumped for both conditions, the difference in water reaching the ground was attributed to vegetation change. For the pre-cut standard simulations, 403.9 mm of water reached the plot surface (as throughfall and stemflow), while after cutting 503.2 mm were recorded as throughfall. Dividing the difference of 99.3 mm by 3 (the number of pre-cut standard simulations) gave an average interception of 33.1 mm.

Due to pumping of a slightly larger volume of water during post-cut standard simulations, a scaling factor was applied to the interception estimate. Prior to brush removal, 830.7 mm were pumped, while for post-cut simulations 841.2 mm were pumped. The original 33.1 mm interception estimate was multiplied by 830.7 / 841.2, yielding a corrected estimate of 32.7 mm.

Surface runoff

Surface runoff was measured using a 6-inch H-flume located at the downhill end of each plot. Due to the metal border around the plots, the flume was the only location where surface runoff could leave the plot area. The flume was manufactured with a very specific shape and dimensions so that the relationship between volumetric flow rate and depth in the flume were related according to a known equation. Actual measurement of depth was taken in a stilling well adjacent to the flume (the box structure attached to the flume as shown in the photograph). This stilling well was connected hydraulically to the flume through several small holes which allow water to flow between them. Water in the stilling well was at the same level as that in the flume but was far less turbulent, making measurement of depth much easier. A float within the stilling well could move up and down with the water level and was connected by a wire to a spindle at the top of the well. Movement of the float thus caused rotation of the spindle, which transmitted a signal to the datalogger. The datalogger then converted the signal to a depth value and stored an average depth once each minute. Depth values could be converted to volumetric flow rate in L/min using an equation based on the dimensions of the flume. The equation used for this study was y = 2378.95*(x^2.129), where y is flow rate in L/min and x is depth in feet. This value could then be converted to an equivalent depth for each 1-minute recording interval by dividing by the plot area of 98 m^2. Summing of depths across a certain time interval represented the total surface runoff amount during that interval. However, this process was not applied at the Honey Creek juniper plot as no surface runoff occurred.

For the grass plot equipment problems prevented recording of surface runoff data by the datalogger. For grass plot standard simulations, manually recorded depths reading taken at the flume at approximately three to five minute intervals were used to estimate surface runoff volume for each run.

Soil moisture storage

Soil moisture was measured using ten ECH_2O probes (Decagon 2005) located randomly throughout the plot. Probes were inserted into the soil below the litter layer, with the measurement surface of the probe inserted at an angle as subsurface rocks prevented vertical insertion. For these probes, probe output in millivolts is related to soil water content. For this study, the probe voltage was stored on the datalogger at one minute intervals and later converted to gravimetric water content (g water/ g soil) through a calibration equation derived by Dr. Keith Owens. The calibration equation is $y = 0.1905 * x - 62.182$, where x is sensor output in mV and y is gravimetric water content in g/g. The gravimetric content was then converted into volumetric water content by multiplying by the bulk density of the soil (0.88 g/cm^3) and assuming an ideal 1 g/cm^3 water density.

Volumetric water content readings from the ten individual probes were then averaged to generate a single value representing the entire plot. To ensure that the ten probes provided sufficient data for a representative average, measurements were made throughout the plot on a 1 by 1.7 m grid using a TDR probe and compared to the ECH_2O probe readings from the same time period. Average moisture contents and data standard deviations were similar for both methods, suggesting that the ten-probe average is a reliable approximation. Readings from any probe displaying clearly erroneous results (water contents < 0 percent or > 100 percent) were omitted from the average for the entire standard simulation. Soil moisture storage change was calculated as the difference in soil water content values before and after each run. Initial soil moisture was considered to be the moisture immediately before the start of the run and final moisture was the moisture reading from immediately before the following run. For the third run of each standard simulation, final moisture was determined at 45 minutes after the end of rainfall application. Calculation of total soil moisture storage required estimation of total soil volume. Based on subsurface exposure at the and a pit adjacent to the plot as well as from probing within the plot itself, the soil layer extended to an estimated depth of approximately 30 cm with a rock content of 75 percent. This was equivalent in volume to a continuous soil layer 76 mm in depth. Water content of the plot was found by multiplying the averaged volumetric water content by this depth, giving total storage in mm. Note that this storage term includes considerable uncertainty due to the limited data available for soil volume estimation and the fact that moisture was measured only in the upper portion of the soil horizon. An example of soil moisture storage change calculation for a given ten minute period is shown below:

(1) *Datalogger output*

Soil Moisture Probe Results from Datalogger					
	Probe Output (mV)				
Time	#1	#2	#3	#4	#5
0:00	549.7	344.4	453.4	399.3	391.9
0:01	551.1	347.1	453.4	403.3	392.6
0:02	553.8	362.5	457.4	410	442.1
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
0:10	574.5	365.8	486.2	453.4	457.4

(2) *Output converted to volumetric water contents*

Converted Soil Moisture Probe Results						
	Volumetric Water Content (%)					
Time	#1	#2	#3	#4	#5	Average
0:00	37.4	3.0	21.3	12.2	11.0	17.0
0:01	37.7	3.5	21.3	12.9	11.1	17.3
0:02	38.1	6.0	22.0	14.0	19.4	19.9
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
0:10	41.6	6.6	26.8	21.3	22.0	23.6

(3) *Change in volumetric storage*

ΔStorage = Final Content - Initial Content = 23.6 % - 17.0 % = 6.6 %

(4) *Converstion to depth*

Depth Stored = ΔStorage * Equivalent Soil Depth = 6.6 % * 76 mm = **5.0 mm**

Lateral subsurface (trench) flow

Trench flow was measured using a tipping bucket system similar to those used for stemflow and throughfall. Water emerging from the trench face flowed down the face and into a narrow channel running the length of the trench along the bottom of the trench wall. This channel sloped downward to a shallow sump at one end of the trench. The sump contained a submersible pump as well as a float switch which activated the pump when the water in the sump reached a certain level. This water was then pumped to a set of three tipping bucket gauges (1 L capacity each), with the total number of signals from each bucket stored on a datalogger at one minute intervals during standard simulations and at fifteen minutes otherwise. Water from the tipping bucket apparatus was then routed away from the plot using long pipes to prevent it from flowing back into the trench. Conversion of datalogger data from L to mm followed the same procedure as applied to stemflow and throughfall but without application of a scaling factor. The grass plot trench also included a gently sloping floor and sump to route shallow lateral subsurface flow to a single location. However, due to the small amount of lateral subsurface flow at the grass plot, measurement of water entering the sump was performed manually using a graduated vessel rather than with a tipping bucket system.

APPENDIX B

Table B1: Juniper Plot Standard Simulation (10-26-2004): Pre-cut

Test Description

Run	Duration	Target (mm)	Actual (mm)	Notes
1	1 h	101.6	111.6	**4"/h, 1h**
2	2 h	50.8	62.5	**1"/h, 2h**
3	45 min	114.3	114.4	**6"/h, 0.75h**

Data Summary

		Depth (mm)							
No.	Items	Run 1	%	Run 2	%	Run 3	%	Total	% of Applied
1	Water applied to plot surface	63.6	100.0%	27.8	100.0%	53.1	100.0%	144.5	100.0%
2	Stemflow	13.3	20.9%	7.4	26.5%	0.0	0.0%	20.6	14.3%
3	Throughfall (manual)	50.3	79.1%	20.4	73.5%	53.1	100.0%	123.8	85.7%
4	Surface Runoff	0.0	0.0%	0.0	0.0%	0	0.0%	0.0	0.0%
5	Soil moisture storage change	4.0	6.3%	5.0	18.0%	-2.1	-4.0%	6.9	4.8%
6	Lateral subsurface flow	19.6	30.8%	23.0	82.9%	40.3	75.8%	82.9	57.4%
7	Unaccounted	40.0	62.9%	-0.3	-1.0%	15.0	28.2%	54.7	37.9%

Ambient Conditions: Overcast, wind 0 - 8 kph.

Rainfall for Previous Week: ?

Comments: The plot was not extremely wet but appeared to have received a small amount of precipitation recently.

Table B2: Juniper Plot Standard Simulation (6-1-2005): Pre-cut

Test Description

Run	Duration	Target (mm)	Actual (mm)	Notes
1	1 h	101.6	108.7	**4"/h, 1h**
2	2 h	50.8	64.2	**1"/h, 2h**
3	45 min	114.3	105.3	**6"/h, 0.75h**

Data Summary

		Depth (mm)							
No.	**Items**	**Run 1**	**%**	**Run 2**	**%**	**Run 3**	**%**	**Total**	**% of Applied**
1	Water applied to plot surface	48.4	100.0%	25.0	100.0%	53.6	100.0%	127.0	100.0%
2	Stemflow	8.5	17.5%	4.0	15.9%	9.5	17.7%	21.9	17.2%
3	Throughfall (manual)	39.9	82.5%	21.0	84.1%	44.1	82.3%	105.1	82.8%
4	Surface Runoff	0.0	0.0%	0.0	0.0%	0	0.0%	0.0	0.0%
5	Soil moisture storage change	4.4	9.1%	1.3	5.4%	1.7	3.1%	7.4	5.8%
6	Lateral subsurface flow	4.0	8.2%	11.2	45.0%	37.2	69.4%	52.4	41.3%
7	Unaccounted	40.0	82.6%	12.4	49.7%	14.7	27.5%	67.1	52.9%

Ambient Conditions: Sunny, temperature 26.7 °C, wind 0 - 3.2 kph.

Rainfall for Previous Week: 72 mm

Comments: The plot surface appeared very wet due to rain early on the morning of the standard simulation. The subsurface seemed to be dry based on examination of the trench. The week leading up to this simulation was warm.

Table B3: Juniper Plot Standard Simulation (6-9-2005): Pre-cut

\Test Description

Run	Duration	Target (mm)	Actual (mm)	Notes
1	1 h	101.6	99.3	**4"/h, 1h**
2	2 h	50.8	57.4	**1"/h, 2h**
3	45 min	114.3	107.2	**6"/h, 0.75h**

Data Summary

		Depth (mm)							
No.	Items	Run 1	%	Run 2	%	Run 3	%	Total	% of Applied
1	Water applied to plot surface	53.5	100.0%	26.0	100.0%	52.9	100.0%	132.4	100.0%
2	Stemflow	9.6	17.9%	4.1	15.7%	11.7	22.1%	25.3	19.1%
3	Throughfall (manual)	44.0	82.1%	21.9	84.3%	41.2	77.9%	107.1	80.9%
4	Surface Runoff	0.0	0.0%	0.0	0.0%	0	0.0%	0.0	0.0%
5	Soil moisture storage change	4.8	9.0%	0.4	1.7%	1.2	2.2%	6.4	4.9%
6	Lateral subsurface flow	23.3	43.5%	20.3	78.2%	50.3	95.0%	93.9	70.9%
7	Unaccounted	25.4	47.4%	5.2	20.1%	1.5	2.8%	32.1	24.2%

Ambient Conditions: Partly cloudy, temperature 32.2 °C, wind 8 - 16 kph.

Rainfall for Previous Week: ?

Comments: The plot was extremely wet during this standard simulation due to a simulated rainfall event on the previous day (which was not included in the analysis due to equipment problems).

Table B4: Juniper Plot Standard Simulation (6-14-2005): Post-cut

Test Description

Run	Duration	Target (mm)	Actual (mm)	Notes
1	1 h	101.6	108.3	**4"/h, 1h**
2	2 h	50.8	59.8	**1"/h, 2h**
3	45 min	114.3	111.6	**6"/h, 0.75h**

Data Summary

		Depth (mm)							
No.	Items	Run 1	%	Run 2	%	Run 3	%	Total	% of Applied
1	Water applied to plot surface	67.1	100.0%	38.9	100.0%	66.4	100.0%	172.4	100.0%
2	Stemflow	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
3	Throughfall (manual)	67.1	100.0%	38.9	100.0%	66.4	100.0%	172.4	100.0%
4	Surface Runoff	0.0	0.0%	0.0	0.0%	0	0.0%	0.0	0.0%
5	Soil moisture storage change	0.7	1.0%	9.3	23.9%	-9.8	-14.7%	0.2	0.1%
6	Lateral subsurface flow	15.9	23.8%	23.1	59.3%	42.7	64.3%	81.7	47.4%
7	Unaccounted	50.4	75.2%	6.5	16.7%	33.5	50.4%	90.4	52.5%

Ambient Conditions: Sunny.

Rainfall for Previous Week: ?

Comments: Plot was wet due to preceding standard simulations on 6/8/05 and 6/9/05.

Table B5: Juniper Plot Standard Simulation (6-15-2005): Post-cut

Test Description

Run	Duration	Target (mm)	Actual (mm)	Notes
1	1 h	101.6	105.8	**4"/h, 1h**
2	2 h	50.8	76.1	**1"/h, 2h**
3	45 min	114.3	92.3	**6"/h, 0.75h**

Data Summary

		Depth (mm)							
No.	Items	Run 1	%	Run 2	%	Run 3	%	Total	% of Applied
1	Water applied to plot surface	65.2	100.0%	34.9	100.0%	69.3	100.0%	169.4	100.0%
2	Stemflow	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
3	Throughfall (manual)	65.2	100.0%	34.9	100.0%	69.3	100.0%	169.4	100.0%
4	Surface Runoff	0.0	0.0%	0.0	0.0%	0	0.0%	0.0	0.0%
5	Soil moisture storage change	5.7	8.8%	1.3	3.8%	0.8	1.1%	7.8	4.6%
6	Lateral subsurface flow	12.5	19.2%	28.7	82.3%	27.2	39.2%	68.4	40.4%
7	Unaccounted	46.9	72.0%	4.9	13.9%	41.4	59.7%	93.2	55.0%

Ambient Conditions: Sunny.

Rainfall for Previous Week: ?

Comments: The plot was extremely wet due to standards simulations on 6/8/05, 6/9/05, and 6/14/05.

Table B6: Juniper Plot Standard Simulation (6-28-2005): Post-cut

Test Description

Run	Duration	Target (mm)	Actual (mm)	Notes
1	1 h	101.6	119.4	**4"/h, 1h**
2	2 h	50.8	64.3	**1"/h, 2h**
3	45 min	114.3	103.5	**6"/h, 0.75h**

Data Summary

		Depth (mm)							
No.	**Items**	**Run 1**	**%**	**Run 2**	**%**	**Run 3**	**%**	**Total**	**% of Applied**
1	Water applied to plot surface	63.5	100.0%	34.6	100.0%	63.3	100.0%	161.4	100.0%
2	Stemflow	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
3	Throughfall (manual)	63.5	100.0%	34.6	100.0%	63.3	100.0%	161.4	100.0%
4	Surface Runoff	0.0	0.0%	0.0	0.0%	0	0.0%	0.0	0.0%
5	Soil moisture storage change	3.1	5.0%	12.0	34.8%	-10.4	-16.5%	4.7	2.9%
6	Lateral subsurface flow	24.0	37.8%	20.7	59.8%	23.3	36.8%	68.0	42.1%
7	Unaccounted	36.3	57.2%	1.9	5.5%	50.5	79.7%	88.7	55.0%

Ambient Conditions: Sunny.

Rainfall for Previous Week: ?

Comments: The plot appeared very dry prior to this standard simulations. While considerable water had been applied to the plot during the month of June, the period between this simulations and the preceding one on 6/15/05 was extremely warm.

Table B7: Grass Plot Standard Simulation (7-6-2004)

Test Description

Run	Duration	Target (mm)	Actual (mm)	Notes
1	1 h	101.6	130.2	**4"/h, 1h**
2	2 h	50.8	60.7	**1"/h, 2h**
3	45 min	114.3	117.5	**6"/h, 0.75h**

Data Summary

		Depth (mm)							
No.	**Items**	**Run 1**	**%**	**Run 2**	**%**	**Run 3**	**%**	**Total**	**% of Applied**
1	Water applied to plot surface	57.6	100.0%	31.3	100.0%	60.5	100.0%	149.5	100.0%
2	Stemflow	0.0	0.0%	0.0%	0.0%	0.0	0.0%	0.0	0.0%
3	Throughfall (manual)	57.6	100.0%	31.3	100.0%	60.5	100.0%	149.5	100.0%
4	Surface Runoff	8.7	15.2%	2.2	7.1%	32.0	52.9%	43.0	28.8%
5	Soil moisture storage change	?	?	?	?	?	?	?	?
6	Lateral subsurface flow	2.3	4.0%	5.0	16.0%	4.1	6.7%	11.4	7.6%
7	Unaccounted	?	?	?	?	?	?	?	?

Ambient Conditions: Partly cloudy, temperature 33.3 °C, wind 8 - 24 kph.

Rainfall for Previous Week: ?

Comments: The plot appeared to have moderate antecedent moisture conditions prior to simulation.

Table B8: Grass Plot Standard Simulation (8-10-2004)

Test Description

Run	Duration	Target (mm)	Actual (mm)	Notes
1	1 h	101.6	68.1	**4"/h, 1h**
2	2 h	50.8	28.3	**1"/h, 2h**
3	45 min	114.3	60.9	**6"/h, 0.75h**

Data Summary

		Depth (mm)							
No.	**Items**	**Run 1**		**Run 2**		**Run 3**		**Total**	**% of Applied**
1	Water applied to plot surface	68.1	100.0%	28.3	100.0%	60.9	100.0%	157.2	100.0%
2	Stemflow	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
3	Throughfall (manual)	68.1	100.0%	28.3	100.0%	60.9	100.0%	157.2	100.0%
4	Surface Runoff	11.4	16.7%	2.2	7.8%	38.8	63.7%	52.4	33.3%
5	Soil moisture storage change	?	?	?	?	?	?	?	?
6	Lateral subsurface flow	0.5	0.7%	1.0	3.4%	2.7	4.5%	4.2	2.7%
7	Unaccounted	?	?	?	?	?	?	?	?

Ambient Conditions: Partly cloudy, temperature 32.2 °C, wind 0 - 16 kph.

Rainfall for Previous Week: 12 mm

Comments: The subsurface at the grass plot was dry in spite of a small rainfall event the previous day.

Table B9: Grass Plot Standard Simulation (8-11-2004)

Test Description

Run	Duration	Target (mm)	Actual (mm)	Notes
1	1 h	101.6	113.6	**4"/h, 1h**
2	2 h	50.8	61.1	**1"/h, 2h**
3	45 min	114.3	109.0	**6"/h, 0.75h**

Data Summary

		Depth (mm)							
No.	**Items**	**Run 1**		**Run 2**		**Run 3**		**Total**	**% of Applied**
1	Water applied to plot surface	70.6	100.0%	38.0	100.0%	63.7	100.0%	172.3	100.0%
2	Stemflow	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
3	Throughfall (manual)	70.6	100.0%	38.0	100.0%	63.7	100.0%	172.3	100.0%
4	Surface Runoff	34.5	48.8%	10.6	28.0%	47.9	75.2%	93.0	54.0%
5	Soil moisture storage change	?	?	?	?	?	?	?	?
6	Lateral subsurface flow	2.9	4.1%	5.2	13.7%	5.9	9.3%	14.0	8.1%
7	Unaccounted	?	?	?	?	?	?	?	?

Ambient Conditions: Sunny, temperature 35.6 °C, wind 0 - 8 kph.

Rainfall for Previous Week: ?

Comments: The plot was extremely wet due to the standard rainfall simulation on the preceding day as well as at least one natural rainfall event.

APPENDIX C

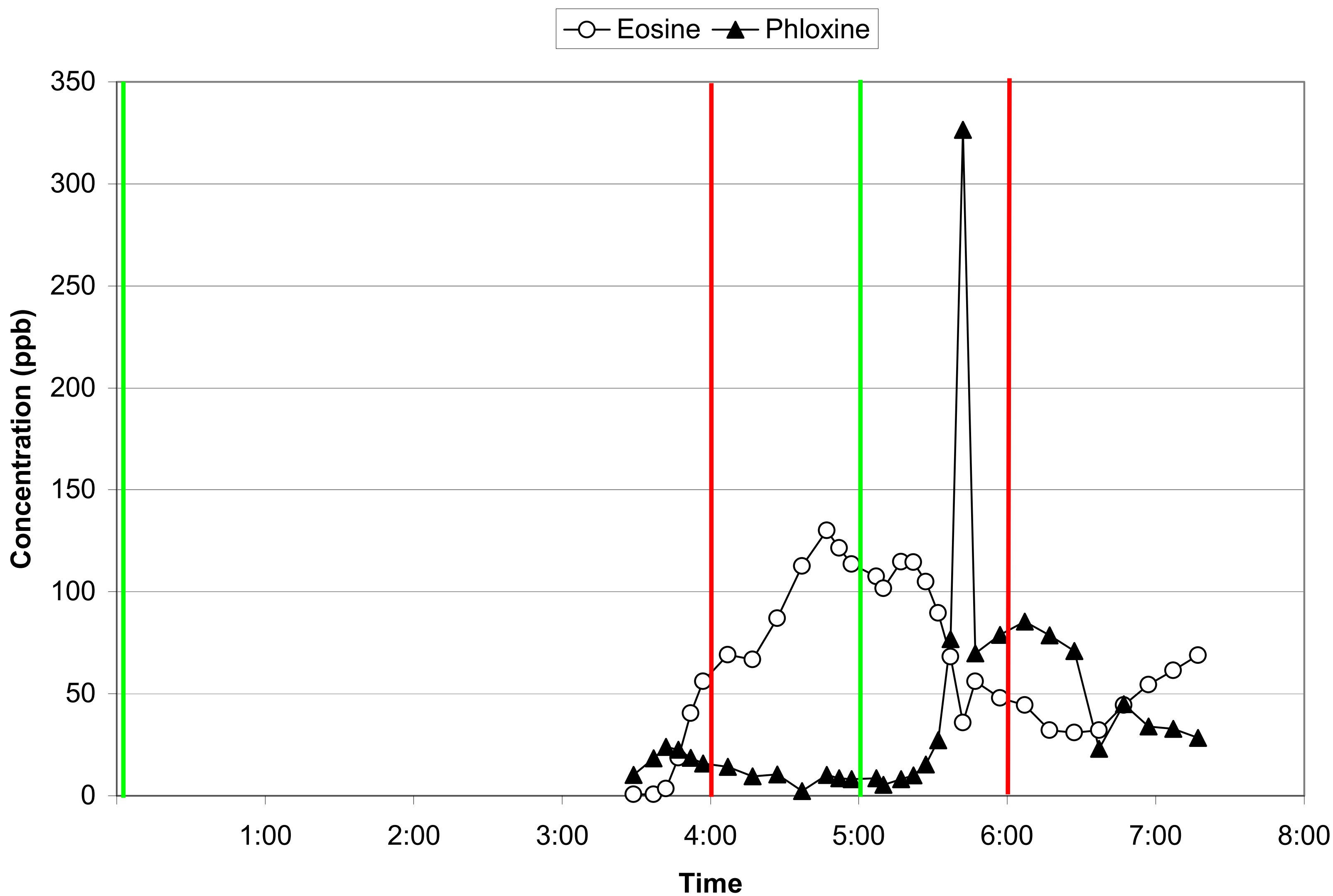

Figure C1: Dye behavior for tracer test II at location A_1 at the juniper covered plot at Honey Creek.

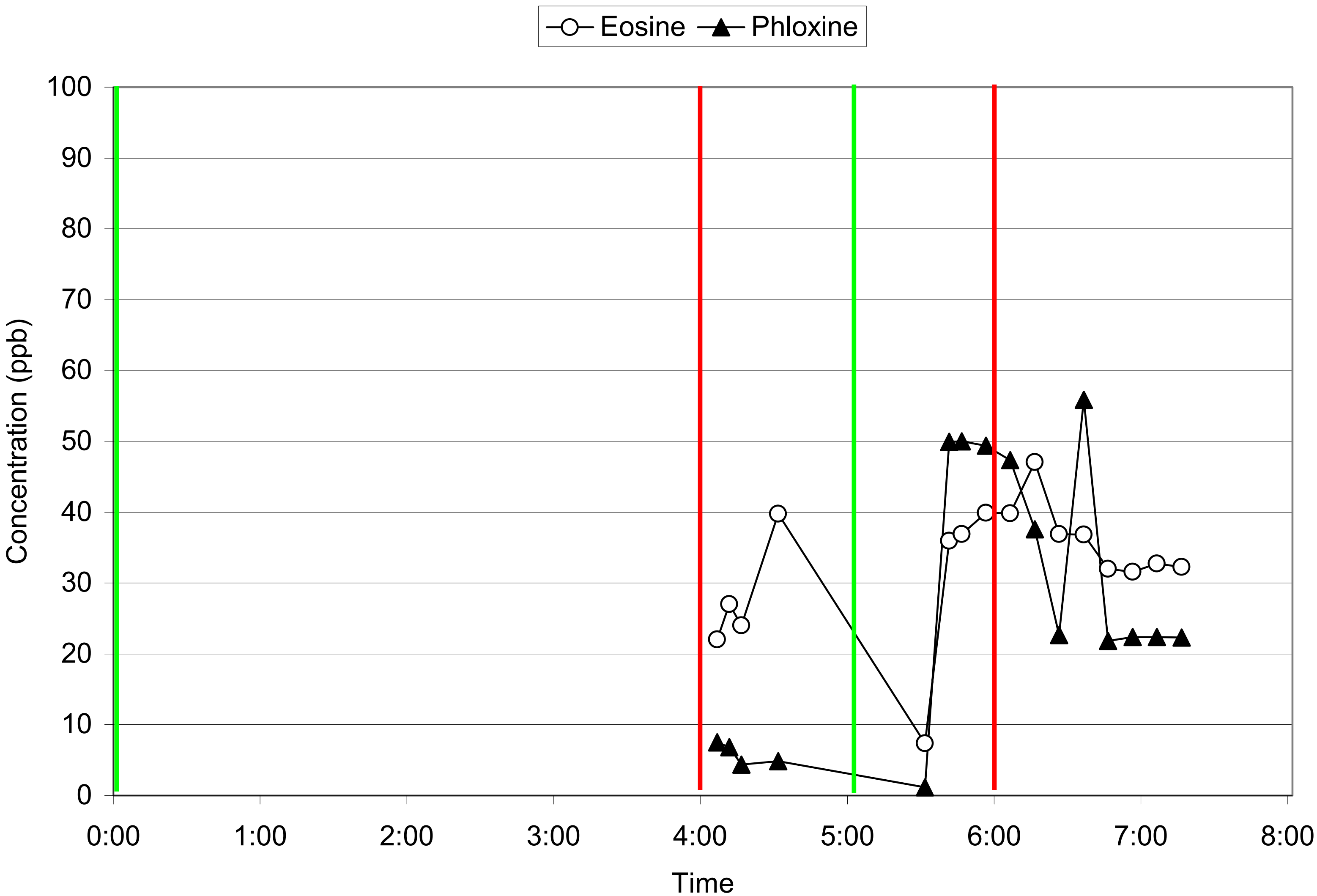

Figure C2: Dye behavior for tracer test II at location A_2 at the juniper covered plot at Honey Creek.

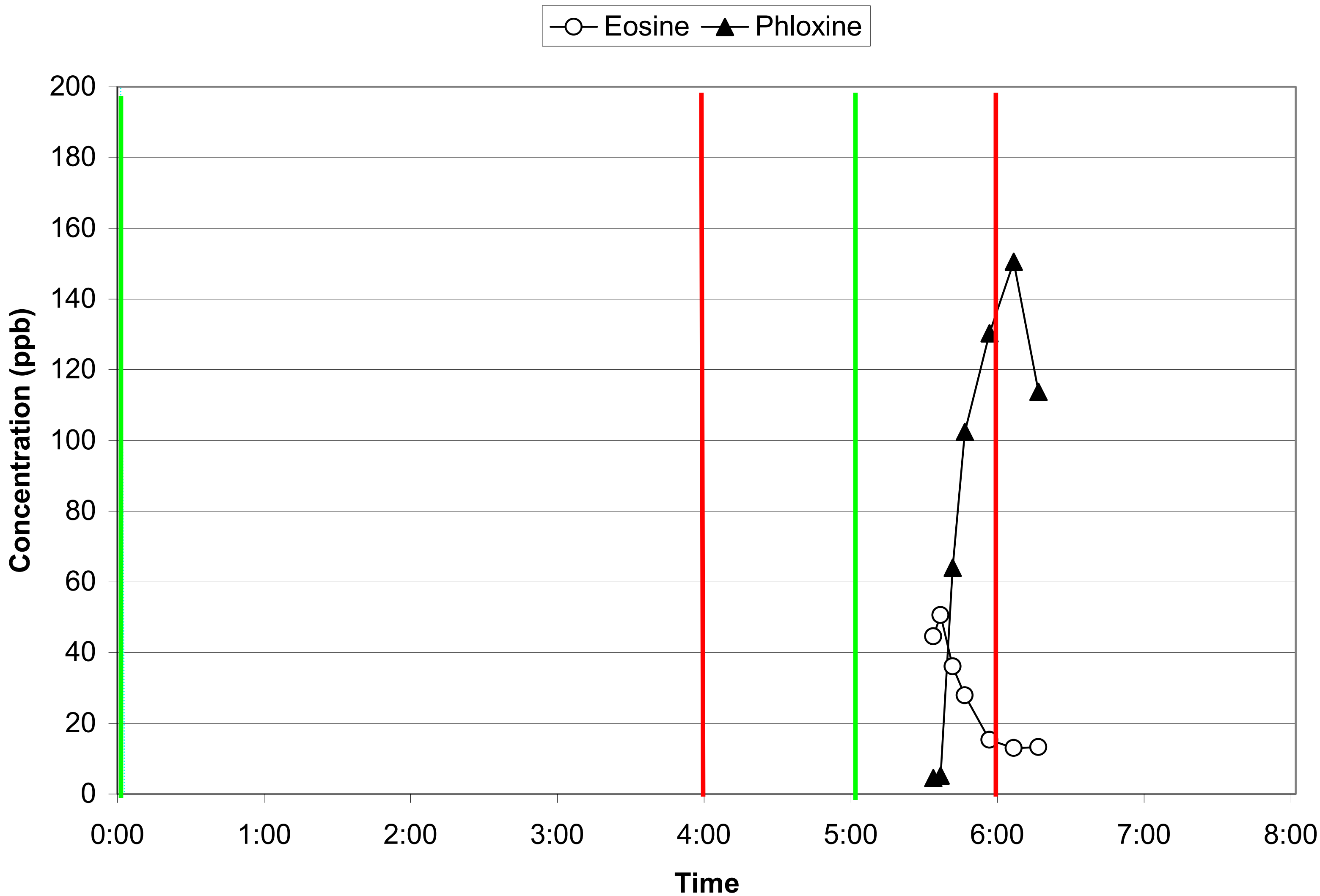

Figure C3: Dye behavior for tracer test II at location A_3 at the juniper covered plot at Honey Creek.

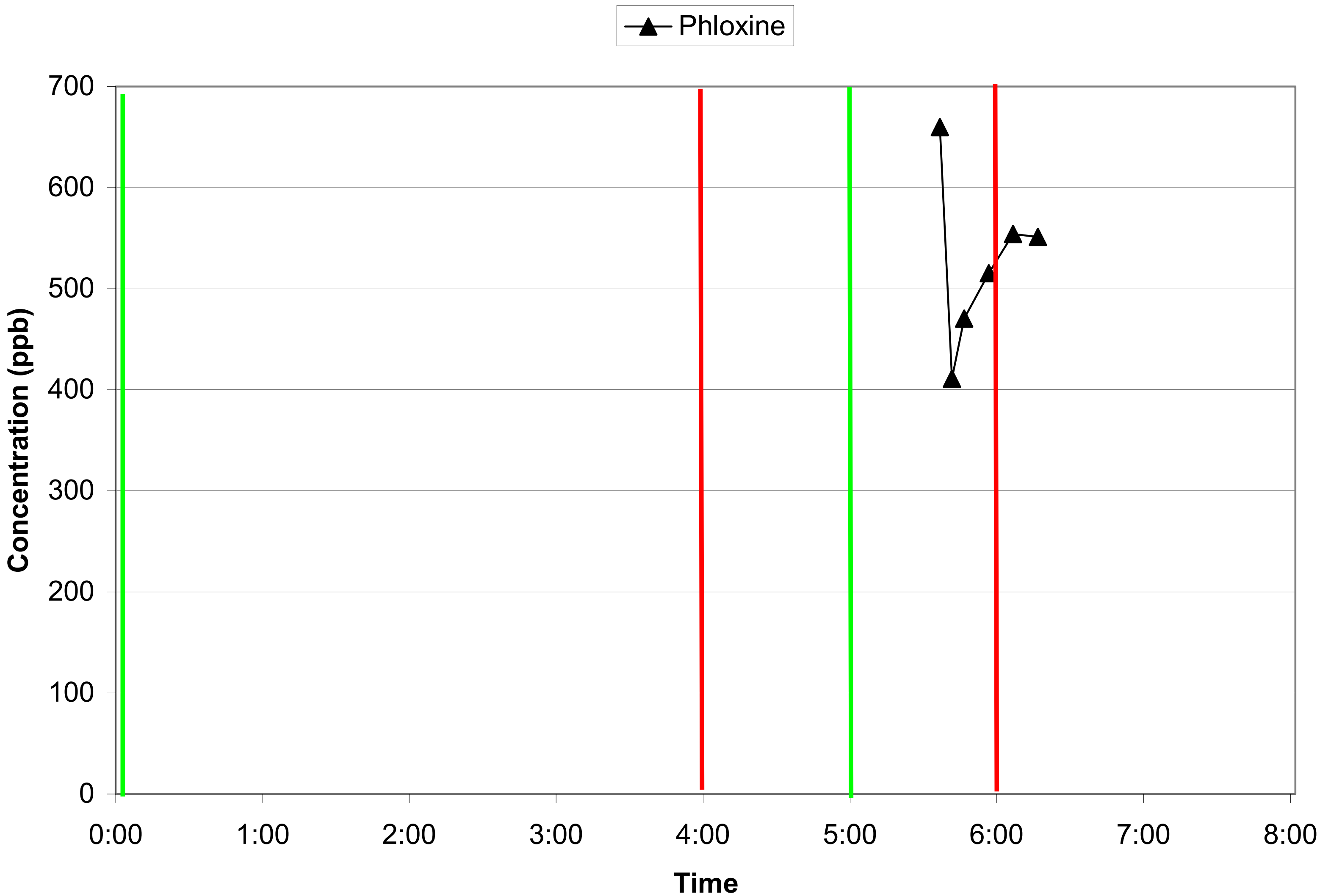

Figure C4: Dye behavior for tracer test II at location A_4 at the juniper covered plot at Honey Creek.

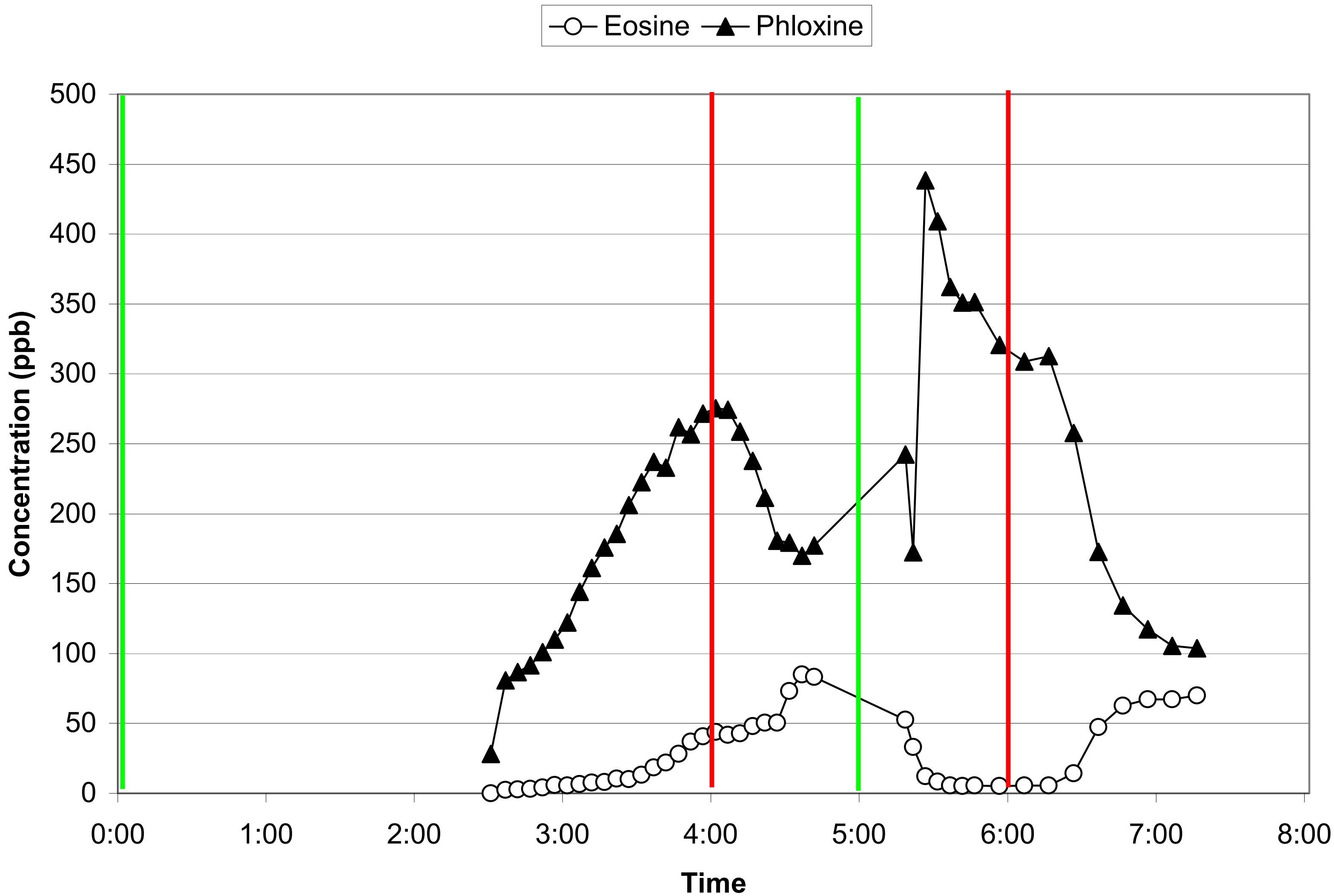

Figure C5: Dye behavior for tracer test II at location B_1 at the juniper covered plot at Honey Creek.

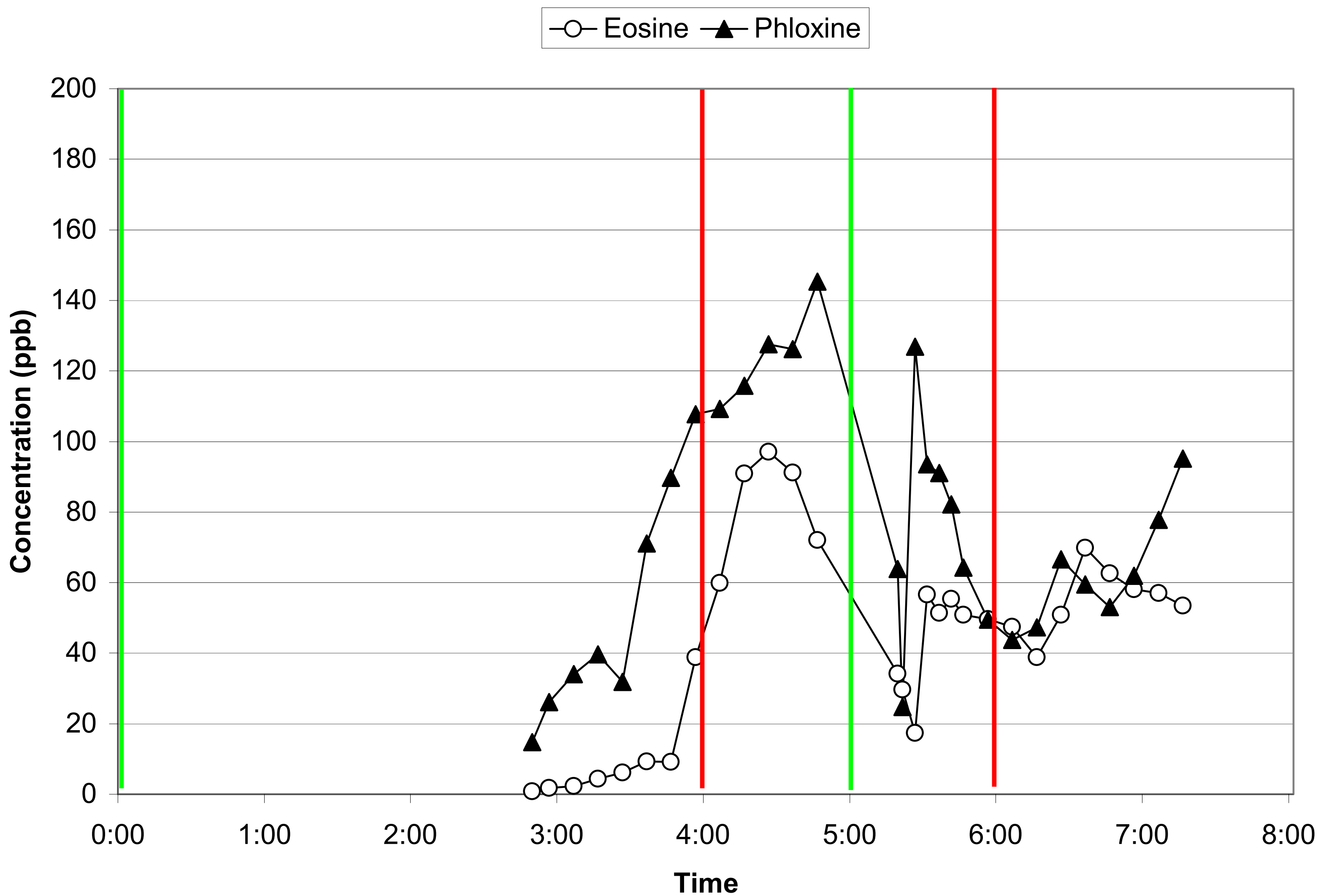

Figure C6: Dye behavior for tracer test II at location B_2 at the juniper covered plot at Honey Creek.

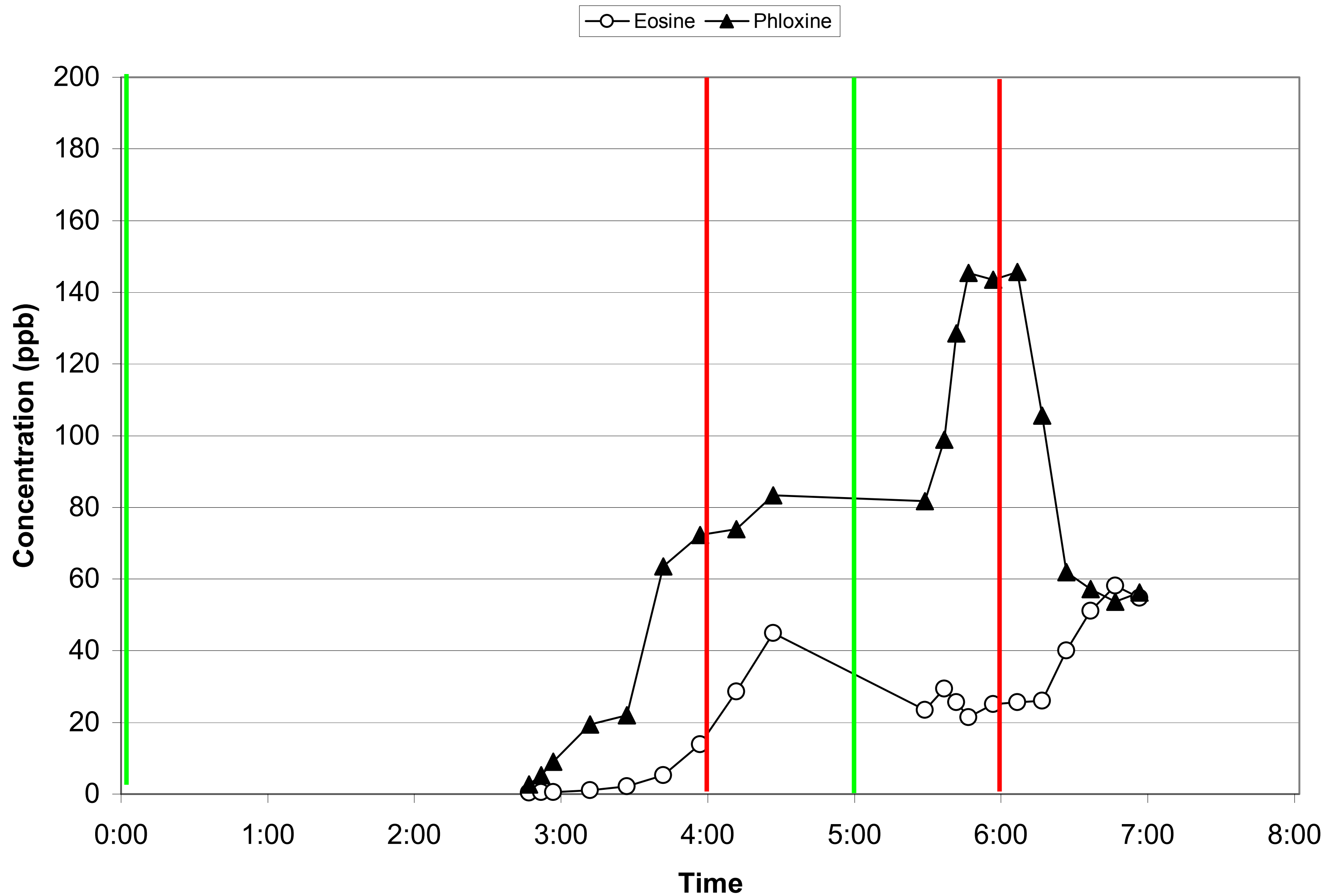

Figure C7: Dye behavior for tracer test II at location B_3 at the juniper covered plot at Honey Creek.

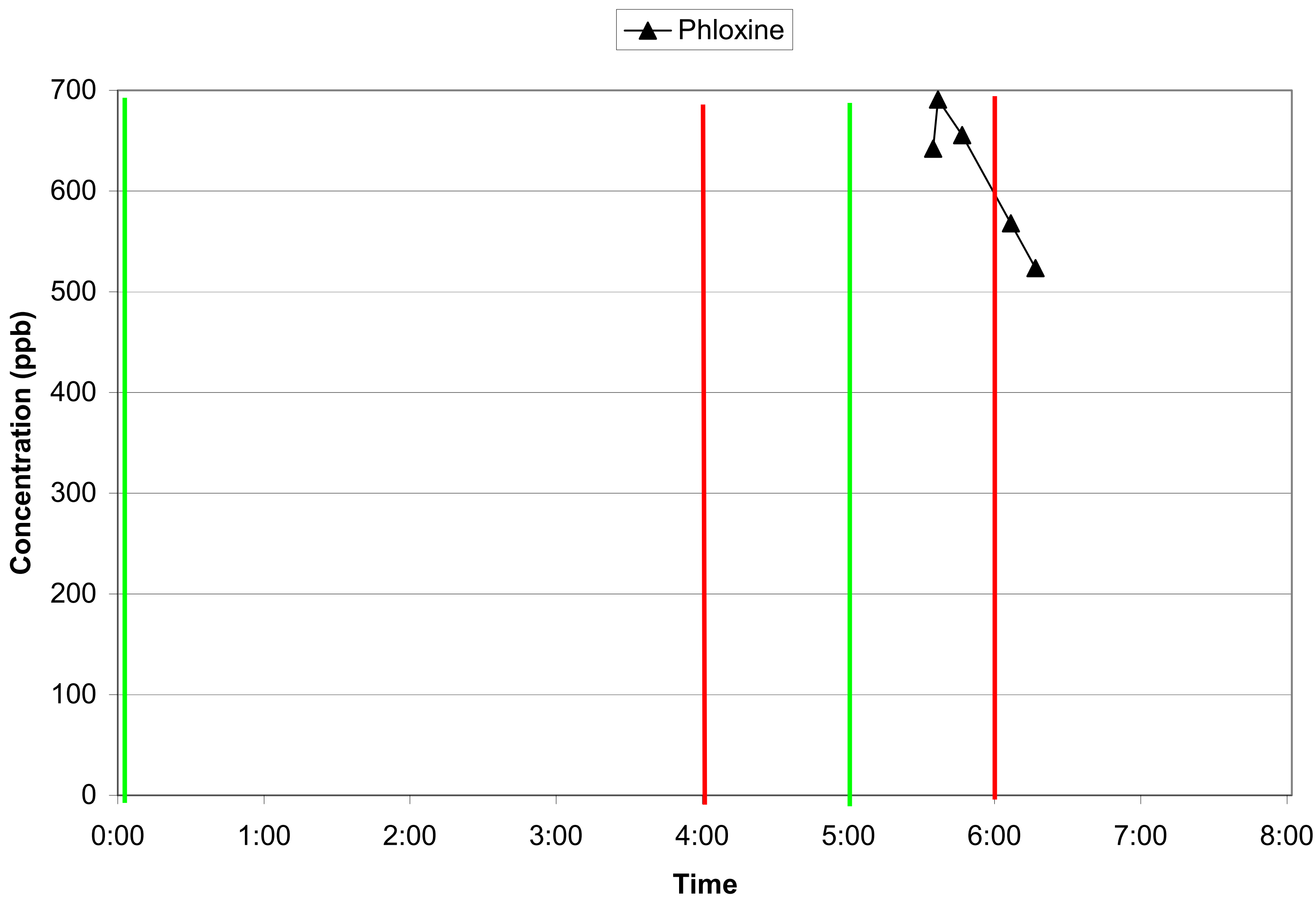

Figure C8: Dye behavior for tracer test II at location B_4 at the juniper covered plot at Honey Creek.

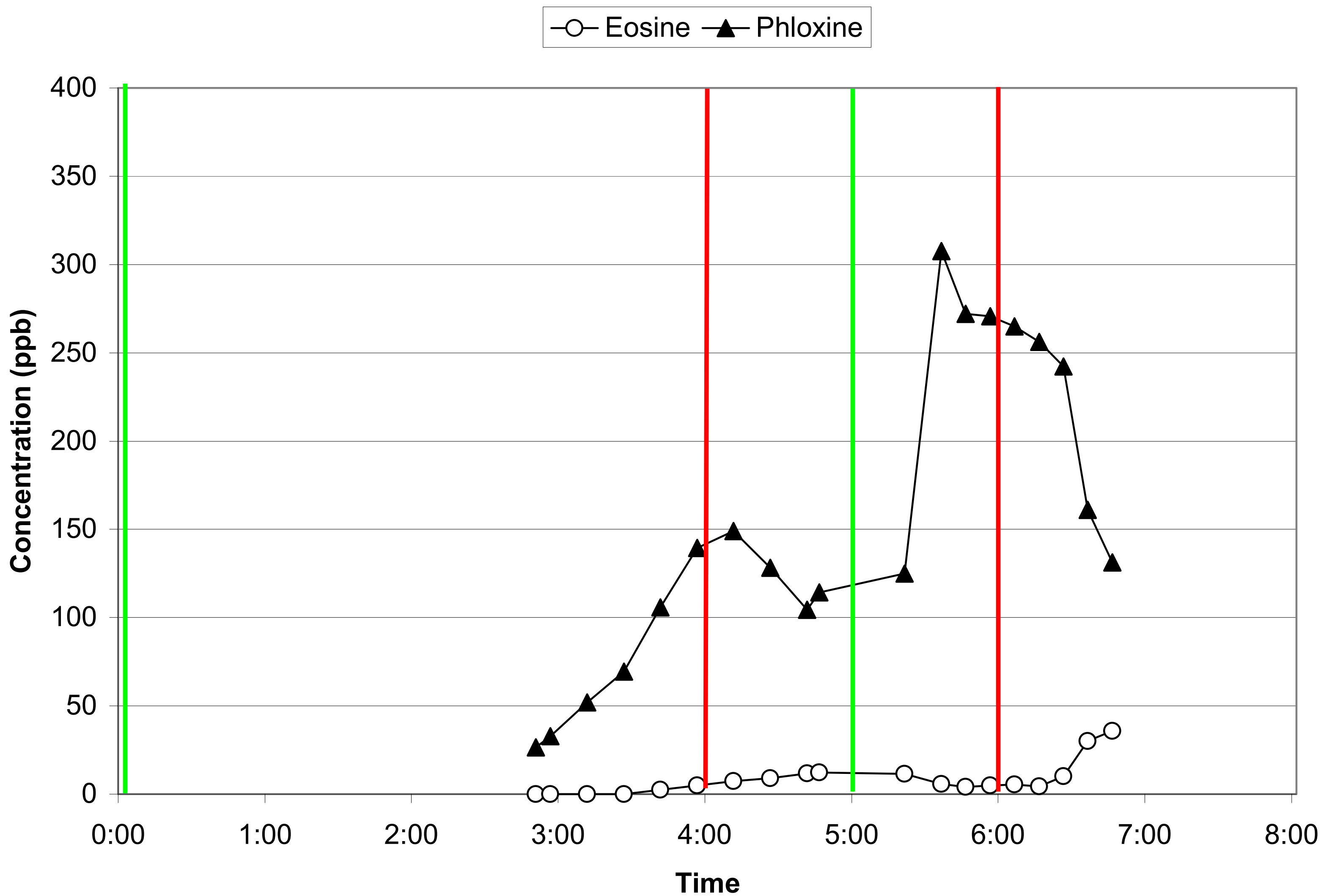

Figure C9: Dye behavior for tracer test II at location C_1 at the juniper covered plot at Honey Creek.

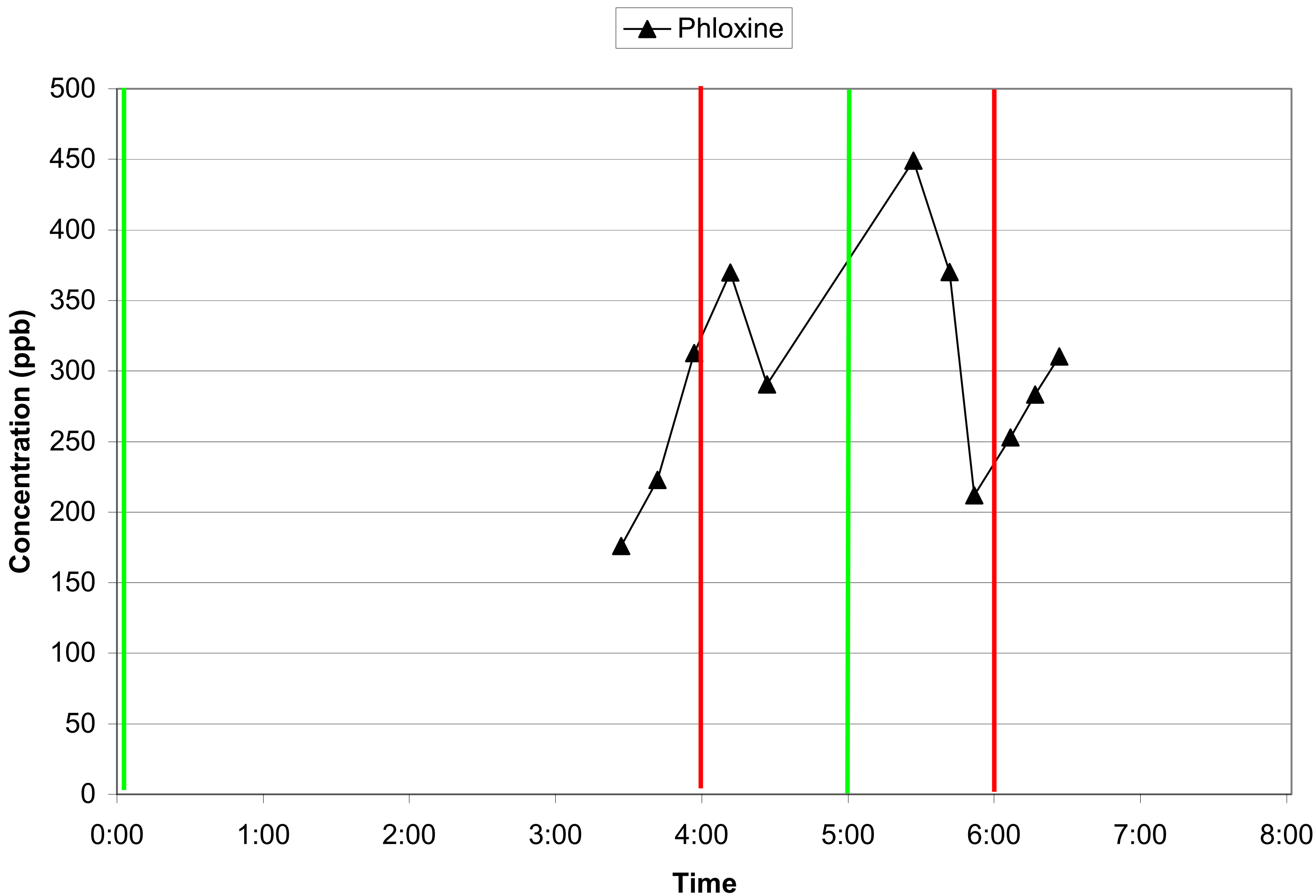

Figure C10: Dye behavior for tracer test II at location C_2 at the juniper covered plot at Honey Creek.

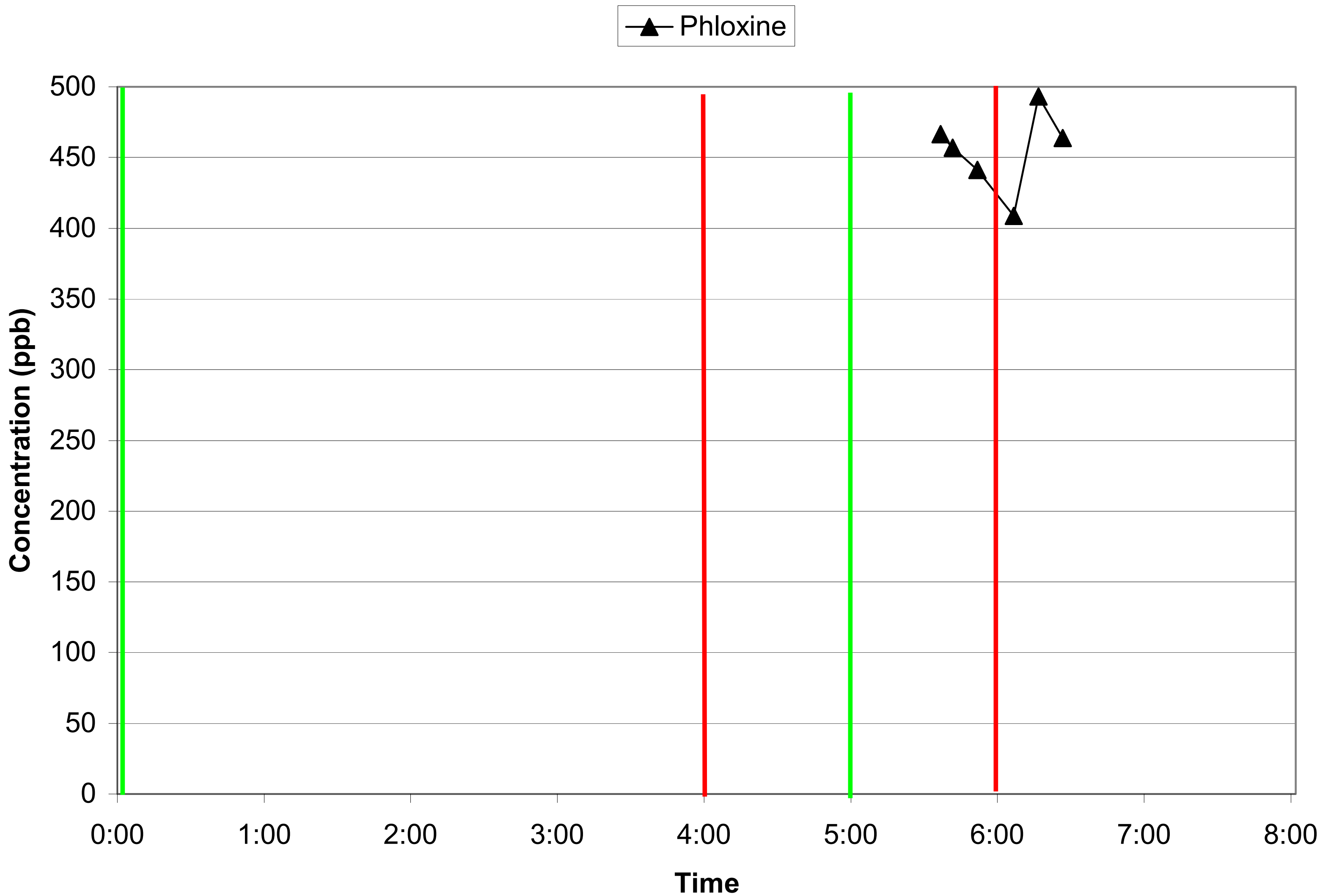

Figure C11: Dye behavior for tracer test II at location C_3 at the juniper covered plot at Honey Creek.

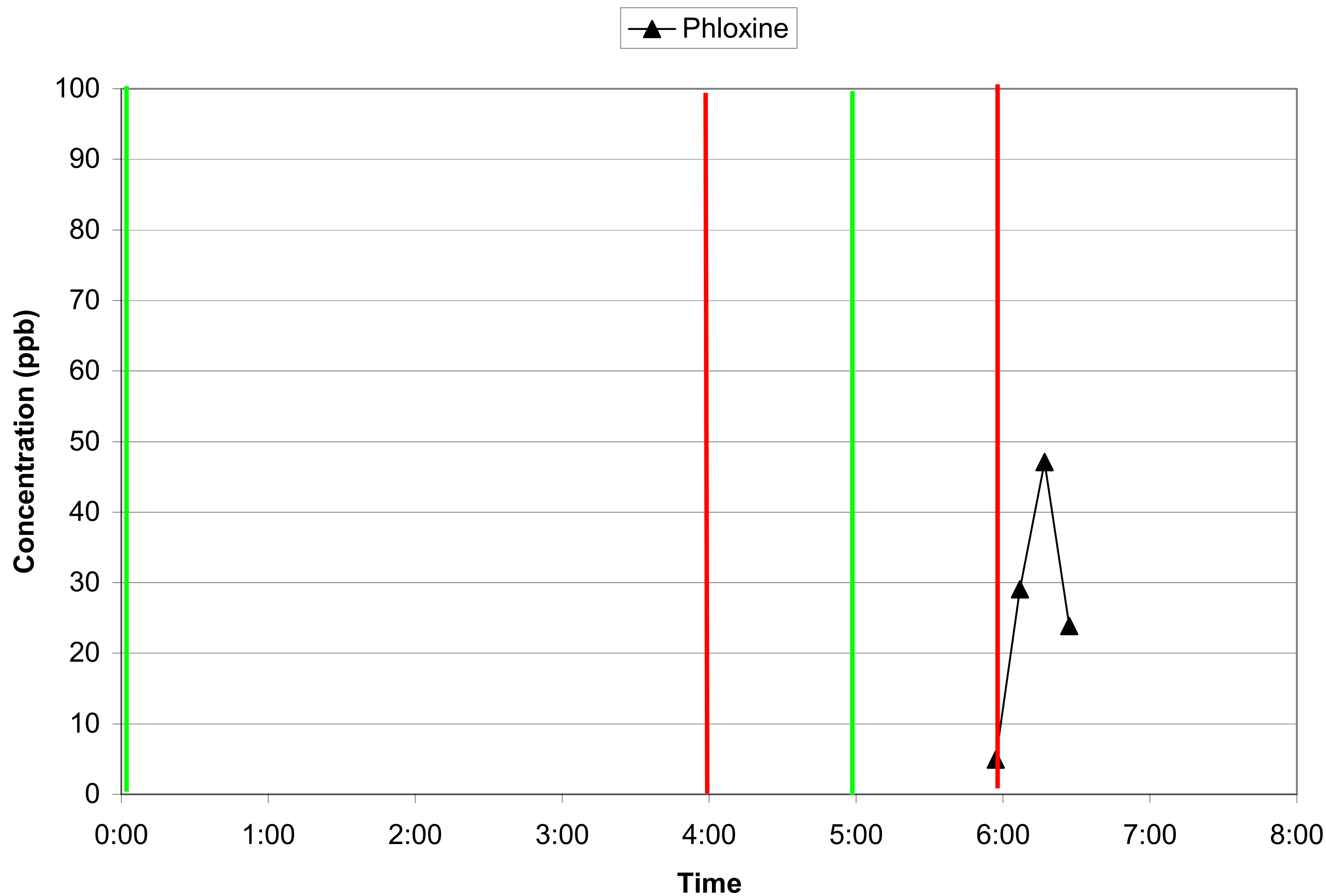

Figure C12: Dye behavior for tracer test II at location D_1 at the juniper covered plot at Honey Creek.

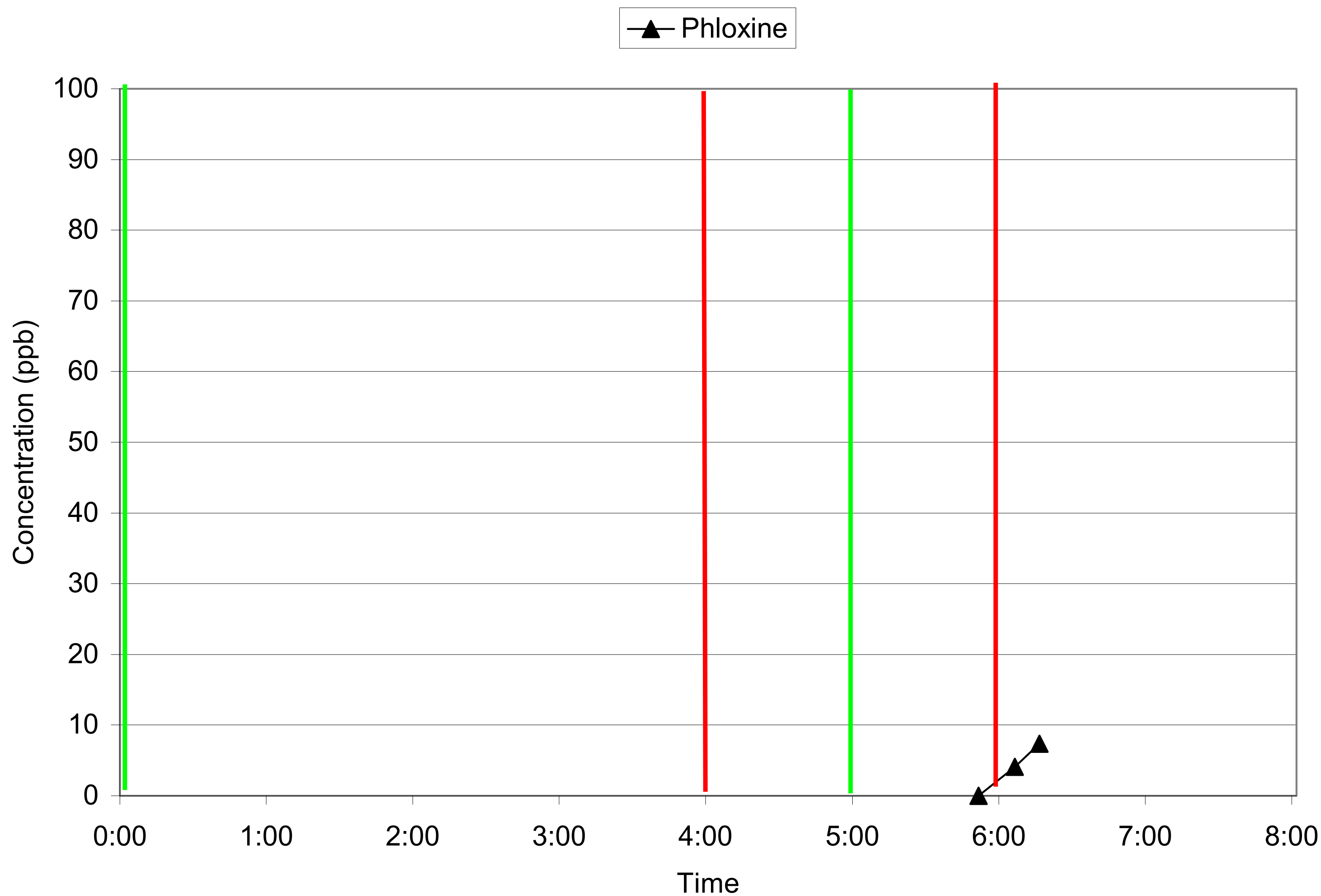

Figure C13: Dye behavior for tracer test II at location D_2 at the juniper covered plot at Honey Creek.

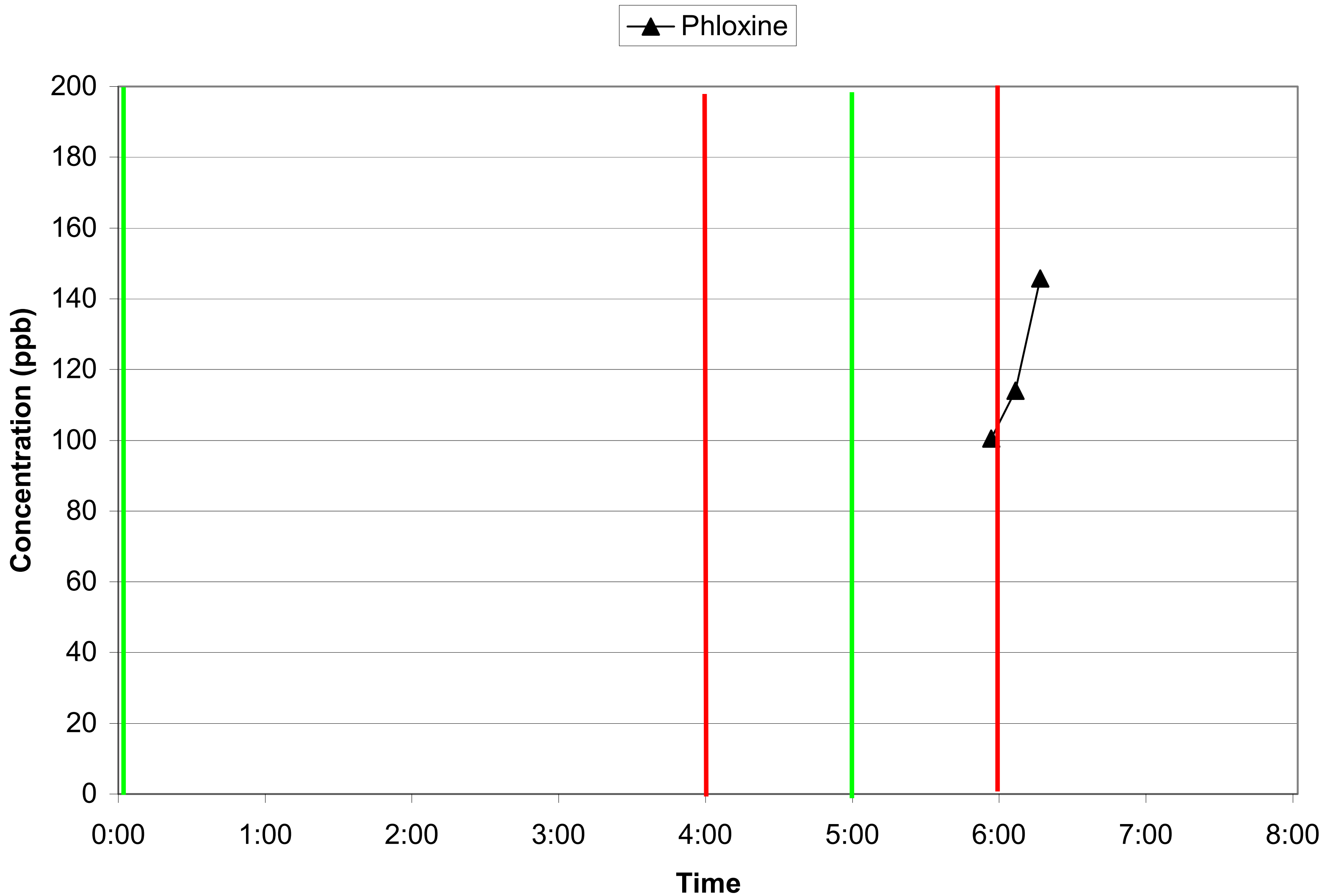

Figure C14: Dye behavior for tracer test II at location D_3 at the juniper covered plot at Honey Creek.

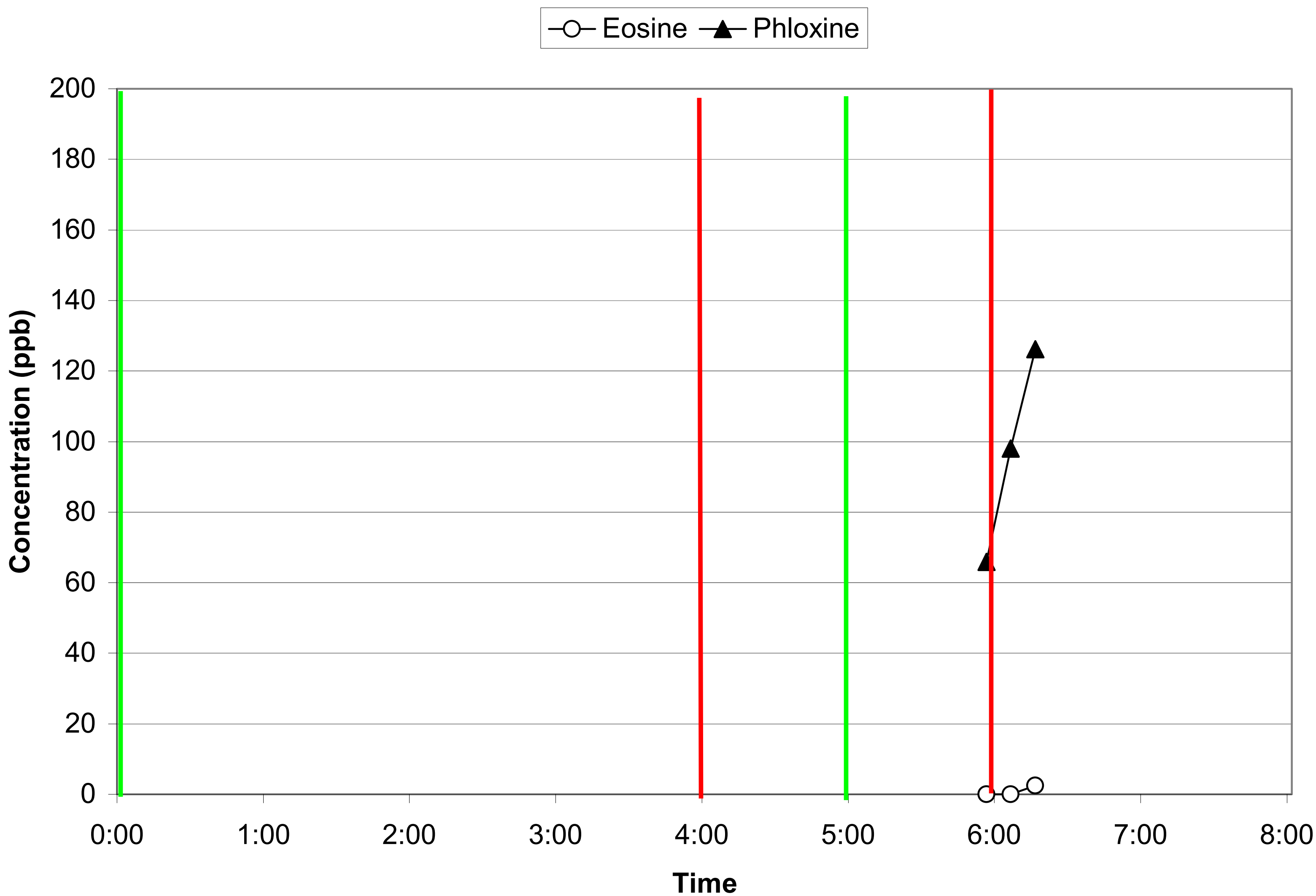

Figure C15: Dye behavior for tracer test II at location D_4 at the juniper covered plot at Honey Creek.

VITA

Name: Philip Isaiah Taucer

Address: Texas A&M University
Dept. of Biological and Agricultural Engineering
MS 2117 TAMU
College Station, TX 77843

Education: B.S., Biological Systems Engineering, Texas A&M University, 2003.
M.S., Biological and Agricultural Engineering, Texas A&M University, 2006.

Employment: Graduate Research Assistant, Department of Biological and Agricultural Engineering, Texas A&M University, 2004-present. Advisor: Dr. Clyde L. Munster.

Organizations: American Society of Agricultural and Biological Engineers, 2001-present.
American Geophysical Union, 2005-present.