THE USE OF A RAINFALL SIMULATOR FOR BRUSH CONTROL RESEARCH ON THE EDWARDS PLATEAU REGION OF TEXAS

A Thesis

by

SHANE COURTNEY PORTER

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

MASTER OF SCIENCE

December 2005

Major Subject: Biological and Agricultural Engineering

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Approved by:

Co-Chairs of Committee,	Clyde L. Munster
	Bradford P. Wilcox
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ABSTRACT

The Use of a Rainfall Simulator for Brush Control Research on the Edwards Plateau Region of Texas. (December 2005)

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Co-Chairs of Advisory Committee: Dr. Clyde L. Munster
Dr. Bradford P. Wilcox

The thicketization of the semi-arid region of the United States has resulted in a dramatic change allowing invasive woody species to dominate the landscape with an unknown impact to the water budget. This landscape transformation has created a need to study the hydrology of the region and in particular the effects of increased brush on the water cycle. To study the effects of invasive brush on the water budget, a portable above-canopy rainfall simulator was developed for plot scale hydrologic research. The rainfall simulator was tested at various field locations, including within the Edwards Plateau, to replicate natural rainfall events on typical hillslope-scale plots. The rainfall simulator was used to quantify aspects of the water budget for a 7 m by 14 m research plot on the Edwards Plateau in Texas. Three rainfall simulation dates were selected for detailed hydrologic analysis. Overall, throughfall accounted for 74% of the water applied to the plot, while 26% of applied water was in the form of stemflow. Lateral subsurface flow represented 33% of the water measured leaving the research plot. A notable result of rainfall simulations was extensive lateral subsurface flow and no surface runoff. The rainfall simulator has proven to be a cost-effective and efficient research tool for replicating natural rainfall in arid and semi-arid environments.

DEDICATION

To my wife Desi for her undying support and devotion

ACKNOWLEDGMENTS

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CHAPTER I

INTRODUCTION

Hydrologists cannot agree on how the transition from grasslands to brush being the dominant species in the Edwards Plateau region of Texas has affected the hydrology of this region. The area that was once primarily populated by native grasses has been invaded over the last century with brush species such as *Juniperus ashei*, which is commonly referred to as cedar (Dugas and Hicks, 1998; Van Auken, 2002; Wilcox, 2002; Owens and Lyons, 2004). Approximately nine million hectares in Texas alone have been affected by the increasing range and density of species of Juniper; this number is almost double for the Intermountain West (Owens and Schliensing, 1995). Causes of this phenomenon have been well documented, and include overgrazing of livestock by landowners and an absence of a fire regime, including natural fires caused by lightning and prescribed burning by landowners (Dugas and Hicks, 1998; Van Auken, 2002). Over time, brush control methods have been created and improved, but usually do not last over twenty years (Owens and Schliensing, 1995). The lack of fire within this grassland landscape, in conjunction with overgrazing, has allowed vigorous brush to prevail as the dominant species (Van Auken, 2002).

This thesis follows the style of the *Transactions of the ASAE.*

The major issue with brush encroachment is the unknown effect it has on the hydrologic cycle. With new brush species dominating the once grass-covered landscape, these trees are believed to capture and transpire a large fraction of water (up to half of the precipitation) on an annual basis (Wilcox, 2002; Thurow and Hester, 2001; Owens and Lyons, 2004). The tree canopy traps more precipitation through a process referred to as interception, which makes water more susceptible to evaporation. During most rainfall events where precipitation does not exceed 5 to 6 mm, all of the available water is retained and never reaches the soil surface (Owens and Lyons, 2004; Thurow and Hester, 2001). A five year study of natural precipitation over a 30 ha brush-dominant area within the Edwards Plateau, Dugas and Hicks (1998) observed evapotranspiration to be 65% of the total precipitation. In a similar study, Owens and Lyons (2004) measured the partioning of natural rainfall at ten research sites across this area, and found that at seven sites 43% of precipitation evaporated from the juniper canopy before arriving at the soil.

Thurow and Hester (2001) discussed the negative effect of brush encroachment as it applied to competition for water with more desirable vegetation. The escalation of juniper density has effectively reduced plant productivity. They noted that multiple studies have shown a substantial decline in grass production resulting from brush encroachment. Thurow and Hester (2001) further discussed the mechanisms for which a juniper can collect water within its environment. It has adapted to be able to collect water from the soil during drought-like conditions. Juniper can also extract water from the beyond the tree's canopy in what is referred to as the inner canopy. Its roots extend into this area, thereby competing with other grasses for water beyond the juniper canopy (Thurow and Hester, 2001; Lyons et al., 1998). Its deep root system allows juniper to extract water at depths that other vegetative species are not able to access, allowing this brush species to thrive during drought conditions (Thurow and Hester, 2001; Lyons et al., 1998).

Alternative beliefs contend that these new trees promote infiltration and groundwater recharge. One such explanation is that the extensive deep root systems of the trees create preferential flow paths that can channel water through the vadose zone to the groundwater (Stephens, 1996). Water that reaches the soil surface from interception in the form of throughfall can take advantage of this phenomenon, directly conveying water beyond the vadose zone. In addition, stemflow can channel the water that has gathered in the tree canopy to the base of the tree and into the soil, where its roots are located. An additional idea is that the microtopology that exists around the base of the tree creates a reservoir effect, giving rise to the ponding of water (Bergkamp, 1998). Ponded water can influence the rapid flow of water within a macropore resulting from the constant pressure head above the macropore (Stephens, 1996). An additional benefit of invasive brush to potential recharge is that evaporation of soil water from the litter layer can be minimized by the shading of juniper trees (Wilcox, 2002; Thurow and Hester, 2001).

These differing views have resulted in varying opinions as to the effectiveness of brush control. However, the amount of available water resulting from brush control practices is still unclear; there is no concrete evidence that brush control can increase streamflow and groundwater recharge, or just how much water will be available (Wilcox, 2002; Thurow and Hester, 2001). The possibility exists that with or without brush species on the landscape, the nature of a semi-arid environment dictates that most of the water will always be lost to processes associated with evaporation (Wilcox, 2002). The perceived problem has prompted legislative actions related to brush control, including state-level cost-share programs for landowners who remove brush from their property (TSSWCB, 2002).

By definition, semi-arid regions do not receive large amounts of annual precipitation, and potential evapotranspiration (PET) greatly exceeds rainfall; the demand for evaporation and transpiration far exceeds precipitation in this area (Wilcox, 2002). As a result, hydrologic research in semi-arid regions is challenging due to limited precipitation. Typically, research studies must be extended over long time periods to encompass many natural rainfall events. However, the use of a rainfall simulator allows for studies to be conducted without relying on the chance of occurrence of natural rainfall events and can be conducted on the schedule of the researchers. Rainfall parameters such as intensity and duration can be easily modified to replicate a storm of record in a timely manner, depending on the design parameters of the simulator. Furthermore, rainfall simulators can produce varying antecedent moisture conditions to provide a range of initial conditions for research studies. Rainfall simulators provide researchers with the ability to install monitoring equipment and to have key personnel on site during a rainfall event. The simulator is an excellent research and teaching tool that allows people to visually observe the hydrological processes that occur within the landscape.

Over the past 50 years, various types of rainfall simulators have been developed to support numerous research efforts. Initial rainfall simulators have played an integral role in erosion research, as they enable controlled experiments to be conducted with known antecedent moisture conditions (Renard 1985). As technology has developed, rainfall simulators have been employed for many hydrologic studies by providing runoff data at a faster rate. However, the development of rainfall simulators has mostly been site-specific, allowing the plot and site conditions to dictate the form of the simulator. Therefore, rainfall simulators are typically designed to be for an individual experiment (Humphry et. al. 2002) and have limitations (typically plot size) based on their intended use. The majority of field-based rainfall simulators have been utilized for small plot research (Humphry et. al. 2002; Schlesinger et. al., 1999) while variations of the rotating boom sprinkler (Swanson, 1965; Johanson et. al., 2001) have permitted the increase in plot sizes scaling up of. All of these sprinklers have typically been used on small vegetation species, such as grasses and shrubs.

Renard (1985) examined the advantages and disadvantages of rainfall simulators. A significant advantage is cost efficiency. The cost of a rainfall simulator is relatively inexpensive when compared to the cost of a long-term hydrologic experiment that relies solely on natural rain events. In addition, rainfall simulators provide utmost control of an experiment, particularly with respect to data collection. The plot conditions can be readily changed for experiments with regards to instrumentation used. Antecedent moisture conditions can be varied prior to testing, and additional water can be added rather quickly. Rainfall intensity can be varied with ease to replicate certain storms of record. However, Renard noted the disadvantages of rainfall simulators, including the high cost of labor to conduct a rainfall simulation. Therefore, most rainfall simulators are relatively small, limiting most experiments to a small plot scale. In addition, simulated rainfall intensities often do not mimic natural rainfall intensities with the same temporal variations and drop-size distributions (Renard, 1985). However, perhaps the biggest inadequacy of most rainfall simulators is the inability to produce water droplets that approach the terminal velocity of natural raindrops.

Myer and McCune (1958) developed a group of features that rainfall simulators should possess. They include drop size distribution and drop velocity similar to natural rain, portability, minimal wind distortion, and the ability to duplicate intensities of runoff – producing storms. Myer and McCune (1958) also developed a rainfall simulator to replicate the kinetic energy of a high intensity storm to compare soil and water losses, as well as infiltration rates using standard rectangular plots (1 m by 1 m). Their simulator used application rates of 63.5 mm/hr and 127 mm/hr. Humphry, et. al. (2002) developed a rainfall simulator designed for a maximum plot size of 2 m square, and can be assembled in ten minutes, placing the nozzle at a height of 3 m. Swanson (1965) developed a trailer mounted rainfall simulator that used a rotating boom to broadcast water over a research plot. By mounting the unit on a trailer, labor costs were reduced and the unit became a portable tool. The boom was 15 m in diameter, and intensity was manually controlled by operating globe valves at the spray nozzles. Rainfall events of 63.5 mm/hr could be obtained by turning half of the nozzles off, while a maximum of 127 mm/hr was achieved with all nozzles open. The entire unit could be set up in two hours by four people and taken down in approximately 30 minutes. The nozzles were 2.7 m above the ground and were applied to plots 10.7 m long by 3.7 m wide. Swanson found drop size and intensity to be near that of natural rainfall. Though he was able to simulate on a larger plot size, the simulator's height limited its application to low land covers (Swanson, 1965).

Swanson's rotating boom could apply water to a circular area of 175 m^2, but was limited in height of application due to the boom design. Rainfall simulators cannot meet all characteristics as outlined by Meyer and McCune (1958), so the attributes important to the research study must be identified and incorporated into the design.

With this in mind, a portable, above-canopy rainfall simulator was developed for use on the Edwards Plateau to assess the influence of juniper on the runoff process and the local water cycle. In addition, the simulator was developed to produce timely hydrologic data as it relates to the interaction of invasive brush with local hydrology. This rainfall simulator was based on design successes of previous rainfall simulators, as well as design constraints of the research area where it would be utilized. The simulator had to be a portable unit that could be deployed on virtually any incline in rugged terrain. Once the rainfall simulator was designed, developed and tested, it was deployed to multiple research sites within the Edwards Plateau region of Texas. Within each site, research plots were established and instrumented to record most aspects of the hydrologic cycle, in an effort to quantify the water budget for each plot. When erected, the rainfall simulator was utilized to replicate natural rainfall events of a given intensity and return period, providing real-time precipitation data for researchers.

CHAPTER II

RAINFALL SIMULATOR DEVELOPMENT

INTRODUCTION

A rainfall simulator was developed to study the interactions between juniper covered hillslopes on the Edwards Plateau and precipitation. The landscape of this region required that a rainfall simulator be placed above the juniper canopy to duplicate natural rainfall conditions. By simulating natural rain over the tree canopy in a research plot, an increased number of parameters of the water budget such as stemflow, throughfall, and soil moisture can be quantified. On the Edwards Plateau, juniper canopy heights can range from 3 m to 10 m depending on location and growth stage. Therefore, the rainfall simulator was designed to extend above 10 m in height, but yet be adjustable to accommodate varying heights of juniper canopy. Based on a review of existing rainfall simulators, a new design was needed to meet the needs of this juniper hillslope hydrology study.

Design Requirements

The rainfall simulator was initially designed to efficiently apply rainfall to a 3 m by 12 m research plot with uniform coverage. This plot size was determined to be small enough to minimize water requirements, as well as large enough to encompass enough juniper trees to accurately represent the landscape. Given that many of the potential research sites are remotely located away from power and water sources, a portable rainfall simulator was required. Ease of setup was also a primary consideration due to the rugged hillslope terrain in the Edwards Plateau. In addition, the components used for the simulator had to be reliable, as the unit would be deployed and set up in remote areas for an undetermined amount of time. For this reason, simplicity was paramount to the rainfall simulator design. Since it was assumed that water would have to be transported to the research sites, the ability to store water was a key design consideration for the rainfall simulator. The rainfall simulator was designed to produce rainfall rates varying from 10 to 100 mm/hr to simulate typical storm events for the Edwards Plateau region (Haan, et al, 1994). To be an effective rainfall simulator that replicated natural rain, the drop size from the simulator had to be as close to rain as possible, while being large enough to account for effects of wind. The unit had to be cost-effective with regards to construction and required labor for set up and operation.

MATERIALS AND METHODS

Based on the design constraints, key components of existing rainfall simulators were identified to be incorporated into the new design. This simulator was designed with individual masts rather than one big mast or boom, in order to increase plot size. The sprinkler heads were located on the top of the mast so as to apply water above the tree canopy. Base plates were used to support each mast and sprinkler manifold. Water would be conveyed using flexible hoses to comply with the potentially rugged terrain. In addition, the flow of water would be monitored using a flow meter and a pressure gauge. Due to the large volume required for simulated rainfall tests on large plots, the issue of water storage would need to be addressed.

Sprinkler Heads

A key component of any rainfall simulator is the type of nozzle to be used for the application of water. Needle drop formers are traditionally used in laboratory simulators. However, they are highly susceptible to the wind under field conditions. Spray nozzles are more effective against the wind and are typically found on field-based simulators. Four basic applicator types were analyzed for optimization of water application: rotary sprinklers, impact sprinklers, spray nozzles, and plate sprinklers.

The most versatile of these sprinklers is the plate sprinkler. This is due to the ability to change the plate shape and nozzle size on the sprinkler. With this flexibility, the sprinkler can be modified to provide small or large throw diameters (3 to 15 m) while producing droplet sizes comparable to rain. They are typically used on center pivot irrigation units and therefore have a wide operating range from low to fairly high pressures (40 to 350 kPa). The plate sprinkler was considered the best choice for this rainfall simulator because of its ruggedness, flexibility, and coverage area.

The S3000 Pivot Spinner from the Nelson Irrigation Corporation (Walla Walla, WA, 2003) is the plate sprinkler that was selected since it can operate at a lower pressure (103 kPa) while incorporating a variety of patterns. Testing of the Nelson S3000 sprinkler demonstrated the maximum rainfall rate to be 51 mm/hr with an application diameter of up to 8 m. The Nelson S3000 sprinkler can be fitted with nozzles that range from 2 L/min to 65 L/min at 103 kPa. The Nelson S3000 sprinkler heads have an add-on pressure regulator that maintains a constant pressure of 103 kPa. In addition, the nozzles can be equipped to limit its spray pattern to 190° from the traditional 360° in an effort to reduce water usage.

Sprinkler Head Manifold

To achieve various application rates, four sprinkler heads were mounted together in a cluster using a sprinkler head manifold. The sprinkler head manifold was designed to be mounted on the top of a mast. The four sprinkler heads could be individually turned off to regulate the application rate at each mast location. Therefore, the sprinkler head manifold produced a combined flow rate and throw distance based on the number of sprinkler heads turned on. Two types of sprinkler head manifolds have been tested. One type of sprinkler head manifold was designed in an H-pattern to maximize the application efficiency. By having sprinklers set at a 90° offset (Fig. 1 and Fig. 2), the entire manifold could account for wind from any direction.

Figure 1. H-pattern sprinkler manifold operating during a test run.

The sprinkler assembly was made of poly vinyl chloride plastic (PVC), which is lightweight, inexpensive, and readily available. The manifold measures 1 m by 1 m and uses 5 cm, 2.5 cm, and 1 cm diameter pipe. The pipe is reduced from 5 cm to 1 cm in order to reduce the total incoming flow rate of water to the requirements of each individual sprinkler. Each of the four sprinklers on the assembly has a valve, which allows for controlling application rates of the entire sprinkler manifold.

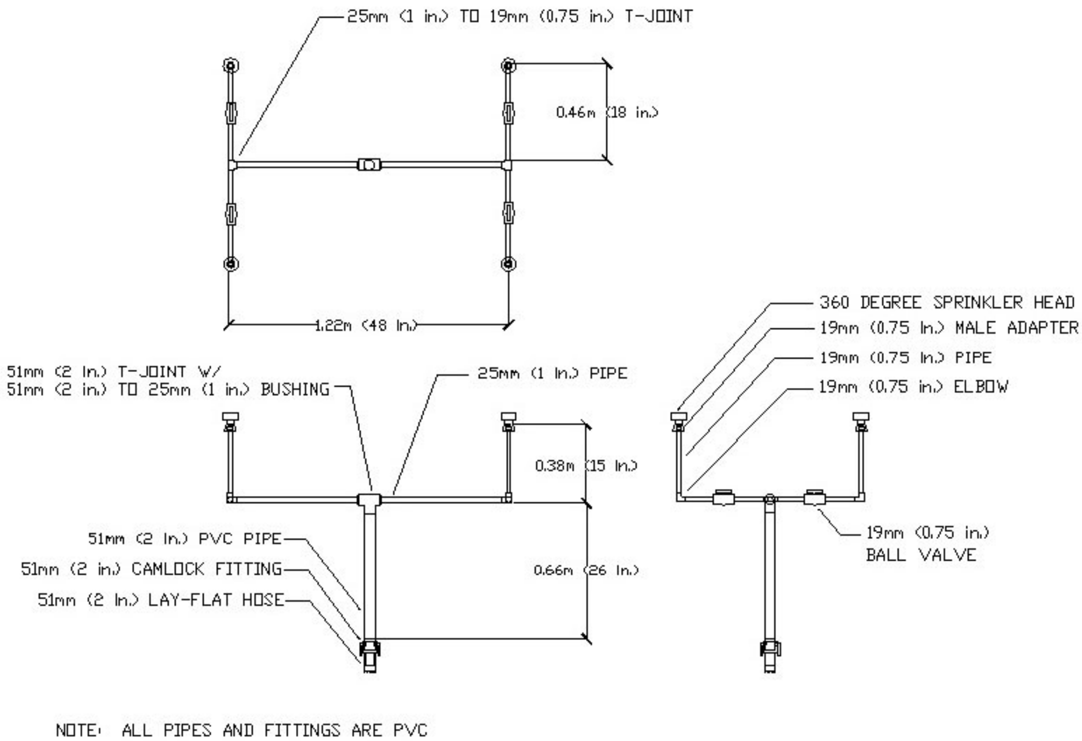


Figure 2. H-pattern sprinkler manifold with ball valves and 360° sprinkler heads.

Since water availability was limited, it was necessary to maximize the water applied to the research plot. Therefore, in an effort to conserve water, a second manifold was designed to be an in-line manifold (Fig. 3) utilizing sprinklers that applied water in a semi-circle (190°), rather than a full circle (360°). This allowed the sprinkler manifolds to be placed around the edge of the plot and for all water to be applied directly on the plot. A greater accuracy was achieved when comparing the volume of water pumped to the sprinkler manifolds with the amount of water recorded within the research plot. This second simulator, which has been successfully deployed on a larger plot of 7 m by 14 m, is capable of simulating rain events ranging from 25 mm to 250 mm/hr.

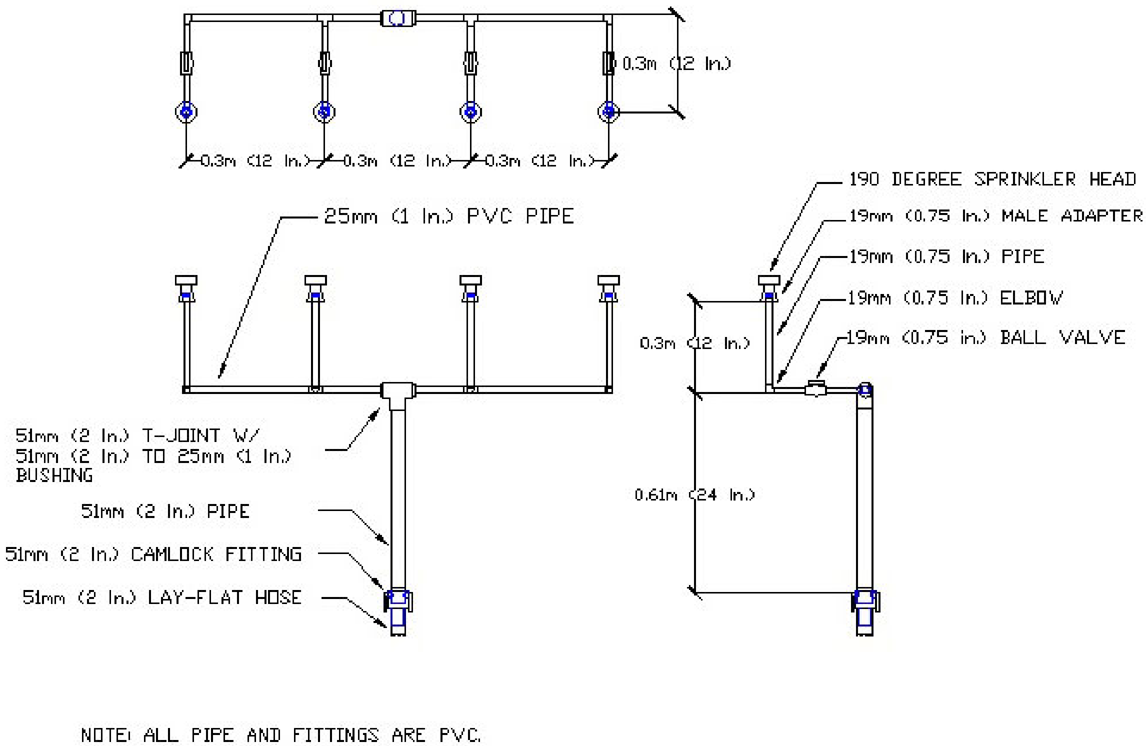


Figure 3. Inline sprinkler manifold with ball valves and 190° sprinkler heads.

The manifold was mounted on a mast and connected to the main water supply line by a 51 mm (2 in.) layflat hose suspended vertically. The manifold is both a conduit for the water supply and a support for the nozzles. The manifold attaches to an aluminum mast using a specially designed connection device (Fig. 4). This connection device simply slips over the top of the mast and is through bolted to prevent rotation. This quick and easy attachment of the manifold to the mast is very important to the design and portability of the rainfall simulator. The sprinkler manifolds can be stored and transported in a compact space after they are de-coupled from the masts. This facilitates the timely set up and removal of the rainfall simulator.

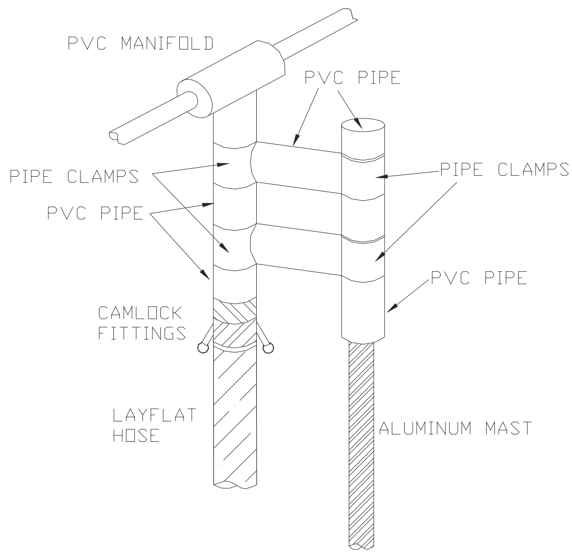


Figure 4. Drawing of the connection device that attaches the sprinkler manifold to the mast.

Masts

An aluminum telescoping mast that can reach heights up to 11 m was selected to support the sprinkler head manifold (Fig. 5). These light-weight, portable masts are easy to install and do not disturb the research plot. The 20 gauge mast has a diameter of 5 cm, and can extend from 3 m to 11 m. This allows the rainfall simulator to be utilized on vegetation of varied species and age with various canopy heights. The mast is supported by four, 4.8 mm diameter, plastic coated guy wires (cut to length) that are secured by 2 cm diameter, 25 cm long steel stakes driven into the ground. Tie-down ratchets are used to tighten the guy wires and plumb the masts. The mast is strong enough to support the sprinkler manifold and suspended water line that weighs approximately 20 kg when filled with water. As mentioned previously, the sprinkler manifold is attached to the top of the mast using an innovative connection device that allows the rainfall simulator to be constructed with modular components (Fig. 4).

Figure 5. Image of completed rainfall simulator with masts supporting the sprinkler assemblies.

Base Plates

The base plates were designed to support and plumb the masts on hillslopes. The square (0.3 m by 0.3 m) base plates are custom fabricated from 6.4 mm thick plate metal and incorporate a 0.3 m long rotating support member (constructed of square metal tubing) that slides inside the mast pole (Fig. 6). The rotating support member is placed between the two semicircles of 3 mm plate metal, and is pinned at the base of the semi-circles. The rotating support member can be locked into a vertical position. The swivel feature of the base plate allows the mast to be plumb on any hill slope. In addition, the rotating feature of the base plate aids with the set up of the masts and the sprinkler head assembly. This is achieved by installing the base plates at the proper location, then the mast is extended to the appropriate length and the sprinkler head assembly is connected to the mast. Finally, the mast pole is slipped over the rotating support member and the mast is erected by "walking" the mast from the horizontal position to the vertical position as the support member rotates in the base plate. After the mast is plumbed, the rotating member is locked into position. A 9.5 mm bolt is placed through the two semi-circles of the base plate and rotating member and locks the mast to the desired angle, so as to be plumb with the land surface. The base plates are secured to the land surface using four metal pins, 2 cm diameter and 25 cm long, that are driven into the ground through four holes drilled through and placed at the corners of the base plate.

Figure 6. Rotating base plates used to support the rainfall simulation mast, set at differing angles.

Water Supply Design and Requirements

To uniformly apply water over a research plot measuring 3 m by 12 m, six H-pattern masts would be set above the juniper canopy at a height of 11 m. The masts were placed uniformly around the plot as shown in Figure 8 to achieve rainfall rates of up to 100 mm/hr. The number of masts was determined by considering the area of application for each sprinkler manifold with overlap from adjacent manifolds. Figure 8 depicts the overall set up of the rainfall simulator around the research plot.

After an analysis of water supply requirements based on a maximum design application rate of 100 mm/hr, a 76 mm diameter hose was chosen as the main water supply line, with 51 mm diameter branch lines connecting the main line to the individual sprinkler manifolds. The maximum distance from the supply tank to the masts was designed to be 46 m. This design supplied each nozzle with up to 19 L/min to achieve the maximum rainfall event of 100 mm/hr. Therefore, each sprinkler manifold required a flow rate of 76 L/min. Thus, the system design flow rate was set to be 455 L/min for all six sprinkler manifolds.

The Bernoulli energy loss equation was utilized to estimate the pumping energy required for this system. The Bernoulli energy loss equation is given as:

$$h_1 + \frac{p_1}{\gamma} + \frac{V_1^2}{2g} + W - F = h_2 + \frac{p_2}{\gamma} + \frac{V_2^2}{2g} \qquad (1)$$

Where

h = Elevation above reference plane (m)

p = Fluid pressure (Pa)

γ = Specific weight of fluid (N/m^3)

V = Fluid velocity (m/s)

g = Acceleration due to gravity (m/s^2)

W = Energy added by a pump (J/N)

F = Energy loss in a pipe due to friction (m)

The energy loss in a pipe was determined using the Darcy friction loss equation (Henderson, 1997). The friction factor for the piping network was estimated to be 0.015 for PVC. The Darcy friction loss equation is given as:

$$F = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right) \tag{2}$$

Where

F = Energy loss in a pipe due to friction (m)

L = Length of pipe (m)

D = Diameter of pipe (m)

V = Average fluid velocity (m/s)

g = Gravitational acceleration (m/s^2)

f = Friction factor (dimensionless)

A friction loss for each section of the water supply main was determined and utilized in the Bernoulli energy loss equation to calculate the pumping requirements for this system. Using these equations, the total dynamic head for the system was found to be 25 m of water based on a maximum slope of 5%.

Hose Network

A 76 mm diameter rigid suction pipe was selected to connect the water supply to the pump. To provide water to the sprinkler heads, layflat hose was selected for its durability, ease of use, availability, and cost. All of the piping on the discharge side of the pump utilized flexible layflat hose. This versatile rubber tubing can be easily installed in rugged landscapes and can be rolled up for compact storage. Layflat hose can be curved to change directions, thereby reducing the need for additional fittings. Camlock quick connect fittings were used for all hose connections. These snap-lock fittings facilitate the set up of the simulator while providing tight connections without screw joints. Once the unit was established at the research plot and following the completion of a simulation, the hoses could be quickly rolled up and stored between uses. The vertical hoses were connected to the elevated PVC sprinkler manifold, and to the main water supply line at a tee at the base of each mast. Each tee was fitted with a valve, which allowed each individual mast to be turned on and off. The main water supply then continued to the next tee and mast (Fig. 7).

A 76 mm diameter hose was used as the primary water supply line to pipe water to the base of all sprinkler masts. An in-line water filter and instrumentation to monitor water flow and pressure was placed in the piping network close to the discharge side of the pump.

Beyond the instrumentation, the 76 mm diameter water main was split into two directions using a tee. Each branch of the 76 mm diameter water main delivered water to three masts on each side of the plot. A 51 mm diameter hose was suspended from the sprinkler manifold on top of the mast and connected to the branched water main using tee connections at the first two masts in the line on each side, followed by an elbow connection for the last mast on each side (Fig. 7).

Each tee and ell connection was galvanized metal with a globe valve attached. This valve allowed for water to be drained from individual sprinkler manifolds without draining the entire water main. In addition, these globe valves provided flexibility for rainfall simulator applications. For example, an individual sprinkler manifold could be turned off while permitting the remaining rainfall simulator manifolds to be fully functional during a test. If a sprinkler manifold were to become clogged or break in the middle of testing, that particular manifold could be turned off without stopping the simulation. The manifold could also be turned off if wind was observed to cause water to drift completely off the plot.

Pump

A small water pump powered by a 4 kW four-stroke gasoline engine was used to supply water to the sprinkler manifolds. This pump was selected to fulfill the head requirement of 25 m. The pump is capable of producing a maximum head of 30 m and had 76 mm diameter suction and discharge ports, which were fitted with Camlock fittings.

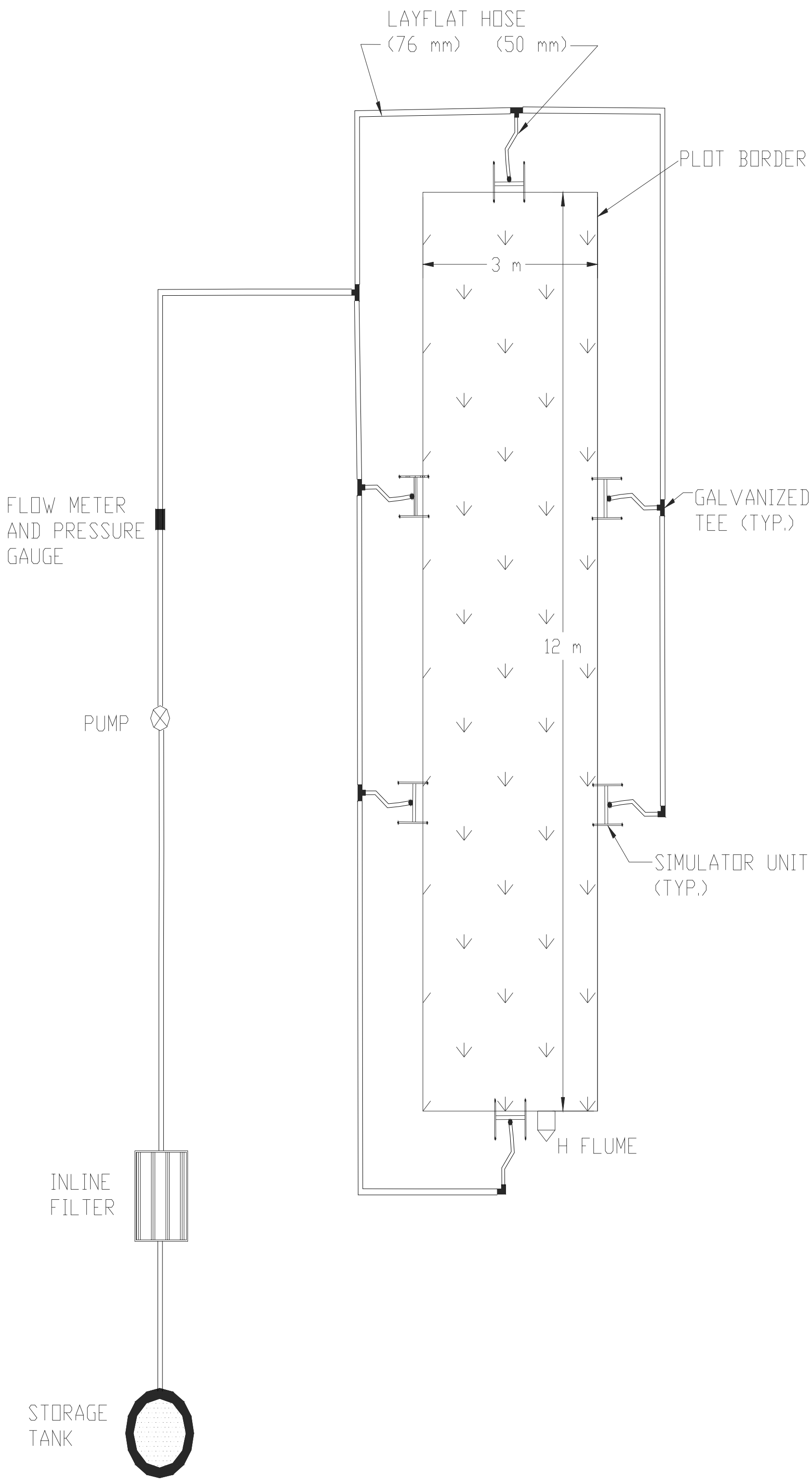


Figure 7. Schematic of rainfall simulator layout with associated components, such as sprinkler manifolds, storage tank, inline filter, pump, flow meter, and hose.

Instrumentation

A 0 to 690 kPa pressure gauge was installed in the main water supply line to monitor pressure within the piping system. In addition, a WT Turbine Meter from Master Meter (Ft. Worth, TX) was selected to monitor the volume of water pumped to the sprinkler heads. The flow meter can detect flow rates from 15 L/min up to 2,000 L/min with 95% accuracy. The flow meter has a rotating needle to measure flow rates and an odometer to quantify total volume pumped. By assuming an average pumping rate for the pump, the volumetric flow rate could be calculated by dividing the volume pumped by the total time that the simulation occurred.

Water Filter

A filter was designed and constructed to prevent sprinkler heads from becoming clogged. The filter for the rainfall simulator consists of four 3.8 cm diameter screen filters arranged in parallel using a filter manifold (Fig. 8). The inlet and outlet of the filter manifold was constructed of 7.6 cm diameter PVC pipe and the four parallel filter lines utilized 3.8 cm diameter high pressure rubber hoses. The filter manifold was placed in-line with the main water line using Camlock fittings between the water supply line suction hose and the pump (Fig. 7). Each individual screen filter is removable for cleaning purposes.

Figure 8. In-line water filter for rainfall simulator.

Water Storage

A 19,000 L (5,000 gal) portable water tank was used to store water for rainfall simulations (Fig. 9). Since the research plot was 3 m by 12 m (36 m^2) and the design application rate of water was determined to be 100 mm/hr, the rainfall simulator would be required to apply up to 3,600 L of water in one hour. Therefore, the portable water tank was able to store enough water for a five hour simulation at the maximum design application rate. For simulations longer than five hours, the tank can be refilled during the experiment using large capacity water trucks.

The portable water tank weighs 60 kg and can be folded and stored in a protective bag that is approximately 1 m^3. When deployed, the tank requires an approximate area of 50 m^2, and stands 1.25 m tall when full. The tank has a 7.6 cm valve that is fitted with a Camlock fitting that allows the main water supply line to be connected to it. The tank was placed on plywood sheeting in the field to prevent punctures in the bottom lining from sharp objects, such as rocks.

Figure 9. The 19,000 L portable collapsible water tank deployed at the research site.

Cost Analysis

The major components of the rainfall simulator were constructed from readily-available parts when possible. This was a strategic plan, so the rainfall simulator could easily be repaired or modified in the field. The largest, most expensive, single component was the water tank. Other expensive components were the layflat hose and accompanying aluminum and galvanized fittings. However, these particular components were necessary for the portability of the rainfall simulator. Another major expense was the purchase of a 6 m enclosed cargo trailer. The trailer provided storage for the rainfall simulator when not in use, and facilitated transport to remote research sites. When the rainfall simulator was installed at a research site, the trailer allowed for secure storage of simulator components during extended rainfall experiments. The trailer also provided shelter from the weather and served as a staging area during the rainfall simulations.

Most of the components of the rainfall simulator, such as the base plates, were original fabrications, since they were not readily available products on the market. Other components such as the PVC sprinkler manifold were constructed from inexpensive parts that were purchased and assembled. In both cases, this allowed for a substantial amount of cost savings, which in turn allowed for flexibility in purchasing other equipment.

Table 1 is an estimated cost breakdown for the rainfall simulator components. However, labor is not factored into this cost estimate. Labor costs were minimized by utilizing student laborers, who are less expensive than professional laborers. Costs are listed in general categories. The plumbing costs include all layflat hose, as well as Camlock and galvanized fittings. Miscellaneous costs include such things as the base plates and stakes, the in-line water filter, the pins with ratchets, and guy wires.

Table 1. Cost analysis of rainfall simulator components.

Description	**Cost**
Sprinkler Heads	$200
Aluminum Masts	$400
Flow Meter / Pressure Gauge	$550
Pump	$500
Plumbing	$1,750
Collapsible Tank	$3,000
Equipment Trailer	$3,500
Miscellaneous	$700
Total Cost	$10,600

RESULTS AND DISCUSSION

The rainfall simulator was tested in an open, grass field for initial evaluations of performance. All six masts were raised to the maximum height of 11 m around a plot measuring 3 m by 12 m. The rainfall simulator took three people less than three hours to set up. The masts were placed around all four sides of the plot. Four masts were placed one-third of the total length from each corner. The remaining two masts were centered along the short end of the plot. Rain gauges were placed in a 1 m grid in the grass plot to quantify application rates from the sprinkler manifolds. Four, 15 minute rainfall simulator tests were performed to evaluate the application rates and uniformity of the simulator. The number of open sprinkler heads on each mast was varied during each test, ranging from one to four sprinkler heads per mast. The simulated rainfall data was spatially analyzed using Surfer 8 surface mapping software (Golden Software, 2002), and can be referenced in Appendix A.

The rainfall simulator test demonstrated a linear relationship between application intensity and the number of nozzles used. Average simulated rainfall applications for the seven minute tests with one, two, three, and four open nozzles were found to be 9.19, 14.45, 16.06, and 38.13 mm respectively (Fig. 10). The rainfall simulator demonstrated reasonably uniform application spatially across the plot area (Appendix A). The effect of wind drift was observed both during testing and graphically, as there were water deficits in the upwind direction and wetted areas far beyond the plot border. It was apparent during larger intensity simulations that the simulated rain was greatly affected by wind, possibly due to the size of water droplet at this intensity, and the sheer volume of water coming from the sprinkler heads. Wind drift was also observed during low intensities, where a fraction of water would discharge the sprinkler in the form of a fine mist.

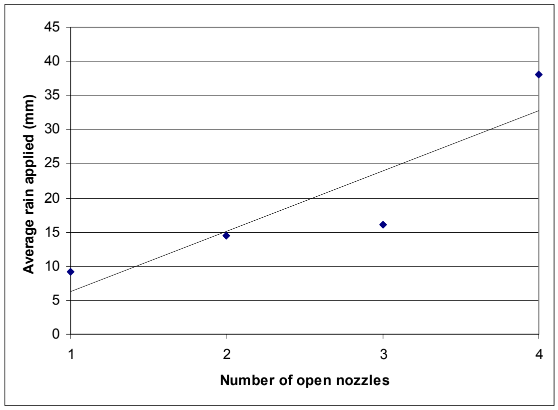


Figure 10. Relationship of applied water to number of open nozzles on sprinkler manifolds.

The new rainfall simulator developed for above-canopy application operated consistently during initial testing and calibration. While replicating precipitation at elevations up to 11 m, the masts which support the sprinkler manifold remained stable with the assistance of the guy wires, even during strong wind gusts. The unit proved to be simple to erect and dismantle with two to three workers. Due to the modular design, the rainfall simulator has many practical applications on a range of plot sizes and vegetation species.

For the purpose of field testing the rainfall simulator and conducting hydrologic studies related to brush control, the rainfall simulator was set up at the Texas Agricultural Experiment Station near Sonora, TX. The unit was assembled around a 3 m by 12 m plot containing heavy brush dominated by juniper. The six rainfall simulator masts were positioned around the plot in the same configuration used in the initial testing. A series of rainfall simulations were conducted over a period of ten months. The rainfall simulator successfully replicated precipitation events varying from 25 mm/hr to 52.5 mm/hr, with durations from 45 minutes to up to seven continuous hours. Water was trucked to the research site from a well at the station headquarters 5 km away. To increase on-site storage capacity, two 7,500 L and one 3,800 L polyethylene storage tanks on loan were brought to the site to provide an additional 18,800 L of total water storage for rainfall simulations. The rainfall simulator remained erect during this time and was subjected to severe winds, natural storms, and temperature extremes. While testing at the Sonora Experiment Station, the simulator exhibited an exceptional performance over this time period without any major equipment failure.

CHAPTER III

FIELD EXPERIMENTATION

INTRODUCTION

Upon successful completion of the development and testing of the rainfall simulator at Sonora, Texas, the simulator was taken to the Honey Creek State Natural Area near Bulverde, Texas. To fully understand the interactions between brush cover and precipitation, the rainfall simulator was deployed to a research site containing a thick stand of multi-stemmed juniper. The research plot was 7 m wide by 14 m long, and was oriented down the length of a 2% slope. The size and shape of the research plot was based on the capabilities of the rainfall simulator with the in-line sprinkler manifold to optimize water application. The research plot was small enough to minimize water applications, yet large enough to encompass entire juniper trees to accurately represent the landscape. The plot size was large enough to account for the complex interactions of heavy juniper cover within the landscape, including the intricate and often interwoven network of tree canopies and roots that this species of cedar exhibits (Thurow and Hester, 2001; Lyons et al., 1998).

Study Area

The site was located at Texas Parks and Wildlife Department's Honey Creek State Natural Area (Honey Creek SNA). This landscape is typical on the Edwards Plateau region of Texas, and the research plot selected may be considered a worse-case scenario of brush encroachment. Honey Creek SNA (Fig. 11) is a 930 ha research site located in Comal County (29.48° N, 98.30° W), within the Upper Guadalupe River Watershed (TPWD, 2004). The park land lies directly above the Trinity Aquifer, and is within the drainage area of the Edwards Aquifer (TWDB, 2002; EAA, 2004). Honey Creek drains directly into the Guadalupe River, and there are numerous springs within the riparian zone of Honey Creek. The Edwards Plateau contains shallow soil layers with highly permeable parent material that is fractured (Wilcox, 2002), as is evident at Honey Creek. The area has a growing season averaging 250 days, and the woody vegetation species within this area include ashe juniper (*Juniperus ashei* Buccholz), live oak (*Quercus virginiana* Mill.), agarita (*Berberis trifolioata* Moric.), Texas persimmon (*Diospyros texana* Scheele). Herbaceous vegetation includes Texas wintergrass (*Stipa leucotricha* Trim. & Rupr.), curly mesquite (*Hilaria belangeri)*, Indiangrass [*Sorghastum nutans* (L.) Nash], little bluestem (*Schizachyrium scoparim* Michx.), and switchgrass (*Panicum virgatum* L) (TPWD, 2004; TAM-REC, 2005). Average annual precipitation is in the range of 375 to 750 mm. The topography within Honey Creek SNA is typical of the Edwards Plateau, including gentle to steep, rolling, rocky hills.

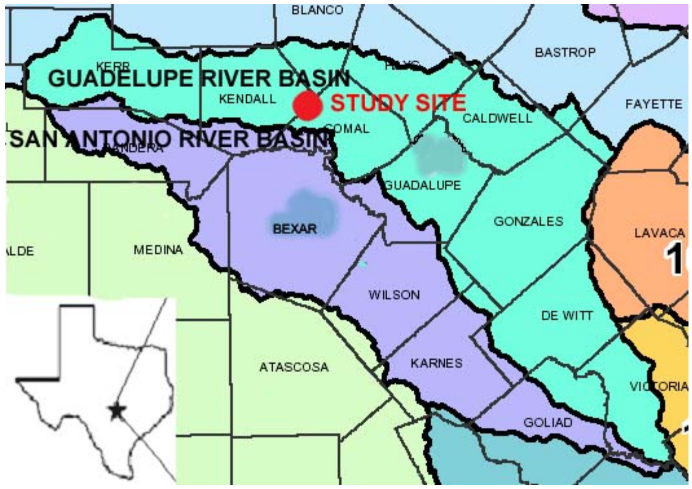


Figure 11. Site map showing location of Honey Creek State Natural Area (TWDB, 2002).

MATERIALS AND METHODS

The instrumentation used in the research plot was designed to quantify the water cycle components illustrated in Figure 12. Woody vegetation alters uniform rainfall distribution to the soil surface as shown in Figure 13. Precipitation is intercepted by tree vegetation, where water is lost back to the atmosphere by evaporation and transpiration. Water drips preferentially through the canopy to the soil surface as throughfall. In addition, intercepted precipitation flows down the branches to the trunk of the tree, and is deposited on the soil surface at the base of the tree as stemflow. Once the precipitation reaches the soil, water is stored in the form of soil moisture as water fills up micropores within the soil system. As the soil moisture increases within the soil, horizontal and vertical subsurface flow processes begin to dominate the movement of water in the vadose zone. The research plot was instrumented to monitor these processes with the purpose of quantifying the components of the water budget for this plot. This research plot is similar to the juniper plot research completed by Sorenson (2004).

Prior to instrumenting the plot, the area immediately surrounding the plot was cleared of brush and large plant species to facilitate the installation of the rainfall simulator and associated instrumentation equipment. This allowed personnel free access around the plot border and minimized traffic within the plot, which subsequently minimized soil disturbance.

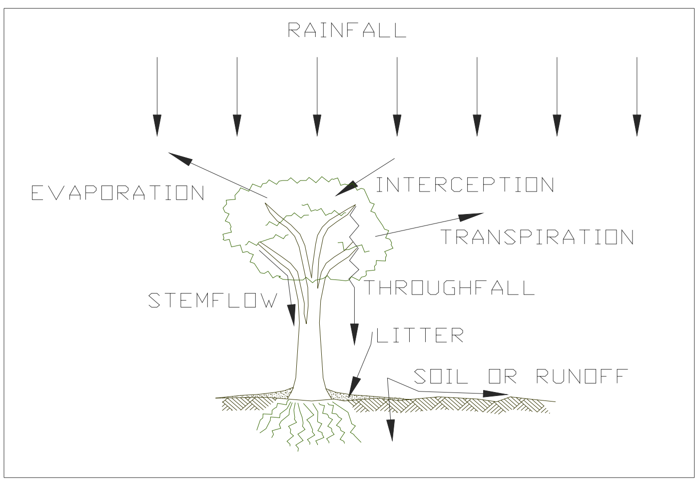


Figure 12. Partitioning of precipitation within a juniper canopy (redrawn from Owens and Lyons, 2004).

The plot was delineated using 16 gauge galvanized sheet metal inserted 50 mm into the soil. Each section of plot border metal was overlapped and joined with bolts to prevent leakage from ponded water. The down-slope plot border directed surface runoff to a standard 0.15 m H flume. The H flume contained a stilling well equipped with a potentiometer attached to a float. This potentiometer was connected to a datalogger to record surface runoff. The change in elevation of the float within the stilling well corresponds to the water level in the H flume. The surface runoff flow rate is directly related to the water level in the H flume.

After the plot border and flume were installed, the rainfall simulator was set up around the research plot. The rainfall simulator consisted of six individual masts that were evenly spaced around the research plot. Three masts were place on either side of the length of the plot. Each telescoping mast, adjustable from 3 m to 11 m, was set at a height of 9.5 m to accommodate the 9 m tree canopy. Mounted on top of each mast was an in-line sprinkler manifold containing four sprinkler heads with a 190° spray pattern. Each of the four sprinklers on the mast was fitted with nozzles to apply water at rates of 25, 50, 75, and 100 mm/hr. Therefore, one simulator mast could effectively apply water in a wide variety of application rates, varying from 25 mm/hr to 250 mm/hr depending on the number of open sprinkler heads. This range covers most storm events on the Edwards Plateau of Texas (Haan, et al, 1994).

Selected trees within the research plot were instrumented to collect the stemflow. Collars with funnels were attached around each tree stem. Each funnel was attached to a tubing network which carried the water to a central collection system at the base of each tree as described by Owens and Lyons (2004). From this central collection point, the water was routed to a 1 L per minute tipping bucket, which was connected to a data logger to quantify the volume of stemflow. The water was then discharged at the base of the tree as it would if the collection system was not in place.

Throughfall was collected in a similar manner as stemflow, which was also described by Owens and Lyons (2004). A throughfall collection system was placed under two trees in the research plot. Each collection system incorporated seven 203 mm diameter funnels, located from the base of the tree to the edge of the canopy. The funnels transferred water to a cylinder equipped with a float and potentiometer instrument system. This system quantified the volume of throughfall, as described by Owens and Lyons (2004) and the water was discharged back into the plot. Throughfall was also measured using 75 small rain gauges set up in a 1 m by 1 m grid throughout the research plot. Values from these rain gauges were recorded manually, and the water was emptied into the plot at the end of each simulation.

Soil moisture was monitored using ten ECHO-10 Dielectric Aquameter probes (Decagon Devices, Inc., Pullman, Washington). These probes were spatially distributed throughout the research plot in a grid at a depth of approximately 4 cm. These capacitance probes measure the dielectric permittivity of the surrounding medium. Since the dielectric permittivity of soil is directly related to the water content, the measured voltage corresponding to the dielectric permittivity essentially provides the volumetric water content of soil (Decagon, 2004).

At the base of the research plot, a trench was excavated for the purpose of quantifying lateral subsurface flow, as well as for the purpose of visual inspection of hydrological processes in the vadose zone (Fig. 13). Excavation was carried out using a backhoe equipped with a hydraulic jackhammer, as well as handheld jackhammers. The 9 m long by 2 m wide (measured at the bottom) trench was excavated across the width of the plot, extending 1 m beyond each corner of the 7 m wide plot, and to a depth of just less than 3 m. This depth was determined by the geology of the area, where a hard limestone layer was encountered. The plot side of the trench face was excavated carefully to avoid disturbance to the seepage face. The trench was offset 1 m from the downslope plot border. This allowed for the installation of the H flume, as well as access to this portion of the plot. The trench was covered with a roof to prevent any natural or simulated rainfall from entering the trench, thereby altering the measured volume of lateral subsurface flow.

Once the trench was excavated, the soil profile could be viewed and characterized closely, as seen in Figure 13. In addition, the entire face of the trench could be observed and monitored for lateral subsurface flow. The soil extended to a depth of nearly 0.3 m below the soil surface, but contained a mixture of rock and roots. The trench face was dominated by a thick layer of fractured limestone with a narrow vertical clay lense close to the center of the plot. Within this fractured layer were large macropores, though possibly the result of rocks removed during the excavation of the trench. The clay lense extended laterally across the trench face and separated the large fractured limestone from what appeared to be a thick layer of marl. Many roots extended beyond the trench face and were sheared during the trench excavation.

Figure 13. Image of excavated trench at the base of the research plot, taken from the East facing West.

Although the flow rate from individual sources of lateral subsurface flow in the trench face was not determined, the total volume of lateral subsurface flow was quantified. A concrete slab was poured in the bottom of the trench and sloped to channel water to a sump that was excavated at one end of the trench. A submersible pump was used to pump lateral subsurface flow into a series of three 1 L tipping buckets that were connected to a datalogger. This data was used to produce a hydrograph of lateral subsurface flow. The concrete slab also served as a platform to work on during simulations, which allowed researchers to remain dry while large quantities of water seeped from the trench face. Observations could be made to assess the driving mechanisms of lateral subsurface flow within this system while quantifying the total volume of water from the seepage face and specific flow channels (Newman et al., 2004).

The instrumentation at the research site (Fig. 14) was connected to CR10X dataloggers (Campbell Scientific, Logan, UT, 2004). The dataloggers were powered by a deep cycle battery recharged by a solar cell. This also allowed the datalogger to be left in the field to collect natural precipitation events. For natural events, the datalogger was set to record information at 15 minute intervals. During simulated rainfall events, the datalogger was changed to one minute intervals to capture the simulated rainfall events with greater precision.

Prior to every simulation, the 75 rain gauges were checked for natural precipitation events between testing dates. This gave the research team an estimation of antecedent moisture conditions and allowed for a complete accounting on the amount of water applied to the plot over the course of the study. Rain gauges were read, recorded and emptied in preparation of rainfall simulations. Heavy plastic sheeting was placed outside the plot border around the entire plot to prevent any overspray from the rainfall simulator from infiltrating into the soil. This allowed the research team to obtain a more precise estimate of lateral subsurface flow, since only a specific area was receiving input of water. Lateral subsurface flow could then be related directly to the 7 m by 14 m plot area.

A series of simulated rainfall tests were conducted over the brush canopy at the Honey Creek research site. The intensity and duration for each simulated rainfall test was to replicate a particular storm event. Rainfall simulation tests ranged from a one hour, 15 mm/hr test to a four hour, 2.5 mm/hr test. Simulations were never conducted at intensities below 2.55 mm/hr, since most rainfall from small precipitation events never reach the soil surface due to water retention and evaporation losses (Owens and Lyons, 2004; Thurow and Hester, 2001). Rainfall simulations were usually conducted over a one or two day time period. Some simulation events were repeated within one week to observe the effects of antecedent moisture conditions and to establish the hydrologic response of the plot.

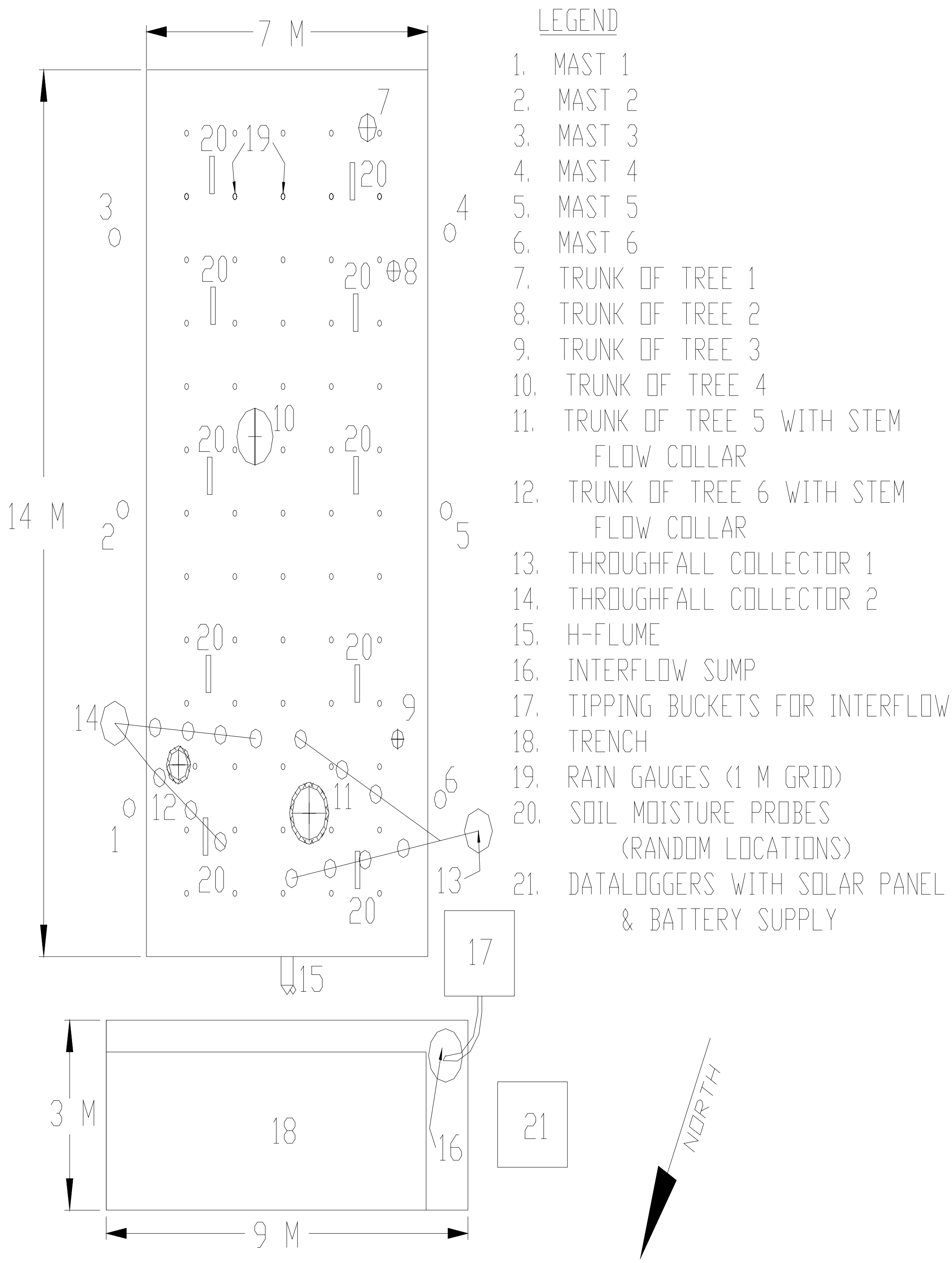


Figure 14. Research site layout and equipment at juniper dominated site at Honey Creek State Natural Area.

RESULTS AND DISCUSSION

Three simulated rainfall events were selected for a detailed water budget analysis. These simulated rainfall events occurred on 5 December, 11 December, and 18 December 2003. These dates were chosen based on the similarities of duration and intensities of tests conducted. On 5 December, two rainfall simulations were conducted. Each simulation lasted 60 minutes. The application rate for the first test was 254 mm/hr and the second test was 152 mm/hr (Table 2). Plots of each process described above have been compiled for each simulation date and test, and can be viewed in Appendix B.

Table 2. Sequence of rainfall simulation intensities and durations on juniper research plot at Honey Creek State Natural Area.

Date	Duration (min)	Total Input (mm)	Intensity (mm/hr)*
5 Dec 2003	60	123.96	254
5 Dec 2003	60	83.06	152
11 Dec 2003	45	74.60	152
11 Dec 2003	60	67.83	102
11 Dec 2003	60	12.32	25
18 Dec 2003	45	68.41	152
18 Dec 2003	60	53.30	102
18 Dec 2003	60	13.33	25

*Theoretical intensities based on sprinkler output

The rainfall simulations on 11 December and 18 December 2003 were nearly identical with respect to duration and intensity (Table 2). On both days, a series of three rainfall simulations were conducted, each lasting for 45, 60, and 60 minutes. Application intensity was identical on theses test dates with rates of 152, 103, and 25 mm/hr, respectively. Total input refers to the amount of water applied to the plot, expressed as mm. This number is derived from the summation of the average measured throughfall and the total recorded stemflow within the research plot.

It is important to note that the initial antecedent moisture conditions for the research plot were identical on 5 December, 11 December and 18 December 2003. All three reported dates had a precipitation event occur one week prior to each test date. A natural rainfall event occurred during the week prior to the 5 December rainfall simulations. Wet antecedent moisture conditions on 11 December and 18 December were the result of rainfall simulations conducted the previous weeks of 5 December and 11 December, respectively. In addition, a minor natural precipitation event occurred on 17 December 2003, but only contributed an average throughfall value of 6.4 mm to the plot.

The objective for rainfall simulations on 5 December 2003 was to establish a hydrologic response that could be compared to future events. The first test on 5 December was a one hour, 254 mm/hr application to "pre-wet" the plot to provide moist antecedent moisture conditions. Therefore, the initial rainfall simulation on 5 December occurred with dry antecedent moisture conditions. All six rainfall simulator units were used, giving the plot a theoretical intensity of 254 mm of rain per hour. While the simulation was only one-third of the way completed, surface ponding was observed within a depression in the center of the research plot (Fig. 15). Most of the water contributing from this area came directly from the stemflow of the juniper trees. At 31 minutes into the first run, the first seepage was observed from the main discharge point in the trench face, which was an apparent fractured channel within the rock layer. Two minutes later, flow started along the clay lense. One hour following the completion of the first one hour test, flow from the seepage face was observed to be dramatically reduced to a slight trickle.

The second rainfall simulation started approximately 2.5 hours following the completion of the first test, and lasted for one hour with an intensity of 152.4 mm/hr. Lateral subsurface flow was visually observed at only 16 minutes into the start of the second test. The seepage face wet up quickly, and the discharge from the same locations started in the same sequence as the first simulation. Just as before, the flow into the trench was drastically reduced from the seepage face one hour after the second test ended. The seepage of water stopped completely three hours after the completion of the second test. Surface runoff was not observed during the three rainfall simulations on this date.

Figure 15. Image of ponded water within juniper research plot during rainfall simulation at Honey Creek State Natural Area.

The first test on 11 December 2003 was also considered a "pre-wetting" for the plot, similar to the first test on 5 December. This rainfall simulation lasted 45 minutes with an intensity value of 152.4 mm/hr. There were no natural precipitation events at the research site since the simulation tests on 5 December. The initial conditions in the plot consisted of a dry litter layer and the trench face appeared to be partially saturated. At ten minutes into the first run, ponded water was observed at a surface depression within the center of the plot (as seen in Fig. 15). At twenty minutes into the simulation, lateral subsurface flow was observed from the main discharge point, as in the previous test. At the completion of this test, the trench face continued to flow with water. The main discharge point continued to flow with a low constant release for one hour following the completion of the simulation.

The second rainfall simulation on 11 December started just over one hour following the completion of the first test and lasted for one hour with an intensity of 102 mm/hr. At the start of this test, the trench face continued to seep with very low flows. Fifteen minutes following the start of the simulation, the main discharge point was flowing at a constant and high flow rate. After another 25 minutes, water was gushing out of this area at a rate of 30 liters per minute. One and a half hours after the test concluded, the main discharge point stopped completely, and water was flowing out from other locations at a slow but constant rate.

The third test on 11 December was initiated 81 minutes following the completion of the second test. Similarly to the second test, the trench face was saturated with water trickling into the trench. This test was conducted at an intensity of 25 mm/hr over a one hour period. There was minimal flow from the main discharge point after thirty minutes, with two other discharge points also flowing. This flow regime continued at the same flow rate throughout the duration and upon completion of the simulation. Water was seeping from the clay lense and certain rock fractures throughout the trench face. Surface runoff was not observed during the three rainfall simulations on this date.

Using the same schedule as the previous series of tests, three rainfall simulations were conducted with varying intensity and duration on 18 December 2003. The first simulation also used an intensity of 152.4 mm/hr for 45 minutes to pre-wet the plot. As in previous tests, the trench face was observed to be partially saturated as a result of the previous simulations of the subsequent week. Nine minutes into the first test, surface ponding was observed at the center of the plot in the same depression as subsequent tests (as seen in Fig. 15). After 22 minutes, this ponding continued throughout a larger section of the plot than was previously observed. However, no seepage occurred at the trench face until 27 minutes after the test started. The main discharge point was observed to be fully flowing at 42 minutes into the simulation.

The second rainfall simulation on 18 December 2003 comprised of a one hour test with an intensity of 102 mm/hr. This test started 87 minutes after the conclusion of the first simulation. At the start of this simulation, water was discharging into the trench as a slow trickle out of portions of the trench face. Seven minutes after restarting the rainfall simulation, surface ponding was again observed within the middle of the plot. The lateral subsurface flow flowing from the trench face was significantly greater 13 minutes after the start of the simulation, as compared to the near trickle at the beginning of the test. Lateral subsurface flow continued to flow heavily 60 minutes after the completion of the test.

The third rainfall simulation consisted of a 60 minute test at an intensity of 25 mm/hr, again similar to the third test on 11December 2003. This test was started 60 minutes following the completion of the second test, with water still flowing at a constant rate from certain discharge points within the trench face. Lateral subsurface flow from the trench face was not as great during this test as compared to the previous tests of the same day, though water was observed flowing 95 minutes after the completion of this test. Surface runoff was not observed during the three rainfall simulations on this date.
The data from the rainfall simulation tests were analyzed and a water budget for the research plot was developed. Water applied above the canopy was the input for the water budget. This input was then quantified for the various hydrologic processes, such as interception, stemflow, throughfall, surface runoff, lateral subsurface flow, and vertical recharge. The goal of the data analysis was to characterize the hydrologic response of the juniper covered research plot to simulated rainfall events.

To relate the volume of lateral subsurface flow that flowed through the trench as a depth, the total volume was divided by the area of the research plot, which was 98 m^2. This allowed for a comparison of the amount of lateral subsurface flow relative to the amount of applied water to the plot. This procedure is further explained in Appendix C, with corresponding hydrographs in Appendix D.

To relate the volume of water collected as stemflow to a unit of length for comparison to precipitation, the total volume was divided by the area of the tree canopy that contributed to each measure of stemflow. A vegetation study was conducted to determine the canopy area of each tree relative to the entire plot. The two instrumented trees were determined to account for approximately 30% of the cover over the entire plot, which exhibited approximately 100% canopy cover. To estimate the total stemflow value for all six trees within the juniper plot, the value collected for the two instrumented trees was scaled up based on the fraction of canopy cover that these trees represented. This procedure is further explained in Appendix E.

Throughfall was measured using two methods, a grid of rain gauges read manually and a series of funnels recorded electronically. However, since the numerous rain gauges were placed throughout the plot, the data for the rain gauges was used to determine throughfall and water input into the plot. The data from the throughfall collection system was used for analytical purposes with respect to the hydrologic response of the plot. The throughfall collection system provided data with time stepped increments, whereas the rain gauges could only provide one measurement after the rainfall simulation was completed. This procedure is further explained in Appendix F.

Tables 3 and 4 present the partitioning of the simulated rainfall for the three experimental runs of 5 December, 11 December, and 18 December 2003 compiled for all eight rainfall simulations.

Table 3. Summary of eight rainfall simulations from 5 December through 18 December 2003 at the juniper dominated plot at the Honey Creek State Natural Area

	Simulated Rainfall (mm)	Percent Applied (%)
Total Input	514.01	100.00
Stemflow	132.31	25.74
Average Measured Throughfall	381.70	74.26
Lateral Subsurface Flow	168.50	32.78
Soil Moisture	83.12	16.17
Surface Runoff	0.00	0.00

Table 4. Partitioning of simulated rainfall at the juniper plot for eight rainfall simulations in December 2003 at the Honey Creek State Natural Area

Rainfall Simulation	Simulated Rainfall (mm)	Percent Applied (%)	Rainfall Simulation	Simulated Rainfall (mm)	Percent Applied (%)
5 Dec 2003: Run 1			**11 Dec 2003: Run 3**		
High intensity, long duration on dry soils			High intensity, long duration on dry soils		
Manual Throughfall	96.64	77.96	Manual Throughfall	8.38	68.02
Stemflow	27.32	22.04	Stemflow	3.94	31.98
Total Input *	123.96	100	Total Input *	12.32	100
Soil Moisture	----	----	Soil Moisture	10.67	86.61
Lateral Subsurface Flow	20.55	18.87	Lateral Subsurface Flow	30.78	71.4
Surface Runoff	0.00	0	Surface Runoff	0.00	0
5 Dec 2003: Run 2			**18 Dec 2003: Run 1**		
High intensity, long duration on wet soils			High intensity, long duration on dry soils		
Manual Throughfall	56.76	68.34	Manual Throughfall	60.26	88.09
Stemflow	26.30	31.66	Stemflow	17.74	25.93
Total Input *	83.06	100	Total Input *	68.41	100
Soil Moisture	----	----	Soil Moisture	9.95	14.54
Lateral Subsurface Flow	30.78	45.22	Lateral Subsurface Flow	17.94	26.22
Surface Runoff	0.00	0	Surface Runoff	0.00	0
11 Dec 2003: Run1			**18 Dec 2003: Run 2**		
High intensity, short duration on dry soils			Intermediate intensity, long duration on wet soils		
Throughfall	56.60	75.87	Throughfall	46.26	86.79
Stemflow	18.00	24.13	Stemflow	20.93	39.27
Total Input *	74.60	100	Total Input *	53.30	100
Soil Moisture	15.59	86.61	Soil Moisture	20.60	38.65
Lateral Subsurface Flow	12.44	16.68	Lateral Subsurface Flow	30.20	56.66
Surface Runoff	0.00	0	Surface Runoff	0.00	0
11 Dec 2003: Run 2			**18 Dec 2003: Run 3**		
Intermediate intensity, long duration on wet soils			Low intensity, long duration on wet soils		
Throughfall	46.67	68.8	Throughfall	10.14	76.07
Stemflow	21.16	31.2	Stemflow	3.19	23.93
Total Input *	67.83	100	Total Input *	13.33	100
Soil Moisture	17.62	25.98	Soil Moisture	8.69	0.652
Lateral Subsurface Flow	30.10	44.38	Lateral Subsurface Flow	18.99	142.5
Surface Runoff	0.00	0	Surface Runoff	0.00	0

*Total input equalls the average manual throughfall reading plus stemflow.

A significant observation was that no surface runoff was observed or recorded from the research plot during any of the rainfall simulations. Surface ponding often did occur, (sometimes rather quickly once the soil and litter layers were saturated), but water never moved out of the research plot over the surface and through the flume. It was observed that the plot exhibited microtopography within the plot around the base of the trees due to the build-up of roots, litter, and soil at the base of the juniper trees. This created reservoirs on the uphill side of the juniper trees and prevented surface runoff.

Much of the water ponding in the center of the plot appeared to be coming from the tipping bucket measuring the stemflow of the trees. Due to the nature of stemflow and the volume of water that is collected at the base of the tree, this amount of water would occur there naturally during a precipitation, with or without the tipping bucket mechanisms. This large volume of water suggests that the trees act as a funnel, concentrating water directly to the base of the tree, where the largest roots are located. This process, in conjunction with the microtopography that is present within the juniper trees, minimizes the available water for overland flow. This results in a reduction or elimination of surface runoff from the research plot following a precipitation event. These are similar soils and geologic features that can be found throughout the Edwards Plateau (Wilcox, 2002). It is very probable that the microtopography under the juniper tree canopy on shallow slopes ($< 5\%$) promotes water infiltration via the macropores that exist within the litter layer and preferential flow paths present within the soil matrix (Stephens, 1996).

Bergkamp (1998) observed a similar response in the lack of surface runoff while using rainfall simulators on a multitude of plot scales in central Spain. He observed minimal surface runoff dominated by ponding water on a research plot measuring 2 m x 10 m under simulated rainfall intensity of 70 mm/hr. Bergkamp (1998) noted that rainfall intensities which produced runoff at small scales did not runoff at the part-slope scale. Precipitation intensities that caused overland flow on smaller plots (1 m x 1 m) did not generate runoff at a larger plot scale (20 m x 100 m), but rather promoted the infiltration of water within the soil matrix under the canopy. Dugas and Hicks (1998) noted that with regards to natural annual precipitation for a 15 ha research site on the Edwards Plateau, surface runoff was usually only generated on a small percentage of the total landscape. The soils and geologic features at Honey Creek are similar to what can be found within the Edwards Plateau (Wilcox, 2002).

The litter layer that is present below the juniper canopy is high in organic matter, as it is comprised of decaying tree needles which have fallen over time. The juniper litter layer exhibits hydrophobic properties which prevents water from infiltrating vertically into the soil matrix. Water wets up the surface of the litter and travels horizontally at or near the surface until a preferential flow path is encountered that permits vertical flow through the litter layer.

At random intervals between simulations (on different testing dates), sections of the litter were excavated with a shovel to a depth of approximately 12 cm to observe the wetting of the litter layer beneath the juniper canopy. A remarkable observation was that after repeated rainfall simulations on the same day, the litter layer was extremely dry. Below the 5 cm depth, the litter was dry in certain areas after 200 mm of water was applied to the soil. This observation supports the argument that the dominant mechanism for water movement under juniper canopies is via preferential flow paths through the litter layer.

The plot response with respect to soil moisture is shown in Figures 16 and 17. These three plots illustrate the overall change in soil moisture with respect to time for the rainfall simulation on 11 December and 18 December 2003. The soil moisture values in Figures 16 and 17 represent an average of the soil moisture probes located throughout the research plot (see Appendix G for details), with outliers removed. The response of soil moisture during and following each rainfall simulation has been documented in Appendix H for 11 December and 18 December 2003. Soil moisture data for 5 December appears to be inaccurate and is therefore excluded in Appendix H. It is remarkable that the soil and litter layer appear to dry with time following a rainfall simulation. This is potentially due to the draining of the macropores within this system. It is very likely that the water within the preferential flow path during one simulation moves to become lateral subsurface flow as the simulations progress.

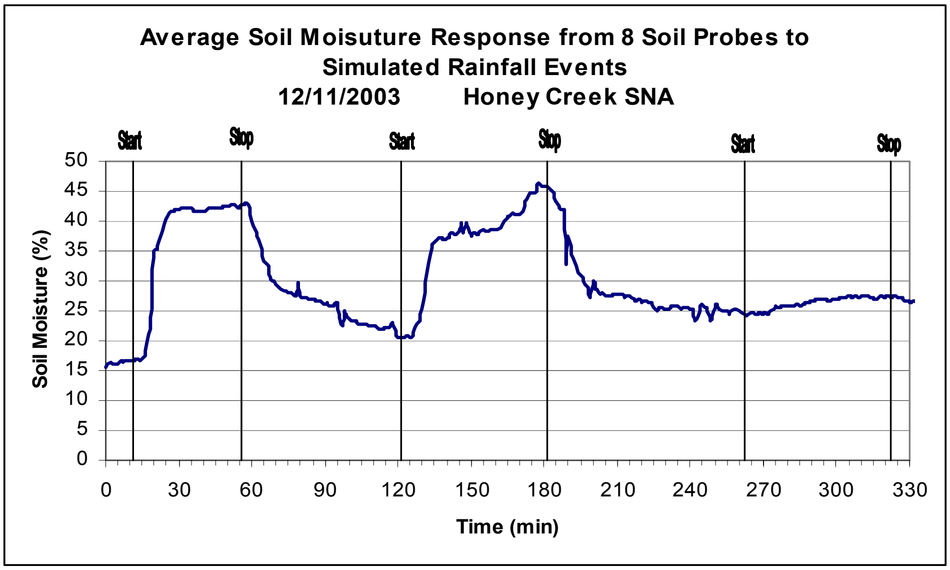


Figure 16. Soil moisture response to simulated rainfall events on 11 December 2003 at Honey Creek State Natural Area.

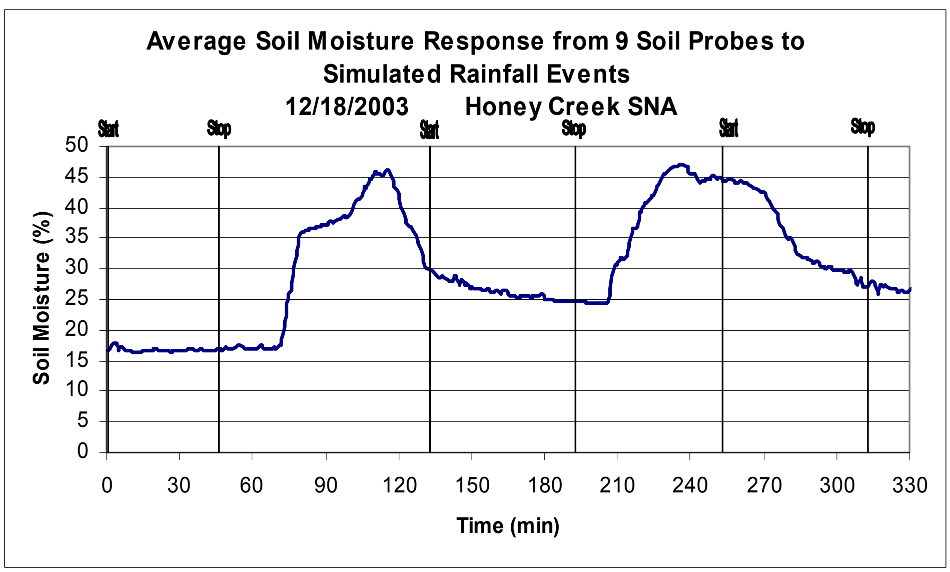


Figure 17. Soil moisture response to simulated rainfall events on 18 December 2003 at Honey Creek State Natural Area.

Lateral subsurface flow was observed and quantified through the trench face for the two identical rainfall simulation tests on 11 December and 18 December 2003, as shown in Appendix C. Lateral surface flow started and stopped at virtually the same time during each rainfall simulation. Visual observations of lateral subsurface flow through the trench face were documented to commence approximately 30 minutes after the start of each rainfall simulation. During the rainfall simulation, the peak in the volume of lateral subsurface flow occurred at or near the completion of the simulation, as seen in Appendix C. This observation suggests that there is a direct relationship between lateral subsurface flow and precipitation. The volume of water measured as lateral subsurface flow was dependent on the volume of water being applied to the research plot.

The research plot showed a similar response with regard to the amount of water that was partitioned as lateral subsurface flow, as seen in Table 4. The volume of lateral subsurface flow on the second runs of 11 December and 18 December 2003 are nearly identical at 30.61 mm and 30.20 mm, respectively. This corresponds to volumes of 3,000 L and 2,960 L, respectively. In addition, the third runs of 11 December and 18 December 2003 showed similar measurements at 6.99 mm and 9.09 mm respectively, which correspond to 685 L and 891 L. This is further evidence that the lateral subsurface flow under the plot was very similar for identical simulated rainfall conditions. This would suggest that, during significant natural precipitation events, large volumes of water will follow virtually the same transport mechanism in the form of lateral subsurface flow.

The process by which the trench face became wet and yielded lateral subsurface flow was consistent every time. As mentioned, the trench face consisted of layers of fractured limestone with a narrow horizontal clay lense between two rock layers running through the center of the trench face. The clay lense would appear to become saturated, yet would take typically over one hour before water would seep from this area. However, water from the conduits and fractures would flow within 25 minutes after the start of most rainfall simulations. In addition, other large limestone fractures near the flowing fractures remained relatively dry. This is consistent with findings noted by Newman, et al (2004), in which a study noted that bedrock in a trench stayed dry while the soil portion of the trench face was wet during snow melt. This indicates that not all fractures are hydrologically connected with the plot surface. The time lag between the start of rainfall simulations and the beginning of lateral subsurface flow suggest that this is the time required for water to fill the conduit and fracture leading to the trench face. Given the shallow soils and fractured underlying limestone that dominate this region, lateral subsurface flow is a key component of the water budget.

As a result of the identical rainfall applications for simulation dates 11 December and 18 December 2003, the research plot exhibited similar hydrologic responses with respect to stemflow and throughfall (Table 4). Visual observations suggest that these responses commenced just over five minutes of the start of intense rainfall simulations. Once a simulated rainfall event commences, a portion of the water becomes stored within the tree canopy. During small precipitation events, the tree canopy intercepts and traps nearly all rain water, up to 10 mm (Owens and Lyons, 2003; Thurow and Hester, 2001). This water then becomes more susceptible to evaporation and transpiration losses. Beyond this threshold, water is quickly (with respect to the beginning of the precipitation event) transported within the stem system to the base of the tree. This suggests that the landscape responds in a similar manner following similar precipitation events. As shown in Figure 18, there is an almost instantaneous response in juniper stemflow within the research plot. This process begins and stops within five minutes of the start and stop of each rainfall simulation. Stemflow measurements were almost identical for these dates as well, as shown in Table 4.

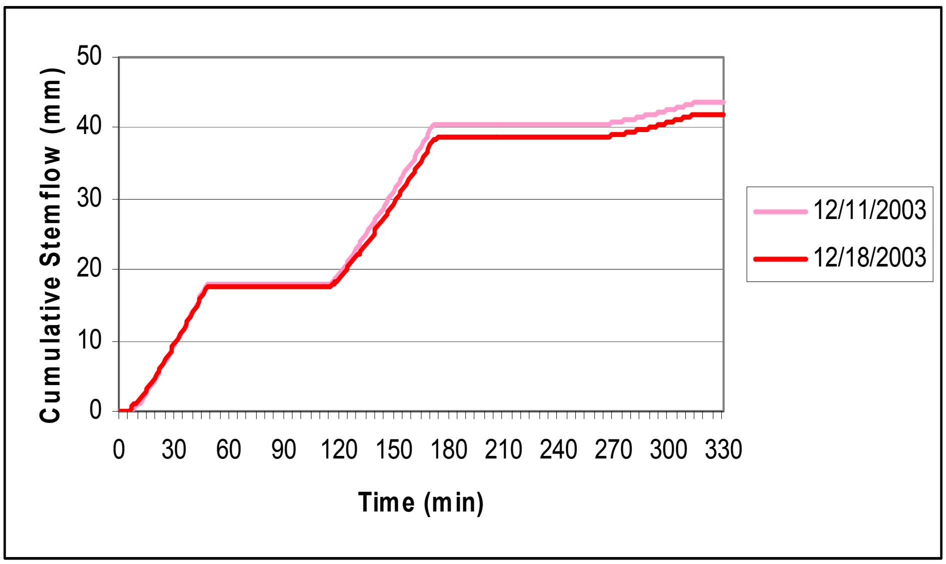


Figure 18. Cumulative response in stemflow from two simulation events one week apart at Honey Creek State Natural Area.

The large volume of stemflow recorded for both trees suggests that the juniper acts as a funnel to collect rainfall and direct it to its roots through the soil matrix. This is especially true when compared to the amount of water measured as throughfall. Overall, stemflow accounted for 25.74% of the water applied to the plot, whereas measured throughfall was recorded to be 74.26% of the total applied water. This is larger than reported by Sorenson (2004) on a similar research plot within the Edwards Plateau, but can be explained by the larger plot size and multi-stemmed juniper branch network at the Honey Creek site. This process could give rise to deep water storage, whereby the trees most likely have the capability of storing a portion of water in the soil within close proximity to its roots, from which it can extract water in times of drought. These species of juniper are fairly deep rooted, and thus have the ability to extract water at deep depths (Wilcox, 2002). What is certainly unknown (and at present, difficult to monitor) is the amount of water that continues vertically past the root zone.

CHAPTER IV

SUMMARY AND CONCLUSIONS

The configuration of the masts around the 3 m by 12 m research plot in Sonora, Texas, equipped with the H-pattern manifold and the 360° irrigation nozzles, was designed to uniformly apply water to the plot while countering the effects of wind regardless of the direction. However, this arrangement resulted in a large amount of overspray that was observed over an area two to three times the area of the plot, depending on the strength and direction of the wind. This gave rise to the development of the in-line manifold with sprinkler heads that incorporated a semi-circular (190°) spray pattern. Though still affected by wind, the sprinklers with the 190° spray pattern proved to effectively and uniformly apply water on a larger 7 m by 14 m plot. It should be noted that the masts were placed outside of these research plots to minimize disturbance.

The H-pattern manifold with the 360° degree irrigation nozzles has the potential to be useful for scaling up the plot size to the hill slope scale. The rainfall simulator and its associated equipment would be placed within these larger plots. The amount of soil disturbance per square meter would be much less at the hillslope scale than for the research plot scale. The minimization of soil disturbance is essential to maintain natural, in-situ conditions.

The rainfall simulator proved to be an efficient tool for studying the interactions of juniper on the hydrologic cycle in semi-arid regions. The modular components used in the design expedited the installation and increased portability. The rainfall simulator can be set up and disassembled by three people in less than four hours. The rotating base plates facilitate the erection of the masts and allow the rainfall simulator to be installed on steep hillslopes. The rainfall simulator was easily transported to remote research sites using the enclosed trailer. However, water supply remains the primary limitation of rainfall simulations in remote areas without a water source.

A unique feature of this simulator is the ability to apply rainfall over a wide range of land covers from tall tree canopies (up to 10 m), to grass covered plots. The rainfall simulator performed exceptionally well during field tests and with research experiments. No major equipment problems were observed beyond minor leaks in the plumbing fixtures. Intensity and duration could be adjusted in a matter of minutes by adjusting the valves on each sprinkler manifold. Longer simulations were achieved by refilling the water storage tanks and by refueling the water pump to sustain prolonged periods of use.

The cost of constructing and operating the rainfall simulator was relatively inexpensive, particularly when compared to studies utilizing natural rainfall events. Most costs were associated with the initial development and construction of the rainfall simulator. These capitol costs are significantly less than the operational costs, and the rainfall simulator is virtually maintenance free. Operating costs are primarily the cost of labor. Other minor operating costs are typically associated with spare parts and gasoline, and vary depending on the research site. When compared to the alternative of mobilizing for natural storm events, specifically for storms of record, the rainfall simulator can reproduce desired rainfall events in a cost efficient and timely manner. Hydrologic studies can be executed and data can be collected in a cost-effective manner by having key personnel and equipment at the research site during the rainfall event.

The rainfall simulator exceeded expectations with respect to water application and coverage area. The unit effectively applied water over a 3 m by 12 m plot using the H-pattern manifold and over a 7 m by 14 m plot with the in-line manifold. Unfortunately, wind continues to be a challenge causing overspray outside of the research plot. Windscreens are not viable solutions for tall canopies due to the cost and logistics of installation around the plot. When possible, simulation testing was performed early in the morning and late in the evening when winds were at minimum velocities. The use of the rainfall simulator for larger areas at the hillslope scale would be possible if an adequate water supply could be provided.

Analysis of testing shows a direct relationship between the volume water applied to the research plot and lateral subsurface flow. The majority of water applied to the research plot was recovered as lateral subsurface flow, indicating that the vadose zone is a key component of the movement of water in this landscape. This suggests that the majority of the water that percolates quickly through the thin soils and travels laterally just below the surface. This occurrence is supported by the lack of overland flow, which suggests that lateral subsurface flow is the dominant flow mechanism of water in this research area. This corresponds to potential water recharge within a fractured zone. The quick movement of water has the potential to reach larger vertical preferential flow paths to provide increased groundwater recharge deep in the ground.

Unfortunately, this experiment can only account for water that appears to the depth of 3 m. Due to the hard limestone rock layers, it is very difficult to account for water beyond this depth. The lack of overland flow or surface runoff from the research plot suggests that areas dominated by brush species do not produce significant runoff on mild slopes (< 5%). It is probable that the dominant flow regime in this area is that of lateral subsurface flow. It is difficult to say if this volume of water would be available as deep recharge to an aquifer, since it is unknown where the lateral subsurface flow intercepted by the trench ultimately goes.

The information presented is part of an ongoing brush control study in the Edwards Plateau. Once a significant amount of data is collected on this research plot, the schedule for this investigation includes removing the brush on the plot. Upon complete removal of the brush from the research plot, rainfall simulations will commence over the plot with the same frequency of tests in an effort to compare data from the covered and cleared landscapes. The implications of this comparison will provide greater insight on the effects of brush and brush control on the local water budget within a brush-dominated region.

REFERENCES

Bergkamp, G. 1998. A hierarchical view of the interactions of runoff and infiltration with vegetation and microtopology in semiarid shrublands. *Catena*. 33:201-220.

Campbell Scientific, Inc. 2004. Company website: Campbell Scientific, Inc. Available at: http://www.campbellsci.com.

Decagon Devices, Inc. 2004. Company website: Decagon Devices, Inc. Available at: http://www.ech2o.com.

Dugas, W.A. and R.A. Hicks. 1998. Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek watershed. *Water Resources Research.* 34:1499-1506.

EAA. 2004. Organization website: Edwards Aquifer Authority. Available at: http://www.edwardsaquifer.org/.

Golden Software. 2002. *Surfer*. Ver. 8. Golden, CO: Golden Software, Inc.

Haan, C.T., B.J. Barfield and J.C. Hayes. 1994. *Design Hydrology and Sedimentology for Small Catchments.* San Diego, CA: Academic Press.

Henderson, S.M., R.L. Perry and J.H. Young. 1997. *Principles of Process Engineering*. St. Joseph, MI: American Society of Agricultural Engineers.

Humphry, J.B., T.C. Daniel, D.R. Edwards, and A.N. Sharply. 2002. A portable rainfall simulator for plot-scale runoff studies. *Applied Engineering in Agriculture*. 18:199-204.

Johanson, M. P., T.E. Hakonson, and D.D. Breshears. 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. *Hydrologic Principles*. 15:2953-2965.

Lyons, R.K., M.K. Owens, and R.V. Machen. 1998. Juniper Biology and Management in Texas. E-54. Texas Agricultural Experiment Station, The Texas A&M University System.

Meyer, L.D. and D. L. McCune. 1958. Rainfall simulator for runoff plots. *Agricultural Engineer*. 39:644-648.

Nelson Irrigation. 2003. Company Web site: Nelson Irrigation. Available at: http://www.nelsonirr.com.

Newman, B.D., B.P. Wilcox, and R.C. Graham. 2004. Snowmelt driven macropore flow and soil saturation in a semiarid forest. *Hydrological Processes*. 18:1035-1042.

Owens, M.K. and T.G. Schliensing. 1995. Invasive potential of ashe juniper after mechanical disturbance. *Journal of Range Management*. 48:503-507.

Owens, M.K. and R.K. Lyons. 2004. Evaporation and interception water loss from juniper communities on the Edwards Aquifer Recharge Area. UREC-02-028, TAEX. The Texas A&M University System.

Renard, K.G. 1985. Rainfall simulators and USDA erosion research: history, perspective, and future. In *Proceedings of the Rainfall Simulator Workshop Tucson, AZ,* pp 3-6. Society of Range Management.

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

Sorenson, J.R. 2004. The use of large plot rainfall simulation to investigate runoff generation on the Edwards Plateau, Texas. MS thesis. College Station, TX: Texas A&M University, Department of Rangeland Ecology and Management.

Stephens, D.B. 1996. *Vadose Zone Hydrology.* Boca Raton, FL: CRC Press.

Swanson, N.P. 1965. Rotating – boom rainfall simulator. *Transactions of the ASAE*. 8:71-72.

Texas A&M Research and Extension Center. 2005. Native Plants of South Texas. Available at: http://uvalde.tamu.edu/herbarium/index.html.

Texas Parks and Wildlife Department. 2004. Texas State Park Guide. Available at: http://www.tpwd.state.tx.us/parkguide.

Texas State Soil and Water Conservation Board. 2002. State Brush Control Plan. Temple, TX: State of Texas.

Texas Water Development Board. 2002. Major Aquifers in Texas. Austin, TX: State of Texas.

Texas Water Development Board. 2002. Major River Basins in Texas. Austin, TX: State of Texas.

Thurow, T.L. and J.W. Hester. 2001. How an Increase or Reduction in Juniper Cover Alters Rangeland Hydrology. *2001 Juniper Symposium*. Texas Agricultural Experiment Station, The Texas A&M University System. Tech. Rep. 01-1. Sonora, TX.

Van Auken, O.W. 2002. Shrub invasions of North American semiarid grasslands. *Annual Review of Ecology and Systematics*. 31:197-215.

Wilcox, B.P. 2002. Shrub control and streamflow on rangelands: A process based viewpoint. *Journal of Range Management*. 55:318-326.

SUPPLEMENTAL SOURCES CONSULTED

Bubenzer, G.D. and L.D. Meyer. 1965. Simulation of rainfall and soils for laboratory research. *Transactions of the ASAE*. 8:73-75.

Hennessy, J.T., R.P. Gibbens, J.M. Tromble, and M. Cardenas. 1983. Water properties of caliche. *Journal of Range Management*. 36:723-726.

Huxman, T.E., B.P. Wilcox, D.D. Breshears, R.L. Scott, K.A. Snyder, E.E. Small, K. Hultine, W.T. Pockman, and R.B. Jackson. 2005. Ecohydrological implications of woody plant encroachment. *Ecology*. 86:308-319.

Johansen, M.P., T.E. Hakonson, and D.D. Breshears. 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. *Hydrologic Processes*. 15:2953-2965.

Munster, C. and Brad Wilcox. 2001. Development of a rainfall simulator for the assessment of basic hydrological processes affected by brush control. Project Narrative.

TAMU. 2002. Academic web site: Clyde Munster. Available at: http://baen.tamu.edu/users/munster.

APPENDIX A

RAINFALL DISTRIBUTION ANALYSIS FROM RAINFALL SIMULATOR TESTING

Rainfall simulations were conducted over a 3 m x 12 m grass covered plot, as described in Chapter II. The simulations shown below were conducted over a 15 minute period each, with simulator masts set at a height of 11 m. Spatial analysis was performed using Surfer 8 plotting software. The following figures show tests using one, two, three, and four nozzles, as indicated.

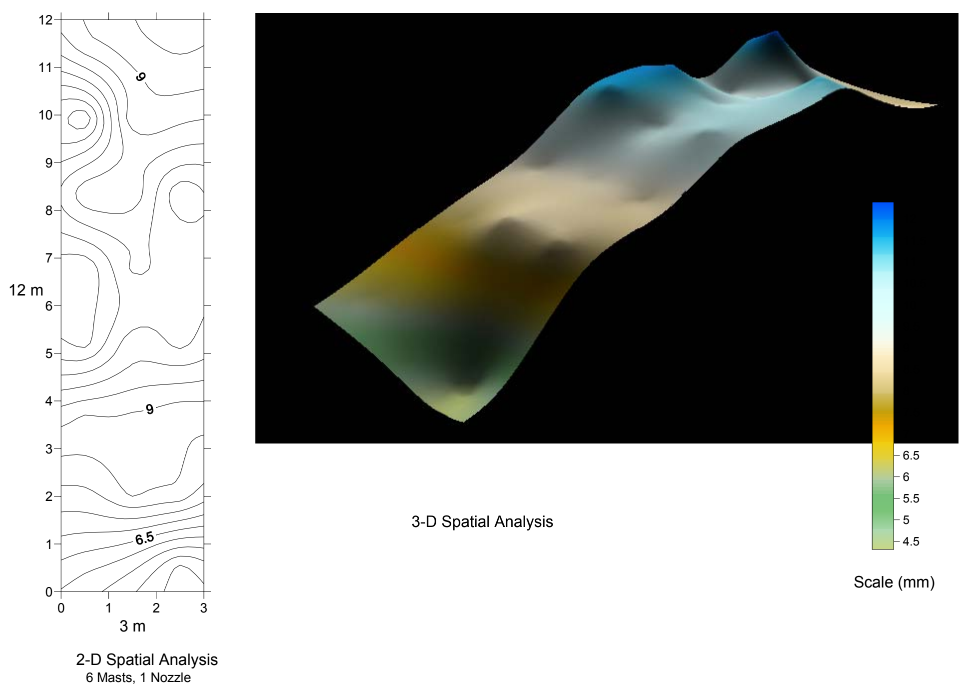


Figure A-1. Rainfall distribution over 3 m x 12 m plot, using 6 masts with one nozzle per mast, conducted over a 15 minute period.

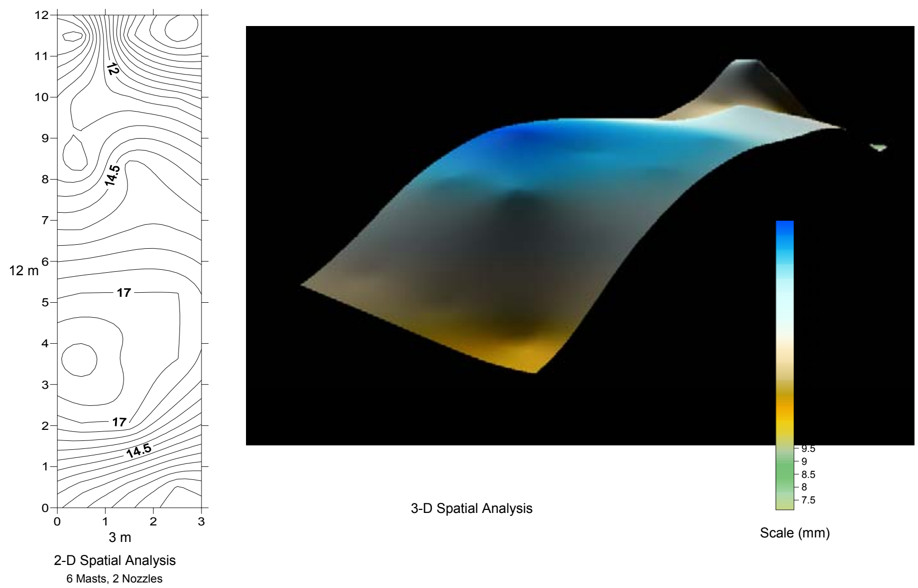


Figure A-2. Rainfall distribution over 3 m x 12 m plot, using 6 masts with two nozzles per mast, conducted over a 15 minute period.

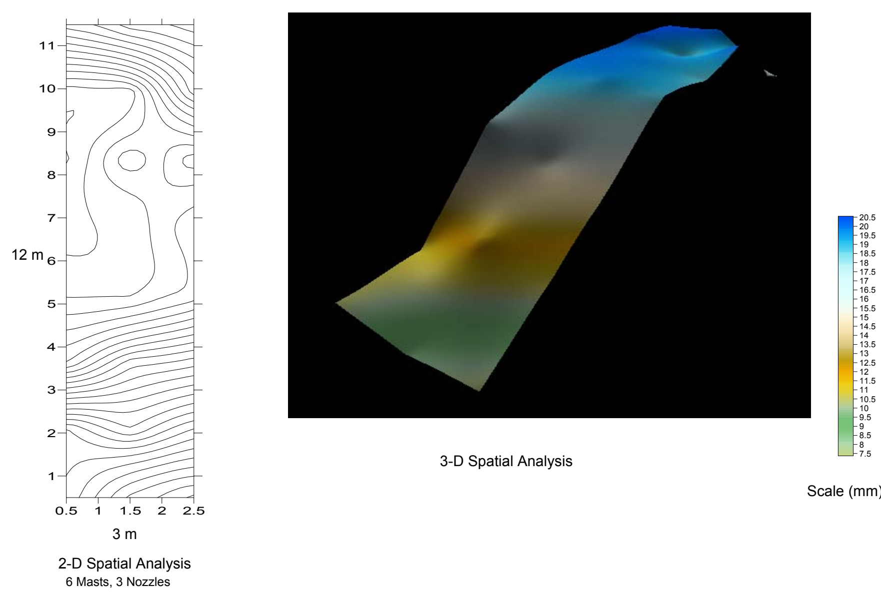


Figure A-3. Rainfall distribution over 3 m x 12 m plot, using 6 masts with three nozzles per mast, conducted over a 15 minute period.

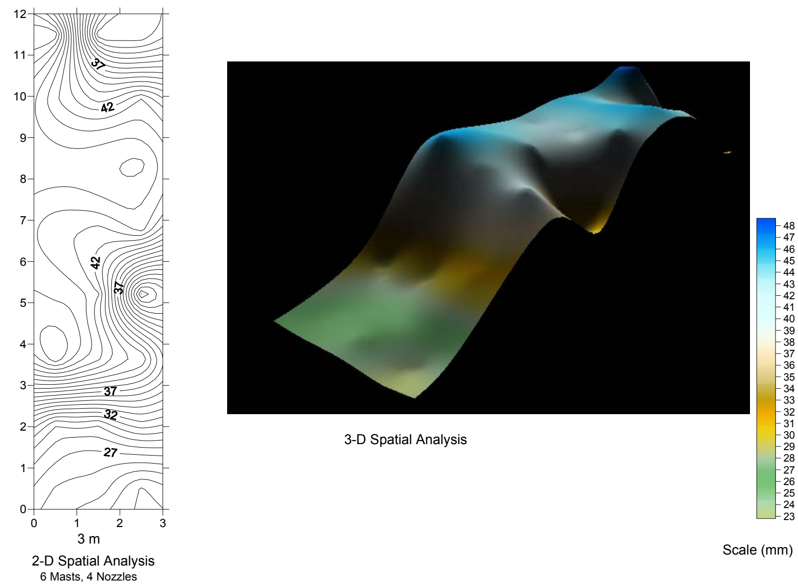
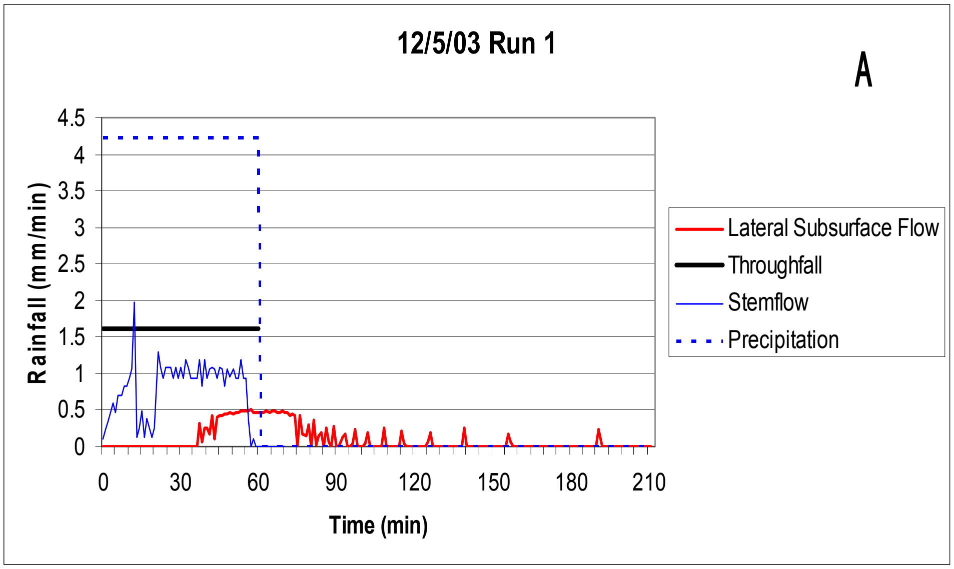


Figure A-4. Rainfall distribution over 3 m x 12 m plot, using 6 masts with four nozzles per mast, conducted over a 15 minute period.

APPENDIX B

HYDROGRAPHS RESULTING FROM THE RAINFALL SIMULATIONS CONDUCTED FROM 5 THROUGH 18 DECEMBER, 2003 AT THE HONEY CREEK STATE NATURAL AREA



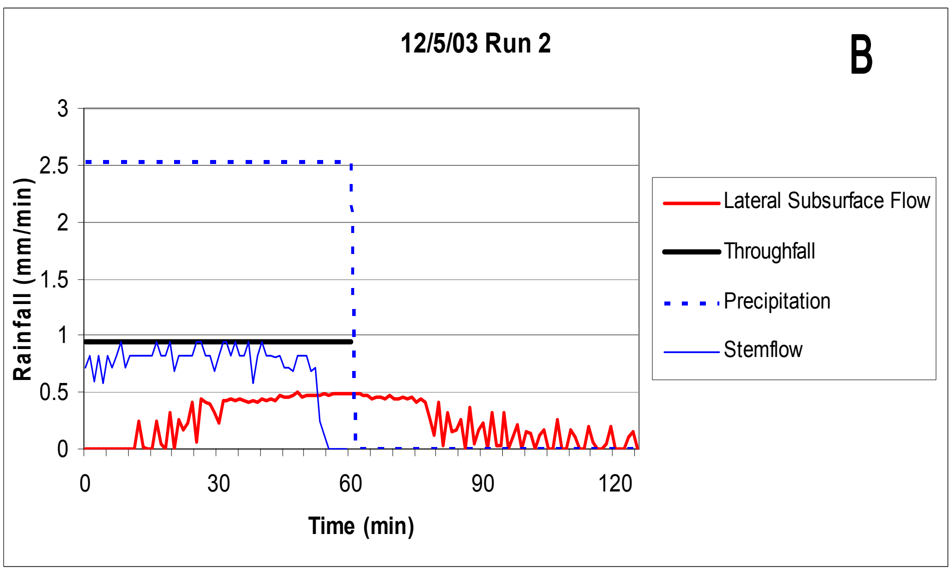
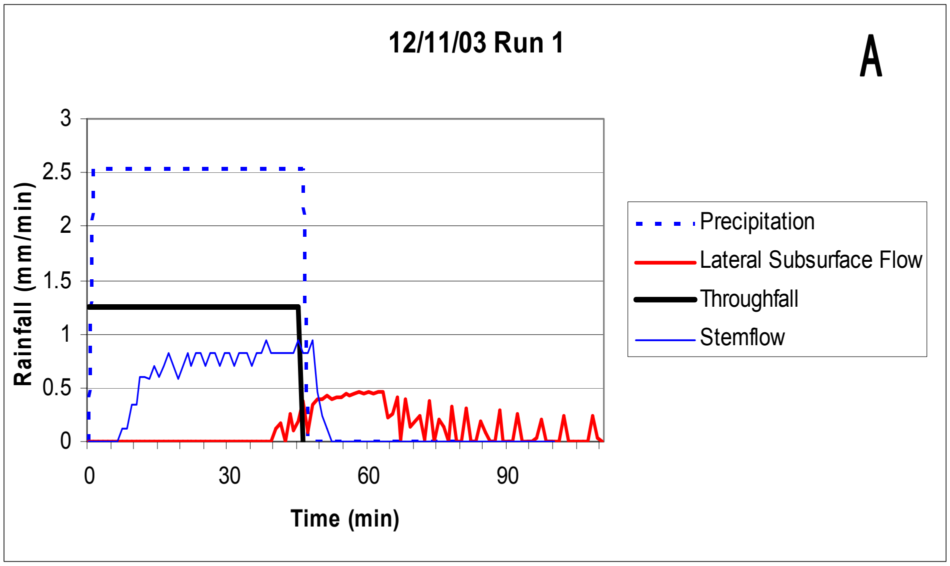
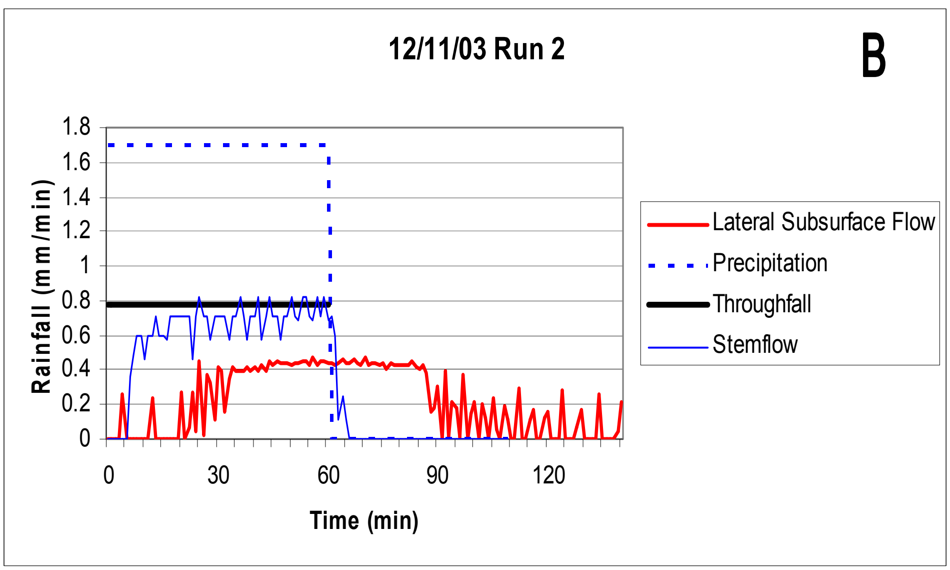


Figure B-1. Hydrographs displaying the partition of water from rainfall simulations on a juniper covered site at the Honey Creek State Natural Area for a (A) 254 mm/hr rainfall event, followed by a (B) 152 mm/hr rainfall event, conducted 5 December 2003.



12/11/03 Run 1
A
Rainfall (mm/min)
3
2.5
2
1.5
1
0.5
0
0
30
60
90
Time (min)
Precipitation
Lateral Subsurface Flow
Throughfall
Stemflow



12/11/03 Run 2
B
Rainfall (mm/min)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
30
60
90
120
Time (min)
Lateral Subsurface Flow
Precipitation
Throughfall
Stemflow

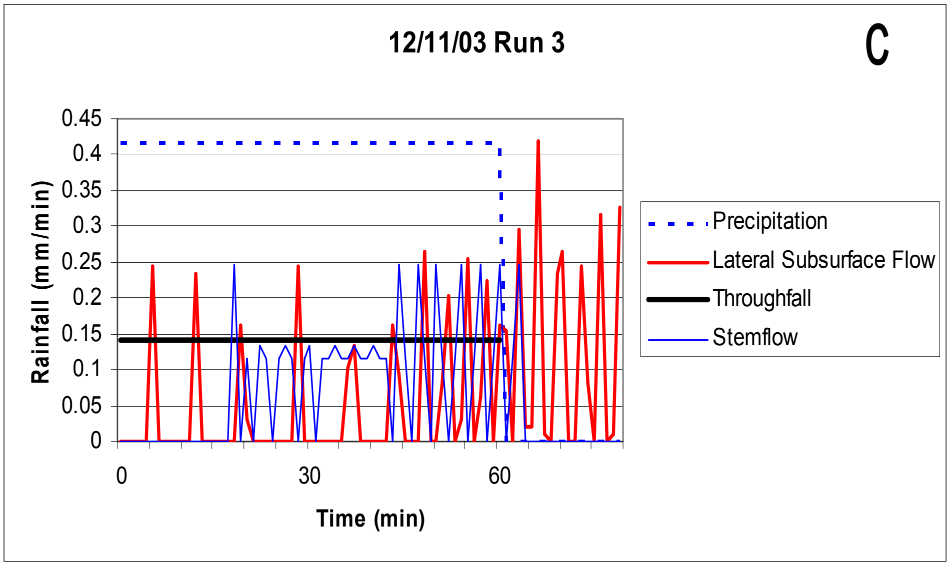
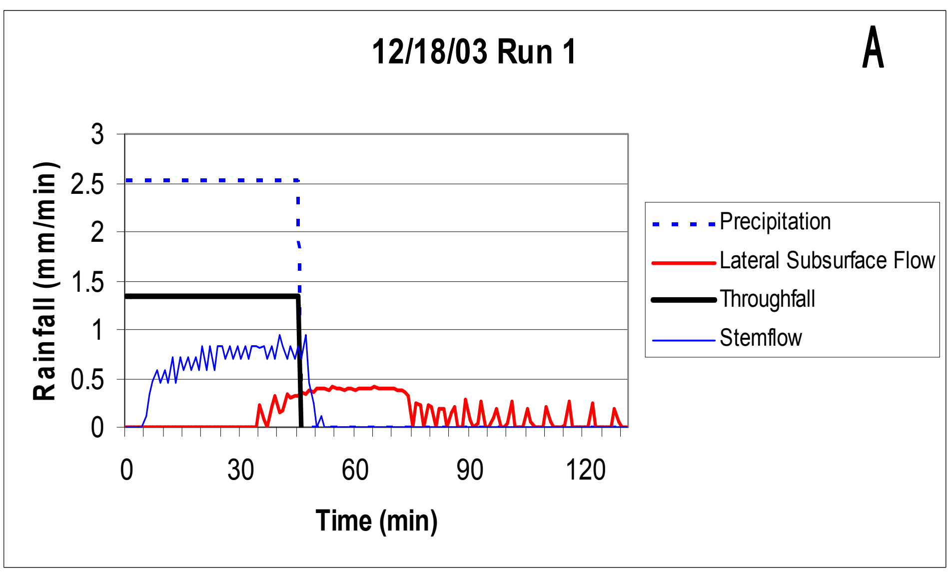
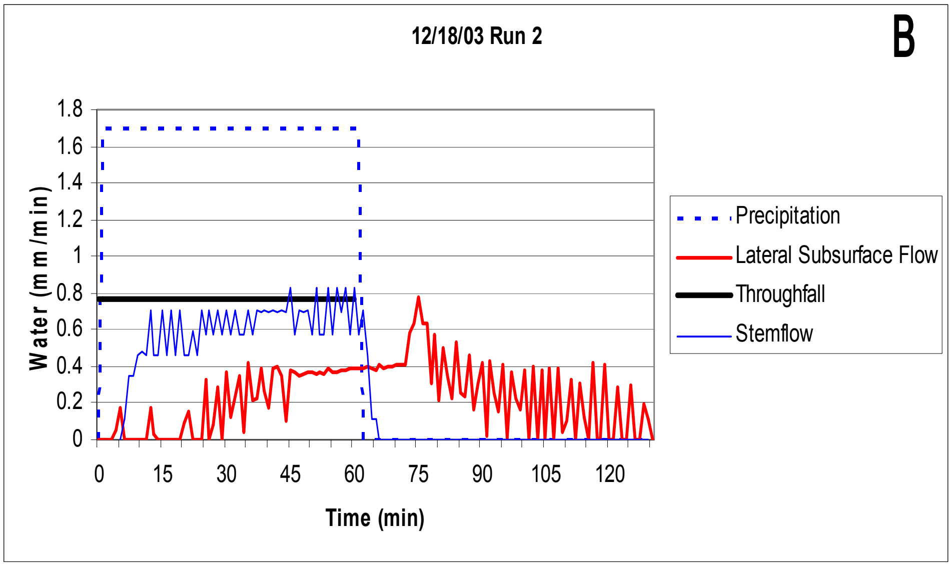


Figure B-2. Hydrographs displaying the partition of water from rainfall simulations on a juniper covered site at the Honey Creek State Natural Area for a (A) 254 mm/hr rainfall event, followed by a (B) 152 mm/hr rainfall event, and a (C) 25 mm/hr rainfall event, conducted 11 December 2003.





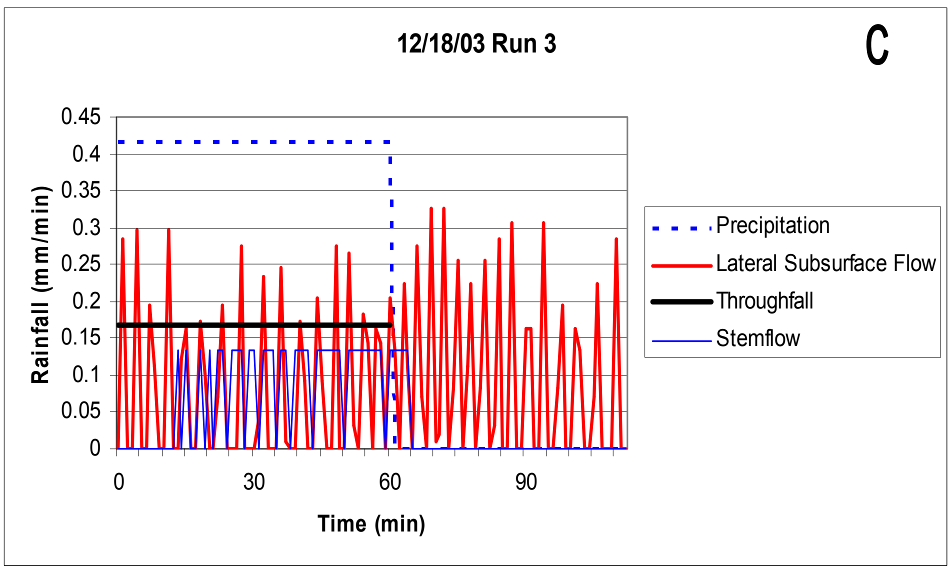


Figure B-3. Hydrographs displaying the partition of water from rainfall simulations on a juniper covered site at the Honey Creek State Natural Area for a (A) 254 mm/hr rainfall event, followed by a (B) 152 mm/hr rainfall event, and a (C) 25 mm/hr rainfall event, conducted 18 December 2003.

APPENDIX C

DETERMINATION OF LATERAL SUBSURFACE FLOW AS A COMPARISON TO PRECIPITATION

Lateral subsurface flow was measured using a sump located within the trench at the edge of the plot. This volume was pumped into three tipping buckets, which recorded the volume of water (see Chapter III). Each tip of the tipping bucket was recorded in the datalogger as a "count." One count from the datalogger was equal to one tip of the 1 L tipping bucket. For example, 5 counts in a one minute time period was the equivalent of 5 L per minute.

To relate the volume of water pumped from the trench as lateral subsurface flow, the total volume pumped was divided by the area in which water was affectively applied. The area of water application was the area of the 14 m by 7 m plot, or 98 m^2. Therefore, by dividing the volume of the recorded water as lateral subsurface flow by the plot area (and converting units), the amount of lateral subsurface flow could be expressed with respect to the amount of water applied to the plot. This allowed for a comparison of the amount of lateral subsurface flow relative to the amount of applied water for budgetary purposes.

Example Calculation

Output from Datalogger

Time	Tipping Buckets (One count = 1 L)			
(min)	1	2	3	Total (L)
0	0	0	0	0
1	0	1	0	1
2	1	1	1	3
3	2	1	2	5
4	4	3	3	10
5	6	5	6	17
6	5	7	6	18
7	4	5	4	13
8	3	3	3	9
9	1	1	2	4
10	0	0	0	0
				80 L Total

80 L measured over 10 minutes from water applied over an area of 98 m^2

$80 \text{ L} = 0.08 \text{ m}^3$

To express this volume as a unit of length, divide the volume by the applied area:

$0.08 \text{ m}^3 / 98 \text{ m}^2 = 8.16 \times 10^{-4}$ m, or **0.82 mm**

This calculation was performed for each run from 5 through 18 December 2003.

APPENDIX D

LATERAL SUBSURFACE FLOW HYDROGRAPHS FOR RAINFALL SIMULATIONS CONDUCTED FROM 5 THROUGH 18 DECEMBER, 2003 AT A JUNIPER COVERED RESEARCH PLOT AT HONEY CREEK STATE NATURAL AREA

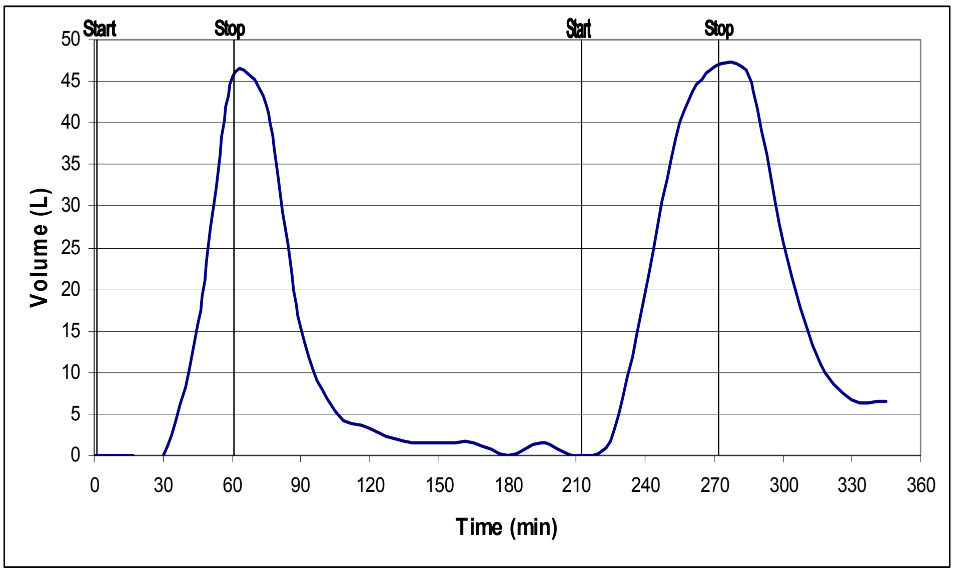


Figure D-1. Hydrograph of lateral subsurface flow from two simulated rainfall events (15 min averages) at Honey Creek State Natural Area, 5 December 2003. Run 1 had a duration of 45 minutes and an intensity of 254 mm/hr. Run 2 had a duration of 60 minutes and an intensity of 152 mm/hr.

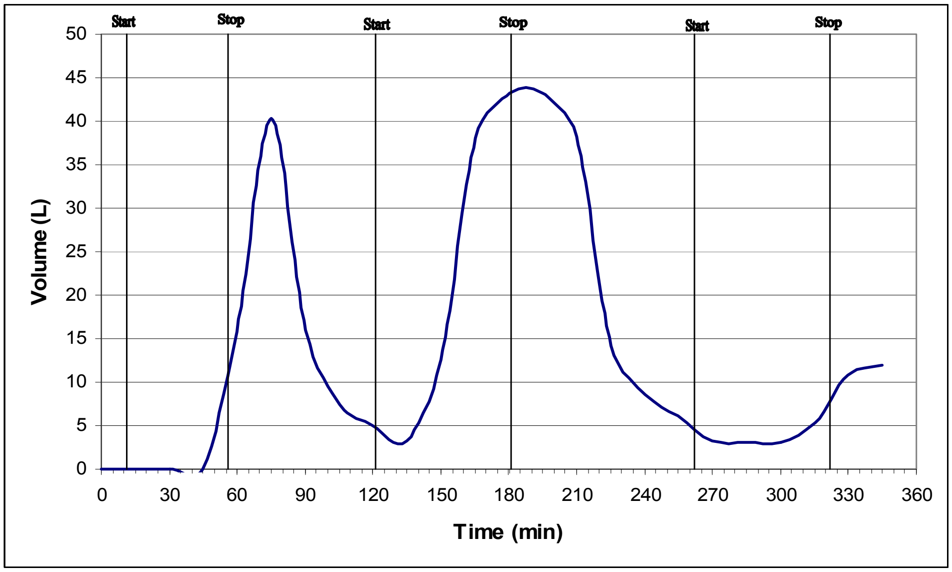


Figure D-2. Hydrograph of lateral subsurface flow from two simulated rainfall events (15 min averages) at Honey Creek State Natural Area, 11 December 2003. Run 1 had a duration of 45 minutes and an intensity of 152 mm/hr. Run 2 had a duration of 60 minutes and an intensity of 102 mm/hr. Run 3 had a duration of 60 minutes and an intensity of 25 mm/hr.

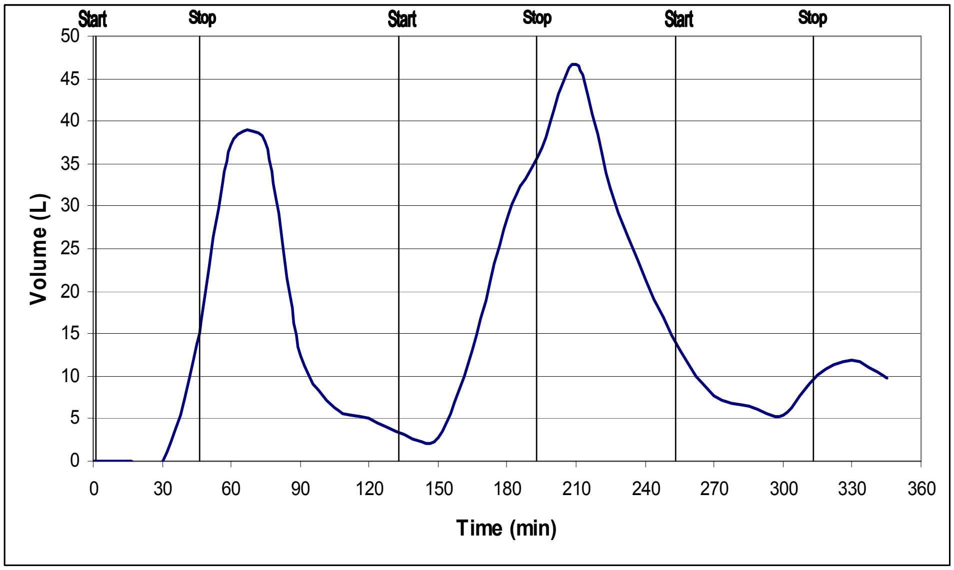


Figure D-3. Hydrograph of lateral subsurface flow from two simulated rainfall events (15 min averages) at Honey Creek State Natural Area, 18 December 2003. Run 1 had a duration of 45 minutes and an intensity of 152 mm/hr. Run 2 had a duration of 60 minutes and an intensity of 102 mm/hr. Run 3 had a duration of 60 minutes and an intensity of 25 mm/hr.

APPENDIX E

DETERMINATION OF THE AMOUNT OF STEMFLOW AS RELATED TO PRECIPITATION

Two trees within the research plot were instrumented with funnels to capture the water that traveled via the trees branches, which can be considered stemflow. As previously mentioned in Chapter III, each funnel was connected to a tube, which conveyed all water as stemflow to a central monitoring station. This station was outfitted with a tipping bucket, which recorded the volume of water from the tree as it filled the tipping bucket. Each tip of the tipping bucket was recorded in the datalogger as a "count." One count from the datalogger was equal to one tip of the 1 L tipping bucket. For example, 5 counts in a one minute time period was the equivalent of 5 L per minute of stemflow. Once the water was measured in the tipping bucket, it was released into the plot at the base of the tree to maintain the natural process of stemflow.

To relate the volume of water collected as stemflow to a unit of length (for comparison to precipitation), the total volume was divided by the area of the tree canopy that contributed to each measure of stemflow. A vegetation study was conducted to determine the canopy area of each tree relative to the entire plot. The two instrumented trees were determined to account for approximately 30% of the cover over the entire plot, which exhibited approximately 100% canopy cover. Therefore, the amount of water (as a unit of length) was multiplied by 1/0.3 (or 3.33) to approximate the volume of water that contributes to the plot as stemflow.

The volume of water recorded as stemflow was converted from L to m^3. This number was then converted to a unit of length by dividing the volume of water by the canopy area contributing to stemflow.

The averaged stemflow was calculated based on the number of trees within the plot instrumented to measure the flow of water at the base of the tree. The average measured stemflow was then applied to all trees within the research plot. The same procedure was applied to measured throughfall. The average throughfall measured for two trees was applied to all trees within the plot. This number was scaled up based on the portion of the trees within the plot recording data, as compared to the total number of trees

Example Calculation

Output from Datalogger

Time (min)	Tipping Buckets (One count = 1 L) 1	2	3	Total (L)
0	0	0	0	0
1	0	1	0	1
2	1	1	1	3
3	2	1	2	5
4	4	3	3	10
5	6	5	6	17
6	5	7	6	18
7	4	5	4	13
8	3	3	3	9
9	1	1	2	4
10	0	0	0	0
				80 L Total

80 L measured over 10 minutes from water applied over an area of 98 m^2

80 L = 0.08 m^3

To express this volume as a unit of length, divide the volume by the applied area:

0.08 m^3 / 98 m^2 = 8.16 x 10^{-4} m, or **0.82 mm**

This calculation was performed for each run from 5 to December 18, 2003.

APPENDIX F

DETERMINATION OF THE AMOUNT OF THROUGHFALL AS RELATED TO PRECIPITATION

Throughfall was measured using a series of rain gauges spaced on a 1 m by 1 m grid, as discussed in Chapter III. Following the completion of each rainfall simulation, the volume of water in each rain gauge (expressed as mm) was recorded, and the water was emptied into the plot for measuring the precipitation from the subsequent simulation. Since the rain gauges provided a measurement of water as a depth, no further calculation was necessary. However, the average value of each data set was recorded as the total throughfall.

Example Calculation

Recorded rain gauge information

Rain gauge location X	Rain gauge location Y	Rainfall Amount mm
0	0	3
0	1	5
0	2	7
1	0	4
1	1	9
1	2	12
2	0	3
2	1	7
2	2	0

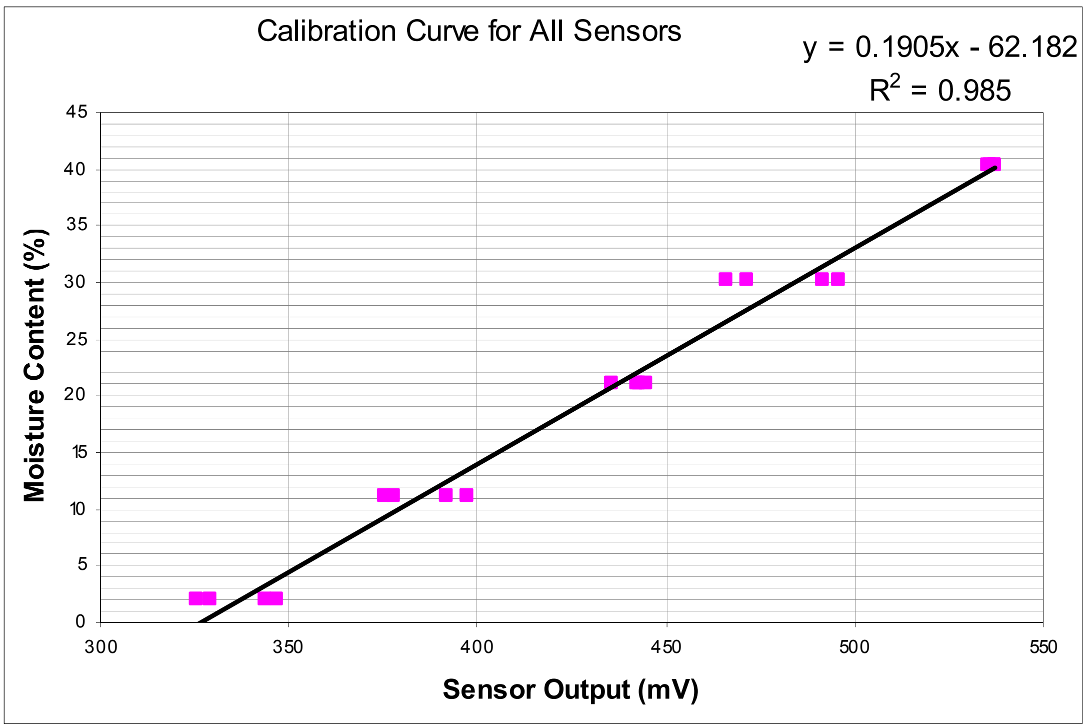
The average of the data set is simply the sum of the observations, divided by the number of observations. The average of the above data set is 5.6 mm.

When rain gauges were observed to be tipped over, no value was recorded (since a value of zero would not be accurate; the gauges would typically fall over as a result of some amount of water, larger than zero). If the gauge remained erect but dry, a value of 0 was recorded. This calculation was performed for each run from 5 through December 18, 2003.

APPENDIX G

DETERMINATION OF SOIL MOISTURE

Ten Echo 10 probes were placed within the research plot to monitor the changes in soil moisture. These probes measure the change in voltage as a result of the change in water content of the soil. The probes were calibrated using soil of known moisture content. The relationship of the output voltage to the moisture content produced a calibration curve as seen below.



Calibration by
Keith Owens, Uvalde, TX

Figure G-1. Calibration curve for Echo 10 soil moisture probes.

As seen by the equation of the regression line, the relationship between soil moisture is given by: $y = 0.1905\,x - 62.182$, where y is the moisture content of the soil, and x is the voltage output recorded by the sensor. The soil moisture and corresponding change with precipitation was then calculated with this equation.

Example Calculation

Example Output from Datalogger from one probe:

Time (min)	Soil Moisture Probe 1 (mV)
0	435.25
1	435.25
2	435.29
3	437.31
4	439.52
5	440.74
6	442.83
7	441.49
8	440.12
9	439.78
10	439.67

This information is then imported to an Excel spreadsheet for further analysis, as seen below.

Time (min)	Soil Moisture Probe 1 (mV)	Soil Moisture (%)	Change in Moisture
0	435.25	20.73	0.00
1	435.25	20.73	0.00
2	435.29	20.74	0.01
3	437.31	21.13	0.40
4	439.52	21.55	0.82
5	440.74	21.78	1.05
6	442.83	22.18	1.45
7	441.49	21.92	1.19
8	440.12	21.66	0.93
9	439.78	21.60	0.87
10	439.67	21.58	0.85

The values for Soil Moisture (%) are computed using the aforementioned calibration equation, $y = 0.1905\,x - 62.182$, where y is the moisture content of the soil, and x is the voltage output recorded by the sensor. The change in moisture is calculated by subtracting the moisture content value for each time step from the initial moisture content at time t = 0. An average value was taken for all moisture probes within the data set. The corresponding change in moisture was calculated based on the calculated average soil moisture.

Calculation of water within the soil matrix:

Depth of Soil ~ 10 cm
Area of Soil = 98 m^2
Volume of soil within plot ~ 10 m^3

Soil Moisture at time t = 0 min 20.73%
Soil Moisture at time t = 6 min 22.18%
Change in soil moisture +1.45%

Volume of water at time t = 6 min (10 m^3) * (0.0145) = 0.145 m^3, or 145 mm

The soil moisture data obtained by the probes was analyzed for anomalies in the data set. These extremities would include any series of data with a sudden spike in the output, resulting from many factors. These data were omitted from the calculation of soil moisture and change in soil moisture. Also, any value that resulted in a value for moisture content of slightly over 100% (but near other values approaching 100%) was slightly adjusted to reflect 100% saturation.

To determine the amount of water within the soil, the total volume of soil within the plot was estimated based on field observations. The average depth of soil within the plot was approximated to be 10 cm, over an area of 98 m^2. The resulting volume of soil was then calculated to be approximately 10 m^3. The change in soil moisture derived from the above calculation was multiplied by the volume of the soil to produce an average value of water volume at this time step. This direct calculation provided an estimate of the volume of water within the soil matrix. To convert the volume of soil water to a unit of length, the volume was divided by the area of the plot (98 m^2); the resulting value in meters was simply converted to millimeters for comparison to precipitation.

APPENDIX H

SOIL MOISTURE RESPONSE UNDER JUNIPER CANOPY

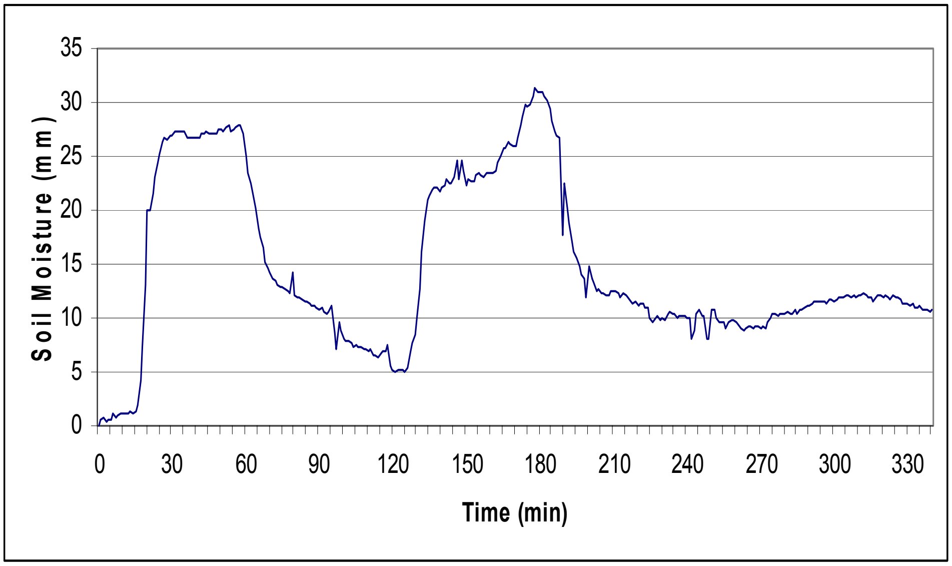


Figure H-1. Soil moisture response expressed in mm, following three rainfall simulations on 11 December 2003 at the juniper research plot at Honey Creek State Natural Area. The simulations included three simulations lasting 45 minutes, 60 minutes, and 60 minutes. Application intensity included 152 mm/hr, 102 mm/hr, and 25 mm/hr respectively.

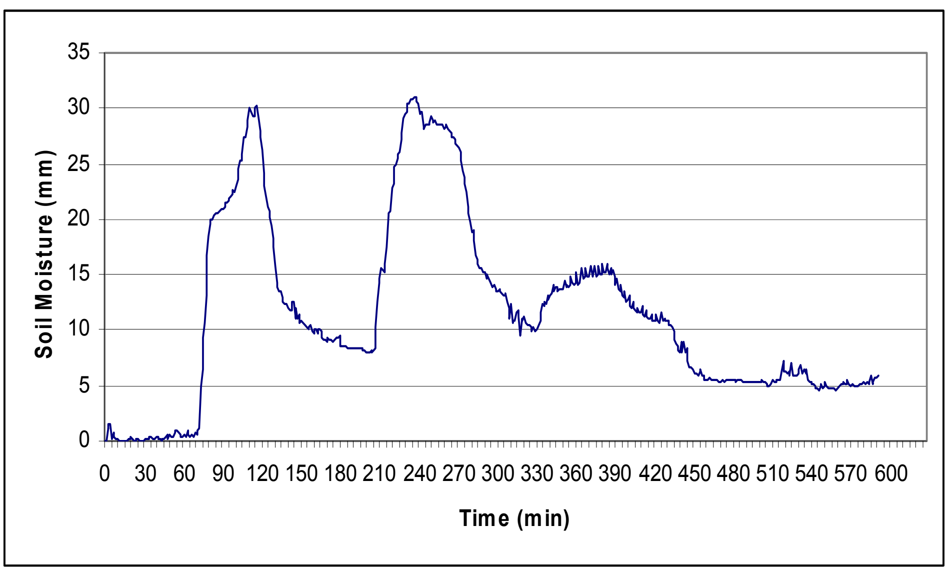


Figure H-2. Soil moisture response expressed in mm, following three rainfall simulations on 18 December 2003 at the juniper research plot at Honey Creek State Natural Area. Simulator duration and intensities were identical to 11 December 2003.

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