THE EFFECT OF ASHE JUNIPER REMOVAL ON GROUNDWATER RECHARGE IN THE EDWARDS AQUIFER

A Thesis

by

ROBERTO ALVARO BAZAN, JR.

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

MASTER OF SCIENCE

December 2010

Major Subject: Water Management & Hydrological Science

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Approved by:

Co-Chairs of Committee,	Bradford P. Wilcox Clyde L. Munster
Committee Member,	Patricia K. Smith
Intercollegiate Faculty Chair,	Ronald A. Kaiser

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ABSTRACT

The Effect of Ashe Juniper Removal on Groundwater Recharge in the Edwards Aquifer.

(December 2010)

Roberto Alvaro Bazan, Jr., B.S., Texas A&M University

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

Understanding groundwater recharge rates has direct relevance for management of the Edwards Aquifer, which serves as the main source of fresh water for the city of San Antonio and surrounding communities. As population around San Antonio continues to grow, so does the demand for water and the stress placed on the aquifer. A method that is commonly believed to augment water yields is brush management. Over the last 150 years an increase in juniper density on the Edwards Plateau has coincided with decreasing streamflow. This has led many to believe that removing juniper would increase available water. Due to its karstic nature, the recharge zone of the Edwards Aquifer is assumed to be a prime location for augmenting water yields through vegetation manipulation.

This study assesses the dynamics of recharge and the effects of manipulating surface vegetation. To accomplish this, a shallow cave located in the Edwards Aquifer recharge zone in San Antonio, Texas was instrumented to monitor drip recharge in response to simulated rainfall events. In 2004, simulations were conducted over the cave to measure recharge rates with a dense Ashe juniper canopy. The data and observations from the initial simulations were used to establish a baseline with the juniper in place. In February 2008 the juniper stand was cleared and the rainfall simulations were reproduced in June and July 2008, and again in early June 2009. Results from the study indicated that even though the amount of rainfall reaching the surface increased, a decrease in the amount of recharge occurred. The decrease can be possibly be explained by the elimination of stemflow, which is believed to direct higher concentrations of water to preferential flow paths near the base of the tree, and an increase in surface runoff. However, because such a large portion of the water reaching the surface is not accounted for by the budget, it is difficult to conclude that a change in recharge did not occur at a larger scale.

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INTRODUCTION

Although the planet is composed primarily of water, only a small percentage is available for freshwater use (Jackson et al., 2001; Oki and Kanae, 2006). Of the fraction of freshwater available, an even smaller portion is accessible for drinking or consumptive use. Spatial and temporal variations in the distribution of freshwater sources cause pressures on availability. Many regions in the world are already limited by the amount and quality of available water. To further complicate the issue, climate change and population growth will alter the water cycle dramatically in the coming century (Jackson et al., 2001). Action has been, and will need to be taken in order to maintain or improve our current sources.

Rangelands are a main focus of water management since they serve as, along with forests, primary sources of freshwater throughout the world (Thurow and Carlson, 1994). In the southwestern United States rangeland watersheds provide a majority of the region's surface flow and aquifer recharge (Thurow and Carlson, 1994). However, over the course of the past 150 years many rangelands in this semiarid region have slowly undergone a conversion from a dominant herbaceous cover to shrublands through a phenomena called "woody plant encroachment" (Van Auken, 2000).

What Is Woody Plant Encroachment?

Woody plant encroachment describes the increase in density and cover of native shrubs and woody plants that have existed on rangelands for thousands of years (Van Auken, 2000). Many causes have been attributed to the change over from grasslands to shrublands, but most have coincided with European settlement (Archer, 1994). The most critical factor, according to Van Auken (2000), is high levels of herbivory or livestock grazing.

This thesis follows the style of *Hydrological Processes*.

Wilcox et al. (2008a) made a case that increases in woody plant vegetation is a recovery response to rangelands being degraded by overgrazing after supporting high stocking rates in the mid-1800s and again in the 1940s. Grazing of herbaceous vegetation allows for a competitive advantage for woody vegetation by reducing biomass cover which allows shrubs to prosper since they are not palatable to animals (Van Auken, 2000).

The removal of biomass serves two functions. In addition to providing competitive advantages it also eliminates fuels that feed wildfires. During the time that correlates with increasing woody vegetation there has been a decrease in fire frequencies (Archer, 1994; Van Auken, 2000). Due to intolerance of shrubs to fires, periodic fires were means to controlling and reducing establishment and growth (Van Auken, 2000). Other factors that have been discussed as possible contributors to woody encroachment are climate change and CO_2 enrichment (Archer, 1994; Van Auken, 2000; Morgan et al., 2007).

Despite the reasons for encroachment, the potential hydrological and ecological implications that are presented by the alteration of grasslands to shrublands need to be further understood (Huxman et al., 2005).

Shrublands and the Water Balance

Several studies have been conducted with the objective to learn about woody plant encroachment and its affect on hydrological processes in semiarid rangelands. By employing a water budget technique, precipitation can be partitioned as it reaches the earth's surface (Wilcox et al., 2003). This partitioning allows for individual components of the water balance to be examined. Precipitation is divided into (1) evapotranspiration, (2) runoff, (3) groundwater recharge, and (4) change in soil water.

Evapotranspiration (ET) refers to water vapor that is returned to the atmosphere through the process of evaporation from the soil, vegetation canopy, ponded water, and/or other surfaces, as well as transpiration from plants, or sublimation from solid state precipitation such as snow (Thurow and Hester, 1997; Wilcox et al., 2003). Wilcox (2002) states that evapotranspiration on semiarid rangelands would be independent of vegetation due to the definition of soil-water-deficient regions. In other words, regardless of the type of vegetation, grass or shrub, most water will either be consumed by the plants or be lost through evaporation because evapotranspiration demands exceed precipitation. However, the rate of evapotranspiration remains variable depending on the characteristics of the vegetation. Rooting depth determines the volume of water that will be available to a plant (Zhang et al., 2001). Trees typically have greater water availability capacities than herbaceous vegetation (Zhang et al., 2001). Hence, woody vegetation will have a higher rate of transpiration because it has access to deeper soil water as the soil starts to dry from the surface down. Where shrubs do exist, evaporation from the soil under the canopy can be reduced due to shading and wind protection (Thurow and Carlson, 1994; Thurow and Hester, 1997). However, due to reduction of herbaceous cover in interspaces between shrubs, in response to competition, these bare areas have higher rates of soil evaporation. Carlson et al. (1990) estimated that evapotranspiration accounted for 95% of the water balance from a honey mesquite (*Prosopis glandulosa*) site on the Rolling Plains of Texas compared to 97% for a mesquite-cleared herbaceous site. On the western Edwards plateau, Dugas et al. (1998) estimated that the removal of ashe juniper (*Juniperus asheii*) reduced ET by 0.3 mm/d for the first two years after treatment. During the third year of monitoring, however, as vegetation re-grew the reduction diminished.

An important component of ET is interception. Interception is known as water that is captured by vegetation and is either held in the canopy or redirected to the surface as stemflow or throughfall. For purposes of the water balance, interception is considered the amount of precipitation that does not reach the soil surface and is evaporated from the canopy or underlying litter. Interception rates or water holding capacity is dependent on physical characteristics of the plant such as, leaf area and leaf roughness, as well as the characteristics of the storm (intensity, duration, wind speed) (Thurow and Carlson, 1994; Wilcox et al., 2003). Owens et al. (2006) found that, at the tree scale, ashe juniper canopy and litter intercepts an annual average of 40% of total precipitation with 35% being strictly accountable to the canopy. This canopy value is similar to the 36.7% value that was reported by Hester (1996). These values however, are higher than those estimated for redberry juniper (*Juniperus pinchotii*) of 25.9% (Hester, 1996), which is similar to 25.4% reported for live oak (*Quercus virginiana*) (Thurow et al., 1987). Interception for ashe juniper can vary anywhere between 100% for small storms (<2.5mm) and 20% for high intensity storms (>70mm over a 15-hr. period) (Owens et al., 2006).

Besides reducing the amount of water that reaches the surface, interception can impact the distribution of rainfall beneath the canopy. When storage capacity of the canopy is exceeded water can be rerouted to the surface either as throughfall, which is precipitation that falls through or drips from the canopy, or funneled to the base of the tree via stemflow (Dunkerley, 2000). A larger proportion of water reaching the surface is from throughfall, which for ashe juniper can account for up to 55% of the water balance (Owens et al., 2006). Thurow et al. (1987) estimated that for live oak, 54% of precipitation reaches the surface as throughfall and stemflow. Although stemflow may be a smaller portion of the water balance (an average of approximately 8.2% for most shrubs) it may play a critical role in distribution of water (Owens et al., 2006; Thurow and Hester, 1997). As water is funneled down the stem and/or trunk of the tree it is concentrated at the base. This concentration can increase the amount of water at the base of the tree compared to under the canopy. Owens et al. (2006) found that for an area of 0.5 m^2 around the base of an ashe juniper stemflow results in a 21 to 1 ratio of water received compared to bulk rainfall. Similarly, Thurow et al. (1987) reported that soil near the base of live oak received about 222% of annual precipitation in comparison to soils at a distance greater than 100mm away from the trunk that received approximately 50.6%. Water that reaches the soil either by throughfall or stemflow will contribute to soil moisture or recharge through infiltration or can produce runoff.

Runoff is water that travels from the land towards the stream channel, either through surface or subsurface routes (Wilcox et al., 2003). Surface runoff can occur as either one, or a combination of both (1) Horton overland flow, also known as, *infiltration-excess runoff*, and (2) *saturation-excess runoff*. Horton overland flow occurs when precipitation rates exceed infiltration rates of the soil, and is commonly recognized as the dominant streamflow generation mechanism in rangelands (Wilcox, 2002). Saturation-excess flow, typically uncommon on rangelands, results when saturated soils have exceeded their holding capacity. Woody plant encroachment is seen to affect surface runoff by increasing infiltration rates under their canopy. Infiltration rates are increased by shrubs due to the large amounts of organic matter and cover that contribute to improved soil structure (Thurow and Hester, 1997). Also, runoff from intercanopy spaces can be minimized by encountering higher infiltration capacities in soils beneath trees. Runoff from rangelands can also be generated in subsurface routes either as (1) shallow subsurface flow (interflow), or (2) groundwater flow. Shallow subsurface flow is water that moves laterally through the soil profile, usually due to an impeding layer (Wilcox, 2002). Most common in humid regions, shallow subsurface flow was considered irrelevant in semiarid rangelands, however recent studies (Newman et al., 1998; Wilcox et al., 2008b; Taucer et al., 2008) have shown that it can be a significant mechanism for runoff generation. Water that infiltrates into the soil that does not become runoff becomes available for plant use, could be evaporated, or percolate beyond the root zone and contribute to groundwater recharge.

Deep drainage, also referred to as recharge, occurs when water infiltrates beyond the root zone to contribute to groundwater sources. In karst landscapes infiltration can occur in two forms: micropore or macropore flow (McDonald and Drysdale, 2007). Micropore flow occurs as seepage or matrix flow through the rock face, where as macropore is defined through preferential or fracture flow. Increases in groundwater recharge appear to be the link to increase water supply for "off-site" users. This is because groundwater flow is generally the source of baseflow for perennial streams (Wilcox, 2002). Several species affiliated with woody plant encroachment are suspected of reducing recharge by accessing groundwater supply with deep roots. Several studies have examined the validity of this suspicion. Jackson et al. (1999), using tree DNA, was able to identify ashe juniper roots in caves located in the Edwards Plateau to a depth of 8 m. Two studies based on stable isotopes (McCole and Stern, 2007; Schwinning, 2008) offer contrasting findings. McCole and Stern (2007) conclude that juniper uptake transitions from deep water sources during summer to more shallow sources during winter. On the other hand, Schwinning (2008) results indicate that uptake does not occur from deep sources, but rather from stored water in the epikarst instead. Heilman et al. (2009), using an energy balance approach supports the conclusion presented by Schwinning (2008) in that water uptake in junipers does not occur from deep sources.

Brush Control and Water Supply

Many believe that an interconnection lies between decreasing streamflow and increasing woody vegetation (Wilcox et al., 2006). One method for improving water supply that has been implemented is brush management. It has been known for some time now that land-use/land cover practices have altered hydrological processes on landscapes. For example, urbanization or increased impervious cover will increase surface runoff and possibly lead to flooding. The theory behind brush management is to increase water yield by replacing deep rooted woody vegetation that evapotranspires significant amounts of water with shallow rooted herbaceous vegetation that consumes less water (Dugas et al., 1998; Archer, 1994; Carlson et al., 1990; Hibbert, 1983; Thurow and Carlson, 1994). Several computer based models have indicated that the removal of certain percentages of brush have the potential to significantly increase water yield (Bednarz et al., 2000; Wu et al., 2001; Afinowicz, 2005). However, little scientific evidence is available, especially at the larger scales, which indicate effective gains through brush management (Wilcox et al., 2006).

Wilcox et al. (2006) present a *shrub-streamflow framework* which classifies areas that are possibly hydrologically sensitive to vegetation change based on physiography, climate, and recharge potential. Criteria three (recharge potential) identifies a region with shallow soils and permeable geology as areas where brush control could augment water yields. This points toward karst landscapes, which are defined as terrains with high rock solubility and well a developed fracture network (Ford and Williams, 2007). Karst landscapes occupy over 10 – 15 % of the continental surface and supply nearly a quarter of the world's groundwater (Ford and Williams, 2007). 40% of the United States depends on karst areas for freshwater sources (White, 1988). Therefore, focus for this study is concentrated on the Edwards Plateau, an area dominated by karst shrublands.

Brush Management on the Edwards Plateau

Brush management has occurred in the state of Texas since the early 1920s (TSSWCB, 2007), but the most well-known account occurred in the late 1960s in West Texas near San Angelo. The "Story of Rocky Creek" (Kelton, 1975) reveals a landowners anecdote of the revival of Rocky Creek, a creek that dried up in the early 1930s, after an extensive brush clearing effort in the early 1960s. In 1985, the 69th Texas Legislature, under Chapter 203 of the Agriculture Code, created a state brush control program to cost-share brush management on private lands deemed beneficial for augmenting water yield (TSSWCB, 2007). Since 1999, the program has spent approximately $45 (US) million in public funds for brush control projects (TSSWCB, 2009).

On the Edwards Plateau in central Texas, which supplies groundwater to nearly 1.7 million people in the greater San Antonio area (McCole and Stern, 2007), increasing water yield is of interest because water demands from the Edwards aquifer have increased while supply has remained constant, or even slightly decreased (Dugas et al., 1998). The Edwards Plateau is one of the largest contiguous karst areas in the United States and has experienced encroachment from woody vegetation over time. Once limited to rocky outcrops in higher elevations, ashe juniper has extended its range to lower elevations and has increased it's density to occupy over 2.7 million hectares on the plateau (Owens et al., 2006).

Juniper is considered a "water waster" mostly due to its rate of evapotranspiration. As an evergreen, juniper is capable of transpiring water year-round, which can amount to higher rates of ET unlike grasses that senesce. A study conducted by Owens (1996) concluded that a mature ashe juniper is capable of transpiring up to 125 L/day. Also contributing to ET rates is the scale-like leaf structure and large leaf area that make juniper ideally suited for interception (Owens et al., 2006). The total tree leaf area is best predicted by the canopy area, which is defined as a broad globular or open, irregular crown (Hicks and Dugas, 1998). The tree usually consists of a single trunk with shaggy bark that has many horizontal and downward-declining branches that create many drip points (Thurow and Hester, 1997). These attributes can be beneficial for throughfall and reduce the proportion of stemflow.

Study Objective

The Edwards Aquifer is a karst aquifer uniquely located in the semiarid climate of south Texas. It is a highly valued source of fresh water due to its ability to recharge quickly because of its highly porous, fractured, and cavernous recharge zone. Common in karstic regions are stream reaches that lose water diffusely through their substrate into underlying aquifers (White, 1988). A majority of recharge for the Edwards aquifer occurs from streams that flow across the recharge zone. Recharge from upland areas (water that reaches through soil infiltration of direct recharge by karst features not located in streams) is assumed to occur, however the amount is unknown (Maclay, 1995). Due to the complex nature of the karst geology of the Edwards aquifer, direct measurement of recharge in upland areas is difficult to accomplish. However, recently a more refined understanding of karst infiltration has been achieved through the use of continuously recording drip measurement devices (McDonald and Drysdale, 2007). By coupling automated drip collectors in a shallow cave with a large-scale rainfall simulator, this study aims to address if the removal of ashe juniper at the hillslope scale can increase direct recharge.

The study was conducted in three stages. (1) A soaker hose test was used to determine the contributing area of the cave footprint. (2) Pre-treatment simulations were conducted to quantify the site water budget with the juniper canopy in situ. (3) Post-treatment simulations were conducted to measure any changes after the removal of the juniper canopy. The first two stages were discussed and detailed by Gregory (2006) and Gregory et al. (2009).

Findings from the pre-treatment simulations at Bunny Hole provided insight to the behavioral characteristics of what would be expected from a juniper dominated karst area. Recharge accounted for between 8 and 17% of the water applied and typically reached peak rates with a minimal lag time of 20 minutes after start of simulation and declined rapidly following the cease of rainfall. This quick response and decline leads to the assumption that recharge is dominated by macropore flow at this site. Interception was estimated to vary between 0 and 23% of water applied, depending on intensity. Stemflow accounted for 4 to 9% of the water reaching the surface, and was highest during wettest conditions. Surface runoff was minimal at the site accounting for 3% of the water budget, however most runoff was directed to the cave entrance and could be assumed to contribute to recharge.

With a base understanding of the site water budget, juniper trees were cleared in February 2008. This research will focus on the post-treatment evaluation, the third phase of this study. The hypothesis for this study states that an increase in recharge is attainable due to more water reaching the surface after the trees are removed and the tree canopy interception component is eliminated. Pre-treatment simulations demonstrated that recharge can occur rapidly and did not reach equilibrium indicating that infiltration rates would be able to handle the greater influx of rainfall.

STUDY AREA

Situated within the southeastern portion of the Edwards Plateau, the research site is approximately 16 km north of downtown San Antonio, Texas on Camp Bullis military reservation (Figure 1). The area climate is considered to be semiarid, characterized by irregular periods of excessive precipitation followed by extensive drought (Maclay, 1995). The average annual precipitation for the San Antonio area is about 740 mm, however it can vary from 250 mm and 1330 mm in certain years. Most of the rainfall in the area is a result of thunderstorms that are common between April and September, but can occur during any month (Taylor et al., 1966). Elevation in the northern third of Bexar County, where the site is located, ranges between 335 and 580 meters above average sea level. The area is classified as moderately hilly with soils in the Tarrant-Brackett association, which are thin (0 – 25 cm deep) stony, clayey soils overlying Edwards or Glen Rose limestone (Taylor et al., 1966). This region is commonly referred to as the Texas “Hill Country” and is heavily occupied by ranches and military reserves, but is subject to urban sprawl.

The Edwards Aquifer in San Antonio

The Edwards Aquifer is contained within the Crestaceous age Edwards Group Limestone, and is confined by the underlying Glen Rose Limestone and overlying Del Rio Clay (Maclay, 1995). The San Antonio segment of the aquifer is 290 kilometers long, extending from Brackettville, Texas (Kinney County) to Kyle, Texas (Hays County) (EAA, 2004). It varies in width from 8 to 64 kilometers. The thickness of the freshwater zone ranges from 133 to 266 meters, but averages about 183 meters. The Edwards Aquifer supplies nearly all municipal, domestic, and agricultural water needs in the area (EAA, 2004). The recharge zone is located at the base of the Balcones Escarpment, where faulting caused Edwards Limestone to be exposed at the surface. The area is characterized by its fractured and cavernous geology that allow for rapid movement of water through the system.

The Balcones Fault line (recharge zone) also serves to divide two major physiographic locations - the Edwards Plateau to the north, which serves as the catchment or drainage area of the Edwards Aquifer, and the Gulf Coast Plain to the south, which serves as the discharge or artesian zone for the aquifer (EAA, 2004). Despite the semiarid climate, perennial streams and rivers, mostly fed by springs, occur on the 13,985 square kilometer plateau and flow in a southeasterly direction across the recharge zone (EAA, 2004). Water that enters the aquifer flows into the artesian zone where water is under artesian pressure and is subject to pumping (EAA, 2004).

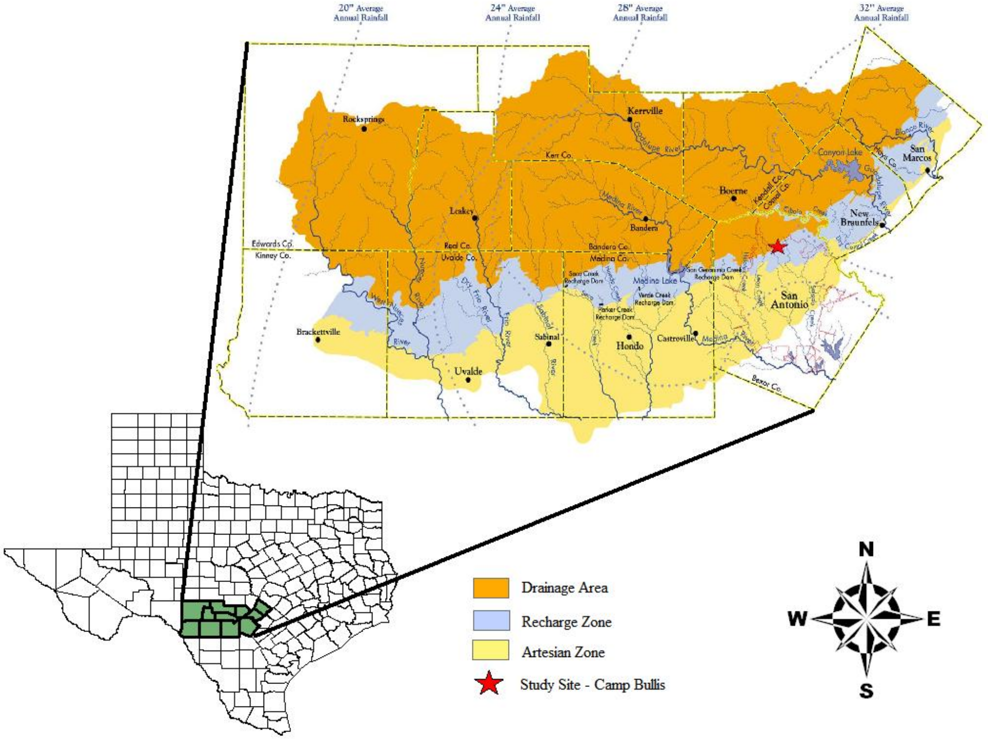


Figure 1: The map shows the location of the study site north of the city of San Antonio on Camp Bullis Training Facility. Also shown in the figure are the various hydrologic zones of the Edwards Aquifer.

Bunny Hole

The research site overlays a shallow cave that has been instrumented for monitoring drip rates. Bunny Hole is a cave that consists of passages that extend 198 m in length and reach a maximum depth of 5 m below the surface (Figure 2). Three parallel crawlways, arranged in a northeast to southwest direction, cover a linear distance of 46 m and average 1.5 m in width and are typically less than a meter in height (Figure 2). The cave also contains some impassable holes and fissures that extend up to 2.5 m deep into the floor and probably reach down to a lower level that is inaccessible (Figure 2).

Bunny Hole is developed in the Dolomitic Member of the Kainer Formation (Veni, 1988). It is considered a rare phreatic conduit system and is believed to pre-date the origin of the modern Edwards Aquifer. It has been suggested by evidence that Bunny Hole was formed by slow moving groundwater flow in an orientation parallel to major Balcones faulting (Veni, 1988). Joint planes exhibit little dissolution possibly due to low hydrostatic pressure during phreatic development and later speleothem development and case hardening of the walls and ceiling that hide the fractures. The floors of some passages were incised as a result of water flowing down to the water table during vadose conditions. Much of the collapse within Bunny Hole occurred along solutioned bedding planes with three of these collapses extending to the surface. There are also three sinkholes, formed by dissolution, that breech the surface of the cave; one of these is the cave entrance and the other two are small impassable sinkholes. Together, these sinkholes drain an area that is approximately 60 m along the cave axis by 50 m wide up the hillslope to the southeast (Veni, 1988).

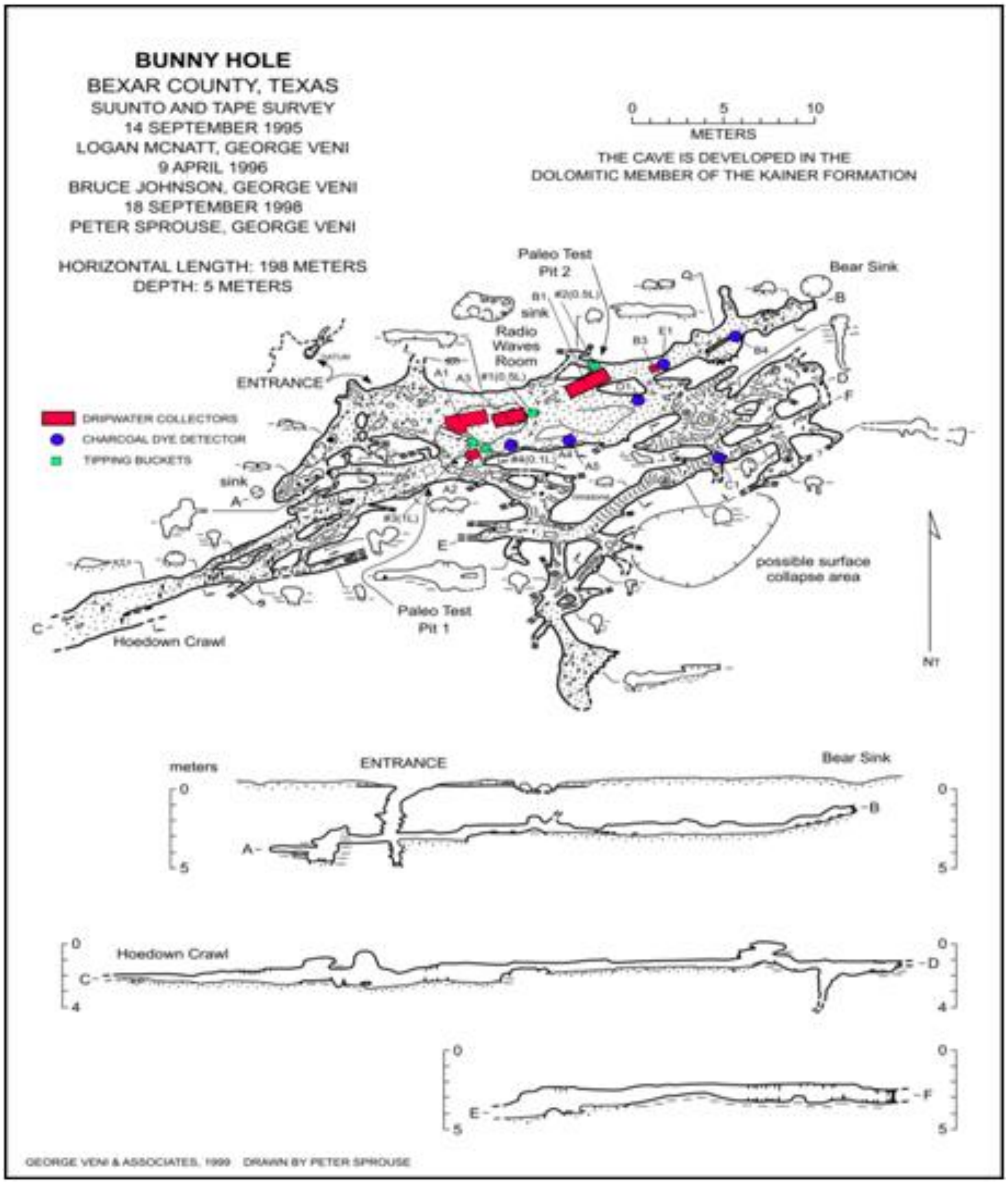


Figure 2: The illustration shows a planar and side view of Bunny Hole. Also shown are the locations of the drip monitoring devices located in the cave.

Site Vegetation

On the surface, the site is characteristic of mixed oak-juniper woodland. The dominant vegetation at the site consists of Ashe juniper (*Juniperus ashei*) and plateau live oak (*Juniperus fusiformis*). The canopy of the two species cover nearly the entire footprint of the cave with some scattered openings. A significant portion of ground cover is rocky outcrops, bare soil, and organic matter (leaf litter). Few understory vegetation exists being mostly agarita (*Berberis trifoliolata*), netleaf hackberry (*Celtis reticulate*), and sparse herbaceous and grass cover.

For an extensive description refer to Gregory (2006).

METHODOLOGY

This study focuses on using large-scale rainfall simulations to evaluate the effect of the removal of ashe juniper on recharge. Research for this study is a continuation of work as described by Gregory (2006) and Gregory et al. (2009).

Before experiments began a soaker hose test was conducted to determine the contributing area of Bunny Hole. The soaker hose test utilized perforated garden hoses to apply water directly to an area approximately 7m x 16 m at a consistent rate using water pumps. A total of six soaker hose applications (shown by blue rectangles in Figure 3) were conducted above and around the footprint Bunny Hole and identified an area of 22m x 16.5m above the footprint that was responsible for contributing to recharge (shown by red rectangle in Figure 3). This contributing area served as the study plot and the application area for the simulations that were conducted.

The pre-treatment stage of the study assessed the behavior and quantity of recharge at the study site with the juniper canopy in place. Four rainfall simulations were conducted at Bunny Hole: June 6, 2005; July 13, 2005; July 14, 2005 and July 28, 2005. Each simulation consisted of three separate runs that varied in rainfall intensity and duration in the attempt to reproduce a summer thunderstorm typical for the area. The first run produced an average of 21.1mm/hr for one hour, the second run produced 5.8mm/hr for two hours, and the third run produced 27.5 mm/hr for 45 minutes.Data collected during the simulations included: throughfall, stemflow, surface runoff and cave recharge.

During post-treatment of the study, simulations from the pre-treatment stage were closely replicated at the site after the removal of the juniper canopy. Juniper from the footprint of Bunny Hole, an area approximately 0.2 acres, was cleared manually using chain saws in late February 2008. Manual clearing was preferred over mechanical (i.e. hydro-axe) clearing to minimize disturbance at the site. Data collected (throughfall, surface runoff, and vertical recharge) for post-treatment simulations was compared to pre-treatment simulation data to analyze any changes, if any, that occurred. Collected data was used to construct a percentage based water budget for individual simulations. This water budget serves to compare before-and after treatment effects. In addition, below ground vegetation and ground cover was estimated at two time frames, 2 months and 1 year after juniper removal.

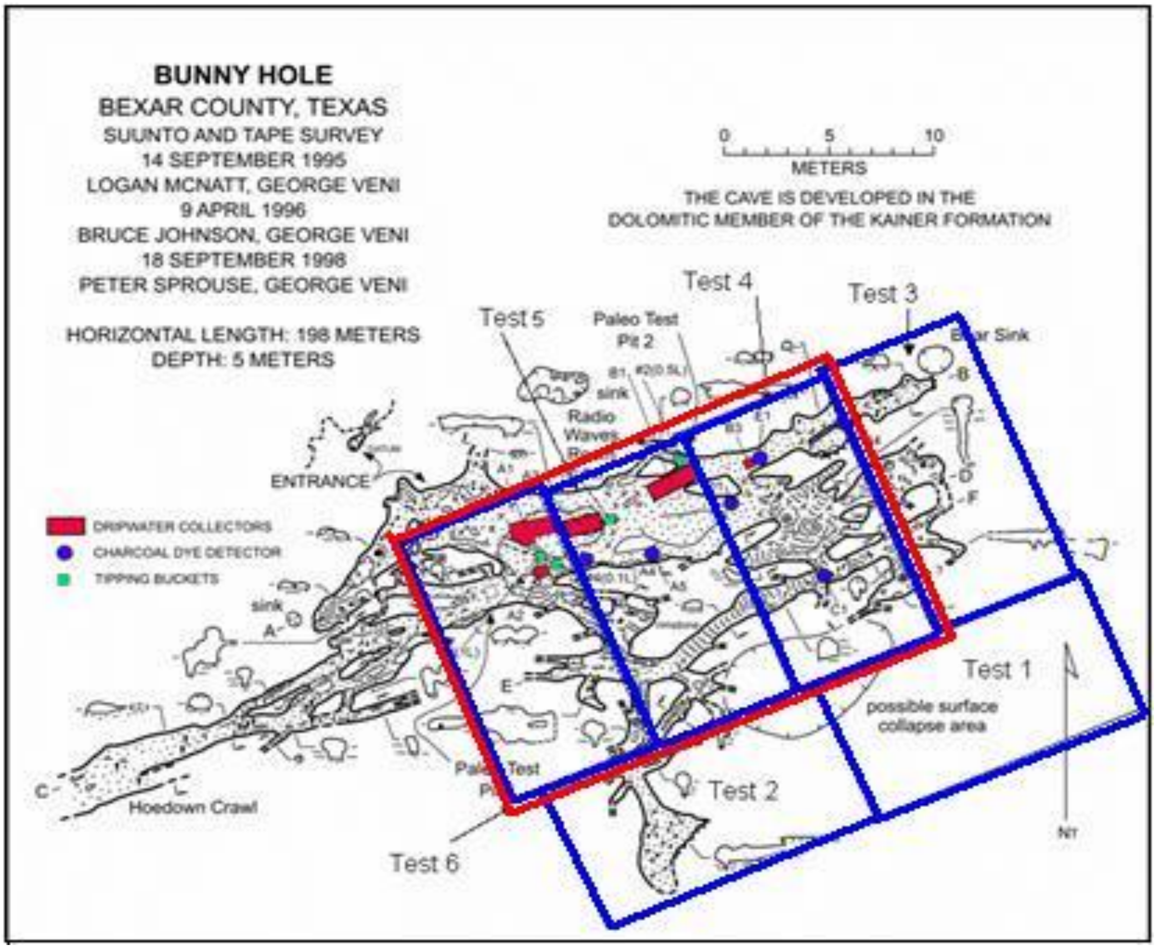


Figure 3: Illustration depicts the cave footprint and where the six soaker hose test were conducted (shown by blue rectangles). The soaker hose tests helped determine the area (22m x 16.5m) contributing to recharge inside Bunny Hole (shown by red rectangle). The four red squares within the footprint identify where the drip collectors were placed in the cave.

Rainfall Simulation

In semiarid regions, spatial and temporal variations in precipitation can lead to complications. For example, runoff generally occurs on rangelands as a result of summertime convective storms which are short duration, high intensity in nature (Wilcox et al., 2003). Owens et al. (2006) also demonstrate that the water budget of juniper, at the tree scale, is variable depending on rainfall quantity and intensity. In order to overcome these complications and control rainfall parameters the study was dependent on artificial rainfall created by an above-canopy rainfall simulator.

The simulator, as described by Munster et al (2006), consists of six telescoping masts that adjust between 3 and 11 m from the ground to extend above the tree canopy. Each mast is attached to the ground by being fastened to a plate that is spiked to the surface. With the lower portion of the mast supported, guide wires attached to the mast and anchored to the ground by steel spikes in four opposite directions allow for stability and levelness.

Mounted atop each mast is an H-pattern PVC manifold. The manifold contains four sprinkler heads that are capable of producing a maximum rainfall rate of 254 mm per hour. The sprinklers, S3000 Pivot Sprinklers (Nelson Irrigation Corp.), are fitted with nozzles that vary in size that yield maximum flow rates of 25.4, 50.8, 76.2, and 101.6 mm per hour and spray in a 360° pattern (Munster et al., 2006). Flow rates can be controlled further by adjusting the throttle of the water pump (Honda WP30X) used to deliver water to the system. Lay-flat hoses of 51 and 76 mm were used to convey water from storage to the manifolds. Water conveyed through the system was measured using a WT turbine meter (Master Meter) capable of reading flow rates from 15 to 2000 L per minute with 95% accuracy (Munster et al., 2006).

Simulations for this study were conducted in three runs: (1) high intensity, long duration (1 hr.); (2) low intensity, long duration (2 hr.); and (3) high intensity, short duration (45 min).

Application rates for each run averaged 21.4, 5.8, and 26.5 mm per hour, respectively. A downtime of one hour was allowed between each run to allow runoff and recharge to drain off as much as possible. This was done to be able to separate the runs on a hydrograph. Simulations were kept consistent for both pre-treatment and post-treatment simulations to better compare results. A total of 9 simulations were conducted post-treatment: June 12, 2008; June 18, 2008; June 19, 2008; July 10, 2008; July 29, 2008; July 30, 2008; July 31, 2008; June 3, 2009; and June 4, 2009. Simulations held in consecutive days were to evaluate the effect of antecedent moisture conditions on measured parameters, specifically surface runoff and cave recharge.

Throughfall Collection

Throughfall data was measured by collecting rainfall depths using a grid of rain gauges. A total of 72 gauges (Figure 4) were arranged throughout the contributing area in an evenly spaced pattern measuring 16.5 m by 23.8 m. Following each run, gauges were read and recorded in units of millimeters then emptied. Throughfall is estimated to be the amount of water reaching the surface. Once water reaches the surface it then either infiltrates the soil or leaves the plot as surface runoff.

Surface Runoff

Surface runoff at Bunny Hole is measured by funneling water into a 15.24 cm H-flume (Figure 4) at a low elevation point near the edge of the footprint. Runoff is channeled to the flume with a steel gutter that extends to both sides of the flume totaling a length of 10.7 m. The gutter is formed using 16-gauge Z-channel that is cemented in place level with the ground surface. A downward lip of the gutter extends 5.1 cm into the ground to prevent underflow. A backsplash protruding 12.7 cm from ground level prevents runoff from overflowing the gutter.

Once in the flume, runoff is measured with a float gage that is placed in a stilling well attached to the flume. As depth of the water varies in the stilling well the float will rise or sink which turns a potentiometer sending a voltage reading to a Campbell Scientific CR10X datalogger (Logan, Utah). The datalogger was calibrated to convert voltage reading to a depth reading in mm. Hand measurements were also taken in case technical difficulties were to arise.

Two flumes were necessary to catch runoff during the post-treatment events. The first flume was installed prior to the pre-treatment events and used to measure surface runoff that was directed towards the cave entrance. However, after the removal of the canopy it became apparent that an additional flume would be needed to capture runoff that was draining thru the middle of the plot and no longer towards the cave entrance. The second flume was installed prior to the fourth post-treatment simulation.

Figure 4: Picture of rain gauge used to collect throughfall (left). Picture of H-flume used to measure surface runoff (center). Picture of drip collector used to collect and measure cave recharge (right). Water collected was piped to a tipping bucket for quantity (liters) measurement.

Cave Recharge

Cave recharge is defined as water that enters the cave via cracks and fractures in the cave ceiling. Dominant drip locations in the ceiling were identified during initial soaker hose tests that were used to determine the contributing area. Four areas (red squares in Figure 3) were identified as main recharge locations and were determined to contribute 60% of the total recharge. Under these locations dripwater collectors were installed to measure recharge.

The dripwater collector (Figure 4) is a funneling device constructed of a 19-mm PVC frame covered by polyethylene sheeting that capture and route cave drips to a tipping bucket for quantification. The tipping buckets varied in size depending on drip capacity. Two collectors drained to 1L tipping buckets, one collector drained to a 500 mL tipping bucket, while the last collector was measured by a 100 mL tipping bucket. Each tipping bucket was fitted with a normally-open pulse magnetic switch that when triggered, or closed during each tip, would send a pulse to a Campbell Scientific CR10X datalogger (Logan, Utah) on the surface. The datalogger was programmed to count pulses and give a 1-minute total for each bucket.

Ground Cover Survey

Shortly after the removal of the juniper trees, on April 19, 2008, a survey was completed to estimate the percentage of ground cover available on the site, both aerial and basal. The *point-intercept* method described by Elzinga et al. (1998) was used to complete the survey. A measuring tape was stretched across the plot 24.7 m starting from the cave entrance and every .31 m a pin was dropped vertically against the tape and the type of ground cover hit by the pin was recorded. This procedure was repeated every .92 m upslope from the starting point to a distance of 16.5 m for a total of 1539 points. Aerial cover refers to the obstacle that a raindrop would first impact at that certain point. Basal cover refers to the cover at ground surface. The survey was repeated again approximately one year, on July 31, 2009, following the removal of the canopy.

Data Analysis

Data collected manually or automatically was entered and stored in Excel® for data management and processing. Cave recharge and surface runoff data was collected on 1-minute intervals and converted to express quantity in millimeters or rate in millimeters per hour. Cave recharge was corrected to account for the 40% of drip water not collected. Runoff data was collected in units of depth (mm), and was scaled to incorporate the 363 m^2 contribution area. Runoff was also converted to estimate the rate of runoff (mm/hr). This was done by calculating the quantity of discharge (m^3/s) and the area of the flume. Discharge was calculated using the formula: $\log Q = A + B \log h_a + C [\log h_a]^2$ where; Q = discharge (m^3/s), A = 0.0372, B = 2.6629, C = 0.1954, and h_a = runoff in meters (Gwinn and Parsons, 1976). The error for this equation is expected to be less than 3% (Gwinn and Parsons, 1976). Throughfall data was analyzed by determining the depth of water reaching the surface across the entire contributing area. The remaining portions of the water budget were determined by subtraction. Interception was determined by subtracting the amount of water reaching the surface (throughfall) form the amount of water being applied. All other water was gruped together and considered unaccounted for. For rainfall distribution plots, gage depths recorded in the field were used. Box plots were constructed to visually compare the pre-treatment data to the post-treatment data for throughfall, surface runoff, and cave recharge. Data used for the box plots was the total values for each simulation (n=4 pre-treatment and n=9 post-treatment).

RESULTS

Vegetation

Removal of the juniper occurred during the last weekend of February 2008 resulting in a 70% reduction in canopy cover. During pre-treatment, canopy cover was estimated (visually) to be 100%. The remaining 30% cover is provided by Texas live oak (*Quercus fusiformis* Small). A total of 45 trees were cut with 22 being contained within the 22 x 16.5 m contributing area (Figure 5).

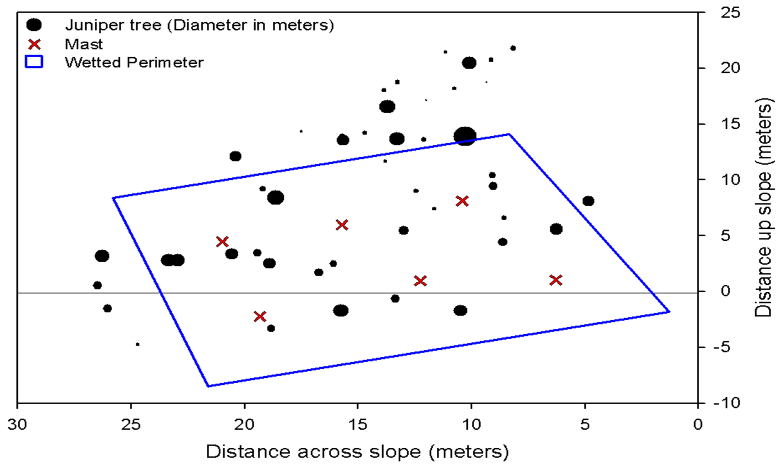
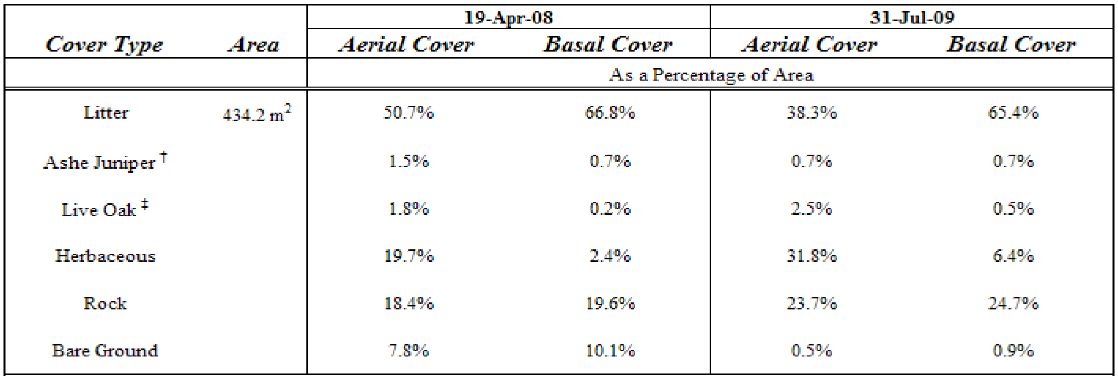


Figure 5: Graph illustrates the location of juniper trees that were cut in respect to the entrance of Bunny Hole (0, 0). For reference the locations of each sprinkler mast and the contributing area are included. The contributing area also represents the study plot.

Below canopy vegetation was estimated shortly after (19-Apr-08) removal of the juniper and again one-year (31-Jul-09) after the treatment. The greatest change was seen in herbaceous cover where an estimated 10% and 4% increase was measured for aerial and basal cover, respectively (see Table I). The increase in herbaceous vegetation is mainly the result of an increase in the amount of light and water reaching the surface. Vegetation species were not identified, but consisted mainly of bunch grasses and sedges. The percentage of rock cover appeared to have increased, however this could be attributed to either the aerial decrease of litter or a shift in transect location from the first survey to the second. The increase in live oak was due to an increase in the number of sprouts.

Table I: Display of the estimated ground cover for the study plot at two periods following the removal of the juniper canopy. Aerial cover refers to the first contact layer for a raindrop. Basal cover refers to cover at the surface.
(† indicates only ground-cut stumps remain, ‡ indicates sprouts only)



		19-Apr-08		31-Jul-09	
Cover Type	*Area*	*Aerial Cover*	*Basal Cover*	*Aerial Cover*	*Basal Cover*
		As a Percentage of Area			
Litter	434.2 m^2	50.7%	66.8%	38.3%	65.4%
Ashe Juniper †		1.5%	0.7%	0.7%	0.7%
Live Oak ‡		1.8%	0.2%	2.5%	0.5%
Herbaceous		19.7%	2.4%	31.8%	6.4%
Rock		18.4%	19.6%	23.7%	24.7%
Bare Ground		7.8%	10.1%	0.5%	0.9%

Water Budget

Data collected from the simulated events was used to construct a water budget to compare changes that might have occurred in response to the applied treatment. Nine post-treatment simulations were conducted during the months of June and July of 2008 and 2009. Seven simulations were completed in summer 2008, with the remaining two being completed in summer 2009. Originally three simulations were planned for 2009, but equipment malfunctions caused a cancellation of the third simulation. Water budgets were created for each individual run within a simulation and averaged to generate the overall simulation budget (see Table II). From these individual water budgets a total average budget (Table III) was produced for easy comparison with pre-treatment values obtained by Gregory et al. (2006).

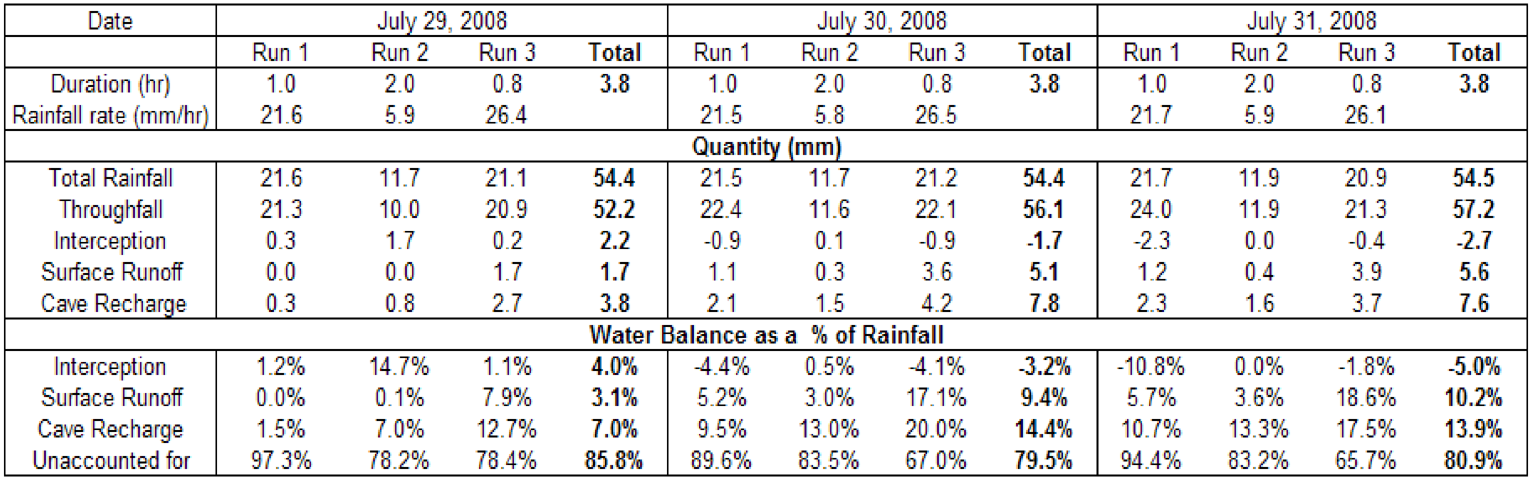
Table II: The table separates the water budgets into individual runs for each simulation during pre-treatment events.

Date	July 6, 2005	July 13, 2005				July 14, 2005				July 28, 2005			
	Total	Run 1	Run 2	Run 3	Total	Run 1	Run 2	Run 3	Total	Run 1	Run 2	Run 3	Total
Duration (hr)	2.3	1.0	2.0	0.8	3.8	1.0	2.0	0.8	3.8	1.0	2.0	0.8	3.8
Rainfall rate (mm/hr)	22.2	21.1	5.8	27.5		21.5	5.7	27.3		21.6	4.4	24.1	
Quantity (mm)													
Total Rainfall	51.0	21.1	11.6	22.0	54.7	21.5	11.4	21.8	54.7	21.6	8.8	19.3	49.7
Stemflow	3.2	0.9	0.1	1.1	2.1	0.9	0.1	1.4	2.4	1.7	0.5	2.0	4.2
Throughfall	35.4	16.3	6.6	17.3	40.2	18.9	6.8	18.3	44.0	19.0	8.5	17.2	44.7
Interception	12.4	3.9	4.9	3.6	12.4	1.7	4.5	2.1	8.3	0.9	-0.2	0.1	0.8
Surface Runoff	0.0	0.0	0.0	1.6	1.6	0.1	0.0	1.7	1.8	0.0	0.0	1.8	1.8
Cave Recharge	4.1	0.2	0.8	3.2	4.2	2.5	1.4	5.2	9.1	0.8	1.7	3.9	6.4
Water Balance as a % of Rainfall													
Interception	24.3%	18.5%	42.2%	16.4%	22.7%	7.9%	39.5%	9.6%	15.2%	4.2%	-2.3%	0.5%	1.6%
Surface Runoff	0.0%	0.0%	0.0%	7.3%	2.9%	0.5%	0.0%	7.8%	3.3%	0.0%	0.0%	9.3%	3.6%
Cave Recharge	8.0%	0.9%	6.9%	14.5%	7.7%	11.6%	12.3%	23.9%	16.6%	3.7%	19.3%	20.2%	12.9%
Unaccounted for	67.6%	80.6%	50.9%	61.8%	66.7%	80.0%	48.2%	58.7%	64.9%	92.1%	83.0%	69.9%	81.9%

Table II (continued): The table separates the water budget into individual runs for each simulation. The first four post-treatment simulations are displayed here.

Date	June 12, 2008				June 18, 2008				June 19, 2008				July 10, 2008			
	Run 1	Run 2	Run 3	Total	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**
Duration (hr)	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**
Rainfall rate (mm/hr)	20.7	5.8	26.3		21.6	5.9	26.0		21.4	5.8	25.7		21.1	5.8	26.3	
Quantity (mm)																
Total Rainfall	20.7	11.5	21.1	**53.3**	21.6	11.7	20.8	**54.1**	21.4	11.6	20.5	**53.5**	21.1	11.7	21.0	**53.8**
Throughfall	17.8	9.0	19.9	**46.6**	22.1	10.1	20.7	**52.9**	23.2	6.4	19.1	**48.7**	22.0	10.1	20.9	**53.0**
Interception	2.9	2.5	1.2	**6.6**	-0.5	1.6	0.1	**1.2**	-1.8	5.2	1.4	**4.8**	-0.9	1.6	0.1	**0.8**
Surface Runoff	0.0	0.0	0.0	**0.0**	0.0	0.0	0.0	**0.0**	0.0	0.0	0.0	**0.0**	0.3	0.2	1.9	**2.3**
Cave Recharge	0.1	0.2	1.2	**1.6**	0.7	0.9	2.3	**3.8**	2.0	1.1	3.3	**6.4**	1.1	1.2	2.7	**5.0**
Water Balance as a % of Rainfall																
Interception	14.0%	22.1%	5.7%	**12.5%**	-2.5%	13.8%	0.6%	**2.2%**	-8.6%	44.9%	7.1%	**9.0%**	-4.3%	13.6%	0.7%	**1.6%**
Surface Runoff	0.0%	0.0%	0.0%	**0.0%**	0.0%	0.0%	0.0%	**0.0%**	0.0%	0.0%	0.0%	**0.0%**	1.2%	1.3%	9.0%	**4.3%**
Cave Recharge	0.5%	1.9%	5.9%	**3.0%**	3.1%	7.8%	10.9%	**7.1%**	9.3%	9.6%	16.2%	**12.0%**	5.4%	10.1%	12.9%	**9.4%**
Unaccounted for	85.5%	76.0%	88.4%	**84.6%**	99.4%	78.4%	88.5%	**90.7%**	99.3%	45.6%	76.8%	**79.0%**	97.6%	74.9%	77.4%	**84.8%**

Table II (continued): The table separates the individual runs for the last three post-simulations completed in 2008. These simulations occurred in consecutive days.



Date	July 29, 2008				July 30, 2008				July 31, 2008			
	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**
Duration (hr)	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**
Rainfall rate (mm/hr)	21.6	5.9	26.4		21.5	5.8	26.5		21.7	5.9	26.1	
Quantity (mm)												
Total Rainfall	21.6	11.7	21.1	**54.4**	21.5	11.7	21.2	**54.4**	21.7	11.9	20.9	**54.5**
Throughfall	21.3	10.0	20.9	**52.2**	22.4	11.6	22.1	**56.1**	24.0	11.9	21.3	**57.2**
Interception	0.3	1.7	0.2	**2.2**	-0.9	0.1	-0.9	**-1.7**	-2.3	0.0	-0.4	**-2.7**
Surface Runoff	0.0	0.0	1.7	**1.7**	1.1	0.3	3.6	**5.1**	1.2	0.4	3.9	**5.6**
Cave Recharge	0.3	0.8	2.7	**3.8**	2.1	1.5	4.2	**7.8**	2.3	1.6	3.7	**7.6**
Water Balance as a % of Rainfall												
Interception	1.2%	14.7%	1.1%	**4.0%**	-4.4%	0.5%	-4.1%	**-3.2%**	-10.8%	0.0%	-1.8%	**-5.0%**
Surface Runoff	0.0%	0.1%	7.9%	**3.1%**	5.2%	3.0%	17.1%	**9.4%**	5.7%	3.6%	18.6%	**10.2%**
Cave Recharge	1.5%	7.0%	12.7%	**7.0%**	9.5%	13.0%	20.0%	**14.4%**	10.7%	13.3%	17.5%	**13.9%**
Unaccounted for	97.3%	78.2%	78.4%	**85.8%**	89.6%	83.5%	67.0%	**79.5%**	94.4%	83.2%	65.7%	**80.9%**

Table II (continued): The table separates the individual runs for the post-treatment simulations completed during the summer of 2009.

Date	June 3,2009				June 4,2009			
	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**
Duration (hr)	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**
Rainfall rate (mm/hr)	21.4	5.7	25.6		21.7	7.5	25.3	
Quantity (mm)								
Total Rainfall	21.4	11.5	20.5	**53.3**	21.7	15.1	20.3	**57.1**
Throughfall	23.3	12.6	21.9	**57.8**	21.3	9.5	18.3	**49.1**
Interception	-1.9	-1.1	-1.4	**-4.5**	0.4	5.6	2.0	**8.0**
Surface Runoff	0.0	0.0	1.6	**1.6**	0.8	0.1	2.5	**3.3**
Cave Recharge	0.5	0.9	2.7	**4.1**	2.0	1.7	4.8	**8.5**
Water Balance as a % of Rainfall								
Interception	-9.0%	-9.6%	-7.0%	**-8.4%**	2.1%	36.9%	9.7%	**13.9%**
Surface Runoff	0.0%	0.0%	8.0%	**3.1%**	3.7%	0.5%	12.2%	**5.9%**
Cave Recharge	2.5%	7.5%	13.2%	**7.7%**	9.3%	11.1%	23.5%	**14.8%**
Unaccounted for	106.5%	102.1%	85.8%	**97.6%**	85.0%	51.5%	54.6%	**65.4%**

Table III: The table details the water budget for Bunny Hole for before and after the removal of the juniper canopy. Values are averages of all the simulations. Column 2 (% of Applied) is a percentage of the process as a portion of the total applied water. Column 3 (% of TF) is a percentage of the process as a portion of throughfall.

	mm	*% of Applied*	*% of TF*
Pre-cut			
Applied	52.5		
Throughfall	41.1	78.2%	
Stemflow	3.0	5.7%	
Interception	11.5	21.8%	
Recharge	6.0	11.3%	14.5%
Runoff	1.3	2.5%	3.2%
Post-cut			
Applied	54.3		
Throughfall	52.6	97.0%	
Stemflow	0.0	0.0%	
Interception	1.6	3.0%	
Recharge	5.4	10.0%	10.3%
Runoff	2.2	4.0%	4.1%

Throughfall and Interception

Removal of the canopy altered the pattern of rainfall distribution across the plot. During pre-treatment events water was routed to the surface as either throughfall or stemflow due to interception. With the elimination of the interception process, from juniper, water had a more direct path to the surface. While an oak canopy still existed it was difficult to estimate interception due to the design of the simulator. With a thinned canopy and water being sprayed in a radial manner, it complicated measurements by allowing water to reach under the oak canopy without primary contact. In other words, a portion of the water being measured under the canopy did not occur as throughfall, and was difficult to account for. Adding to difficulties was the placement of rain gages. Spaced evenly across the plot, some ended up collecting drip points from oak trees that caused inflated gage readings (see Figure 6, also see Appendix A). Drip locations changed for simulations 8 and 9 from the first seven simulations because of gage placement (see Appendix A). In order to minimize the effect of these drips, a spatial average was used (Figure 7) versus a total average. An average was calculated for rainfall that occurred on each 5 m^2 area using four rain gages. Each of these values were then was summed to give a rainfall depth for the plot area of 363 m^2. This average was used as the throughfall value for the water budget.

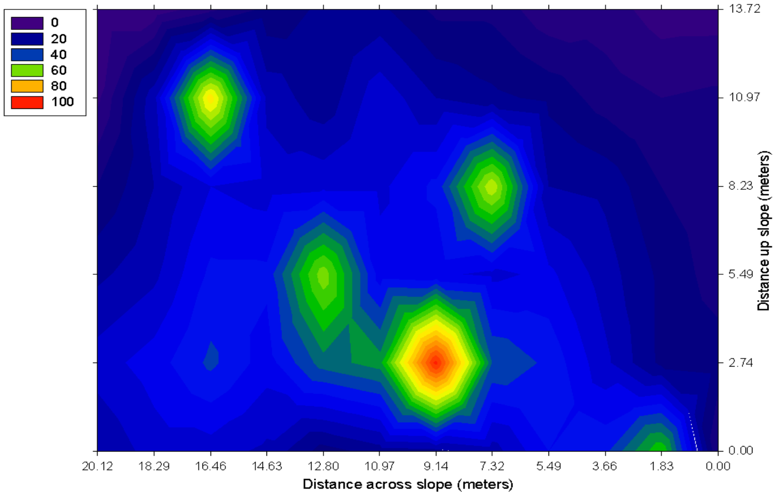


Figure 6: Graph illustrates the rainfall distribution across the plot for simulation 1 - run 3. The contours are in units of millimeters. Point (0,0) represents the first rain gage on the grid which is located at the cave entrance. For distributions of other simulations refer to Appendix B.

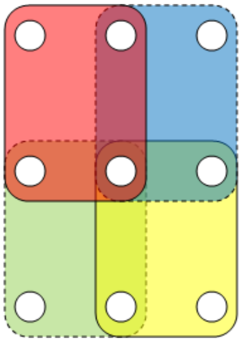


Figure 7: The illustration describes the use of four spatially related rain gages to determine the throughfall average. This was done throughout the plot for 72 rain gages. Each grid of four gages represented 5 m^2 of the total 363 m^2 area plot. The circles represent rain gages and colored boxes represent a grid of four gages.

The clearing of the juniper also caused an average of 15.5% increase in the amount of water reaching the surface (Figure 8). During pre-treatment events the average effective rainfall (water reaching surface) was approximately 44.1 mm over four simulations, or 84% of the applied water (Table III). This value was measured by summing the values of throughfall and stemflow. For post-treatment events effective rainfall only included throughfall and was averaged to be 52.6 mm, or 97% of applied water (Table III). Certain simulations (6 & 7) resulted in higher throughfall values than the amounts of water applied (see Table II). The same occurred for several individual runs during other simulations most notably run 1 of simulations 2, 3, and 4 (see Table II). The most likely cause for these glitches is the drips mentioned previously not being smoothed out completely by the spatial averaging.

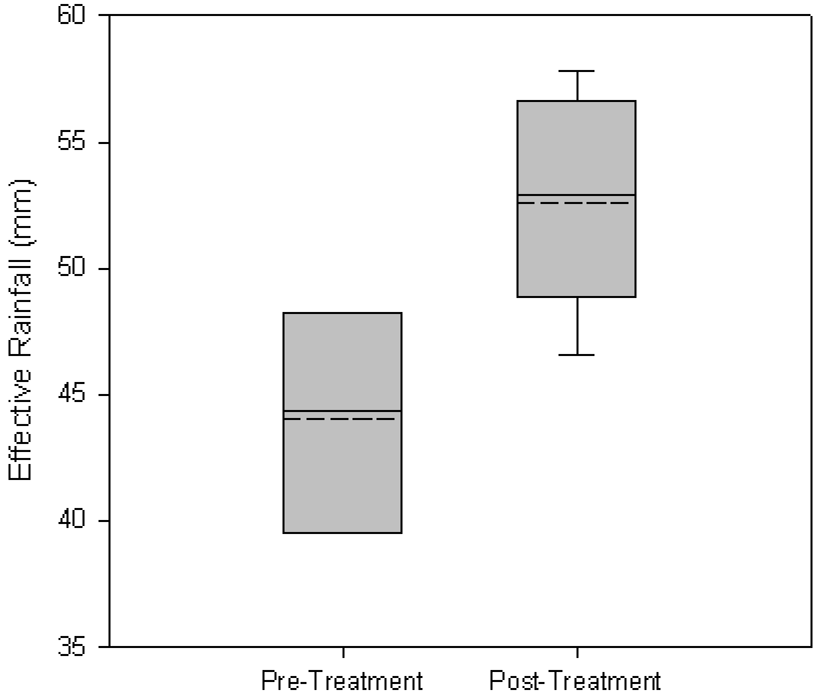


Figure 8: The box plot illustrates the difference in effective rainfall, or water reaching the surface between pre- and post-treatment simulations. Dashed line identifies the mean.

Surface Runoff

The first notable difference between pre- and post-treatment surface runoff did not come in the form of measured data, but rather as a visual observation. During pre-treatment simulations when runoff would occur, it flowed toward the lower right (looking up slope) corner of the plot towards a sink feature and the entrance of Bunny Hole. However, when runoff occurred during post-treatment simulations flow was concentrated toward the lower center of the plot. This could be attributed to the location of the remaining oak canopy in the plot, which happens to occur closer to the cave entrance. This remaining canopy intercepts a portion of rainfall allowing less water to reach the surface in this area. Meanwhile, the majority of the open-canopy area that allows for more throughfall is on the left side (looking up slope) of the plot, which is furthest from the entrance. This is evident in the rainfall distribution plots (Appendix A). The quantity of surface runoff, 1.3 mm and 2.2 mm for the pre- and post-treatment simulations, respectively (Table III), netted an average 28% increase as a proportion of throughfall. Figure 9 illustrates the upward shift in runoff after treatment.

As identified during pre-treatment simulations, antecedent moisture condition (AMC) factors into the amount of runoff produced. This is best exposed in simulations that were conducted in consecutive days for the purpose of determining the role of AMC. Four such simulations were performed, one pre-treatment (July 13 – 14, 2005) and three post-treatment (June 18 – 19, 2008; July 29 – 31, 2008, and June 3 – 4, 2009). Due to moist conditions caused by the previous days' simulation, the second day on each occasion produced an increase in the amount of surface runoff from the first day (see referenced dates in Table II). For simulations on June 18 – 19, 2008 surface runoff was observed, however, due to the unexpected shift in runoff direction, data was not collected.

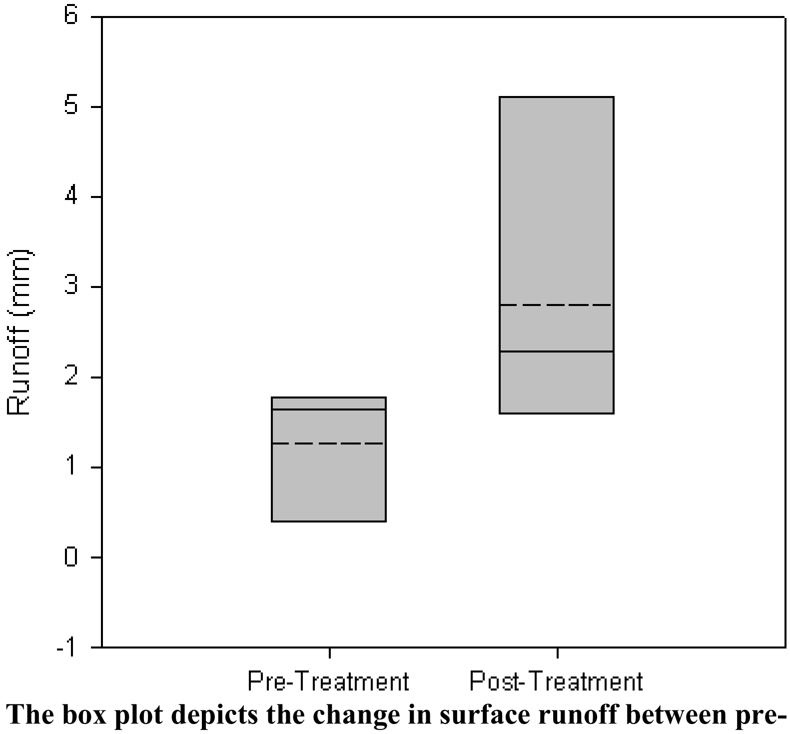


Figure 9: The box plot depicts the change in surface runoff between pre- and post-treatment events. Dashed line identifies the mean.

Cave Recharge

Like surface runoff, recharge was also determined by pre-treatment simulations to be dependent on AMC. This process again was shown in post-treatment events. Figure 10 compares the hydrographs of six simulations and illustrates the behavior of surface runoff and recharge. Graphs A and D detail pre-treatment simulations carried out on June 13 and 14, respectively, during the summer of 2005. Graphs B and E detail post-treatment simulations conducted June 29 and 30, respectively, during the summer of 2008. Graphs C and F depict post-treatment simulations conducted June 3 and 4 during the summer of 2009. The effect of AMC is most notable during the first run of the second days' simulation, when considerably more recharge is measured than the first run of the preceding simulation. The same concept can apply to the pattern of surface runoff, reassuring the importance of AMC.

Also shown in the hydrographs (Figure 10) is the shape of the rising and falling limbs. The pattern remains constant between treatments, indicating that the response and drain time of recharge was not hampered by the removal of the juniper. This continues to support the notion presented by Gregory et al. (2006) that recharge at Bunny Hole is dominated by macropore flow. To view supplementary hydrographs for remaining simulations refer to Appendix B.

The total average for recharge suggests that a slight decrease occurred in response to removal of juniper from 14.5% of throughfall to 10.3% of throughfall (Table III), which is a 29% decrease. Box plots comparing the treatments illustrate the subtle decrease (Figure 11).

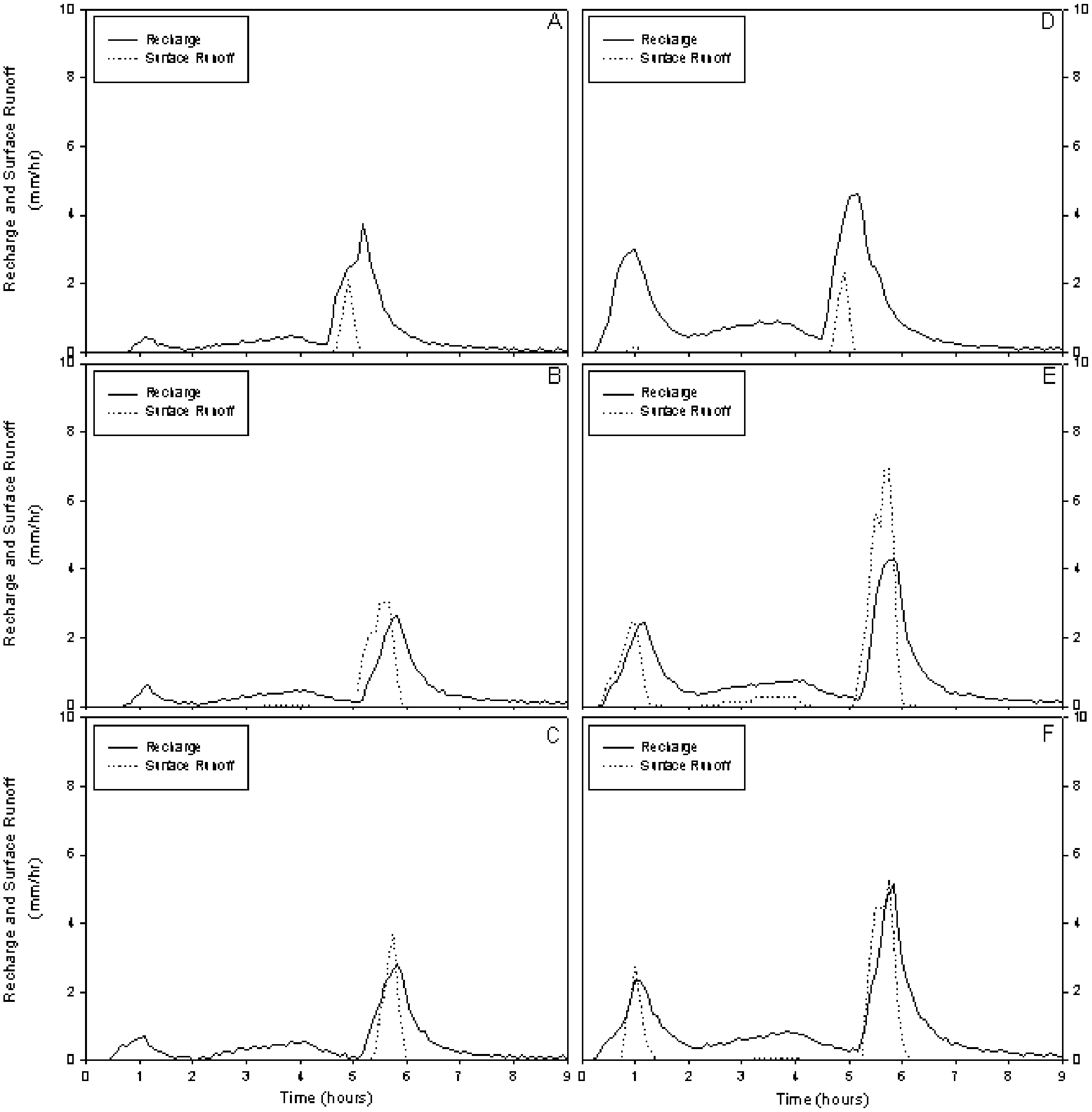


Figure 10: The hydrographs illustrate the rate of recharge and surface runoff at Bunny Hole for select pre- and post-treatment simulations. The hydrographs displayed are three of the four sets of simulations conducted in consecutive days. Graphs A and D are pre-treatment simulations from July 13 and 14, 2005, graphs B and E are post-treatment simulations from July 29 and 30, 2008, and graphs C and F are post-treatment simulations from June 3 and 4, 2009.

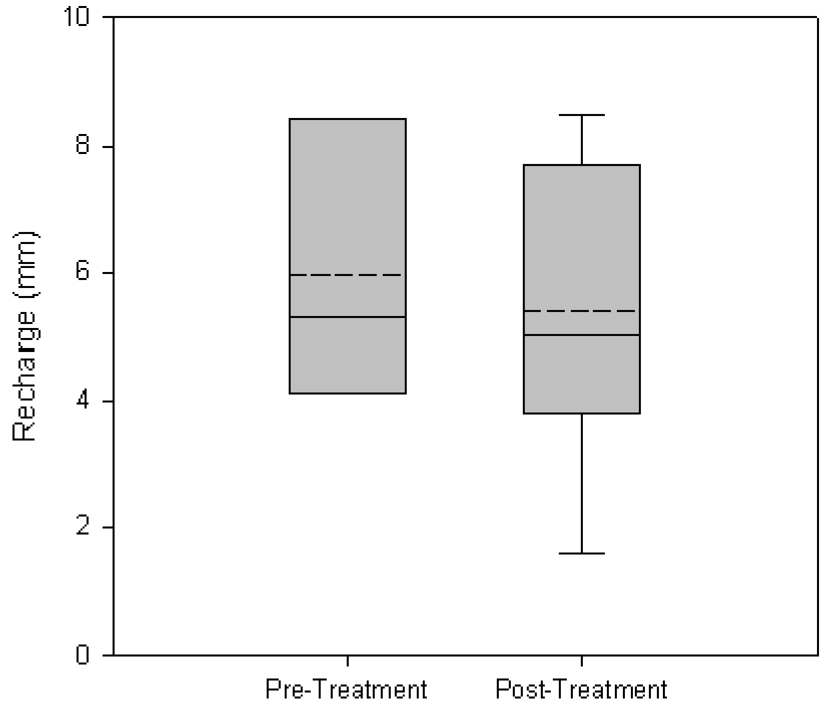


Figure 11: The box plots illustrate the difference in recharge totals between pre- and post-treatment simulations.

DISCUSSION AND CONCLUSIONS

Results from the study fail to support the hypothesis that the removal of juniper at the site would translate into additional recharge. Data does show that a decrease in the amount of recharge occurred on the plot. The increase in the amount of effective rainfall makes this observation puzzling, however the combination of two processes, stemflow and surface runoff, could possibly provide an explanation.

Pre-treatment simulations found that stemflow averages 5.7% of the water budget, a small portion considering throughfall accounted for 78.2%. However, a paired study using mass balance of chloride (Taniguchi et al., 1996) and cylindrical infiltration model (Tanaka et al., 1996) approaches caution to not disregard the recharge capacity of stemflow. Studied in Japanese red pine (*Pinus densiflora* Sieb. et Zucc.) stands, both approaches found that ratio of recharge rate by stemflow was relatively larger than the ratio of stemflow to bulk precipitation. Stemflow serves as a funnel to redirect water from the canopy to the base of the tree. Pressland (1976) found for mulga (*Acacia aneura* F. Muell) trees in arid Australia that infiltration rates are highest near the base of the tree and decline as distance is increased. More locally, Thurow et al. (1987) obtained similar results for live oak mottes on the Edwards Plateau, reporting that a 100 mm radius around the base of the tree would receive approximately 222% of annual precipitation, while areas further away would receive 53.9%. The greater influx of water near the base of the tree could be routed to preferential flow paths created by root channels. Heilman et al. (2009) describe that excavations on the Edwards recharge zone show juniper root mats forming in the shallow soil above the rock, but some roots penetrated into cracks and fissures. Using dye tracer tests, Dasgupta et al. (2006) reported that fractures and juniper root channels serve as conduits for preferential flow to occur. Also, Wilcox et al. (2008b) found that in trench faces exposed to study lateral subsurface flow, fractures and root channels were the primary locations of shallow subsurface runoff.

By removing the canopy, the process of stemflow is eliminated reducing the amount of water directed to preferential flow paths at or near the base of the tree. This allows more uniform application of water at the surface. Because a shift in recharge response did not occur, as shown by the hydrographs (Appendix B), it indicates that flow paths are still accessible. So infiltration across the plot is still supplying and maintaining the quantity of recharge.

With more water reaching the surface and infiltration rate remaining the same, excess water must go somewhere. Infiltration-excess runoff did increase at the site following treatment. Other simulation studies (Wilcox et al., 2008b) on the Edwards Plateau found that surface runoff did not change after the removal of juniper, however, the surface slope of their study sites were relatively flat compared to Bunny Hole. Dugas et al. (1998) using a paired watershed study on the Seco Creek watershed reported that runoff increased following the clearing of juniper, but decreased as herbaceous vegetation established. The two simulations conducted one-year after treatment at Bunny Hole did not see a decreasing pattern even with increased surface vegetation.

With recharge and surface runoff only accounting for 14% of the water budget, 86% of the total water applied is unaccounted for. Gregory et al. (2009) made note of challenges and uncertainties about the fate of water unaccounted for listing three possible explanations; 1) soil storage, 2) runoff via lateral subsurface flow, and 3) recharge through conduits not connected to the cave. After post-treatment events the uncertainties remain the same. As during pre-treatment events, soil moisture was not measured for post-treatment events, thus it is difficult to estimate the capacity of water stored in the shallow, rocky soils at the site. Results presented by Wilcox et al. (2008b) proving that shallow subsurface flow is an important runoff process on semiarid karst shrublands leads to the possibility that it could be occurring at Bunny Hole. Gregory et al. (2009) contributes the third possibility as a probable overestimation of contributing area.

Wong and Banner (In Review) also measured recharge before and after removal of 2 acres of juniper by monitoring cave drips at Natural Bridge Caverns in New Braunfels, Texas. Relying on natural precipitation, results from the study were variable, but suggested that clearing had no affect on recharge. Since the study was bound by the scale of the cave, it can only be concluded that the removal of juniper did not increase on-site recharge. Because it is not definitively known what occurred to unaccounted for water or water leaving the plot as surface runoff it is difficult to assume that recharge was not affected at a larger scale.

The study plans to continue monitoring natural rainfall events at the site to monitor if any changes may occur over the long-term. Also, a similar study is under way to evaluate the effects of ashe juniper on recharge over a deeper cave (Headquarters) where drips are predominantly micropore flow. Will the presence of a deeper soil layer and different drip mechanism make a difference in recharge potential? The study at the Natural Bridge Caverns (Wong and Banner, In Review), which is also a deeper cave system, suggests that a change does not occur.

With research results indicating that the effects of brush management on water supply are negligible or minimal at most, it would be fair to say that subsidized brush management programs are not seeing a return on investment. However, that does not mean that benefits do not exist. The removal of brush species can have a positive effect on range management, for example by increasing herbaceous vegetation for grazing animals. From a public perception though the verdict is still out and research in the area will continue to find questions and look for answers.

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APPENDIX A

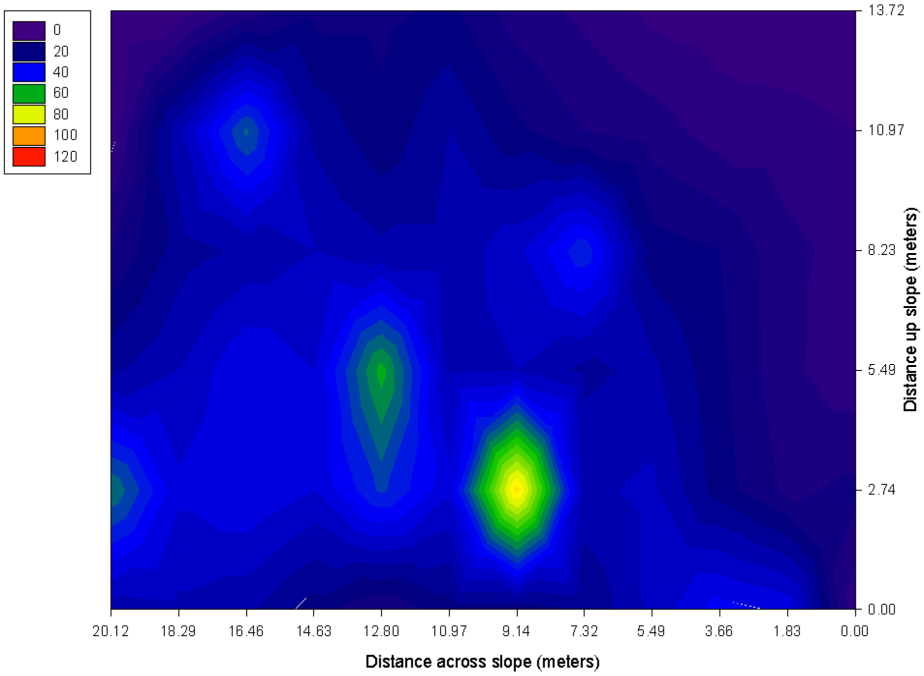


Figure A-3: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 1 (June 12, 2008) run 1.

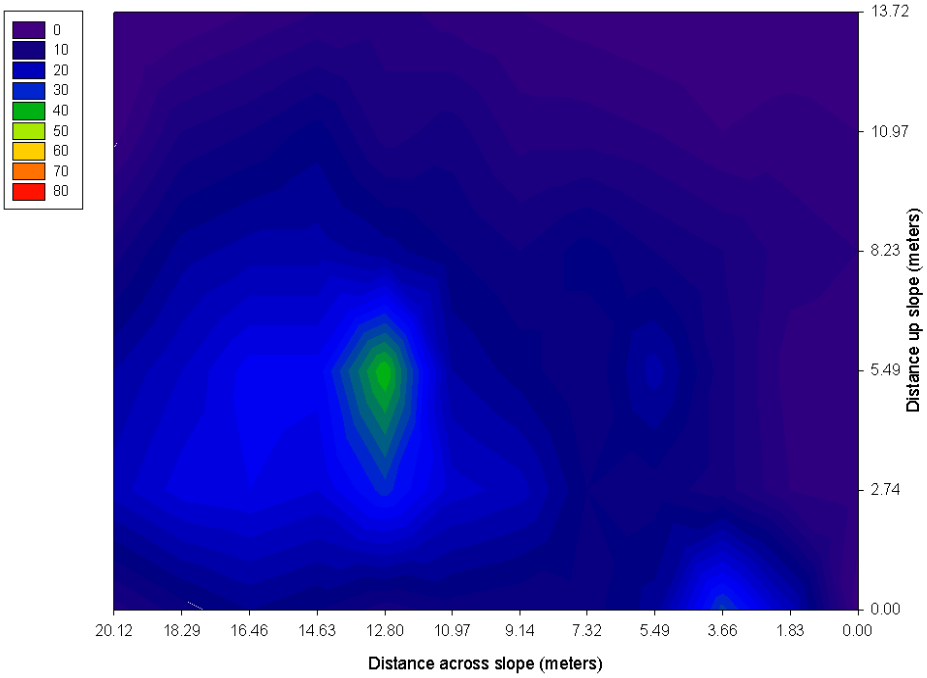


Figure A-4: graph shows the rainfall distribution across the contributing area for post-treatment simulation 1 (June 12, 2008) run 2.

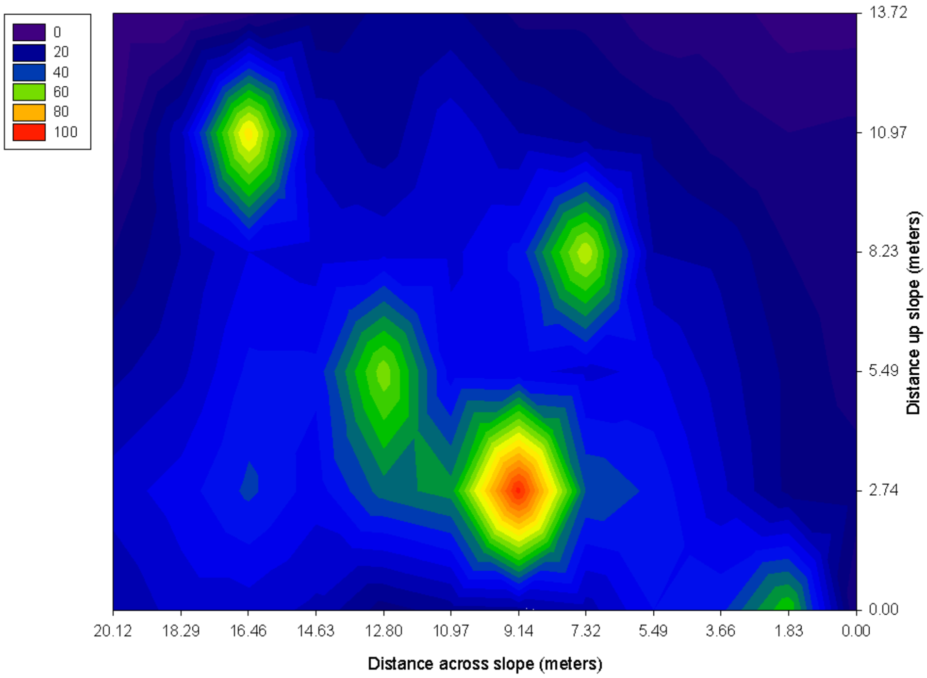


Figure A-5: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 1 (June 12, 2008) run 3.

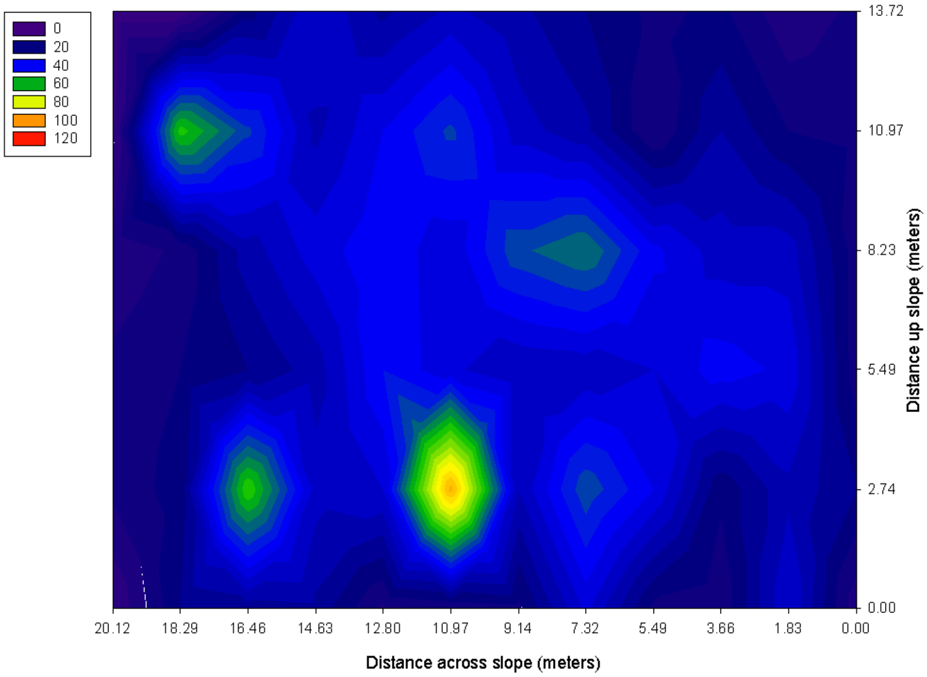
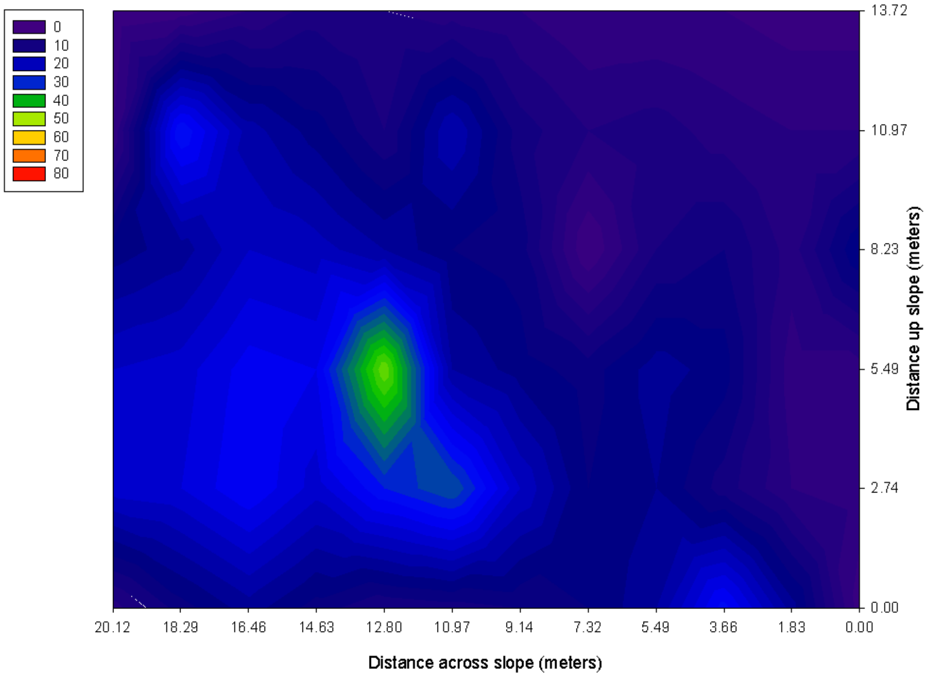


Figure A-6: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 2 (June18, 2008) run 1.



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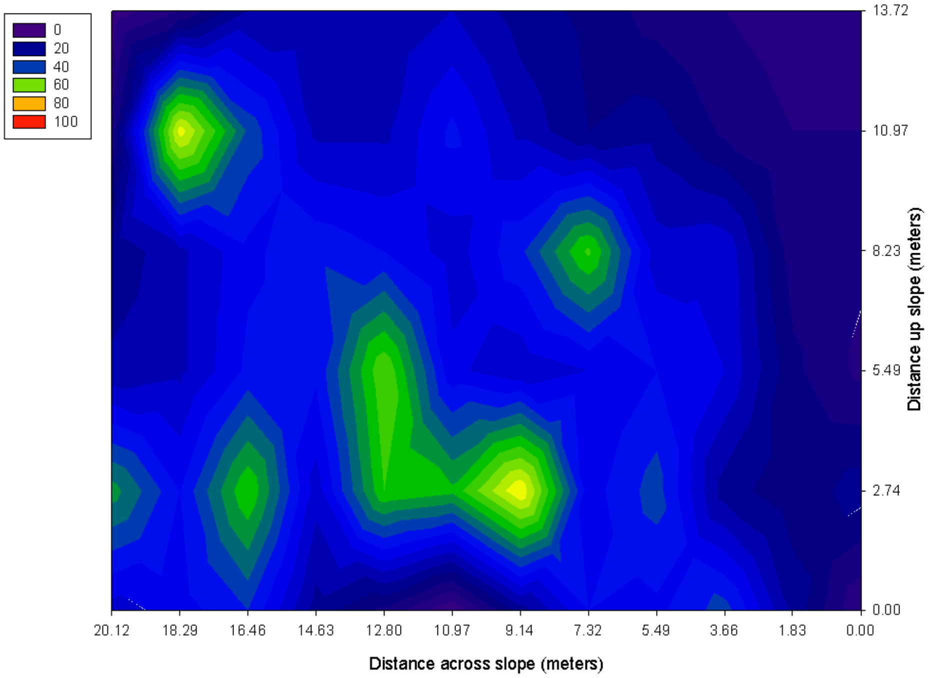


Figure A-8: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 2 (June 18, 2008) run 3.

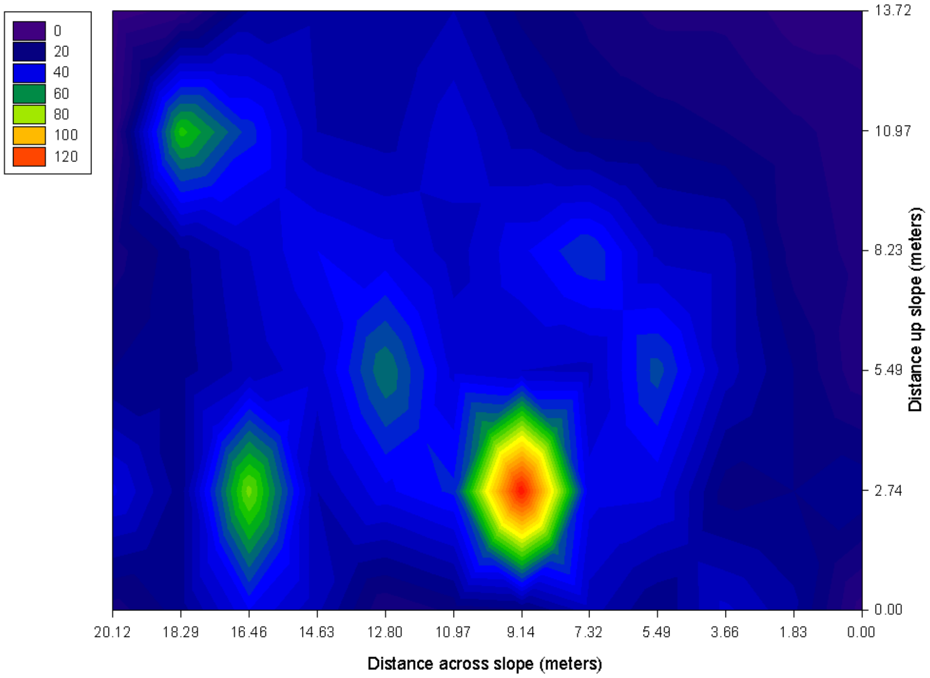


Figure A-9: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 3 (June 19, 2008) run 1.

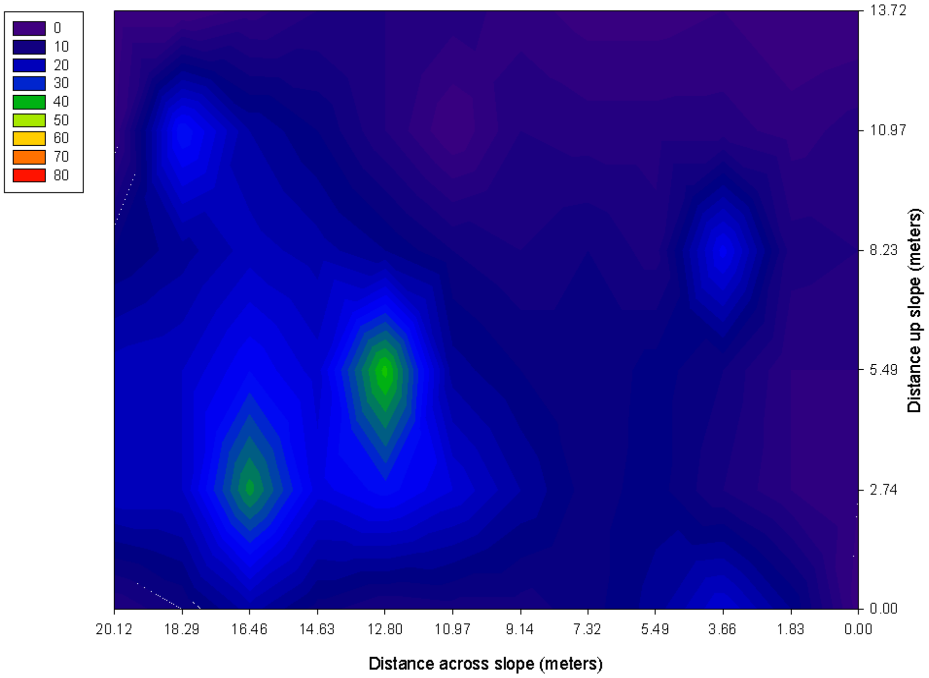


Figure A-10: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 3 (June 19, 2008) run 2.

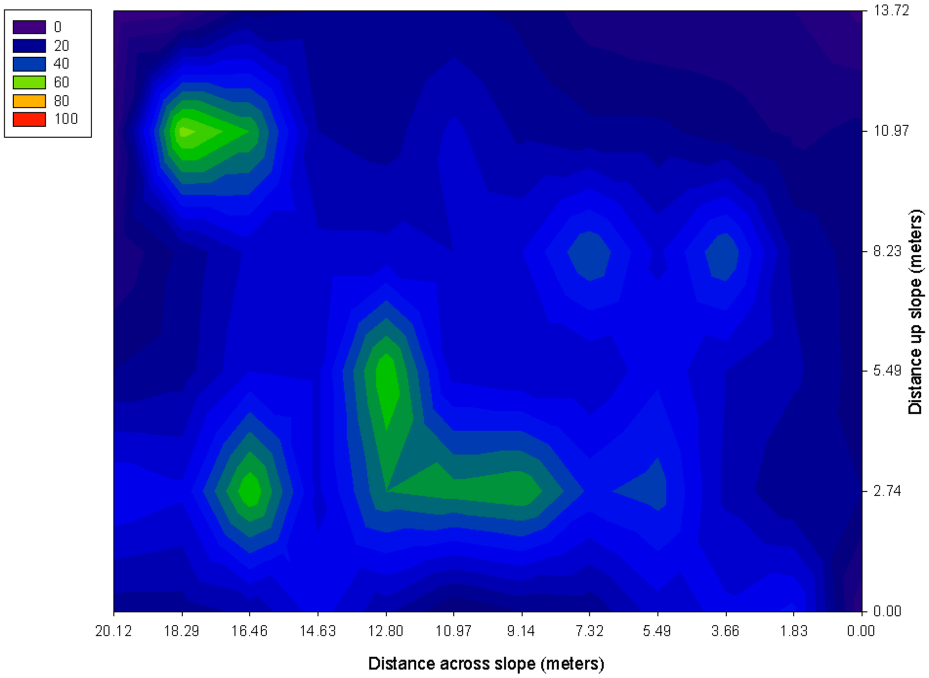


Figure A-11: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 3 (June 19, 2008) run 3.

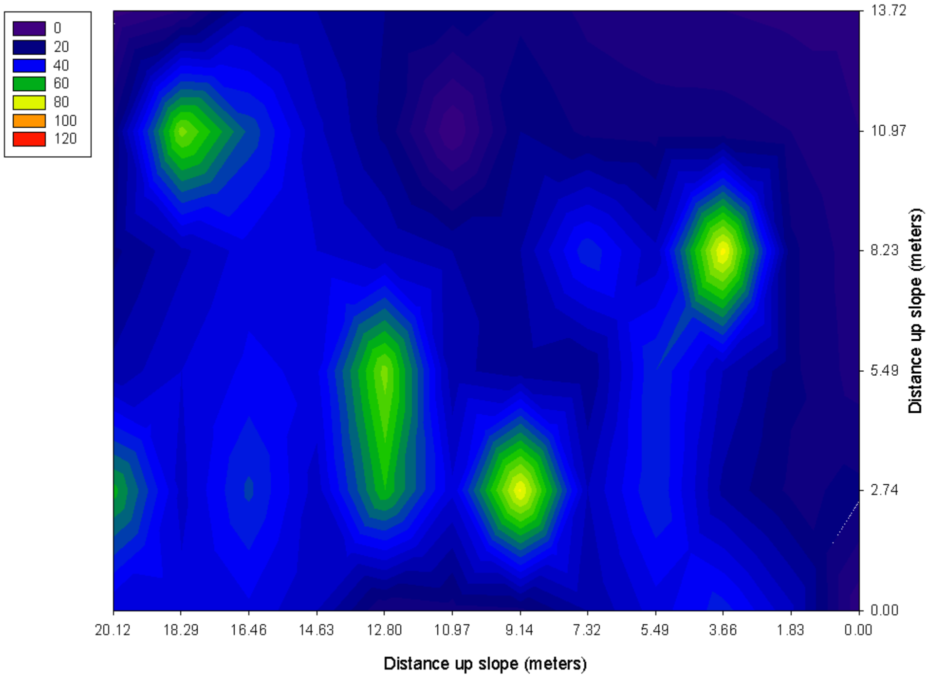


Figure A-12: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 4 (July 10, 2008) run 1.

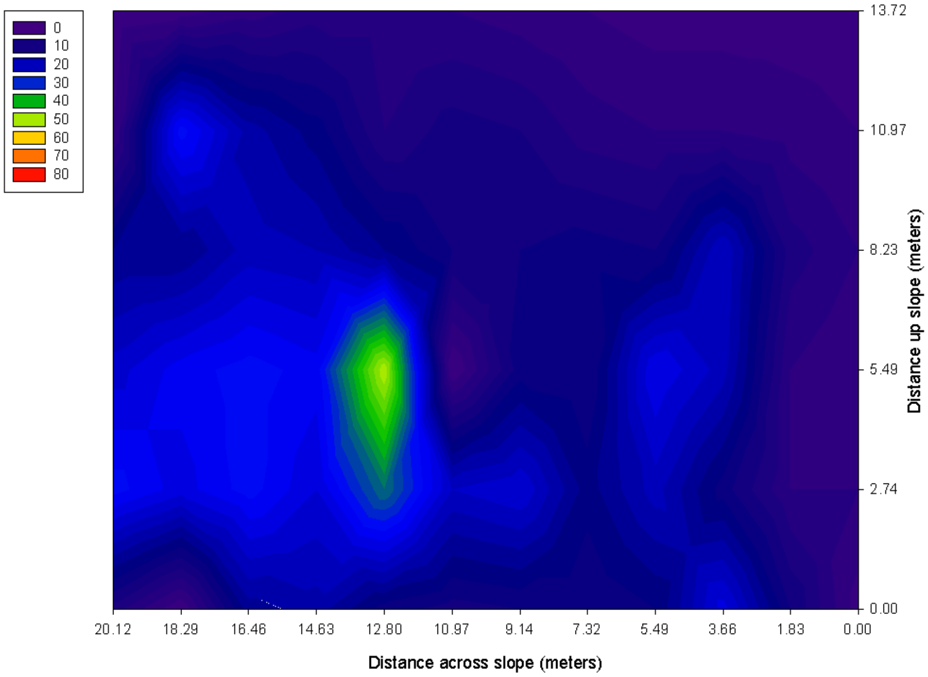


Figure A-13: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 4 (July 10, 2008) run 2.

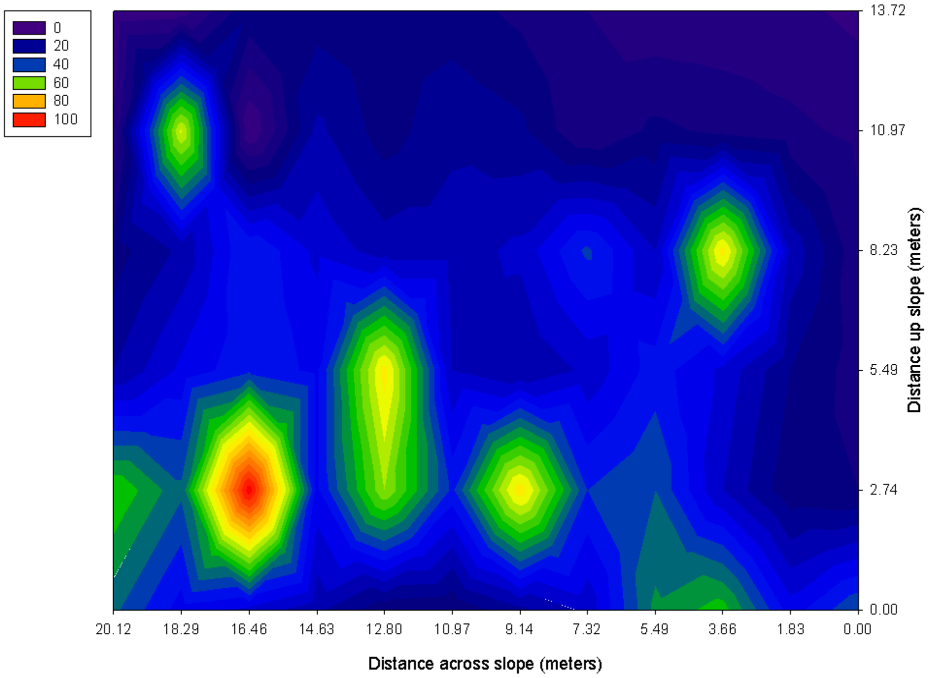


Figure A-14: Graph shows the rainfall distribution across the contributing area for post-simulation 4 (July 10, 2008) run 3.

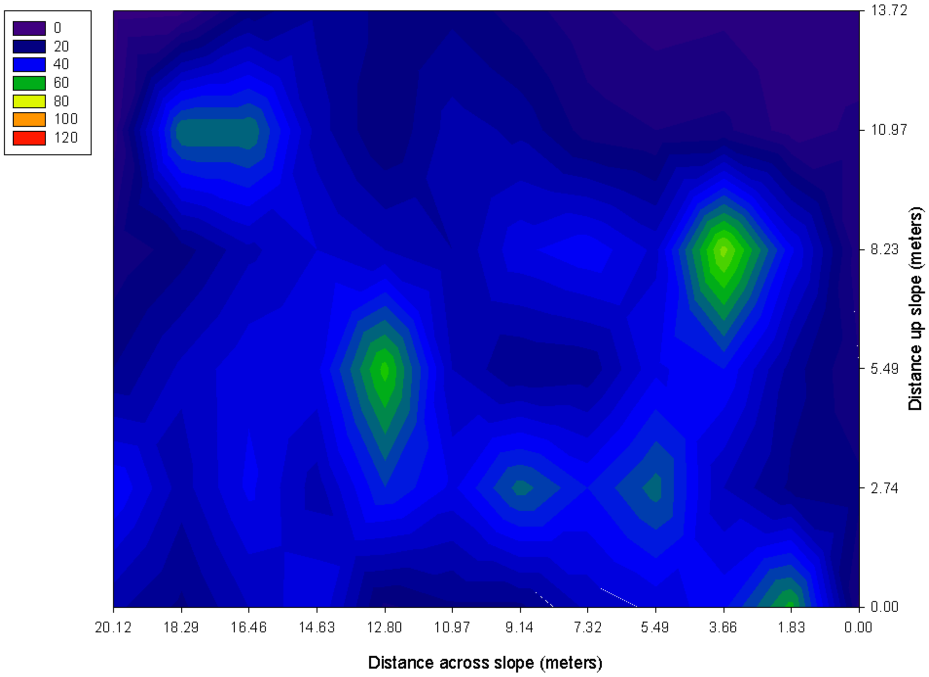
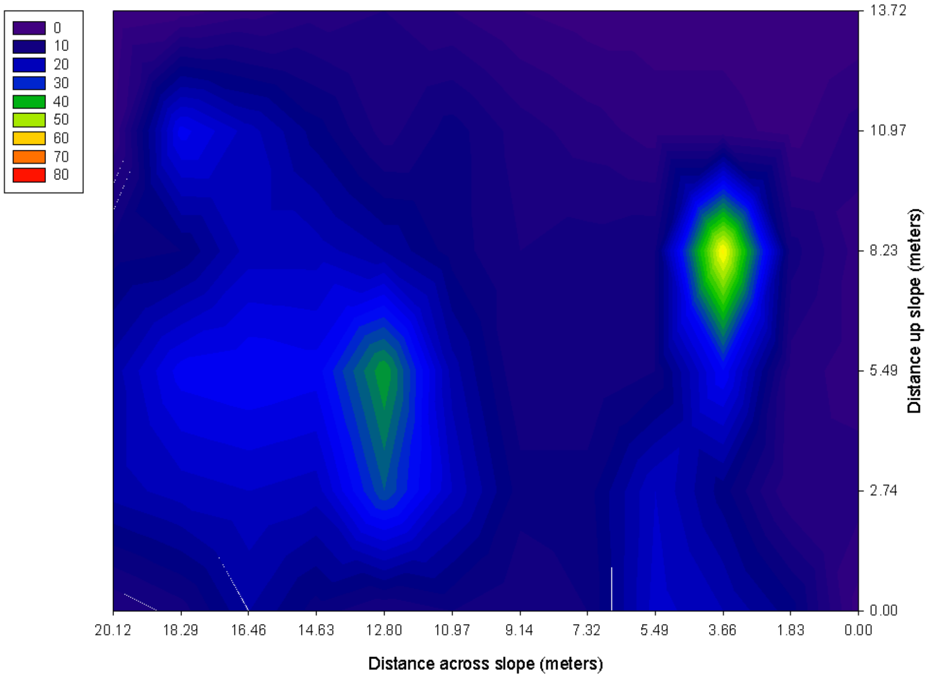


Figure A-15: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 5 (July 29, 2008) run 1.



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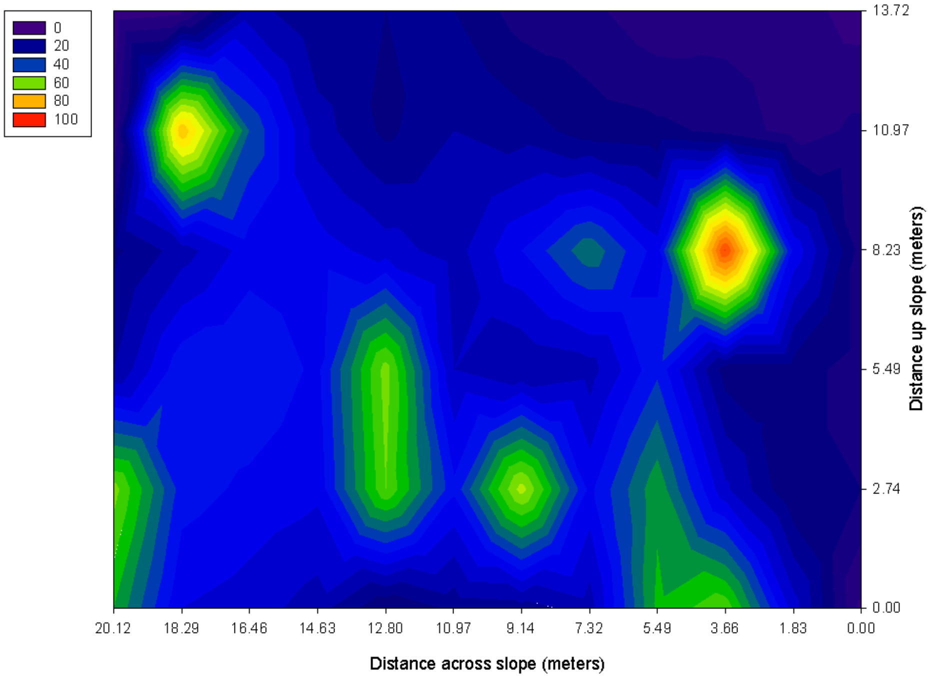

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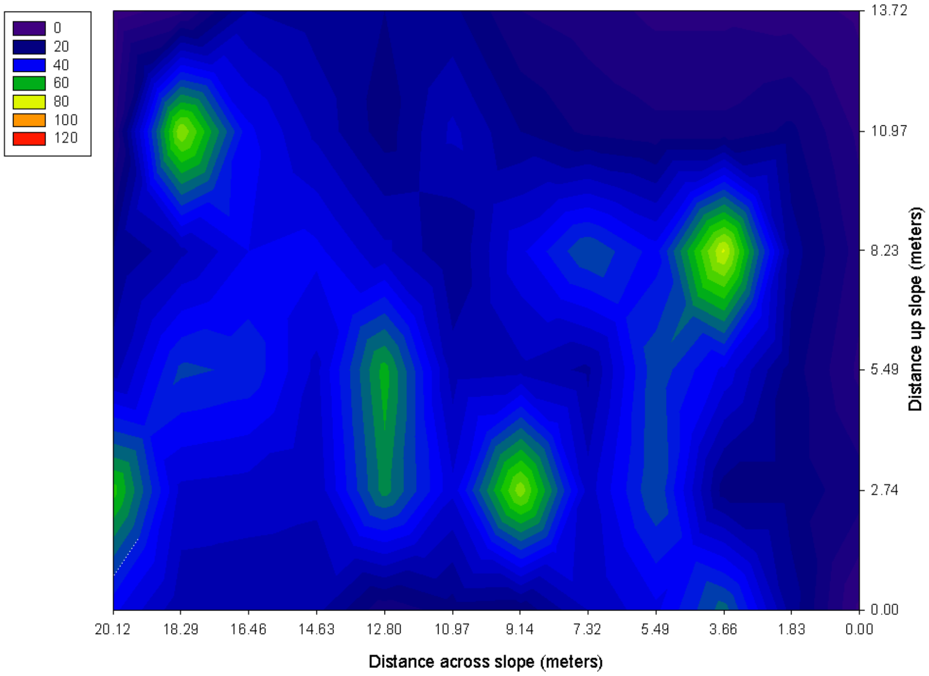


Figure A-18: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 6 (July 30, 2008) run 1.

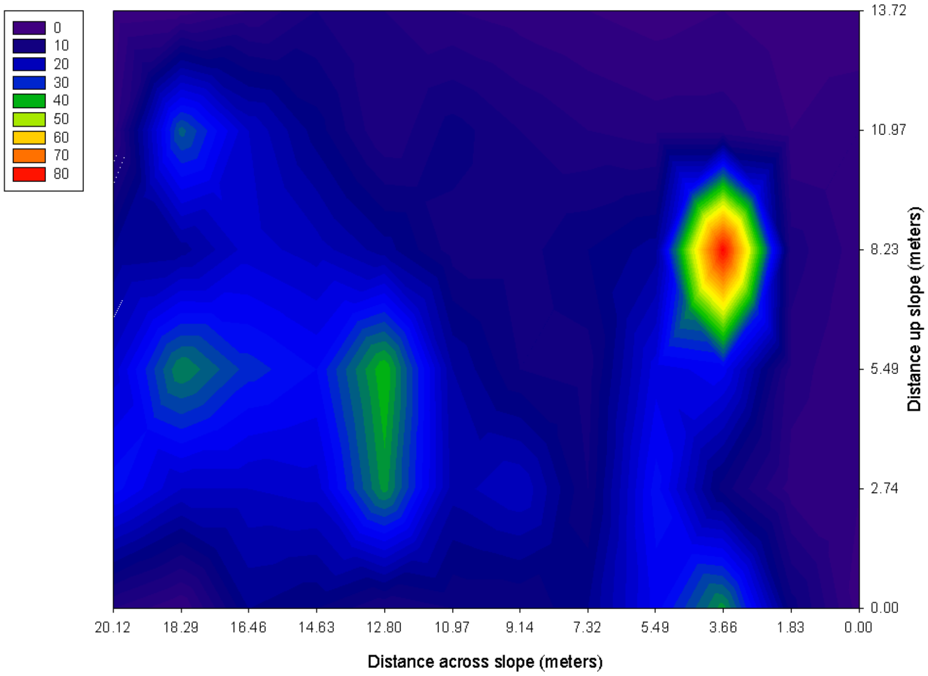


Figure A-19: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 6 (July 30, 2008) run 2.

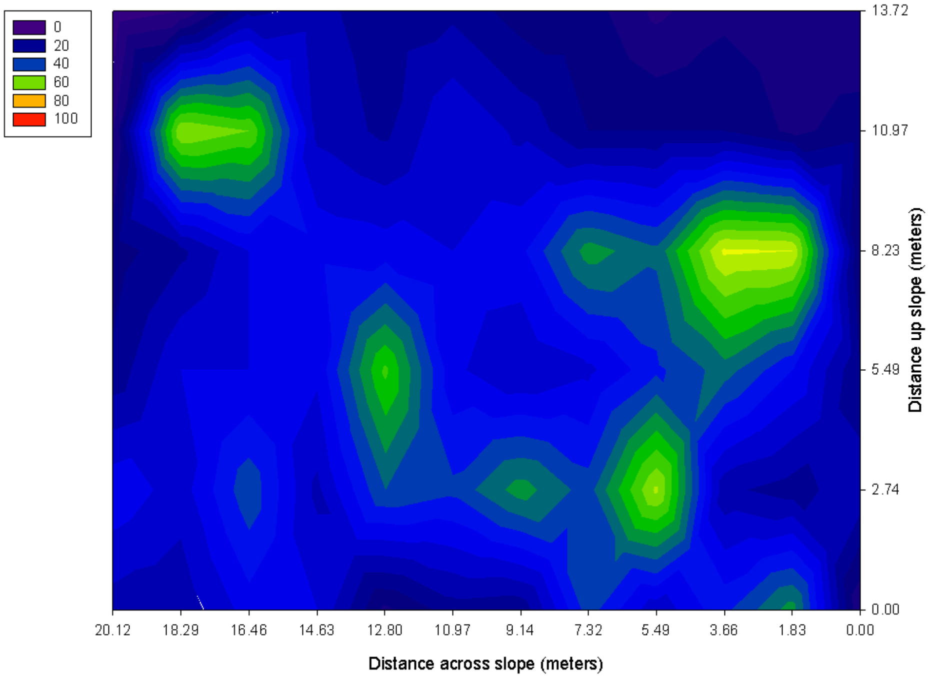


Figure A-20: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 6 (July 30, 2008) run 3.

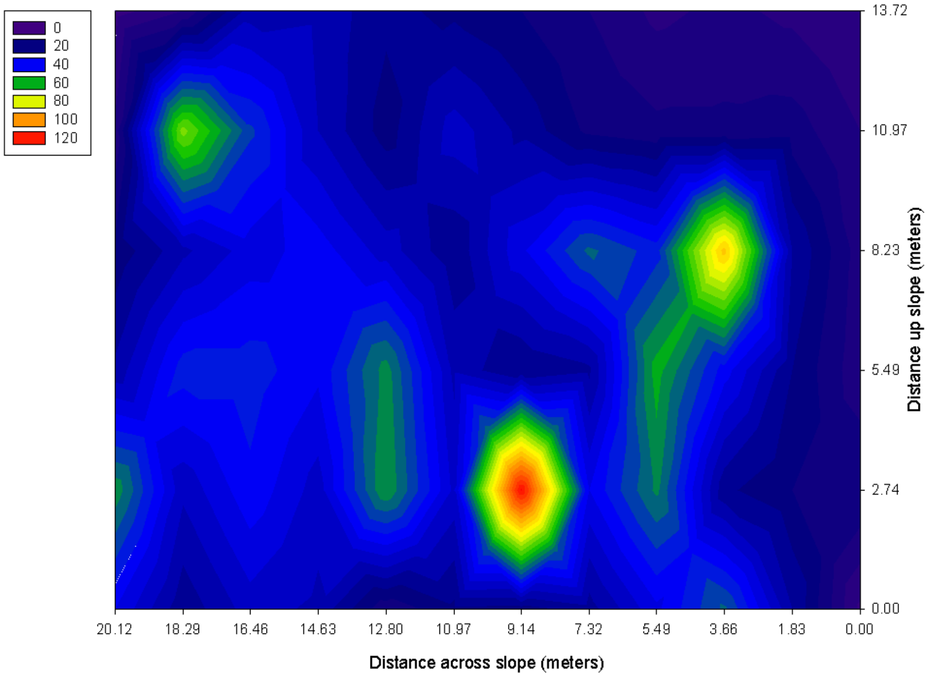


Figure A-21: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 7 (July 31, 2008) run 1.

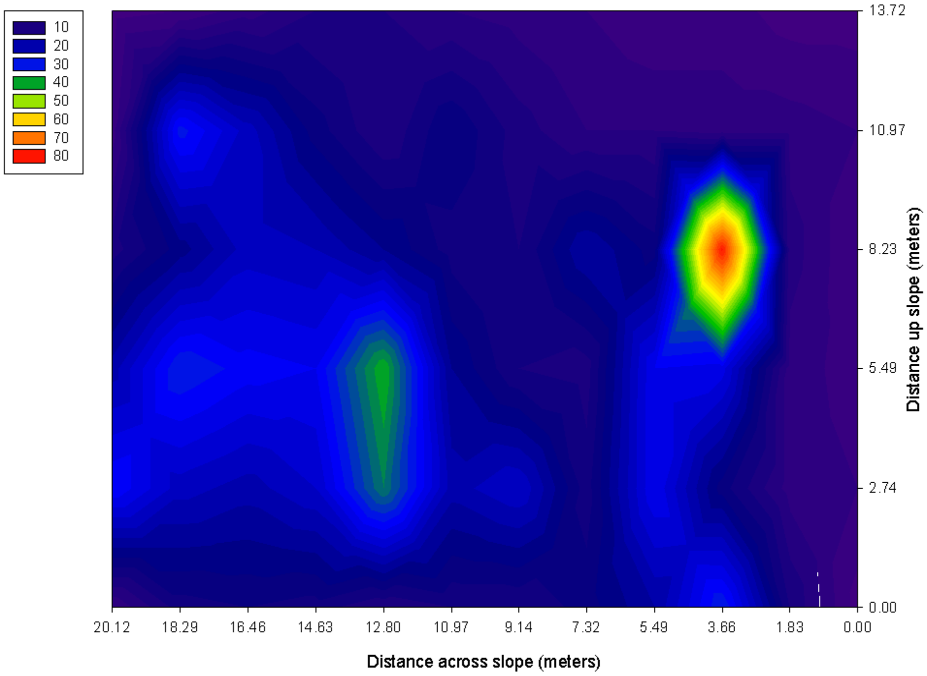
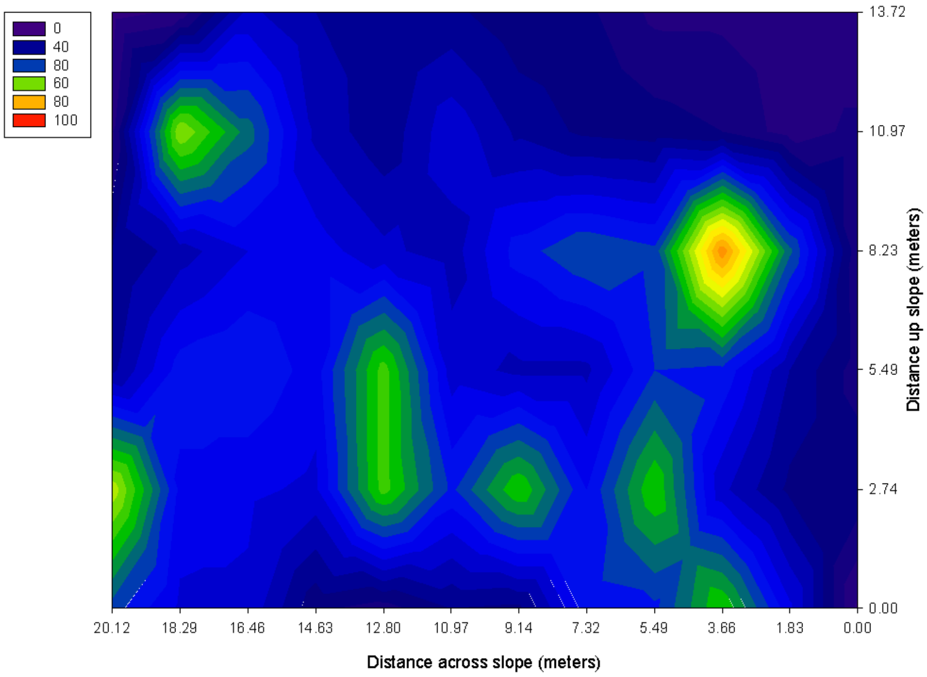


Figure A-22: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 7 (July 31, 2008) run 2.



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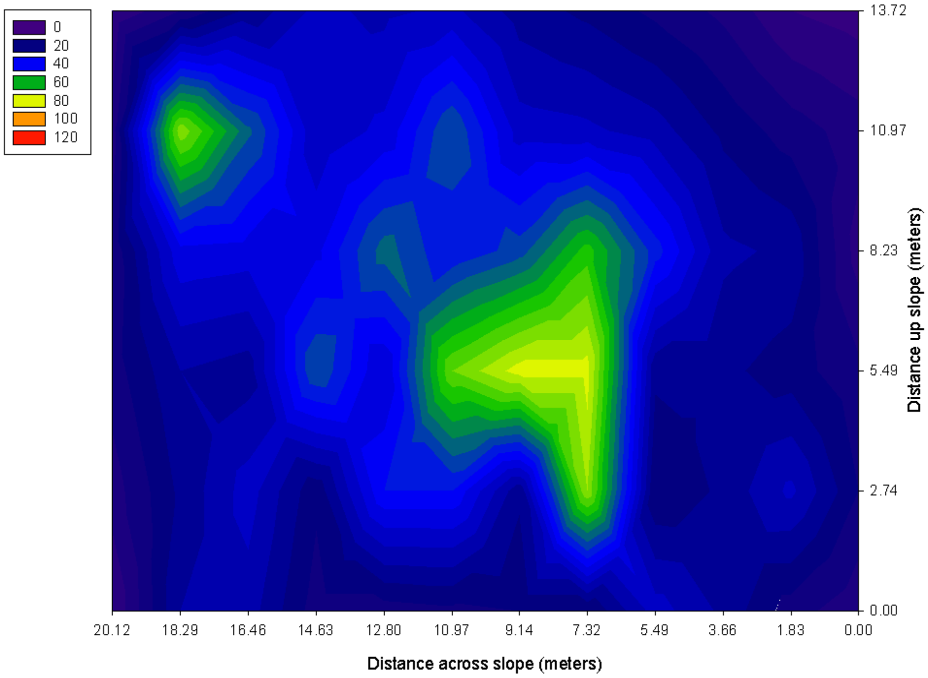

Figure A-24: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 8 (June 3, 2009) run 1.

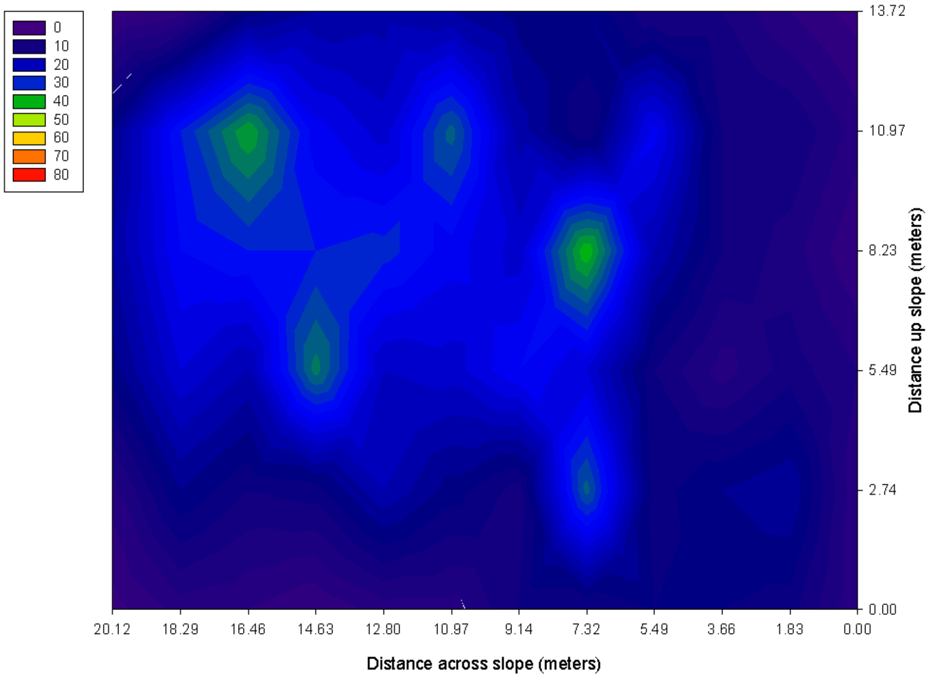

Figure A-25: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 8 (June 3, 2009) run 2.

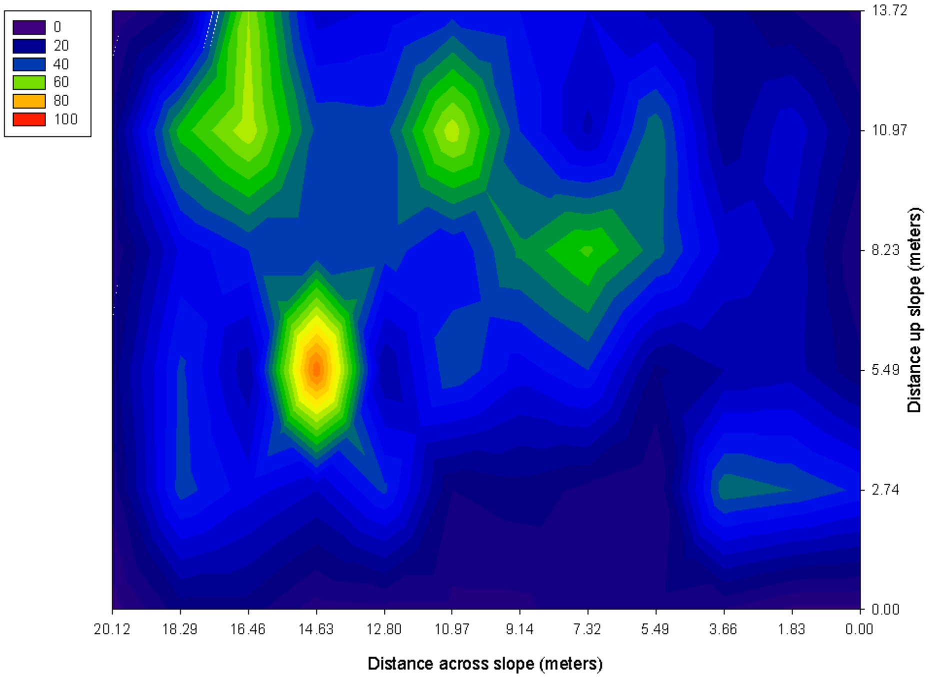

Figure A-26: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 8 (June 3, 2009) run 3.

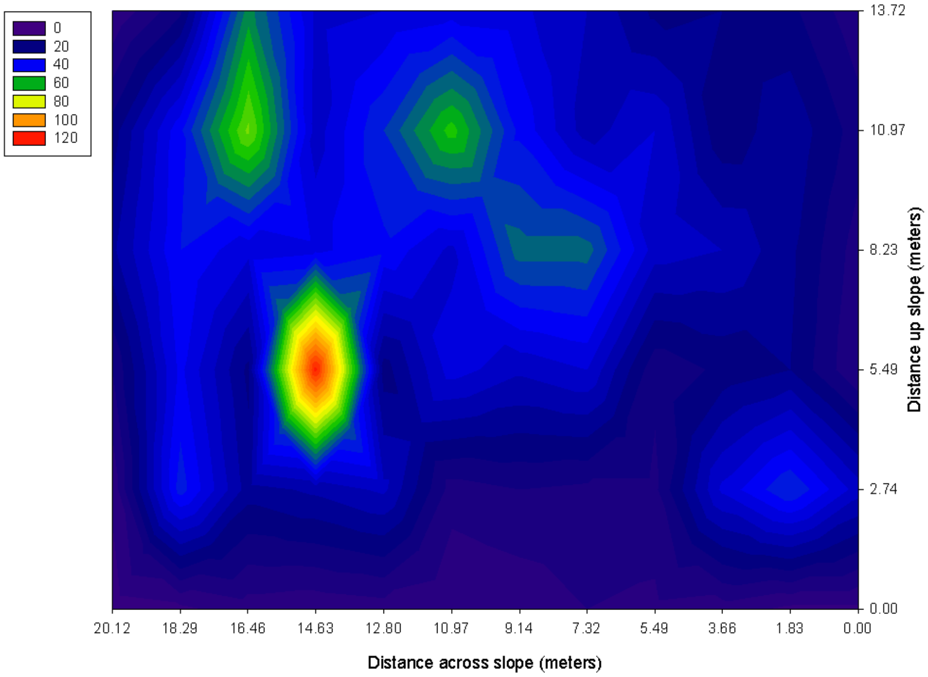

Figure A-27: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 9 (June 4, 2009) run 1.

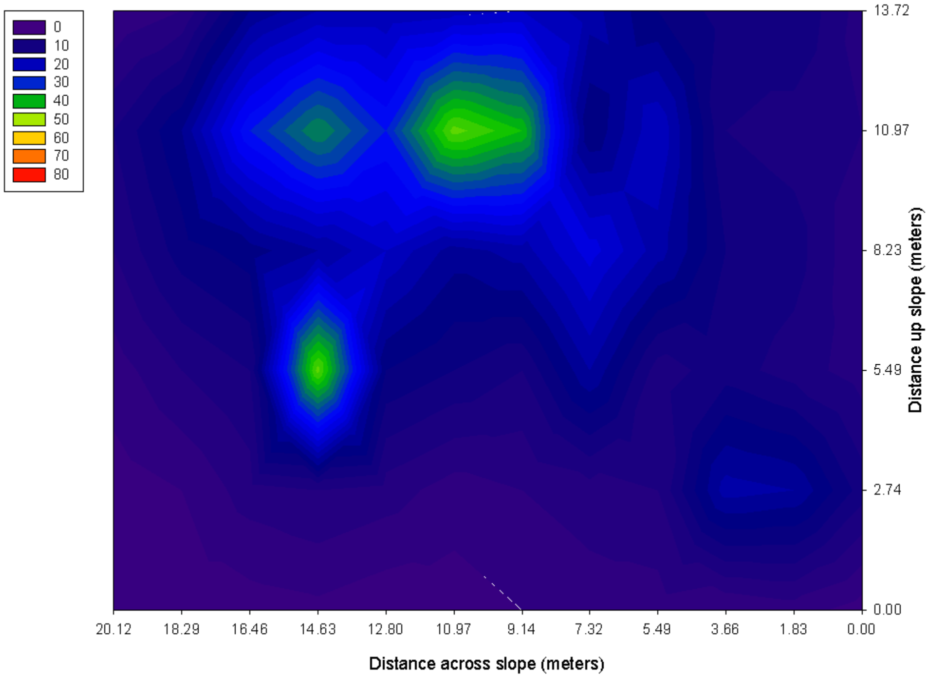

Figure A-28: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 9 (June 4, 2009) run 2.

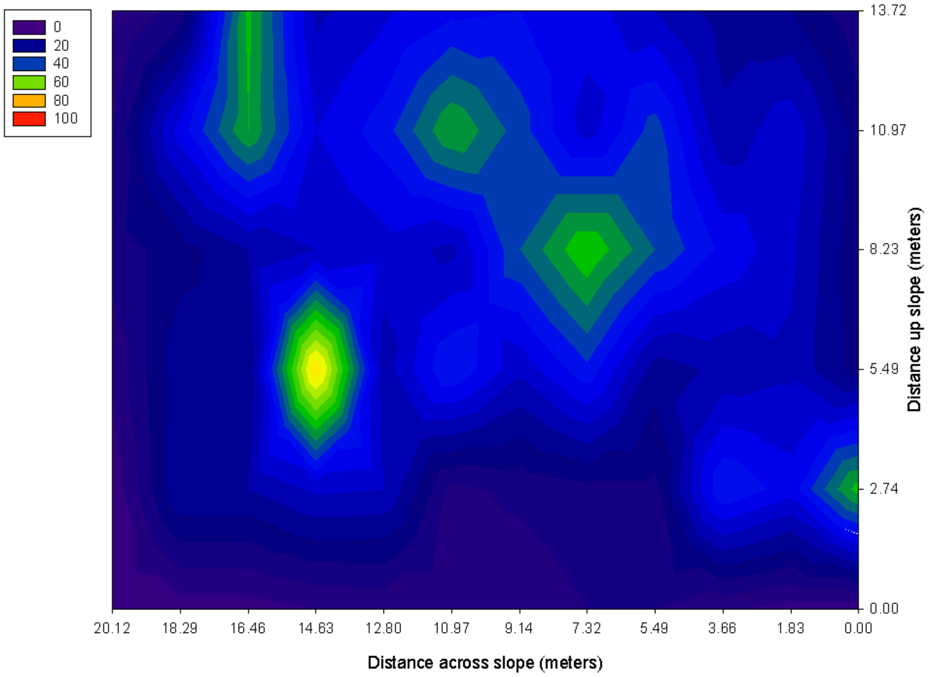

Figure A-29: Graph shows the rainfall distribution across the contributing area for post-treatment simulation 9 (June 4, 2009) run 3.

APPENDIX B

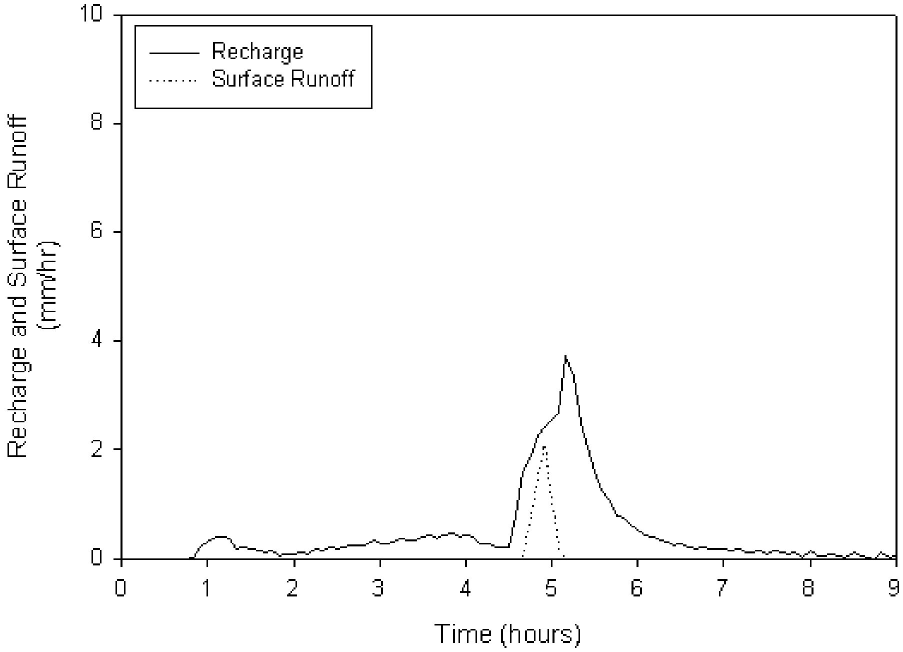

Figure B-30: Hydrograph of pre-treatment simulation conducted on July 13, 2005.

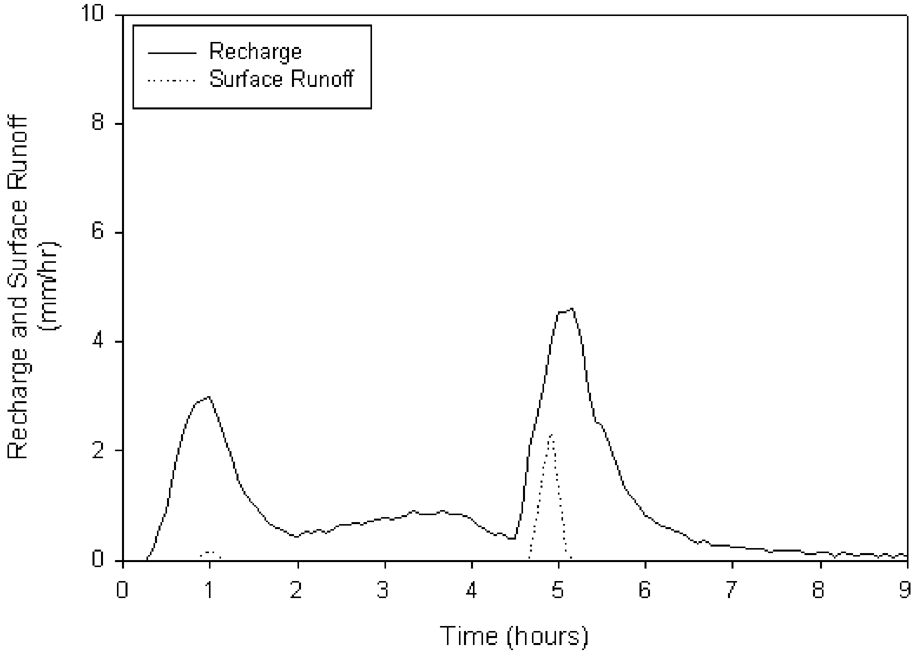

Figure B-31: Hydrograph of pre-treatment simulation conducted on July 14, 2005.

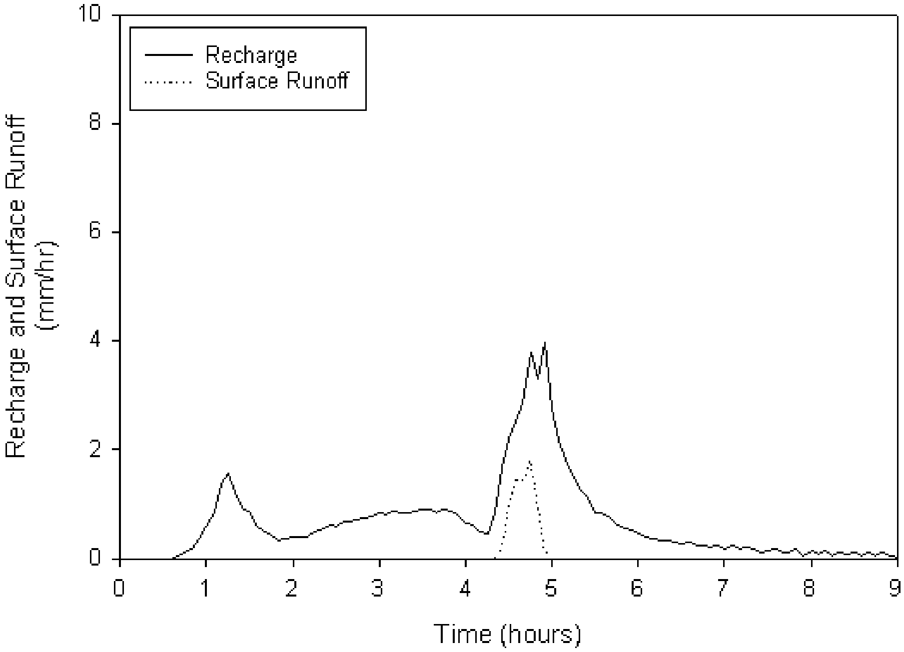

Figure B-32: Hydrograph of pre-treatment simulation conducted on July 28, 2005.

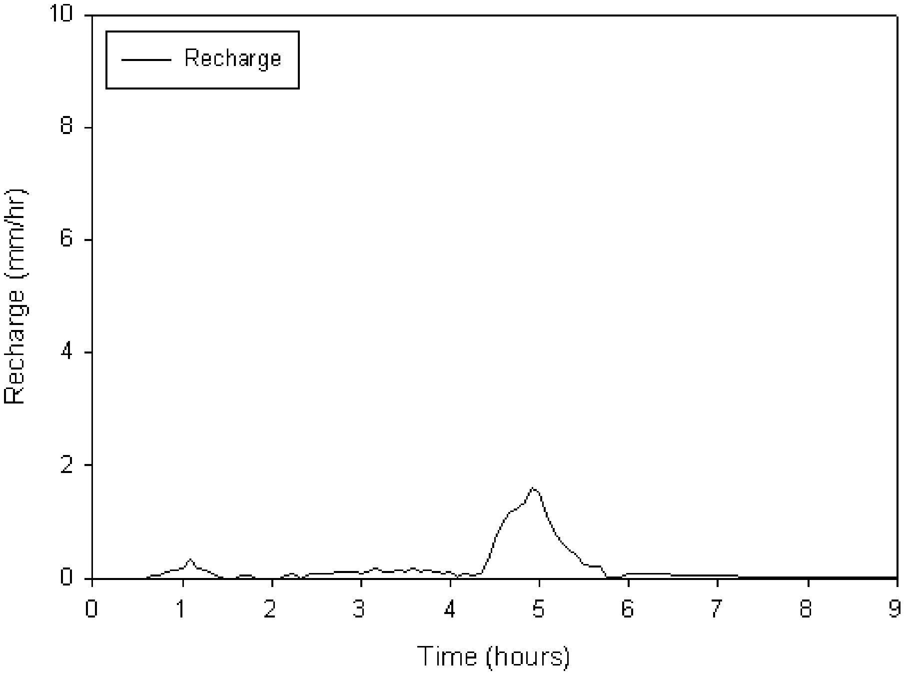

Figure B-33: Hydrograph of post-treatment simulation 1 conducted on June 12, 2008.

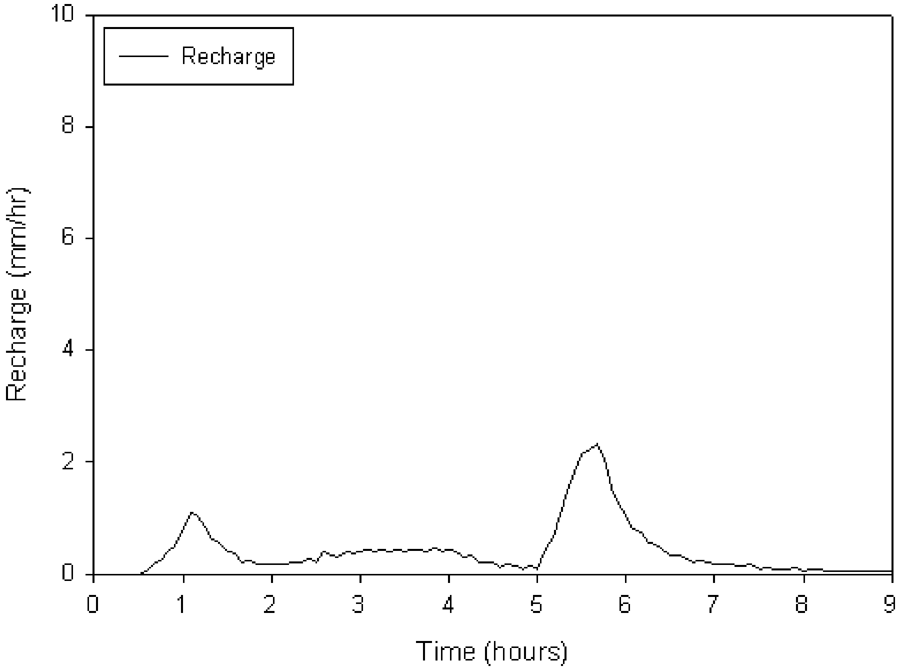

Figure B-34: Hydrograph of post-treatment simulation 2 conducted on June 18, 2008.

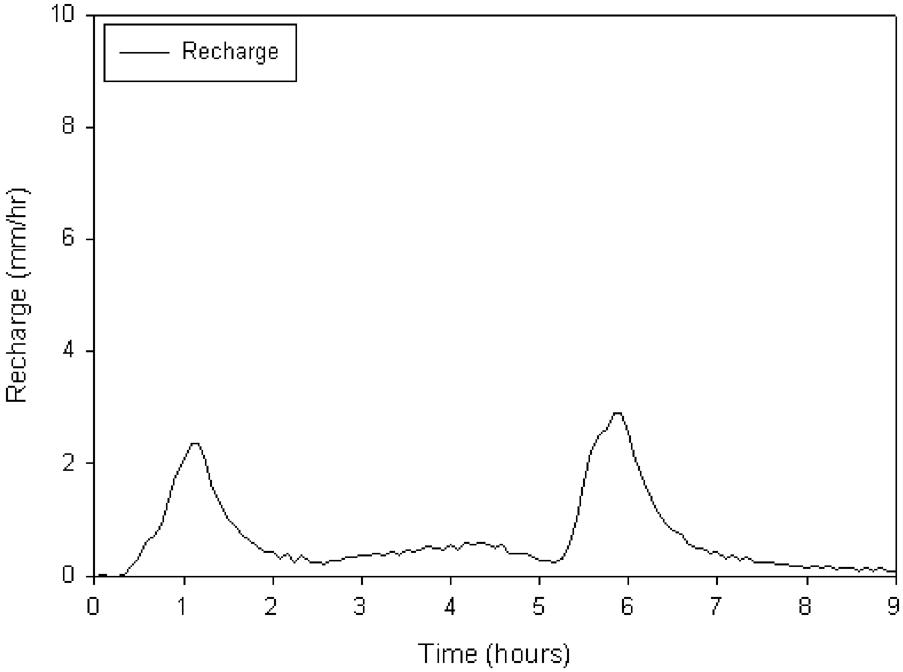

Figure B-35: Hydrograph of post-treatment simulation 3 conducted on June 19, 2008.

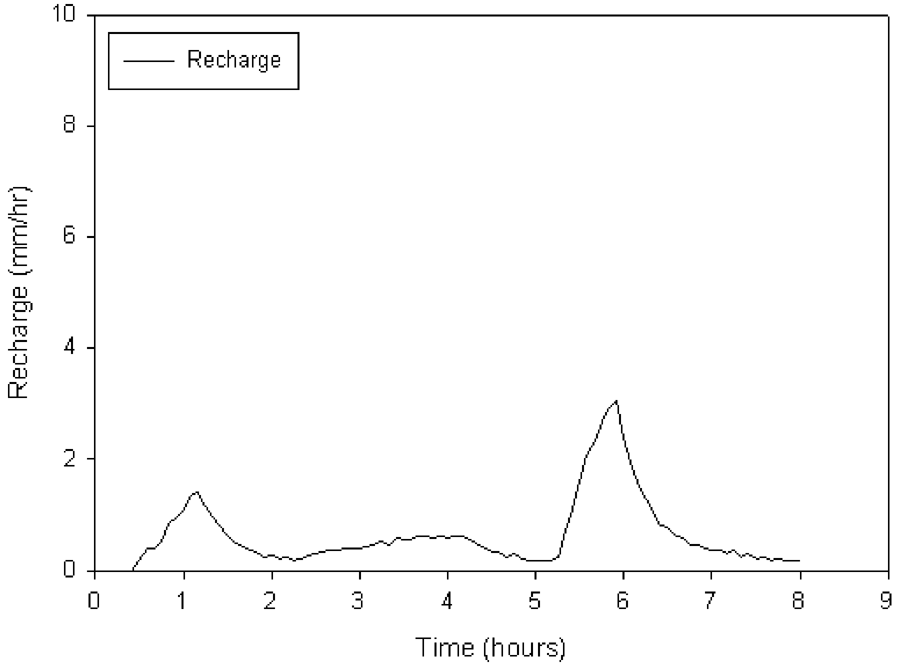

Figure B-36: Hydrograph of post-treatment simulation 4 conducted on July 10, 2008.

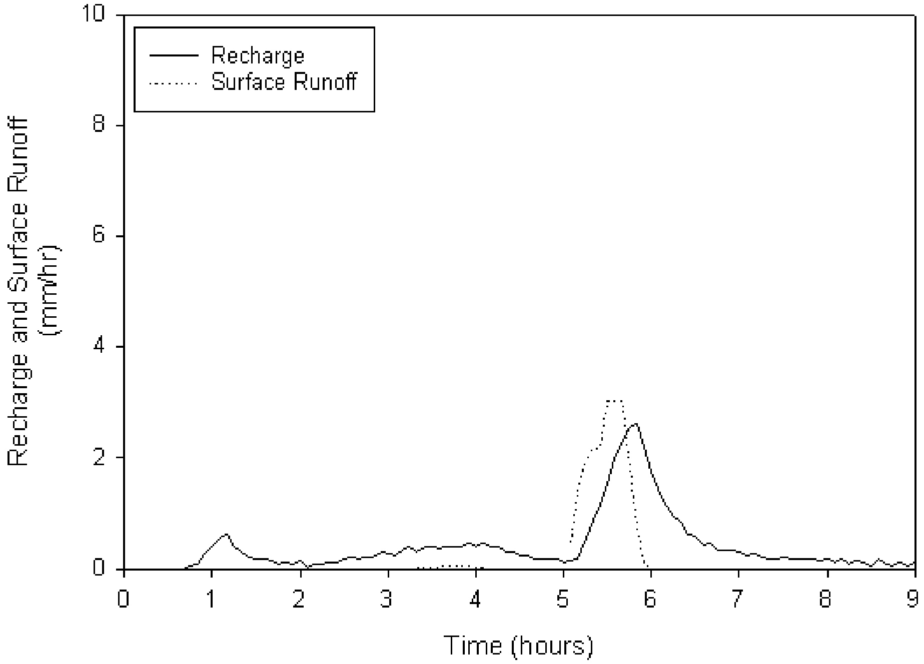

Figure B-37: Hydrograph of post-treatment simulation 5 conducted on July 29, 2008.

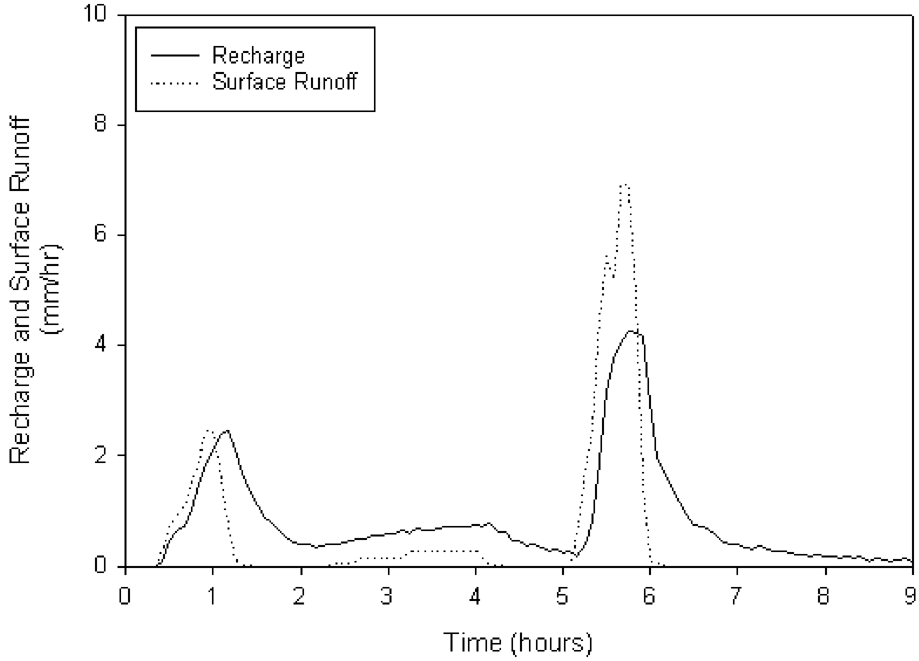

Figure B-38: Hydrograph of post-treatment simulation 6 conducted on July 30, 2008.

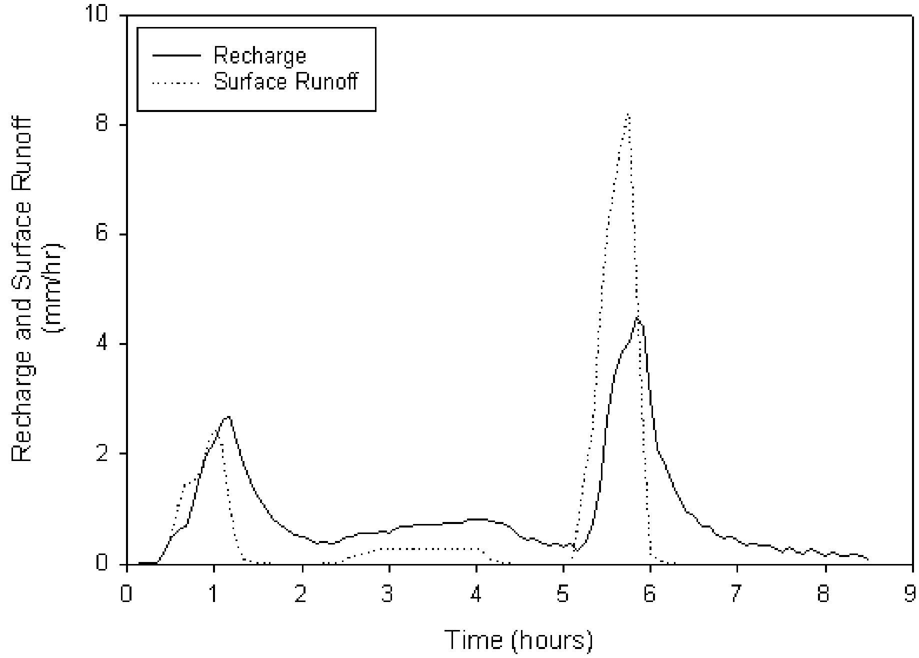

Figure B-39: Hydrograph of post-treatment simulation 7 conducted on July 31, 2008.

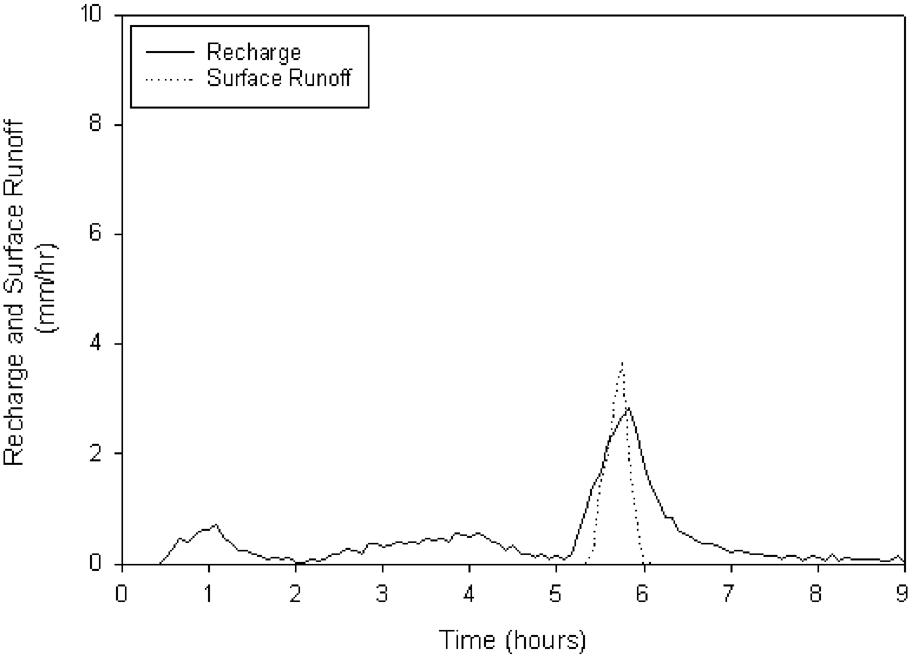

Figure B-40: Hydrograph of post-treatment simulation 8 conducted on June 3, 2009.

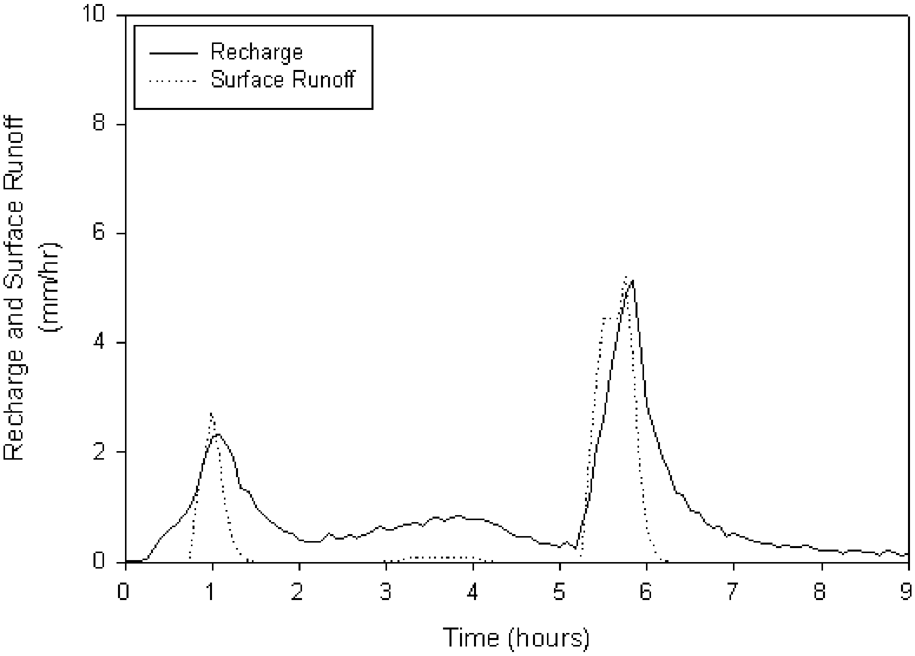

Figure B-41: Hydrograph of post-treatment simulation 9 conducted on June 4, 2009.

VITA

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