THE ECOHYDROLOGICAL IMPLICATIONS OF A RESTORED RANGELAND IN CENTRAL TEXAS

A Senior Scholars Thesis

by

PATRICK SCOTT HALEY

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

May 2012

Major: Ecological Restoration

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Approved by:

Research Advisor: Bradford Wilcox
Associate Director, Honors and Undergraduate Research: Duncan MacKenzie

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ABSTRACT

The Ecohydrological Implications of a Restored Rangeland in Central Texas.
(May 2012)

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Military training lands are among the most degraded rangelands in the United States. Tracked vehicle training represents the largest source of soil disturbance on these rangelands (Fang et al. 2002). Training activities facilitate changes in vegetation composition towards alternate floral communities characteristic of highly disturbed soils (Johnson 1982). The Department of Defense (DoD) manages the land to mitigate disturbance, however the effectiveness of their mitigation and restoration strategies are not well known. Furthermore, the long-term effects of intensive training activities on the ecohydrology of the landscape are not well understood.

This study uses large-scale rainfall simulation to develop an understanding of the dynamic relationships between rainfall, runoff, and erosion. Simulations were conducted on two areas of interest: (1) a degraded grassland that underwent a conversion to a mesquite woodland and was restored via mechanical brush removal and (2) a highly degraded hillslope will little to no topsoil. Data suggests that: (1) runoff is rapid when no topsoil or vegetation is present; (2) runoff velocity is significantly lower after restoration, and (3) sediment loads do not move across the landscape in large flushes following restoration.

ACKNOWLEDGMENTS

The author wishes to gratefully acknowledge Dr. Bradford Wilcox who encouraged me to challenge myself and get the most of my undergraduate degree by giving me the opportunity to join his research team. I also would like to acknowledge Dr. Steven G. Whisenant who has mentored me throughout my college career. Thanks go out to everyone who has provided me with guidance and assistance throughout the course of this project: Dr. Clyde Munster, Jordan “Soggy Shoes” Grier, Jason McAlister, Dr. Bill Fox, Maxwell Lukenbach, Matthew Berg, Steven Potter, Peter “Min-Cheng” Tu, and the Department of Ecosystem Science & Management.

Personal thanks go out to my mother and father, Clark and Michelle Haley, who offered the moral and financial support throughout my college career and especially my loving girlfriend, Heather Michelle Medina, who was always there to embrace me after those long nights of analyzing data and writing countless rough drafts for this thesis. I would also like to express my gratitude toward the nighttime custodian, Maria, who would occasional check on me late at night to make sure I was still breathing.

NOMENCLATURE

BMP	Best Management Practice
DEP	Defense Environmental Programs
DoD	Department of Defense
Q	Runoff
Q_t	Runoff Start Time
SSC	Suspended-Sediment Concentration
TSS	Total Suspended Solids

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CHAPTER I

INTRODUCTION

Military training exercises are frequently conducted on land maintained by the Department of Defense (DoD) throughout the United States. They are crucial for the development of new weapons systems and maintaining combat readiness of the armed forces. It is for these reasons that training exercises are conducted at the absolute highest quality possible. These exercises must recreate real-world scenarios in natural environments that resemble the terrain of the battlefield. However, these activities increase the rate of erosion by changing the structure of soil, microtopographical attributes, and vegetative cover (Fang et al. 2002). A paradox exists between the costs and benefits of training activities. Though these activities are necessary for national security, they are dependent on the ecological sustainability of natural resources (i.e. soil erosion, water quantity, water quality, vegetation management, etc.) and their subsequent recovery to facilitate high quality military training activities. The degree of degradation can damage equipment, delay training, and cause offsite water quality problems for communities surround military training lands. Consequently the DoD is faced with the dilemma of maintaining combat readiness while simultaneously managing the land so that training activities can be safely carried out with minimal offsite degradation.

This thesis follows the style of *Restoration Ecology*.

The DoD manages approximately 11.7 million hectares of wetlands, grasslands, scrublands, and forests across the United States. Historically less emphasis was placed on sustaining natural resources, however contemporary DoD policy recognizes their importance in facilitating high quality training missions. The DoD manages the intensity, frequency, and timing of training activities to mitigate for degradation, however a significant amount of money is spent on reactive ecological restoration. In 2010 alone the DoD spent $1.6 billion, or 36% of the Defense Environmental Programs budget, on restoration projects (DEP 2011).

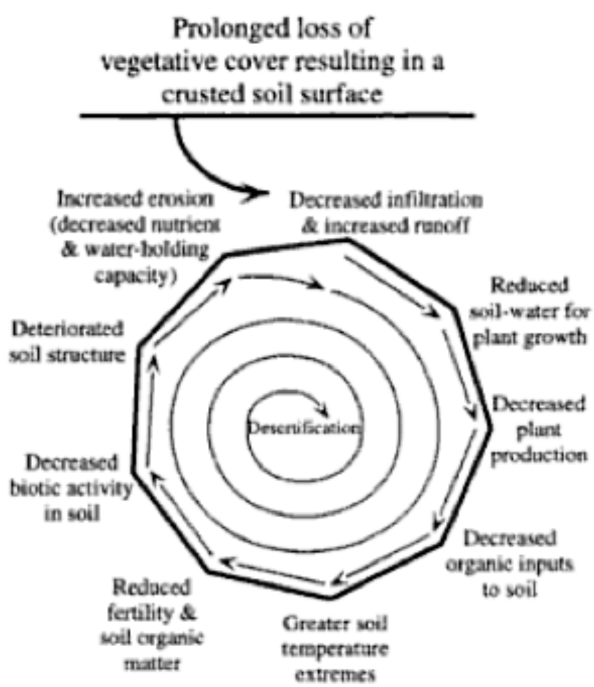

Figure 1. Positive feedback cycle of soil degradation where prolonged loss of vegetative cover leads to a downward spiral of increased magnitude towards greater degrees of erosion (Whisenant 1999).

Soil degradation is a cycle initiated by positive feedbacks where prolonged disturbance increases in magnitude over relatively short temporal scales having substantial ecohydrological implications on ecosystem functions and processes (Figure 1). Tracked vehicles are the main sources of disturbance on military training lands (Fang et al. 2002). This is no exception at Fort Hood where there are more than 55,000 ha of maneuver area and 25,500 ha of live fire area (Texas Military Preparedness Commission 2008). In this semiarid grassland located in the Blackland Prairie ecoregion of Texas, tracked vehicles have resulted in resulted in a reduction in plant cover and have significantly increased soil erosion (Anderson et al. 2005a, Johnson 1982). These training areas are managed and rotated for several years to allow for natural recovery. However, the climax grassland vegetative communities have crossed ecological thresholds into alternate stable states such as degraded hillslopes almost completely void of vegetation and topsoil, and mesquite (*Prosopis glandulosa*) woodlands so dense that they no longer resemble battlefield conditions. Furthermore the erosion of these training lands has led to the formation of wide gullies that damage vehicles and are expensive to fill. As these training areas approach the end of their recovery periods the DoD is finding that they still cannot be used and must be subject to expensive mechanical treatments and further recovery before training can be resumed.

The degree of impact and the subsequent recovery is dependent on vegetation type, soil texture, soil moisture during the time of impact, and climactic conditions during recovery (Thurow et al. 1993). The DoD wants to preserve the training areas of at Fort

Hood, the largest military installation in the United States, and minimize the amount of sediment transported by runoff through the Cowhouse Creek watershed to nearby Belton Lake. However, no general consensus currently exists on which management practices best mitigate for erosion. First, the relationship between disturbance from training activities and soil erosion needs to be estimated in order to control erosion (Fang et al. 2007).

Rainfall simulation has been used to measure various aspects of ecohydrology–the multidisciplinary spaciotemporal linkages between the hydrological and ecologic dynamics of the environment (Rodriguez-Iturbe 2000). Rainfall simulation is a scientific tool that is used to recreate natural rainfall events at a selected location with a controlled quantity and intensity of precipitation. Its use in ecohydrological studies has been well documented over the past 30 years. Simulations have been conducted at scales as small as 0.24 m^2 (Cerda et al. 1997) and hundreds of square meters (Menard 1985). Early rainfall simulations utilized a capillary drip system and were conducted at scales usually not exceeding 1 m^2 with a single application rate. Stone & Paige (2003) note several problems associated with single application rates in rainfall simulation studies: (1) they do not ensure that the entire plot is contributing to runoff; (2) they may lead to misinterpretations of results; and (3) they may lead to the misidentification of relationships between hydrologic variables and plot characteristics. It is important to note that a tradeoff between rainfall simulator size and associated technical constraints exists (Esteves et al. 2000). It is for these reasons that no universal rainfall simulator applicable to all situations though large-scale simulators seek to achieve similar rainfall and operational characteristics (Table 1).

In this study the large-scale above canopy rainfall simulator described by Munster et al. (2006) was used to explore the relationships between erosion and runoff dynamics on lands that have been degraded military training exercises. The methodology was to simulate rainfall on plots 7 X 14 m in size at two different sites. One site was a disturbed grassland that was converted to a mesquite woodland during the recovery period and was subject to mechanical brush removal. The second site was a degraded hillslope with little vegetation and almost no topsoil.

Specific objectives were to:

1. Determine the amount of time and intensity of rainfall required to generate runoff.
2. Calculate the percentage of rainfall exiting the plots as runoff.
3. Analyze the sediment load suspended in runoff at various points during the course of runoff.

Table 1. Rainfall and operational characteristics important for rainfall simulation (Tossell et al. 1987).

Rainfall Simulator Characteristics
1. Drop-size distribution similar to natural rainfall given comparable rainfall intensities.
2. Drop impact velocity approximating terminal velocity of natural raindrops.
3. Rainfall intensity representing the geographical region where studies are to be conducted.
4. Uniform rainfall over the study area.
5. Energy characteristics corresponding to natural rainfall for comparable intensities.
6. Rainfall intensity continuous over the storm event.
7. Storm pattern reproduction.
8. Sufficient area of coverage.
9. Drop impact angle near vertical.
10. Site to site portability.

CHAPTER II

METHODS

Study area

Fort Hood is located in central Texas in Bell and Coryell counties approximately 97 km north of Austin and 80 km south of Waco. At 881 km^2, this massive military installation is the largest active duty armored post in the United States Armed Services. Fort Hood lies within the Texas Blackland Prairie ecoregion, which historically encompassed 43,000 km^2 and stretched from Dallas/Fort Worth to parts of Northern Austin and San Antonio. The region is characterized by a wide precipitation gradient with the cooler months being the most abundant in moisture and the hotter summer months the driest. Soil varies across the landscape and can quickly transition from deep alluvial clays to infertile islands of bare ground and exposed bedrock.

Figure 2. Location of Fort Hood and study plots. *Left* is the mesquite plot before restoration. *Right* is the degraded hillslope.

Rainfall was simulated at two study sites located within the Cowhouse Creek watershed (Figure 2): the “mesquite plot” (31°14'52"N 97°52'7"W) and the “degraded hillslope” (31°15'88"N 97°52'28"W). The study areas were located several kilometers inside the western entrance of Fort Hood off Farm Market Rd 116 Antelope Rd. The region has a mean annual temperature of 900 mm and receives most of its rainfall in the spring and fall. Monthly rainfall ranges from 115 mm in May to less than 50 mm in July. On average 11 days per year receive more than 25 mm of precipitation (Harmel et al. 2003). This region is historically a southern extension tall grass prairie with a savannah complex of scattered oaks but primarily dominated by perennial grasses. Under climax conditions the predominate woody vegetation consisted of ashe juniper (*Juniperus ashei*) and various oak species (*Quercus sp.*). Herbaceous vegetation consisted of little bluestem (*Schizachyrium scoparium*) and indian grass (*Sorghastrum nutans*) (Anderson et al. 2005). The Blackland Prairie was formed by low to moderately intense wildfire, both naturally caused and manmade. Their frequent return interval of 1-5 years stimulated the growth of herbaceous forbs and grasses and eliminated woody species (Collins & Gibson 1990).

The study sites where simulations were conducted are less than half a kilometer from one another yet they vary markedly in soil geomorphology. Referring to the Soil Conservation Service’s Soil Survey of Bell County (Huckabee et al. 1977), the soils that characterize the mesquite and degraded sites are of the Lewisville and Real series respectively. The Lewisville series are dark brown clayey soils formed in alluvium. They are common of landscapes that are nearly level to gently sloping. They classified as well drained with moderate permeability and a high water holding capacity. The A horizon–the organic surface horizon–is deep extending to about 46 cm. The clayey soils have a high shrink/swell potential. During dry conditions deep cracks form on the surface, which water rapidly permeates, but under saturated soil conditions the cracks close and water moves very slowly through the soil. The soils of the Real series that characterize the degraded site are shallow and gravelly formed from weathered limestone. They are well drained and moderately permeable, but are known to have a very low water holding capacity. Bedrock is usually reached in less than 38 cm.

A large scale above canopy rainfall simulator was used on two rectangular 7 X 14 m plots of two training areas for tracked vehicles. The study sites were subject to heavy vehicle traffic as well as heavy grazing pressure for a number of years before all training was ceased approximately five years before simulations began to allow for natural recovery. Deferment has had mixed success, but recovery has taken an unintended trajectory crossing ecological thresholds. Both sites have undergone a conversion from a mixed grassland prairie to alternate stable states not capable of satisfying the training requirements of the Department of Defense. The mesquite plot has been rescheduled for training purposes but was converted to a dense thicket of three-meter tall mesquite trees with an understory of cool season perennial forbs and grasses. The degraded hill slope is just that, an almost barren sloping wasteland with 60 percent bareground and rock. The remaining 40 percent being a mixture of live plant and litter. This paradigm shift in species composition is a characteristic of habitats where the soil is frequently disturbed (Johnson 1982). The two sites represent two degrees of degradation and were selected based on their designation for ecological restoration. Rainfall was simulated seven times above the canopy of the mesquite plot in October of 2010 at various durations and application rates. The percentage and type of ground cover was determined using the basal point method to sample 105 data points in the research plot along five, seven meter long transects distanced 1.5 meters from each other the ran along the width of the plot. One year later the mesquite plot was mechanically treated with a mechanical grubber–a high impact machine that rips trees out of the ground by their roots–and then run over with an I-beam to even out and compact the disturbed soil. The study site was not reseeded and all regeneration was from the seed bank before the second series of three simulations were conducted in February of 2012. The dominant basal cover types were recorded again for comparison for the mesquite site post treatment. At the time of writing there are currently no plans for the degraded hill slope however basal cover percentages were determined and three simulations were also run.

Rainfall simulation

A portable large-scale rainfall simulator was used to simulate rainfall at varying intensities above the canopy of the mesquite plot and before and after brush removal and on the degraded hillslope. The rainfall simulator has six telescoping masts that can be raised to a height of 11 m with a manifold that contains 1-4 pivoting sprinklers heads. The masts were positioned around the perimeters of the 7 X 14 m study plots. The sprinkler head manifolds were raised a height of 4.5 meters to allow the generated precipitation to the reach terminal velocity and the to better simulate natural rainfall. Nelson S3000 Pivot Spinner plate sprinklers were used for their versatility, ability to be reconfigured easily with new nozzle sizes, and their ability to produce droplet sizes comparable to rain. Each sprinkler head sat on a regulator that could easily be removed to control the angle of spray from 180° to 360°. Different nozzle size inserts were used interchangeably to achieve different application rates. Each individual sprinkler head also contained a ball valve that could be switched on and off to help regulate rainfall application.

Instrumentation and hydrologic measurements

The amount and distribution of rainfall applied during each simulation was measured by a matrix of 140 mm rain gauges arranged in a grid pattern of 1 m intervals. The depth of the gauges were recorded and emptied after each trial so that the spatial distribution of precipitation could be visualized (Figures 4-16). An aluminum barrier was constructed around the perimeter of each plot to contain runoff so that it could be measured. The level and flow of runoff were determined by positioning a flume at the lowest point of each plot. On the mesquite plot the flume was positioned at the northeast corner and at the degraded hillslope the flume was positioned at the center of the eastern edge of the perimeter downslope. An H-Flume with a 15.25 cm (6-inch) throat width was used during the pretreatment mesquite plot simulations as well as the degraded hillslope simulations. A Parshall Flume with a 5.08 cm (2-inch) head was used for the mesquite plot post treatment. The depth of the flume was recorded automatically using two ISCO model 3200-bubble flow meters. The depth levels were then converted to flow using a known relationship between depth level and the volume of runoff. Manual measurements of the depth level were also taken every 2-3 minutes as a precaution. This was done after the simulation had stopped until runoff no longer occurred. 100 ml water samples were collected simultaneously with manual flume level readings at least once every five minutes until runoff ended. The water samples were labeled according to their trial number and the minute into the simulation they were collected. They were then filtered through a 1 micro filter, dried, and weighed to give the sediment concentration in ppm suspended in the water column at the given time.

Rainfall simulation on the mesquite before restoration

The first series of simulations were conducted at the mesquite site on October 15-17, 2010. During these simulations an H-shaped manifold with 4 sprinkler heads was used, though two nozzles at most were in use per manifold. All heads were mounted on a regulator that confined the precipitation to spray 180° so as to contain as much water as possible on the plot. Nelson S3000 3TN 25 nozzle inserts, rated at 0.8767 m^3 hr^{-1} at 1.0 BAR, were used for all seven simulations. Wind was minimal throughout the course of these simulations and never exceeded 5 mph. The target intensities were one, 60-minute high intensity simulation, three 30 minute moderate intensity simulations, and three 45 minute low intensity simulations. The first simulation ran with two nozzles open per manifold for 60 minutes achieved and intensity of 99 mm hr^{-1}. The goal of this trial was to set a baseline of which to compare subsequent simulations by saturating the soil. The second simulation was conducted with one nozzle open per manifold for 47 minutes after runoff ended from trial one. This low intensity rainfall event produced 35 mm hr^{-1}. The third simulation was conducted the following day with two nozzles open per manifold for 30 minutes producing a 71 mm hr^{-1} rainfall event. The fourth simulation was conducted with one nozzle open per manifold for 45 minutes after runoff from trial three was no longer visible. Produced a low intensity, 28 mm hr^{-1} rainfall event. The fifth simulation was purposely started before runoff from trial four had stopped to generate a response curve on the hydrograph and analyze its impact on sediment concentration. It was a moderately intense, 68 mm hr^{-1} rainfall event that was conducted with two nozzles open per manifold for 30 minutes. The sixth simulation was conducted the following day with one nozzle open per manifold for 45 minutes. This event produced a rainfall event with a 41 mm hr^{-1} intensity. The seventh and final simulation of the mesquite site prior to restoration was also started before runoff from the previous trial ended. It was conducted with two nozzles open per manifold for 15.5 minutes with an intensity of 74 mm hr^{-1}. This simulation was originally supposed to last for 30 minutes but the time was cut short due to a shortage of water.

Rainfall simulation on the mesquite plot after restoration

The second series of simulations at the mesquite plot were conducted on February 25-26, 2012. This series took place after the mesquite had been removed through restoration in the exact same 7 X 14 m plot. This series used manifolds with a single sprinkler head as opposed the H-shaped manifolds. Different nozzle insert sizes were used according to the desired application rate. The goal of this series was to simulate a produce a 60-minute low intensity rainfall event to compare with the 60-minute high intensity rainfall event from the pretreatment mesquite plot simulations. The other target intensities were a 25-year storm with an intensity of 85.8 mm hr^{-1} and a 2-year storm with an intensity of 47.3 mm hr^{-1} as specified by the known Rainfall Intensity Duration Frequency Coefficient (IDF Curve) for Coryell County, Texas. Wind posed the greatest problem during this series and was constantly blowing at 15-20 mph with occasional gusts up to 25 mph coming from the east and southeast. Uneven spatial distributed is clearly visible in Figures 11-16. The first trial was conducted for 30 minutes with 3TN 40 nozzle inserts, rated at 0.2462 m^3 hr^{-1} at 1.0 BAR. This simulation produced a rainfall event slightly below the 25-year storm with an application rate equal to 83mm hr^{-1}. The second trial was simulated for 58 minutes using 3TN 18 nozzle inserts, rated at 0.486 m^3 hr^{-1} at 1.0 BAR. This simulation produced desired low intensity storm with an application rate of 20 mm hr^{-1}. The third and final trial of this series was plagued by high gusty winds. The regulators were removed from the two most windward manifolds allowing them to spray at a 360° angle in order to increase the amount of precipitation on that side of the plot as can be seen in. The two manifolds furthest downwind were switched off because the high winds inhibited their contribution to the plot. This trial lasted for 20 minutes with size 3TN 34 nozzle inserts, rated at 0.1774 m^3 hr^{-1} at 1.0 BAR, producing rainfall event with the targeted application rate of 41 mm hr^{-1}.

Rainfall simulation on the degraded hillslope

The third series of the simulations were conducted on February 24-25, 2012. The 7 X 14 m plot was divided into two separate catchments using a large portable tube that was laid down the center of the plot length wise and then filled with water to keep in in position. Two 6-inch H-Flumes were positioned adjacent to each other and installed in the very center of the lowest edge of the plot to measure the respective runoff. Each subplot was referred to as subplot "*a*" and "*b*" (Figure 3)**.** However, the microtopography of the plot and high winds complicated the measurements, resulting in a much higher application rate on average to subplot *a*. Rain gauges were not distinguished and averaged separately. The objective for this study location was to produce three, 15-minute variable intensity capable of producing rainfall relatively quickly. The first trial utilized the high intensity 3TN 40 nozzle inserts for a 15 minute rainfall event and was able to generate an application rate of 86.73 mm hr^{-1}; the equivalent of a 25-year storm on the Texas IDF Curve. The second trial was also simulated for 15 minutes produced an intensity 99.27 mm hr^{-1} with the equivalence of a 50-year rainfall event according to the Texas IDF Curve for Coryell County. For the third and final simulation of this study the low intensity 3TN 18 nozzles were used to simulate a 24.26 mm hr^{-1} rainfall event for 21 minutes.

Figure 3. The degraded hillslope divided into subplot “*a*” (*left*) and subplot “*b*” (*right*)

CHAPTER III

RESULTS

Basal cover measurements

Basal cover varied between the mesquite plot (before and after restoration) and the degraded hillslope. Before brush removal, the mesquite plot consisted of 36.2% litter, 24.8% bareground, 38.1% live plant, and 0.9% rock. The mesquite plot after brush removal contained of 21.9% litter, 27.6% bareground, 50.5% live plant, and 0.0% rock. The degraded hillslope consisted of 20.9% litter, 42.9% bareground, 19.0% live plant, and 17.4% rock (Table 2).

Table 2. Basal data collected for the three plots expressed as percentages of total cover.

Cover Type	*2010 Mesquite plot*	*2012 Mesquite plot*	*Degraded hillslope*
Litter	36.2	21.9	21.0
Bareground	24.8	27.6	42.9
Live plant	38.1	50.5	19.0
Rock	1.0	0.0	17.1
Total	100.00	100.00	100.00

Precipitation and runoff measurements

Precipitation measurements for the mesquite plot before brush was removed ranged from 19 to 99 mm and achieved intensities ranging from 28 to 99 mm hr^{-1} (Table 3). Low to moderate winds allowed for a relatively even spread of precipitation however canopy interception effected the spatial distribution of rainfall (Figures 4-10). The first of the seven trials received 35 mm of precipitation in 60 minutes. Heterogeneous ponding occurred throughout the plot 30 minutes into simulation with runoff starting at 37 minutes. 28 mm of runoff was measured flowing off the plot, accounting for 28.7% of the total precipitation applied to the plot. The second trial received 27 mm of rainfall in 47 minutes. Ponding from the previous simulation was present in the lower portion of the plot towards the flume at the start of this trial, though runoff did not occur until six minutes after the start of the simulation. 11 mm was measured leaving the site as runoff, accounting for 32.5% of the total precipitation applied. The third trial of this series received 35 mm of precipitation in 30 minutes. Ponding was observed after 7.5 minutes and runoff occurred after 17 minutes with 10 mm, or 13.9% of the total precipitation, flowing offsite as discharge. The fourth trial of this series averaged 21 mm of applied precipitation in 45 minutes. Ponding still existed from the previous simulation prior to the start of this trial with homogeneous ponding occurring within two minutes. Runoff was generated four minutes after the simulation began with 8 mm of precipitation, 29.2% of total rainfall, flowing offsite. The fifth simulation received 34 mm of precipitation in 30 minutes. Homogeneous ponding was present before the simulation was started and runoff was observed within three minutes. 22 mm of runoff was measured accounting for 32.1% of the total precipitation applied. The sixth simulation received rainfall averaging at 31 mm in 45 minutes. Ponding occurred after five minutes with runoff starting 17 minutes after the start of the simulation. 17mm of runoff was measured flowing offsite, accounting for 40.4% of the total precipitation. Runoff continued to be recorded and did not cease prior to the start of the seventh trial. The seventh and final trial received 19 mm of precipitation in 15.5 minutes. This trial was originally intended to last for 30 minutes, but complications with water supply caused it to run shorter than expected. However, 11 mm of runoff was still measured flowing offsite totaling 14.8% of the rainfall applied to the plot.

Table 3. Precipitation and runoff data for the 2010 mesquite plot where Q is runoff and Q_t is the time runoff began.

Trial	*Duration (min)*	*Input (mm)*	*Intensity (mm hr^{-1})*	*Q_t (min)*	*Q (mm)*	*% Q*
1	60	99.45	99.4	38	28.5	28.67
2	47	27.03	34.5	10	11.2	32.46
3	30	35.37	70.7	14	9.8	13.86
4	45	20.08	27.7	4	8.1	29.24
5	30	34.00	68.00	3	21.8	32.06
6	45	31.01	41.3	17	16.7	40.44
7	15.5	19.08	73.9	0	10.9	14.75

Precipitation measurements for the mesquite plot after brush was removed ranged from 14 to 42 mm and achieved intensities ranging from 19 to 85 mm hr^{-1} (Table 4). This series of simulations was conducted under to moderate to high winds, which effected the spatial distribution of precipitation throughout the plot (Figures 11-13). The soil was already saturated at the start of this trial from recent rainfall contributing to rather rapid runoff. The first trial received 42 mm of precipitation in 30 minutes. Ponding was observed within two minutes, though only 5 mm of runoff was measured, accounting for 11.5% of the total precipitation applied. The second trial was twice as long as the first, however only 19 mm of precipitation was applied after 58 minutes of constant application. The intensity of this trial was 25% that of the first trial. Ponding occurred within four minutes, but the low intensity event did not produce rainfall for 40 minutes. Less than 1 mm of runoff was measured flowing offsite accounting for 1.4% of the total applied precipitation. Due to high winds, this trial received relatively little rainfall on the far end of the plot (Figure 12). The third trial received 14 mm of precipitation in 20 minutes. Runoff flowing off site was measured to be 3 mm even though homogenous ponding was observed at the start of this trial. Discharge accounted for 18.5% of the total applied precipitation.

Table 4. Precipitation and runoff data for the 2012 mesquite plot where Q is runoff and Q_t is the time runoff began.

Trial	*Duration (min)*	*Input (mm)*	*Intensity (mm hr^{-1})*	*Q_t (min)*	*Q (mm)*	*% Q*
1	30	42.31	84.6	17	4.87	11.51
2	58	18.62	19.3	40	0.26	1.40
3	20	13.63	40.9	8	2.52	18.49

Precipitation measurements for the degraded hillslope ranged from 8 to 25 mm and achieved intensities ranging 24 to 99 mm hr^{-1} (Table 5). This plot was originally divided into subplot *a* and *b*. This series of simulations was subject to high winds which contributed to higher amounts of precipitation on subplot *a* than *b* (Figures 14-16). Irregular patterns in the microtopography also contributed to in higher rates of ponding on subplot *b*. As runoff started to occur on subplot *b*, it became apparent that the barrier put in place to separate the two plots was not sufficiently containing runoff. Discharge from both subplots was combined to quantify the total runoff of the degraded hillslope. Hydrographs for each simulation were created to help visualize the runoff data collected (Figures 17-21). The first trial received 22 mm of precipitation in 15 minutes. Runoff started to occur 3.75 minutes into the simulation and was measured at 9 mm, accounting for 41.2% of applied precipitation. The second trial received 25 mm of precipitation in

15 minutes. Runoff began at 2.25 minutes and measured at 19 mm, or 74.6% of applied precipitation. The third trial received 8 mm of precipitation in 21 minutes. Runoff began at 7 minutes measuring 3 mm, or 40.9% of the total.

Table 5. Precipitation and runoff data for the 2012 degraded hillslope where Q is runoff and Q_t is the time runoff began.

Trial	*Duration (min)*	*Input (mm)*	*Intensity (mm hr^{-1})*	*Q_t (min)*	*Q (mm)*	*% Q*
1	15	21.68	86.73	3.75	8.93	41.18
2	15	24.82	99.28	2.25	18.51	74.58
3	21	8.49	24.26	7	3.48	40.99

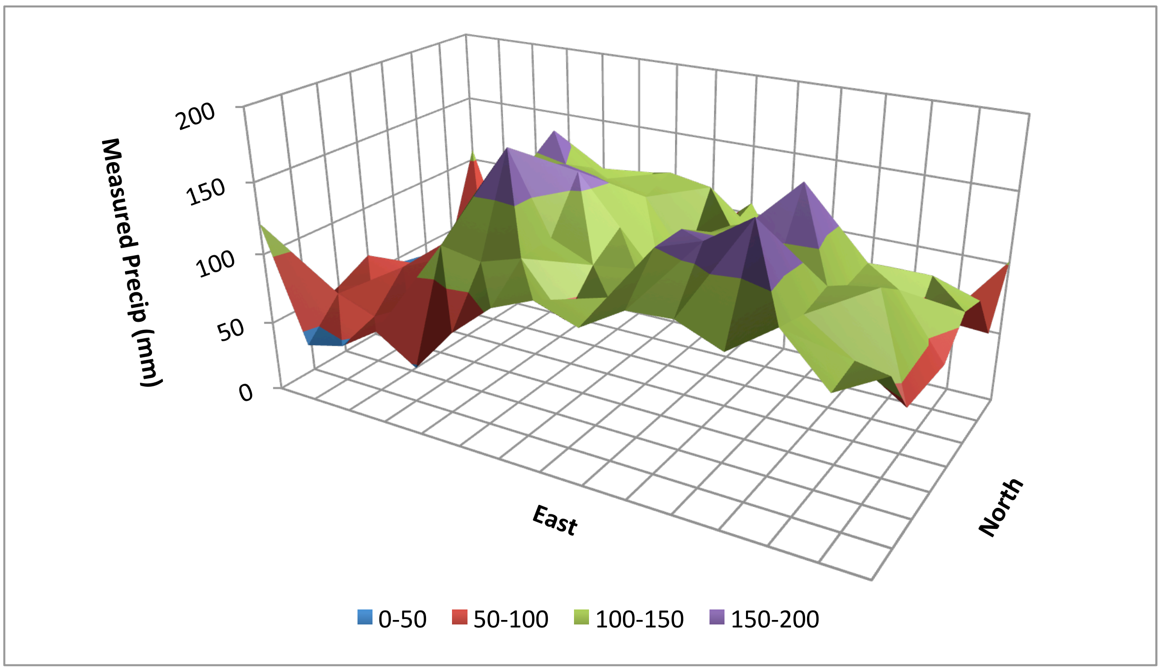

Figure 4. Spatial distribution of rainfall for trial 1 of the 2010 mesquite plot before restoration. The flume is located in the northeast corner of the plot.

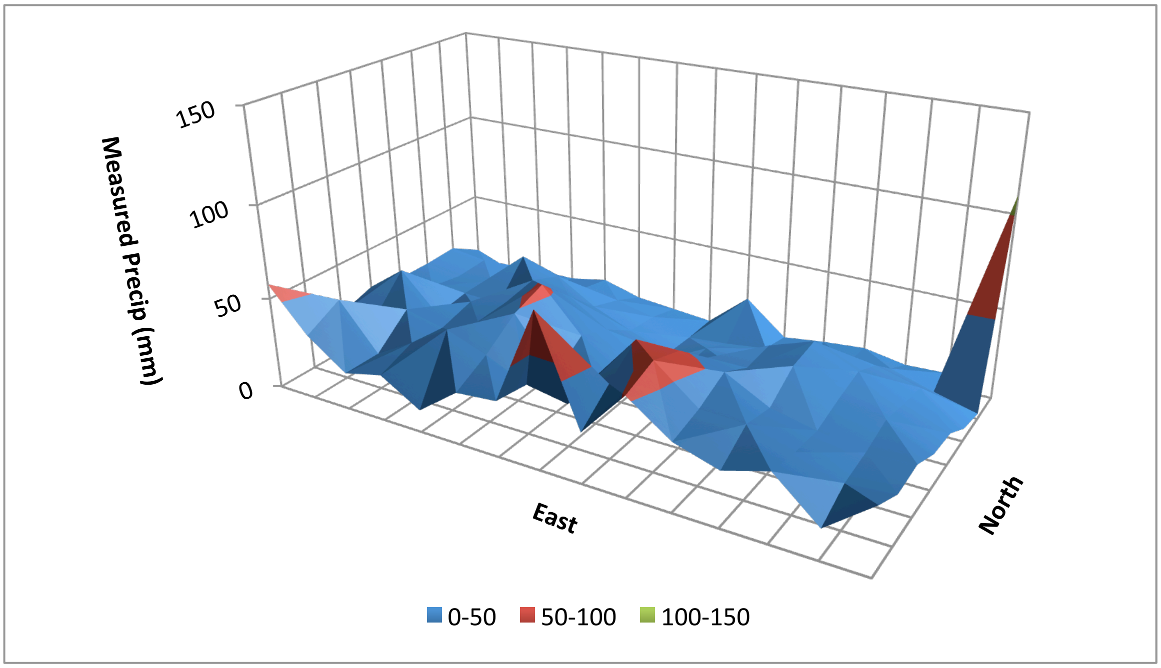

Figure 5. Spatial distribution of rainfall for trial 2 of the 2010 mesquite plot before restoration. The flume is located in the northeast corner of the plot.

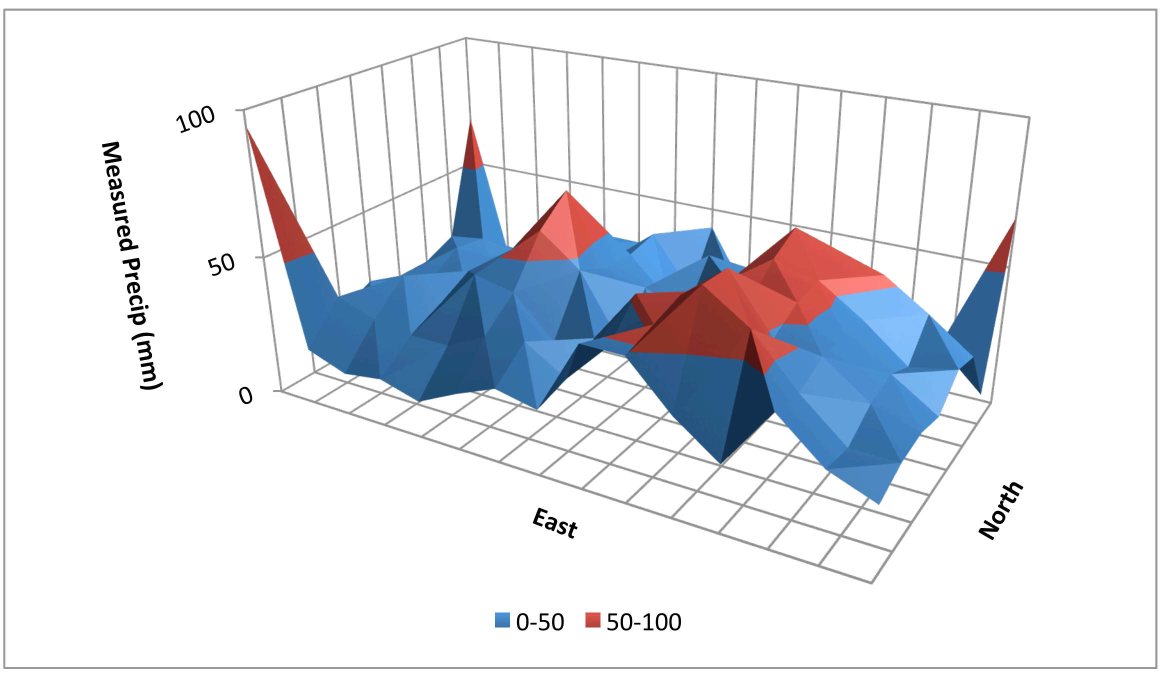

Figure 6. Spatial distribution of rainfall for trial 3 of the 2010 mesquite plot before restoration. The flume is located in the northeast corner of the plot.

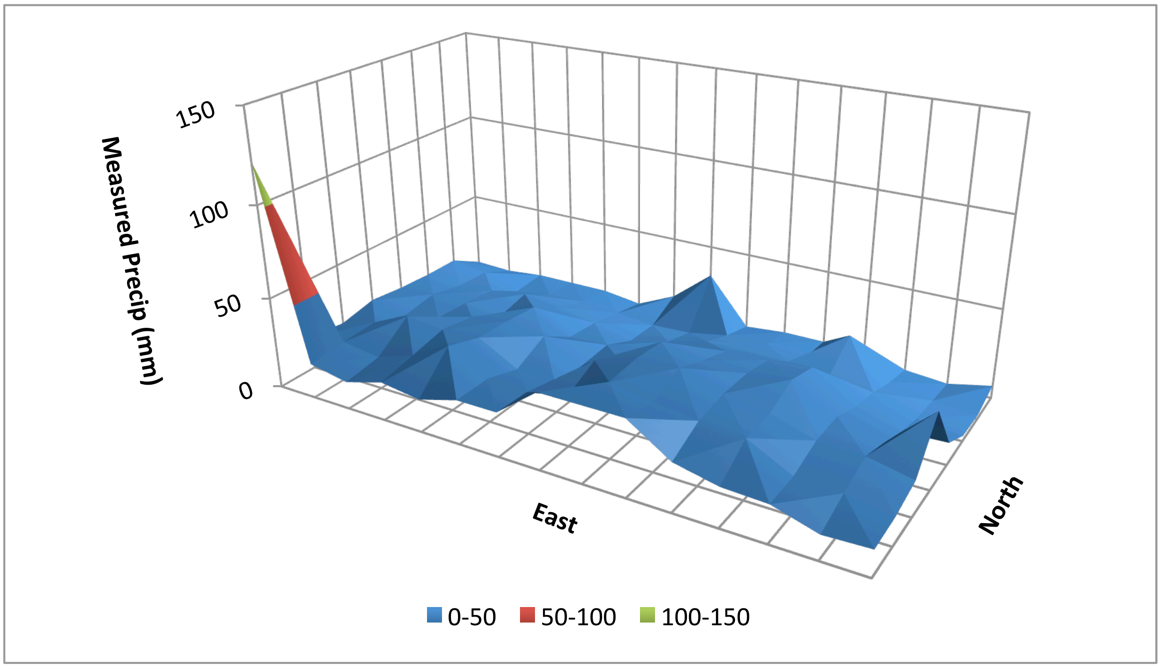

Figure 7. Spatial distribution of rainfall for trial 4 of the 2010 mesquite plot before restoration. The flume is located in the northeast corner of the plot.

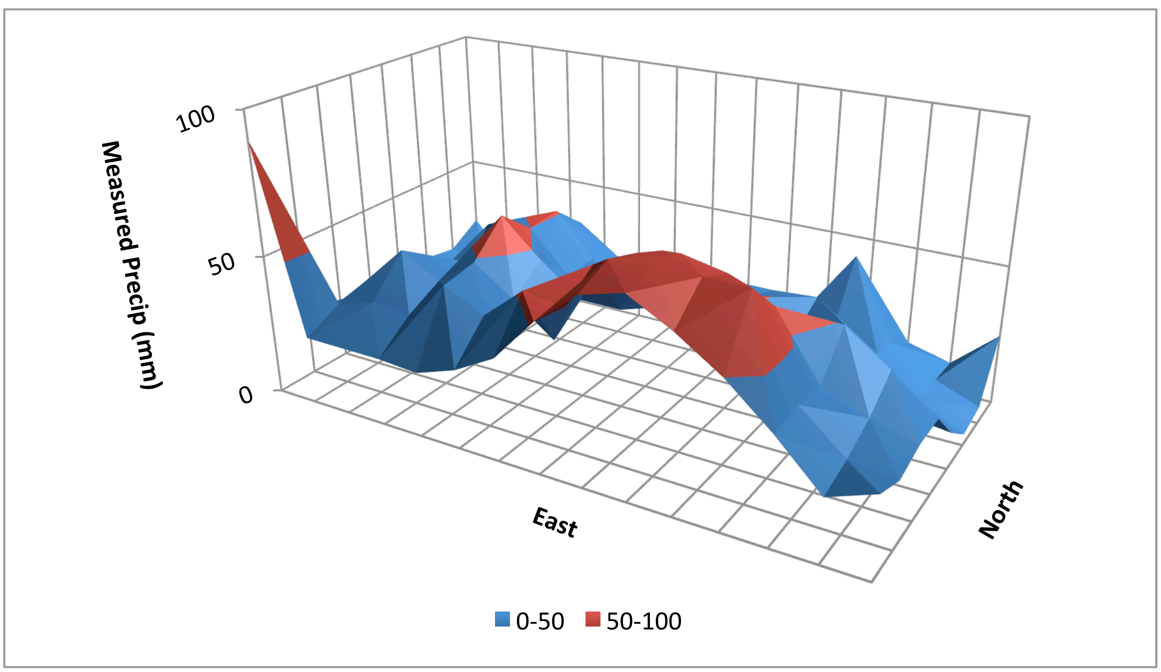

Figure 8. Spatial distribution of rainfall for trial 5 of the 2010 mesquite plot before restoration. The flume is located in the northeast corner of the plot.

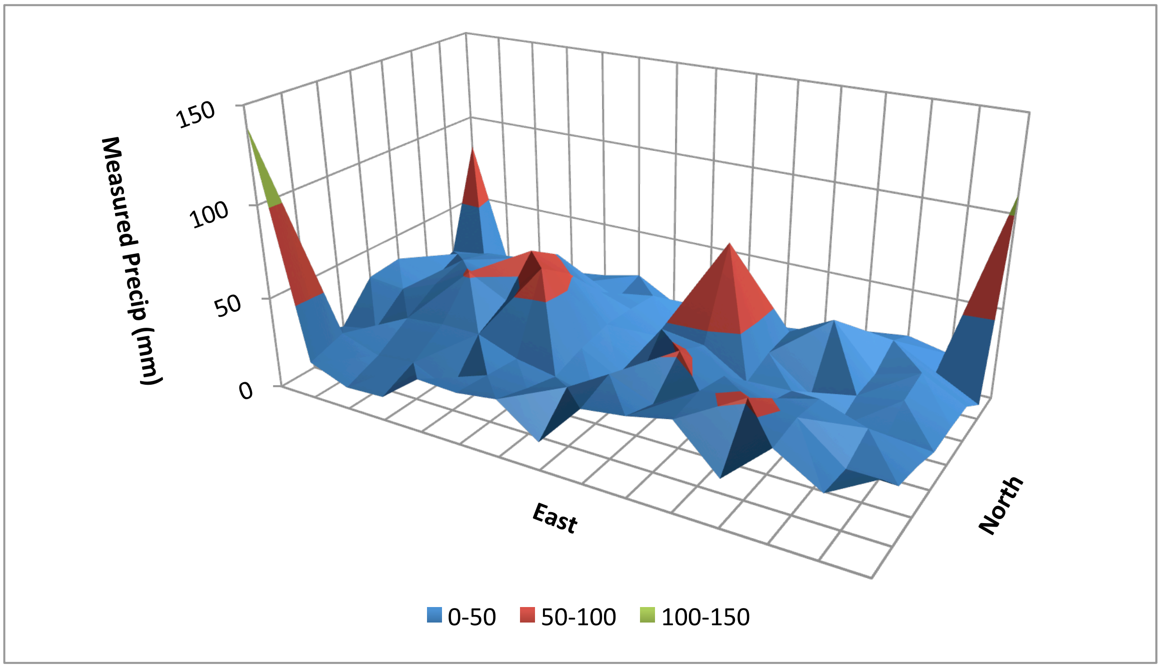

Figure 9. Spatial distribution of rainfall for trial 6 of the 2010 mesquite plot before restoration. The flume is located in the northeast corner of the plot.

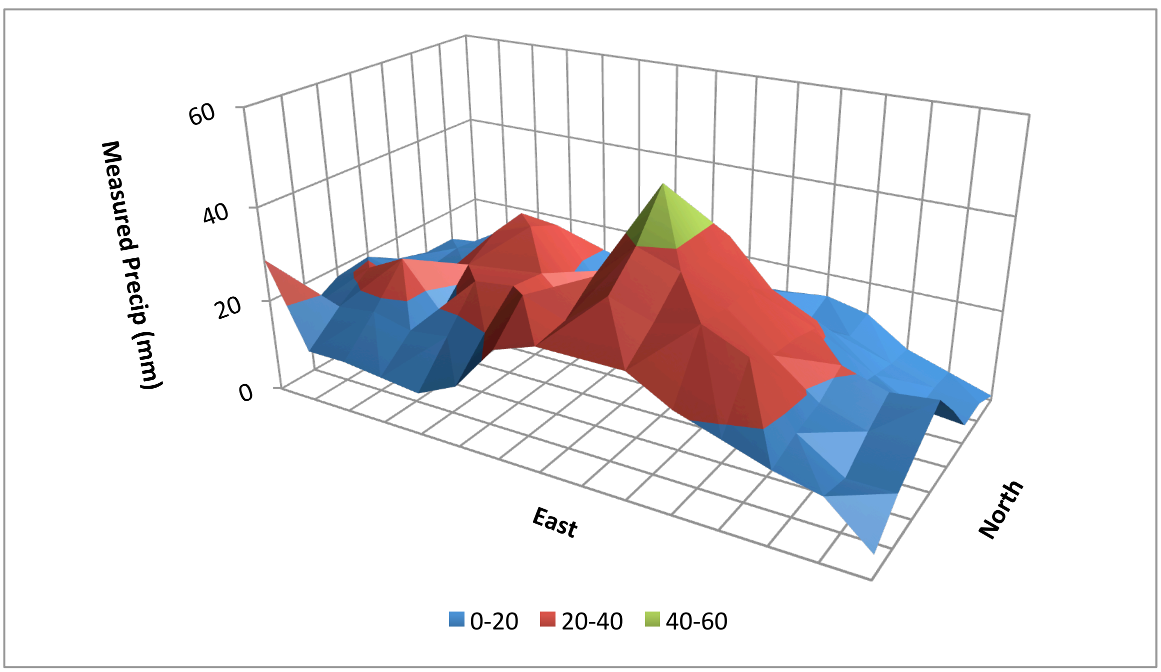

Figure 10. Spatial distribution of rainfall for trial 7 of the 2010 mesquite plot before restoration. The flume is located in the northeast corner of the plot.

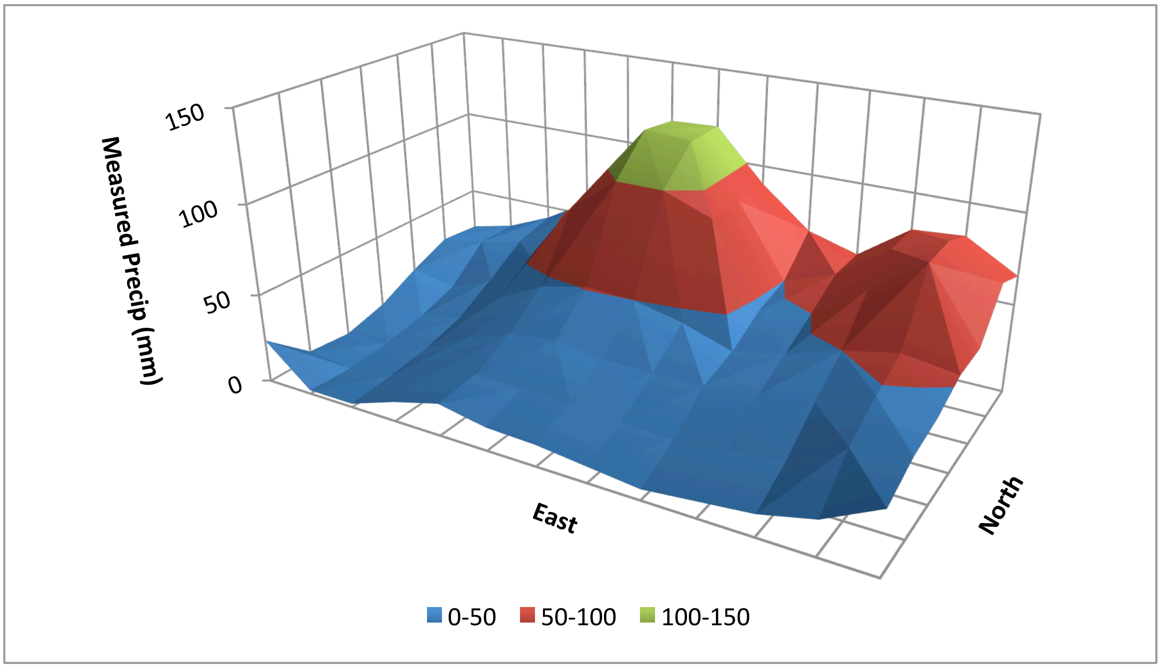

Figure 11. Spatial distribution of rainfall for trial 1 of the 2012 mesquite plot after restoration. The flume is located in the northeast corner of the plot.

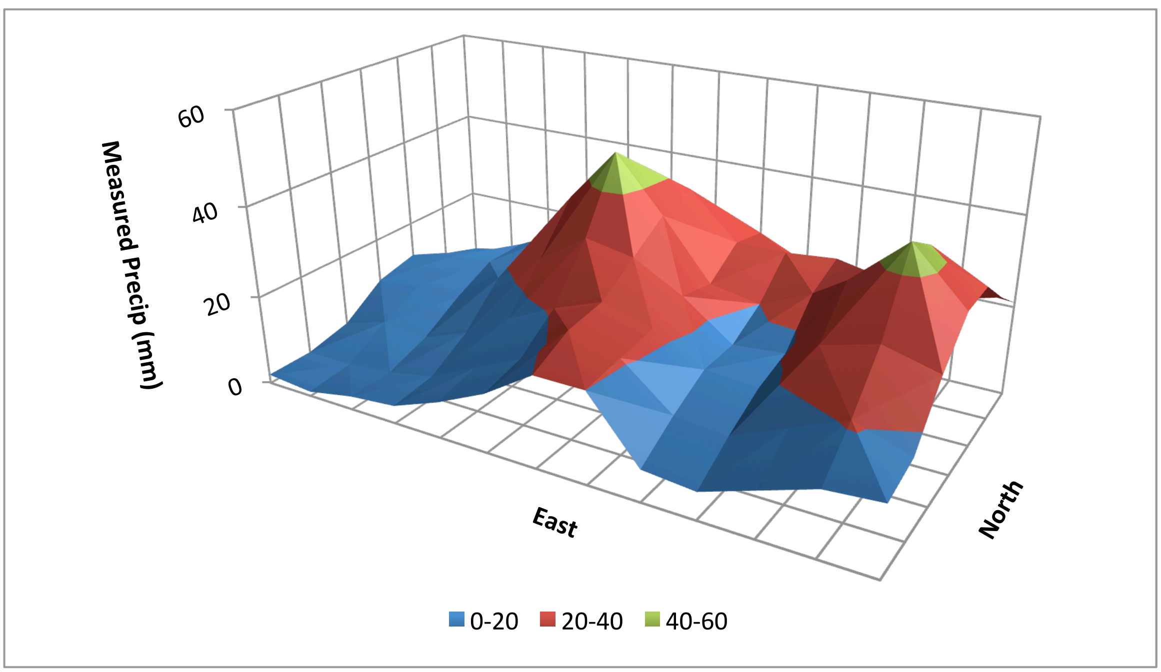

Figure 12. Spatial distribution of rainfall for trial 2 of the 2012 mesquite plot after restoration. The flume is located in the northeast corner of the plot.

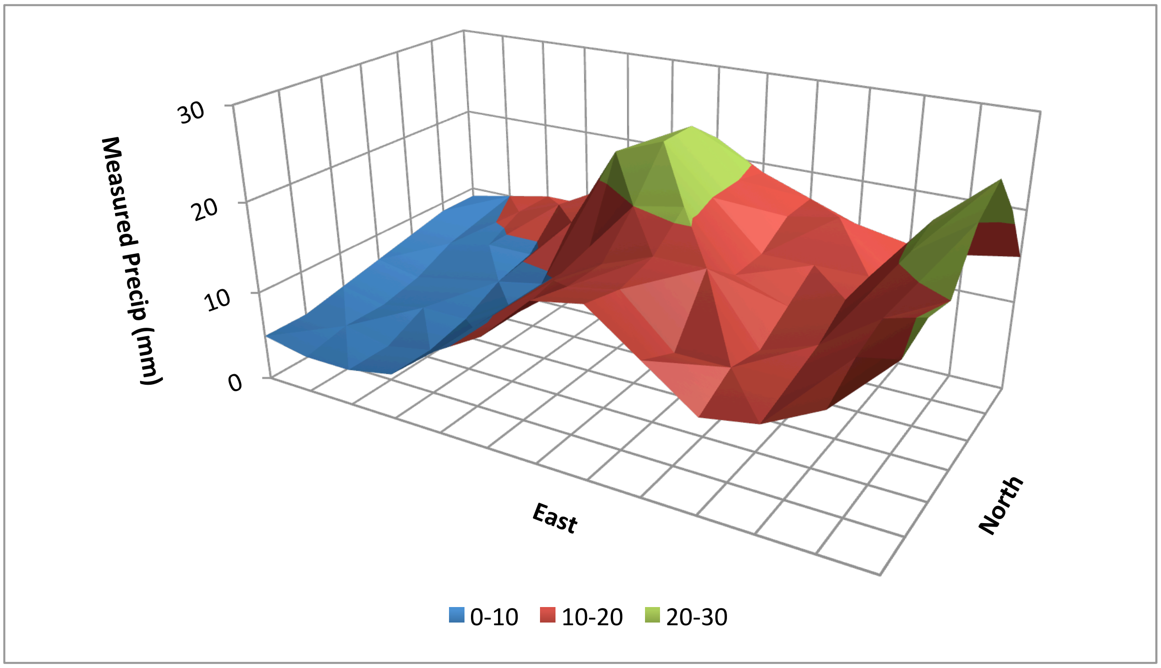

Figure 13. Spatial distribution of rainfall for trial 3 of the 2012 mesquite plot after restoration. The flume is located in the northeast corner of the plot.

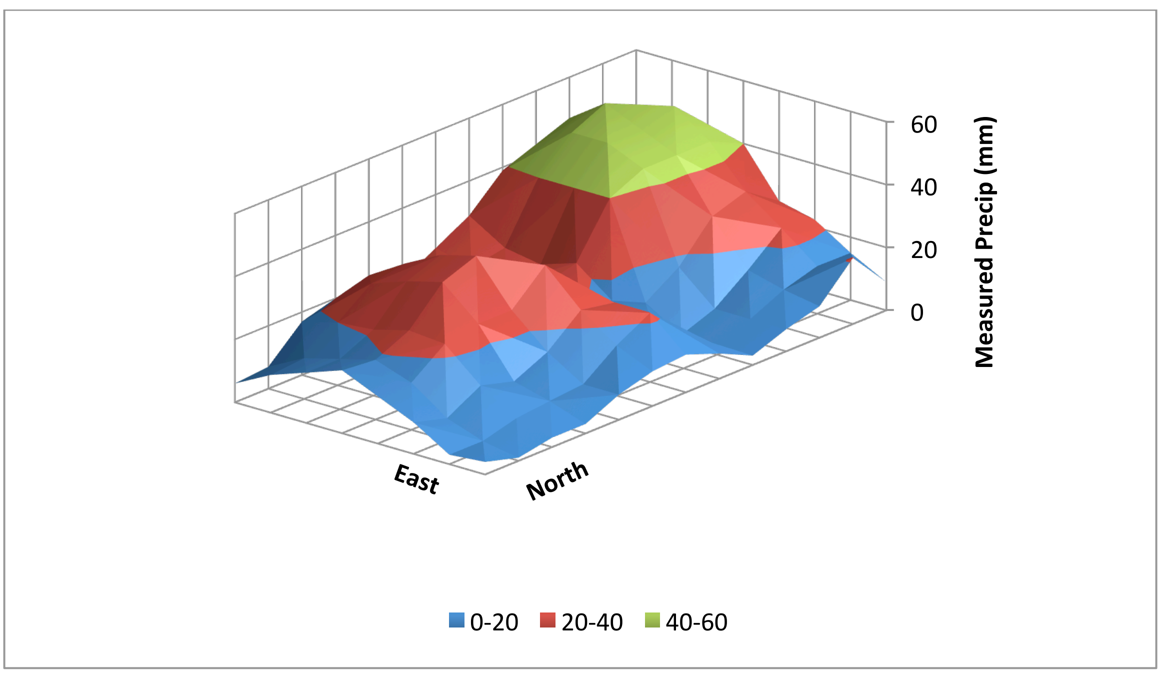

Figure 14. Spatial distribution of rainfall for trial 1 of the 2012 degraded hillslope. The flume is located in the center of the eastern edge of the plot.

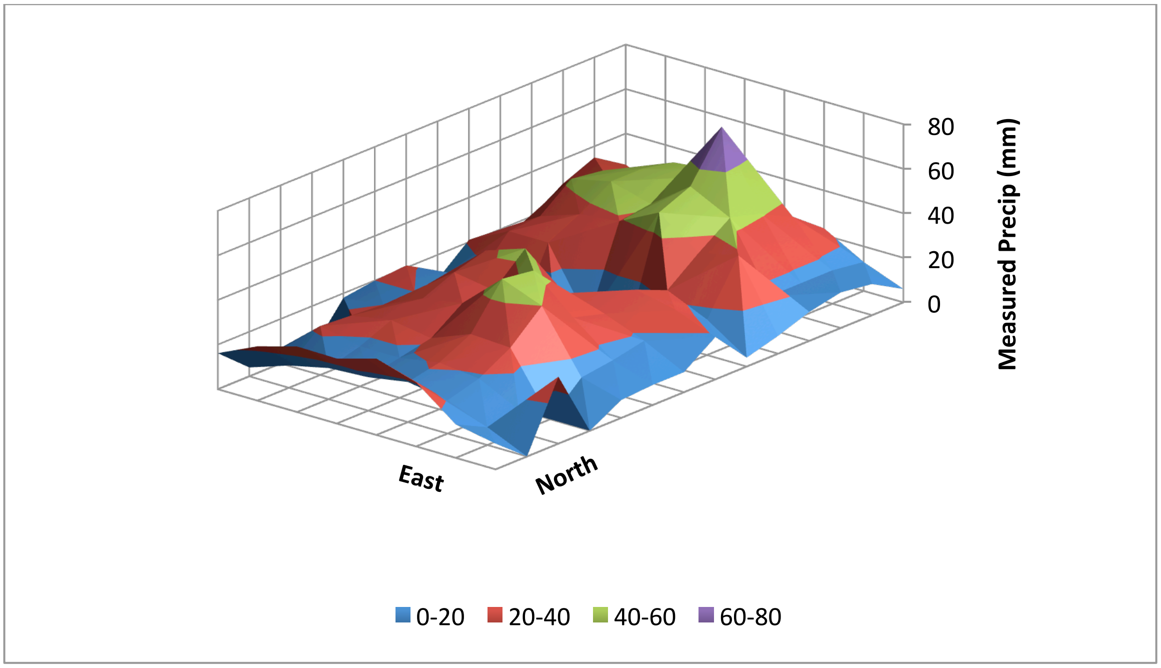

Figure 15. Spatial distribution of rainfall for trial 2 of the 2012 degraded hillslope. The flume is located in the center of the eastern edge of the plot.

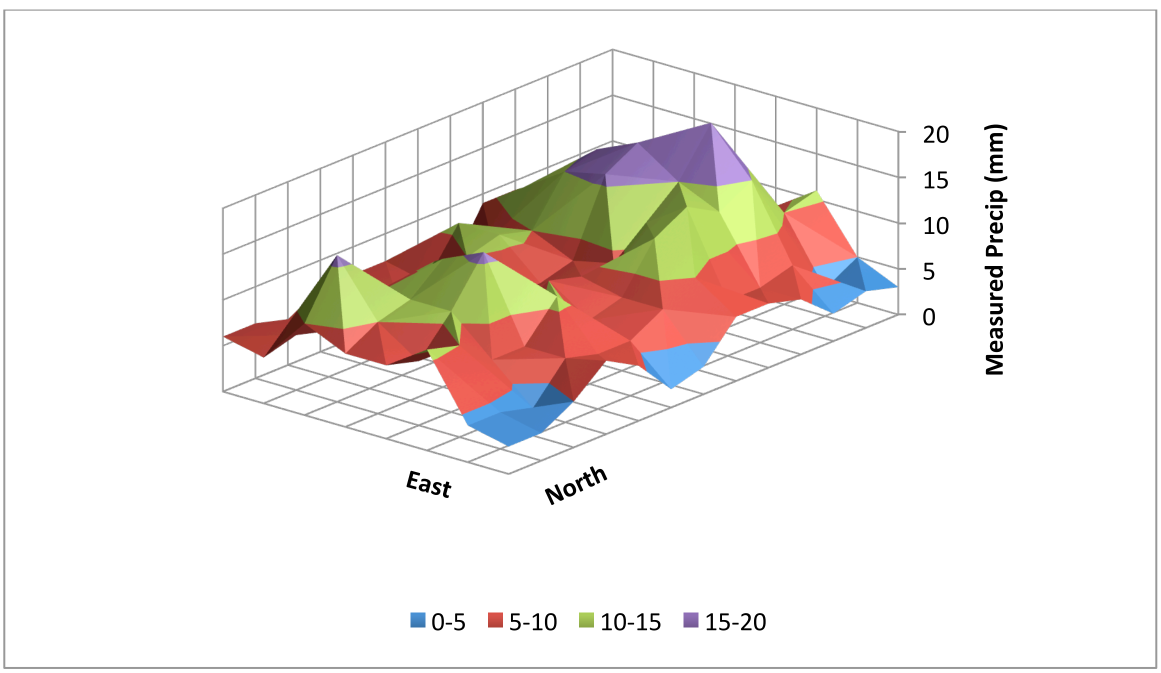

Figure 16. Spatial distribution of rainfall for trial 3 of the 2012 degraded hillslope. The flume is located in the center of the eastern edge of the plot.

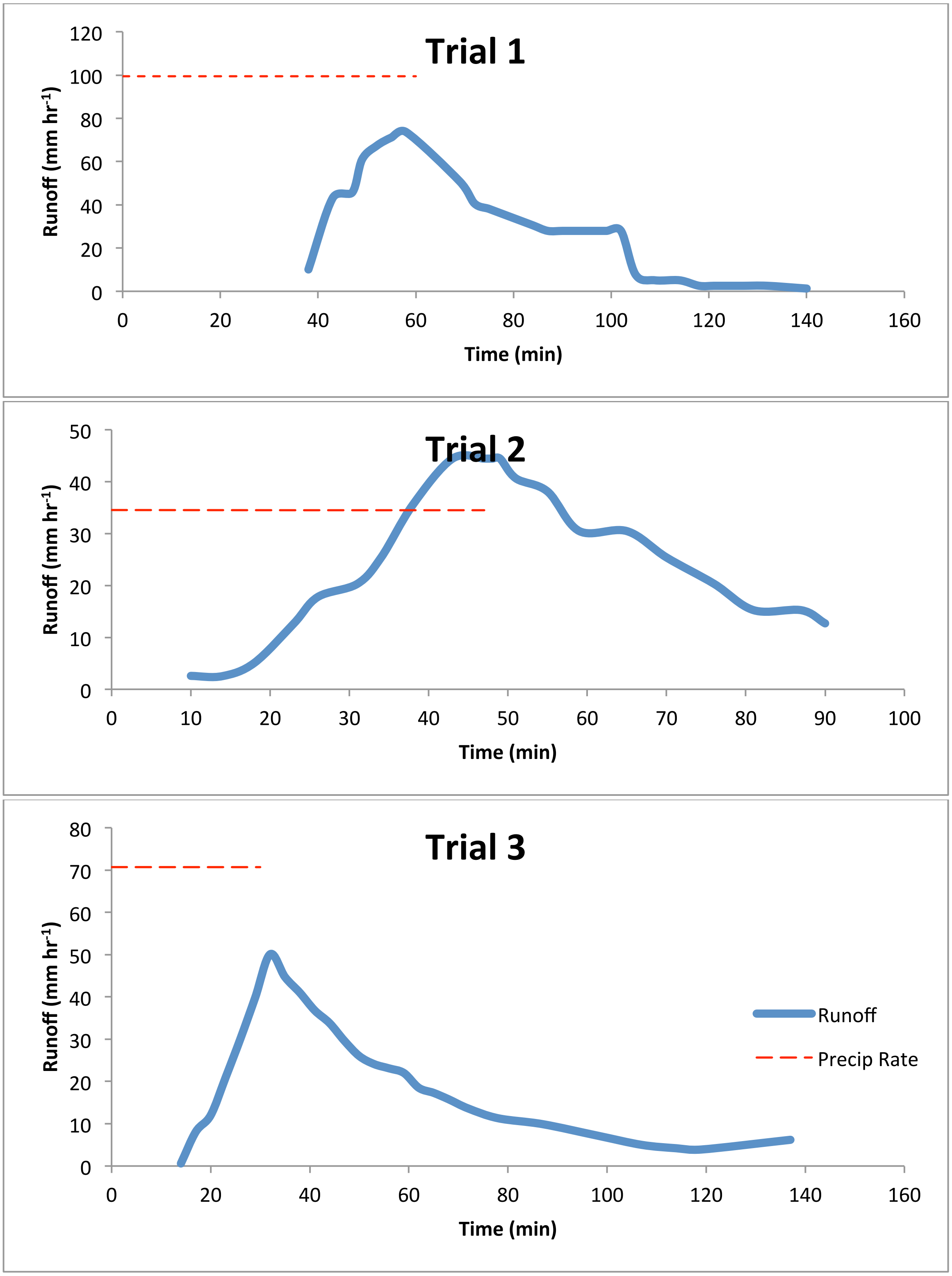

Figure 17. Hydrographs generated for trials 1-3 of the 2010 mesquite plot simulations before restoration.

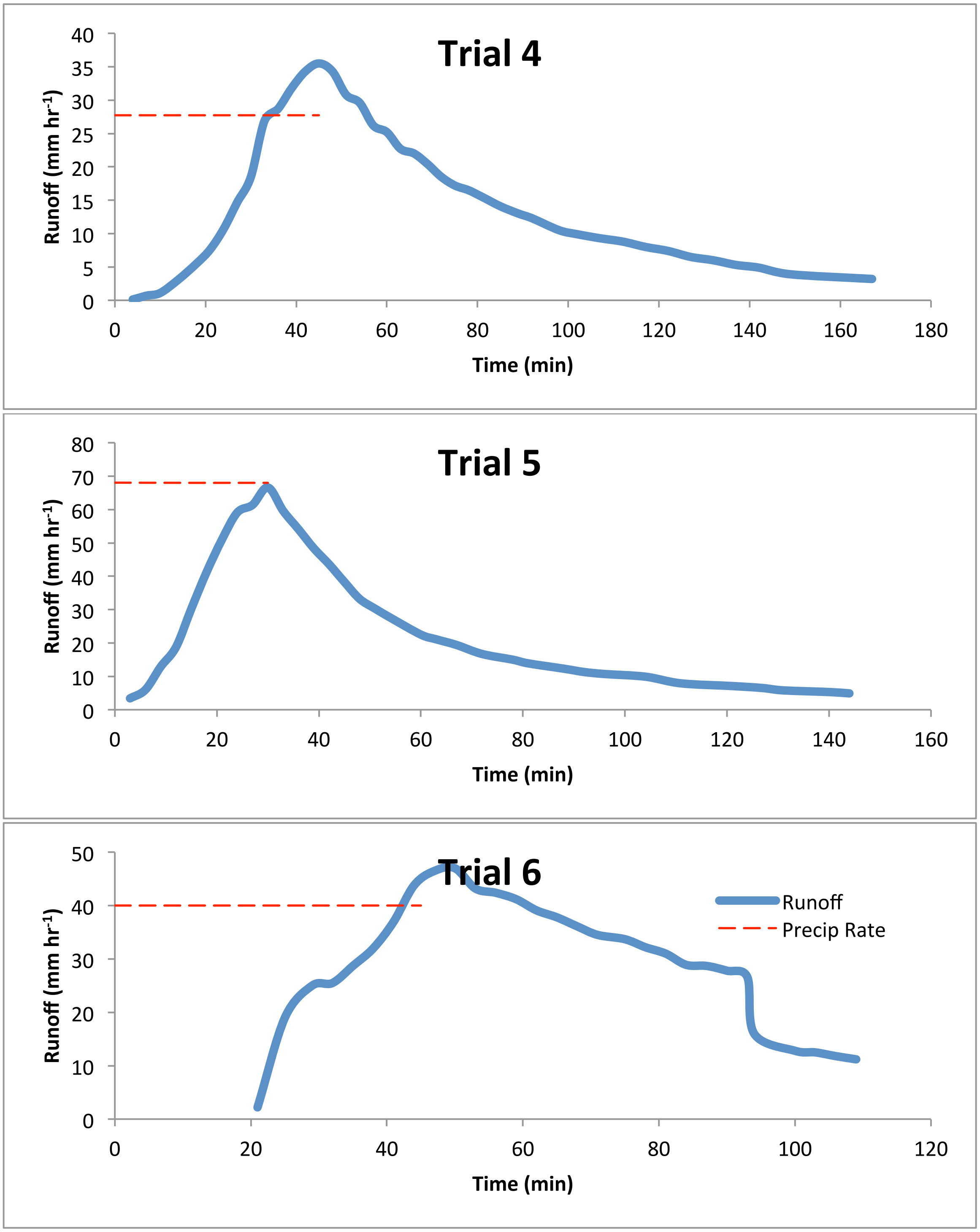

Figure 18. Hydrographs generated for trials 4-6 of the 2010 mesquite plot simulations before restoration.

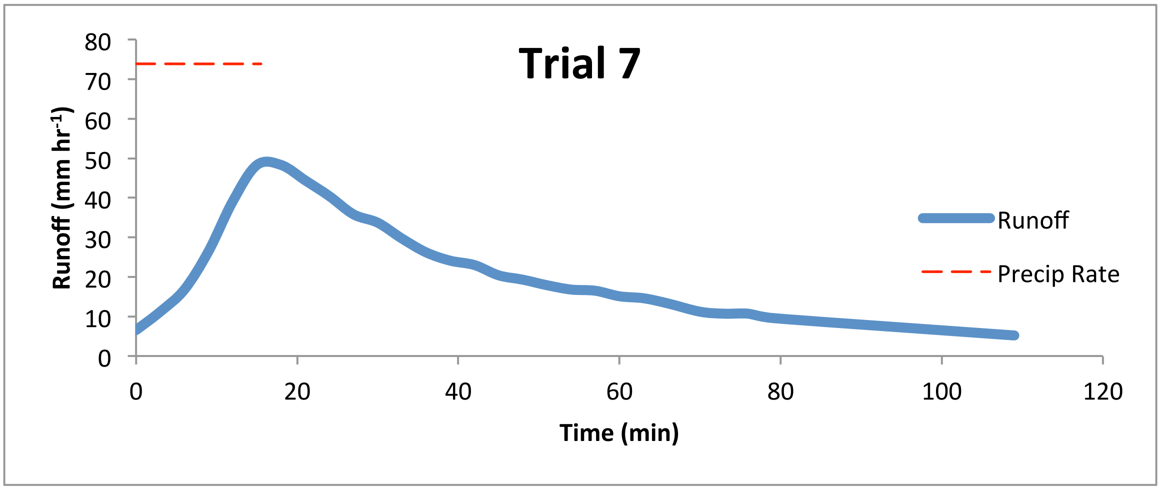

Figure 19. Hydrograph generated for trials 7 of the 2010 mesquite plot simulations before restoration.

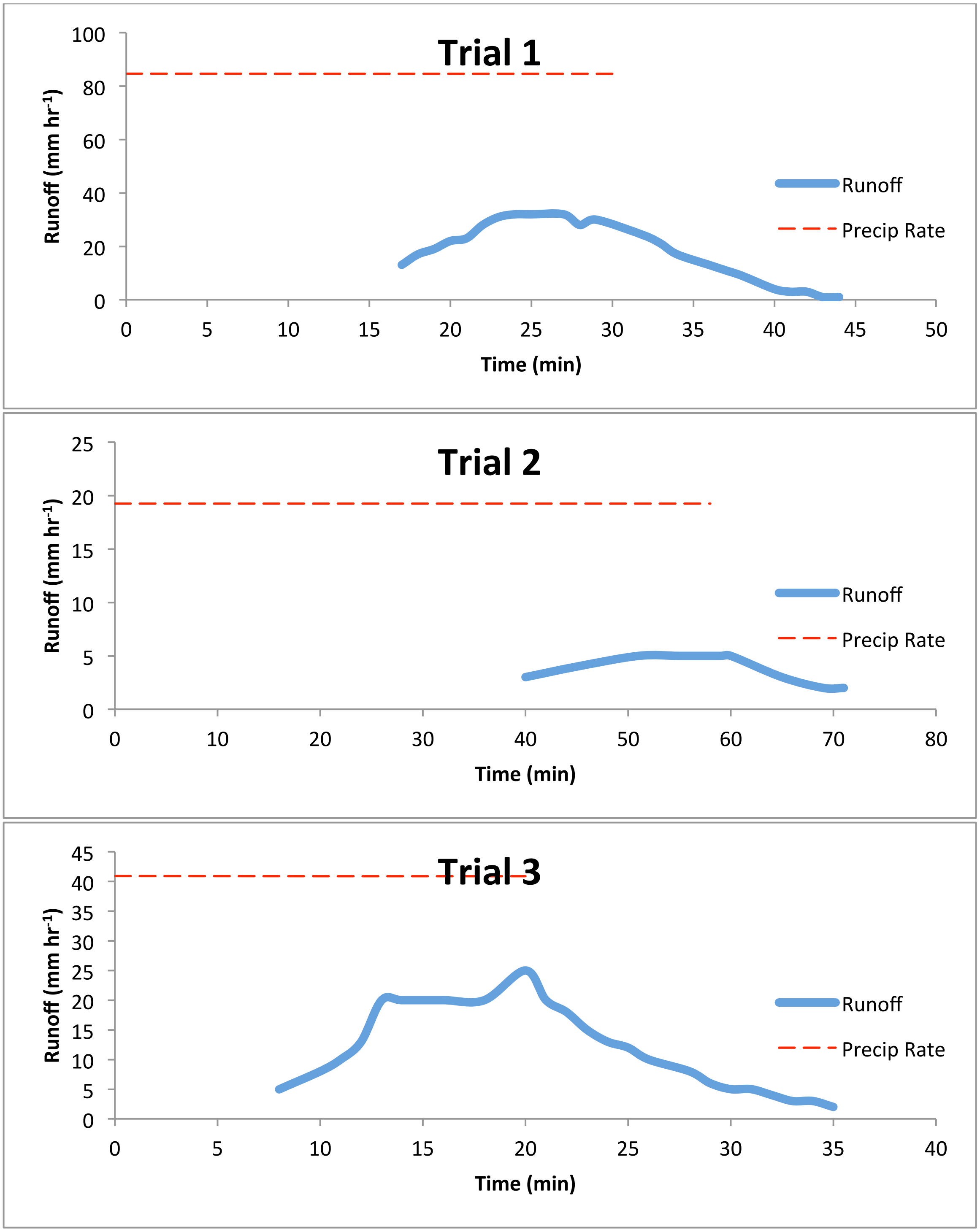

Figure 20. Hydrographs generated for trials 1-3 of the 2012 mesquite plot simulations after restoration.

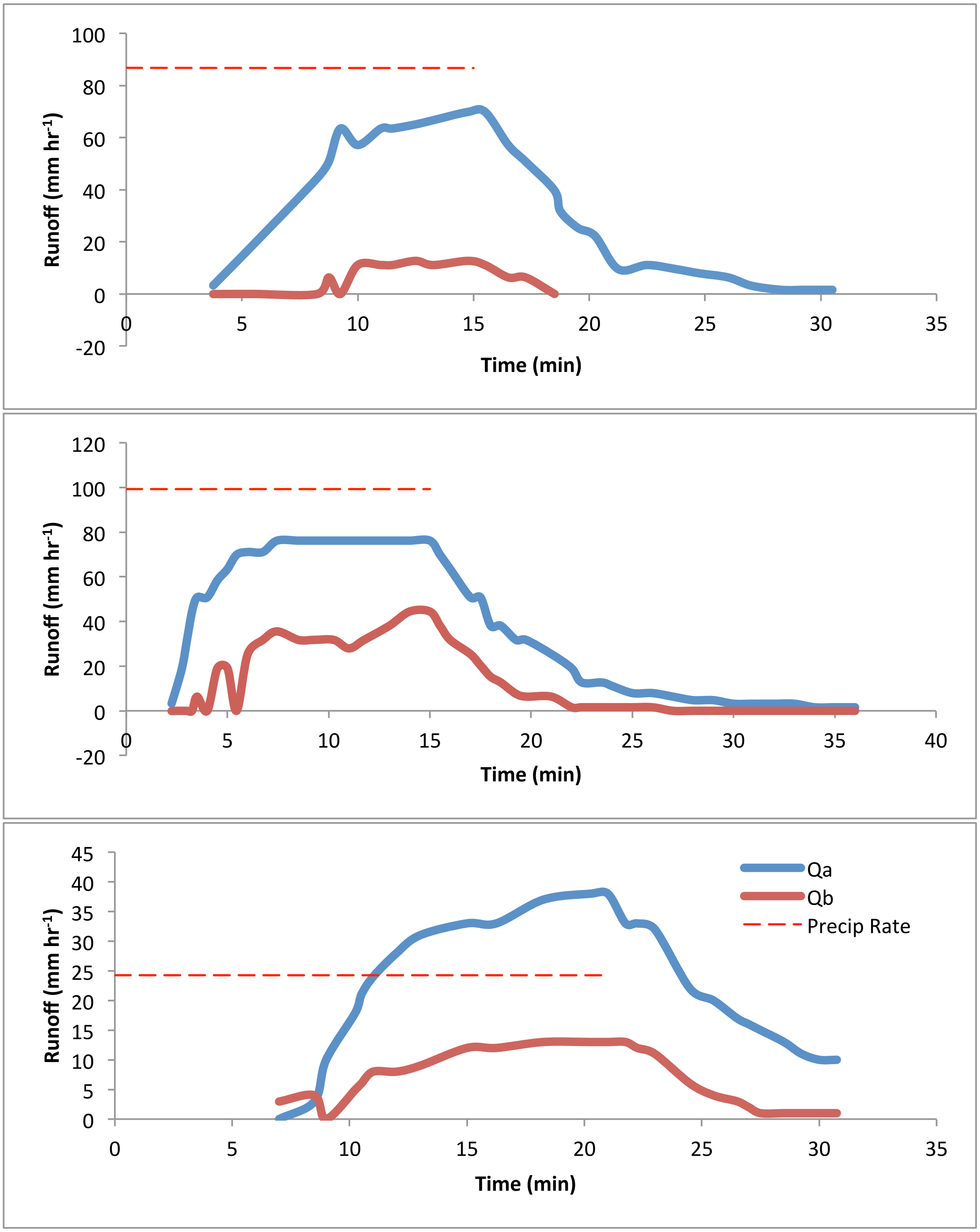

Figure 21. Hydrographs generated for trials 1-3 of the 2012 degraded hillslope simulations where Q_a is runoff flowing through flume *a* and Q_b is runoff flowing through flume *b*.

Sediment load measurements

Water samples were collected and analyzed for total sediment loads for all of the plots using the total suspended solids (TSS) and suspended-sediment concentration (SSC) analytical methods. However only trials one, two, three, and six with analyzed for the simulations conducted on the mesquite plot in 2010. Sediment loads for this series averaged 41.4 ppm. Trial one had an average sediment concentration of 9.4 ppm. Trial two had an average of 51.6 ppm, trial three had an average of 69.4 ppm, and trial six had an average of 35.2 ppm. Sediment concentration of the second series of simulations on the mesquite plot in 2012 had an average of 10.4 ppm. The first trial had an average of 9.2 ppm, trial two had an average of 10.7 ppm, and trial three had an average of 11.3 ppm. Simulations on the degraded hillslope had 13.8 ppm total suspended solids on average. Trial one of this series had an average of 11.8 ppm, trial two had an average of 14.5 ppm, and trial three had an average of 15.1 ppm. (Table 6).

Table 6. Average sediment loads in ppm for each trial.

2010 Mesquite Plot Before Restoration

Trial	*Sediment (ppm)*
1	9.4
2	51.6
3	69.4
4	-
5	-
6	35.2
7	-
Average	*41.4*

2012 Mesquite Plot After Restoration

Trial	*Sediment (ppm)*
1	9.23
2	10.71
3	11.26
Average	*10.4*

2012 Degraded Hillslope

Trial	*Sediment (ppm)*
1	11.8
2	14.5
3	15.1
Average	*13.8*

CHAPTER IV

DISCUSSION

Basal cover

Changes in basal cover between the degraded site and mesquite site simulations varied markedly. The most notable differences between the mesquite plot simulations were the 49.2% decrease in litter and the 27.9% increase in live plant cover after restoration. The degraded hillslope differed as much as was expected with 48.3% more bareground and 79.7% less live plant cover than the average basal cover of the mesquite plots (Figure 22). The degraded hillslope's bare soil and exposed rock probably contributed greatly to the amount of runoff generated so quickly. The differences in bareground, live plant, and litter cover alone do not explain mechanisms behind the reduction in runoff from the 2012 mesquite plot simulations. Significant amounts of precipitation are not accounted from the 2010 mesquite plot simulations and it is highly likely that some water was lost to canopy interception and stemflow. However, this series of simulations still produced substantially more runoff. Evapotranspiration is not considered have played a major role in the loss of water from the system due to such short amounts of time that runoff was present at on the surface. This decrease in runoff is most likely the result of reduced soil compaction from the disturbance caused by the mechanical grubber, which increased the infiltration rate and water holding capacity of the soil.

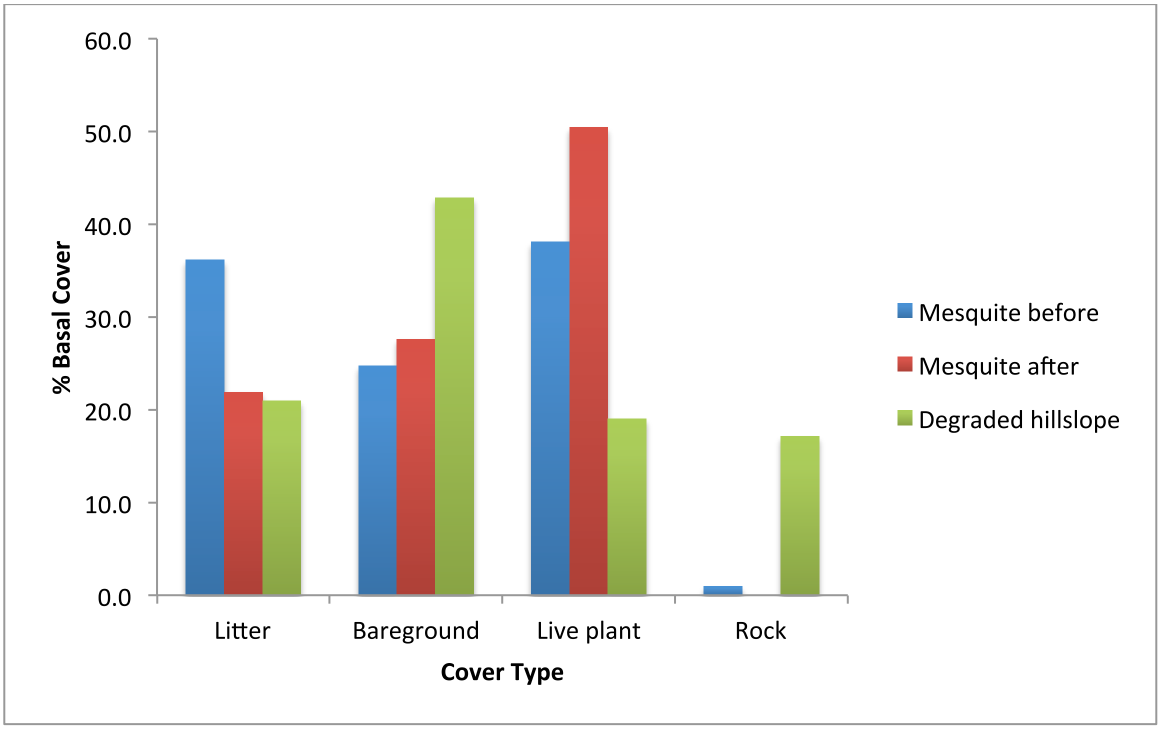

Figure 22. Percent basal cover and cover type of the three study plots.

Precipitation and runoff

Precipitation and flow data yielded surprising results that provide insight into the ecohydrology of this system. Several significant differences were observed when comparing simulations from all three series based on similarities between simulations. Trials three and five from the 2010 mesquite plot simulations and trial one from the 2012 mesquite plot simulations were compared based on having the same duration of rainfall. In each simulation rainfall was applied for 30 minutes and achieved similar application amounts and intensities (Table 7). However, trial three and one required more than 14 minutes to generate runoff while trial five, which had the lowest intensity, produced runoff in just three minutes. Trial three also displayed the greatest percentage of runoff despite having the lowest amount of rainfall applied. A similar trend was observed when analyzing trials two, four, and six from the 2010 mesquite plot precipitation data (Table 8). All three of these trials were approximately 45 minutes in duration. They too achieved similar application amounts and intensities. However, trials two and six did not generate runoff until at least 10 minutes while trial four produced runoff within four minutes.

Table 7. Comparison between trials three and five of the 2010 mesquite plot and trial one of the 2012 mesquite plot where Q is runoff and Q_t is the time runoff began.

Plot	*Trial*	*Duration (min)*	*Input (mm)*	*Intensity (mm hr^{-1})*	*Q_t (min)*	*Q (mm)*	*% Q*
Mesquite 2010	3	30	35.37	70.7	14	9.8	13.86
Mesquite 2010	5	30	34.00	68	3	21.8	32.06
Mesquite 2012	1	30	42.31	84.6	17	4.87	11.51

Table 8. Comparison trials two, four, and six of the 2010 mesquite plot where Q is runoff and Q_t is the time runoff began.

Plot	*Trial*	*Duration (min)*	*Input (mm)*	*Intensity (mm hr^{-1})*	*Q_t (min)*	*Q (mm)*	*% Q*
Mesquite 2010	2	47	27.03	34.5	10	11.2	32.46
Mesquite 2010	4	45	20.08	27.7	4	8.1	29.24
Mesquite 2010	6	45	31.01	41.3	21	16.7	40.44

A review of the original notes from the data collection process provided insight into why some plots produced runoff much more rapidly than others. The variance in runoff start times resulted from the amount of time the soils were allowed to drain in between simulations. All simulations that were conducted at the beginning of each day were exposed to 12 plus hours of soil drainage in between successive rainfall simulations. All subsequent simulations were conducted while the soil was at maximum water holding capacity. This allowed precipitation to exceed infiltration, resulting in rapid runoff.

The first trial of the mesquite plot in 2010 before brush was removed received the most water of all the simulations by far. However, this trial also took the longest of any of the other simulations to generate runoff. When simulations were conducted in 2010 the region was under drought conditions and the soil was almost completely dry. Runoff did not occur for 38 minutes despite a high intensity just shy of a 100-year storm and three times the amount of water applied to subsequent simulations. The first simulation on the mesquite plot in 2012 received rain less than a week before simulations were conducted. The moderately saturated soils are what contributed to runoff occurring much earlier and of higher percentages. These findings are consistent with those of Harmel et al. (2006) whose long-term dataset describes the effects of runoff during dry and wet periods in the Blackland Prairie ecoregion. They concluded that during drier months that receive 2-9 mm, runoff would be virtually non-existent. Wetter months receiving just 9-28 mm of precipitation are able saturate soils enough to cause substantial surface runoff.

The only exception to this trend was observed on the degraded hillslope where the shallow and rocky soils produced runoff within two to four minutes. However, runoff in this system was not acting independent of time between rainfall simulations. Runoff start times remained relatively consistent with one another, though the amount of runoff was significantly different. Percentages of runoff doubled in trial two which, was conducted immediately after runoff had ceased from trial one, as opposed to trial three, which was conducted the following day. Trial three had the same rate of runoff as trial one even though it had a much lower intensity.

Another difference between the sites was the microtopography. The relatively level slope of the mesquite plot prevented runoff from achieving velocities similar to those of the degraded hillslope. It became apparent during the first trial in 2010 that runoff that discharged from the site had nowhere to flow once it left the site to resulting in considerable ponding to occur at the base of the flume in a depression outside of the plot. Eventually the excess discharge began to backflow into the flume and the decision was made to dig a pit to capture excess runoff. The water was then pumped out creating a drop in flow in the hydrograph after 105 minutes into this simulation (Figure 17). Each series of simulations were subject to comparable rainfall conditions yet produced drastically different results. Even simulations yielding similar percentages of runoff had substantially different peak flows (Figure 23). Peak flow was greatest on the degraded hillslope. The data also shows a decrease in peak flow from 2010 to 2012 on the mesquite plot. Runoff is not simply a factor of rainfall intensity alone. It is dependent on a suite of variables including intensity, soil type, soil moisture, slope, vegetation type, basal cover, infiltration, and time.

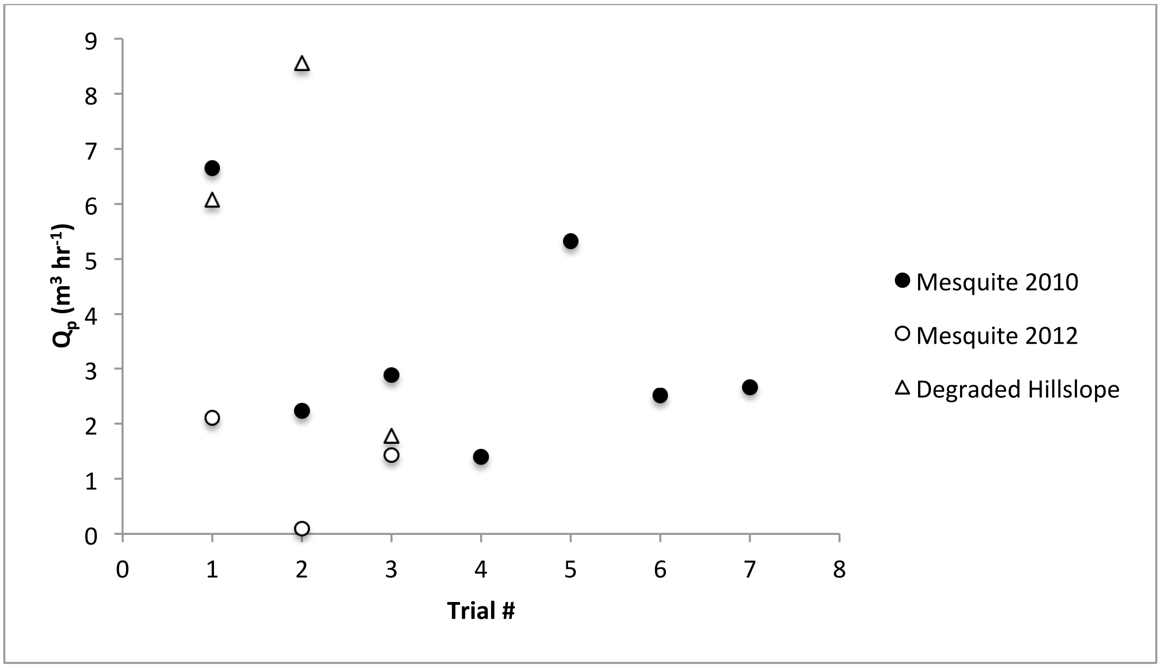

Figure 23. Differences in peak flows between each trial.

Sediment load

Upon analyzing the sediment samples it became apparent that an error was made in the processing of the data. Samples collected on the mesquite plot before restoration in October 2010 were analyzed using the total suspended solids (TSS) method and samples collected after restoration and at the degraded site were analyzed using the sediment-sample concentration (SSC) method. These two analytical methods are often used interchangeably to describe sediment loads in mg/L or the equivalent, ppm. However, Gray et al. (2000) found that that these two methods vary significantly when sand-sized material composes a substantial percentage in the sediment. They noted that one of the greatest disparities between the two methods is that the SSC method can determine the percentage of sand-sized and finer materials whereas the TSS method cannot.

Furthermore, the differences between the two methodologies become more pronounced as the percentage of sand-sized particles in the sediment increase in abundance.

Sediment loads for all trials are given in ppm (Table 6). The flow of runoff and amount of discharge from the mesquite plot after restoration, which were analyzed using SSC, were significantly lower than that of the mesquite plot before restoration, which was analyzed using TSS. When attempting to calculate the sediment load in kg/ha it was found that the SSC method were 15 times larger on average than those analyzed using the TSS method, despite having much lower rates of flow. This data insinuates that these disturbed soils contain a much greater percentage of sands than previously thought. It also means that sediment loads calculated from the 2010 mesquite plot data were substantially undervalued. Because two different analytical methods were used, it is unclear as to whether the sand percentage increased, decreased, or remained the same in response to the mechanical mixing of the soil during the restoration of the mesquite plot. Sand requires more kinetic energy to transport. If the sand percentage has increased in response to restoration, than the increased energy requirements could slow the movement of runoff and increase infiltration. However, soils that frequently dry out, like those at of the Blackland Prairie among other sandy clays, can result the surface soil becoming water repellent and increase runoff (Dekker & Ritsema 1994). The ecohydrological implications of the sand content may provide valuable insight into the dynamic relationship between sediment and the percentage of sand.

Despite these differences, the data was consistent in regards to when the greatest percentage of sediment was measured during the course of runoff. All three series of simulations were log-linear relationships between sediment load and runoff time. Higher amounts of sediment were observed within the first few minutes of runoff with a general waning trend of lower sediment percentages as runoff subsided. However, the relative abundance of sediment was different between the simulations. The 2010 trials of the mesquite plot displayed a significant decrease in sediment load after the initial flush **(**Figure 24**)** whereas the 2012 mesquite plot simulations displayed a much more gradual decline to comparatively constant levels of sediment **(**Figure 25**)**. The sediment for the degraded hillslope contained much less vegetative cover than the 2010 and 2012 mesquite plots, but sediment concentrations were comparable to that of the 2012 mesquite plot simulations (Figure 26). Also, the declines in sediment content over the course of runoff are not as drastic as the 2010 mesquite plot simulations thus showing no signs of a large initial flush. This suggests that initial predictions made by Johnson (1982) were correct that the training areas of Fort Hood displaying worst case scenario degradation, like that of the degraded hillslope, do not produce high amounts of sediment due to most of the topsoil already being eroded from years of intensive disturbance. Many questions remain unanswered regarding the sediment loads in this system, however it is likely related to a multitude of variables from soil moisture to soil aggregate formation and everything in between. More accurate details can be provided in future studies if samples are subject to both the TSS and SSC analytical methods.

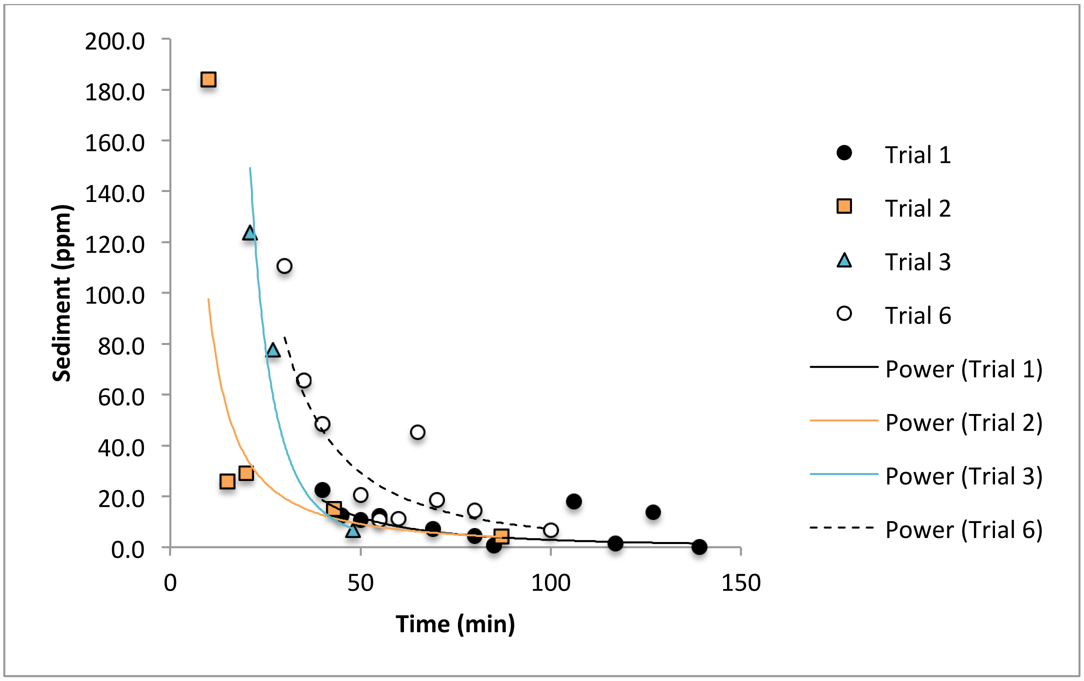

Figure 24. Sediment loads and their corresponding logarithmic equations for the 2010 mesquite plot before restoration.

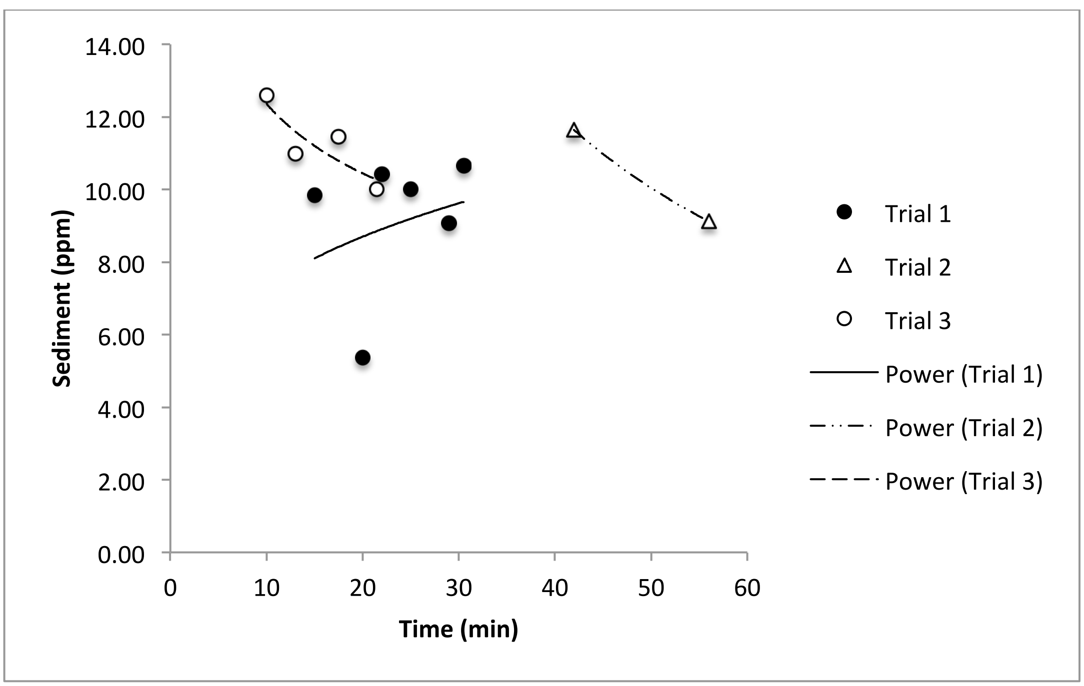

Figure 25. Sediment loads and their corresponding logarithmic equations for the 2012 mesquite plot after restoration.

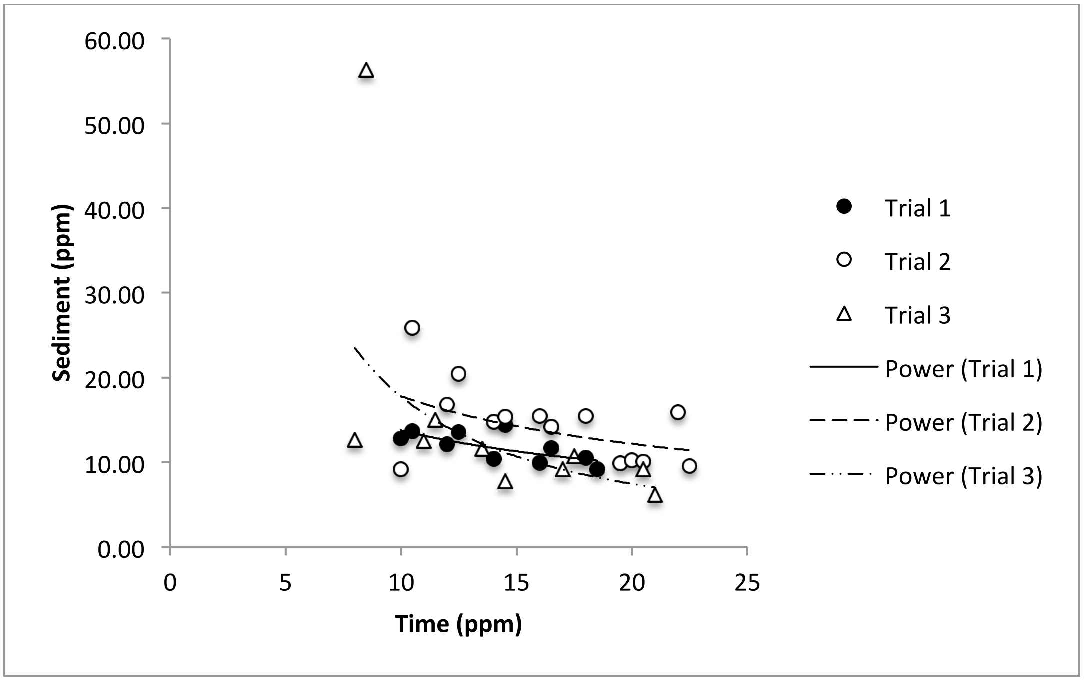

Figure 26. Sediment loads and their corresponding logarithmic equations for the 2012 degraded hillslope.

CHAPTER V

CONCLUSION

This study used large-scale above canopy rainfall simulation to identify the ecohydrological implications of a restored and highly degraded military tracked vehicle-training area. The areas of interest were a degraded hillslope and a mesquite plot before and after restoration though a machinery intensive, high disturbance, individual plant treatment brush removal method. The analysis addressed the dynamic relations between rainfall intensity, duration, runoff, and sediment load. Statistical data on basal cover in response to land use change was investigated. Principal findings were that the amount of live plant cover increased after the restoration of the mesquite site. The degraded hillslope was characterized by bareground and exposed bedrock. Runoff occurred very rapidly on the degraded hillslope though the amount of sediment transported was relatively low. The mesquite plots displayed higher infiltration rates and decreased surface runoff in response to restoration. Furthermore the amount of sediment being transported decreased substantially once restored.

Several complications occurred with the rainfall simulator with the most limiting factors being water supply and high winds. Initially the objective was to conduct rainfall simulations in 2011. However, with Texas in the midst of the worst drought since the 1950s, the DoD was much more reluctant to grant permission to obtain water from Fort Hood. Complications also arose with the bubble flow meters at least once during each series of simulations requiring measurements of the flume depth to be made manually. Sometimes sediment samples were simply lost and could not be located, making comparisons between data sets difficult. Collecting rain gauge data within the plot was not possible without causing some disturbance in the plot, which may have caused fluctuations in the sediment data. The only exception being the degraded site where enough rock was exposed to take measurements with minimal soil disturbance. The two different sediment analysis methods also prevented an accurate comparison of sediment load in terms of kg/ha, which is why that information was not presented. Other inconsistencies in measurements varied between the person recording the data, however these usually required minor conversions from imperial to metric units. Rainfall simulation and the subsequent data collection procedures caused significant amounts of disturbance within and around the plots, leaving them almost unrecognizable after simulations were concluded.

Researchers attempting to replicate this study should conduct rainfall simulations under similar conditions (i.e. soil moisture, weather, season, climate, time before previous simulation, etc.) to ensure statistical validity. Statistically based replicated plot studies will best help researchers and land managers assess the impacts of disturbance at different spatial scales and facilitate a collective understanding of the ecohydrological implications that influence restoration. It is also important to recognize when, where, and how the site was impacted to fully assess the ecohydrological implications at the landscape level (Anderson et al. 2005b).

Future research should analyze the ecohydrological processes affected on other highly degraded areas like explosives training range and areas that are accidently burned with high frequency from artillery training. Future studies should also focus on quantifying the amount of sediment being transported offsite at the landscape level in terms of kg/ha. This information may benefit the DoD by helping determine if their costly best management practices (BMPs) are successful. The types of information and data collected through rainfall simulation can be valuable to land managers who are seeking to implement a BMP or who assess the effectiveness of an existing BMP. Lastly, this may benefit the communities surrounding Fort Hood that rely on Belton Lake and the Cowhouse Creek watershed for clean drinking water. The analyses conducted in this study just barely graze the surface of the ecohydrological processes at work in this system, however the data presented provide valuable insight into the role ecohydrology plays in this highly disturbed landscape.

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