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Storm Hydrograph Characteristics and Curve Numbers of Loose-Dumped Spoil in Eastern Kentucky

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STORM HYDROGRAPH CHARACTERISTICS AND CURVE NUMBERS OF LOOSE-DUMPED MINE SPOIL IN EASTERN KENTUCKY

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Biosystems and Agricultural
Engineering in the College of Engineering at the University of Kentucky

By

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ABSTRACT OF THESIS

STORM HYDROGRAPH CHARACTERISTICS AND CURVE NUMBERS OF LOOSE-DUMPED MINE SPOIL IN EASTERN KENTUCKY

Traditional mine reclamation often results in highly compacted lands which prohibit tree growth and survival, reduce infiltration rates, and increase runoff. In 2005, six 0.4 ha plots were constructed on the Bent Mountain surface mine in eastern KY by the University of Kentucky in accordance with Forestry Reclamation Approach's low compaction guidelines. The plots consisted of two replications each of (1) brown weathered sandstone (BROWN), (2) gray unweathered sandstone (GRAY), (3) and a combination of both sandstones and shales (MIXED). The goal of this project was to assess the hydrologic performance on a *storm event basis* (monitoring years 2012-2013) of the plots. It was hypothesized that the increase in tree growth on the plots, especially in BROWN, would result in storm-based hydrological changes since plot construction. Results showed that no significant differences were found between the 2005-2006 and 2012-2013 monitoring periods for the storm parameters of discharge volume, discharge duration, and curve number. A significant increase was noted for peak discharge, lag time, and response time. No significant differences were found between spoil types in spite of the difference in vegetative cover. Results suggest that placement of spoil has the greatest influence over storm hydrology at this point in time.

KEYWORDS: Storm hydrology, curve number, Forestry Reclamation Approach, surface mining, reclamation.

Mary Katherine Weatherford

July 1, 2014

STORM HYDROLOGRAPH CHARACTERISTICS AND CURVE NUMBERS OF LOOSE-DUMPED MINE SPOIL IN EASTERN KENTUCKY

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For my family

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

The Appalachian coal fields stretch from Alabama to Pennsylvania covering parts of Alabama, Kentucky, Ohio, Tennessee, Virginia and West Virginia (Figure 1.1). This region encompasses over 186,000 km^2 of which over 80% is forested (Vogel, 1981; Zipper et al., 2011). From 1973 to 2000, mining was the largest, direct anthropogenic influence on land cover change within the region, in terms of material removed (Sayler, 2012). As of 2012, Kentucky was the third largest coal producing state (Wyoming was first and West Virginia was second), employing over 11,800 people in the eastern part of the state (USEIA, 2013). However, employment levels for the eastern part of the state decreased by nearly 20% due in part to economic competition from the natural gas sector (USEIA, 2012; 2013; Estep, 2014; Rocco, 2014). Regulations, such as the proposed Clean Power Plan from the Environmental Protection Agency (EPA) (2014), are also expected to negatively impact coal mining jobs. Although mining has and continues to decrease in the Appalachian region, hundreds of thousands of hectares of previously mined lands remain as grass and shrub lands and not forested ecosystems (Chaney et al., 1995; Zipper et al., 2011; Sayler, 2012).

The Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires the restoration of mined lands largely to pre-mining levels with a focus on reconstructing original or approximate original contours and stabilizing mine spoils to prevent erosion. The common result of the law was to produce highly compacted lands which provide poor conditions for tree growth but provide a suitable habitat for grasses and shrubs (Graves et al., 2000; Angel et al., 2008; Zipper et al. 2011). Hence, much of the post-SMCRA reclaimed mined lands were converted from forests to herbaceous communities (Burger, et al. 2011; Zipper et al., 2011). Since then, efforts such as the Appalachia Regional Reforestation Initiative (ARRI) have focused on planting high value hardwood trees and increasing tree survival rates and natural succession (Angel et al., 2005; Angel et al., 2008).

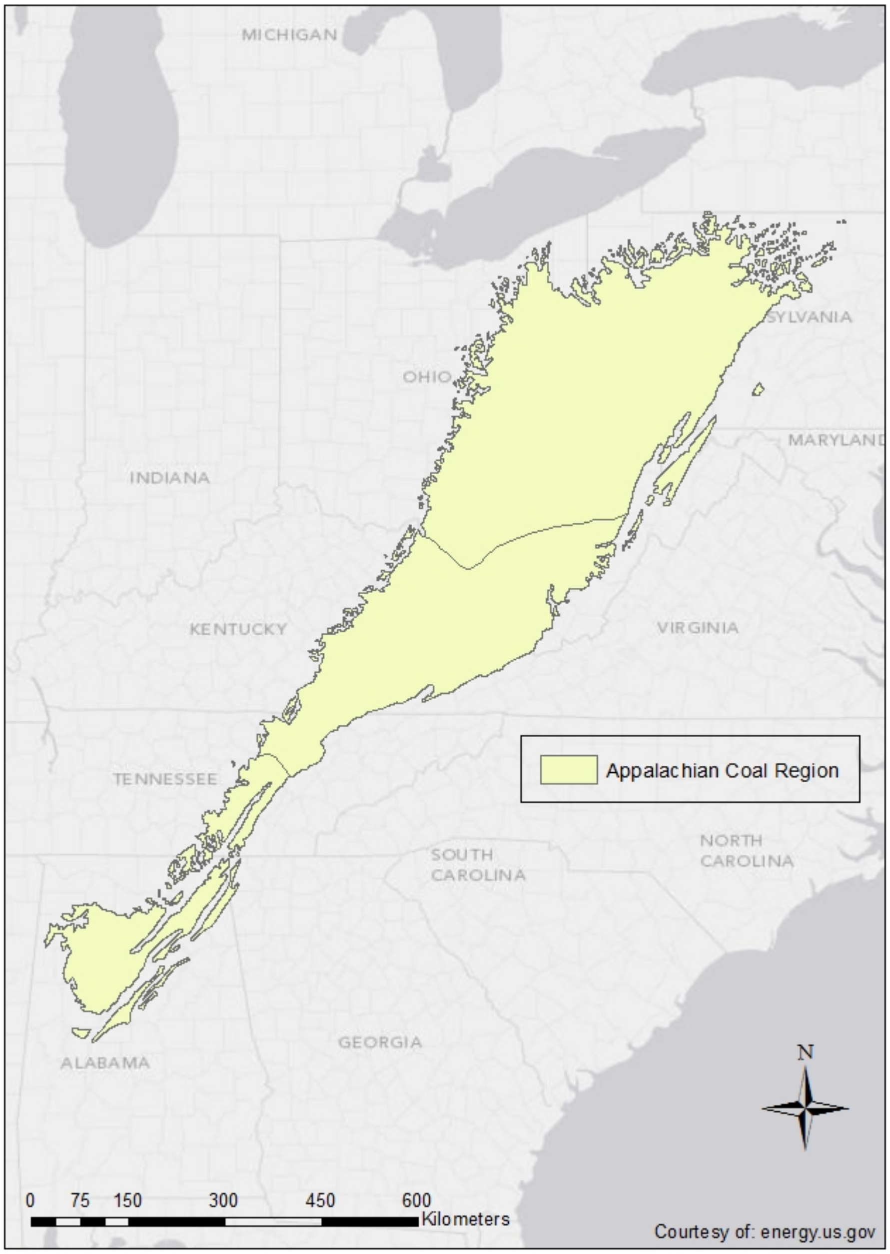

Figure 1.1: The Appalachian coal fields extend from Alabama to Pennsylvania with forest serving as the dominate land cover.

The Forestry Reclamation Approach (FRA) was created in an effort to re-establish native hardwood forests on mine sites (Angel et al., 2005). The FRA consists of five steps for re-establishing a forested ecosystem on mined lands, one of which is the use of a non-compacted topsoil or topsoil substitute (i.e. loose-dumped spoil) as a planting medium (Burger, et al. 2005). While the FRA is relatively young, research to date indicates it has been a successful tool in the mined land reforestation effort in regards to vegetation, hydrology and water quality (Graves et al., 2000; Burger et al., 2005; Angel et al., 2008; Taylor et al., 2008; Emerson et al., 2009; Sena, 2014) (Figure 1.2). However, research on hydrologic characteristics, particularly storm-based, has only been conducted on a young (1-2 year old) forest. Hence, the effect of interception and storage was not realized at that time, but may be significant after a 7-8 year period (Taylor et al., 2009b).


(a)


(b)

Figure 1.2: Tree growth on brown, weathered sandstone, placed in accordance with FRA, (a) immediately after planting and (b) eight years after planting.

1.2 OBJECTIVES

This project was conducted to evaluate the storm hydrologic characteristics (rainfall-runoff relationships) on 7-8 year old plots consisting of either (1) brown, weathered sandstone (BROWN), (2) gray, unweathered sandstone (GRAY), and (3) a mixture of BROWN and GRAY and shale (MIXED). The objectives for the project were:

1. Determine and compare the storm hydrologic characteristics for these three loose dumped spoil types (years 7 and 8) and compare the results to those from years 0 and 1 (Chapter 2).
2. Develop and compare curve numbers for the loose dumped spoil types (years 7 and 8) and compare the results to those from years 0 and 1 as well as to those from a forested, reference watershed (Chapter 3).

1.3 ORGANIZATION OF THESIS

Chapter 1 contains an introduction of the research problems and research objectives. Chapters 2 and 3 provide a detailed description of the work done to satisfy the objectives of this thesis. Chapter 4 discusses the conclusions of the research while Chapter 5 explores options for future work.

CHAPTER 2: STORM HYDROGRAPH CHARACTERISTICS OF A YOUNG FOREST ESTABLISHED ON LOOSE-DUMPED SPOIL IN EASTERN KENTUCKY

2.1 INTRODUCTION

Since the passage of the Surface Mining Control and Reclamation Act (SMCRA) of 1977, over 600,000 ha of land, much of it forested, has been mined in the Appalachian coal fields of the eastern United States (Zipper et al., 2011). Once mined, these lands are reclaimed largely not as forests but as herbaceous communities dominated by grasses and shrubs (Chaney et al., 1995; Zipper et al., 2011). The reason for the transformation in vegetation type is due in large part to the high levels of surface compaction associated with traditional mine reclamation techniques which inhibit tree growth and survival and favor herbaceous communities (Graves et al., 2000; Conrad et al., 2002; Burger et al., 2011; Zipper et al., 2011).

Along with the change from a forested ecosystem to a herbaceous one, compacted mine lands also result in a myriad of changes in the hydrology (Ritter and Gardner 1993; Negely and Eshleman, 2006; McCormick et al., 2009; McCormick and Eshleman 2011) such increased runoff volumes and peak flows (Dick et al., 1983; Weiss and Razem, 1984; Bonta et al., 1997; Bonta and Dick, 2003) which are primarily caused by significant reductions in soil infiltration rates (Jorgensen and Gardner, 1987; Guebert and Gardner, 2001) though changes in evapotranspiration rates associated with different vegetation communities may also play a role (Hornbeck et al., 1970; Bosch and Hewlett, 1982). Traditional mine reclamation techniques, as noted by Ferrari et al. (2009), can produce a hydrologic state similar to that resulting from the urbanization of a watershed. Forested ecosystems such as those found in Central Appalachian ecoregion of the United States provide many valuable goods and services related to water quantity and quality, habitat, carbon sequestration, and the like (Turner and Daily, 2008; Fields-Johnson., 2011; Zipper et al., 2011). How to best reclaim mined lands to support tree growth and survival has been the focus of much research in Central Appalachia and has resulted in the development of the Forestry Reclamation Approach (FRA) (Burger et al., 2005). The FRA consists of five steps: (1) selection of a suitable medium for tree growth by using best material available with topsoil or weathered sandstone preferred, (2) minimizing compaction of the medium by allowing only one or two dozer passes, (3) use of minimal, tree-compatible ground cover, (4) use of early successional and commercially valuable tree species, and (5) use proper tree planting techniques.

Research evaluating the ability of the FRA to re-establish forested ecosystems has largely examined tree growth and survival (Angel et al., 2008; Emerson et al., 2009; Showalter et al., 2010; Wilson-Kokes et al., 2013; Sena, 2014) though some studies have examined soil genesis (Miller et al., 2012), water quality (Agouridis et al., 2012; Sena, 2014) and hydrology (Taylor et al., 2009a; Taylor et al., 2009b; Sena 2014). With regards to hydrology, Taylor et al. (2009b) examined storm hydrograph characteristics (discharge volume, peak discharge, discharge duration, lag time, and response time) of a 1-2 year old forest planted on three types of loose-dumped soil placed in accordance with FRA. The spoil types examined were (1) brown, weathered sandstone (BROWN), (2) gray, unweathered sandstone (GRAY), and (3) a mixture of the two sandstone types and shale (MIXED). The authors concluded that spoil type did not significantly influence storm hydrology, but rather it was the placement of the spoil in accordance with FRA specifications that was controlling, and as also seen by Taylor et al. (2009a), could result in a hydrograph similar to a forested watershed. Taylor et al. (2009b) also noted that as the forest matures, it was expected that interception and evapotranspiration would play a greater role in hydrologic response.

Sena (2014) re-examined the effect of spoil type on vegetation growth and interflow (storm and base flows) on the same plots used in Taylor et al. (2009a) and Taylor et al. (2009b). Vegetation growth was significantly different between the spoil types with BROWN exhibiting substantially greater tree volumes (12,270 cm^3) and ground cover (99%) as compared to GRAY (237 cm^3 and 10%) and MIXED (1,840 cm^3 and 20%). Sena (2014) also noted significantly less rainfall (storm and base flows) discharged as interflow during the growing season on BROWN as compared to GRAY and MIXED; no significant differences were noted between spoil types during the non-growing season. The author attributed the differences in interflow volumes on BROWN during the growing season to higher rates evapotranspiration. No separation of storm and base flows was performed, and as seen in work by Beasley (1976), a substantial portion of flow in forested watersheds can be classified as baseflow. Thus, the effect of soil type, and hence the vegetation, on storm flow characteristics was not determined.

Calder and Aylward, (2006) note that forests, theoretically, influence storm hydrology primarily through evapotranspiration which creates soil moisture deficits. These soil moisture deficits allow for the storage of more stormwater, and hence less runoff, particularly for small storm events where a greater percentage of the total rainfall may be held in the soil profile (Lull and Reinhart, 1972). Thus, the objective of this study was to evaluate the influence of spoil type (BROWN, GRAY and MIXED) on storm hydrologic characteristics (discharge volume, peak discharge, lag times, response times, and discharge duration) for a young (7 and 8 year old) forest. Results from this study will further the understanding as to how loose-dumped mine spoil affects hydrology and will aid reclamationists as they seek to restore forest ecosystems on surface mined lands.

2.2 METHODS

2.2.1 Study Site

The research was conducted on the Bent Mountain surface mine (BM), which is located in the Cumberland Plateau in eastern Kentucky (latitude 37° 35.88 N; longitude 82° 24.31 W) (Figure 2.1). The average annual rainfall is 114 cm and the climate is humid and temperate with summer temperatures ranging from 18 to 32 °C and winter temperatures ranging from -4 to 7°C. Underlying geology is dominated by sandstone followed by some shale and siltstone all of the Breathitt formation of Lower to Middle Pennsylvania age (Wunsch, 1993).

In 2005, six 0.4 ha plots (three spoil types, two replicates of each) were constructed at the BM surface mine. The spoil types consisted of: (1) brown, weathered sandstone (BROWN), (2) gray, unweathered sandstone (GRAY), and (3) a mixture of both BROWN and GRAY in addition to shale (MIXED). The loose-dumped spoil was placed overtop a compacted layer in accordance with the FRA (Burger et al., 2005) to a depth of approximately 2.5 m. It was assumed that the compacted layer was impervious. The suface topography was left rough creating macropores and ridge to depression depths of 0.5-1.5 m. The underlying compacted layer was graded with a longitudinal slope of approximately 2% and side slopes between 3-10%. A 10.2 cm, perforated PVC pipe was

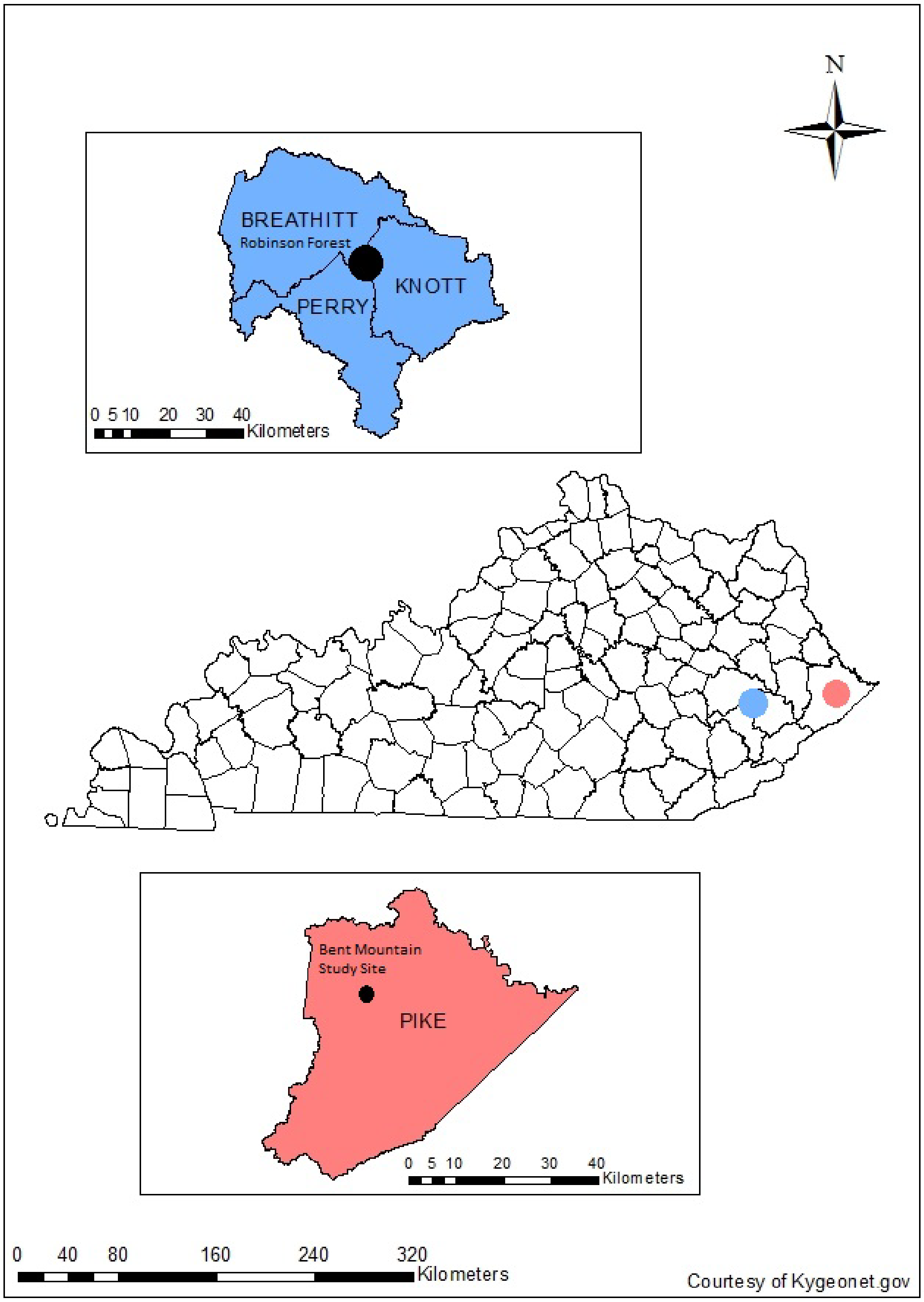

Figure 2.1: Location of the Bent Mountain (BM) Surface Mine and the University of Kentucky's Robinson Forest (RF).

placed along the center of the plots to direct interflow to the data acquisition equipment (Taylor et al., 2009b). Interflow from the data acquisition outlet was then directed into an underlying deep mine to ensure plots remained hydrologically separated. The plots were planted immediately after construction with 1:0 bare root seedlings (1.8 m x 2.4 m spacing) of white oak (*Quercus alba*), red oak (*Quercurs rubr*a), yellow-poplar (*Liriodendron tulipfera*), and green ash (*Fraximus pennsylvanica*). Groundcovers were not used in order to help minimize competition to tree seedlings.

2.2.2 Hydrologic Data

Precipitation data were recorded using a Rain Collector II tipping bucket rain gage (Davis Instruments, Hayward, CA) equipped with a HOBO Event datalogger (Onset Computer Corporation, Cape Cod, MA) in 2005 and 2006. This rain gage was located approximately 300 m from the plots. However, due to equipment failure, for 2012 and 2013, precipitation data (15 minute intervals) were obtained from the USGS gage 03210000, which is located approximately 8 km from the plots near the community of Meta, KY. A total of 24 rainfall events were used in the analysis: 12 events (14.5-42.9 mm) from the 2005-2006 monitoring period and 12 events (15.4-44.4 mm) from the 2012-2013 monitoring period (Table 2.1). The mean and median rainfall depths for the 2005-2006 monitoring period were 23.4 and 25.8 mm, respectively; for the 2012-2013 monitoring period, the mean and median rainfall depths were 26.9 and 19.5 mm, respectively. Rainfall events less than 25.4 mm were included in the analysis to increase sample size.

Interflow data were recorded using calibrated metal tipping buckets and HOBO Event dataloggers, which were located at the outlet of each plot. Interflow was measured as no runoff was observed on the plots due to their hummocky nature. Baseflow separation was conducted using the concave method (McCuen, 2005). Discharge volume, peak discharge, lag times, response times, and discharge durations were determined for all plots during the 2012-2013 monitoring period (Figure 2.2). For the 2005-2006 monitoring period, these hydrograph data were obtained from Taylor et al. (2009b). Lag time was defined as the difference in time from the start of precipitation to the time of peak discharge. Response time was defined as the start of precipitation to the start of

Table 2.1: Storm Event Characteristics for Bent Mountain Plots.

Date	Precipitation (mm)	Duration (h)	Total 5-day antecedent rainfall (mm)	Average Intensity (mm h^{-1})
--------------------2005-2006--------------------[1]				
July 21, 2005	20.1	0.9	7.6	22.3
August 6, 2005	16.0	0.9	0.0	17.8
August 16, 2005	19.6	4.6	0.0	4.3
September 16, 2005	19.4	1.1	0.0	17.6
October 7, 2005	25.4	5.3	4.6	4.8
April 7, 2006	38.1	17.7	27.3	2.2
August 11, 2006	44.1	4.6	11.7	9.6
August 19, 2006	15.4	2.3	3.7	6.7
August 29, 2006	18.3	7.0	9.6	2.6
September 22, 2006	16.3	3.1	1.1	5.3
October 16, 2006	30.6	13.3	3.1	2.3
November 1, 2006	16.9	4.5	12.7	3.8
Mean±Std.Dev. (all events)	23.4±9.4	5.4±5.2	6.8±7.9	8.3±7.0
--------------------2012-2013--------------------				
June 1, 2012	23.4	15.0	0.1	1.5
August 6, 2012	33.3	6.0	0.6	5.3
August 10, 2012	14.5	2.0	1.9	6.4
August 15, 2012	28.2	2.0	0.6	12.5
September 17, 2012	33.0	29.0	0.0	1.1
October 28, 2012	42.9	9.5	0.2	1.8
April 17, 2013	17.5	3.8	0.5	4.4
May 20, 2013	20.1	3.0	0.1	6.2
June 30, 2013	22.9	42.5	0.5	0.5
July 11, 2013	42.4	2.3	0.3	17.0
August 10, 2013	16.0	4.5	0.3	3.4
November 25, 2013	28.7	0.63	0.2	1.0
Mean±Std.Dev. (all events)	26.9±9.6	10.0±13.0	0.4±0.5	5.1±4.8

[1]Source: Taylor et al. (2009b).

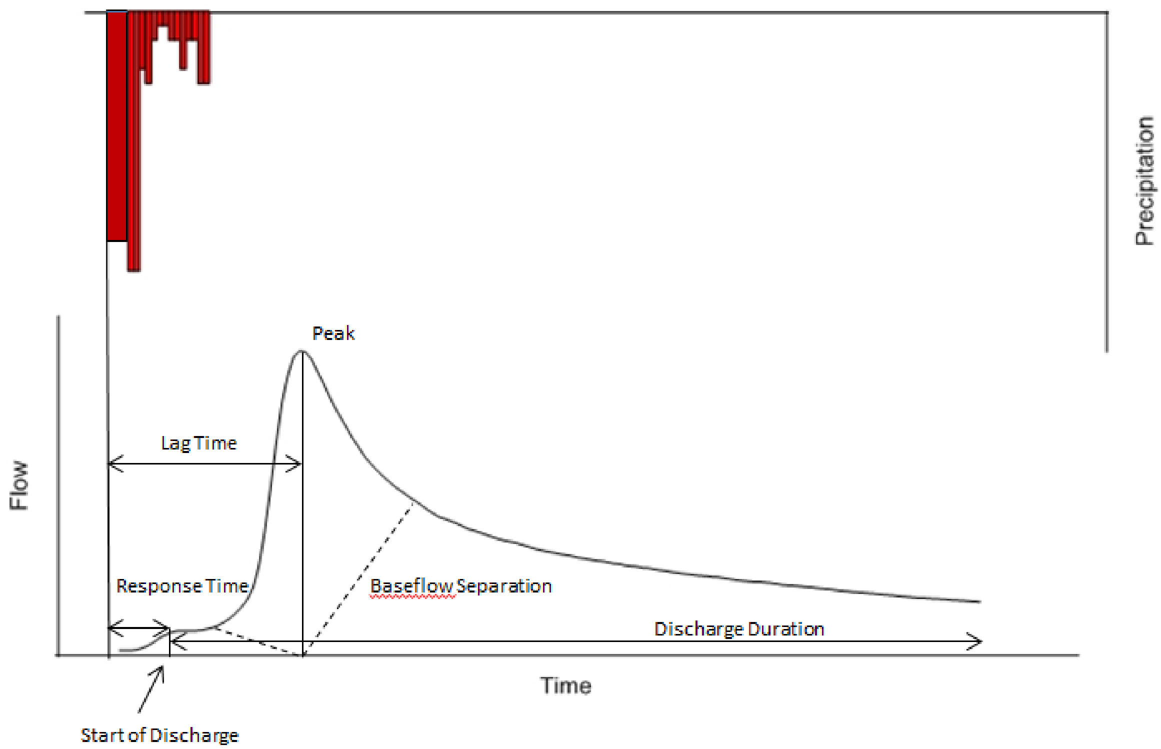

Figure 2.2: Example of Hydrograph Baseflow Separation and Parameter Estimation.

discharge. The start of discharge was determined by the lowest discharge value before the rising limb, per McCuen (2005) or as soon as a discharge increase was noted. For an unknown reason, one of the GRAY plots (plot 6) hydrologically behaved quite differently than the other plots (discharge was seldom recorded) and therefore was not used in this study.

2.2.3 Statistical Analysis

A general linear model (PROC GLM) in Statistical Analysis Software 9.3 (SAS, 2011) was used to test for significant differences in the storm hydrograph parameters discharge volume, peak discharge, lag time, response time, and discharge duration due to spoil type (BROWN, GRAY and MIXED) and hence vegetation (α=0.05. Temporal changes were across the 2005-2006 and 2012-2013 monitoring periods. Precipitation depth and growing season (April 20-October 26) served as covariates.

2.3 RESULTS AND DISCUSSION

2.3.1 Temporal

No significant differences were noted between the monitoring periods 2005-2006 and 2012-2013 for the storm hydrograph parameters discharge volume and duration. For the 2005-2006 monitoring period, mean discharge volume was 12.9 m^3 and mean discharge duration was 5.5 days. For the 2012-2013 monitoring period, the values were 17.5 m^3 and 2.6 days, respectively (Tables 2.2-2.3). Though not quantified in this study, data indicated that baseflow was sustained on the plots throughout the length of the study. Significant differences were found for the storm hydrograph parameters peak discharge, lag time, and response time (Tables 2.4-2.6). From the 2005-2006 monitoring period to the 2012-2013 monitoring period, mean peak discharge increased from 6.3 $x10^{-4}$ m^3 to 7.1 $x10^{-4}$ m^3. Mean lag time increased from 0.10 to 0.33 days (2.1 to 7.9 hours), and mean response time increased from 0.05 to 0.16 days (1.2 to 3.8 hours) (Table 2.7).

The increase in lag time and response time is likely linked to the weathering of the spoils. Miller et al. (2012) observed that BROWN, GRAY and MIXED spoils all weathered as a result of freeze-thaw forces and dissolution of carbonate cements. During a one-year period, the authors observed that BROWN and MIXED had a normalized

Table 2.2: Bent Mountain Plot Discharge Volumes (m^3).

Date	Plots[1]				
	1	2	3	4	5
--------------------2005-2006--------------------[2]					
July 21, 2005	13.9	8.8	12.0	--	13.8
August 6, 2005	11.0	7.2	6.5	6.9	8.3
August 16, 2005	10.6	5.7	6.7	6.0	5.9
September 16, 2005	2.1	1.5	1.1	2.0	2.1
October 7, 2005	6.3	1.3	1.3	3.0	2.5
April 7, 2006	34.7	20.2	--	57.5	54.9
August 11, 2006	12.9	19.4	5.2	18.3	19.7
August 19, 2006	2.9	5.3	0.2	4.8	3.0
August 29, 2006	7.5	11.2	0.7	6.6	4.9
September 22, 2006	9.0	--	2.4	3.1	2.9
October 16, 2006	27.7	19.1	15.8	24.8	27.3
November 1, 2006[3]	11.8	7.4	8.8	--	12.1
Mean ±SD (all events)	12.5±9.6	9.7±6.9	5.5±5.1	13.3±17.2	13.1±15.3
--------------------2012-2013--------------------					
June 1, 2012	7.1	8.6	--	23.5	24.7
August 6, 2012	31.9	34.0[4]	35.0	--	--
August 10, 2012	0.2	--	0.1	--	--
August 15, 2012	8.0	--	8.5	--	--
September 17, 2012	--	--	--	33.0	25.3
October 28, 2012[3]	2.1	--	1.7	2.5	4.8
April 17, 2013[3]	27.7	9.3	37[4]	16.7	17.7
May 20, 2013	0.3	0.4	0.0[4]	1.4	1.6[4]
June 30, 2013	0.2	1.1	0.1	2.8	1.9
July 11, 2013	25.7	26.6	15.4[4]	23.2	23.1
August 10, 2013	3.3[4]	--	--	17.3	16.0
November 25, 2013[3]	24.1	50.0	--	44.2	57.8
Mean ±SD (all events)	11.9±12.7	18.6±18.8	12.2±15.6	18.3±14.7	1.29±17.3

[1]Plots 1 and 3 are brown, weathered sandstone; plot 2 is gray, unweathered sandstone; and plots 4 and 5 are a mixture of both brown, weathered sandstone and gray, unweathered sandstone and shale. Plot 6 (gray, unweathered sandstone) was not used in the analysis.
[2]Source: Taylor et al. (2009b).
[3]Non-growing season.
[4]Hydrograph was incomplete after the peak, so value was estimated.

Table 2.3: Bent Mountain Plot Discharge Durations (d).

Date	Plots[1]				
	1	2	3	4	5
--------------------2005-2006--------------------[2]					
July 21, 2005	4.8	1.7	4.1	1.8	5.9
August 6, 2005	7.4	5.9	8.4	7.3	9.8
August 16, 2005	3.4	3.7	6.5	4.2	3.7
September 16, 2005	5.7	6.2	0.6	5.4	6.6
October 7, 2005	8.0	14.7	0.7	14.9	17.8
April 7, 2006	2.8	11.2	--	15.0	9.7
August 11, 2006	7.7	7.8	5.3	14.6	14.6
August 19, 2006	4.2	6.0	1.9	5.4	4.9
August 29, 2006	4.0	3.2	1.8	4.0	3.1
September 22, 2006	0.7	--	1.2	1.5	1.0
October 16, 2006	13.0	13.4	10.2	10.3	14.3
November 1, 2006[3]	3.7	1.2	1.6	--	2.2
Mean ±SD (all events)	5.4±3.2	6.8±4.5	3.8±3.3	7.7±5.2	7.8±5.4
--------------------2012-2013--------------------					
June 1, 2012	0.7	1.1[4]	--	15.7	13.7[4]
August 6, 2012	2.4[4]	1.5[4]	4.2[4]	--	--
August 10, 2012	0.6	--	0.4	--	--
August 15, 2012	3.1	--	8.0	--	--
September 17, 2012	--	--	--	7.6[4]	7.8[4]
October 28, 2012[3]	1.9[4]	--	3.1[4]	1.5	2.1
April 17, 2013[3]	9.8	10.7	10.7	10.8	6.3
May 20, 2013	1.5	1.0	--	1.5	1.5
June 30, 2013	0.2	0.8[4]	0.6	0.8[4]	0.8[4]
July 11, 2013	2.0	2.4[4]	3.0[4]	4.0[4]	2.1[4]
August 10, 2013	1.0	--	--	--	2.2
November 25, 2013[3]	3.8[4]	4.5[4]	--	4.2[4]	4.5[4]
Mean ±SD (all events)	2.5±2.5	3.1±3.3	4.3±3.5	5.8±4.9	4.6±3.9

[1]Plots 1 and 3 are brown, weathered sandstone; plot 2 is gray, unweathered sandstone; and plots 4 and 5 are a mixture of both brown, weathered sandstone and gray, unweathered sandstone and shale. Plot 6 (gray, unweathered sandstone) was not used in the analysis.
[2]Source: Taylor et al. (2009b).
[3]Non-growing season.
[4]Hydrograph was incomplete after the peak, so value was estimated.

Table 2.4: Bent Mountain Plot Peak Discharge ($m^3\ s^{-1} \times 10^{-4}$).

Date	Plots[1]				
	1	2	3	4	5
--------------------2005-2006--------------------[2]					
July 21, 2005	10.9	7.2	9.8	--	5.6
August 6, 2005	3.5	8.1	8.8	2.4	3.0
August 16, 2005	10.0	7.4	10.3	--	4.3
September 16, 2005	6.6	5.6	5.5	3.7	2.3
October 7, 2005	6.3	3.8	2.5	2.1	4.8
April 7, 2006	25.2	7.7	--	4.4	4.7
August 11, 2006	29.1	11.5	6.6	14.2	10.5
August 19, 2006	4.6	3.9	7.2	1.0	0.2
August 29, 2006	10.1	12.0	2.4	6.9	3.0
September 22, 2006	7.2	--	2.1	1.9	1.0
October 16, 2006	7.2	5.2	2.4	2.5	2.3
November 1, 2006[3]	8.4	10.5	5.5	--	1.3
Mean ±SD (all events)	10.8±8.0	7.5±2.8	5.7±3.1	4.3±4.1	4.5±3.7
--------------------2012-2013--------------------					
June 1, 2012	7.0	12.6	--	12.6	12.6
August 6, 2012	12.6	12.6[4]	8.3	--	12.6
August 10, 2012	0.5	--	1.1	--	--
August 15, 2012	8.3	--	8.3	--	--
September 17, 2012	--	--	--	8.2	7.0
October 28, 2012[3]	0.7	--	0.5	2.5	1.8
April 17, 2013[3]	12.6	5.2	8.3	10.2	10.2
May 20, 2013	1.0	1.4	.03	1.7	0.6
June 30, 2013	1.0	3.5	0.8	4.7	1.8
July 11, 2013	12.6	12.6	12.5	12.6	12.6
August 10, 2013	5.2	--	--	11.5	10.6
November 25, 2013[3]	7.0	8.3	--	10.0	8.9
Mean ±SD (all events)	6.2±5.0	8.0±4.8	5.0±4.9	8.2±4.3	7.9±4.7

[1]Plots 1 and 3 are brown, weathered sandstone; plot 2 is gray, unweathered sandstone; and plots 4 and 5 are a mixture of both brown, weathered sandstone and gray, unweathered sandstone and shale. Plot 6 (gray, unweathered sandstone) was not used in the analysis.
[2]Source: Taylor et al. (2009b).
[3]Non-growing season.
[4]Hydrograph was incomplete after the peak, so value was estimated.

Table 2.5: Bent Mountain Plot Lag Time (d x 10^{-2}).

Date	Plots[1]				
	1	2	3	4	5
--------------------2005-2006--------------------[2]					
July 21, 2005	2.9	1.5	1.2	--	7.1
August 6, 2005	0.0	1.8	1.3	1.1	0.0
August 16, 2005	1.4	1.5	1.5	--	1.9
September 16, 2005	2.2	2.2	2.7	2.4	3.3
October 7, 2005	15.7	15.8	16.9	19.9	32.4
April 7, 2006	9.2	3.4	--	10.1	54.3
August 11, 2006	9.4	9.6	9.2	10.1	9.7
August 19, 2006	1.5	1.5	2.3	1.8	21.3
August 29, 2006	2.6	2.6	3.9	2.7	3.5
September 22, 2006	8.3	--	9.1	8.9	21.2
October 16, 2006	30.9	56.8	31.3	53.2	61.4
November 1, 2006[3]	4.7	4.1	4.7	--	1.8
Mean ±SD (all events)	7.4±8.7	9.2±16.4	7.7±9.2	12.2±16.5	18.1±21.1
--------------------2012-2013--------------------					
June 1, 2012	55.8	52.8	--	52.8	56.9
August 6, 2012	15.2	10.8[4]	11.0	--	12.1
August 10, 2012	9.9	--	8.1	--	--
August 15, 2012	3.7	--	2.6	--	--
September 17, 2012	--	--	--	67.3	69.7
October 28, 2012[3]	158.7	--	159.0	53.5	77.3
April 17, 2013[3]	11.5	9.2	3.2	6.7	15.7
May 20, 2013	12.2	7.5	5.6	10.3	12.5
June 30, 2013	14.4	9.7	9.4	14.2	16.3
July 11, 2013	1.2	--	33.3	1.3	2.2
August 10, 2013	18.6	--	--	13.8	20.2
November 25, 2013[3]	89.7	89.9	--	76.3	91.2
Mean ±SD (all events)	35.5±48.6	30.0±34.2	29.0±53.4	32.9±29.2	37.4±32.7

[1]Plots 1 and 3 are brown, weathered sandstone; plot 2 is gray, unweathered sandstone; and plots 4 and 5 are a mixture of both brown, weathered sandstone and gray, unweathered sandstone and shale. Plot 6 (gray, unweathered sandstone) was not used in the analysis.
[2]Source: Taylor et al. (2009b).
[3]Non-growing season.
[4]Hydrograph was incomplete after the peak, so value was estimated.

Table 2.6: Bent Mountain Plot Response Time (d x 10^{-2}).

Date	Plots[1]				
	1	2	3	4	5
--------------------2005-2006--------------------[2]					
July 21, 2005	0.1	0.2	0.1	0.1	0.2
August 6, 2005	10.4	1.2	0.5	0.1	13.6
August 16, 2005	0.3	0.2	0.1	--	0.5
September 16, 2005	1.8	1.7	2.0	1.8	1.9
October 7, 2005	7.9	8.5	9.9	8.8	17.2
April 7, 2006	2.8	2.4	59.4	2.9	3.4
August 11, 2006	6.9	4.9	5.6	5.6	8.0
August 19, 2006	0.7	0.1	1.5	0.2	1.5
August 29, 2006	2.2	1.9	2.3	2.3	2.6
September 22, 2006	0.8	--	0.7	1.4	1.5
October 16, 2006	8.4	8.2	22.4	25.1	27.3
November 1, 2006[3]	0.9	1.6	2.3	--	1.3
Mean ±SD (all events)	3.6±3.7	2.8±3.1	8.9±17.1	4.8±7.6	6.6±8.5
--------------------2012-2013--------------------					
June 1, 2012	51.4	51.5	--	10.1	10.2
August 6, 2012	4.5[4]	10.5[4]	4.9	--	3.3
August 10, 2012	7.1	--	7.5	--	--
August 15, 2012	1.9	--	2.6	--	--
September 17, 2012	--	--	--	42.8	26.6
October 28, 2012[3]	130.7	--	116.1	47.6	48.9
April 17, 2013[3]	0.6	0.9	0.4	0.9	0.9
May 20, 2013	8.5	3.4	3.9	5.8	9.2
June 30, 2013	12.3	2.3	0.5	0.7	3.7
July 11, 2013	0.4[4]	3.6[4]	4.0[4]	2.8[4]	0.4[4]
August 10, 2013	11.4	--	--	10.0	3.0
November 25, 2013[3]	9.9	8.9	--	16.8	15.2
Mean ±SD (all events)	21.7±37.0	11.6±16.6	17.5±37.3	15.3±16.8	12.1±14.4

[1]Plots 1 and 3 are brown, weathered sandstone; plot 2 is gray, unweathered sandstone; and plots 4 and 5 are a mixture of both brown, weathered sandstone and gray, unweathered sandstone and shale. Plot 6 (gray, unweathered sandstone) was not used in the analysis.
[2]Source: Taylor et al. (2009b).
[3]Non-growing season.
[4]Hydrograph was incomplete after the peak, so value was estimated.

Table 2.7: Hydrologic Parameters Means and Standard Deviations.

Parameter	Monitoring Year				Monitoring Period	
	2005	2006	2012	2013	2005-2006	2012-2013
Discharge volume (m^3)	6.1±4.0	14.4±14.1	14.8±13.4	16.5±16.6	10.9±11.7	15.8±15.3
Discharge volume (% rainfall)	8.5±5.5	14.2±10.3	14.6±13.2	19.3±19.6	11.7±9.0	17.5±17.4
Peak Discharge (m^3 s^{-1} x 10^{-4})	5.4±3.1	7.0±6.5	7.2±4.9	7.0±4.7	6.3±5.3	7.0±4.7
Lag Time (d x 10^{-2})	6.2±8.4	13.0±16.4	48.7±47.7	22.9±28.7	10.2±14.0	33.5±39.3
Response Time (d x 10^{-2})	3.7±5.1	6.6±11.7	32.1±38.3	5.2±4.9	5.4±9.5	16.0±27.6
Discharge Duration (d)	6.4±4.3	6.3±4.8	4.4±4.6	3.6±3.4	6.3±4.5	4.0±3.9

settling of 10 cm while it was 2 cm for GRAY. GRAY spoils were more resistant to weathering per slake durability and freeze-thaw tests. Settling of the spoil over time likely decreased permeability as finer material from the weathering process began to fill in pore spaces thus reducing the size and/or number of macropores. Sena (2014) found that silt and clay contents increased in the GRAY and MIXED plots and remained stable in the BROWN plots between the 2005-2006 and 2012-2013 monitoring periods. The findings suggest that the spoils had a greater ability to hold water.

As noted by Taylor et al. (2009b), it is important to note the overall smallness of the peak discharges, length of flow duration (multiple days), and low percentage of rainfall that is discharged. For the storms analyzed, 11% and 17% of the rainfall was discharged as storm flow for the 2005-2006 and 2012-2013 monitoring periods, respectively (Table 2.8). No significant difference between monitoring periods was noted. These findings demonstrate that spoil placed in accordance with the minimal compaction specification of the FRA (i.e. loose-dumped spoil) and at a depth of 2.5 m provides a substantial amount of storage for rainfall. Infiltrated rainfall is slowly released as interflow during and long after the storm, and as shown by Sena (2014) for the BROWN spoil, evapotranspired by vegetation in between storm events.

2.3.2 Spoil Type

While Taylor et al. (2009b) found significant differences between spoil types with respect to storm discharge volume (% rainfall only), peak discharge, lag time, response time, and duration, no significant differences were found for the 2012-2013 monitoring period. For the 2005-2006 monitoring period, Taylor et al. (2009b) noted that BROWN had higher peak discharges and shorter durations of storm flow. Even with the substantially greater amount of tree growth and ground cover on the BROWN spoil by the 2012-2013 monitoring period, as noted by Sena (2014), spoil type did not significantly affect storm hydrograph characteristics. These findings suggest that the placement of spoil has a greater influence on hydrology than vegetation at this point in time though that may change as the forest continues to develop. Qi et al. (2009) found that forest composition and spatial pattern significantly affected runoff volumes and peak

Table 2.8: Bent Mountain Plot Discharge Volume as Percentage of Rainfall (%).

Date	Plots[1]				
	1	2	3	4	5
--------------------2005-2006--------------------[2]					
July 21, 2005	16.7	12.9	15.7	--	18.6
August 6, 2005	14.4	10.4	10.8	13.3	14.0
August 16, 2005	13.2	8.0	8.9	9.5	8.2
September 16, 2005	2.9	2.5	1.5	3.2	2.9
October 7, 2005	6.5	1.6	1.7	3.7	2.6
April 7, 2006	23.9	16.5	--	47.0	38.8
August 11, 2006	7.4	12.4	3.1	12.3	11.6
August 19, 2006	5.0	10.8	0.3	9.8	5.2
August 29, 2006	10.7	19.2	0.9	11.3	7.2
September 22, 2006	11.8	--	4.1	5.8	4.8
October 16, 2006	23.7	19.7	14.2	25.3	24.1
November 1, 2006[3]	18.4	13.8	14.4	--	19.4
Mean ±SD (all events)	12.9±6.9	11.6±5.9	6.9±6.0	14.1±13.1	13.1±10.7
--------------------2012-2013--------------------					
June 1, 2012	7.6	10.9	--	31.5	33.0
August 6, 2012	24.0	30.0	31.1	--	--
August 10, 2012	0.3	--	0.1	--	--
August 15, 2012	7.1	--	8.9	--	--
September 17, 2012	--	--	--	31.3	24.0
October 28, 2012[3]	1.2	--	1.2	1.9	3.5
April 17, 2013[3]	39.4	15.5	62.3	29.8	31.6
May 20, 2013	0.4	0.6	0.1	2.1	2.5
June 30, 2013	0.3	1.4	0.1	3.8	2.6
July 11, 2013	15.1	18.4	10.7	17.1	17.0
August 10, 2013	5.1	--	--	33.9	31.3
November 25, 2013[3]	21.0	51.2	--	44.2	63.0
Mean ±SD (all events)	11.0±12.6	18.3±17.7	14.3±22.1	21.7±15.9	23.2±19.7

[1]Plots 1 and 3 are brown, weathered sandstone; plot 2 is gray, unweathered sandstone; and plots 4 and 5 are a mixture of both brown, weathered sandstone and gray, unweathered sandstone and shale. Plot 6 (gray, unweathered sandstone) was not used in the analysis.
[2]Source: Taylor et al. (2009b).
[3]Non-growing season.
[4]Hydrograph was incomplete after the peak, so value was estimated.

flows with forests comprised of vegetation able to intercept greater amounts of rainfall more effective at reducing runoff volumes and peak flows. Like in this study, the authors noted that soil properties were important in controlling hydrology; soils with greater infiltration rates and higher soil water holding capacities were more effective at reducing discharge volumes and peak flows.

2.3.3 Growing Season

With regards to growing season, data from only four storm events were available: one storm during the 2005-2006 monitoring period and three storms during the 2012-2013 monitoring period. As such, comparisons between growing (April 20-October 26) and non-growing (October 27-April 19) are tenuous. Table 2.9 contains mean and standard deviation values of the hydrologic parameters separated by growing and non-growing seasons. With the exception of lag time in the 2012-2013 monitoring period, no significant relationships were noted using t-tests between growing and non-growing seasons for the two monitoring periods.

2.3.4 Precipitation Depth

The hydrograph parameters discharge volume, peak discharge, lag time, and response time displayed a slight increase with precipitation depth (Figures 2.3-2.6). Greater rainfall depths tended to produce greater volumes of discharge with larger peaks. Interestingly, the time until runoff generation and peak runoff also increased indicating that storm characteristics such as intensity were likely influential. Warner et al. (2010) noted that intense storms yield greater amounts of runoff while longer duration multi-interval storms produce less runoff. With multi-interval and longer storms, rainfall has more time to infiltrate. No increase was seen with discharge duration or percent rainfall discharged (Figures 2.7-2.8).

Table 2.9: Hydrologic Parameters for Growing and Non-Growing Seasons (All Years) Means and Standard Deviations.

Parameter	Monitoring Period			
	2005-2006		2012-2013	
	Growing	Non-Growing	Growing	Non-Growing
Discharge volume (m^3)	10.9±12.1	10.0±2.3	14.1±12.5	23.4±24.0
Discharge volume (% rainfall)	11.4±9.2	16.5±2.8	13.0±12.4	28.1±22.9
Peak Discharge ($m^3\ s^{-1}$ x 10^{-4})	6.3±5.4	6.4±4.0	7.5±4.8	5.0±4.0
Lag Time (d x 10^{-2})	10.3±14.3	3.8±1.4	18.8±19.5	99.4±38.6
Response Time (d x 10^{-2})	5.7±9.8	1.5±0.6	8.8±13.1	49.3±48.5
Discharge Duration (d)	6.6±4.6	2.2±1.1	4.1±4.3	3.2±1.2

2.4 CONCLUSIONS

The objective of this study was to evaluate storm hydrograph characteristics (discharge volume, peak discharge, lag time, response time, and discharge duration) for 7-8 year old forests (monitoring years 2012-2013) established on three types of loose-dumped spoil placed in accordance with FRA guidelines. The three spoil types were (1) brown, weathered sandstone (BROWN), (2) gray unweathered sandstone (GRAY) and (3) a mixture of both theses sandstones and shales (MIXED). The hydrograph characteristics were then compared to initial conditions (monitoring years 2005-2006) to assess temporal changes. It was expected that since the different spoil types demonstrated remarkably different amounts of tree growth and groundcover by the 2012-2013 monitoring period, significant differences in hydrograph characteristics would be found.

No significant differences were found between the 2005-2006 and 2012-2013 monitoring periods for the storm hydrograph parameters discharge volume and duration. Significant increases were found for the hydrograph parameters peak discharge, lag time, and response time. This is thought to be due to the weathering and settling of the spoils. overall smallness of the peak discharges, long length of flow durations, and low percentage of discharged rainfall indicate that the FRA's guidelines for minimal compaction allows for high infiltration rates and, with sufficient spoil thickness, provides ample room for rainfall storage in the spoil profile. The continued lack of significant differences between the spoil types, by the 2012-2013 monitoring period, indicates that although vegetation was significantly different between the plots, spoils properties as dictated by its placement, has a much greater influence on storm hydrology at this point in time. However, as the forest continues to mature, the effect of vegetation in the form of increased interception and evapotranspiration could begin to significantly influence storm hydrology.

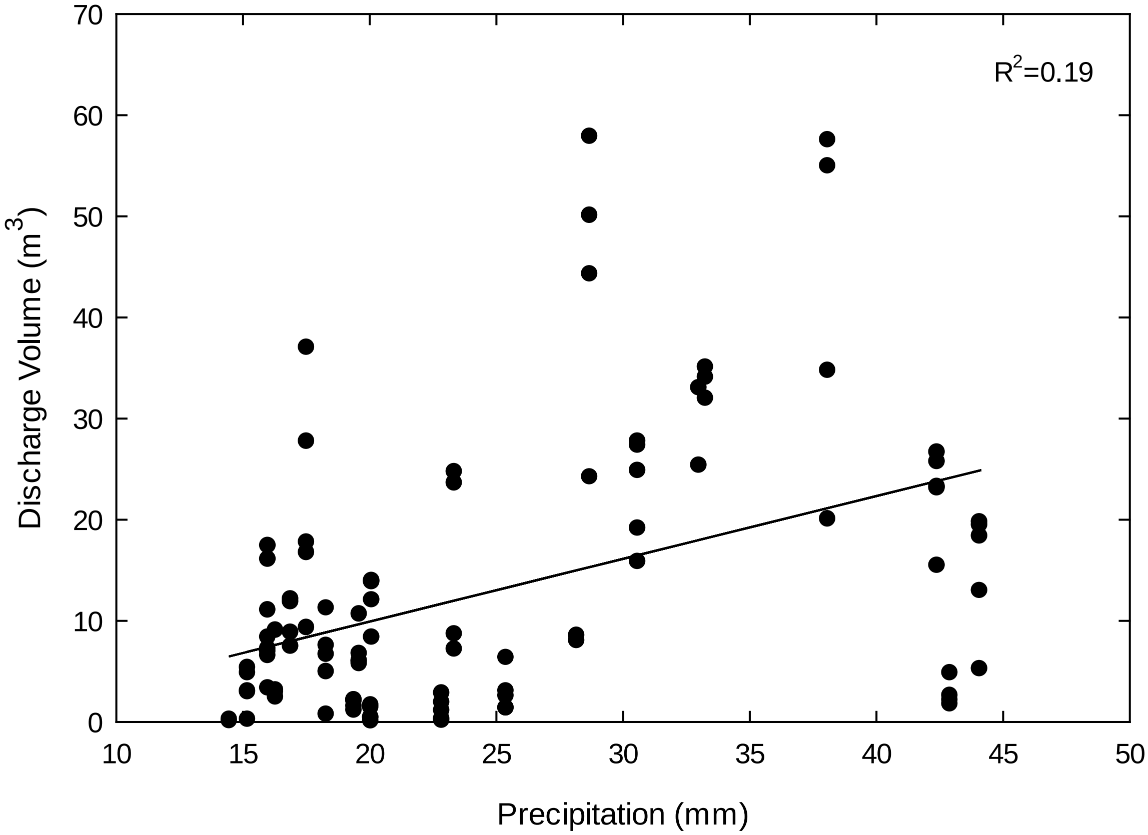

Figure 2.3: Discharge Volume versus Precipitation Depth.

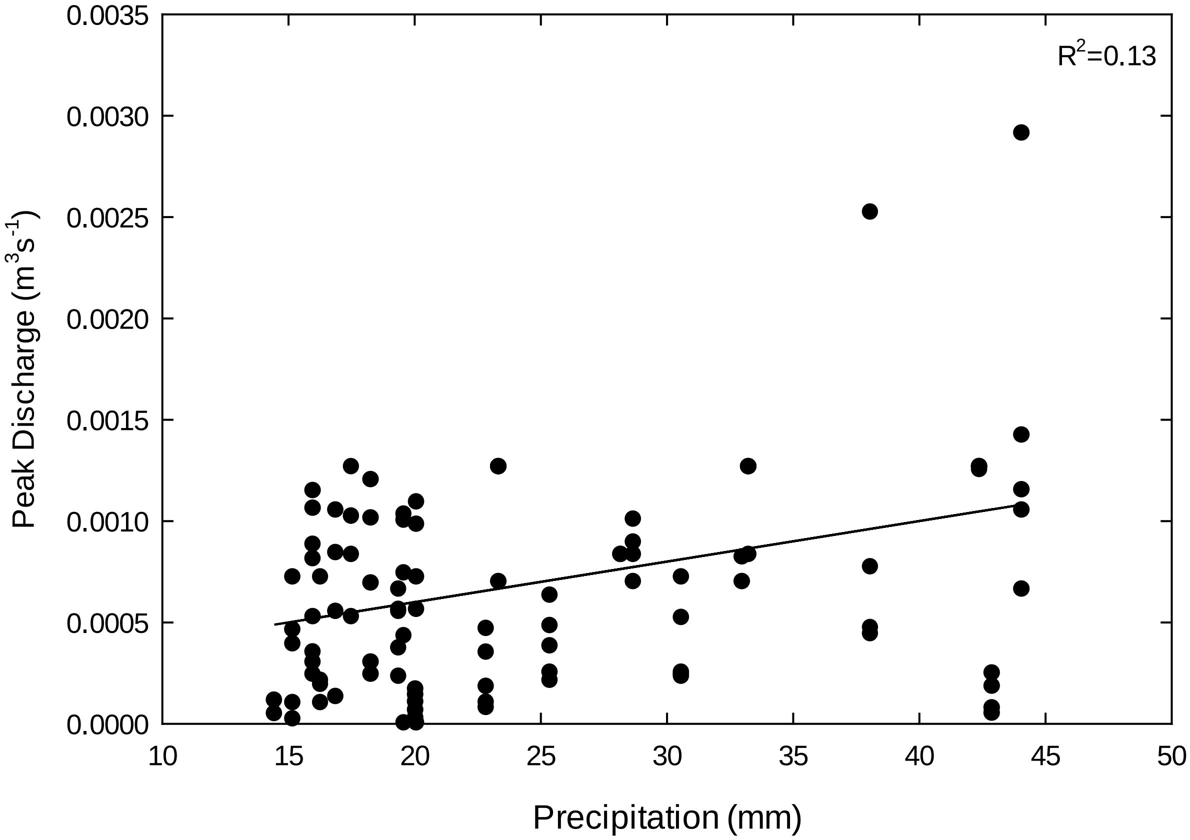

Figure 2.4: Peak Discharge versus Precipitation Depth.

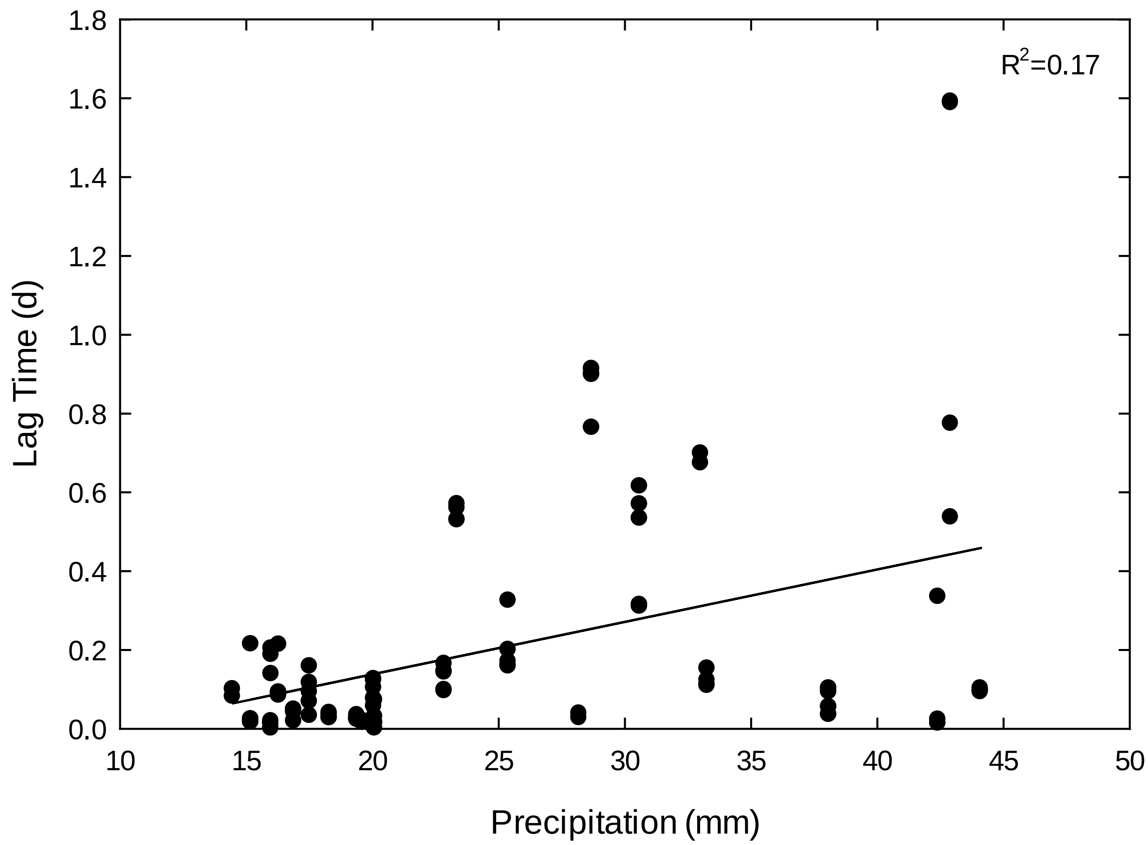

Figure 2.5: Lag Time versus Precipitation Depth.

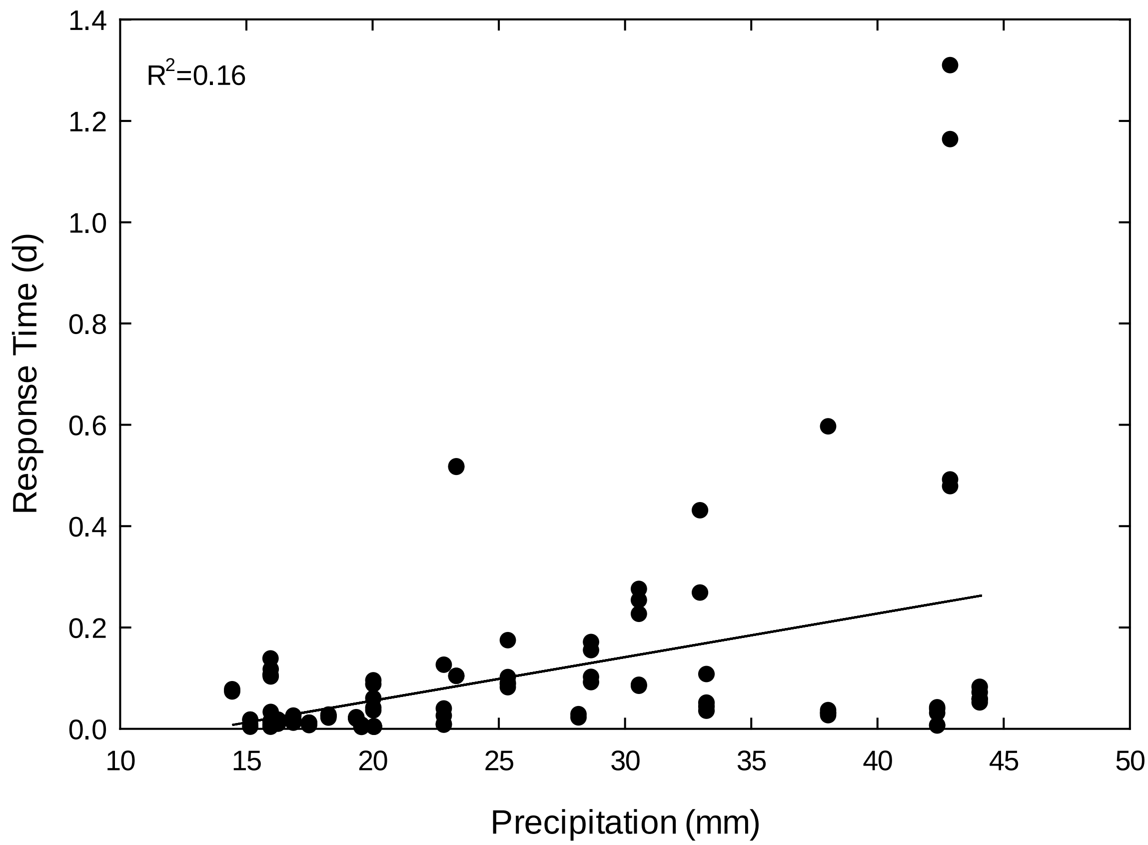

Figure 2.6: Response Time versus Precipitation Depth.

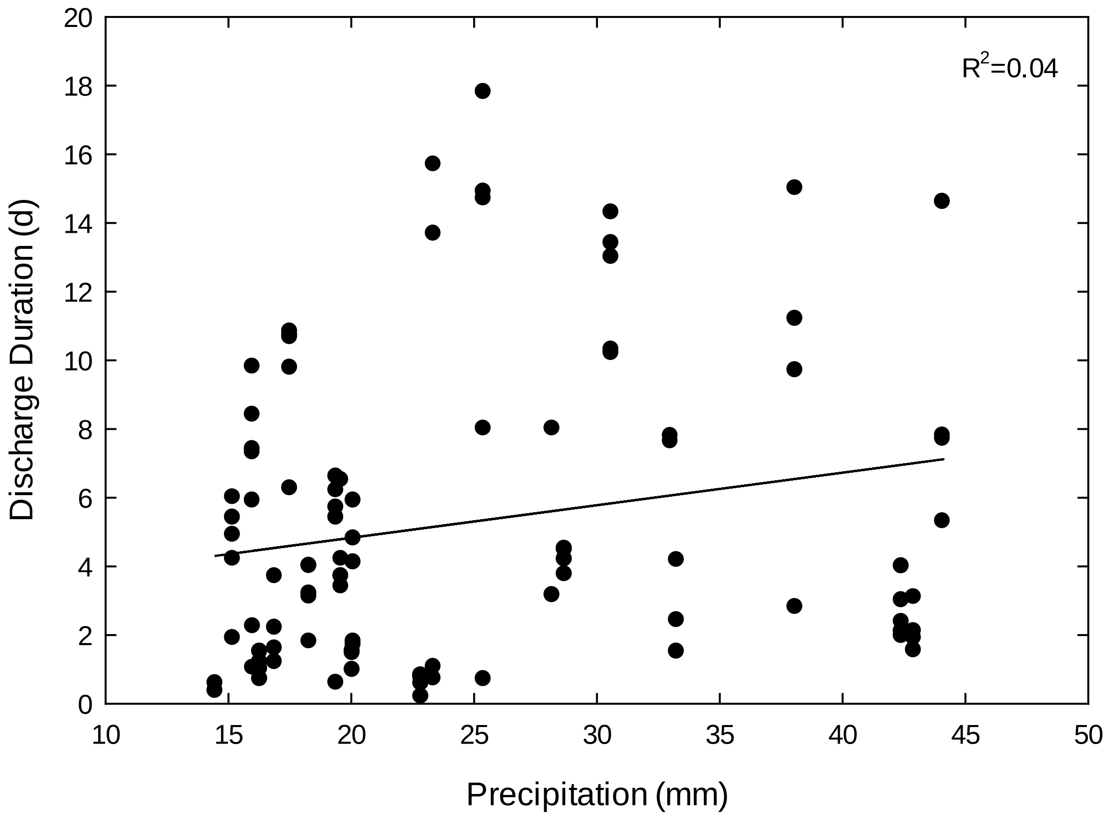

Figure 2.7: Discharge Duration versus Precipitation Depth.

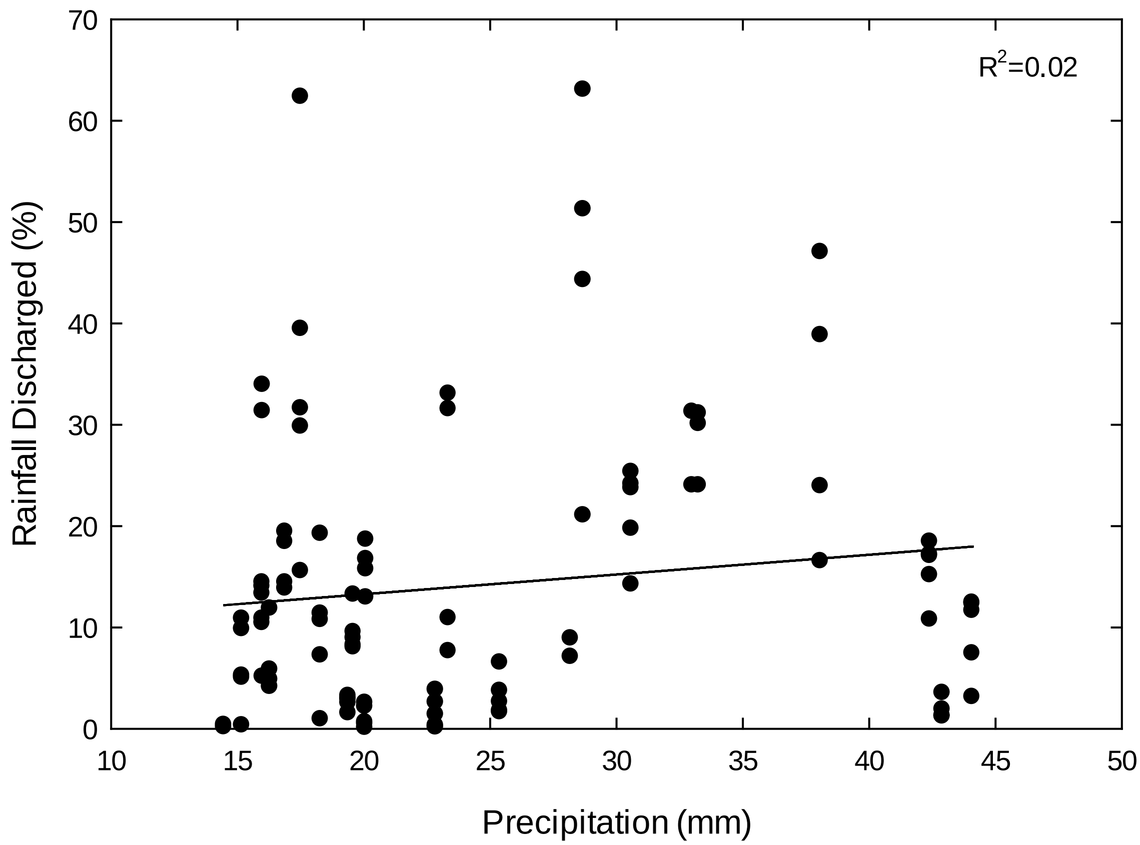

Figure 2.8: Percent Rainfall Discharged versus Precipitation Depth.

CHAPTER 3: EFFECT OF SPOIL TYPE ON CURVE NUMBERS FOR LOOSE-DUMPED MINE SPOIL INTERFLOW

3.1 INTRODUCTION

From 1973-2000, mining has resulted in the conversion of 2,620 km^2 of forest to mined lands, a 34% reduction, in Central Appalachian ecoregion of the United States (Sayler, 2012). Once mined, most of the lands are reclaimed using techniques that promote compaction, and hence the establishment of grasses and shrubs, instead of those that promote the establishment of forested ecosystems (Chaney et al., 1995; Wickham et al., 2006; Angel et al., 2008; Zipper et al., 2011). The heavy compaction of mined lands is due in large part to regulatory and mine operator interpretation of the Surface Mining Reclamation and Control Act of 1977 (SMCRA). SMCRA requires that mined lands are reclaimed in a manner that ensures stability meaning they are not prone to excessive erosion or landslides. While not specified in the regulations, mine operators and regulators tend to equate land stability with high levels of compaction and the planting of herbaceous vegetation to control erosion (Angel et al., 2008; Zipper et al., 2011). As a result, many pre-mined lands that were once forested now resemble grasslands.

By converting forested communities into herbaceous ones, ecosystem goods and services such as those related to hydrology (Sheil and Murdiyarso, 2009; Lima et al., 2014), nutrient cycling (Jones et al., 2001; Gomi et al., 2002), and habitat (Riedel et al., 2008; McKie and Malmqvist, 2009) are negatively affected (Wickham et al., 2007; Zipper et al., 2011). Costanza et al. (1997) estimated that forests alone provide US$4.7 trillion yr^{-1} in ecosystem goods and services, which is the second highest value for a terrestrial system with wetlands at US$4.9 trillion yr^{-1} being the first. The largest benefits for temporal/boreal forests were seen in the areas of climate regulation, soil formation, waste treatment, food production, raw materials, and recreation.

One of the fundamental components of a forested ecosystem is water and how it is transported throughout the ecosystem, meaning its hydrology (Chang, 2003; Harmon et al., 2012). Precipitated water can be intercepted by the forest canopy, evapotranspired, infiltrated (shallow and deep), and/or transported as surface runoff or overland flow (Ponce and Hawkins, 1996; Chang, 2003). In Central Appalachia, steep sloping forests tend to produce little overland flow but instead are typically dominated by interflow which is due to high soil infiltration rates and the presence of an underlying low hydraulic conductivity layer such as bedrock (Hursh, 1936; Hewlett and Hibbert, 1965; Whipkey, 1969; Neary et al., 2009; USEPA, 2011). The high infiltration rates of forested soils are created in part by the presence of macropores from biotic sources such as roots and burrowing insects and animals as well as abiotic ones such as mineral dissolution and freeze/thaw cycles (Aubertin, 1971). Macropores in forested soils also increase shallow subsurface flow rates (Chang, 2003).

In comparison to forested soils, traditional post-SMCRA mine reclamation practices result in lands with significantly reduced infiltration rates (Jorgensen and Gardner, 1987; Guebert and Gardner, 2001), which in turn results in larger and flashier amounts of surface runoff (Dick et al., 1983; Weiss and Razem, 1984; Bonta et al., 1997; Bonta and Dick, 2003). Thus, returning mined lands to forested ecosystems requires an understanding of how to best restore mined soils for tree growth and hydrology as well as water quality – all factors that influence the value of forested ecosystem goods and services.

One method that has demonstrated success in regrowing trees on mined lands is the Forestry Reclamation Approach (FRA) (Graves et al., 2000; Angel et al., 2008; Emerson et al., 2009; Cotton et al., 2012; Sena et al., 2014). The FRA, as detailed in Burger et al. (2005), is comprised of five steps: (1) create a medium using topsoil, weathered sandstone, or best available material, (2) minimize compaction of the medium, (3) use tree compatible ground covers, (4) plant early successional and high-value tree species, and (5) properly plant the trees. The FRA has also been shown to exhibit hydrologic characteristics similar to that of a forested ecosystem. Taylor et al. (2009a; 2009b) found that the spoil placed in accordance with the FRA's minimum compaction recommendation exhibited curve numbers and discharge volumes, peaks and durations that were similar to those from a reference forested watershed even though the trees were quite young (1-2 years old). The structure of the 2.5 m deep layer of loosed-dumped spoil above a compacted layer allowed for high levels of infiltration and subsequently the creation of interflow even for such a young forest. Taylor et al. (2009b) hypothesized that as the forest matures, discharge volumes and peaks would continue to decline as interception and evapotranspiration increased. Thus while Taylor et al. (2009a; 2009b) concluded that spoil type did not influence storm hydrology at this point of early forest development, the influence of spoil type may change over time because soil type influences vegetation development.

One means of assessing the influence of FRA, and consequently spoil type and vegetation, on hydrology is through the use of curve numbers (CN). The CN method was developed by the United States Department of Agriculture's Natural Resource Conservation Service (formerly Soil Conservation Service) as a means of predicting runoff volumes and peak flows (USDA-SCS, 1972; USDA-NRCS, 2004). Estimations of CNs are based on four criteria (1) hydrologic soil group, (2) land use, (3) hydrologic surface conditions, and (4) the antecedent moisture condition (Ponce and Hawkins 1996). CNs are calculated using equations 3.1-3.4:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad \text{For } P \geq I_a \qquad \text{(eqn. 3.1)}$$

$$Q = 0 \quad \text{For } P \leq I_a \qquad \text{(eqn. 3.2)}$$

$$I_a = \lambda S \qquad \text{(eqn. 3.3)}$$

$$S = \frac{25{,}400}{CN} - 254 \qquad \text{(eqn. 3.4)}$$

The variable Q denotes stormwater runoff depth (mm) resulting from rainfall, P is storm precipitation (mm), I_a is the initial absraction (mm) and is defined as the amount of precipitation required before the start of runoff, λ is the initial abstraction coefficient, and S denotes the storage retention (mm). The initial abstraction is based the amount of rainfall that infiltrates, becomes surface storage, or is intercepted before runoff begins (Ponce and Hawkins, 1996). A value of 0.2 is commonly used for λ (USDA-SCS, 1972; USDA-NRCS, 2004) although a number of more recent studies indicate that λ may be much lower. Hawkins et al. (2002) and Shi et al. (2009) recommend a λ value of 0.05. Fu et al. (2011) found a median value of 0.05 for λ when examining 205 storm events on nine runoff plots in the Loess Plateau of China.

The CN method is widely used by design professional when developing mine and reclamation plans. In Kentucky, the selection of CNs is guided by Technical Reclamation Memorandum (TRM) #6 (Eddins, 1982). For undisturbed forests, TRM #6 recommends a CN of 73 while a CN of 60 is recommended for mined lands reclaimed as forests (non-FRA). Taylor et al. (2009a) noted that CNs for forested watersheds in the eastern Kentucky ranged between 85 and 93, values that agreed with work by Hawkins (1993) that found mean CN of 85 for a reference watershed (Little Millseat) in eastern Kentucky. These values are well above the TRM #6 recommended CN of 73 for undisturbed forests. TRM #6 was developed well prior to the development of FRA, thus the document contains no information on the selection of CNs for mined lands reclaimed using the FRA. While Taylor et al. (2009a) developed CN for newly established FRA plots, these CN values are hypothesized to change over time as the forest matures and as the influence of different spoil types is exerted through vegetation growth. The objective of this study was to develop and compare CNs from interflow for three types of loosely dumped spoil with a 7-8 year old forest to those from the same plots with a 0-1 year old forest as well with a 90+ year old forested reference watershed. Results from this study will aid reclamationists in their understanding of how the FRA can be used in the restoration of a watershed’s hydrology and how spoil type selection can influence such efforts.

3.2 METHODS

3.2.1 Study Sites

The study was conducted at two sites located in the Cumberland Plateau in eastern Kentucky: the Bent Mountain (BM) surface mine and the University of Kentucky’s Robinson Forest (Figure 3.1). The BM surface mine is located in Pike County, Kentucky (latitude 37° 35.88 N; longitude 82° 24.31 W). The climate is humid and temperate with summer temperatures ranging from 18 to 32 °C and winter

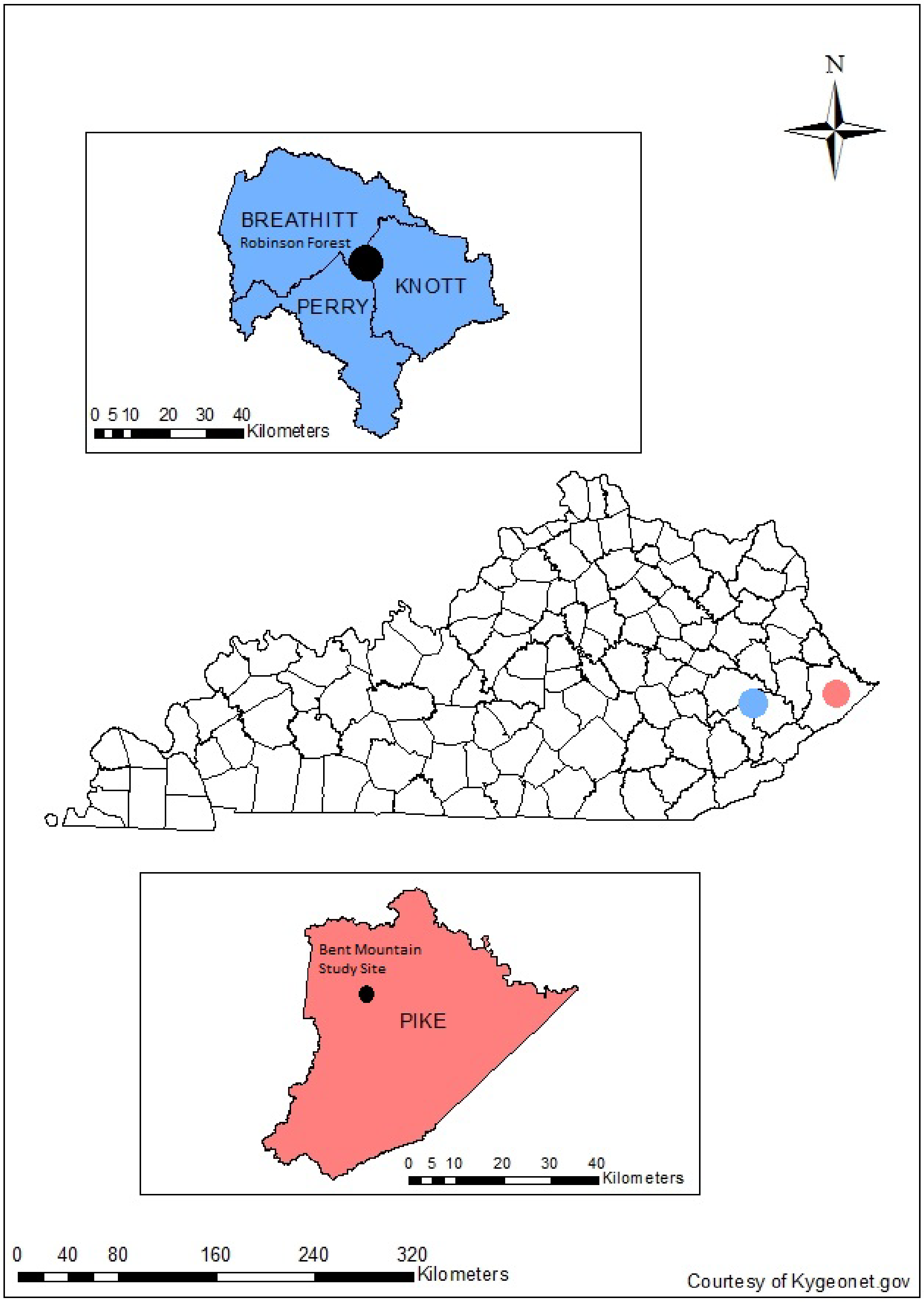

Figure 3.1: Location of the Bent Mountain (BM) Surface Mine and the University of Kentucky's Robinson Forest (RF).

temperatures ranging from -4 to 7°C. The average annual rainfall is 114 cm. The underlying geology is dominated by sandstone followed by some shale and siltstone all of the Breathitt formation of Lower to Middle Pennsylvania age. Quartz, rock fragments, feldspar, and mica grains are the major components of the sandstone with calcite as the main cementing agent (Wunsch, 1993).

Six 0.4 ha plots were constructed at the BM surface mine in 2005. The plots consisted of two replicates each of (1) brown, weathered sandstone (BROWN), (2) gray, unweathered sandstone (GRAY), and (3) a mixture of both BROWN and GRAY in addition to shale (MIXED). Plots were constructed overtop a compacted layer to a depth of approximately 2.5 m. The compacted layer was graded with a longitudinal slope of approximately 2% and side slopes between 3-10% to direct interflow via a 10.2 cm perforated PVC pipe to data acquisition equipment (Taylor et al., 2009a). The underlying compacted layer was assumed to be impervious. Following measurement by the data acquisition equipment, interflow from each plot was then directed into a deep mine so that all plots remained hydrologically separated. Loose-dumped spoil was then placed overtop the compacted layer in accordance with the FRA (Burger et al., 2005). Following construction, the plots were planted with 1:0 bare root seedlings (1.8 m by 2.4 m spacing) of white oak (*Quercus alba*), red oak (*Quercurs rubr*a), yellow-poplar (*Liriodendron tulipfera*), and green ash (*Fraximus pennsylvanica*). No groundcover was seeded to help minimize competition to tree seedlings. Since the establishment of the plots at BM, studies on vegetation, hydrology, and water quality have been conducted (Angel et. al., 2008; Taylor, 2009a; 2009b; Agouridis et al., 2012; Sena, 2014).

Robinson Forest (RF) is a nearly 6,000 ha 90+ year-old second growth mixed-mesophytic forest owned and operated by the University of Kentucky for research, education and outreach purposes. RF is located near the community of Clayhole (latitude 37° 27.01 N; longitude 83°09.01 W). The climate is humid and temperate with summer temperatures ranging from 18 to 30 °C and winter temperatures ranging from -5 to 6°C. The average annual rainfall for RF is 118 cm. For this study, the reference watershed Little Millseat (LMS) was used. LMS is an 81 ha watershed with steep side slopes (25-60%) and with elevation ranging from 305-451 m. The LMS watershed has a drainage density of 0.0038 m m^{-2}. Underlying soils are comprised of the Dekalb-Marowbone-

Lantham (1.0 depth), Cloverlick-Shelocata-Cutshin (1.2-1.8 m depth), Shelocta-Gilpin-Hazleton (1.2 m depth), and Shelocta-Gilpin-Kimper (1.2 m depth) complex mapping units (Hayes, 1991; Cherry, 2006). The LMS serves as a control or reference watersheds for numerous hydrologically-based studies in RF. Data from the period of 2000-2004 were used for LMS.

3.2.2 Hydrologic Data

3.2.2.1 Bent Mountain

At the BM surface mine, precipitation data were recorded using a Rain Collector II tipping bucket rain gage (Davis Instruments, Hayward, CA) equipped with a HOBO Event datalogger (Onset Computer Corporation, Cape Cod, MA) in 2005 and 2006. The rain gage was located approximately 300 m from the plots. Due to equipment failure, in 2012 and 2013, precipitation data were obtained from the USGS gage 03210000, which is located approximately 8 km from the plots. Data from this rain gage were recorded in 15 minute intervals. For the 2005-2006 monitoring period, a total of 12 events (15.4-44.4 mm) were used in the analysis while a total of 12 events (14.5-42.9 mm) were used for the 2012-2013 monitoring period (Taylor et al., 2009a) (Table 3.1). The mean and median rainfall depths for the 2005-2006 monitoring period were 23.4 and 25.8 mm, respectively; for the 2012-2013 monitoring period, it was 26.9 and 19.5 mm, respectively. Rainfall events less than 25.4 mm were included in the analysis to increase the sample size. Because of this, bias towards larger CN values was examined (Hjelmfelt, 1991; Hawkins, 1993; Warner et al., 2010). For each monitoring period, rainfall was separated into ranges of small (12.7-19.0), medium (19.0-25.4), and large (<25.4) storms depths and examined for each monitoring period individually and together. Flow data were recorded using calibrated metal tipping buckets and HOBO Event dataloggers, which were located at the outlet of each plot. Baseflow separation was conducted using the concave method (McCuen, 2005). For an unknown reason, one of the GRAY plots (plot 6) behaved quite differently than the other plots. As such, it was not used in this study.

Table 3.1: Storm Event Characteristics for Bent Mountain Plots.

Date	Precipitation (mm)	Duration (h)	Total 5-day antecedent rainfall (mm)
--------------------2005-2006--------------------[1]			
July 21, 2005	20.1	0.9	7.6
August 6, 2005	16.0	0.9	0.0
August 16, 2005	19.6	4.6	0.0
September 16, 2005	19.4	1.1	0.0
October 7, 2005	25.4	5.3	4.6
April 7, 2006	38.1	17.7	27.3
August 11, 2006	44.1	4.6	11.7
August 19, 2006	15.4	2.3	3.7
August 29, 2006	18.3	7.0	9.6
September 22, 2006	16.3	3.1	1.1
October 16, 2006	30.6	13.3	3.1
November 1, 2006	16.9	4.5	12.7
Mean±Std.Dev. (all events)	23.4±9.4	5.4±5.2	6.8±7.9
--------------------2012-2013--------------------			
June 1, 2012	23.4	15.0	0.1
August 6, 2012	33.3	6.0	0.6
August 10, 2012	14.5	2.0	1.9
August 15, 2012	28.2	2.0	0.6
September 17, 2012	33.0	29.0	0.0
October 28, 2012	42.9	9.5	0.2
April 17, 2013	17.5	3.8	0.5
May 20, 2013	20.1	3.0	0.1
June 30, 2013	22.9	42.5	0.5
July 11, 2013	42.4	2.3	0.3
August 10, 2013	16.0	4.5	0.3
November 25, 2013	28.7	0.63	0.2
Mean±Std.Dev. (all events)	26.9±9.6	10.0±13.0	0.4±0.5

[1]Source: Taylor et al. (2009a).

3.2.2.2 Robinson Forest

For the LMS watershed in RF, precipitation data were recorded via a centrally located tipping bucket rain gage and a Campbell Scientific CR10X data logger (Campbell Scientific, Logan, UT). Data were recorded in intervals of 15 minutes. From 2000-2004, a total of 12 events (28.4-67.6 mm) > 25.4 mm were used in the analysis while a total of 12 events (27.4-46.5 mm) > 25.4 mm were used for the 2012-2013 monitoring period (Taylor et al., 2009a) (Table 3.2). A cut off of 25.4 mm was selected to minimize bias in CN computations with shallow storms (Hawkins et al., 2002; Schneider and McCuen, 2005). The mean and median rainfall depths for the 2000-2004 monitoring period were 43.0 and 43.8 mm, respectively; for the 2012-2013 monitoring period, they were 39.5 and 39.9 mm, respectively. Flow data the LMS watershed were continuously recorded using an 8:1 side-sloped broad-crested combination weir (Cherry, 2006). Baseflow was separated using the concave method (McCuen, 2005).

3.2.3 Curve Numbers

Curve numbers were computed using equations 3.1-3.4 and values of 0.2 and 0.05 for λ (Appendix B). As noted in Taylor et al. (2009a), the CN method is generally used for surface runoff; however, surface runoff does not occur at the plots at BM due to the hummocky topography (Angel et al., 2008; Taylor et al., 2009 a; 2009b). The interflow occurring at the plots is quite similar to that seen in the mountainous terrain in eastern Kentucky. In this environment, rainfall tends to rapidly infiltrate the shallow soils where it meets a low hydraulic conductivity layer, such as bedrock, and then proceeds as interflow towards streams (Whipkey, 1967; Sloan and Moore, 1984; Ormsbee and Khan, 1987). Antecedent moisture condition (AMC) II was used (Fennesey and Hawkins, 2001; McCuen, 2005) although total 5-day prior rainfall amounts are provided if adjustments are desired.

Table 3.2: Storm Event Characteristics for Little Millseat.

Date	Precipitation (mm)	Duration (h)	Total 5-day antecedent rainfall (mm)
--------------------2000-2004--------------------[1]			
April 4, 2000	36.3	15.5	12.4
December 16, 2000	42.7	20.5	48.5
January 20, 2001	45.2	25.2	8.4
February 14, 2001	47.2	21.0	13.7
February 16, 2001	30.0	18.8	52.8
July 13, 2002	67.6	23.2	0.0
April 6, 2003	28.4	16.0	10.9
June 7, 2003	30.2	13.0	14.2
September 3, 2003	53.6	5.5	23.6
November 17, 2003	44.7	19.2	14.7
January 2, 2004	42.9	18.8	12.7
March 5, 2004	47.0	7.8	6.4
Mean±Std.Dev. (all events)	43.0±11.1	17.0±5.9	18.2±16.2

[1]Source: Taylor et al. (2009a).

3.2.4 Statistical Analysis

The influence of spoil type (BROWN, GRAY and MIXED), and hence vegetation, over the periods of 2005-2006 and 2012-2013 were examined using a general linear model (PROC GLM) in Statistical Analysis Software 9.3 (SAS, 2011). Temporal changes were examined for individual years (2005, 2006, 2012 and 2013) and the combined initial (2005-2006) and latter (2012-2013) periods. Precipitation depth served as a covariate in the model.

Differences in precipitation depth between the 2005-2006 and 2012-2013 periods were examined for BM and RF using t-tests in SigmaPlot (α=0.05). One-way analysis of variances (ANOVAs) in SigmaPlot (α=0.05) were performed to 1) compare CNs from BM, LMS and FR and 2) evaluate the effect of rainfall depth on CN.

3.3 RESULTS AND DISCUSSION

3.3.1 Bent Mountain

In 2012-2013, CN values (λ=0.2) ranged from 60 to 97 for all plots at BM with a mean of 81 (Table 3.3). Using a λ=0.05, CN values ranged from 29 to 89 with a mean of 60. Taylor et al. (2009a) measured CN values (λ=0.2) between 64 and 90 with a mean of 83 in 2005-2006. For a λ=0.05, the authors measured CNs values ranging from 39 to 72 with a mean of 69. While a reduction in the mean CN was found between the 2005-2006 and 2012-2013 monitoring periods (83 vs. 81 for λ=0.2 and 69 vs. 60 for λ=0.05, respectively), the differences were not significant at α=0.05. For CNs generated using λ=0.05, significant differences between the two monitoring periods (all treatments combined) were found at α=0.10 (Figures 3.2-3.3). No differences were noted in rainfall depths for the 2005-2006 (mean=24 mm, median=19.5 mm) and 2012-2013 periods (mean=27 mm, median=26 mm) (Table 3.1).

Using values of I_a for the 2005-2006 and 2012-2013 data sets at BM, values of λ were computed (Table 3.4) (Appendix B). Values of λ varied with storm event, a phenomenon also noted by Woodward et al. (2003), as well as for plot, For the 2005-2006 monitoring period, values of λ had an overall mean of 0.125 (median=0.046); for the 2012-2013 monitoring period, λ had an overall mean of 0.051 (median=0.007). These

Table 3.3: Curve Numbers for Bent Mountain Plots.[1]

Date	CN (λ=0.2)					CN (λ=0.05)				
	Test Cells[2]					Test Cells[2]				
	1	2	3	4	5	1	2	3	4	5
--------------------2005-2006--------------------[3]										
July 21, 2005	88	86	88	--	88	80	76	80	--	81
August 6, 2005	90	89	88	89	89	83	80	79	80	81
August 16, 2005	86	84	85	85	84	77	70	73	72	70
September 16, 2005	79	79	78	80	80	58	57	54	59	59
October 7, 2005	78	73	73	76	75	60	47	47	54	51
April 7, 2006	82	78	--	90	88	73	65	--	87	84
August 11, 2006	69	74	64	74	73	49	58	40	58	58
August 19, 2006	85	88	79	88	85	69	77	51	77	70
August 29, 2006	86	89	78	86	84	74	82	53	75	70
September 22, 2006	89	--	84	85	84	80	--	67	70	68
October 16, 2006	85	83	81	86	86	77	73	70	79	78
November 1, 2006	90	88	89	--	90	82	79	81	--	84
Mean±Std.Dev. (all events)	84±6	83±6	81±8	84±6	84±6	72±11	69±11	63±15	71±11	71±11
--------------------2012-2013--------------------										
June 1, 2012	81	83	--	91	90	65	70	--	86	85
August 6, 2012	84	87	87	--	--	76	81	81	--	--
August 10, 2012	80	--	79	--	--	31	--	30	--	--
August 15, 2012	77	--	79	--	--	53	--	56	--	--
September 17, 2012	--	--	--	87	83	--	--	--	81	74
October 28, 2012	60	--	60	62	64	40	--	40	43	48
April 17, 2013	94	89	97	92	92	74	58	82	68	67

Table 3.3 cont'd.

Date	CN (λ=0.2)					CN (λ=0.05)				
	Test Cells[2]					Test Cells[2]				
	1	2	3	4	5	1	2	3	4	5
May 20, 2013	75	75	73	78	78	32	33	29	39	39
June 30, 2013	71	74	70	78	76	32	37	30	44	40
July 11, 2013	76	78	73	77	76	72	76	66	75	72
August 10, 2013	84	--	--	94	93	44	--	--	69	66
November 25, 2013	85	93	--	93	94	71	88	--	87	89
Mean±Std.Dev. (all events)	79±8	83±7	77±11	84±11	83±10	54±19	62±21	52±23	66±19	65±18

[1]AMC II

[2] Plots 1 and 3 are brown, weathered sandstone; plot 2 is gray, unweathered sandstone; and plots 4 and 5 are a mixture of both brown, weathered sandstone and gray, unweathered sandstone and shale. Plot 6 (gray, unweathered sandstone) was not used in the analysis.

[3]Source: Taylor et al. (2009a).

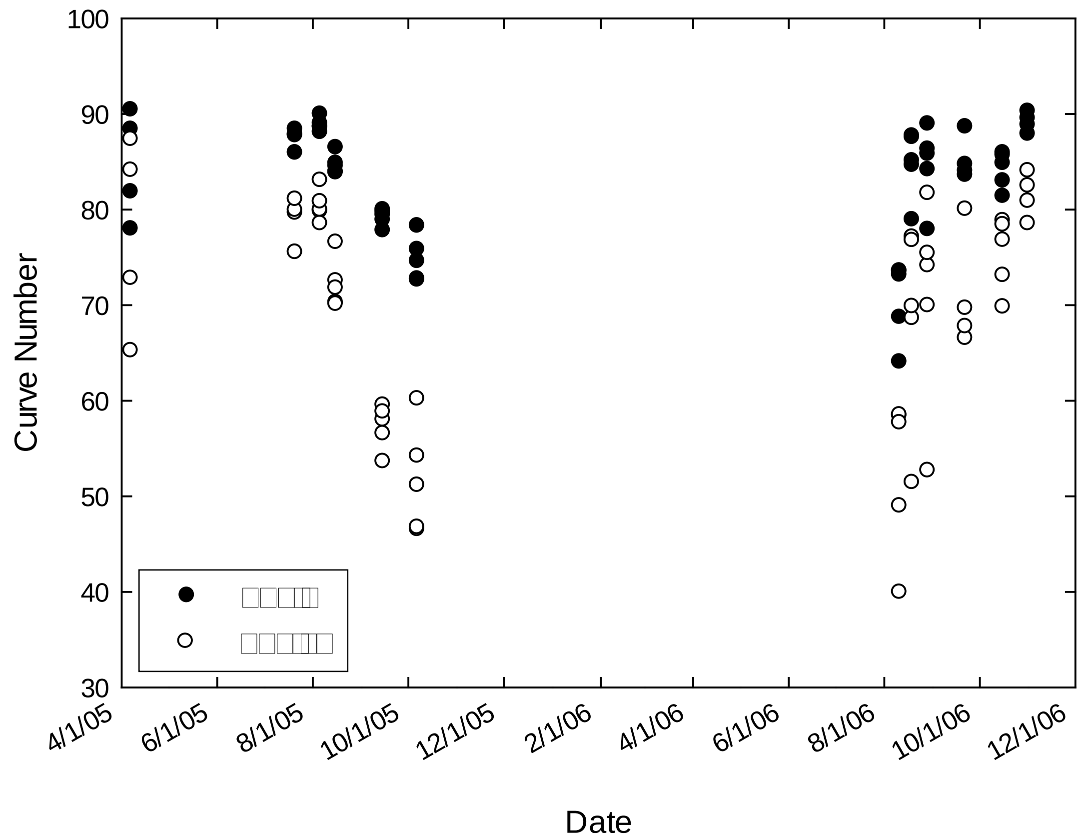

Figure 3.2: Curve Numbers for Bent Mountain Plots for the 2005-2006 Monitoring Period.

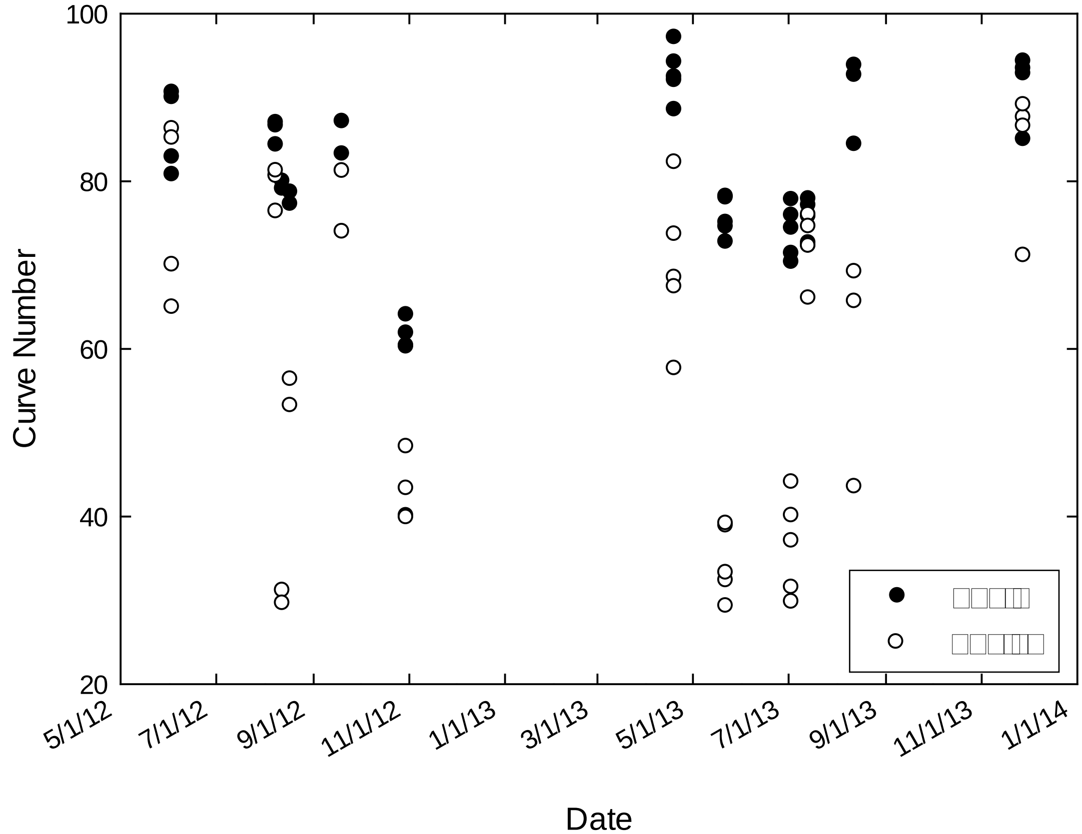

Figure 3.3: Curve Numbers for Bent Mountain Plots for the 2012-2013 Monitoring Period.

Table 3.4: Values of λ for Bent Mountain Plots.

Date	Plot				
	1	2	3	4	5
--------------------2005-2006--------------------					
July 21, 2005	0.01	0.0084	0.0088	--	0.0134
August 6, 2005	--	--	0.0129	0.0053	--
August 16, 2005	0.0590	0.0161	0.0103	--	0.1766
September 16, 2005	0.0622	0.0205	0.2246	0.0948	0.1644
October 7, 2005	0.0363	0.0121	0.0121	0.0365	0.9246
April 7, 2006	0.0315	0.0193	--	0.1014	0.0738
August 11, 2006	0.0763	0.0554	0.0148	0.0631	0.6385
August 19, 2006	0.0338	0.0040	0.0124	0.0060	0.2808
August 29, 2006	0.2569	0.0486	0.0501	0.8028	0.9359
September 22, 2006	0.0750	--	0.0165	0.0463	0.0422
October 16, 2006	--	--	--	--	--
November 1, 2006	0.0236	0.0518	0.1215	--	0.0701
Mean±Std.Dev.	0.0663±0.0706	0.0263±0.0200	0.0493±0.0706	0.1445±0.2684	0.3320±0.3629
--------------------2012-2013--------------------					
June 1, 2012	0.0092	0.0014	--	0.0954	0.1048
August 6, 2012	0.0223	0.398	0.0322	--	--
August 10, 2012	0.0001	--	0.0013	--	--
August 15, 2012	0.3090	--	0.0018	--	--
September 17, 2012	--	--	--	0.1603	0.0654
October 28, 2012	0.0065	--	0.0091	0.0077	0.0131
April 17, 2013	0.0098	0.0027	0.0253	0.0064	0.0058
May 20, 2013	0.0001	0.0001	0.0000	0.0006	0.0104
June 30, 2013	0.0004	0.0005	0.0000	0.0009	0.0011
July 11, 2013	0.0057	--	--	--	--
August 10, 2013	0.2822	--	--	0.0276	0.0206
November 25, 2013	0.0024	0.0535	--	0.0699	0.6578
Mean±Std.Dev.	0.0581±0.1177	0.0163±0.0239	0.0100±0.0133	0.0461±0.0580	0.1099±0.2243

results suggest that CNs computed using λ=0.05 are more representative of actual rainfall-interflow conditions at the study site.

No significant treatment differences were noted for the 2012-2013 monitoring period (Figure 3.4). For the 2012-2013 monitoring period and λ=0.2, BROWN had a mean CN of 78 while GRAY and MIXED each had a mean CN of 83. For λ=0.05, the mean CNs for BROWN, GRAY and MIXED were 53, 63 and 65, respectively. Similar results were noted by Taylor et al. (2009a) during the 2005-2006 monitoring period. The authors found no difference in CN with spoil type. These findings were unexpected as it was hypothesized that significant treatment effects would occur by 2012-2013 for storm events and would be noted by changes in CNs. By the 2012-2013 monitoring period, BROWN had significantly more vegetation as compared to GRAY and MIXED. Sena (2014) found that groundcover on BROWN was nearly 10% greater than on GRAY and over 20% greater than on MIXED (Table 3.5). Furthermore, Sena (2014) found tree volume (12,270 cm^3) on BROWN was over 50 times greater than GRAY (237 cm^3) and nearly 7 times greater than MIXED.

While tree growth and ground cover were significantly greater on BROWN and did influence the overall annual water budget (storm and base flows) as noted by Sena (2014), vegetation did not significantly influence storm interflow though reductions in mean CN were measured. These finding suggest that interception and evapotranspiration may have some influence on storm hydrology, but that the placement of the spoil using FRA is overriding the influence of vegetation at this point in time. In essence, the FRA placed spoil, with its hummocky surface and high infiltration rates (Angel et al., 2008; Taylor et al., 2009b) acts much like a rain garden with amended soils. During storm events, evapotranspiration exerts little influence on the water budget in rain gardens (Dietz and Clausen, 2005; Li et al., 2009; WEF, 2012). However, evapotranspiration can significantly increase storage capacity in the soil between storm events (WEF, 2012). Because of a lack of data during the non-growing season (October 27-April 19), CN separation based on times of high and low evapotranspiration (i.e. growing versus non-growing seasons) could not be performed.

As noted by Miller et al. (2012), the BROWN, GRAY and MIXED spoils all weather, and hence settle, due to factors such as freeze-thaw forces and dissolution of

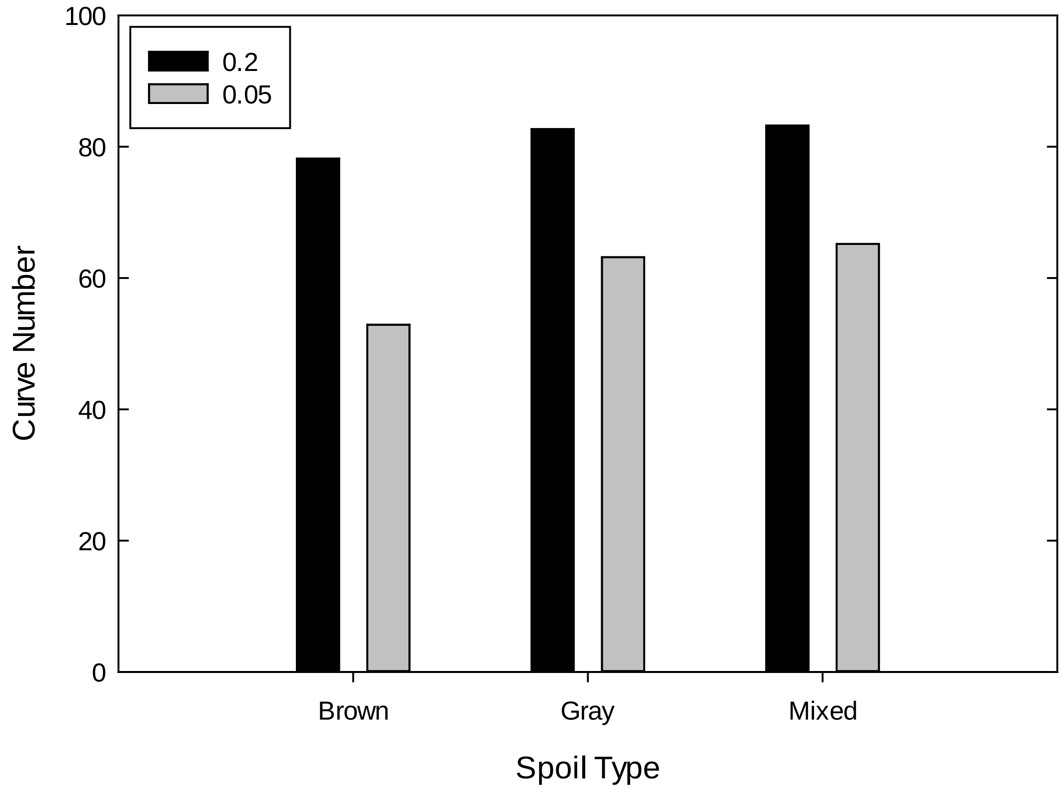

Figure 3.4: Curve Numbers versus Spoil Type (monitoring period 2012-2013).

Table 3.5: Tree Volume and Ground Cover on Bent Mountain Plots in 2013.[1]

Tree Volume (cm^3)			Ground Cover (%)		
Brown	Gray	Mixed	Brown	Gray	Mixed
12,270±292	237±115	1,837±277	99.1±0	9.8±0.05	20.2±0.07

[1]Source: Sena (2014).

carbonate cements. This settling is expected to reduce infiltration rates as sandstones and shales break down into finer particles and begin to fill in some of the macropores. Also as noted by Miller et al. (2012), the rate of weather varies with spoil type. Brown sandstones and shale weathered most rapidly with gray sandstone weathering much more slowly. Thus, weathering likely accounted in part for the lower, though not significant, mean CN in BROWN.

A significant trend was noted between rainfall depth and CN (λ=02 and 0.05) for the 2005-2006 and 2012-2013 monitoring periods as well as for both monitoring periods combined (Table 3.6). As expected, lower rainfall depths produced significantly larger CNs (Figures 3.5 and 3.6) (Hjelmfelt, 1991; Hawkins, 1993; Warner et al., 2010), particularly with λ=0.2 where the initial abstraction was assumed to be higher. Van Mullem et al., (2002) noted that higher initial abstractions for small storms that do produce runoff resulted in the computation of artificially high CNs. As seen in Figures 3.5 and 3.6, the significant relationship between CN and rainfall depth was much less pronounced with λ=0.05.

3.3.2 Robinson Forest

For the reference watershed LMS (2000-2004), mean CNs were 83 and 62, respectively, for λ=0.2 and were 75 and 31, respectively, for λ=0.05 (Table 3.7). Hawkins (1993) computed a mean CN of 85 for LMS using λ=0.2. For the LMS watershed, CN decreased with precipitation depth for both λ=0.2 and 0.05 (Figures 3.7-3.8). Hawkins (1993) classified the LMS as “violent” for larger storms (>25.4 mm) meaning CNs rise rapidly with increasing rainfall depth before reaching a constant or “threshold” value. For this study, results from the storms (>25.4 mm) analyzed in this study do not show the same “violent” trend.

Table 3.6: Bent Mountain Plot Curve Numbers[1] Related to Precipitation Categories.

	2005-2006[2]		2012-2013		All Years	
Precipitation (mm)	CN (λ=0.2)[3]	CN (λ=0.05)[3]	CN (λ=0.2)[3]	CN (λ=0.05)[3]	CN (λ=0.2)[3]	CN (λ=0.05)[3]
12.7 - 19.0	87±3 a	75±8 a	89±6 a	59±18 ab	88±4 a	69±15 a
19.0 - 25.4	81±5 b	64±12 b	78±6 b	47±20 b	80±6 b	57±18 b
>25.4	81±7 b	69±13ab	79±11 b	69±16 a	80±9 b	69±14 a

[1]AMC II
[2]Source: Taylor et al. (2009a).
[3]Statistical differences within column indicated by differing letter.

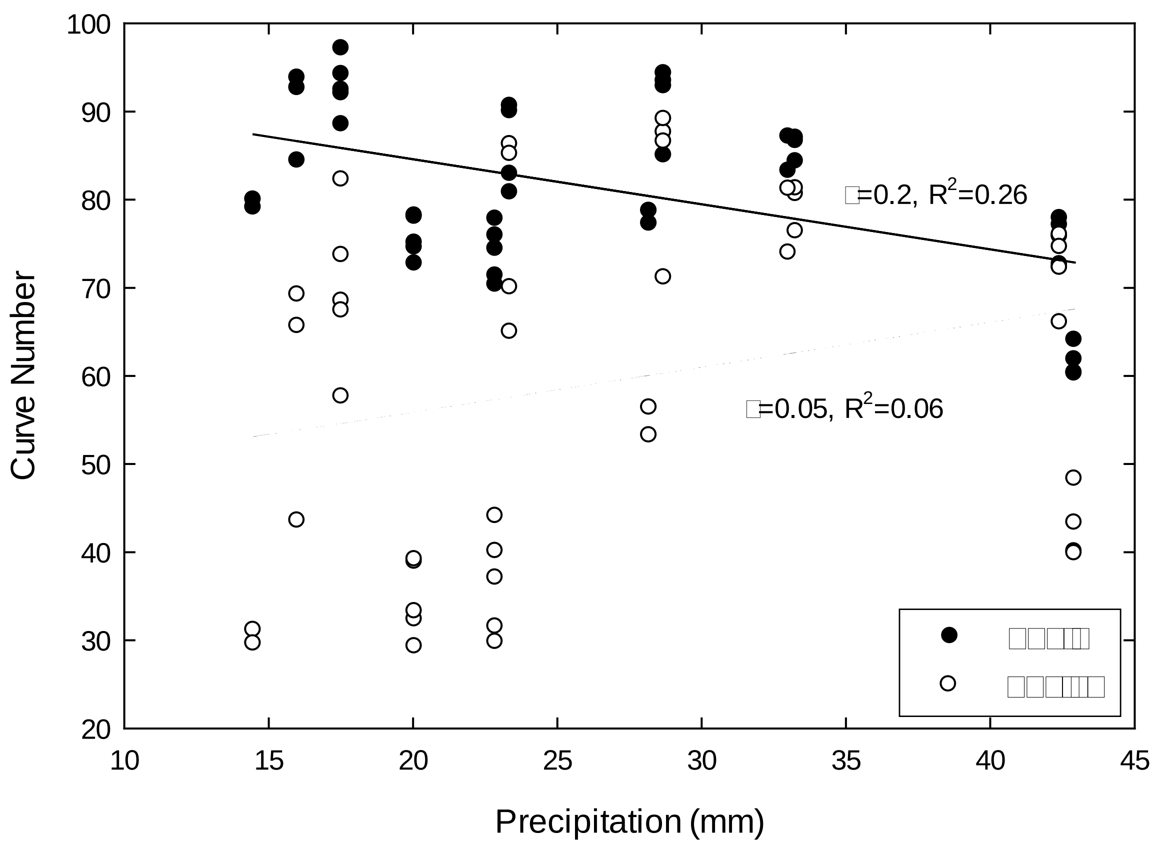

Figure 3.5: Curve Numbers from Bent Mountain (2012-2013 Monitoring Period) in Relation to Precipitation Depths.

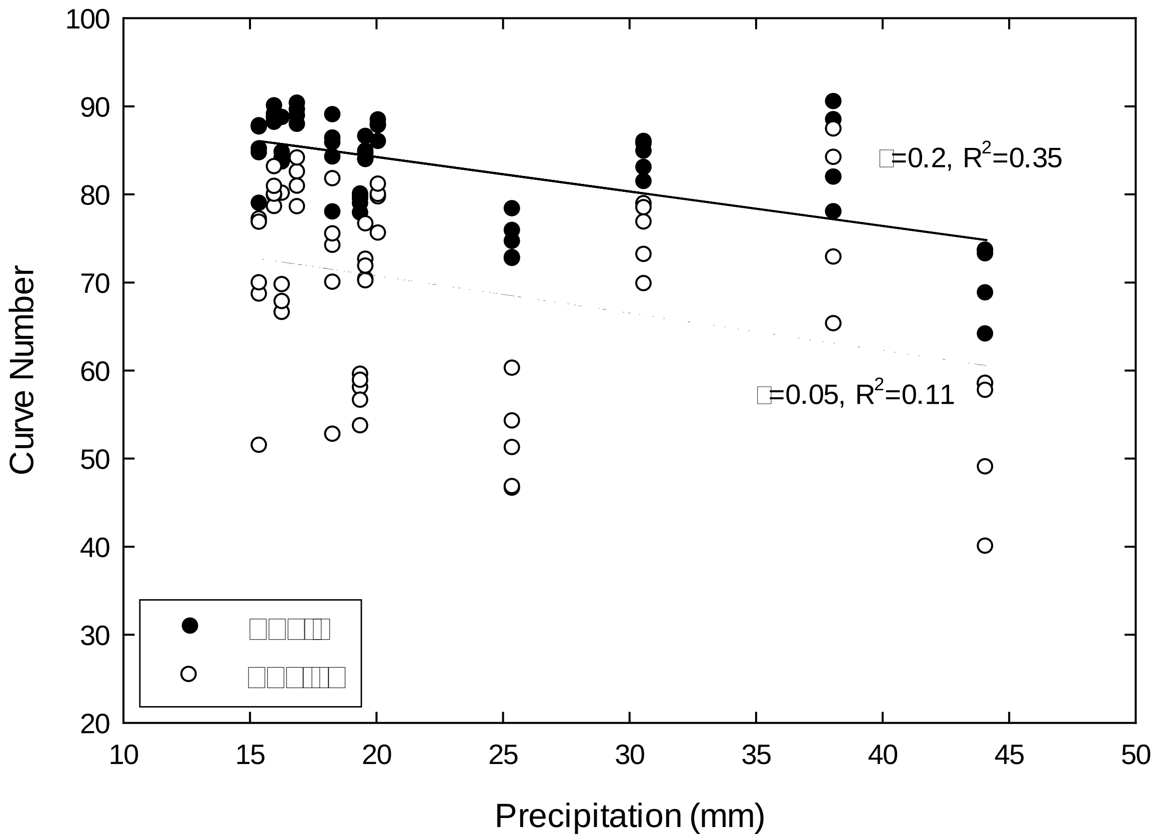

Figure 3.6: Curve Numbers from Bent Mountain (2005-2006 Monitoring Period) in Relation to Precipitation Depths.

Table 3.7: Curve Numbers for Little Millseat Watershed.

Date	CN (λ=0.2)	CN (λ=0.05)
---------------------2000-2004---------------------[2,3]		
April 4, 2000	88	83
December 16, 2000	91	89
January 20, 2001	76	63
February 14, 2001	87	83
February 16, 2001	88	83
July 13, 2002	54	31
April 6, 2003	90	86
June 7, 2003	89	84
September 3, 2003	65	46
November 17, 2003	81	73
January 2, 2004	93	91
March 5, 2004	90	87
Mean±Std.Dev. (all events)	83±12	75±19

[1]AMC II
[2] Little Millseat.
[3]Source: Taylor et al. (2009a).

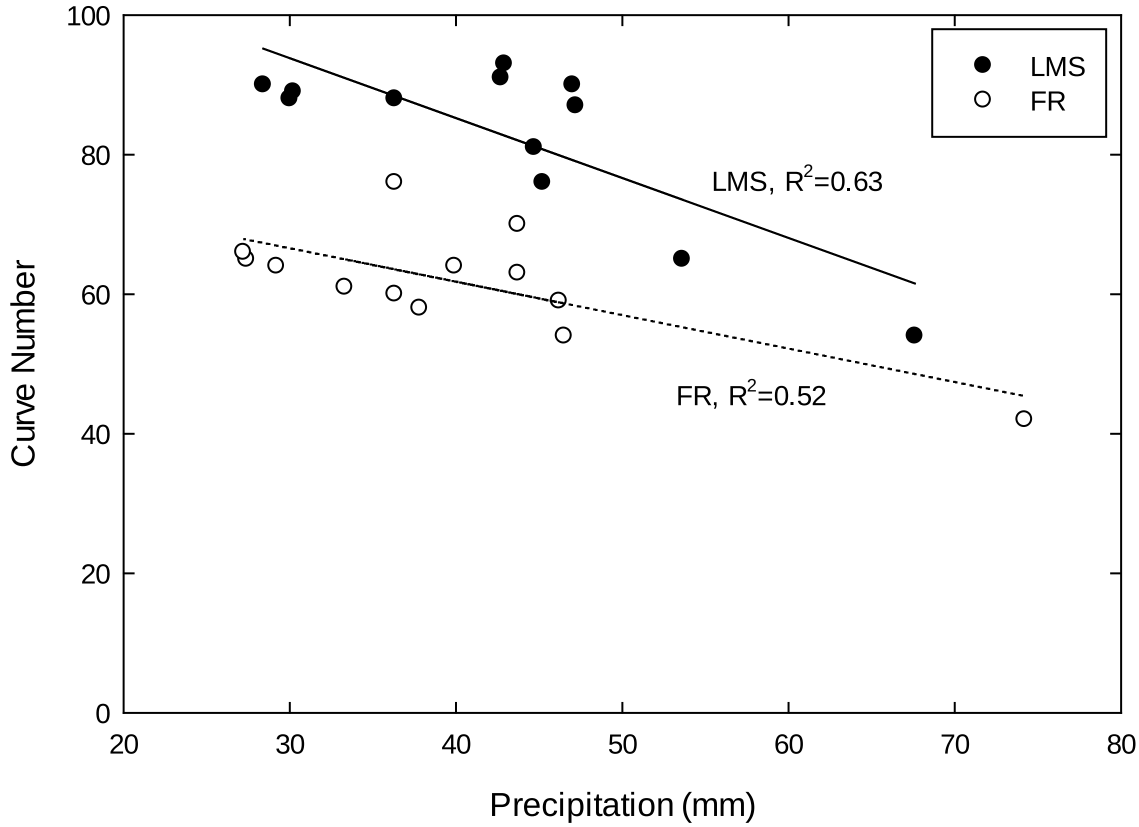

Figure 3.7: Curve Numbers from Little Millseat (LMS) (2000-2004) and Falling Rock (FR) (2012-2013) in Relation to Precipitation Depths, λ=0.2.

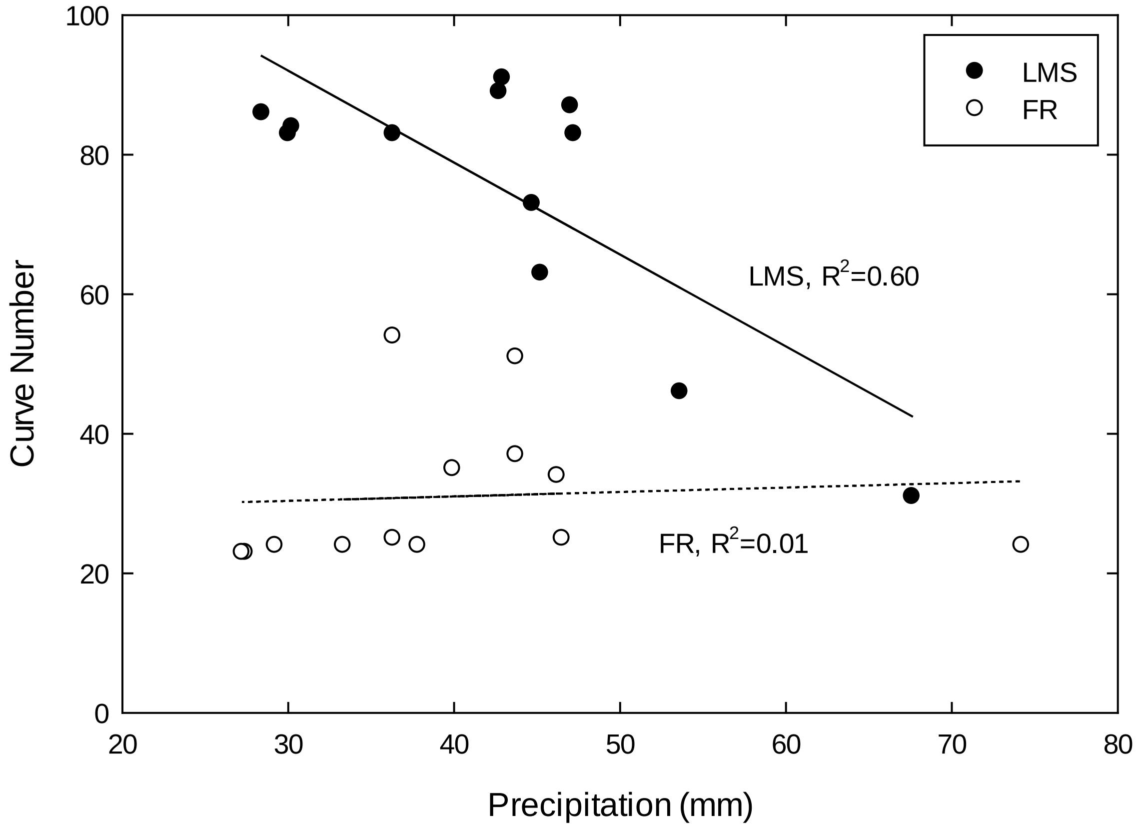

Figure 3.8: Curve Numbers from Little Millseat (LMS) (2000-2004) and Falling Rock (FR) (2012-2013) in Relation to Precipitation Depths, λ=0.05.

3.3.3 CN Comparison

Results from the one-way ANOVAs (nonparametric) indicated that median CNs (λ=0.2 and λ=0.05) measured at BM were similar to the median CN measured at LMS (Table 3.8). As noted by Taylor et al. (2009a), from the time of placement, loose-dumped spoil behaves hydrologically similar to a forested, reference watershed (LMS), and it continues to do so even after a period of 7-8 years.

3.4 CONCLUSIONS

This study developed CNs from 7-8 year old forests established on three different types of spoil: (1) brown, unweathered sandstone, (2) gray, weathered sandstone, and (3) a mixture of both sandstones and shale. These CNs were compared to CNs from the same plot with a 0-1 year old forest (Taylor et al., 2009a) as well as a two reference watersheds with 90+ year old forests. Since 2005-2006 (years 0 and 1), tree growth and ground cover on the BROWN plots has substantially outpaced vegetation growth on the GRAY and MIXED plots. Tree volumes on the BROWN plots are 50 times greater than those on the GRAY plots and 7 times greater than those on the MIXED plots. As such, it was hypothesized that by 2012-2103, CNs on the BROWN plots would be significantly less than those on the GRAY and MIXED plots due to the additional storage capacity provided via evapotranspiration.

No significant differences were found between treatments (BROWN vs. GRAY vs. MIXED) or between monitoring periods (2005-2006 vs. 2012-2013). These findings indicate that while vegetation did influence the overall annual water budget (storm and

Table 3.8: Medians from CN Comparison between Bent Mountain (BM) Plots and the Little Millseat (LMS) Watershed.[1]

Location	λ=0.2	λ=0.05	Discharge Volume (m^3)
BM (2005-2006)	85 a[2]	72 ab	10.9±11.7
BM (2012-2013)	80 a	65 b	15.8±15.3
LMS	88 a	83 a	13.7±7.9

[1]AMC II
[2]Statistical differences within column indicated by differing letter.

base flows), as noted by Sena (2014), vegetation did not significantly influence CNs. While no significant differences in CN were noted amongst the treatments, the mean CN for the BROWN plots was lower than the mean CNs from the GRAY and MIXED plots suggesting that vegetation may be exerting some small influence on storm hydrology. Findings from this study indicate that it is the placement of the spoil using FRA that has the greatest influence at this point in time. Important to note is that while this study found no significant differences in spoil type with respect to CN, reclamationists must consider a myriad of other factors such as water quality, nutrient cycling, and aquatic and terrestrial habitats in addition to hydrology when restoring forested ecosystems on mined lands.

CHAPTER 4: CONCLUSIONS

This study evaluated the hydrologic performance of three spoil types (1) brown, weathered sandstone (BROWN), (2) gray unweathered sandstone (GRAY), and (3) a mixture of shales and both sandstones (MIXED). Spoil was placed in accordance to minimal compaction guidelines set forth in the Forestry Reclamation Approach (FRA. The research site was located in eastern Kentucky on the Bent Mountain surface mine (BM), which is located near the community of Meta, KY. Both reference watersheds (FR and LMS) were located at the University of Kentucky's research forest also in eastern Kentucky. Results from this study may aid reclamationists in their attempts to restore hydrologic function to reclaimed mine lands.

Chapter one provided an outline of research objectives as well as background information about surface mining and reclamation techniques.

Chapter two evaluated the interflow storm hydrologic characteristics discharge volume, peak discharge, lag time, response time, and discharge duration for the monitoring period of 2012-2013 and compared them to values at initial plot conditions of 2005-2006 (Table 3.9). Background research and plot construction methods were discussed. For the extent of this study, no significant differences in discharge volume and discharge duration were found between monitoring periods 2005-2006 and 2012-2013. Lag time, response time, and peak discharge all increased significantly. Discharge volume remained quite small; only 17% of rainfall was discharged as storm flow. As in 2005-2006, no significant treatment differences were noted between plots for monitoring period 2012-2013. These findings indicate that the placement of the spoil controls storm hydrology at this point in time.

Chapter three developed curve numbers for the 7-8 year old young forest and compared these to CN values found at year 0-1 as well as a 90+ year reference watershed. Curve numbers did not significantly change between monitoring periods (2005-2006 and 2012-2013) or between the three spoil types (BROWN, GRAY, and MIXED). However, it was noted that the mean CN for the BROWN, highly vegetated plot, was slightly lower than the CN from GRAY and MIXED. This might suggest that vegetation can exert some small influence on storm hydrology indicating that the overall water budget will decrease

Table 3.9: Summary Table of Mean Storm Hydrology Parameters and CNs from Bent Mountain and Little Millseat.

Parameter	Monitoring Period (BM)		LMS
	2005-2006	2012-2013	
Discharge volume (m^3)	10.9±11.7	15.8±15.3	--[1]
Discharge volume (% rainfall)	11.7±9.0	17.5±17.4	--
Peak Discharge ($m^3\ s^{-1}$ x 10^{-4})	6.3±5.3	7.0±4.7	--
Lag Time (d x 10^{-2})	10.2±14.0	33.5±39.3	--
Response Time (d x 10^{-2})	5.4±9.5	16.0±27.6	--
Discharge Duration (d)	6.3±4.5	4.0±3.9	--
CN (λ=0.2)	83	81	83
CN (λ=0.05)	69	57	75

[1]Values were not determined.

overtime as vegetation continues to develop. Results from CN comparison of BM to LMS measured similar values for both λ=0.2 and λ=0.05. This suggests that in the case of LMS, after 8 years loose-dumped spoil will continue to behave in a similar manner to a forested watershed.

This study indicates that the method of spoil placement (i.e. minimal compaction), and not vegetation growth, is driving the hydrology on a storm event basis for these plots. However, it is important to note that surface mine reclamation encompasses many other factors such as habitat, water quality, and nutrient cycling and that while no difference between spoil treatments in terms of hydrology was found, BROWN demonstrated remarkable vegetation growth compared to GRAY and MIXED.

CHAPTER 5: FUTURE WORK

Future research should continue to evaluate the influence vegetation growth on baseflow conditions and storm response. After 8 years, hydrograph characteristics and curve numbers did not greatly change from initial plot construction conditions. However, as vegetation continues to grow, it could exert a greater influence over storm hydrology and differences between treatments may become apparent.

During the extent of this analysis, few large storms were available. Because precipitation depth can bias curve number, work should be done to evaluate CN response to larger storms and for a longer monitoring time period.

Although spoil type at this point does not influence storm hydrology, other aspects of reclamation, such as spoil stability on steeper slopes, should be considered for optimal reclamation conditions.

APPENDIX A: BENT MOUNTAIN HYDROGRAPHS

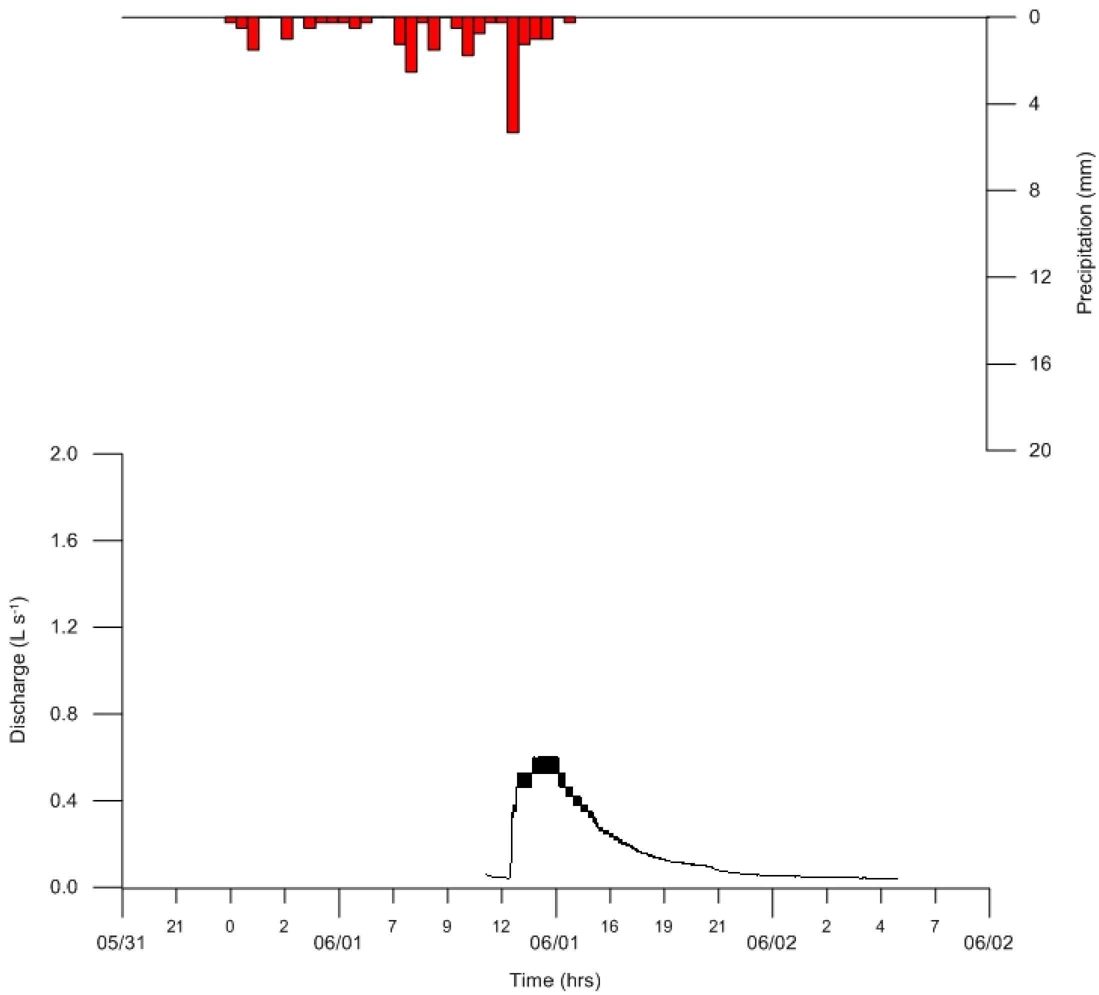

Figure A.1. Rainfall-Runoff Response at Bent Mountain on June 1, 2012. BM1, BROWN.

Table A.1: Storm Hydrograph Characteristics and CNs.

Start of Storm	6/1/12 0:00
Storm Duration	23.4
Precipitation Depth (mm)	15.0
CN (λ=0.2)	81
CN (λ=0.05)	65
Discharge volume (m^3)	7.1
Discharge volume (% rainfall)	7.6
Peak Discharge (m^3 s^{-1} x 10^{-4})	7.0
Lag Time (d x 10^{-2})	55.8
Response Time (d x 10^{-2})	51.4
Discharge Duration (d)	0.7

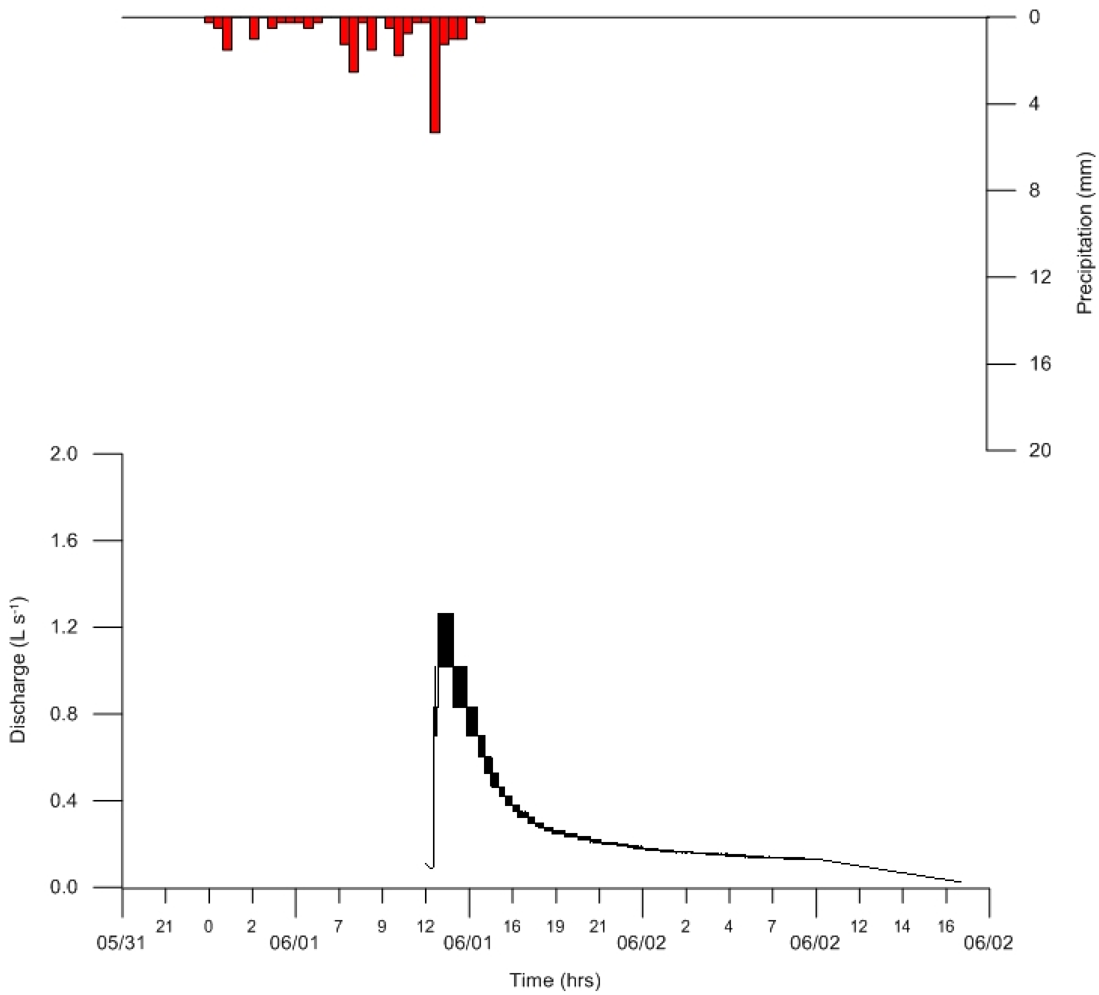

Figure A.2. Rainfall-Runoff Response at Bent Mountain on June 1, 2012. BM2, GRAY.

Table A.2: Storm Hydrograph Characteristics and CNs.

Start of Storm	6/1/12 0:00
Storm Duration	23.4
Precipitation Depth (mm)	15.0
CN (λ=0.2)	83
CN (λ=0.05)	70
Discharge volume (m^3)	8.6
Discharge volume (% rainfall)	10.9
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	52.8
Response Time (d x 10^{-2})	51.5
Discharge Duration (d)	1.1

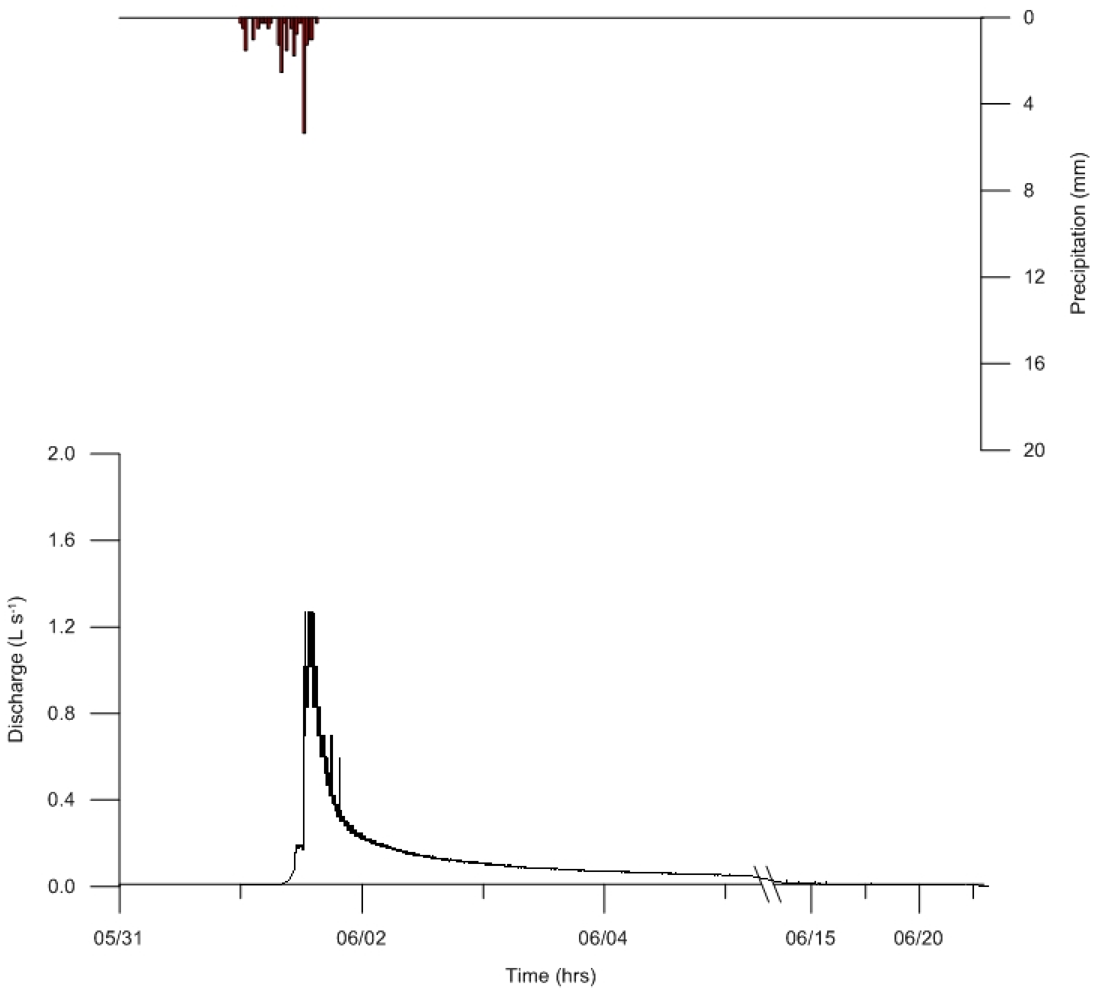

Figure A.3. Rainfall-Runoff Response at Bent Mountain on June 1, 2012. BM4, MIXED.

Table A.3: Storm Hydrograph Characteristics and CNs.

Start of Storm	6/1/12 0:00
Storm Duration	23.4
Precipitation Depth (mm)	15.0
CN (λ=0.2)	91
CN (λ=0.05)	86
Discharge volume (m^3)	23.5
Discharge volume (% rainfall)	31.5
Peak Discharge ($m^3\ s^{-1}$ x 10^{-4})	12.6
Lag Time (d x 10^{-2})	52.8
Response Time (d x 10^{-2})	10.1
Discharge Duration (d)	15.7

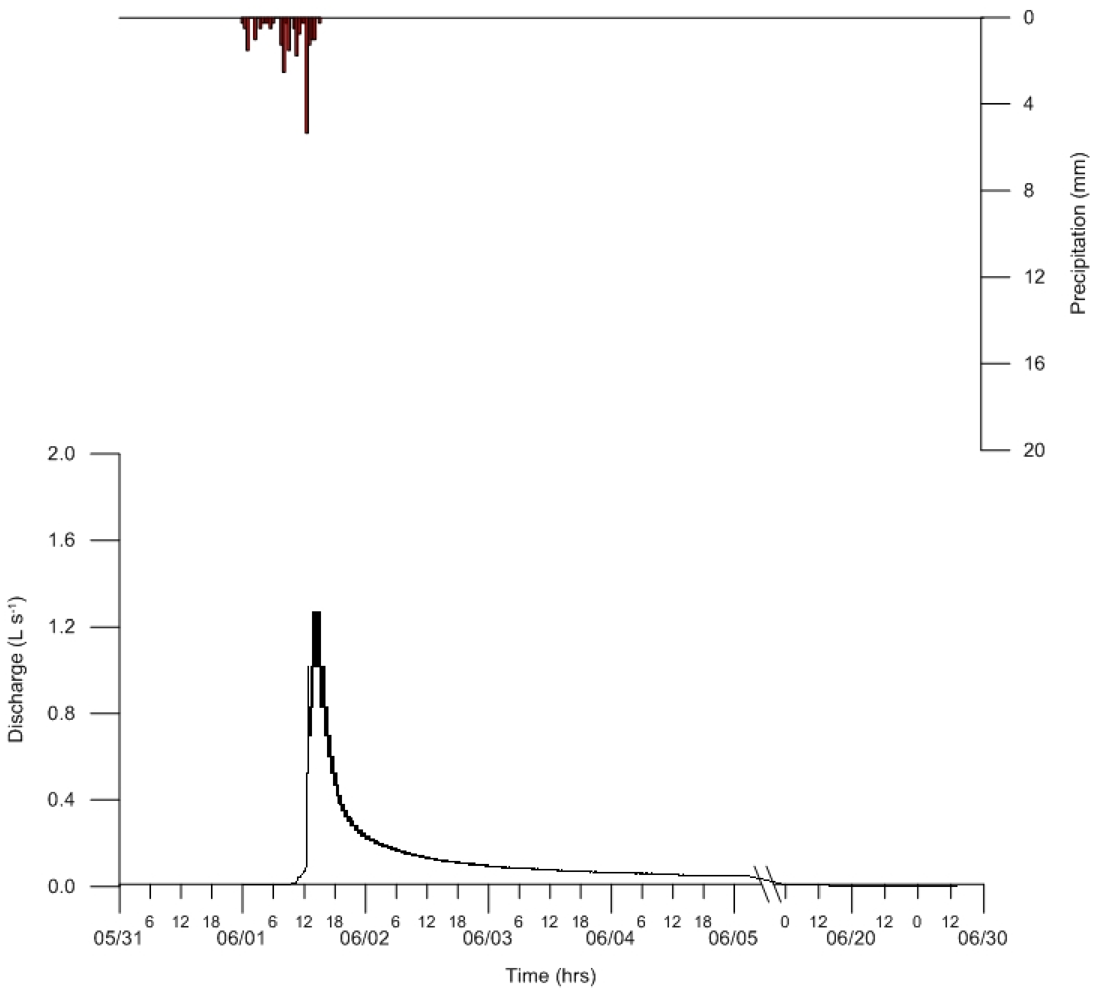

Figure A.4. Rainfall-Runoff Response at Bent Mountain on June 1, 2012. BM5, MIXED.

Table A.4: Storm Hydrograph Characteristics and CNs.

Start of Storm	6/1/12 0:00
Storm Duration	23.4
Precipitation Depth (mm)	15.0
CN (λ=0.2)	90
CN (λ=0.05)	85
Discharge volume (m^3)	24.7
Discharge volume (% rainfall)	33.0
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	56.9
Response Time (d x 10^{-2})	10.2
Discharge Duration (d)	13.7

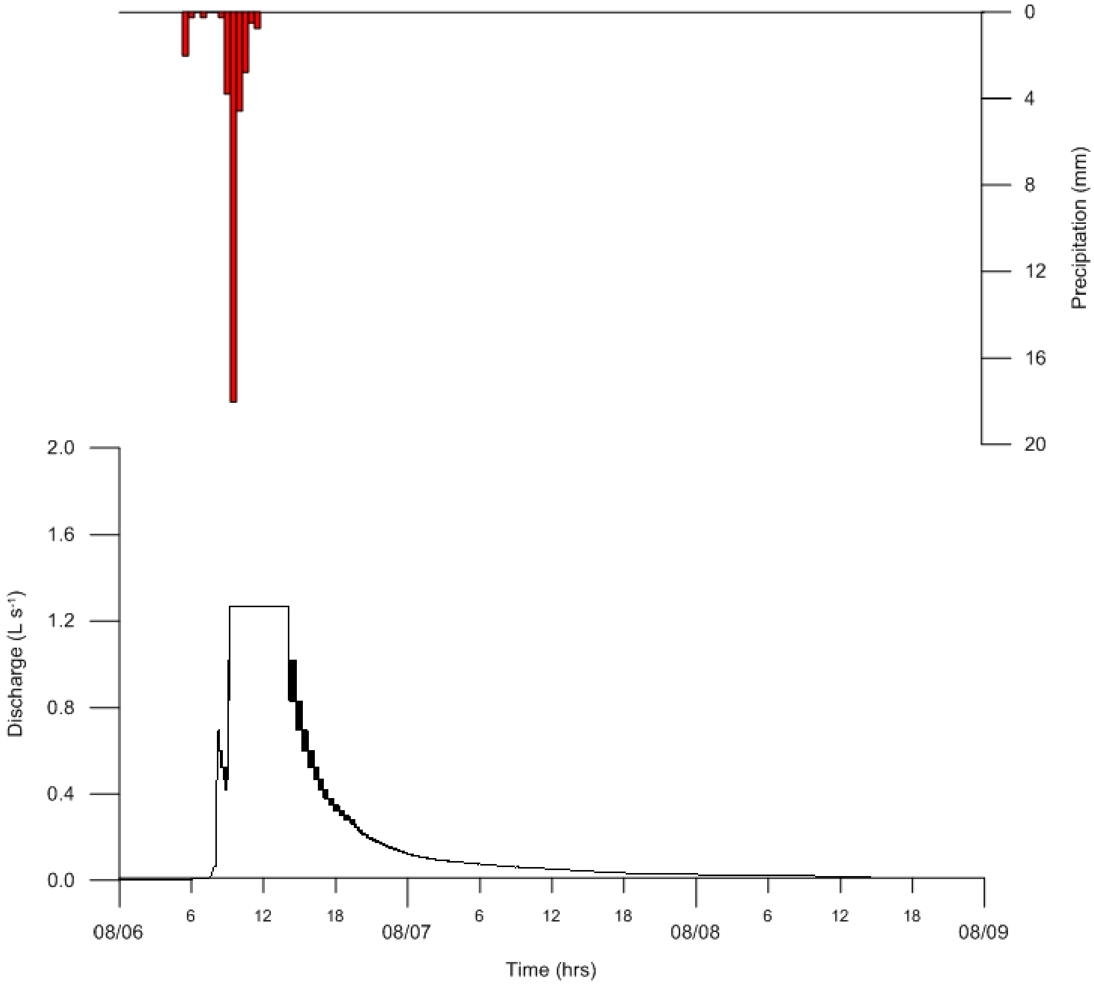

Figure A.5. Rainfall-Runoff Response at Bent Mountain on August 6, 2012. BM1, BROWN.

Table A.5: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/6/12 5:30
Storm Duration	33.3
Precipitation Depth (mm)	6.0
CN (λ=0.2)	84
CN (λ=0.05)	76
Discharge volume (m^3)	32.0
Discharge volume (% rainfall)	24.0
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	15.2
Response Time (d x 10^{-2})	4.1
Discharge Duration (d)	2.4

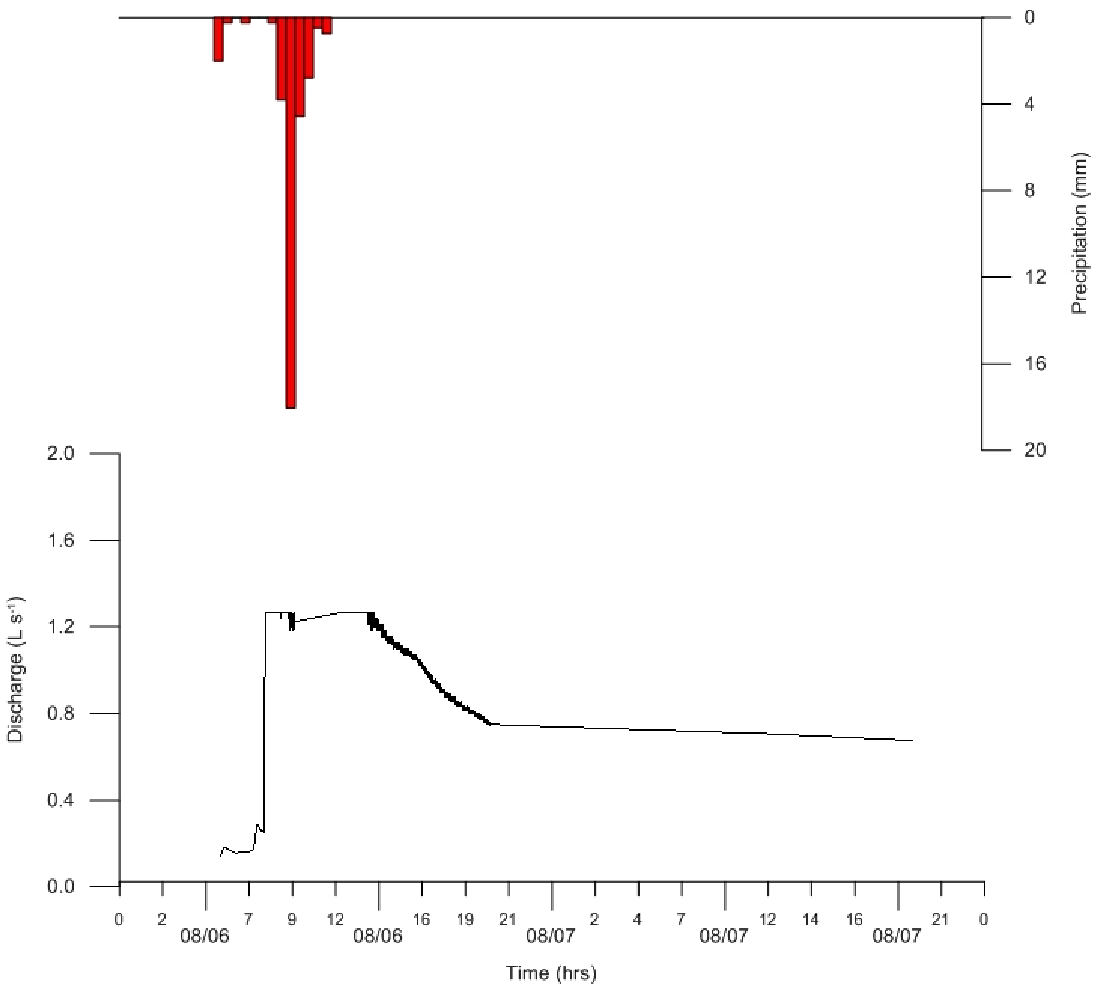

Figure A.6. Rainfall-Runoff Response at Bent Mountain on August 6, 2012. BM2, GRAY.

Table A.6: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/6/12 5:30
Storm Duration	33.3
Precipitation Depth (mm)	6.0
CN (λ=0.2)	87
CN (λ=0.05)	81
Discharge volume (m^3)	34.0
Discharge volume (% rainfall)	30.0
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	10.8
Response Time (d x 10^{-2})	10.5
Discharge Duration (d)	1.5

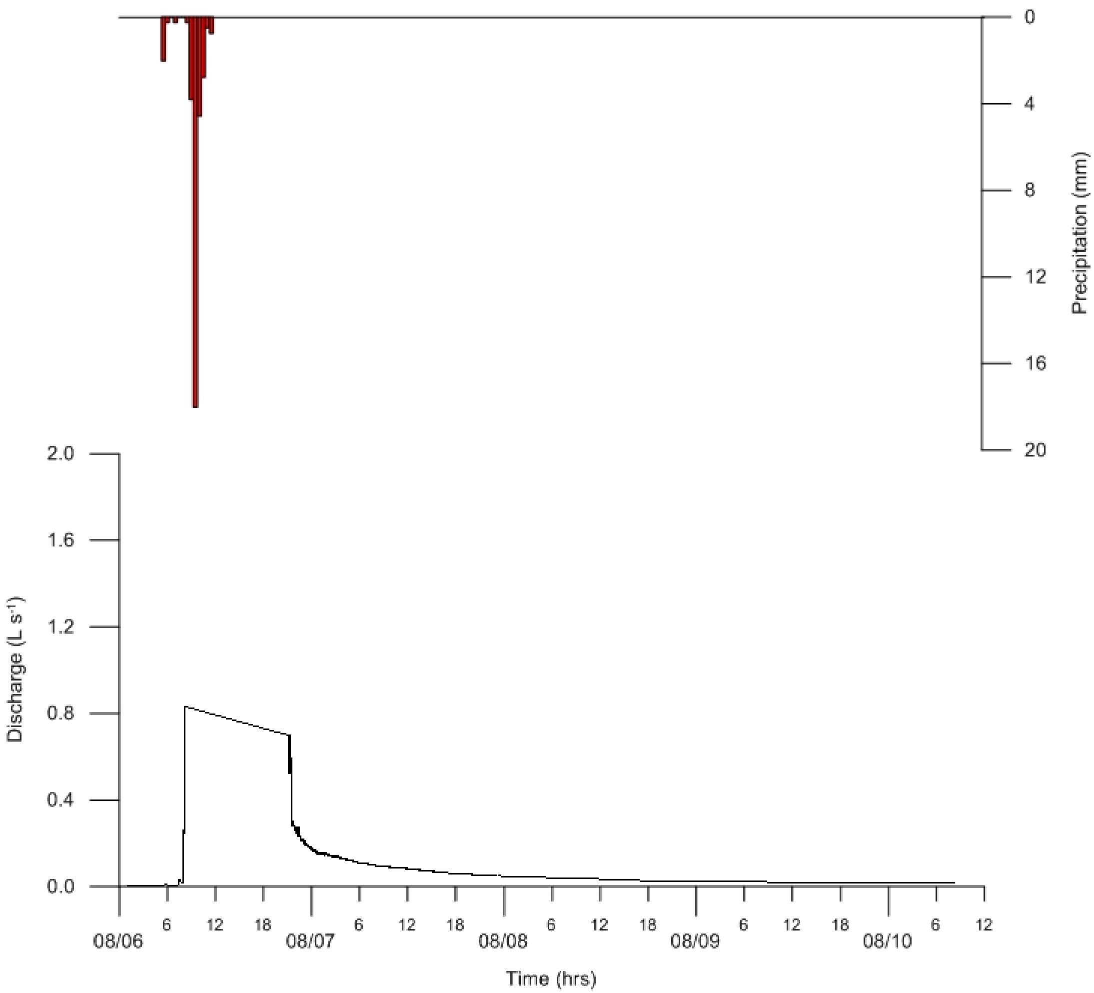

Figure A.7. Rainfall-runoff response at Bent Mountain on August 6, 2012. BM3, BROWN.

Table A.7: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/6/12 5:30
Storm Duration	33.3
Precipitation Depth (mm)	6.0
CN (λ=0.2)	87
CN (λ=0.05)	81
Discharge volume (m^3)	35.0
Discharge volume (% rainfall)	31.1
Peak Discharge (m^3 s^{-1} x 10^{-4})	8.3
Lag Time (d x 10^{-2})	11.0
Response Time (d x 10^{-2})	4.9
Discharge Duration (d)	4.2

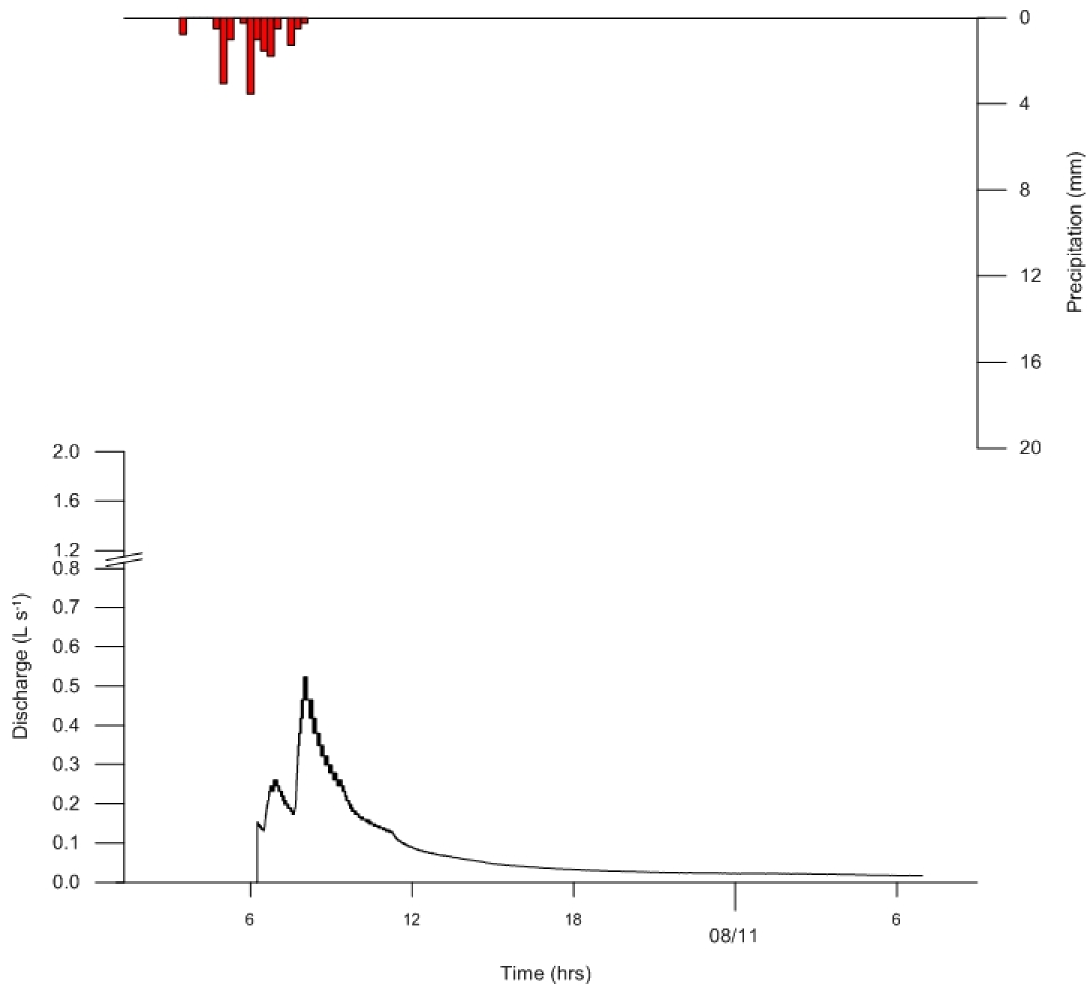

Figure A.8. Rainfall-Runoff Response at Bent Mountain on August 10, 2012. BM1, BROWN.

Table A.8: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/10/12 8:30
Storm Duration	14.5
Precipitation Depth (mm)	2.0
CN (λ=0.2)	80
CN (λ=0.05)	31
Discharge volume (m^3)	0.2
Discharge volume (% rainfall)	0.3
Peak Discharge (m^3 s^{-1} x 10^{-4})	0.5
Lag Time (d x 10^{-2})	9.9
Response Time (d x 10^{-2})	7.1
Discharge Duration (d)	0.6

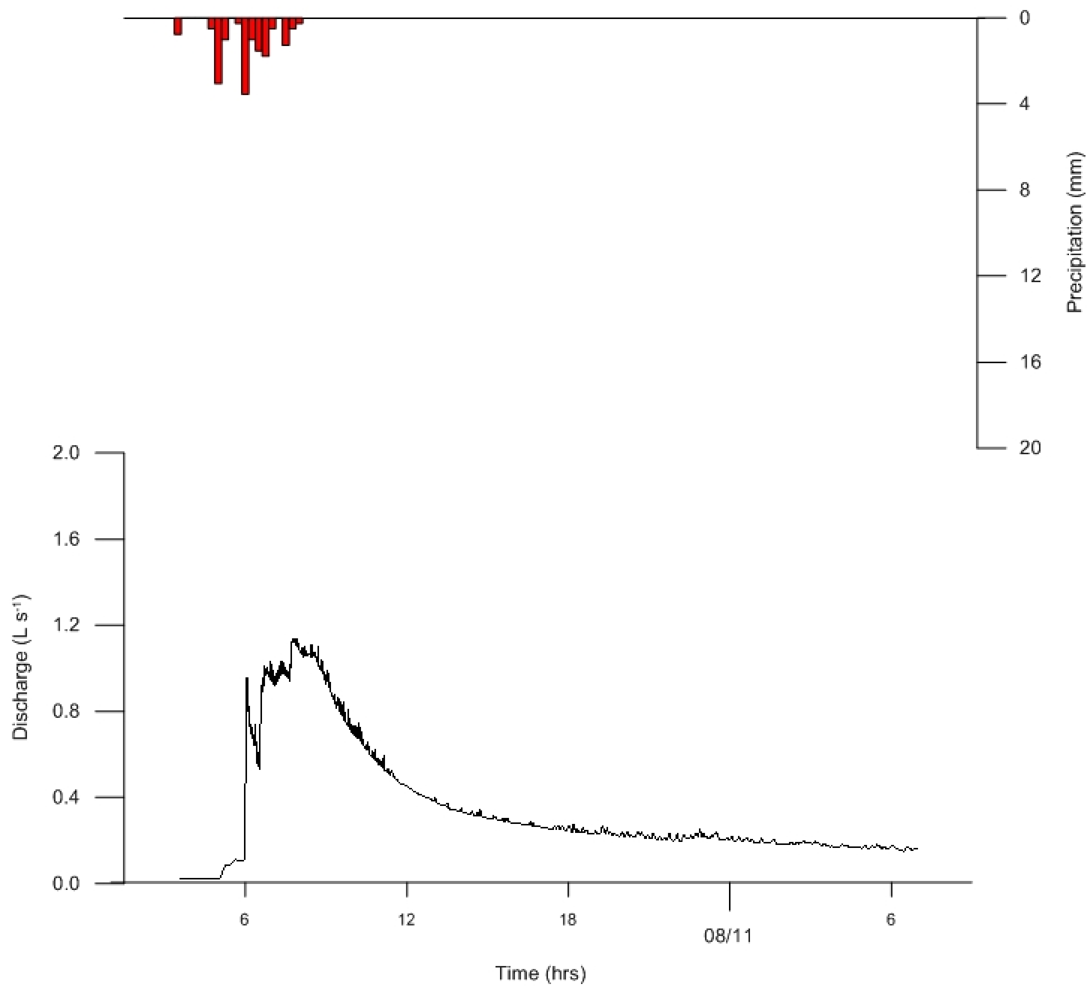

Figure A.9. Rainfall-Runoff Response at Bent Mountain on August 10, 2012. BM3, MIXED.

Table A.9: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/10/12 8:30
Storm Duration	14.5
Precipitation Depth (mm)	2.0
CN (λ=0.2)	79
CN (λ=0.05)	30
Discharge volume (m^3)	0.1
Discharge volume (% rainfall)	0.1
Peak Discharge (m^3 s^{-1} x 10^{-4})	1.1
Lag Time (d x 10^{-2})	8.1
Response Time (d x 10^{-2})	7.5
Discharge Duration (d)	0.4

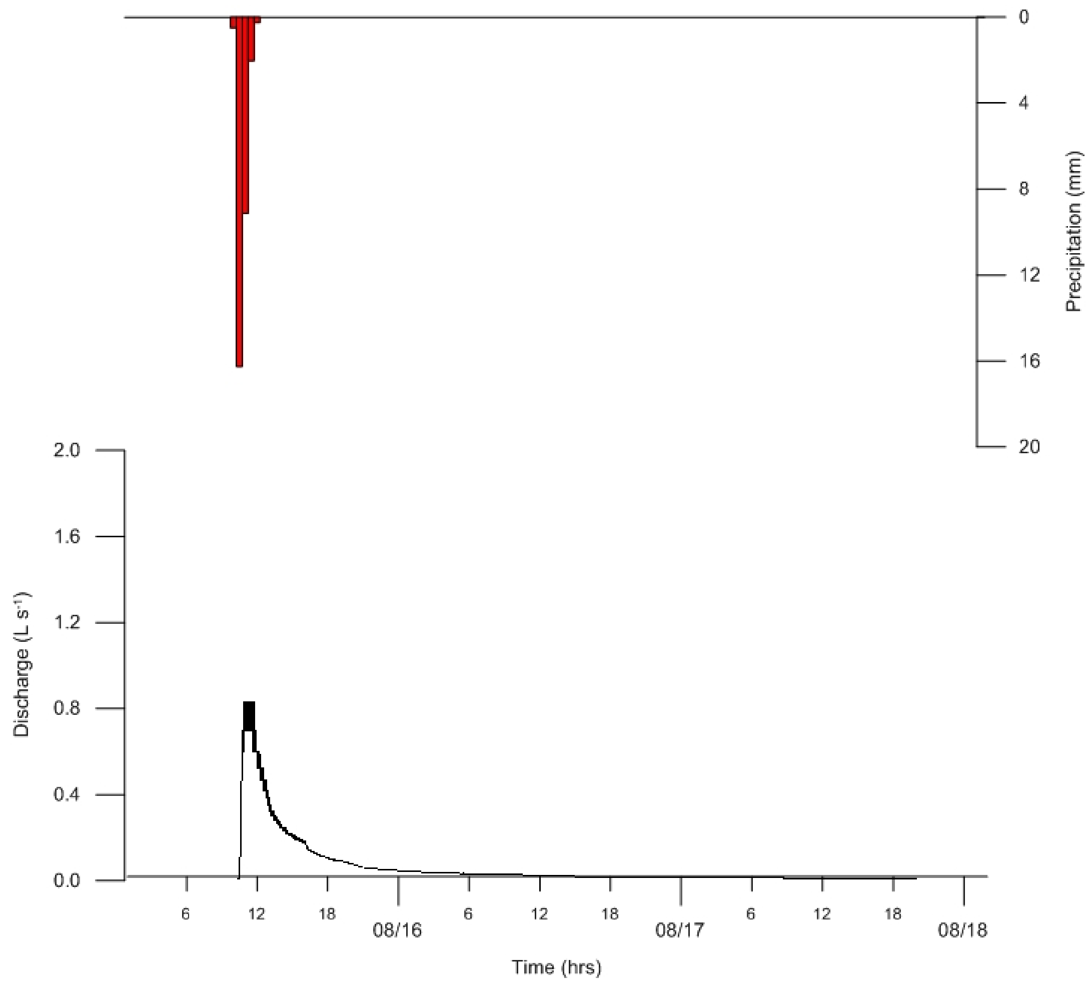

Figure A.10. Rainfall-Runoff Response at Bent Mountain on August 15, 2012. BM1, BROWN.

Table A.10: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/15/12 10:00
Storm Duration	28.2
Precipitation Depth (mm)	2.0
CN (λ=0.2)	77
CN (λ=0.05)	53
Discharge volume (m^3)	8.0
Discharge volume (% rainfall)	7.1
Peak Discharge (m^3 s^{-1} x 10^{-4})	8.3
Lag Time (d x 10^{-2})	3.7
Response Time (d x 10^{-2})	1.9
Discharge Duration (d)	3.1

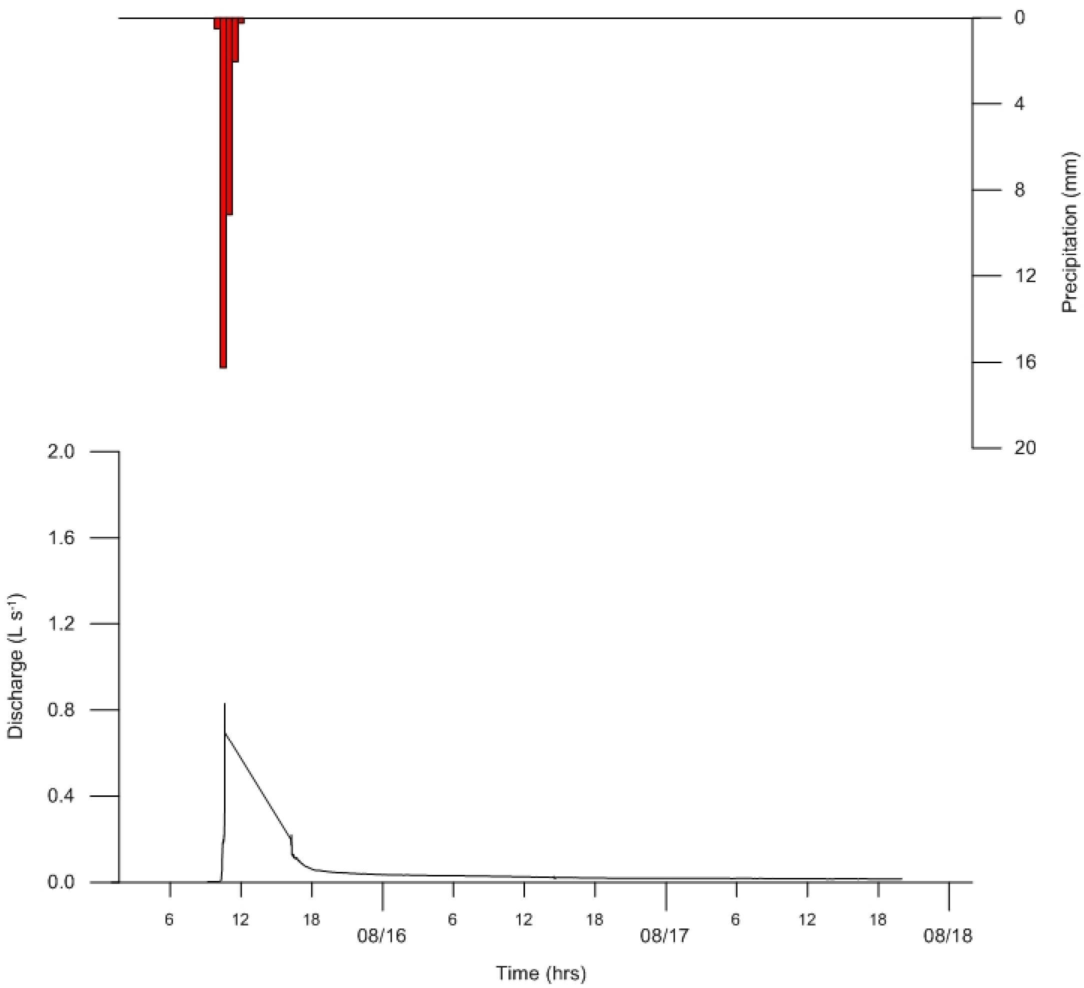

Figure A.11. Rainfall-Runoff Response at Bent Mountain on August 15, 2012. BM3, BROWN.

Table A.11: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/15/12 10:00
Storm Duration	28.2
Precipitation Depth (mm)	2.0
CN (λ=0.2)	79
CN (λ=0.05)	56
Discharge volume (m^3)	8.5
Discharge volume (% rainfall)	8.9
Peak Discharge (m^3 s^{-1} x 10^{-4})	8.3
Lag Time (d x 10^{-2})	2.6
Response Time (d x 10^{-2})	2.6
Discharge Duration (d)	8.0

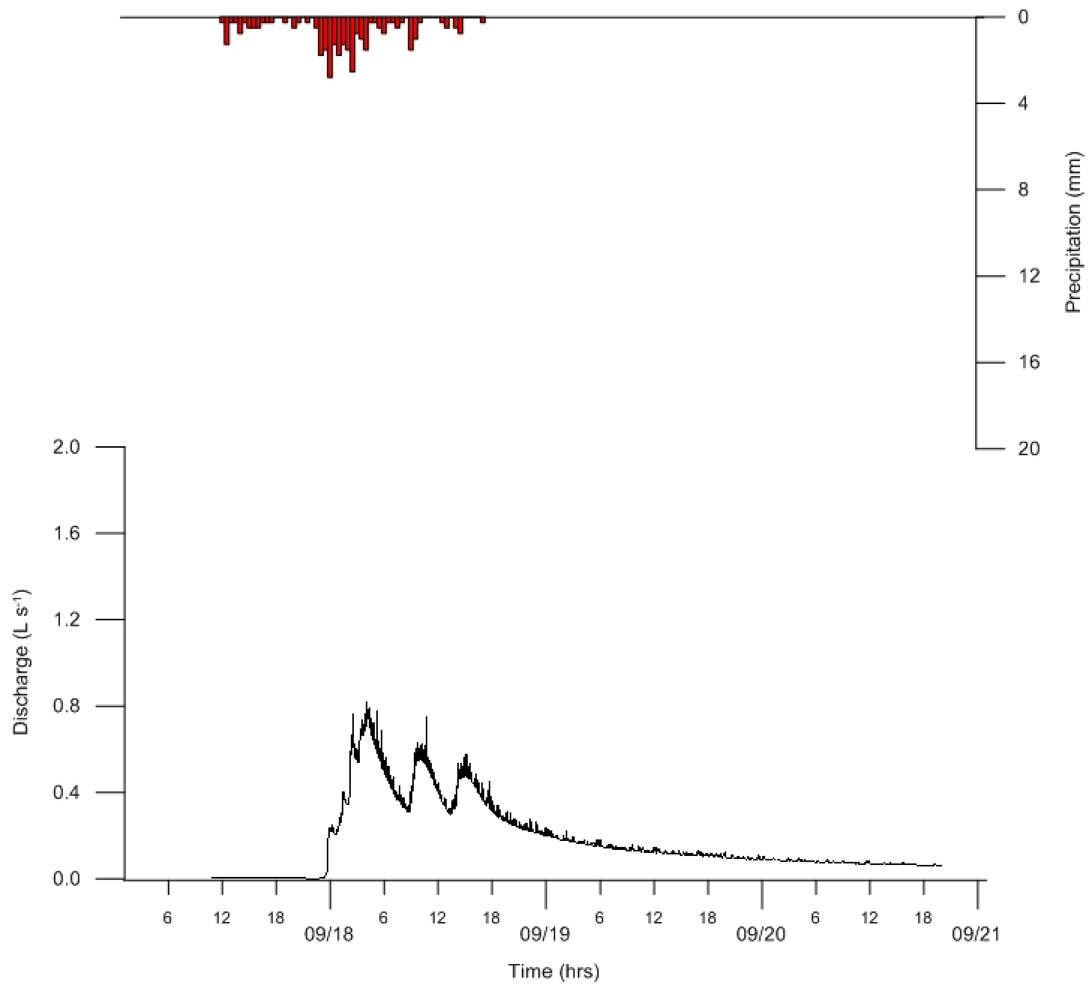

Figure A.12. Rainfall-Runoff Response at Bent Mountain on September 17, 2012. BM4, MIXED.

Table A.12: Storm Hydrograph Characteristics and CNs.

Start of Storm	9/17/12 12:00
Storm Duration	33.0
Precipitation Depth (mm)	29.0
CN (λ=0.2)	87
CN (λ=0.05)	81
Discharge volume (m^3)	33.0
Discharge volume (% rainfall)	31.3
Peak Discharge (m^3 s^{-1} x 10^{-4})	8.2
Lag Time (d x 10^{-2})	67.3
Response Time (d x 10^{-2})	42.8
Discharge Duration (d)	7.6

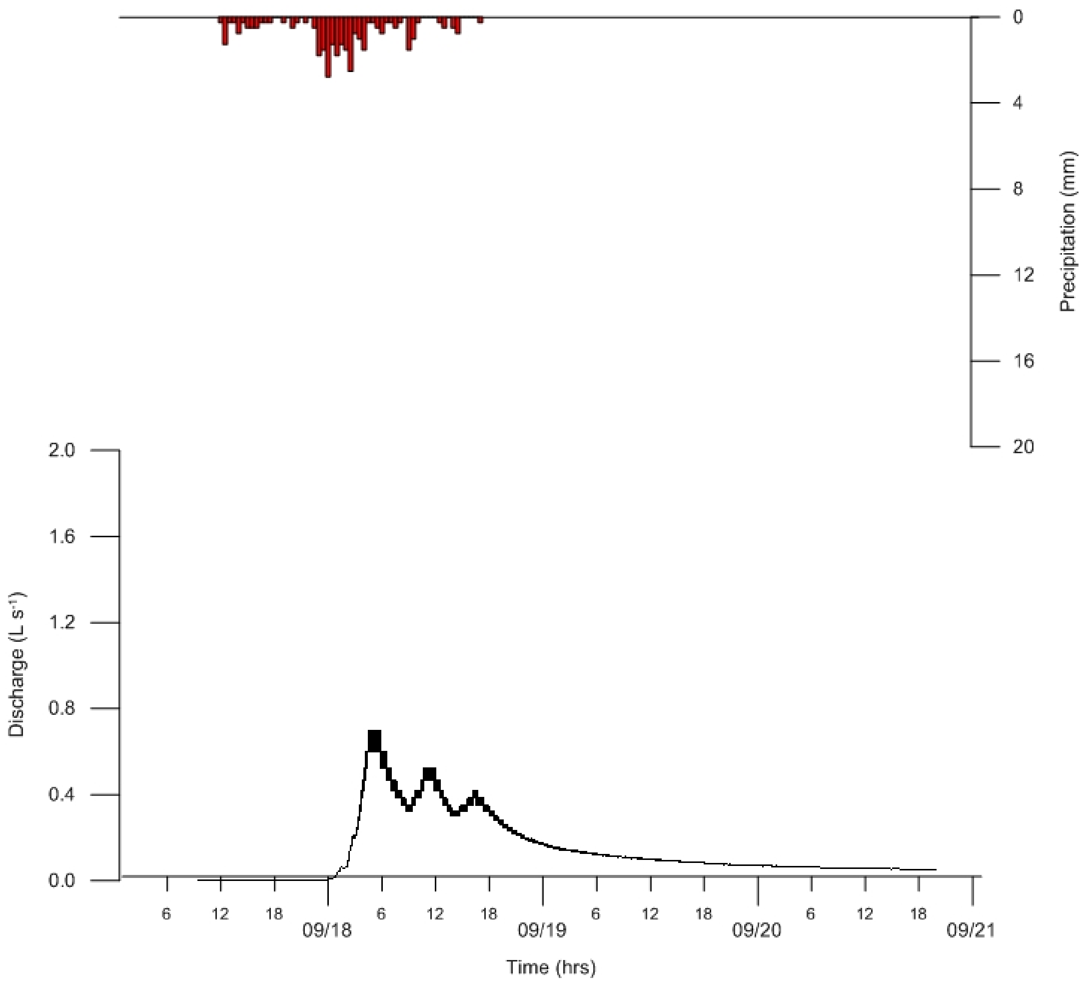

Figure A.13. Rainfall-Runoff Response at Bent Mountain on September 17, 2012. BM5, MIXED.

Table A.13: Storm Hydrograph Characteristics and CNs.

Start of Storm	9/17/12 12:00
Storm Duration	33.0
Precipitation Depth (mm)	29.0
CN (λ=0.2)	83
CN (λ=0.05)	74
Discharge volume (m^3)	25.3
Discharge volume (% rainfall)	24.0
Peak Discharge (m^3 s^{-1} x 10^{-4})	7.0
Lag Time (d x 10^{-2})	69.7
Response Time (d x 10^{-2})	26.6
Discharge Duration (d)	7.8

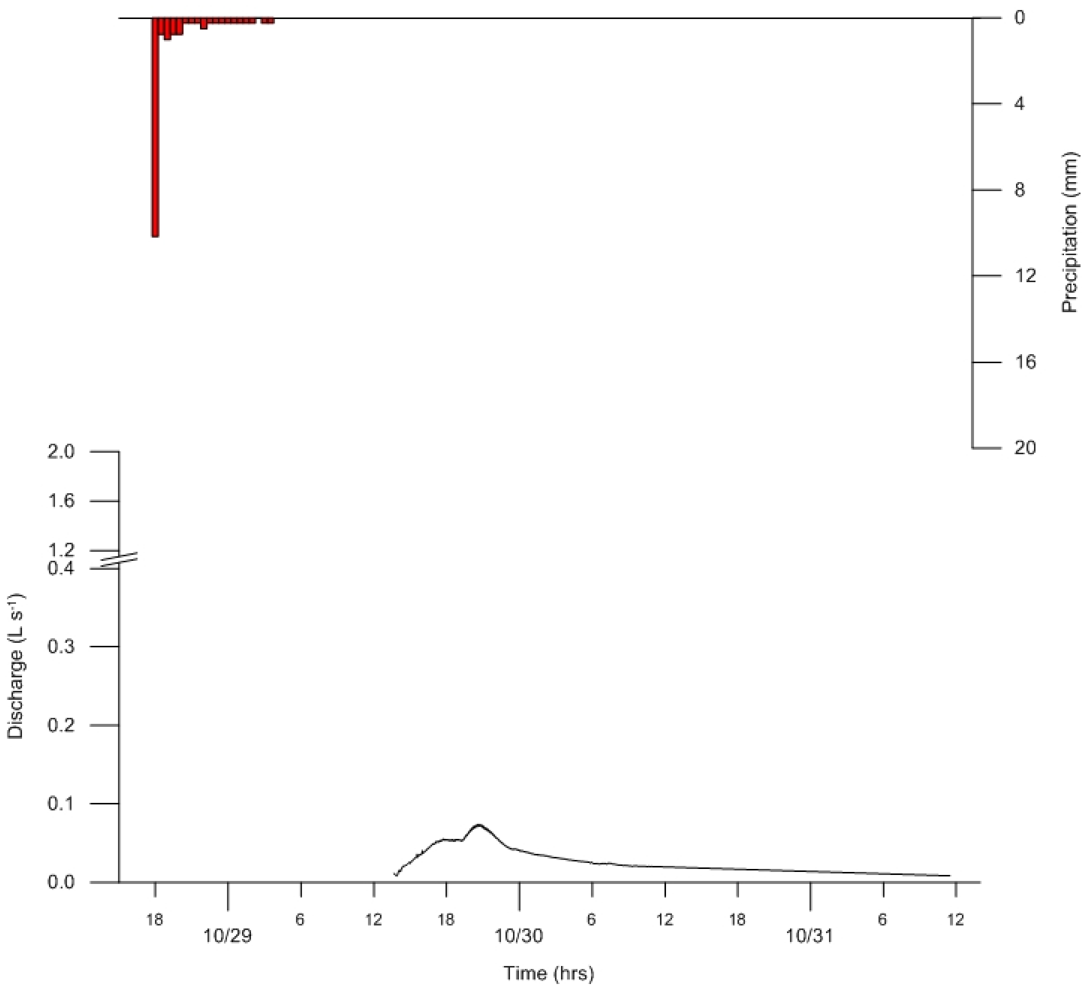

Figure A.14. Rainfall-Runoff Response at Bent Mountain on October 28, 2012. BM1, GRAY.

Table A.14: Storm Hydrograph Characteristics and CNs.

Start of Storm	10/28/12 6:30
Storm Duration	42.9
Precipitation Depth (mm)	42.9
CN (λ=0.2)	60
CN (λ=0.05)	40
Discharge volume (m^3)	2.1
Discharge volume (% rainfall)	1.2
Peak Discharge (m^3 s^{-1} x 10^{-4})	0.7
Lag Time (d x 10^{-2})	158.7
Response Time (d x 10^{-2})	130.7
Discharge Duration (d)	1.9

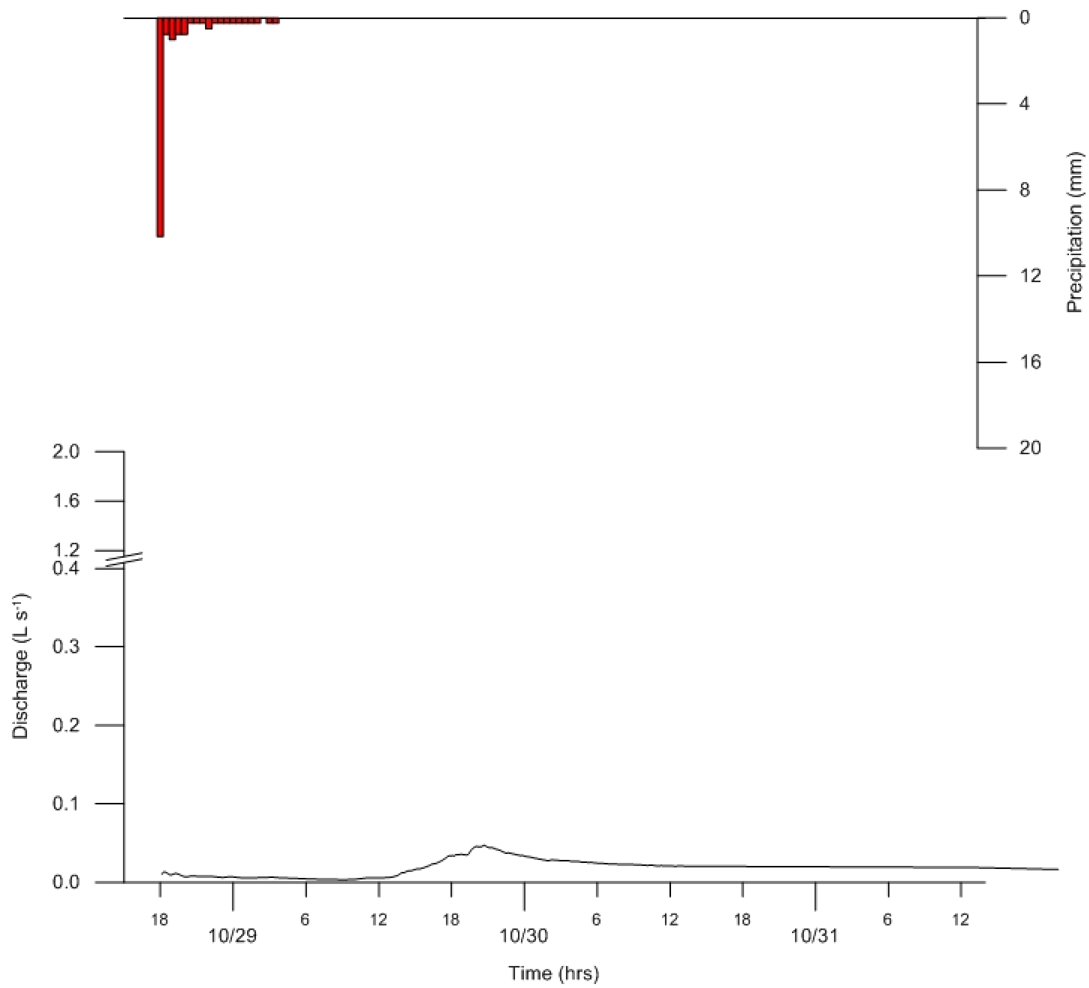

Figure A.15. Rainfall-Runoff Response at Bent Mountain on October 28, 2012. BM3, BROWN.

Table A.15: Storm Hydrograph Characteristics and CNs.

Start of Storm	10/28/12 6:30
Storm Duration	42.9
Precipitation Depth (mm)	9.5
CN (λ=0.2)	60
CN (λ=0.05)	40
Discharge volume (m^3)	1.7
Discharge volume (% rainfall)	1.2
Peak Discharge (m^3 s^{-1} x 10^{-4})	0.5
Lag Time (d x 10^{-2})	159.0
Response Time (d x 10^{-2})	116.1
Discharge Duration (d)	3.1

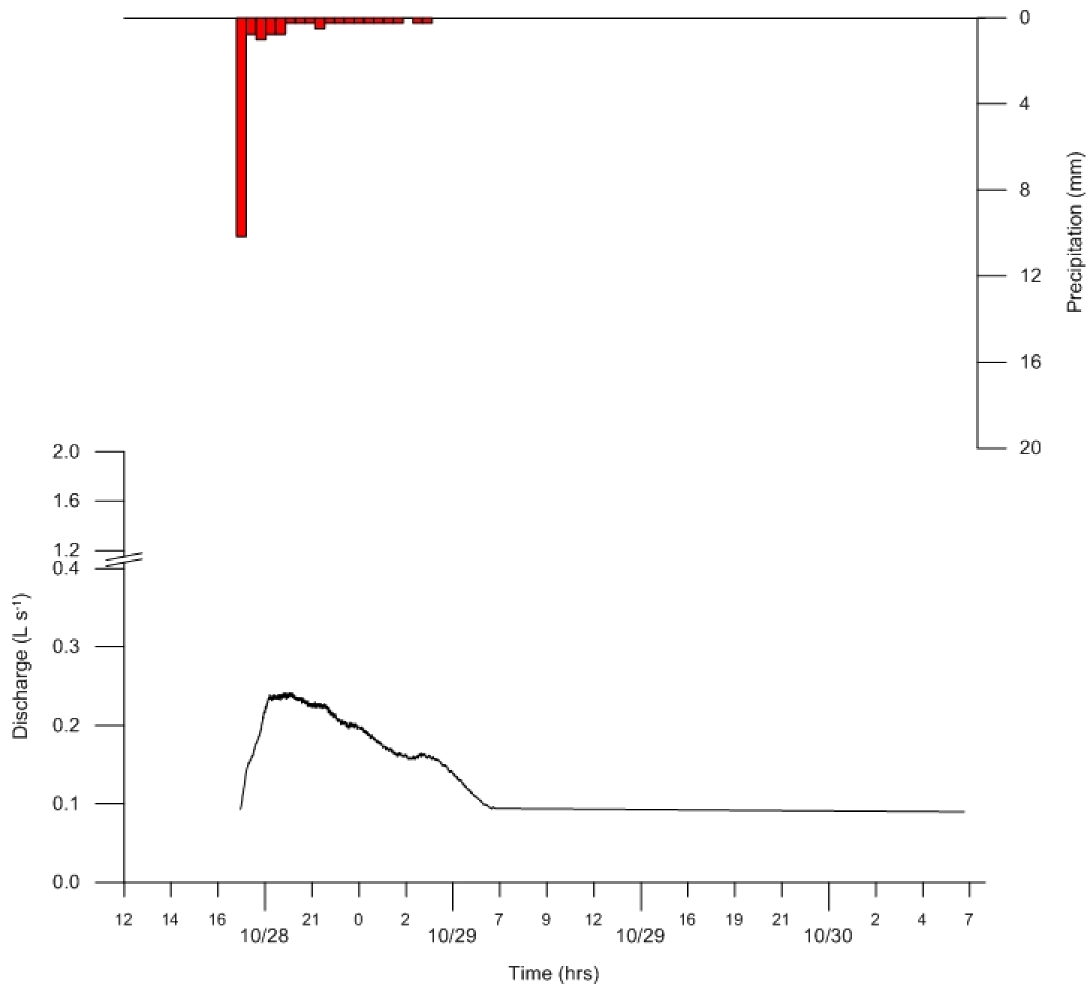

Figure A.16. Rainfall-Runoff Response at Bent Mountain on October 28, 2012. BM4, MIXED.

Table A.16: Storm Hydrograph Characteristics and CNs.

Start of Storm	10/28/12 6:30
Storm Duration	42.9
Precipitation Depth (mm)	9.5
CN (λ=0.2)	62
CN (λ=0.05)	43
Discharge volume (m^3)	2.5
Discharge volume (% rainfall)	1.9
Peak Discharge (m^3 s^{-1} x 10^{-4})	2.5
Lag Time (d x 10^{-2})	53.5
Response Time (d x 10^{-2})	47.6
Discharge Duration (d)	1.5

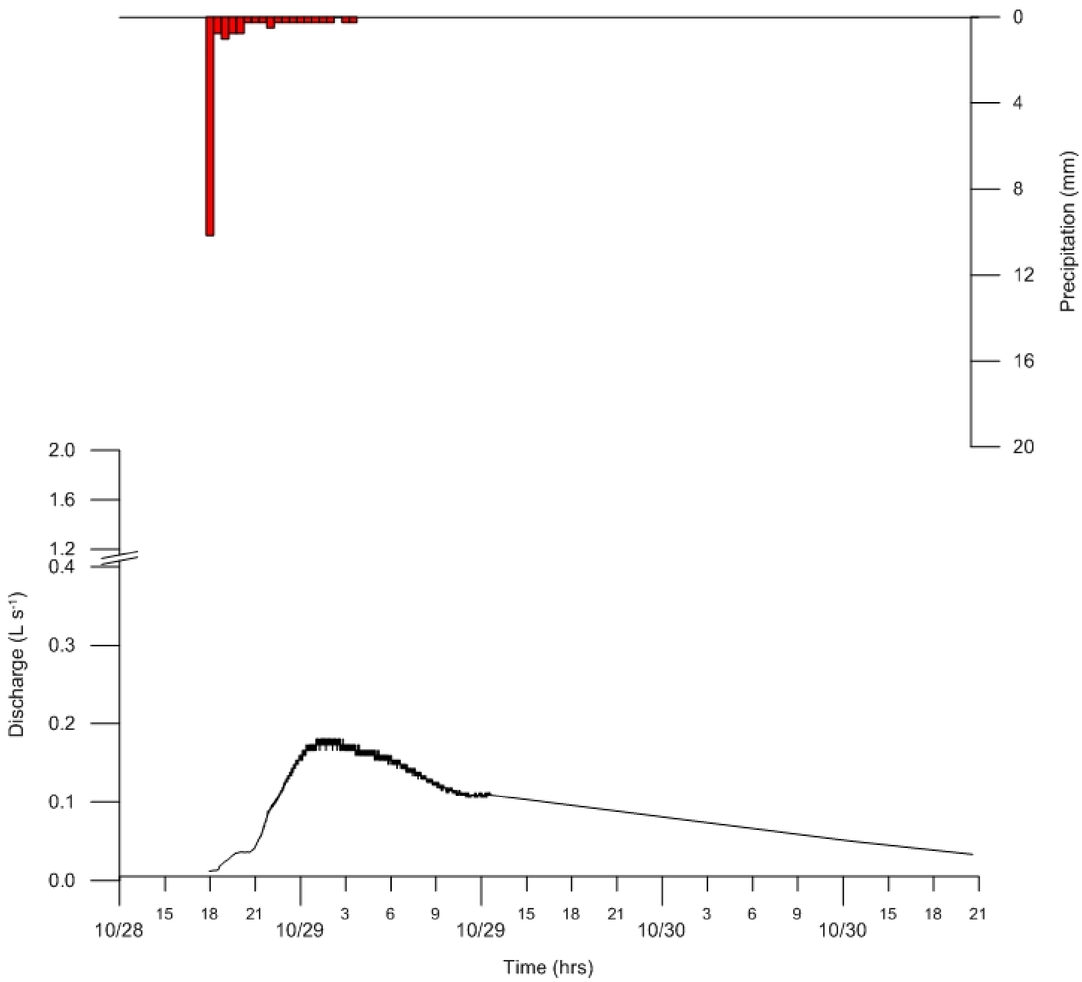

Figure A.17. Rainfall-Runoff Response at Bent Mountain on October 28, 2012. BM5, MIXED.

Table A.17: Storm Hydrograph Characteristics and CNs.

Start of Storm	10/28/12 6:30
Storm Duration	42.9
Precipitation Depth (mm)	9.5
CN (λ=0.2)	64
CN (λ=0.05)	48
Discharge volume (m^3)	4.8
Discharge volume (% rainfall)	3.5
Peak Discharge (m^3 s^{-1} x 10^{-4})	1.8
Lag Time (d x 10^{-2})	77.3
Response Time (d x 10^{-2})	48.9
Discharge Duration (d)	2.1

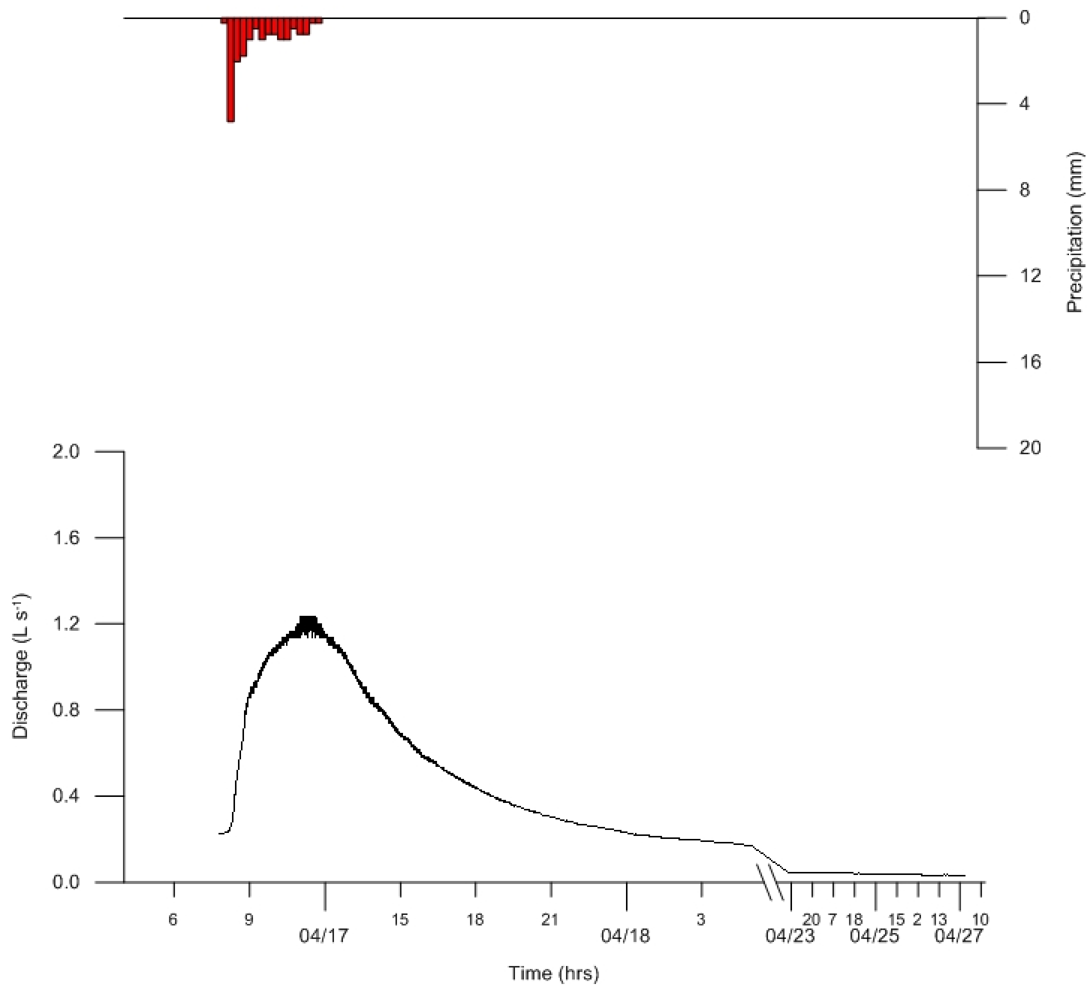

Figure A.18. Rainfall-Runoff Response at Bent Mountain on April 17, 2013. BM1, BROWN.

Table A.18: Storm Hydrograph Characteristics and CNs.

Start of Storm	4/17/13 8:00
Storm Duration	17.5
Precipitation Depth (mm)	3.8
CN (λ=0.2)	94
CN (λ=0.05)	74
Discharge volume (m^3)	27.7
Discharge volume (% rainfall)	39.4
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	11.5
Response Time (d x 10^{-2})	0.6
Discharge Duration (d)	9.8

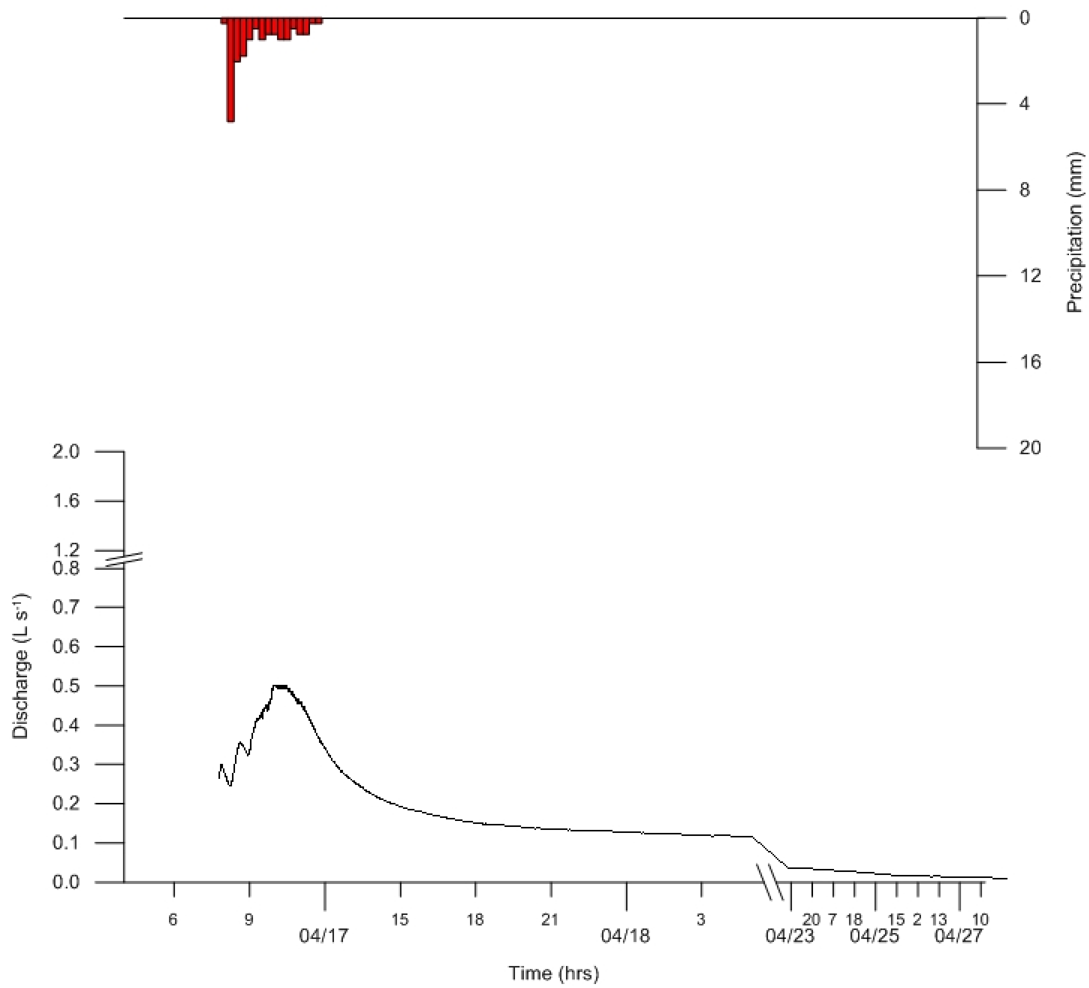

Figure A.19. Rainfall-Runoff Response at Bent Mountain on April 17, 2013. BM2, GRAY.

Table A.19: Storm Hydrograph Characteristics and CNs.

Start of Storm	4/17/13 8:00
Storm Duration	17.5
Precipitation Depth (mm)	3.8
CN (λ=0.2)	89
CN (λ=0.05)	58
Discharge volume (m^3)	9.3
Discharge volume (% rainfall)	15.5
Peak Discharge (m^3 s^{-1} x 10^{-4})	5.2
Lag Time (d x 10^{-2})	9.2
Response Time (d x 10^{-2})	0.9
Discharge Duration (d)	10.7

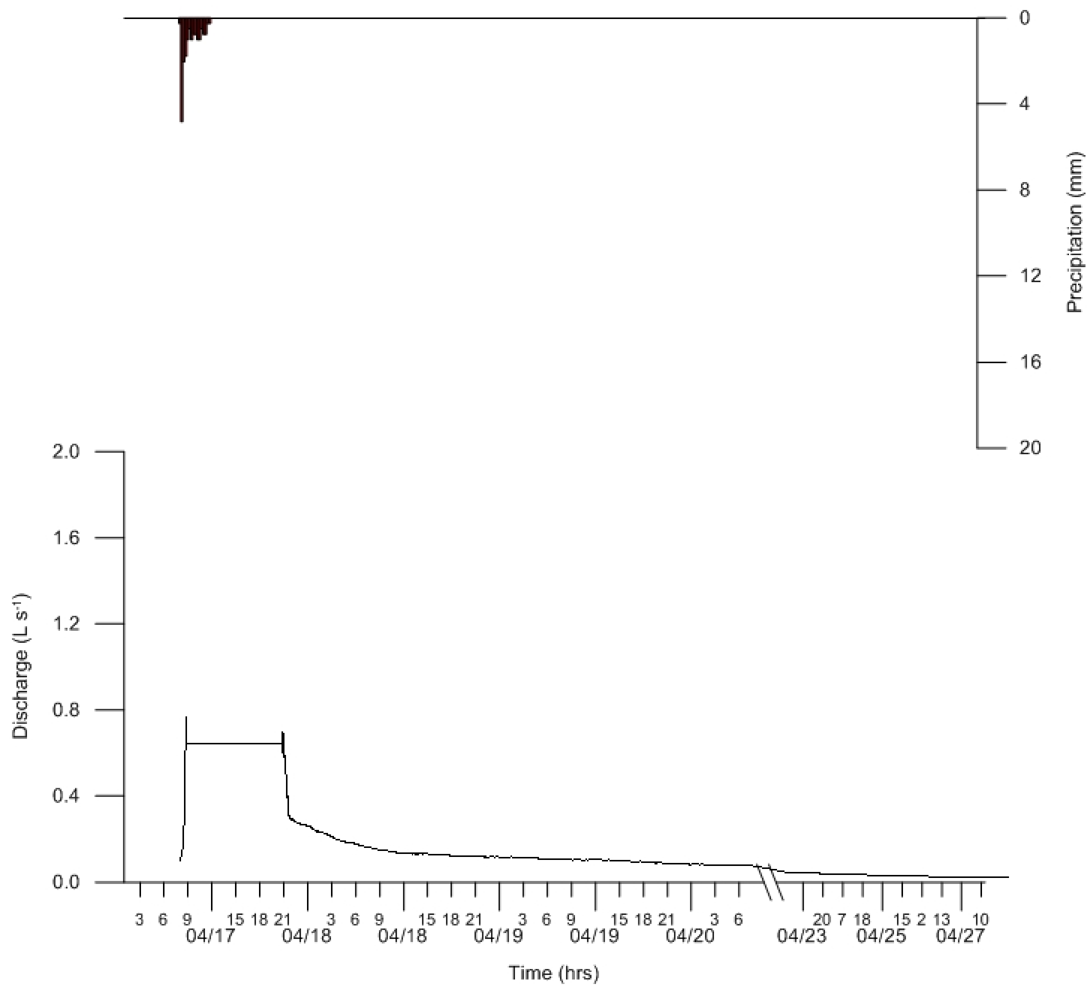

Figure A.20. Rainfall-Runoff Response at Bent Mountain on April 17, 2013. BM3, BROWN.

Table A.20: Storm Hydrograph Characteristics and CNs.

Start of Storm	4/17/13 8:00
Storm Duration	17.5
Precipitation Depth (mm)	3.8
CN (λ=0.2)	94
CN (λ=0.05)	74
Discharge volume (m^3)	27.7
Discharge volume (% rainfall)	62.3
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	11.5
Response Time (d x 10^{-2})	0.6
Discharge Duration (d)	9.8

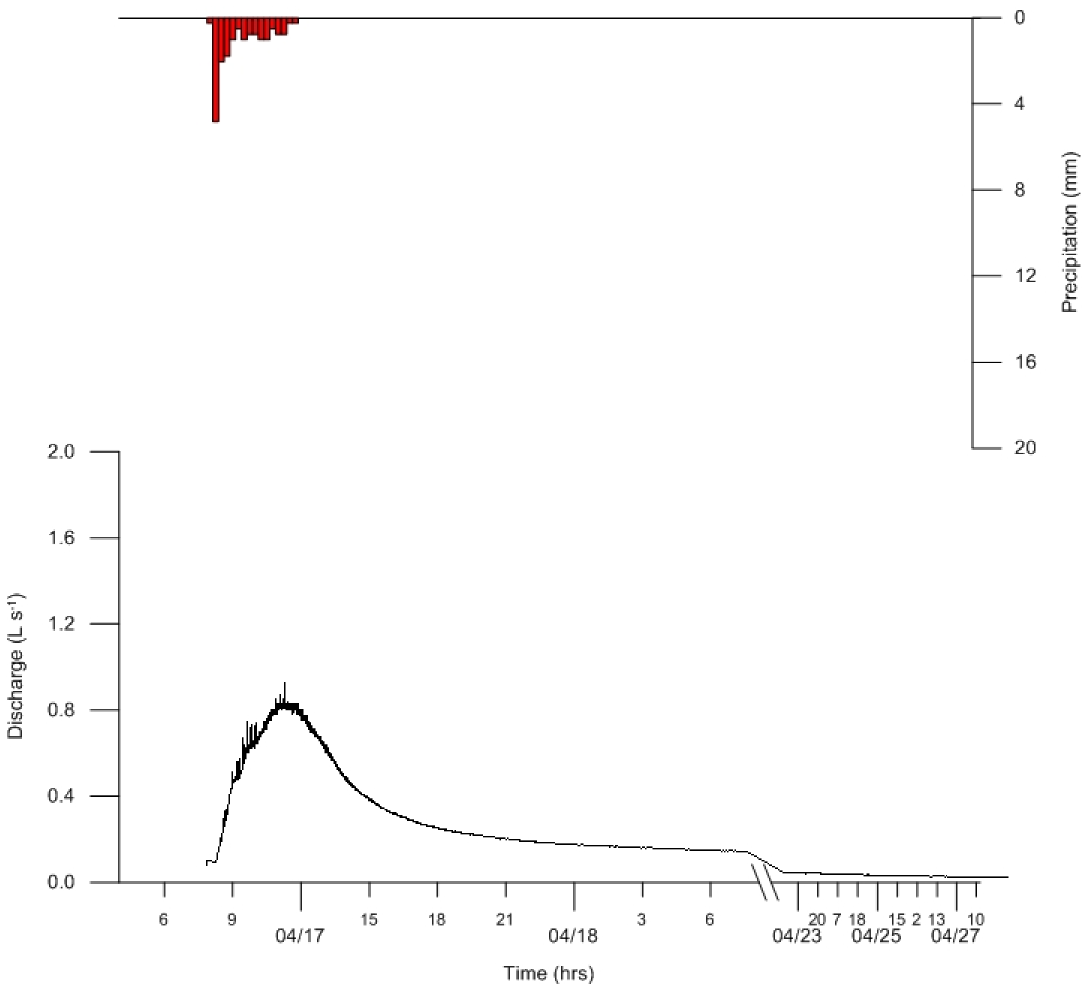

Figure A.21. Rainfall-Runoff Response at Bent Mountain on April 17, 2013. BM4, MIXED.

Table A.21: Storm Hydrograph Characteristics and CNs.

Start of Storm	4/17/13 8:00
Storm Duration	17.5
Precipitation Depth (mm)	3.8
CN (λ=0.2)	97
CN (λ=0.05)	82
Discharge volume (m^3)	29.8
Discharge volume (% rainfall)	62.3
Peak Discharge (m^3 s^{-1} x 10^{-4})	8.3
Lag Time (d x 10^{-2})	3.2
Response Time (d x 10^{-2})	0.4
Discharge Duration (d)	10.7

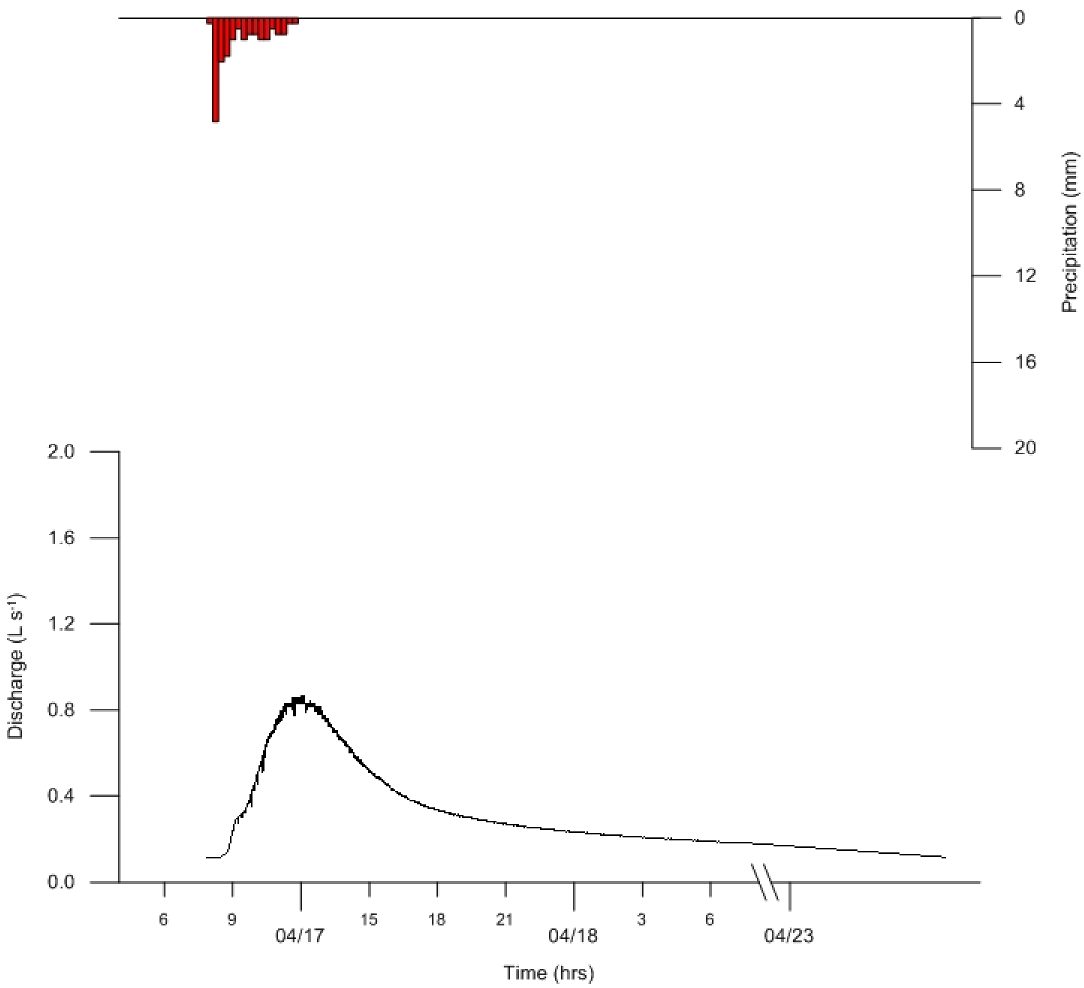

Figure A.22. Rainfall-Runoff Response at Bent Mountain on April 17, 2013. BM5, MIXED.

Table A.22: Storm Hydrograph Characteristics and CNs.

Start of Storm	4/17/13 8:00
Storm Duration	17.5
Precipitation Depth (mm)	3.8
CN (λ=0.2)	92
CN (λ=0.05)	67
Discharge volume (m^3)	17.7
Discharge volume (% rainfall)	31.6
Peak Discharge (m^3 s^{-1} x 10^{-4})	10.2
Lag Time (d x 10^{-2})	15.7
Response Time (d x 10^{-2})	0.9
Discharge Duration (d)	6.3

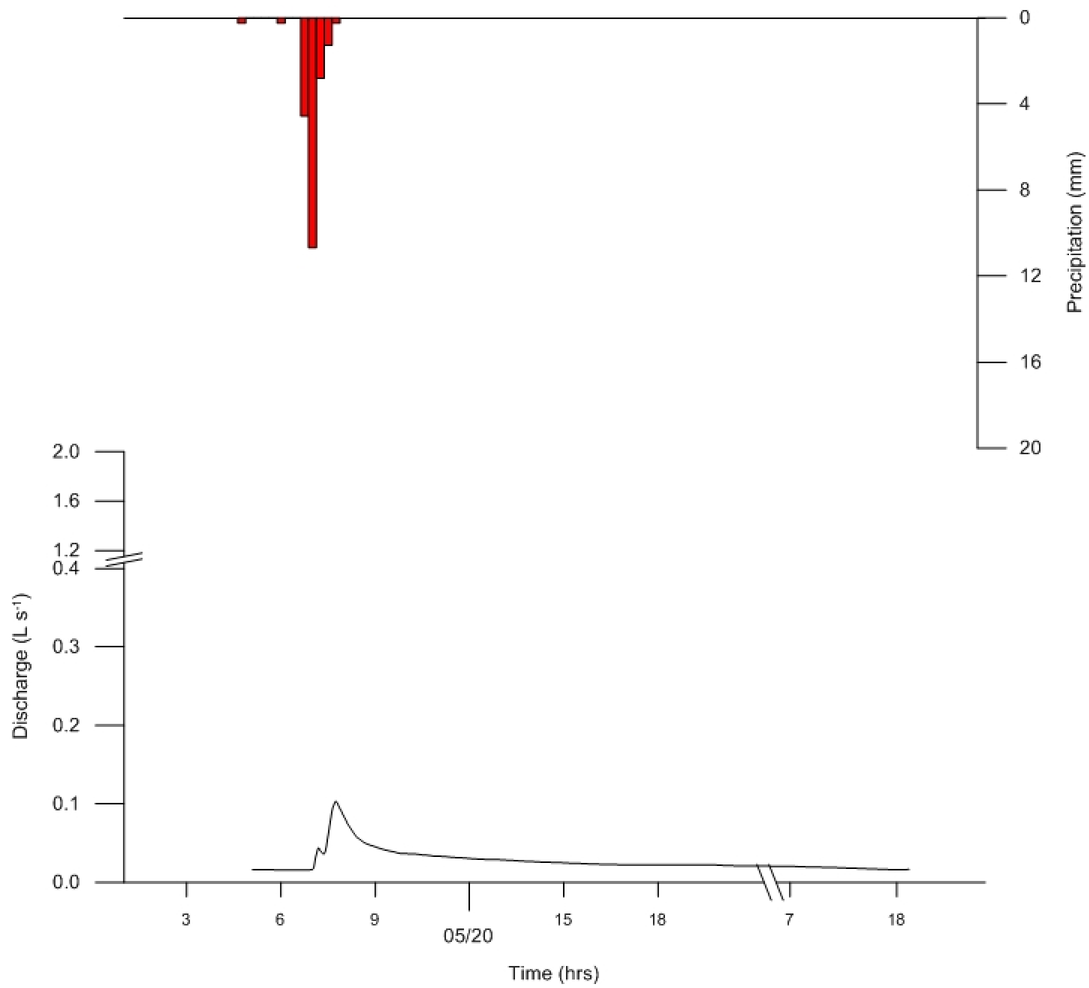

Figure A.23. Rainfall-Runoff Response at Bent Mountain on May 20, 2013. BM1, BROWN.

Table A.23: Storm Hydrograph Characteristics and CNs.

Start of Storm	5/20/13 4:45
Storm Duration	20.1
Precipitation Depth (mm)	3.0
CN (λ=0.2)	75
CN (λ=0.05)	32
Discharge volume (m^3)	0.3
Discharge volume (% rainfall)	0.4
Peak Discharge (m^3 s^{-1} x 10^{-4})	1.0
Lag Time (d x 10^{-2})	12.2
Response Time (d x 10^{-2})	8.5
Discharge Duration (d)	1.5

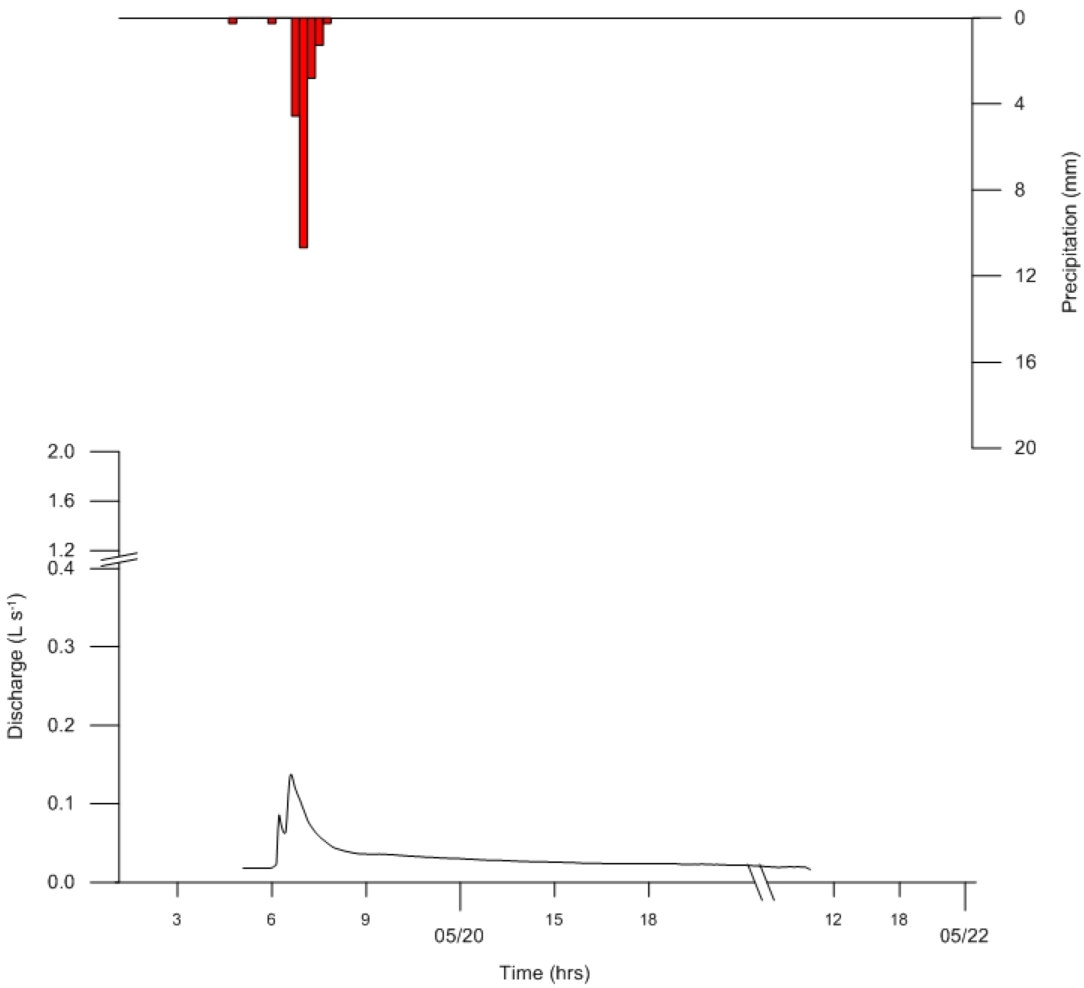

Figure A.24. Rainfall-Runoff Response at Bent Mountain on May 20, 2013. BM2, GRAY.

Table A.24: Storm Hydrograph Characteristics and CNs.

Start of Storm	5/20/13 4:45
Storm Duration	20.1
Precipitation Depth (mm)	3.0
CN (λ=0.2)	75
CN (λ=0.05)	33
Discharge volume (m^3)	0.4
Discharge volume (% rainfall)	0.6
Peak Discharge (m^3 s^{-1} x 10^{-4})	1.4
Lag Time (d x 10^{-2})	7.5
Response Time (d x 10^{-2})	3.4
Discharge Duration (d)	1.0

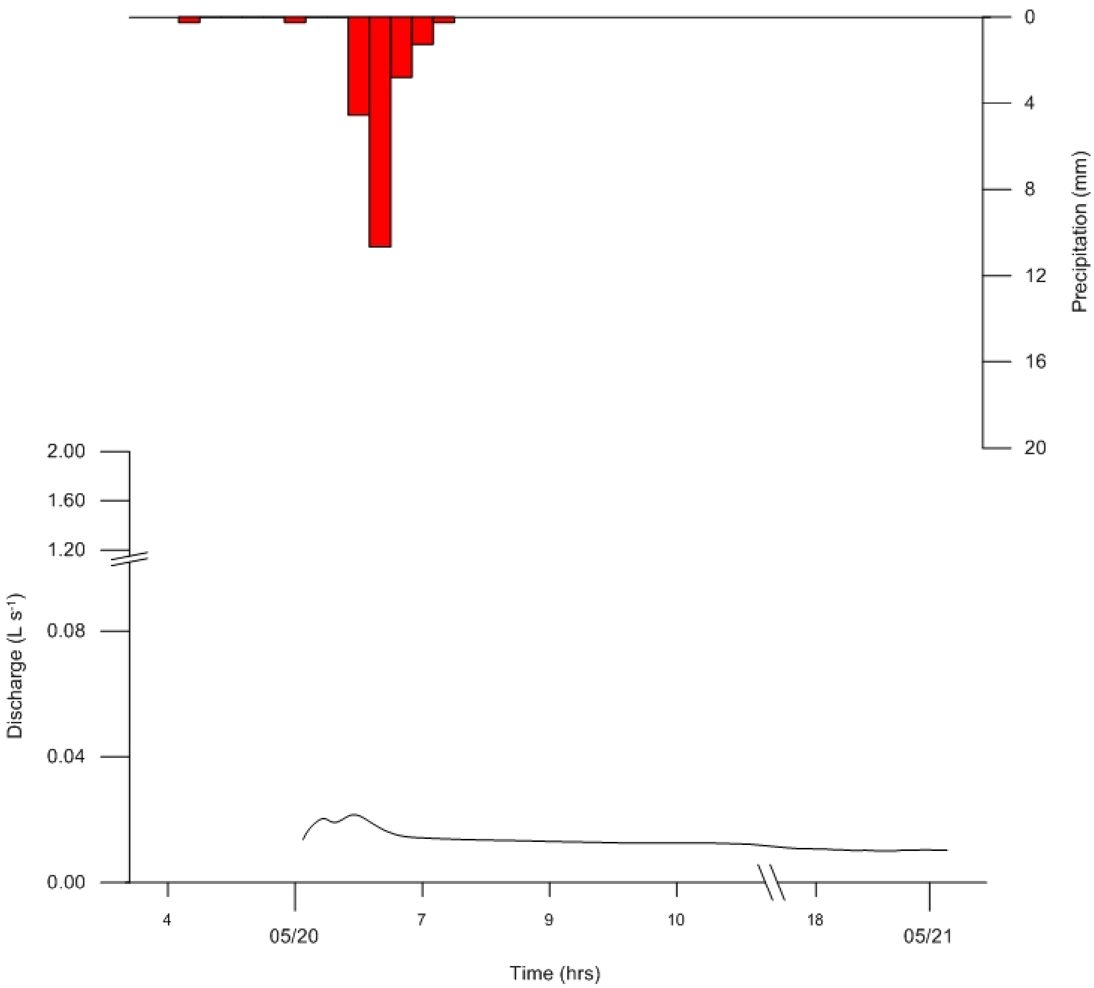

Figure A.25. Rainfall-Runoff Response at Bent Mountain on May 20, 2013. BM3, BROWN.

Table A.25: Storm Hydrograph Characteristics and CNs.

Start of Storm	5/20/13 4:45
Storm Duration	20.1
Precipitation Depth (mm)	3.0
CN (λ=0.2)	73
CN (λ=0.05)	29
Discharge volume (m^3)	0.0
Discharge volume (% rainfall)	0.1
Peak Discharge (m^3 s^{-1} x 10^{-4})	0.3
Lag Time (d x 10^{-2})	5.6
Response Time (d x 10^{-2})	3.9
Discharge Duration (d)	--

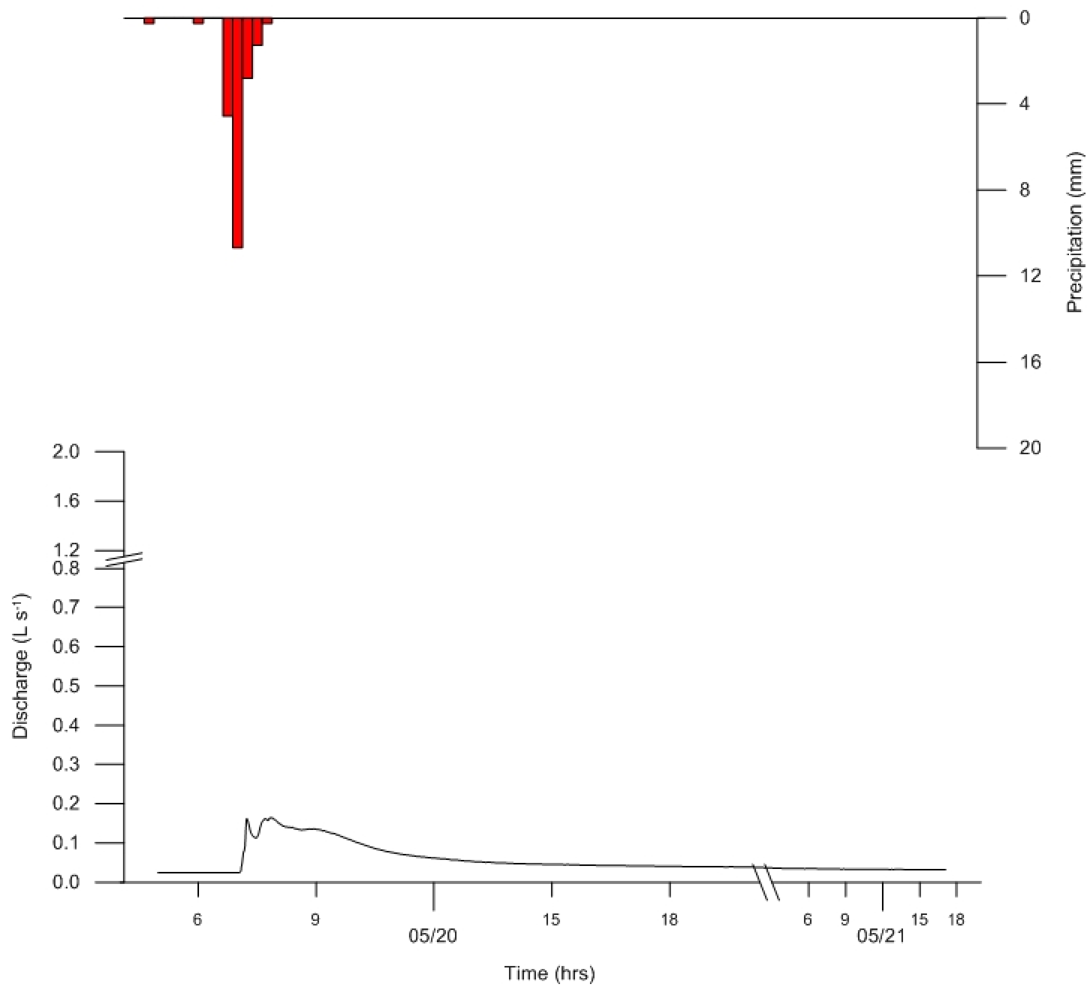

Figure A.26. Rainfall-Runoff Response at Bent Mountain on May 20, 2013. BM4, MIXED.

Table A.26: Storm Hydrograph Characteristics and CNs.

Start of Storm	5/20/13 4:45
Storm Duration	20.1
Precipitation Depth (mm)	3.0
CN (λ=0.2)	78
CN (λ=0.05)	39
Discharge volume (m^3)	1.4
Discharge volume (% rainfall)	2.1
Peak Discharge ($m^3\ s^{-1}$ x 10^{-4})	1.7
Lag Time (d x 10^{-2})	10.3
Response Time (d x 10^{-2})	5.8
Discharge Duration (d)	1.5

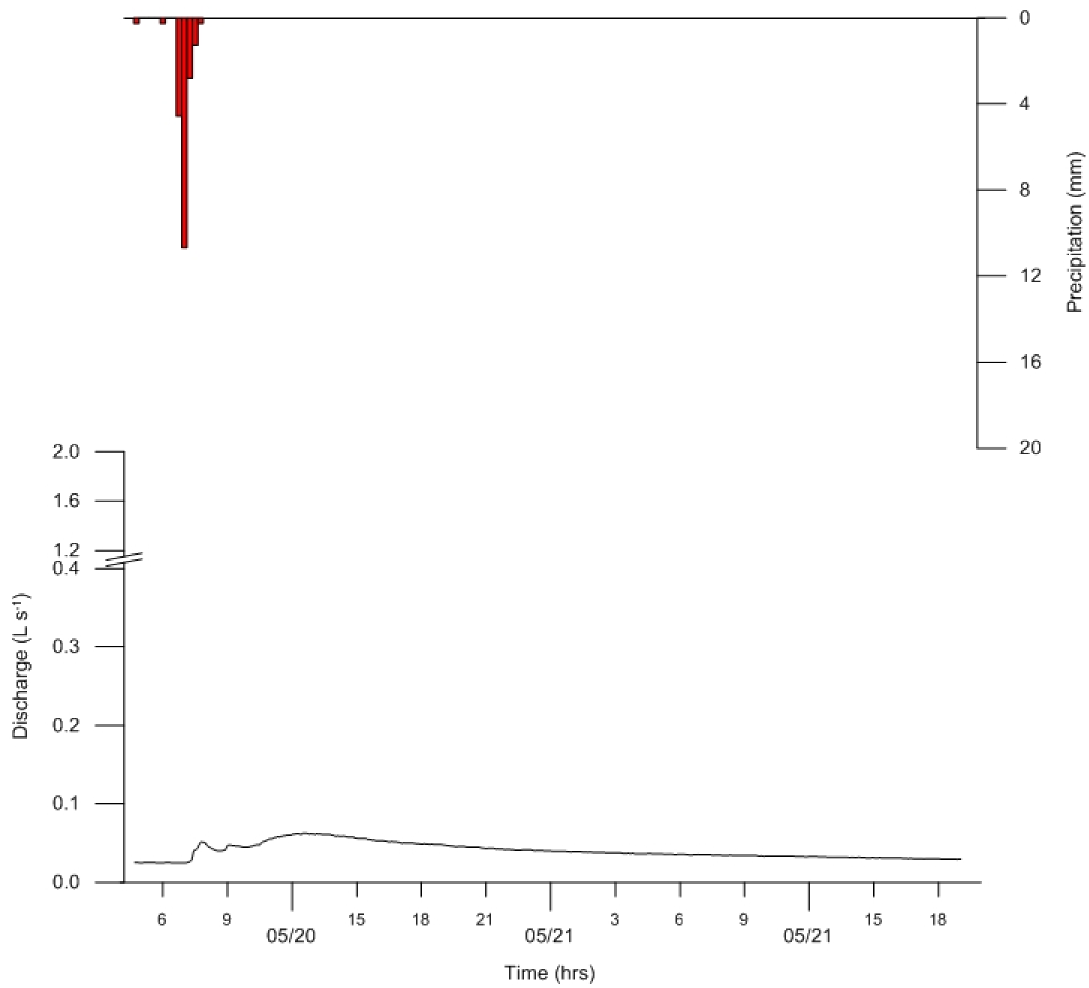

Figure A.27. Rainfall-Runoff Response at Bent Mountain on May 20, 2013. BM5, MIXED.

Table A.27: Storm Hydrograph Characteristics and CNs.

Start of Storm	5/20/13 4:45
Storm Duration	20.1
Precipitation Depth (mm)	3.0
CN (λ=0.2)	78
CN (λ=0.05)	39
Discharge volume (m^3)	1.6
Discharge volume (% rainfall)	2.5
Peak Discharge (m^3 s^{-1} x 10^{-4})	0.6
Lag Time (d x 10^{-2})	12.5
Response Time (d x 10^{-2})	9.2
Discharge Duration (d)	1.5

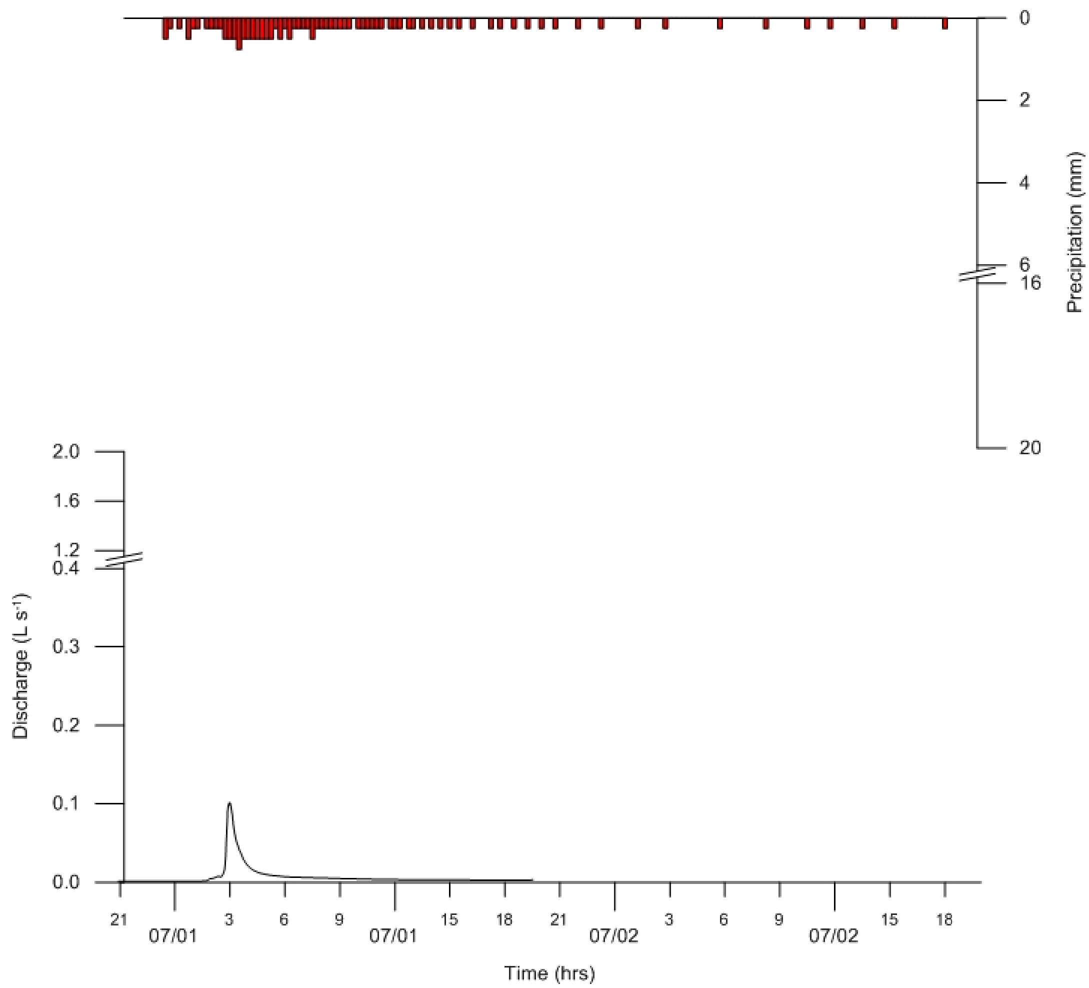

Figure A.28. Rainfall-Runoff Response at Bent Mountain on June 30, 2013. BM1, BROWN.

Table A.28: Storm Hydrograph Characteristics and CNs.

Start of Storm	6/30/13 23:30
Storm Duration	22.9
Precipitation Depth (mm)	42.5
CN (λ=0.2)	71
CN (λ=0.05)	32
Discharge volume (m^3)	0.2
Discharge volume (% rainfall)	0.3
Peak Discharge (m^3 s^{-1} x 10^{-4})	1.0
Lag Time (d x 10^{-2})	14.4
Response Time (d x 10^{-2})	12.3
Discharge Duration (d)	0.2

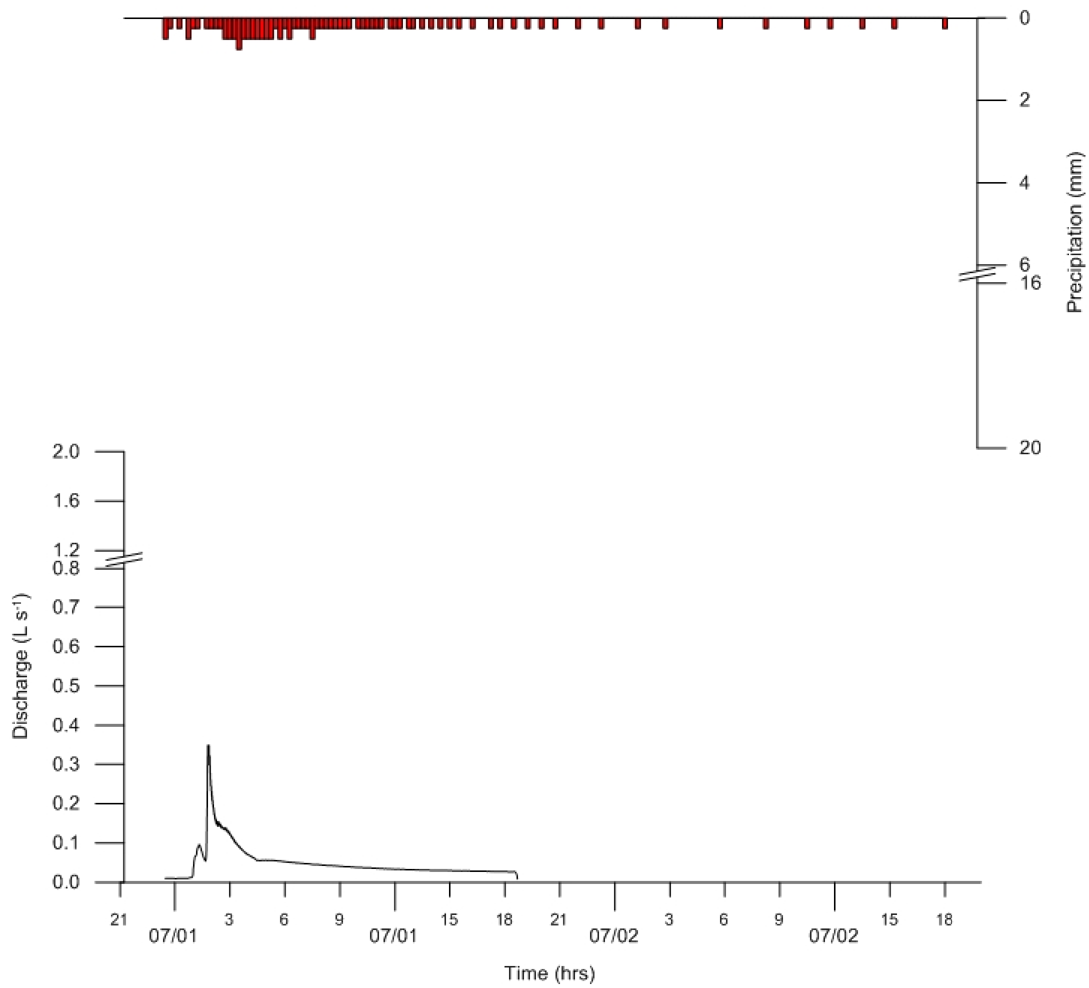

Figure A.29. Rainfall-Runoff Response at Bent Mountain on June 30, 2013. BM2, GRAY.

Table A.29: Storm Hydrograph Characteristics and CNs.

Start of Storm	6/30/13 23:30
Storm Duration	22.9
Precipitation Depth (mm)	42.5
CN (λ=0.2)	74
CN (λ=0.05)	37
Discharge volume (m^3)	1.1
Discharge volume (% rainfall)	1.4
Peak Discharge (m^3 s^{-1} x 10^{-4})	3.5
Lag Time (d x 10^{-2})	9.7
Response Time (d x 10^{-2})	2.3
Discharge Duration (d)	0.8

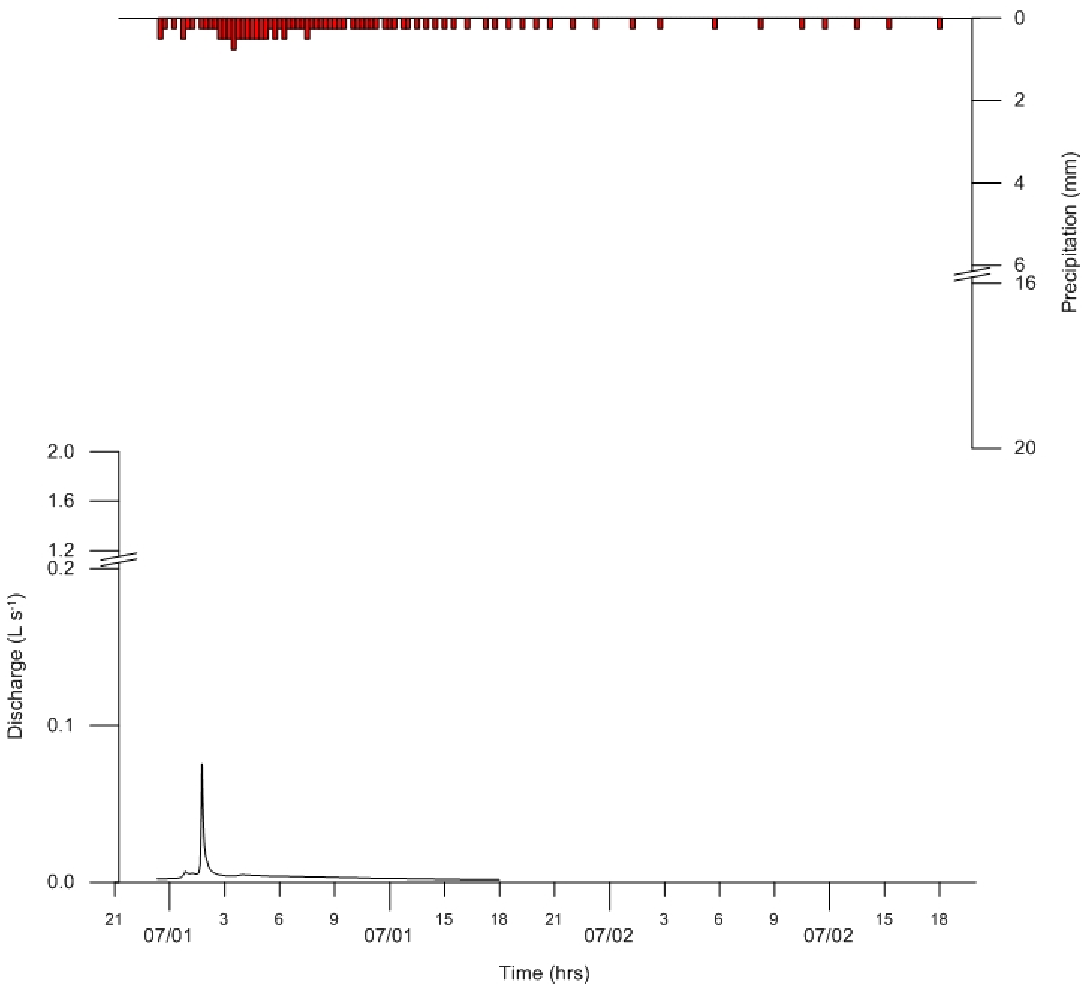

Figure A.30. Rainfall-Runoff Response at Bent Mountain on June 30, 2013. BM3, BROWN.

Table A.30: Storm Hydrograph Characteristics and CNs.

Start of Storm	6/30/13 23:30
Storm Duration	22.9
Precipitation Depth (mm)	42.5
CN (λ=0.2)	71
CN (λ=0.05)	32
Discharge volume (m^3)	0.2
Discharge volume (% rainfall)	0.1
Peak Discharge (m^3 s^{-1} x 10^{-4})	1.0
Lag Time (d x 10^{-2})	14.4
Response Time (d x 10^{-2})	12.3
Discharge Duration (d)	0.2

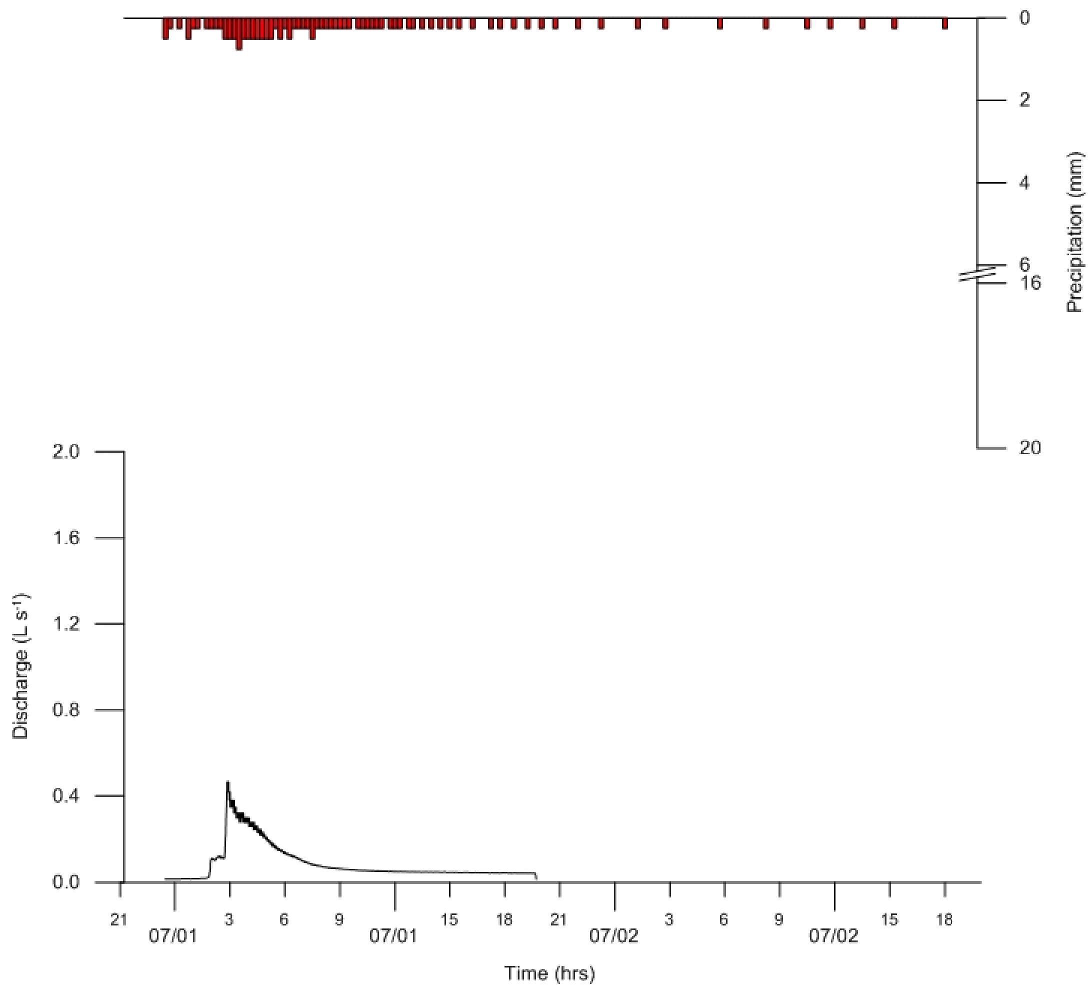

Figure A.31. Rainfall-Runoff Response at Bent Mountain on June 30, 2013. BM4, MIXED.

Table A.31: Storm Hydrograph Characteristics and CNs.

Start of Storm	6/30/13 23:30
Storm Duration	22.9
Precipitation Depth (mm)	42.5
CN (λ=0.2)	78
CN (λ=0.05)	44
Discharge volume (m^3)	2.8
Discharge volume (% rainfall)	3.8
Peak Discharge (m^3 s^{-1} x 10^{-4})	4.7
Lag Time (d x 10^{-2})	14.2
Response Time (d x 10^{-2})	0.7
Discharge Duration (d)	0.8

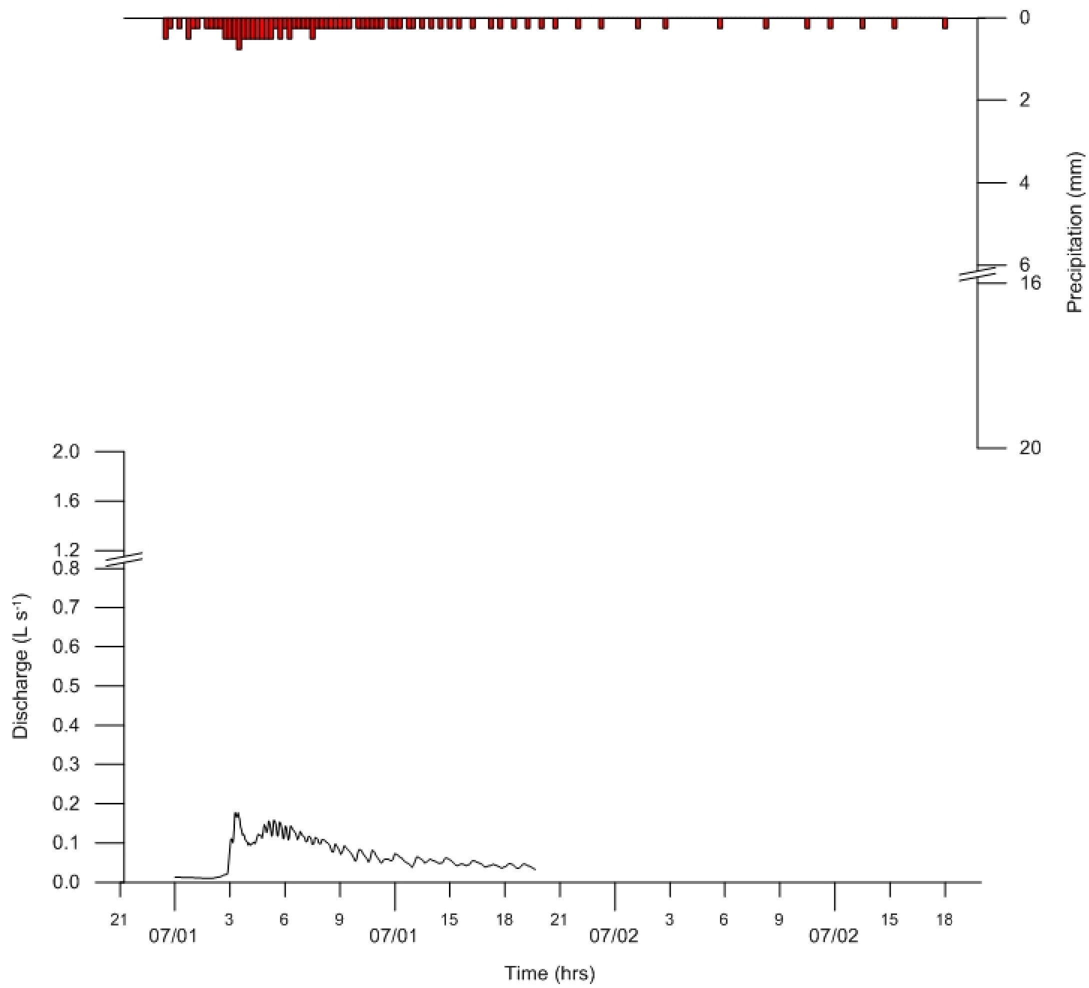

Figure A.32. Rainfall-Runoff Response at Bent Mountain on June 30, 2013. BM5, MIXED.

Table A.32: Storm Hydrograph Characteristics and CNs.

Start of Storm	6/30/13 23:30
Storm Duration	22.9
Precipitation Depth (mm)	42.5
CN (λ=0.2)	76
CN (λ=0.05)	40
Discharge volume (m^3)	1.9
Discharge volume (% rainfall)	2.6
Peak Discharge (m^3 s^{-1} x 10^{-4})	1.8
Lag Time (d x 10^{-2})	16.3
Response Time (d x 10^{-2})	3.7
Discharge Duration (d)	0.8

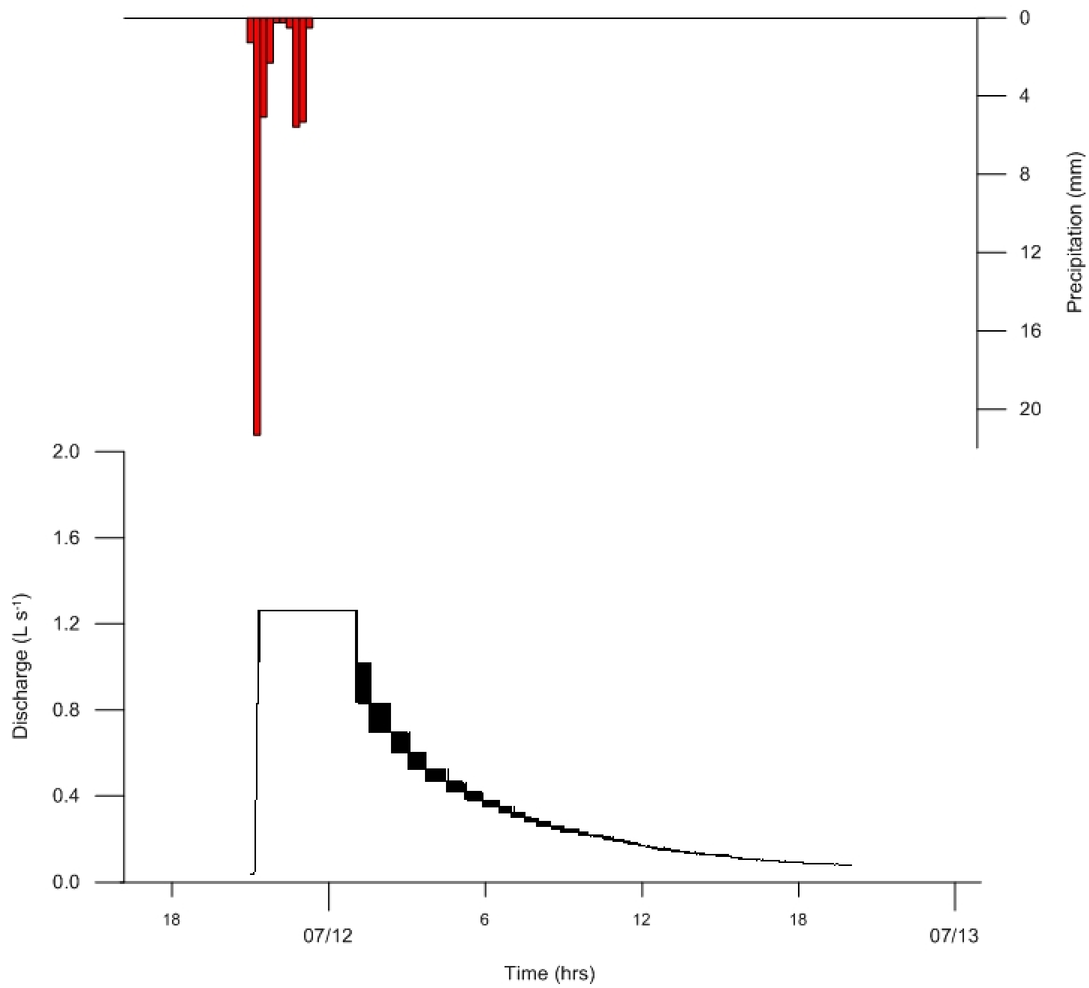

Figure A.33. Rainfall-Runoff Response at Bent Mountain on July, 11 2013. BM1, BROWN.

Table A.33: Storm Hydrograph Characteristics and CNs.

Start of Storm	7/11/13 21:00
Storm Duration	42.4
Precipitation Depth (mm)	2.3
CN (λ=0.2)	76
CN (λ=0.05)	72
Discharge volume (m^3)	25.7
Discharge volume (% rainfall)	15.1
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	1.2
Response Time (d x 10^{-2})	0.4
Discharge Duration (d)	2.0

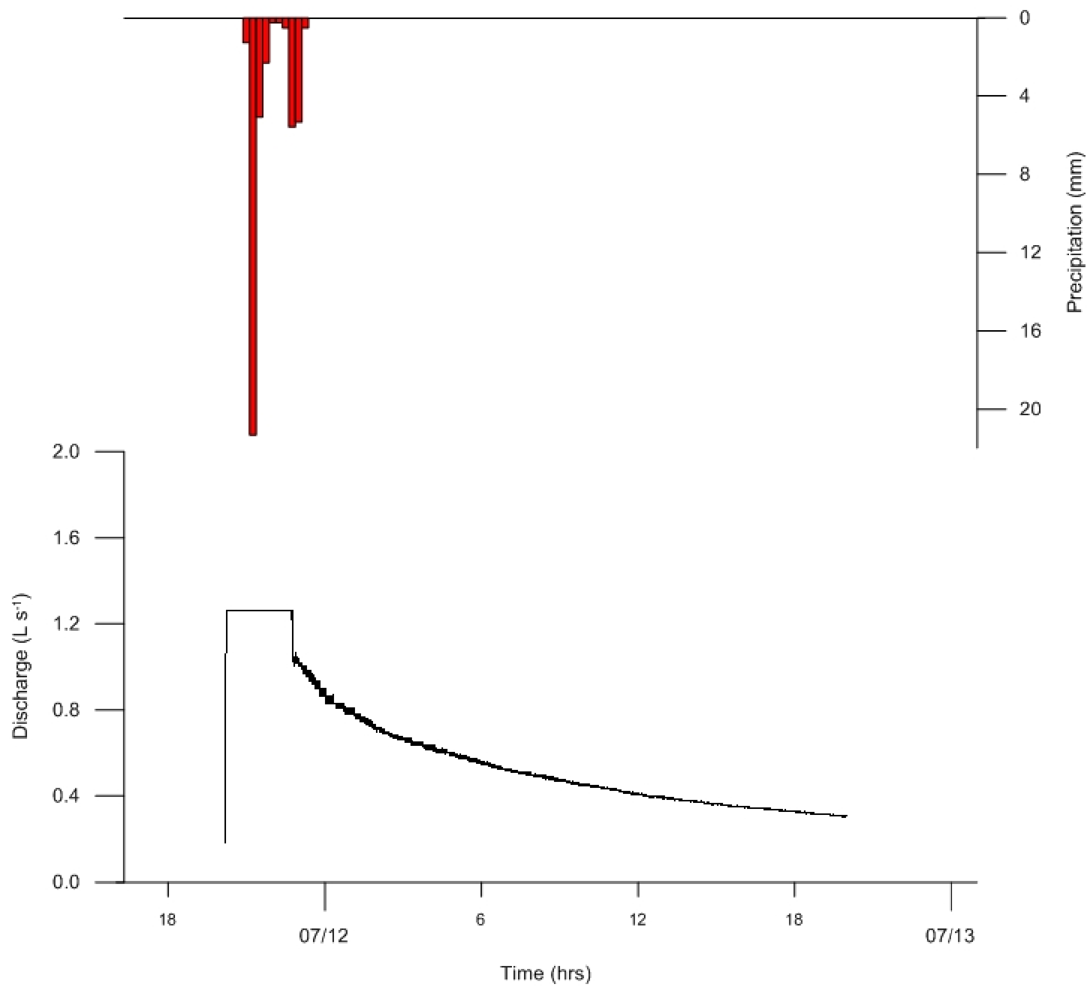

Figure A.34. Rainfall-Runoff Response at Bent Mountain on July, 11 2013. BM2, GRAY.

Table A.34: Storm Hydrograph Characteristics and CNs.

Start of Storm	7/11/13 21:00
Storm Duration	42.4
Precipitation Depth (mm)	2.3
CN (λ=0.2)	78
CN (λ=0.05)	76
Discharge volume (m^3)	26.6
Discharge volume (% rainfall)	18.4
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	0.0
Response Time (d x 10^{-2})	3.6
Discharge Duration (d)	2.4

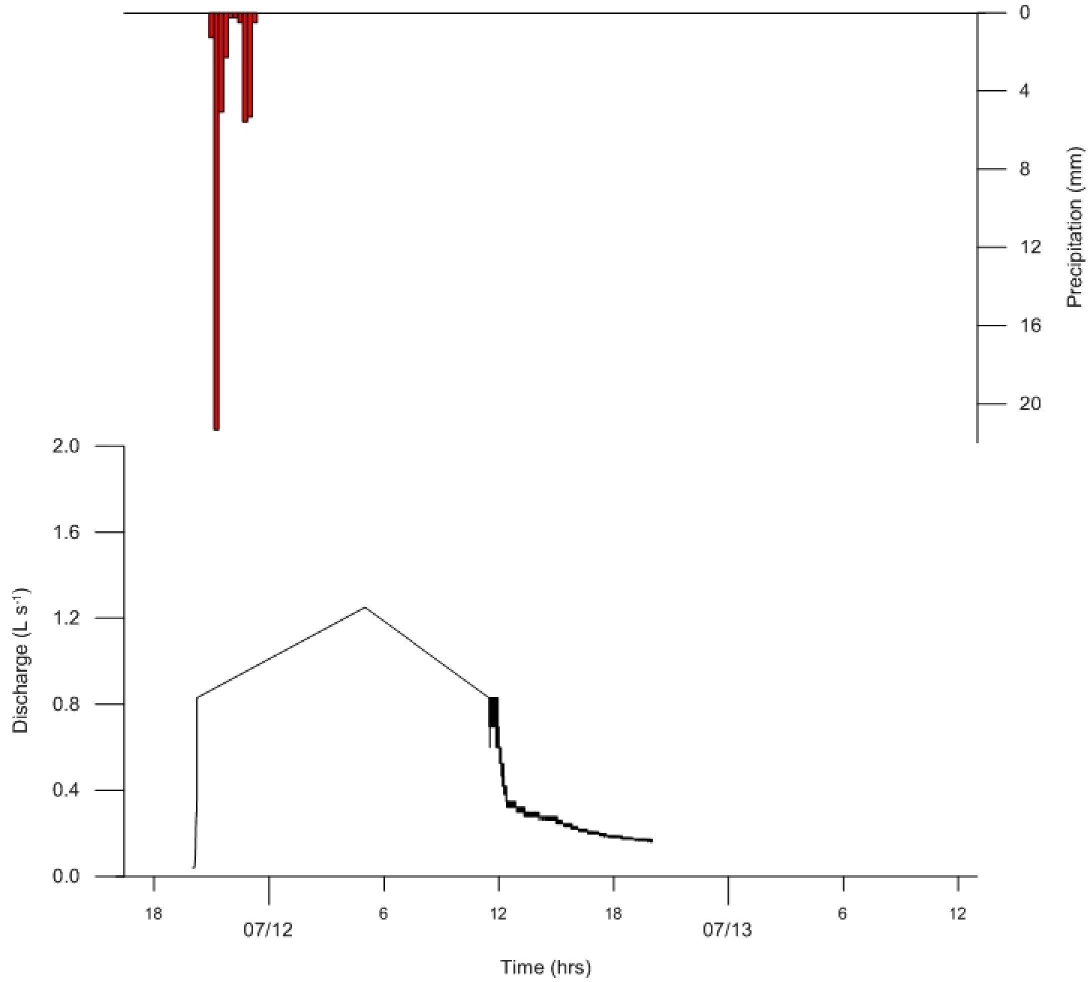

Figure A.35. Rainfall-Runoff Response at Bent Mountain on July, 11 2013. BM3, BROWN.

Table A.35: Storm Hydrograph Characteristics and CNs.

Start of Storm	7/11/13 21:00
Storm Duration	42.4
Precipitation Depth (mm)	2.3
CN (λ=0.2)	73
CN (λ=0.05)	66
Discharge volume (m^3)	15.4
Discharge volume (% rainfall)	10.7
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.5
Lag Time (d x 10^{-2})	33.3
Response Time (d x 10^{-2})	4.0
Discharge Duration (d)	3.0

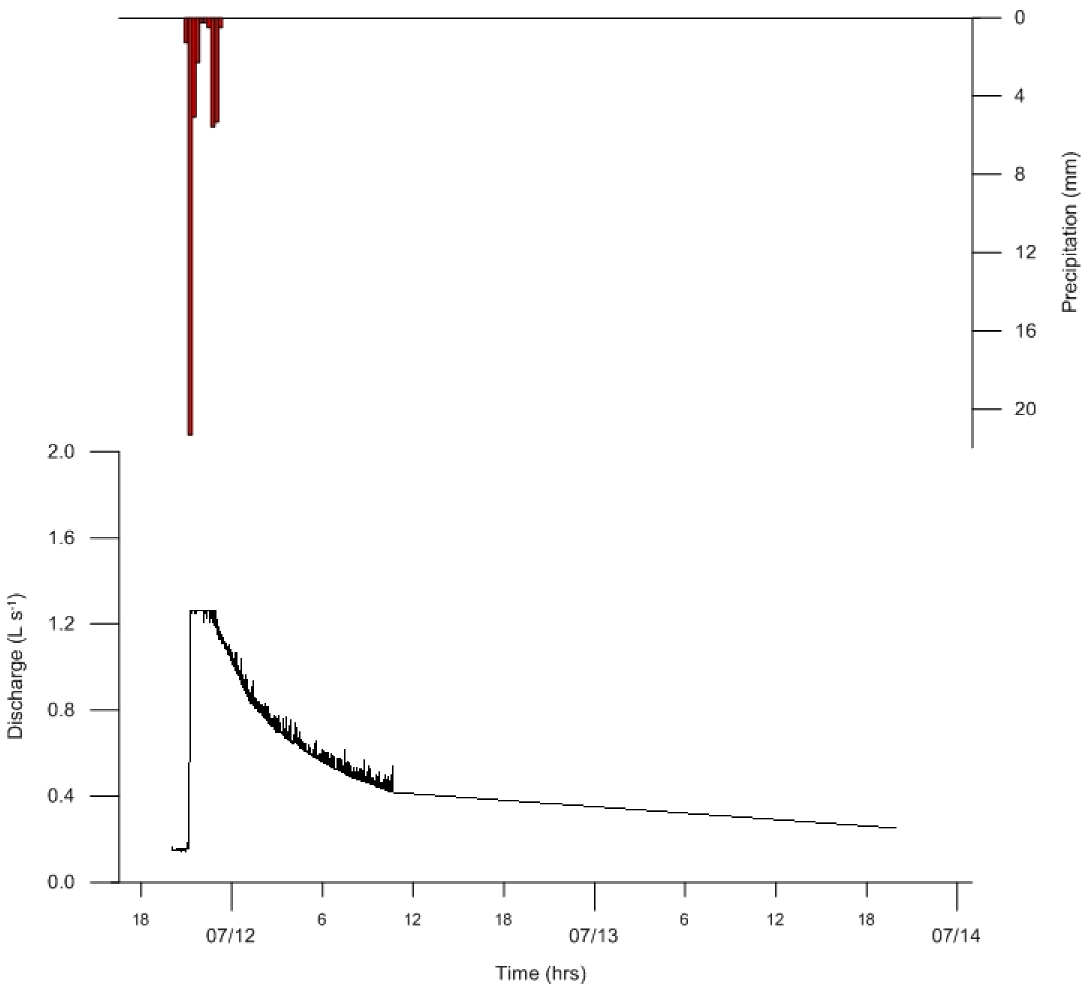

Figure A.36. Rainfall-Runoff Response at Bent Mountain on July, 11 2013. BM4, MIXED.

Table A.36: Storm Hydrograph Characteristics and CNs.

Start of Storm	7/11/13 21:00
Storm Duration	42.4
Precipitation Depth (mm)	2.3
CN (λ=0.2)	77
CN (λ=0.05)	75
Discharge volume (m^3)	23.2
Discharge volume (% rainfall)	17.1
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	1.3
Response Time (d x 10^{-2})	2.8
Discharge Duration (d)	4.0

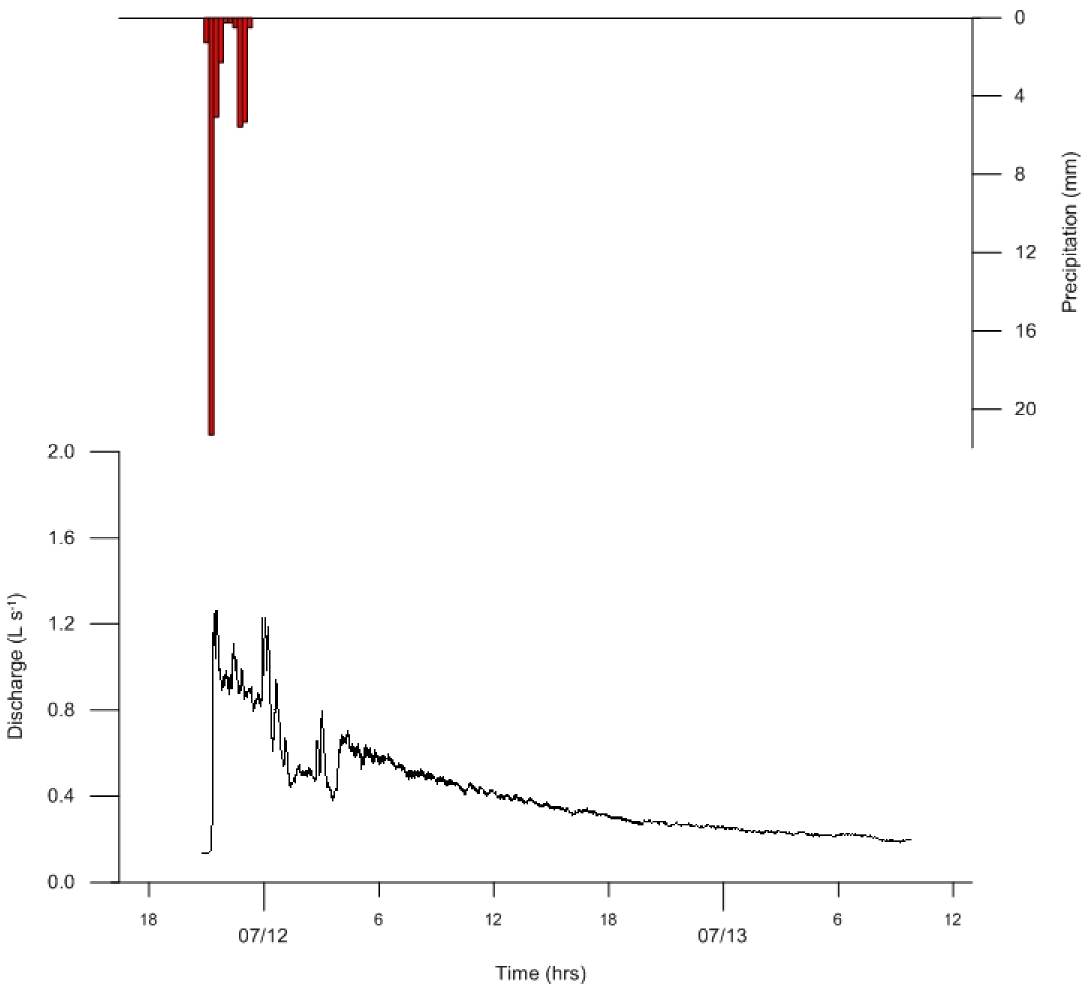

Figure A.37. Rainfall-Runoff Response at Bent Mountain on July, 11 2013. BM5, MIXED.

Table A.37: Storm Hydrograph Characteristics and CNs.

Start of Storm	7/11/13 21:00
Storm Duration	42.4
Precipitation Depth (mm)	2.3
CN (λ=0.2)	76
CN (λ=0.05)	72
Discharge volume (m^3)	23.1
Discharge volume (% rainfall)	17.0
Peak Discharge (m^3 s^{-1} x 10^{-4})	12.6
Lag Time (d x 10^{-2})	2.2
Response Time (d x 10^{-2})	0.4
Discharge Duration (d)	2.1

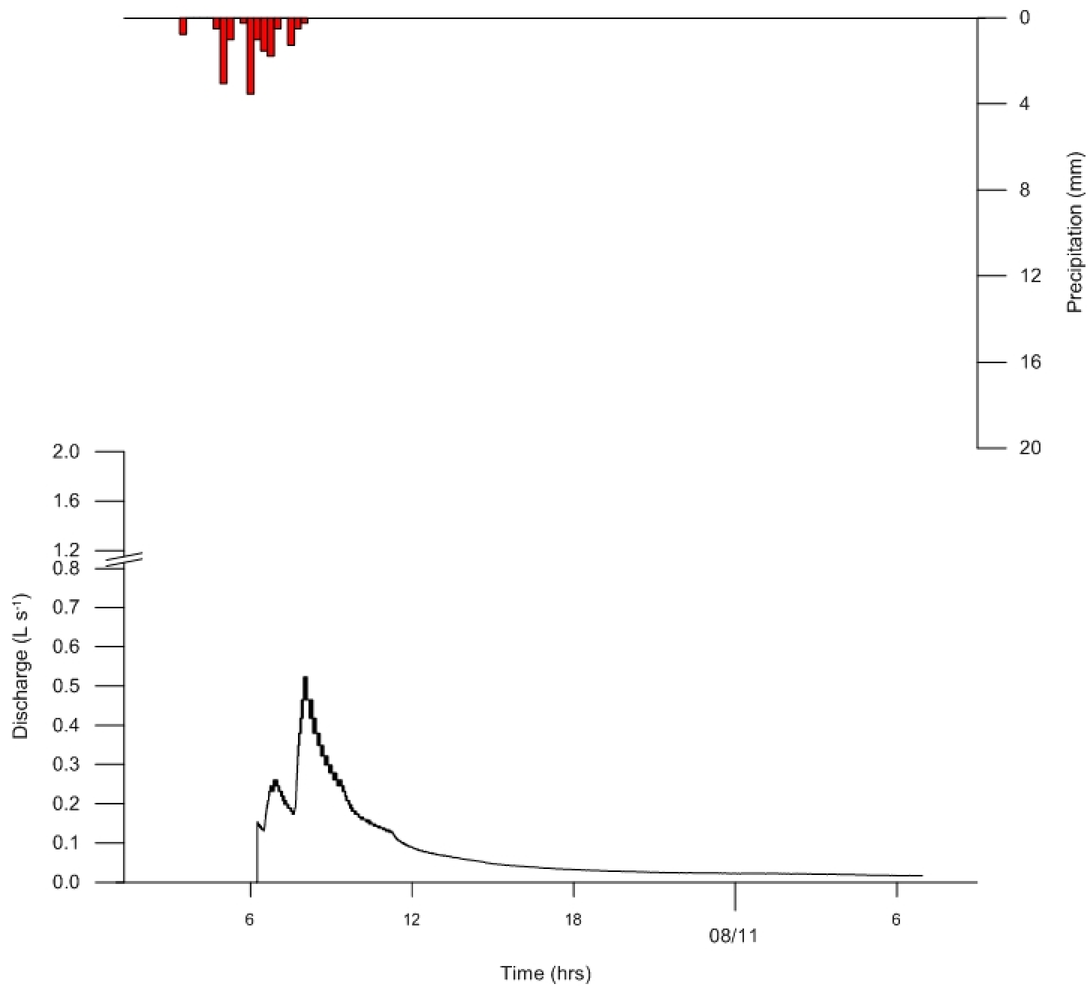

Figure A.38. Rainfall-Runoff Response at Bent Mountain on August 10, 2013. BM1, BROWN

Table A.38: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/10/13 3:30
Storm Duration	16.0
Precipitation Depth (mm)	4.5
CN (λ=0.2)	84
CN (λ=0.05)	44
Discharge volume (m^3)	3.3
Discharge volume (% rainfall)	5.1
Peak Discharge (m^3 s^{-1} x 10^{-4})	5.2
Lag Time (d x 10^{-2})	18.6
Response Time (d x 10^{-2})	11.4
Discharge Duration (d)	1.0

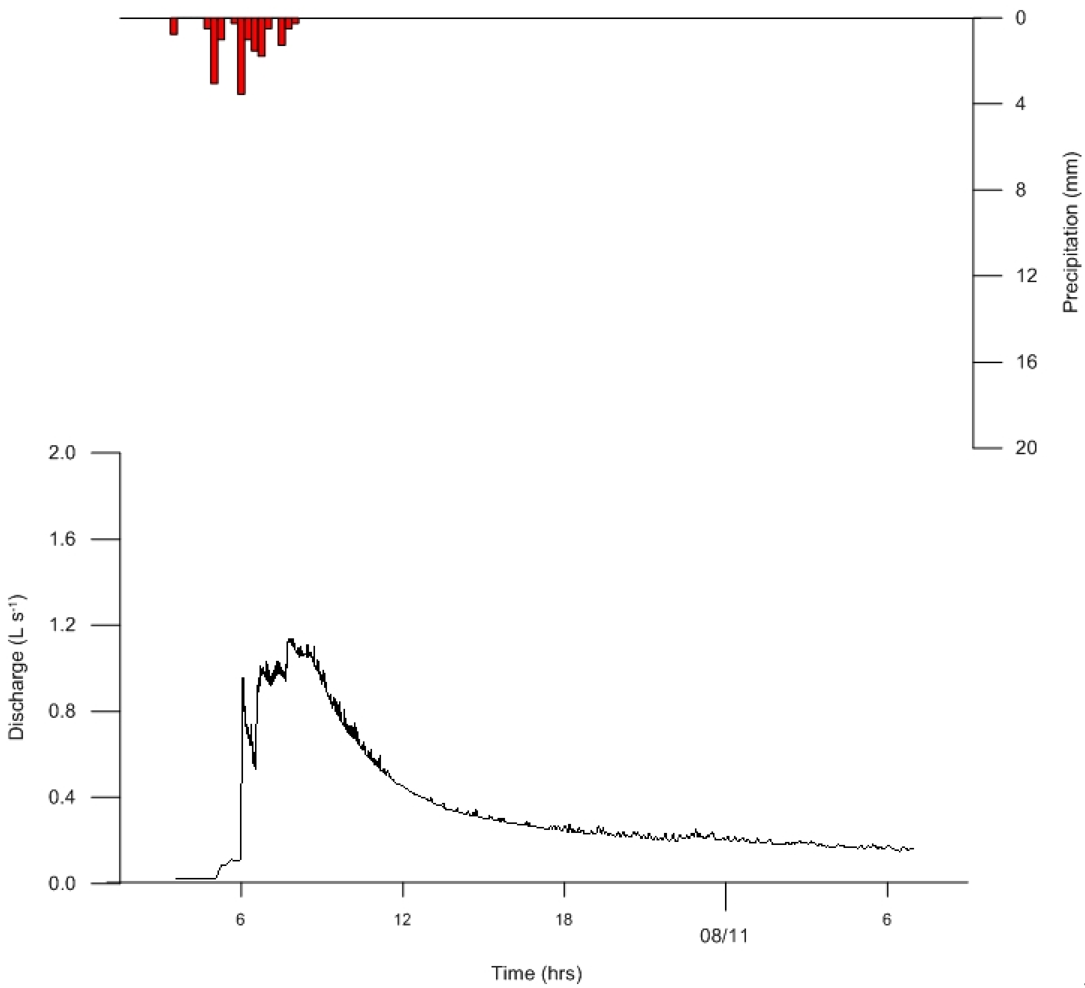

Figure A.39. Rainfall-Runoff Response at Bent Mountain on August 10, 2013. BM4, MIXED.

Table A.39: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/10/13 3:30
Storm Duration	16.0
Precipitation Depth (mm)	4.5
CN (λ=0.2)	94
CN (λ=0.05)	69
Discharge volume (m^3)	17.4
Discharge volume (% rainfall)	33.9
Peak Discharge (m^3 s^{-1} x 10^{-4})	11.5
Lag Time (d x 10^{-2})	13.8
Response Time (d x 10^{-2})	10.0
Discharge Duration (d)	--

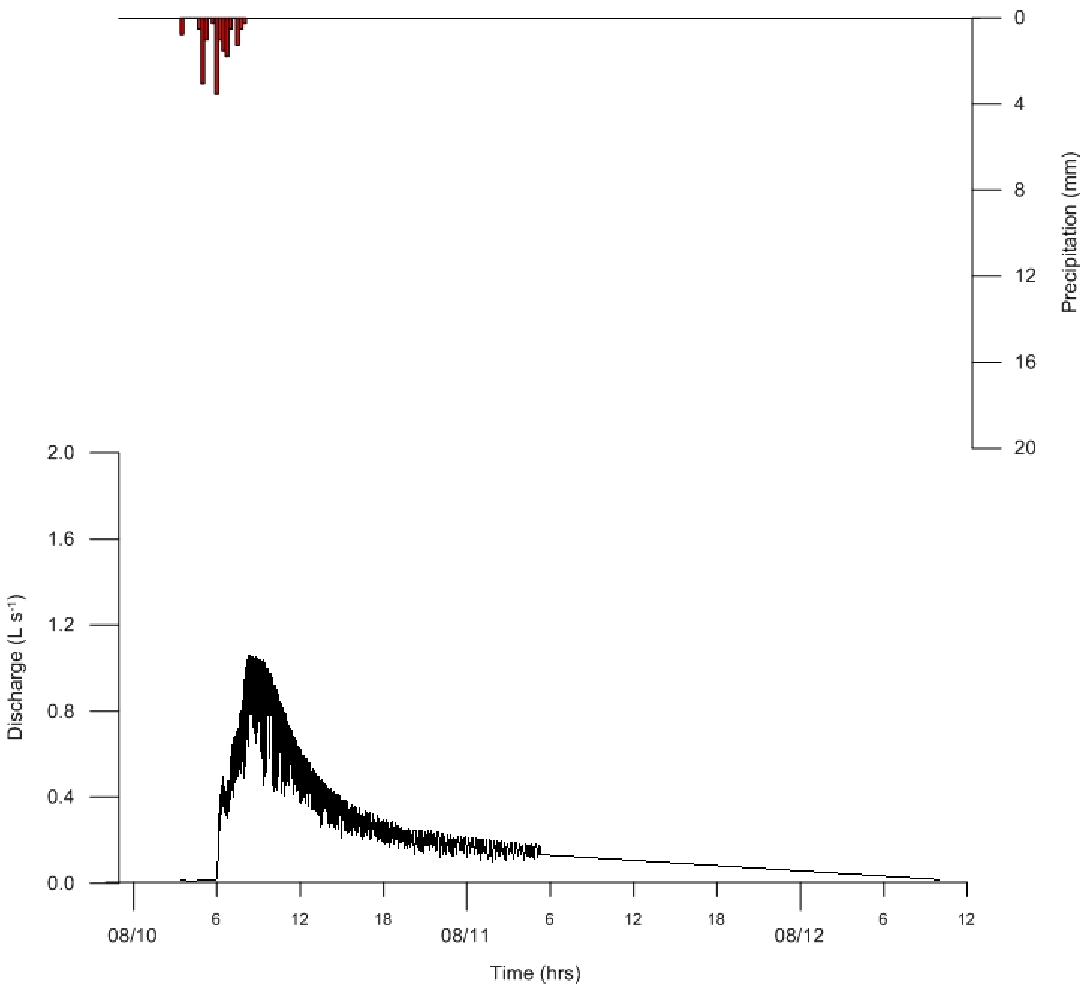

Figure A.40. Rainfall-Runoff Response at Bent Mountain on August 10, 2013. BM5, MIXED.

Table A.40: Storm Hydrograph Characteristics and CNs.

Start of Storm	8/10/13 3:30
Storm Duration	16.0
Precipitation Depth (mm)	4.5
CN (λ=0.2)	93
CN (λ=0.05)	66
Discharge volume (m^3)	16.0
Discharge volume (% rainfall)	31.3
Peak Discharge (m^3 s^{-1} x 10^{-4})	10.6
Lag Time (d x 10^{-2})	20.2
Response Time (d x 10^{-2})	3.0
Discharge Duration (d)	2.2

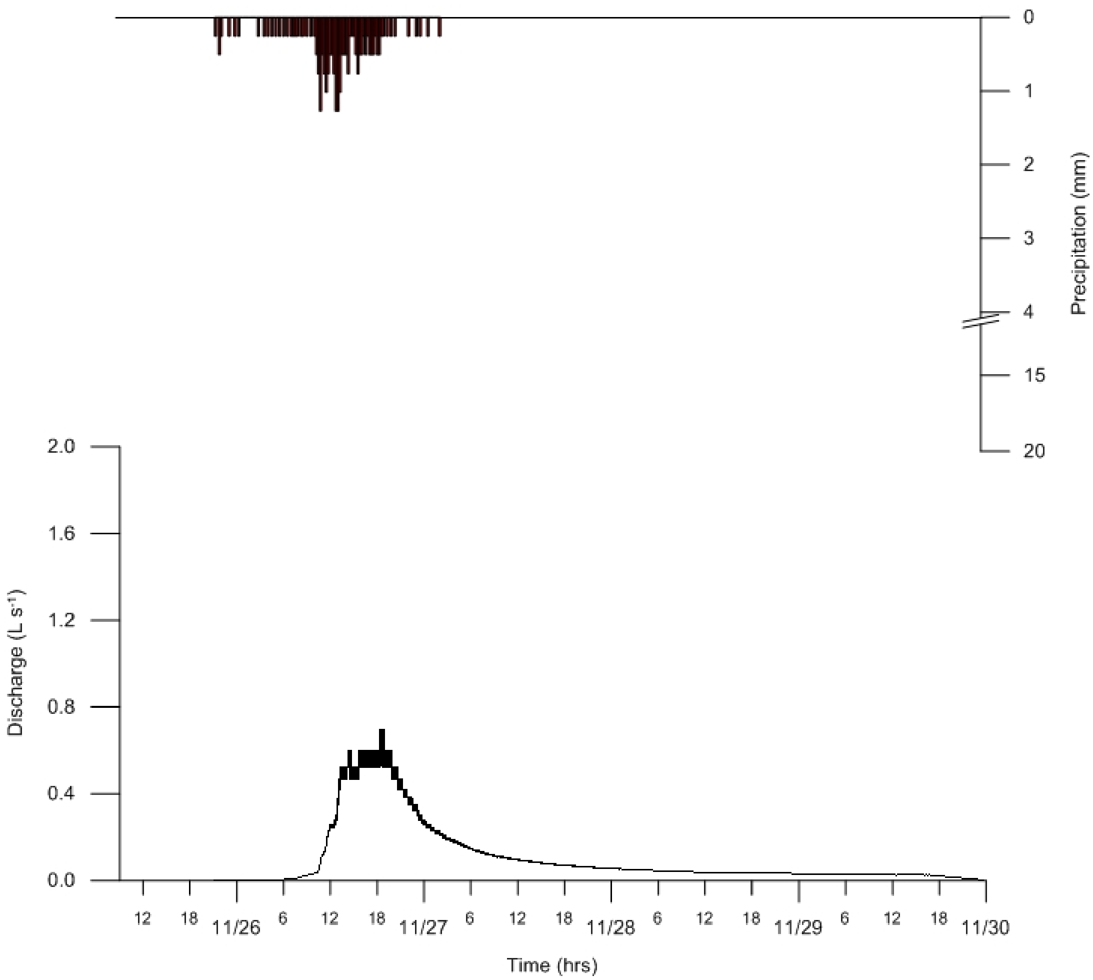

Figure A.41. Rainfall-Runoff Response at Bent Mountain on November 11, 2013. BM1, BROWN.

Table A.41: Storm Hydrograph Characteristics and CNs.

Start of Storm	11/25/13 21:15
Storm Duration	28.7
Precipitation Depth (mm)	0.6
CN (λ=0.2)	85
CN (λ=0.05)	71
Discharge volume (m^3)	24.2
Discharge volume (% rainfall)	21.0
Peak Discharge ($m^3 s^{-1} \times 10^{-4}$)	7.0
Lag Time (d x 10^{-2})	89.7
Response Time (d x 10^{-2})	9.9
Discharge Duration (d)	3.8

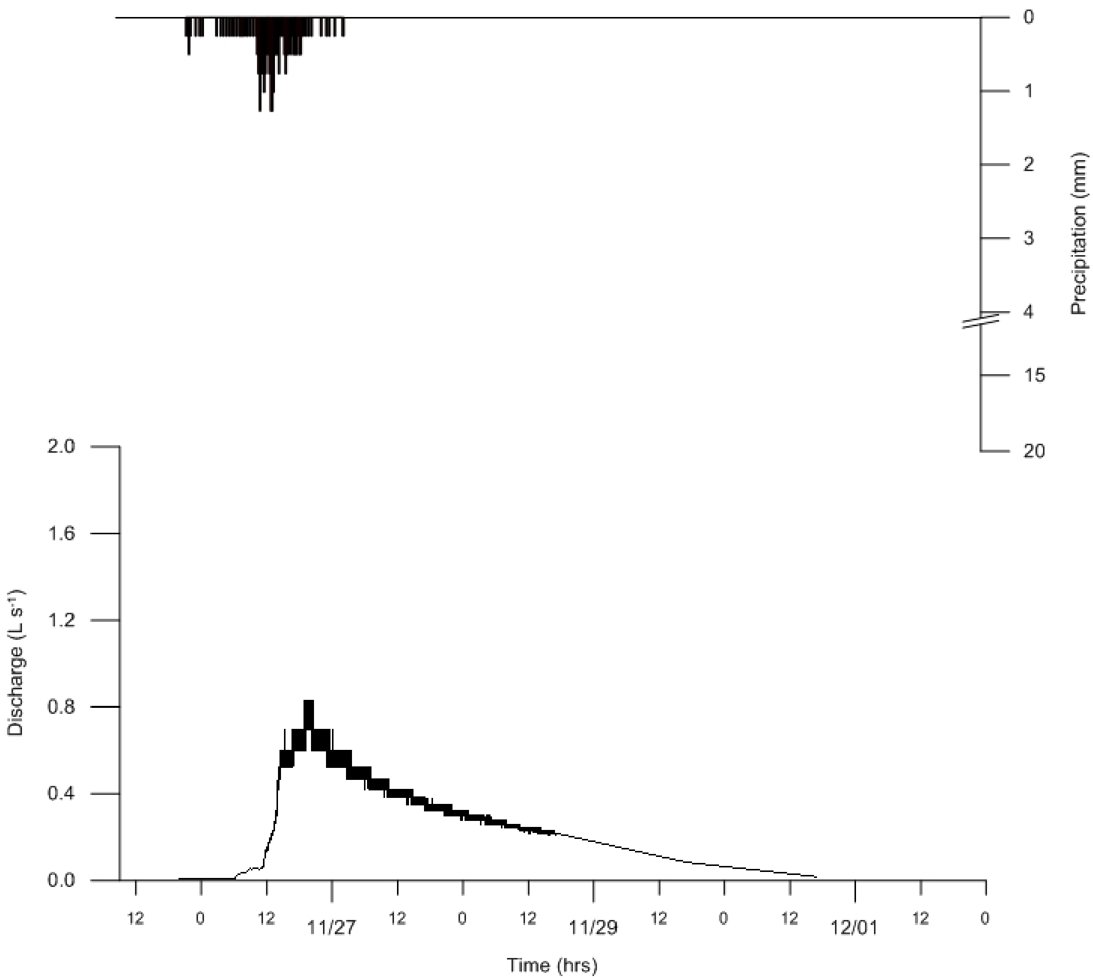

Figure A.42. Rainfall-Runoff Response at Bent Mountain on November 11, 2013. BM2, GRAY.

Table A.42: Storm Hydrograph Characteristics and CNs.

Start of Storm	11/25/13 21:15
Storm Duration	28.7
Precipitation Depth (mm)	0.6
CN (λ=0.2)	93
CN (λ=0.05)	88
Discharge volume (m^3)	50.0
Discharge volume (% rainfall)	51.2
Peak Discharge (m^3 s^{-1} x 10^{-4})	8.3
Lag Time (d x 10^{-2})	89.9
Response Time (d x 10^{-2})	8.9
Discharge Duration (d)	4.5

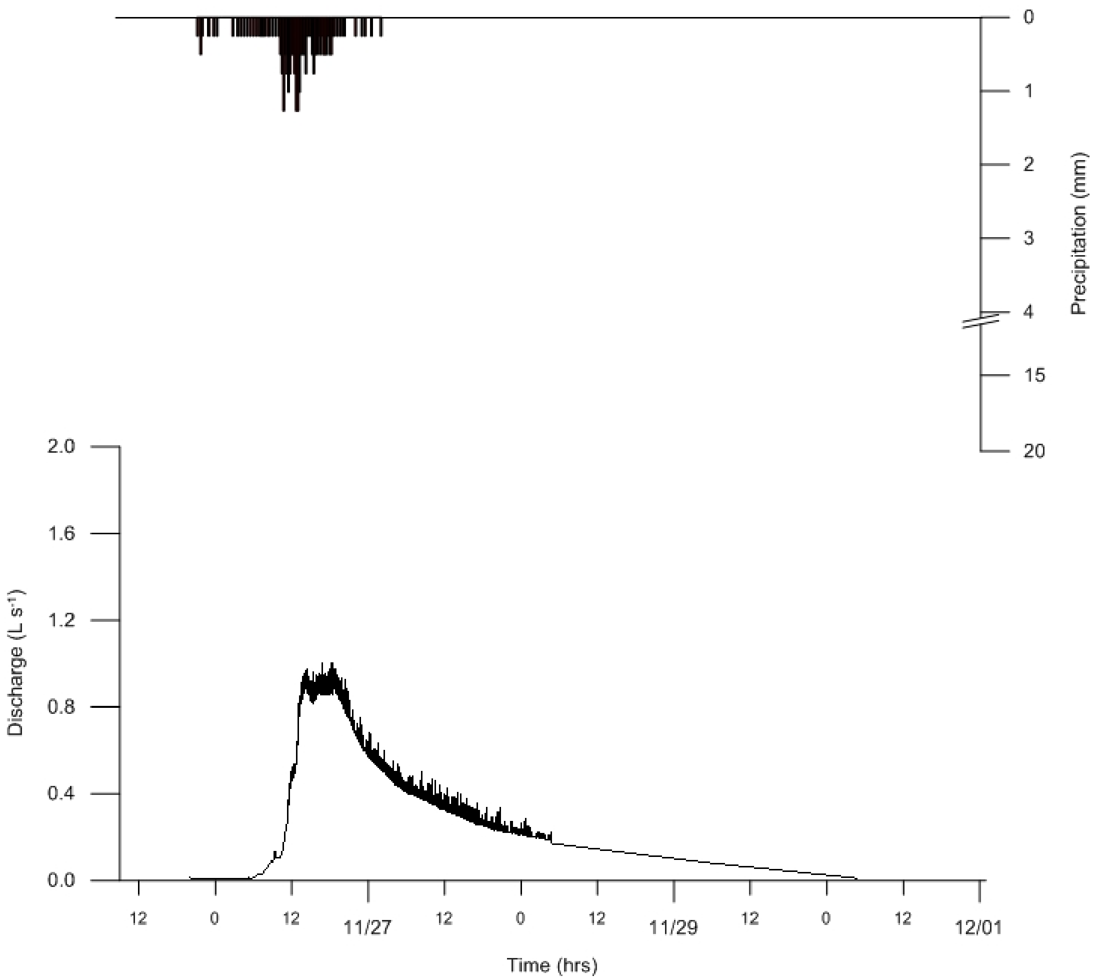

Figure A.43. Rainfall-Runoff Response at Bent Mountain on November 11, 2013. BM4, MIXED.

Table A.43: Storm Hydrograph Characteristics and CNs.

Start of Storm	11/25/13 21:15
Storm Duration	28.7
Precipitation Depth (mm)	0.6
CN (λ=0.2)	93
CN (λ=0.05)	87
Discharge volume (m^3)	44.3
Discharge volume (% rainfall)	33.9
Peak Discharge (m^3 s^{-1} x 10^{-4})	10.0
Lag Time (d x 10^{-2})	76.3
Response Time (d x 10^{-2})	16.8
Discharge Duration (d)	4.2

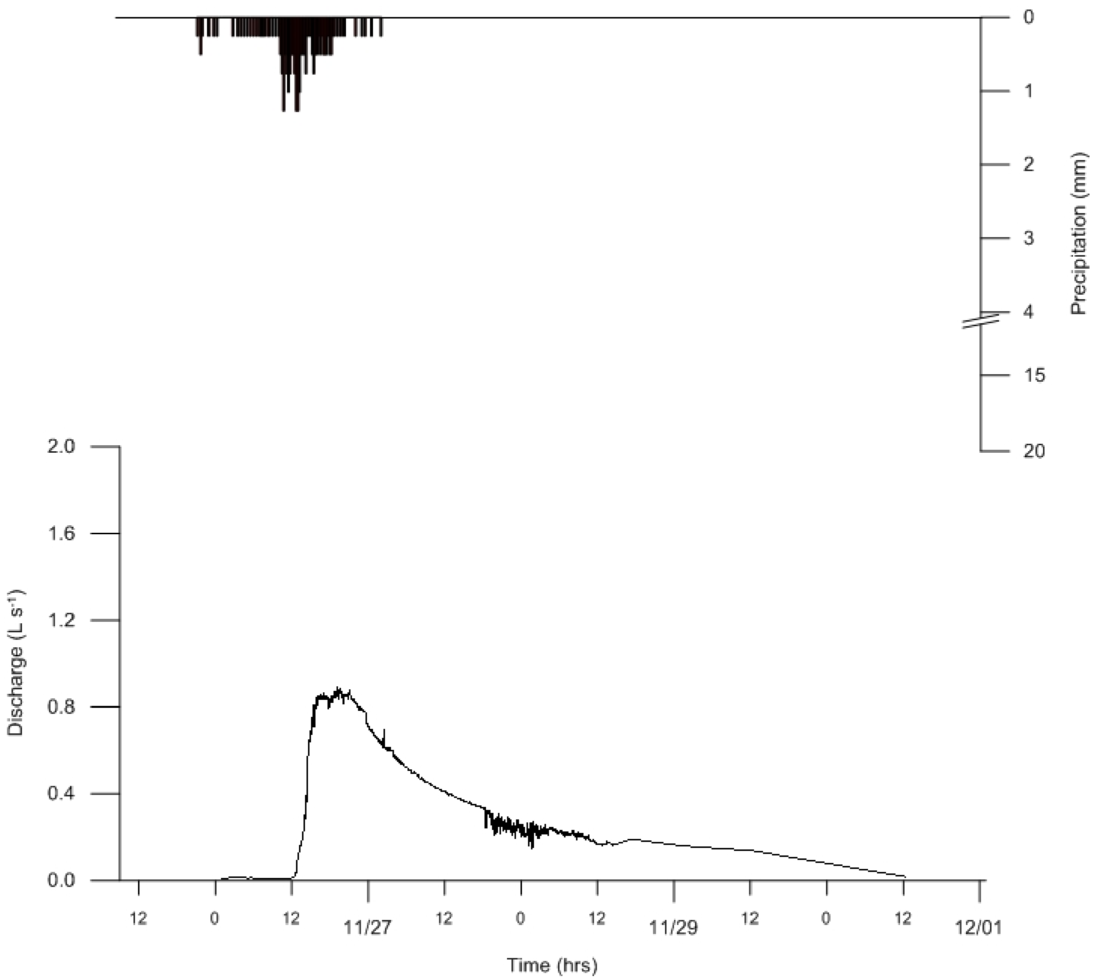

Figure A.44. Rainfall-Runoff Response at Bent Mountain on November 11, 2013. BM5, MIXED.

Table A.44: Storm Hydrograph Characteristics and CNs.

Start of Storm	11/25/13 21:15
Storm Duration	28.7
Precipitation Depth (mm)	0.6
CN (λ=0.2)	94
CN (λ=0.05)	89
Discharge volume (m^3)	57.8
Discharge volume (% rainfall)	63.0
Peak Discharge (m^3 s^{-1} x 10^{-4})	8.9
Lag Time (d x 10^{-2})	91.2
Response Time (d x 10^{-2})	15.2
Discharge Duration (d)	4.5

APPENDIX B: CALCULATED λ VALUES FOR BENT MOUNTAIN

Table B.1: Precipitation Depth, P (mm)

Date	Plot				
	BM1	BM2	BM3	BM4	BM5
July 21, 2005	20.1	20.1	20.1	20.1	20.1
August 6, 2005	16	16	16	16	16
August 16, 2005	19.6	19.6	19.6	19.6	19.6
September 16, 2005	19.4	19.4	19.4	19.4	19.4
October 7, 2005	25.4	25.4	25.4	25.4	25.4
April 7, 2006	38.1	38.1	38.1	38.1	38.1
August 11, 2006	44.1	44.1	44.1	44.1	44.1
August 19, 2006	15.4	15.4	15.4	15.4	15.4
August 29, 2006	18.3	18.3	18.3	18.3	18.3
September 22, 2006	16.3	16.3	16.3	16.3	16.3
October 16, 2006	30.6	30.6	30.6	30.6	30.6
November 1, 2006	16.9	16.9	16.9	16.9	16.9
June 1, 2012	23.4	23.4	23.4	23.4	23.4
August 6, 2012	33.3	33.3	33.3	33.3	33.3
August 10, 2012	14.5	14.5	14.5	14.5	14.5
August 15, 2012	28.2	28.2	28.2	28.2	28.2
September 17, 2012	33.0	33.0	33.0	33.0	33.0
October 28, 2012	42.9	42.9	42.9	42.9	42.9
April 17, 2013	17.5	17.5	17.5	17.5	17.5
May 20, 2013	20.1	20.1	20.1	20.1	20.1
June 30, 2013	22.9	22.9	22.9	22.9	22.9
July 11, 2013	42.4	42.4	42.4	42.4	42.4
August 10, 2013	16.0	16.0	16.0	16.0	16.0
November 25, 2013	28.7	28.7	28.7	28.7	28.7

Table B2: Flow Depth, Q (mm)

Date	Plot				
	BM1	BM2	BM3	BM4	BM5
July 21, 2005	3.5	2.6	3.5		3.8
August 6, 2005	2.8	2.1	1.9	2.1	2.3
August 16, 2005	2.6	1.7	2.0	1.9	1.6
September 16, 2005	0.5	0.5	0.3	0.6	0.6
October 7, 2005	1.6	0.4	0.4	0.9	0.7
April 7, 2006	8.7	5.9	--	18.0	15.2
August 11, 2006	3.2	5.7	1.5	5.7	5.5
August 19, 2006	0.7	1.6	0.0	1.5	0.8
August 29, 2006	1.9	3.3	0.2	2.1	1.4
September 22, 2006	2.3	--	0.7	1.0	0.8
October 16, 2006	6.9	5.6	4.7	7.8	7.6
November 1, 2006	3.0	2.2	2.6	--	3.3
June 1, 2012	1.8	2.5	--	7.4	6.8
August 6, 2012	8.0	10.0	10.3	--	--
August 10, 2012	0.0	0.0	0.0	--	--
August 15, 2012	2.0	0.0	2.5	--	--
September 17, 2012	0.0	0.0	--	10.3	7.0
October 28, 2012	0.5	0.0	0.3	0.8	1.3
April 17, 2013	6.9	2.7	10.9	5.2	4.9
May 20, 2013	0.1	0.1	0.0	0.4	0.4
June 30, 2013	0.1	0.3	0.0	0.9	0.5
July 11, 2013	6.4	7.8	4.5	7.3	6.4
August 10, 2013	0.8	--	--	5.4	4.4
November 25, 2013	6.0	14.7	--	13.8	16.0

Table B3: Initial Abstraction, I_a (mm)

Date	Plot				
	BM1	BM2	BM3	BM4	BM5
July 21, 2005	0.8	1.0	0.8	1.0	1.0
August 6, 2005	--	--	1.3	0.5	--
August 16, 2005	4.3	2.5	1.5	--	9.4
September 16, 2005	9.9	6.9	14.7	10.7	12.4
October 7, 2005	7.1	8.6	10.9	9.4	21.1
April 7, 2006	3.3	3.3	43.2	3.3	3.3
August 11, 2006	16.3	9.7	10.4	10.4	26.2
August 19, 2006	4.8	0.5	9.4	0.8	9.7
August 29, 2006	9.1	2.8	11.4	11.7	13.2
September 22, 2006	4.1	--	3.6	5.3	5.6
October 16, 2006	--	--	--	--	--
November 1, 2006	1.5	3.6	5.1	--	3.0
June 1, 2012	0.3	0.3	--	3.3	3.8
August 6, 2012	2.0	2.5	2.0	0.0	--
August 10, 2012	0.2	--	6.1	--	--
August 15, 2012	16.8	--	0.5	--	--
September 17, 2012	0.0	0.0	--	6.6	5.3
October 28, 2012	11.9	--	17.3	10.2	10.2
April 17, 2013	0.3	0.3	0.3	0.3	0.3
May 20, 2013	0.5	0.3	0.3	0.5	5.1
June 30, 2013	2.8	0.8	0.5	0.5	1.0
July 11, 2013	1.3	--	--	--	--
August 10, 2013	10.2	--	--	0.8	0.8
November 25, 2013	0.3	1.3	--	1.8	6.1

Table B4: Storage Retention, S (mm)

Date	Plot				
	BM1	BM2	BM3	BM4	BM5
July 21, 2005	88.4	121.2	86.3	--	75.8
August 6, 2005	--	--	98.7	96.5	95.4
August 16, 2005	73.1	158.0	147.6	--	53.2
September 16, 2005	159.2	334.8	65.6	112.5	75.7
October 7, 2005	196.0	713.3	515.2	257.8	22.8
April 7, 2006	104.9	170.9	--	32.6	44.7
August 11, 2006	213.0	174.2	705.2	165.1	41.0
August 19, 2006	142.7	127.8	756.4	127.5	34.4
August 29, 2006	35.6	57.5	228.1	14.6	14.1
September 22, 2006	54.2		215.4	115.1	132.5
October 16, 2006	104.9	135.9	170.2	90.2	93.3
November 1, 2006	64.7	68.7	41.8	--	43.5
June 1, 2012	277.5	187.3	--	34.6	36.4
August 6, 2012	91.1	63.8	63.1	--	--
August 10, 2012	4309.3	--	4529.9	--	--
August 15, 2012	54.3	--	278.8	--	--
September 17, 2012	--	--	--	41.2	81.5
October 28, 2012	1832.7	--	1904.4	1318.7	776.3
April 17, 2013	25.9	92.4	10.0	39.9	43.5
May 20, 2013	4580.8	3331.0	36361.7	873.1	486.8
June 30, 2013	6959.3	1555.3	27123.5	554.8	900.1
July 11, 2013	223.1	--	--	--	--
August 10, 2013	36.0	--	--	27.6	37.1
November 25, 2013	105.7	23.8	--	25.5	9.3

Table B5: Initial Abstraction Coefficient, λ

Date	Plot				
	BM1	BM2	BM3	BM4	BM5
July 21, 2005	0.01	0.01	0.01	--	0.01
August 6, 2005	--	--	0.01	0.01	--
August 16, 2005	0.06	0.02	0.01	--	0.18
September 16, 2005	0.06	0.02	0.22	0.09	0.16
October 7, 2005	0.04	0.01	0.02	0.04	0.92
April 7, 2006	0.03	0.02	--	0.10	0.07
August 11, 2006	0.08	0.06	0.01	0.06	0.64
August 19, 2006	0.03	0.00	0.01	0.01	0.28
August 29, 2006	0.26	0.05	0.05	0.80	0.94
September 22, 2006	0.08	--	0.02	0.05	0.04
October 16, 2006	--	--	--	--	--
November 1, 2006	0.02	0.05	0.12	--	0.07
June 1, 2012	0.00	0.00	--	0.10	0.10
August 6, 2012	0.02	0.04	0.03	--	--
August 10, 2012	0.00	--	0.00	--	--
August 15, 2012	0.31	--	0.00	--	--
September 17, 2012	--	--	--	0.16	0.07
October 28, 2012	0.01	--	0.01	0.01	0.01
April 17, 2013	0.01	0.00	0.03	0.01	0.01
May 20, 2013	0.00	0.00	0.00	0.00	0.01
June 30, 2013	0.00	0.00	0.00	0.00	0.00
July 11, 2013	0.01	--	--		
August 10, 2013	0.28	--	--	0.03	0.02
November 25, 2013	0.00	0.05	--	0.07	0.66

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