2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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# Influence of Storm Characteristics on Soil Erosion and Storm Runoff

**Johnny M. Grace III, Research Engineer**

USDA Forest Service, Forest Operations Research, 520 Devall Drive, Auburn, AL 36849, e-mail; jmgrace@fs.fed.us.

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**Abstract.** *Unpaved forest roads can be major sources of sediment from forested watersheds. Storm runoff from forest roads are a concern due to their potential delivery of sediments and nutrients to stream systems resulting in degraded water quality. The volume and sediment concentrations of stormwater runoff emanating from forest roads can be greatly influenced by storm characteristics, road management practices, and/or the interaction of management practices and subsequent storm events. In an attempt to gain a better understanding of storm runoff characteristics and erosion losses from forest roads, an investigation was initiated to quantify the influence of storm characteristics on runoff concentrations, runoff volumes, and soil erosion using data from three field experiments in Alabama and Georgia. Collected field data included a total of 54, 156, and 24 observations for field experiments 1(Appalachian Highlands of NW Alabama), 2 (Coastal Plain of SE Alabama), and 3 (Blue Ridge Mountains of NE Georgia), respectively. Mean event precipitation for the field experiments ranged from 33.5 to 62.5 mm and average storm intensities were 8.7, 3.8, and 3.5 mm* $hr^{-1}$ *for field experiments 1, 2, and 3, respectively. Storm characteristics explained as much as 40 percent of the variability in runoff concentrations and soil erosion losses from the field experiments. Total precipitation, average rainfall intensity, and maximum 30-minute rainfall intensity were detected as the most influential storm characteristics in determining soil erosion based on the field experimental data from Coastal Plain and Appalachian forest roads.*

**Keywords.** Soil Erosion, Storm Energy, Intensity, Runoff, Forest Roads

## Introduction

Surface water quality in the U.S., particularly streams and rivers, has become a major topic of discussion and concern in the 21st century. One of the primary concerns related to water quality is the introduction of sediments into stream systems from upslope sources due to various land uses. Sediments continue to be of particular interest because they not only cause water impairment but can also transport other pollutants (nutrients) bound to the soil particles resulting in further degradation of stream systems (Davies-Colley and Smith, 2001). Best Management Practices (BMPs) are often recommended and implemented to minimize or eliminate the impacts of upslope land use activities on surface waters. These practices typically have commonalities which include protecting the surface soil from raindrop impact and concentrated flow, increasing retention time for storm runoff, and increasing infiltration (Swift, 1986). Coincidently, these characteristics are commonly found in one of the nation's most valuable natural systems - forests. For example, forestlands are considered to have optimal erosion control properties and high water quality in their undisturbed state (Binkley et al. 2004). These undisturbed forestlands typically have erosion rates lower than 0.30 t $ha^{-1}yr^{-1}$ (Beasley 1979; Yoho 1980). Land-cover change and forest operations are often implicated in increased soil erosion and degraded water quality (Croke and Hairsine, 2006) and have come under increased inquiry over the past 30 years. However, the results of investigations focused on assessing the impact of forest operations on soil erosion and water quality in the southern United States are highly variable (Grace, 2005). One of the primary focus areas in regards to forest operations and its effects on forest water quality has been soil erosion from forest roads (Clinton and Vose, 2003; Grace and Elliot, 2008; Van Lear et al., 1997). For example, Van Lear et al. (1997) estimated that within a large southern Appalachian watershed, the road corridor was the source of more than 80 percent of observed sedimentation.

Forest stormwater runoff and resultant soil losses in the Appalachians and Coastal Plain regions of the southeastern United States are influenced by many factors. Some of these include land use, management practices, past and present disturbance patterns, climatic factors, site characteristics and soil properties. Land use, management practices, and present disturbance patterns can be manipulated or optimized to mitigate effects on stormwater runoff and soil erosion. Conversely, changes in these factors can increase soil erosion with consequent negative impacts on water quality. Previous work has shown the influence of BMPs, alternative soil erosion control practices, land use changes, and improved management practices on mitigating impacts of soil erosion on water quality (Croke and Hairsine, 2006; Grace and Clinton, 2007; Riedel et al., 2003, 2004). Conversely, soil and climatic factors for a given watershed or site are a function of the specific location of the watershed and are typically beyond management control. The degree of soil erosion depends largely on storm energy (storm characteristics) and soil surface protection during the storm event (Wischmeier, 1962), and storm characteristics (e.g., storm intensity, duration, frequency, and total precipitation) can substantially influence soil erosion. Previous work has investigated the impact of storm characteristics on erosion losses from agricultural lands in various geographical regions (Wischmeier and Smith, 1958). However, the effect of storm characteristics on forestlands has been given less consideration. Specifically, their influence on forest road stormwater runoff and erosion from various components of the road corridor has not been as extensively investigated. The objective of this paper is to explore and compare the influence of storm characteristics on soil erosion from forest roads and stormwater runoff in Coastal Plain and Appalachian watersheds of Alabama and Georgia.

## Methods

Stormwater data were collected from three field experiments in Alabama and Georgia with two road study locations in the Appalachian region of Alabama and Georgia and a road study location in the Coastal Plain regions of Alabama (Figure 1). Precipitation characteristics (event total accumulated, intensity, frequency, and duration) were recorded for each storm event with data loggers based on tipping bucket rain gauge sensors located at each field experiment (FE) site. Site specific information for each field experiment is provided below.

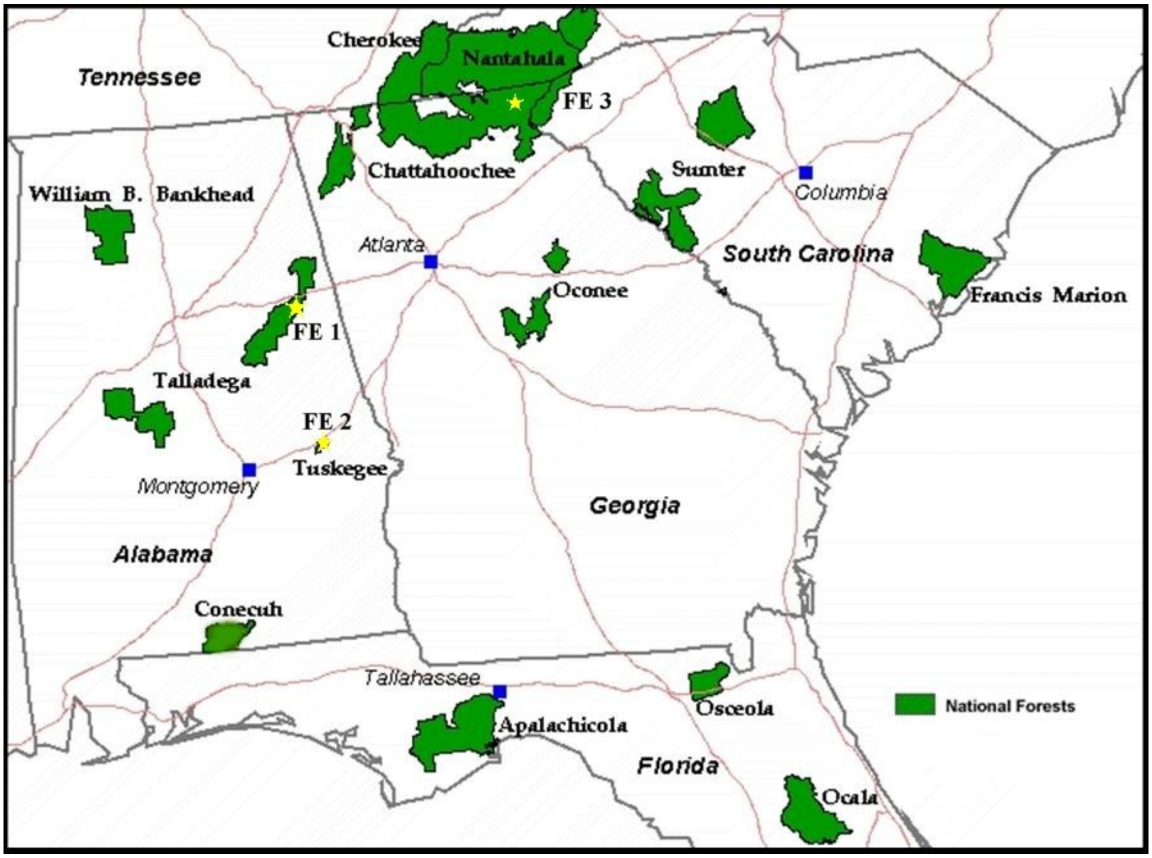

**Figure 1. General location of the three field experiments within National Forests in the Southern Region of the U.S. FE 1, FE 2, and FE 3 represent field experiment 1, field experiment 2, and field experiment 3, respectively.**

### *Field Experiment 1*

Field experiment 1 (FE 1) was initiated in 1995 and concluded in 2003. The primary objective of this experiment was to investigate the effect of vegetative cover on soil erosion from forest road sideslopes. The study area for FE 1 was located in the southern Appalachian region of Alabama at approximately 33° N, 85° W on the Talladega National Forest, near Heflin, Alabama. Long-term average precipitation for the study area is 1400 mm. FE1 has an elevation of 400 m above mean sea level (msl) with Tatum series soils. Storm runoff was collected in 200-L storage containers at the toe of the road sideslope sections. Storm runoff volume was measured directly from the storage containers. The suspended sediment fraction was quantified by analyzing 500 ml grab samples using gravimetric filtration. The deposited sediment fraction was quantified by oven drying the sediment deposited in the storage containers after removing the suspended sediment fraction.

### *Field Experiment 2*

Field experiment 2 (FE 2) was initiated in 1997 and concluded in 2007. The purpose of this experiment was to investigate the effect of sediment control practices on mitigating sediment export from forest road surfaces. The study area for FE 2 was located in the Coastal Plain region of Alabama (approximately 32° N, 85° W) on the Tuskegee National Forest near Tuskegee, Alabama. A total of 12 experimental road sections are located on a 7 m-wide crowned forest road traversing an uneven age managed pine stand. Long-term average precipitation for the study area is 1300 mm. FE 2 has an elevation of 80 m above msl. Soils on the study site are a Norfolk sand loam ranging from 6 to 12 percent slope. Stormwater runoff was sampled using stormwater samplers located at the outlet of lead-off ditch sections. Stormwater runoff concentration was quantified by analyzing 500 ml grab samples using gravimetric filtration.

### *Field Experiment 3*

Field experiment 3 (FE 3) was initiated in 2003 and monitoring continues to date. The main objective of this experiment is to quantify soil erosion losses from Appalachian forest roads and to evaluate the effect of forest road sediment control techniques in controlling erosion losses. FE 3 is located (35° N, 83° W) on the Chattahoochee National Forest near Dillard, Georgia. Long-term average precipitation for the Dillard area is 1800 mm. FE 3 has an elevation of 900 m above msl. Soils on the study site are a Hayesville fine sandy loam. Stormwater runoff volume and concentrations were determined using trapezoidal flumes in conjunction with stormwater samplers. Similar to FEs 1 and 2, the stormwater concentrations were quantified by analyzing 500 ml grab samples using gravimetric filtration.

### *Data Analysis Procedures*

Storm runoff data from field experiments were analyzed using SAS GLM procedures to determine the factors influencing runoff concentrations (SAS, 2004). Developing relationships relating storm characteristics to observed runoff concentrations, storm runoff volume, and soil erosion required a polynomial regression approach. The method of least squares, as presented by Grace (2005), was used in two stages to reveal the contribution of variables or combination of variables in predicting dependent variables (runoff concentration (TSS), storm runoff volume, and soil erosion) in the field experiments. Variables detected as insignificant at the one percent level were removed from the full model (stage 1) and the remaining factors were incorporated into a reduced model. In the second stage, the reduced model was fit to determine the most influential variables in predicting dependent variables. The refined model was then developed retaining only variables detected as significant at the 5 percent level.

## Results and Discussion

Mean precipitation for the storm events in the field experiments ranged from 33.5 mm in FE 2 to 62.5 mm in FE 1 (Table 1). Storm duration means were 14.6, 15.0, and 16.9 hours for field experiments 1-3, respectively. Means for the dependent response variables, storm runoff volume, soil erosion, and runoff concentration, are presented in Table 1 along with the independent variables consisting of precipitation, duration, average intensity ($I_{avg}$), maximum 15-minute intensity ($I_{15}$), and maximum 30-minute intensity ($I_{30}$). In FE 2, storm runoff volume and soil erosion were excluded from the analysis because the primary measurement in the field experiment was storm runoff concentration.

Table 1. Number of observations, means, standard deviations, and coefficients of variation for storm event variables by forest road field experiment study site.

| Variable | N | Mean | Std. Dev. | COV |
|---|---|---|---|---|
| **FE 1** | | | | |
| Storm Runoff, $m^3$ | 54 | 0.09 | 0.04 | 50.4 |
| Soil Erosion, t $ha^{-1}$ | 54 | 2.5 | 2.5 | 100.5 |
| Concentration, g $L^{-1}$ | 53 | 12.6 | 10.0 | 78.8 |
| Precipitation, mm | 54 | 62.5 | 28.3 | 45.3 |
| Duration, hrs | 30 | 14.6 | 8.7 | 59.7 |
| $I_{avg}$, mm $hr^{-1}$ | 54 | 8.7 | 3.9 | 44.0 |
| $I_{15}$, mm $hr^{-1}$ | 42 | 16.1 | 18.6 | 115.3 |
| $I_{30}$, mm $hr^{-1}$ | 36 | 15.4 | 8.0 | 52.2 |
| **FE2** | | | | |
| Storm Runoff, $m^3$ | -- | -- | -- | -- |
| Soil Erosion, t $ha^{-1}$ | -- | -- | -- | -- |
| Concentration, g $L^{-1}$ | 128 | 1.6 | 1.6 | 99.1 |
| Precipitation, mm | 156 | 33.5 | 24.0 | 71.8 |
| Duration, hrs | 156 | 15.0 | 13.0 | 86.5 |
| $I_{avg}$, mm $hr^{-1}$ | 156 | 3.8 | 2.7 | 70.0 |
| $I_{15}$, mm $hr^{-1}$ | -- | -- | -- | -- |
| $I_{30}$, mm $hr^{-1}$ | 156 | 8.7 | 6.7 | 76.8 |
| **FE3** | | | | |
| Storm Runoff, $m^3$ | 24 | 8.2 | 28.7 | 350.3 |
| Soil Erosion, t $ha^{-1}$ | 23 | 0.65 | 2.1 | 321.5 |
| Concentration, g $L^{-1}$ | 23 | 0.89 | 0.56 | 62.9 |
| Precipitation, mm | 24 | 53.7 | 40.5 | 75.5 |
| Duration, hrs | 24 | 16.9 | 9.3 | 55.1 |
| $I_{avg}$, mm $hr^{-1}$ | 24 | 3.5 | 2.6 | 75.8 |
| $I_{15}$, mm $hr^{-1}$ | 24 | 17.6 | 11.7 | 66.2 |
| $I_{30}$, mm $hr^{-1}$ | 24 | 13.5 | 9.1 | 67.2 |

Storm event data from each field experiment were modeled using a polynomial regression approach to evaluate the significant storm characteristics in determining soil erosion, storm runoff volume, and runoff concentration in the experiments. This method of least squares was used in two stages to determine variables and/or combination of variables influencing runoff concentrations, storm runoff volumes, and soil erosion from the field experiments. Stage one involved fitting the full model which included independent variables and their interactions independent terms. Variables significant at the one percent level in the first stage were considered factors with the strongest relationship to dependent variables and were retained for analysis in the second stage of model refinement. The reduced model was fitted in the second stage of the regression analysis. The final model was then defined by retaining only variables significant at the five percent level of significance which provided the most sensitive variables in predicting runoff concentration, storm runoff volume, and soil erosion from the field experiments (Tables 2 - 6).

Table 2. Summary Analysis of Variance table for runoff concentration for study site FE 1 excluding insignificant variables (α = 0.05).

| **Source** | **df** | **Sum of Squares** | **Mean Square** | **F-value** | **P-value** |
|---|---|---|---|---|---|
| $I_{30}$ | 1 | 244 | 244 | 10.0 | 0.0051 |
| Precipitation * Duration | 1 | 237 | 237 | 9.8 | 0.0056 |
| $I_{avg}$ | 1 | 189 | 189 | 7.78 | 0.0117 |
| Model | 3 | 671 | 224 | 9.2 | 0.0006 |
| Residuals | 19 | 463 | 24 | | |
| Total | 22 | 1134 | | | |
| Equation | Runoff Concentration (g $L^{-1}$) = -5.65($I_{30}$) + 0.026 (Precipitation*Duration) + 6.46 ($I_{avg}$) + 47.8 | | | | |

Table 3. Summary Analysis of Variance table for runoff concentration for study site FE 2 excluding insignificant variables (α = 0.05).

| **Source** | **df** | **Sum of Squares** | **Mean Square** | **F-value** | **P-value** |
|---|---|---|---|---|---|
| Precipitation * Duration | 1 | 51 | 51 | 27.1 | <0.0001 |
| $I_{30}$ | 1 | 15 | 15 | 8.2 | 0.0050 |
| $I_{avg}$ | 1 | 10 | 10 | 5.3 | 0.0229 |
| Model | 3 | 76 | 25.5 | 13.5 | <0.0001 |
| Residuals | 124 | 233 | 1.9 | | |
| Total | 127 | 309 | | | |
| Equation | Runoff Concentration (g $L^{-1}$) = -0.0008 (Precipitation*Duration) + 0.18 ($I_{30}$) – 0.10 ($I_{avg}$) + 0.88 | | | | |

Table 4. Summary Analysis of Variance table for runoff concentration for study site FE 3 excluding insignificant variables (α = 0.05).

| **Source** | **df** | **Sum of Squares** | **Mean Square** | **F-value** | **P-value** |
|---|---|---|---|---|---|
| Duration | 1 | 1.46 | 1.46 | 5.62 | 0.0274 |

| | | | | | |
|---|---|---|---|---|---|
| Model | 1 | 1.46 | 1.46 | 5.62 | 0.0274 |
| Residuals | 21 | 5.45 | 0.26 | | |
| Total | 22 | 6.92 | | | |
| Equation | Runoff Concentration (g $L^{-1}$) = -0.029 (Duration) + 1.41 | | | | |

The interaction of precipitation amount and duration was the most sensitive term in the runoff concentration model for FEs 1 and 2 (Table 2 & 3). The intensity terms ($I_{avg}$ and $I_{30}$) were also detected as significant variables in predicting runoff concentrations from the two experiments. Intensity terms represented a large component of the variability in the runoff concentrations with R-square values of 0.60 and 0.25 for FEs 1 and 2, respectively. However, in FE 3 only duration was detected as significant in determining runoff concentrations from the road sections (Table 4). The interaction of precipitation amount and duration was significant at the 10 percent level of significance but that level was beyond the level for inclusion as a significant variable based on the acceptance limits defined in the analysis. The one variable model presented above for FE 3 had a very low R-square value (0.21) and the addition of the precipitation terms made no improvement (to 0.21) in the R-square value. This suggests that influences other than precipitation characteristics measured in the experiment are likely having a greater influence on runoff concentrations in the experiment. Runoff concentrations were detected as significantly different between field experiments in this investigation. Site differences, as opposed to storm characteristics, explained as much as 60 percent of the variability in runoff concentration data based on the partitioning of the sum of squares.

Site differences in the field experiments were detected in both the runoff volume and soil erosion data as can be seen in Tables 5 and 6 based on the lumped FE data, with the exclusion of FE2 as previously mentioned. The site variable contributed 5 and 12 percent of the variability in the models for runoff volume and soil erosion, respectively. Precipitation amount and intensity were the most influential variables in determining runoff volume and soil erosion in the experiments based on ANOVA results (Tables 5 and 6). In fact, precipitation and the square of precipitation explained nearly 30 percent of the variability in the runoff volume model. The interaction of precipitation and site was also detected as significant in the runoff volume model. This result indicates that there were site differences in precipitation and precipitation patterns between these two experimental sites. However, the three intensity variables ($I_{avg}$, $I_{15}$ and $I_{30}$), expected to show the effect of storm energy in the field experiments, were not detected as significant in the runoff volume model. Intensity variables were expected to have a greater influence on runoff because increased precipitation depth (amount) and intensity typically result in increased runoff from the forest road prism. Even small amounts of precipitation at higher intensities can result in less infiltration and more storm runoff. Recorded storm events in these experiments were relatively low intensity events and ranged from 1.0 to 17.5 mm $hr^{-1}$, $I_{15}$ values ranged from 1.0 to 61.0 mm $hr^{-1}$, and $I_{30}$ values ranged from 1.0 to 38.6 mm $hr^{-1}$. The energy associated with sheet flow and the flow concentrated in the roadside ditch likely influenced runoff volumes in each of the experiments to a greater extent than storm intensity. The dominance of the precipitation amount variable in the runoff model would seem to support this statement.

Table 5. Summary Analysis of Variance table for runoff volume excluding insignificant variables ($\alpha = 0.05$).

| **Source** | **Df** | **Sum of Squares** | **Mean Square** | **F-value** | **P-value** |
|---|---|---|---|---|---|
| Site | 1 | 1091 | 1091 | 6.9 | 0.0107 |

| | | | | | |
|---|---|---|---|---|---|
| Precipitation * Precipitation | 1 | 2859 | 2859 | 18.0 | <0.0001 |
| Precipitation | 1 | 2663 | 2663 | 16.8 | 0.0001 |
| Precipitation*Site | 1 | 1801 | 1801 | 11.3 | 0.0012 |
| Model | 4 | 8414 | 2104 | 13.2 | <0.0001 |
| Residuals | 73 | 11607 | 159 | | |
| Total | 77 | 20022 | | | |

Table 6. Summary Analysis of Variance table for soil erosion excluding insignificant variables ($\alpha = 0.05$).

| **Source** | **Df** | **Sum of Squares** | **Mean Square** | **F-value** | **P-value** |
|---|---|---|---|---|---|
| Site | 1 | 35 | 35 | 13.7 | 0.0005 |
| Precipitation | 1 | 64 | 64 | 25.6 | <0.0001 |
| $I_{avg}$ | 1 | 26 | 26 | 10.4 | 0.0021 |
| $I_{avg} * I_{30}$ | 1 | 24 | 24 | 9.5 | 0.0032 |
| Model | 4 | 150 | 37.5 | 14.8 | <0.0001 |
| Residuals | 54 | 137 | 2.5 | | |
| Total | 58 | 287 | | | |

Precipitation amount and intensity variables ($I_{avg}$ and $I_{30}$) were found to be the most sensitive variables in predicting soil erosion from these field experiments (Table 6). In the soil erosion model, site differences only explained 12 percent of the total sum of squares of the model. Similar to the runoff model, precipitation was the most influential variable in soil erosion losses from the field experiments. Intensity variables did have a greater influence on soil erosion than seen for runoff volume from the field experiments. This influence could have been expected because previous investigations found that variables representing storm energy ($I_{avg}$ and $I_{30}$) can significantly influence soil erosion.

A plot of predicted soil erosion based on storm characteristics (precipitation, $I_{avg}$, and $I_{30}$) versus observed soil erosion losses revealed that the model reasonably predicted soil erosion losses (Figure 2). The coefficient of determination was high at 0.83 indicating reduction of the variability in the dependent variable (soil erosion) by the introduction of the independent variables (precipitation, $I_{avg}$, and $I_{30}$ in this model) (Neter et al., 1996). That is, the high R-square value reveals a strong relationship between predicted and observed soil erosion in the field experiments. In fact, storm characteristics of precipitation amount, $I_{avg}$, and the interaction of $I_{avg}$ and $I_{30}$ explained 40 percent of the variability in the soil erosion model. Based on these results, storm characteristics can have a significant influence on soil erosion losses from the forest road prism with all other factors held constant. Storm characteristics measured and analyzed in this work account for as much as 30 and 40 percent of the variation in runoff volume and soil erosion from the forest road corridor, respectively. These storm variables, as previously stated, are also highly variable and uncontrollable.

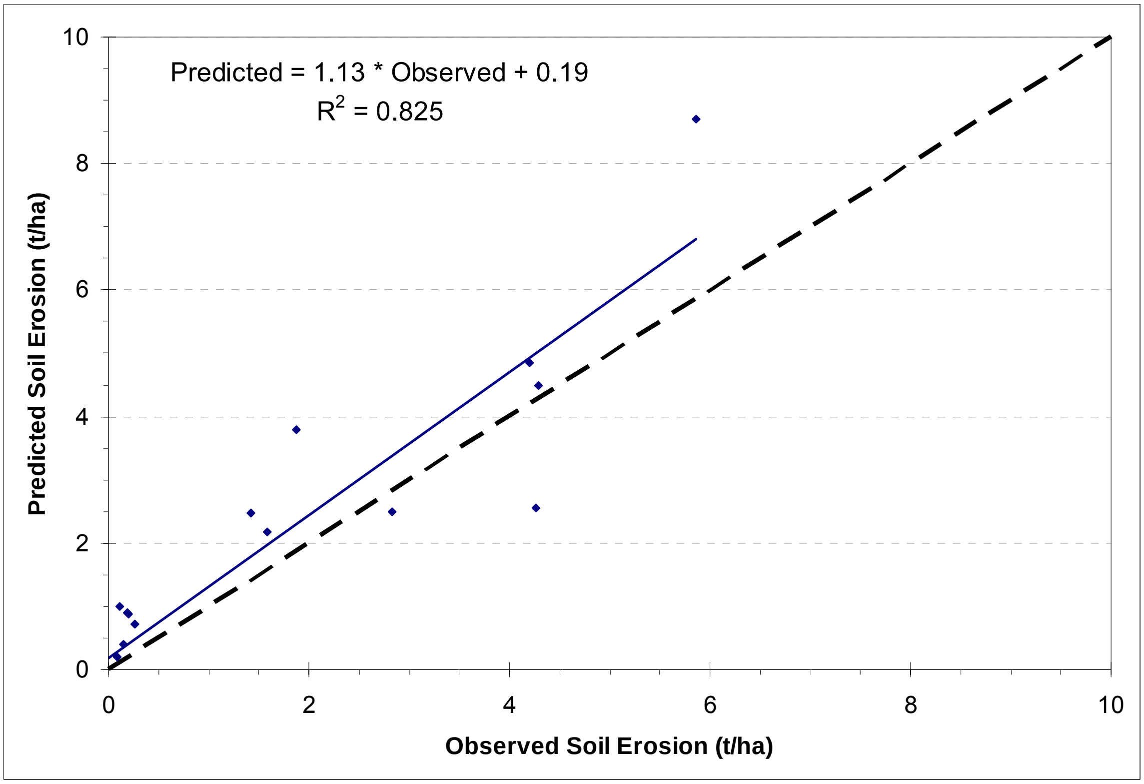

**Figure 2. Relationship of soil erosion predicted from regression (equation) model based on storm characteristics and observed soil erosion losses from the field experiments. Perfect agreement between predicted and observed is represented by the dashed line (a 1:1 relationship).**

## Summary and Conclusions

Storm event data collected from three field experiments on forest roads was analyzed to determine the effect of storm characteristics on storm runoff concentrations, storm runoff volume, and soil erosion. Storm characteristics measured in these experiments included total event precipitation, event duration, average storm intensity ($I_{avg}$), maximum 15-minute intensity ($I_{15}$) and maximum 30-minute intensity ($I_{30}$). This collected field data included a total of 54, 156, and 24 observations for FEs 1, 2, and 3, respectively. Mean event precipitation for the field experiments ranged from 33.5 to 62.5 mm. Average storm intensities were 8.7, 3.8, and 3.5 mm $hr^{-1}$ for FEs 1, 2, and 3, respectively.

The interaction term ‘event precipitation*duration’ and ‘intensity’ variables ($I_{avg}$ and $I_{30}$) were detected as having a significant influence on runoff concentrations from FEs 1 and 2 based on the method of least squares used in the analysis. The maximum 30-minute intensity explained the largest proportion of the variability in runoff concentrations from FE 1, whereas, the interaction term event precipitation*duration explained the largest proportion of the runoff concentration variability in FE 2. In contrast, duration was detected as the sole variable significantly influencing runoff concentration from FE 3. The three parameter runoff concentration model exhibited by FEs 1 and 2 explained a large component of the variability with R-square values greater than 0.60. However, the one parameter runoff concentration model presented for FE 3 explained little of the variability observed and had a low R-square value of 0.21. This indicates that influences other than storm characteristics played a larger role in determining runoff concentrations for the experiment.

Site differences in the field experiments were also detected in the analysis of runoff volume and soil erosion data. However, site differences explained less than 12 percent of the variability in runoff volume and soil erosion data. In a result similar to that of the runoff concentration analysis, precipitation amount and intensity had a significant influence on both runoff volumes and soil erosion from the field experiments. Event precipitation and the square of precipitation explained nearly 30 percent of the variability in runoff volume from the field experiments. Similarly, soil erosion was found to be significantly influenced by event precipitation, $I_{avg}$, and the interaction of $I_{avg}$ and $I_{30}$. These storm characteristics were found to explain more than 40 percent of the variability in soil erosion from the field experiments. Based on these results, storm characteristics can have a significant influence on runoff and soil erosion from the forest road corridor, yet these are variables that can not be controlled or manipulated in the real world. This emphasizes the need for BMPs and sediment control practices that minimize the effect of road systems on downslope resources.

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