FACTORS INFLUENCING SEDIMENT PLUME DEVELOPMENT FROM FOREST ROADS

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Johnny M. Grace III, Ph.D., is a research engineer with the USDA Forest Service, Southern Research Station, Forest Operations Research Unit. Forest Operations Research, SRS-4703, specializes in providing cutting edge technology integrating ecological and engineering disciplines for sustainable forest resource management. Dr. Grace has authored numerous papers on hydrology, road sediment and erosion control, NPS pollution, and BMPs related to forest operations over the past nine years. Dr. Grace's research focuses on evaluating and mitigating impacts of forest operations (site preparation, thinning, harvesting, and road operations) on forest soil erosion, water quality, and hydrology.

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ABSTRACT

Forest roads have been presented as the major source of soil erosion from forest activities in recent years. Controlling sediment movement from forest roads is emphasized in forest management throughout the nation. However, design and development of Best Management Practices (BMPs) to control sediment movement from the forest road prism requires a better understanding of the factors influencing sediment transport distances downslope. Relationships developed specifically for national forests will give managers additional planning and evaluation tools for roads and can be used to assess the potential for environmental impacts on existing forest roads. The USDA Forest Service Southern Research Station, Forest Operations Research Unit, initiated a study to evaluate factors influencing sediment plume development downslope of forest roads on national forests in Alabama and Georgia. A total of 235 sites were measured based on replications of downslope gradients, road gradient classes, soil textures, and forest floor indices. The data were used to develop a prediction equation based on site specific characteristics. Road characteristics (road section length and road width) had the greatest influence on the distance sediment traveled downslope from forest road lead-off ditch outlets. Generally, visible sediment plume development extended less than 90 m.

Key Words: forest roads; soil erosion; research; prediction; surface runoff

INTRODUCTION

Clearly, forest roads can be a major source of erosion and sediments in forested watersheds based on previous investigations and assessments (Authur et al., 1998; Packer, 1967; Van Lear et al., 1997). Introduction of sediments to forest stream systems can adversely affect water quality by increasing turbidity, nutrient concentrations, and decreasing water clarity (Davies-Colley and Smith, 2001; Elliot, 2000). However, erosion losses observed from the forest road prism may not increase stream sedimentation due to the increased surface roughness and infiltration associated with the forest floor and implementation of forestry BMPs (Swift, 1986).

The influence of forest roads on soil erosion and sediment delivery to water systems has been a major focus in forest management in recent years. However, sediment movement from forest roads has been an area of research for the past 70 years. Initial observations of accelerated erosion rates from the forest road prism were reported as early as the 1930s (Hursh, 1935; 1938; 1939). Hursh (1939) evaluated soil erosion from forest road sideslopes and recommended mitigation techniques to reduce erosion rates. These study findings on the road prism's influence on soil erosion and sediment movement have been substantiated by numerous researchers in most geographical regions of the U.S. over the past 50 years (Authur et al., 1998; Bethlahmy and Kidd, 1966; Grace, 2002; Smith and Stamey, 1965; Swift, 1984).

Trimble and Sartz (1957) took the next logical step in understanding forest road sediment movement by investigating the effects of roads on forest water quality. The investigators presented logging roads as one of the main sources of degrading water quality in forested areas while offering the forest floor as an efficient filter of sediment laden storm runoff. Filter strips, consisting of narrow strips of undisturbed forest adjacent to forest water bodies, were recommended. The investigators concluded that the width of strips to reduce the potential for sediment delivery to streams was influenced by the degree of road slope, soil properties, culvert spacing, road-surface conditions, steepness of roads, sediment trapping, and age of culverts. This pioneering research in road erosion emphasized the need for new road design and location criteria that considered minimizing the water quality impact of forest roads. Currently, a gap still exists in the understanding of sediment movement from forest roads and the factors that are beneficial in minimizing sediment travel distances. This paper reports findings of a study to determine the factors influencing sediment travel distances downslope from forest road lead-off ditch outlets for national forests in Alabama and Georgia.

METHODS

Sediment plume lengths downslope of road lead-off ditch outlets were assessed for 235 sites on the national forests of Alabama and the Chattahoochee National Forest in Georgia. Comparisons of sediment plume lengths to forestry streamside management zone BMP guidelines have been reported for Alabama and Georgia (Grace, 2004). This initial analysis found that 80 percent of observed lead-off ditch spacings were less than forestry BMP guidelines for both states. The aforementioned observation was an important characteristic in assessing sediment plume development in this investigation because the distance sediment moves downslope is expected to be representative of transport distances provided by lead-off ditch spacing guidelines for both states.

The study sites were located within five national forests; Bankhead, Chattahoochee, Conecuh, Talladega, and Tuskegee National Forests in the southern region, specifically concentrated in Alabama and Georgia. The Chattahoochee National Forest consists of 300,000 ha in North Georgia and the national forests of Alabama consist of 270,000 ha within four national forests (Figure 1).

Potential study roads were identified in consultation with Forest Service personnel, topographic and forest maps, and field reconnaissance. Roads with similar construction, maintenance levels, traffic intensity, and drainage characteristics were selected for the evaluation to minimize variability in statistical analysis. Road type was constrained to crowned roads with native and gravel surfacing drained by lead-off ditches. Roads selected in the investigation ranged in traffic intensity from low to moderate. Roads selected for the investigation ranged in age from 5 years to greater than 20 years. However, road age was one of the most difficult parameters to pinpoint because records were essentially unavailable for older roads (> 20 years).

Following selection of the study roads, potential study sites were mapped, individually numbered, and tagged for measurement. Study sites consisted of forest road sections, the lead-off ditch draining the road section, and the flow path of storm runoff downslope of the lead-off ditch. Site characteristics hypothesized to influence downslope sediment movement from lead-off ditch outlets were downslope gradient (G_d), road width (R_w), road section length (R_l), and road gradient (R_g).

Initially, a sub-sample (sites) was selected that met each of the class combinations considered in the investigation (Table 1). This procedure involved collecting sufficient data across the sample population to develop estimates of sample sizes needed for class combinations. Variances were estimated for each class combination in the sub-sample from the observed plume lengths. A Neyman allocation was then applied to the sub-sample to ensure data collection was efficient. That is, the allocation allowed the collection of only the required sample size in each class combination by weighting the allocation of sites by standard deviations. Data was collected from 235 sites

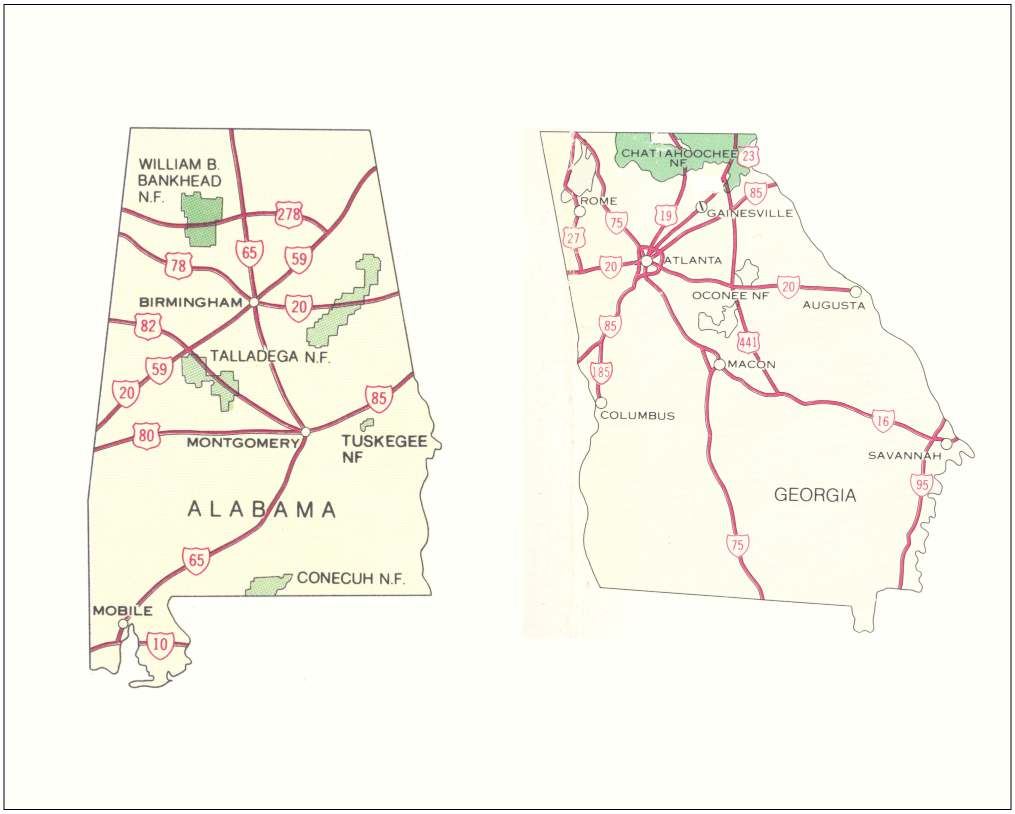

Figure 1. General locations of study areas within the National Forests of Alabama and Georgia. National Forests shaded within each state map. (Map Source: U.S. Forest Service (Southern Region) and USGS.)

Table 1. Description of Study Variables Hypothesized to Influence Sediment Plume Development in this Study.

Parameter	Category	Description
Downslope Gradient	Low	0 to 10 percent slope
	Moderate	11 to 30 percent slope
	High	31 + percent slope
Soil Texture	Coarse	Sandy Loam-Sand Soils
	Fine	Clay-Loam Soils
Road Gradient	Low	0–3 percent slope
	Moderate	4–5 percent slope
	High	6–9 percent slope
	Steep	10 + percent slope
Forest Floor Index	Low	Obstructions < = 2 cm
	High	Obstructions > 2 cm

based on replications of three downslope gradients (low, moderate and high), two soil textures (fine and coarse), four road gradients (low, moderate, high, and steep), and two forest floor indices (low and high).

Sediment deposition areas downslope of lead-off ditches were identified and tracked to the most remote deposition area visible in the flow path. Total sediment plume length was measured along the stormwater flow path from the roadway edge to the most remote location in the flow path. Replicate soil samples (0.5 kg) were taken for particle size analysis at three locations along each deposition area. Road characteristics measured for each study site included road section length, road width, road gradient, ditch width, ditch depth, and contributing drainage area upslope. Road section length was defined as the slope length of the road section of interest. Road width, measured from the inside edge of each roadside ditch, was determined as the average of measurements at three locations along the road section length. Gradients (road and downslope) were measured with clinometers as percent slopes.

Forest floor index, a somewhat subjective parameter, relates to the obstructions (surface roughness) to stormwater runoff from lead-off ditches. Obstructions in the flow path typically result in decreased flow velocity (energy) which decreases the sediment transport capacity of the runoff. Decreased flow velocity can also provide additional detention time, thereby increasing infiltration. Obstructions to flow were either measured as vertical or horizontal obstacles to flow. The forest floor index was classified as low if either the forest litter layer depth was less than or equal to 2 cm or if obstructions to flow were less than or equal to 2 cm. A high forest floor index was defined as a flow path with forest litter in place with a depth greater than 2 cm or obstructions to flow greater than 2 cm.

Data Analysis

One of the objectives of this study is to gain a better understanding of factors influencing the distance that sediment moves downslope from lead-off ditch outlets across the forest floor. Accomplishing this objective involved characterizing road conditions and forest floor characteristics and relating these conditions to observed sediment plume lengths. Relating sediment plume lengths to road and forest floor characteristics considered in this investigation required a polynomial regression approach. Sediment plume length data were analyzed using SAS GLM procedures to determine the factors influencing the distance sediment moved downslope using least squares estimates (SAS, 1991). Variables detected as not significant at the one percent level were excluded from the model to form a refined prediction equation.

RESULTS AND DISCUSSION

The mean distance sediment plumes extended downslope from lead-off ditch outlets was 30 m for all sites (Figure 2). Plume length and road section length were highly variable with standard deviations of 18.7 and 28.1 m, respectively. Road section lengths were consistent with BMP guidelines for lead-off ditch spacing which are based on road gradient. That is, steeper road gradients require shorter road section lengths. Therefore, the variation in road section length should be expected since it is primarily dependent on road gradients. Road width and road gradient had the narrowest range of values for the parameters measured in the study.

Factors Influencing Plume Lengths

Characteristics hypothesized to influence sediment movement were tested using a polynomial regression approach to determine significant factors in predicting plume lengths. The statistical model tested was:

$$PL_i = \beta_o + \beta_1(G_d)_i + \beta_2(R_w)_i + \beta_3(R_l)_i + \beta_4(R_g)_i + \beta_5(G_d^2)_i + \beta_6(G_d * R_g)_i + \beta_7(G_d * R_w)_i + \beta_8(G_d * R_l)_i + \beta_9(R_g^2)_i + \beta_{10}(R_g * R_w)_i + \beta_{11}(R_g * R_l)_i + \beta_{12}(R_w^2)_i + \beta_{13}(R_w * R_l)_i + \beta_{14}(R_l^2)_i + \beta_{15}(G_d * R_g * R_l)_i + \beta_{16}(R_g * R_w * R_l)_i + \beta_{17}(R_g * R_l^2)_i$$

where:

- PL_i = predicted plume length for the ith observation
- $\beta_{(j)}$ = regression coefficients
- G_d = Downslope gradient
- R_w = Road section width
- R_l = Road section length
- R_g = Road section gradient

The method of least squares was used in two stages to develop the model and reveal the contribution of each factor (or combination of factors) in predicting sediment plume lengths downslope of lead-off ditch outlets. In stage one, the full model was fitted as defined above and factors significant at the one percent level were considered factors with the highest relationship to sediment plume lengths. These factors were retained for the next model refinement in stage two. The statistical model was then refined (stage two) to include only factors detected as significant at the 0.5 level to determine the most

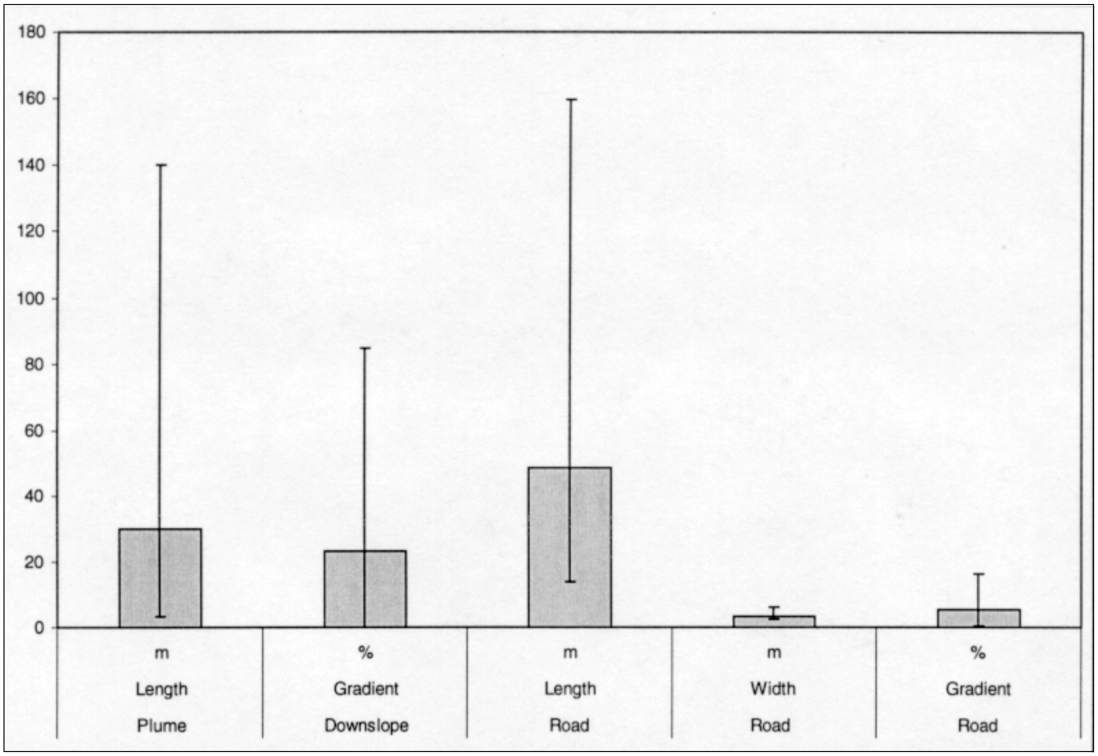

Figure 2. Means and ranges for primary variables measured in this investigation of factors influencing the distance sediment moves downslope.

sensitive factors in predicting sediment plume lengths (Table 2). Road section characteristics were the most significant factors in predicting sediment plume lengths. Road section length had the largest contribution to variation in sediment plume lengths. The other two factors explaining significant variation in the model were the product of road length and width (area of the road section) and the square of road section width.

The prediction equation relating sediment plume length to road characteristics for the national forests evaluated is:

$$PL = 26.9 - 0.28 (R_l) + 0.16 (R_l * R_w) - 0.80 (R_w^2)$$

where:

PL is the predicted plume length in m
R_l is the road section length in m
R_w is the road section width in m

Predicted plume lengths are plotted against observed plume lengths based on the above equation (Figure 3). The equation presented here explains 60 percent of the variation in sediment plume lengths observed in the investigation. The mean square error of estimate of the equation is 17 m for the sites included in this study.

The factors detected as most beneficial in prediction of sediment plume lengths are consistent with fluid flow theory. That is, the quantity and velocity of flow increases the energy of runoff to transport detached soil particles. Energy associated with open channel flow is greatly increased by the mass and velocity of flow (velocity head term in the energy balance equation). However, based on this analysis, slope (road gradient and downslope gradient) had no significant effect on the distance sediment plumes extended downslope.

The lack of statistical significance for downslope gradient in predicting the distance sediment moved is consistent with findings by Haupt (1959). The researcher presented a regression equation that was a function of the obstruction index, road section length squared, embankment slope length, and the product of road length and road gradient. In contrast, the lack of statistical significance of downslope gradient in predicting plume length is contrary to the findings of

Table 2. Final Analysis of Variance Summary Table Excluding Variables Not Significant at the 5 Percent Level.

Source	df	Sum of Squares	Mean Square	F-value	P-value
Intercept	1	198075	198075	683	< 0.0001
R_l	1	10503	10503	36.2	< 0.0001
R_w*R_l	1	2927	2927	10.1	0.0017
R_w^2	1	1219	1219	4.2	0.0415
Model	4	212724	53181	183.4	< 0.0001
Residuals	220	63802	290		
Total	225	276527			

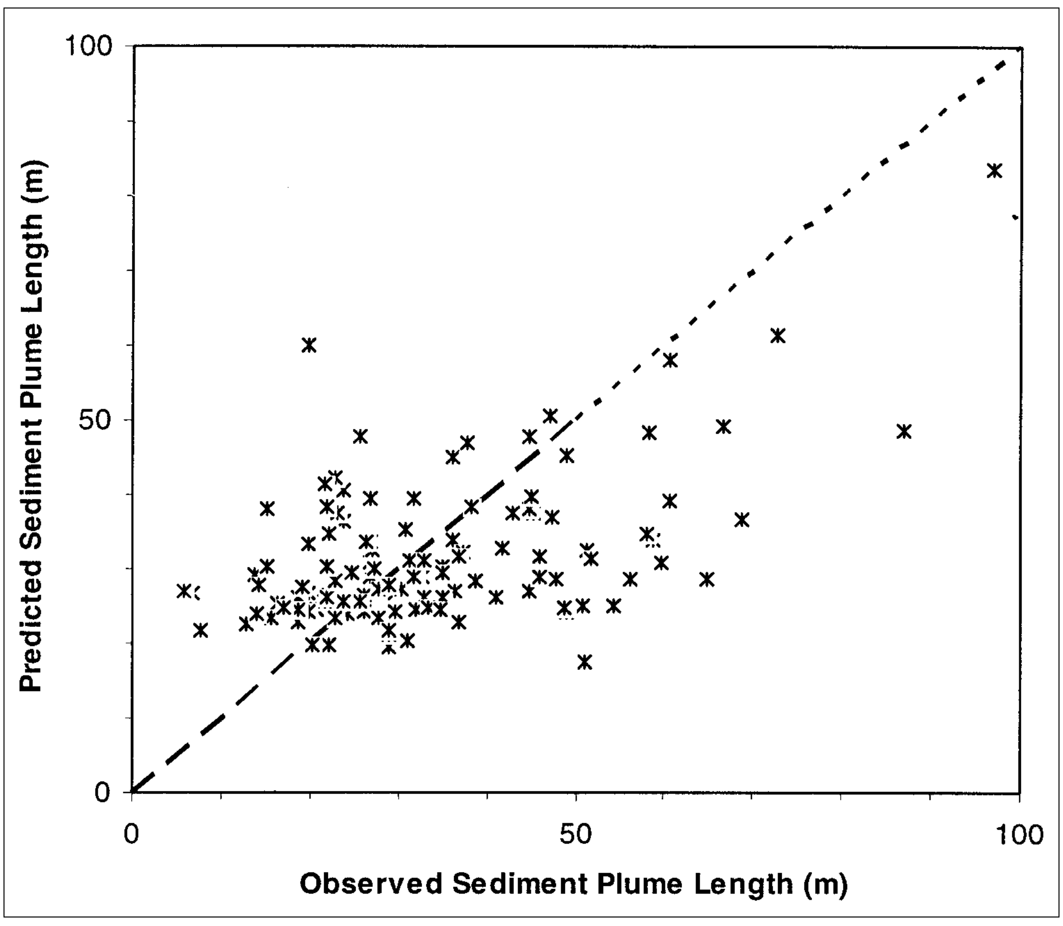

Figure 3. Observed sediment plume lengths plotted against sediment plume length predicted based on the formulated regression equation. The dashed line represents perfect agreement (a 1:1 relationship) between predicted and observed.

Swift (1986) which defined guides for filter strip widths below grassed fills with and without bush barriers. Swift (1986) found the distance sediment moved downslope was primarily a function of downslope gradient. Brush barriers (synonymous with increased obstruction index in the above mentioned research by Haupt (1959)) reduced the distance sediment moved downslope.

The effect of downslope obstruction index was not considered in this analysis; however, this does not indicate that obstruction index did not influence plume lengths. In fact, obstruction index and eroded particle size are factors that have been found to influence the distance sediment moves downslope in previous research. However, defining the obstruction index can be somewhat subjective which eliminated inclusion at this point in the analysis of sediment plume data. For example, Haupt (1959) defined the obstruction index by assigning numerical ratings based on the size or sum of obstructions of flow. This method proved beneficial in explaining variation in sediment travel distances in this previous investigation; however, a more objective definition of obstruction index may have resulted in a stronger relationship. Further definitions of obstructions in this investigation are under development and will be used in an attempt to explain additional variation in observed sediment plume lengths.

CONCLUSIONS

Sediment plume lengths downslope of forest road lead-off ditch outlets were examined in the national forests of Alabama and Georgia. Mean sediment plume length from the 235 sites studied was 30 m with a standard deviation of 18.7 m. As expected, road length which is primarily determined by road gradient was highly variable. Road characteristics hypothesized to influence the distance sediment moves downslope from lead-off ditches were tested to determine factors with the greatest influence. Factors detected as significant in predicting sediment plume lengths downslope in the national forests of Alabama and Georgia were road section length, the product of road section length and road width, and the square of road width. The sediment plume length prediction equation developed in this work explained 60 percent of the variation in observed plumes and had a mean square error of estimate equal to 17 m.

Factors detected as significantly influencing sediment plume lengths are consistent with previous investigations while being inconsistent with a select few. Road length and width parameters, detected as the primary factors in sediment plume lengths, influence flow volume which in turn influences the energy of flow. However, additional work is required to relate the relative contribution of obstruction index and eroded particle sizes to sediment plume lengths. A better definition of the obstruction index is critical to gain a better understanding of the distance sediment moves downslope.

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