THESIS

SEDIMENT PRODUCTION AND DELIVERY FROM FOREST ROADS AND OFF-HIGHWAY VEHICLE TRAILS IN THE UPPER SOUTH PLATTE RIVER WATERSHED, COLORADO

Submitted by

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WE HEREBY RECOMMEND THAT THIS THESIS PREPARED UNDER OUR SUPERVISION BY MATTHEW J. WELSH ENTITLED “SEDIMENT PRODUCTION AND DELIVERY FROM FOREST ROADS AND OFF-HIGHWAY VEHICLE TRAILS IN THE UPPER SOUTH PLATTE RIVER WATERSHED, COLORADO” BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

SEDIMENT PRODUCTION AND DELIVERY FROM FOREST ROADS AND OFF-HIGHWAY VEHICLE TRAILS IN THE UPPER SOUTH PLATTE RIVER WATERSHED, COLORADO

Sediment is a principal cause of impairment to surface water quality. Erosion is a particularly important environmental issue in the Upper South Platte River (USPR) watershed of Colorado because it is the primary source of drinking water for Denver, has a high-value fishery, and several stream reaches are impaired by high levels of sediment. Unpaved roads are often considered a dominant source of sediment in forested watersheds, and off-highway vehicle (OHV) trails are another potentially important but largely unquantified sediment source. The objectives of this study were to: (1) quantify sediment production and delivery from forest road and OHV trail segments in the USPR watershed; (2) test the accuracy of WEPP:Road, SEDMODL2, and two empirical models for predicting sediment production from roads and OHV trails; and (3) compare sediment production, sediment delivery, and sediment yields from forest roads and OHV trails.

Rainfall, site characteristics, and sediment production were measured on 14-22 native surface road segments from 2001 to 2006, and these data were used to test the accuracy of WEPP:Road and SEDMODL2. Empirical models for predicting storm-based and annual sediment production were developed from the first four years of data; the last two years of data were used for model testing. Similar measurements on 5-10 OHV trail segments from 2005 to 2006 were used to test WEPP:Road and SEDMODL2. Sediment delivery was assessed by detailed surveys along 17 km of roads and 10 km of OHV trails.

In 2006 mean sediment production from the 10 OHV trail segments was 18.5 kg m^{-2} yr^{-1}, or six times the mean value from the 21 road segments. The percentage of OHV trails connected to streams was 24%, or 70% higher than for roads, largely because more OHV trails were in the valley bottoms. None of the models accurately predicted sediment production from roads or OHV trails, but the performance of SEDMODL2 was greatly improved by calibrating the geology and traffic factors to the study area. SEDMODL2 also could be improved by adjusting the slope factor, better accounting for rill density on native surface roads, and making the rainfall factor dependent on rainfall erosivity rather than rainfall depth. WEPP:Road could be improved by making sediment production decrease rather than increase with higher soil rock content, and increasing the effect of a categorical change from no traffic to low traffic.

Road density in the study area is 0.6 km km^{-2}, or three times the density of OHV trails. Multiplying unit area sediment production normalized by summer erosivity times the density, mean active width, and percent connectivity indicates that roads and OHV trails are respectively delivering approximately 1.1 Mg km^{-2} and 0.8 Mg km^{-2} of sediment to the stream network per year. Sediment delivery to streams can be reduced by locating roads and OHV trails out of valley bottoms and off steep hillslopes, decreasing segment lengths, and reducing segment slopes.

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1. INTRODUCTION

Excessive sediment is one of the leading causes of impairment to surface water quality in both the United States and the State of Colorado (EPA, 2008). The associated high levels of turbidity and suspended sediment concentrations can adversely impact aquatic resources (Cederholm et al., 1981; Suttle et al., 2004) as well as complicate water treatment for domestic use. Erosion is a particularly important environmental issue in the Upper South Platte River (USPR) watershed of Colorado because it is the primary source of drinking water for Denver, has a high-value fishery, and several stream reaches are impaired by high levels of sediment (CDPHE, 2006; CDPHE, 2008).

Most of the USPR watershed is forested (USDA, 2000), but undisturbed forests in Colorado typically generate little sediment because infiltration rates are high and overland flow is rare (Troendle, 1987; MacDonald and Stednick, 2003; Libohova, 2004; Brown, 2008). This means that the elevated sediment loads are almost always a result of soil disturbance (MacDonald and Stednick, 2003). The USPR watershed has a long history of mining, timber harvesting and grazing, and it is now intensively used for recreation and development (USDA, 2000; USDA, 2005). Since 1996 there have been a series of high-severity wildfires and forest thinning projects to reduce wildfire risk (USDA, 2000; Libohova, 2004; Rough, 2007; Brown, 2008). All of these disturbances have the potential to increase sediment production and watershed-scale sediment yields (MacDonald and Stednick, 2003), and data are needed to quantify the different sediment sources.

Previous research in the USPR watershed has quantified sediment production from wildfires (Libohova, 2004; Pietraszek, 2006; Rough, 2007), forest thinning (Libohova, 2004; Brown, 2008), and forest roads (Libohova, 2004; Brown, 2008). The results indicate that wildfires and forest roads are dominant sediment sources, while forest thinning does not increase sediment production relative to undisturbed areas (Libohova, 2004; Pietraszek, 2006; Rough, 2007; Brown, 2008). Wildfires are a large and intermittent sediment source (Pietraszek, 2006; Rough, 2007), while forest roads deliver sediment to streams annually (Libohova, 2004; Brown, 2008). The chronic nature of sediment inputs from roads means that road rehabilitation treatments may be able to more consistently improve water quality than treatments to prevent wildfires.

A relatively small proportion of the road length in forested watersheds is typically responsible for the road-related increase in sediment loads (e.g., Reid and Dunne, 1984; Wemple et al., 1996; Croke and Mockler, 2001; Coe, 2006; Brown, 2008). This indicates that the adverse effects of forest roads on water quality and stream habitat can be most efficiently reduced by identifying and treating those road segments that are generating and delivering the largest amounts of sediment. In most cases the large number of forest roads precludes the collection of sediment production data and detailed surveys of each road segment. This means that resource managers must use models to estimate road sediment production, and these include: (1) physically-based models, such as the Water Erosion Prediction Project (WEPP) model (Elliot, 2004); (2) models with both conceptual and empirical components, such as Sediment Model Version 2.0 (SEDMODL2) (BCC and NCASI, 2003); and (3) empirical models developed from local data (e.g., Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005; Coe, 2006; Sugden and Woods, 2007; Brown, 2008). The problem is that there have been limited efforts to test the accuracy of these models against field data and to use the results for model improvement.

Given the need for accurate predictions of road sediment production and the lack of model testing, the first goal of this study was to test the performance of WEPP:Road, SEDMODL2, and two local empirical models (Chapter 2). The dataset consisted of sediment production, site characteristics, and rainfall from 14-22 native surface road segments in the USPR watershed from 2001 to 2006. This entire dataset was used to test the accuracy of WEPP:Road and SEDMODL2. The first four years of data were used to develop empirical models for predicting storm-based and annual sediment production (Brown, 2008), and the last two years of data were used for model testing. Sensitivity analyses and detailed analyses of the field data were used to identify potential model improvements.

The large network of OHV trails is another unquantified and potentially important sediment source in the USPR watershed (USDA, 2000; USDA, 2005). Sediment production rates from OHV trails have been hypothesized to be similar to forest roads (Elliot et al., 1999), as both forest roads and OHV trails decrease infiltration rates and increase surface runoff (MacDonald et al., 2001; Sack and da Luz, 2003; Foltz, 2006; Ramos-Scharrón and MacDonald, 2007), decrease surface cover (Leung and Marion, 1996; Libohova, 2004; Brown, 2008), and greatly increase sediment production rates relative to undisturbed areas (Willshire et al., 1978; Griggs and Walsh, 1981; Sack and da Luz, 2003; Libohova, 2004; Brown, 2008). However, it is unknown whether the relative lack of design standards for OHV trails at the time of their construction and the difference in the amount and type of use will increase sediment production rates from

OHV trails relative to roads. Accordingly, the second main goal of this study was to quantify sediment production from OHV trail segments in the USPR watershed. To this end sediment production, site characteristic, and rainfall data were collected from 5-10 OHV trail segments in 2005 and 2006, and these results are presented in Chapter 3. These data also were used to test the accuracy of WEPP:Road and SEDMODL2 for predicting annual sediment production from OHV trail segments.

The amount of sediment that is delivered to streams from roads and OHV trails depends on their connectivity with the channel network. Sediment from these sources can be delivered to streams at stream crossings, or when an outlet rill or sediment plume extends to a stream channel. Detailed surveys along 17 km of roads in the USPR watershed indicated that sediment delivery is related to the hillslope position of the road, road segment slope, and road segment length (Libohova, 2004; Brown, 2008). Since there is a paucity of data on the connectivity between OHV trails and streams, the third goal of this study was to evaluate sediment delivery by conducting detailed surveys along 10 km of OHV trails in the USPR watershed (Chapter 3).

The results presented here provide a critical assessment on predicting road sediment production and crucial data on sediment production and delivery from OHV trails. The suggested changes to WEPP:Road and SEDMODL2 should greatly improve the accuracy of these models, particularly in the Colorado Front Range. The data from the OHV trails provide new insights into the importance of OHV trails and the underlying physical processes that control sediment production and delivery from this largely unstudied sediment source. The combination of data from roads and OHV trails provides a unique opportunity to compare their respective contributions to sediment production, sediment delivery, and sediment yields at the watershed scale. On a more practical level, the results and insights can help resource managers to assess the importance of roads and OHV trails for evaluating cumulative watershed effects and to prioritize rehabilitation treatments.

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2. PREDICTING SEDIMENT PRODUCTION FROM FOREST ROADS: AN EVALUATION OF WEPP:ROAD, SEDMODL2, AND EMPIRICAL MODELS

2.1. ABSTRACT

Unpaved roads are a large and chronic source of sediment in forested watersheds, and accurate predictions of road sediment production are needed to guide road treatments and assess cumulative watershed effects. WEPP:Road and SEDMODL2 are commonly used for predicting road sediment production, and the first objective of this study was to test the performance of these two models along with two empirical models. The dataset includes rainfall, site characteristic, and sediment production data from 14-22 native surface road segments in the Colorado Front Range from 2001 to 2006. The data from 2001-2004 were used to develop empirical models for predicting storm-based and annual road sediment production, and the data from 2005-2006 were used to validate these empirical models. The second objective was to compare the results of sensitivity analyses to the relationships observed from the field data. These comparisons were used to identify model shortcomings and potential model improvements.

For all four models the measured and predicted sediment production values were poorly correlated (R^2=0.28-0.42), and each model over-predicted low sediment production values and under-predicted high values. SEDMODL2 was the best predictor of road sediment production (R^2_{eff}=0.31), while WEPP:Road had the poorest performance (R^2_{eff}= -0.54). Both of the empirical models had surprisingly poor performance (R^2_{eff}=0.14-0.27); however, the annual empirical model was the most accurate predictor

of sediment production values greater than 1000 kg yr^{-1}, and was the most accurate model when tested against the 2005 and 2006 data.

Suggested improvements to WEPP:Road include: (1) a greater increase in predicted sediment production with increasing precipitation; (2) decreasing rather than increasing predicted sediment production with higher soil rock content; (3) expanding the range of soil texture classes; and (4) having a greater increase in sediment production as traffic increases from none to low. SEDMODL2 could be improved by: (1) linearly increasing sediment production with segment slope instead of an exponential increase; (2) doubling the maximum geology factor; (3) expanding the range of road surface factors to account for rill density; and (4) replacing annual rainfall with summer erosivity. The results of this study show that SEDMODL2 and possibly the annual empirical model are the best models for predicting road sediment production in the Colorado Front Range. Future data collection efforts should focus on calibrating SEDMODL2 to the study area and conducting additional testing of the annual empirical model.

2.2. INTRODUCTION

Sediment is a leading cause of surface water quality impairment in both the United States and the State of Colorado (CDPHE, 2006; CDPHE, 2008; EPA, 2008). High sediment loads also are a primary cause of impaired aquatic habitat (Eaglin and Hubert, 1993; Forman and Alexander, 1998; Trombulak and Frissell, 1999). In the western United States forested areas are the dominant source of water supply and also provide the majority of aquatic habitat (Dissmeyer, 2000). Hence it is critical to identify the largest sources of sediment in order to improve water quality and aquatic habitat.

Most undisturbed forested watersheds generate little sediment because infiltration rates are high and overland flows are rare (Troendle, 1987; MacDonald and Stednick, 2003; Libohova, 2004; Brown, 2008). Management activities that can increase sediment yields include timber harvest, grazing, unpaved roads, and recreational trails (Heede, 1986; Lopes et al., 1999; MacDonald and Stednick, 2003). The increasing regulation of timber harvest activities means that unpaved roads are often the dominant sediment source in forested watersheds (e.g., Reid and Dunne, 1984; Luce and Black, 1999; Luce and Wemple, 2001; MacDonald and Stednick, 2003; MacDonald et al., 2004).

Sediment from forest roads can be generated by: surface erosion on the road surface, fillslopes, ditches, and cutslopes; mass movements induced by roads; and gullies created by road runoff. Within the study area the dominant sediment source is surface erosion from the road travelway, as cutslope and fillslope erosion are negligible and mass movements are very rare (Libohova, 2004; Brown 2008). The predominance of road surface erosion suggests that roads are a chronic source of fine sediment in streams, and studies in other areas have shown that fine sediment can increase turbidity, alter channel substrate and morphology, reduce aquatic productivity, and limit the survival and growth of fishes (Cederholm et al., 1981; Bilby et al., 1989; Newcombe and MacDonald, 1991; Forman and Alexander, 1998; Trombulak and Frissell, 2000; Suttle et al., 2004).

Previous studies have shown that a small proportion of the roads in forested watersheds are responsible for the road-related increases in sediment loads (Reid and Dunne, 1984; Coe, 2006; Brown, 2008). This indicates that the adverse effects of forest roads on water quality and aquatic resources can be most efficiently reduced by identifying which road segments are generating and delivering large amounts of sediment. Since most forest managers are unable to measure road sediment production and delivery, models must be used to prioritize rehabilitation treatments.

The models for predicting road sediment production can be grouped into three classes: (1) physically-based models, such as the Water Erosion Prediction Project (WEPP) model (Elliot, 2004); (2) conceptual-empirical models, such as Sediment Model Version 2.0 (SEDMODL2) (BCC and NCASI, 2003); and (3) empirical models developed from local road erosion data (e.g., Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005; Coe, 2006; Sugden and Woods, 2007; Brown, 2008). A major problem is that there have been almost no efforts to test the accuracy of these models against field data, so the uncertainty and bias associated with predicted sediment production is unknown. Model testing also can be used to evaluate model structures and equations, and in this study comparisons of sensitivity analyses to field data are used to identify potential model improvements and areas where additional work is needed.

No previous assessments have compared the relative performance of physically-based, conceptual, and empirical models for predicting road sediment production. These types of evaluations are needed because physically-based models such as WEPP require the parameterization of over 400 variables (Flanagan and Nearing, 1995) and empirical models require a large dataset for development (e.g., Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005; Coe, 2006; Brown, 2008), while a conceptual model like SEDMODL2 has only a handful variables (BCC and NCASI, 2003). Hence comparing the relative performance of the three model classes would indicate whether there is a benefit to collecting large amounts of local data as opposed to collecting a limited amount of data to calibrate a conceptual model.

Given the need for accurate predictions of road sediment production and the lack of model testing, the first objective of this study was to test the accuracy of two commonly used road erosion models: (1) WEPP:Road (Elliot, 2004), which is a web-based interface that simplifies the use of the WEPP model (Flanagan and Nearing, 1995); and (2) SEDMODL2 (BCC and NCASI, 2003), which is a road erosion and delivery model developed for the Pacific Northwest. These two models were tested using six years of rainfall, site characteristic, and sediment production data from 14-22 native surface road segments in the central Colorado Front Range. In addition to testing these two models, the field data collected from 2001-2004 were used to develop empirical models for predicting storm-based and annual road sediment production, respectively; the data from 2005-2006 were used for validation. The second main objective of this study was to compare the results of sensitivity analyses to the relationships observed from the field data to identify possible model improvements and needs for future research.

2.3. MODEL DESCRIPTIONS AND FIELD DATA

2.3.1. WEPP:Road

The WEPP model was developed to estimate surface erosion from crop, range, and forested lands at the hillslope and small watershed scales (Flanagan and Nearing, 1995). WEPP uses a stochastically generated climate to predict runoff and sediment production. The stochastic climate file inputs are generated using monthly climate statistics from one of the more than 2,600 weather stations in the WEPP database (Elliot et al., 1999). The monthly climate statistics include the: number of wet days; mean, standard deviation, and skew coefficient of the amount of precipitation on a day with precipitation; probabilities of a wet day after a wet day and a wet day after a dry day; mean wind speed; and mean and standard deviation of maximum and minimum temperatures (Elliot et al., 1999). The historic monthly data from the selected weather station are used to calculate the daily precipitation depth, duration, and intensity for up to 200 years of stochastically simulated climate (Elliot et al., 1999).

Infiltration is simulated using a modified version of the Green and Ampt equation for transient rainfall (Chu, 1978). Overland flow occurs when the rainfall or snowmelt rate exceeds the infiltration rate and depression storage capacity is exceeded. The interrill detachment rate is a function of the soil interrill erodibility (K_i), rainfall or snowmelt intensity, interrill runoff rate, interrill particle size, and slope (Flanagan and Nearing, 1995). The soil detached from interrill areas is assumed to be delivered to rills, where it can be either deposited or transported depending on the rill geometry and transport capacity. Soil detachment within a rill occurs when the shear stress (τ) of rill flow exceeds the critical shear stress (τ_c). The amount of soil loss within the rill is a function of the excess shear stress (τ-τ_c) and the rill erodibility (K_r). Sediment production is calculated on a daily basis, and the daily values are summed to obtain an annual value for each year being simulated. WEPP calculates a mean annual sediment production rate for the number of years being simulated (Elliot, 2004).

Since WEPP is physically based it requires the parameterization of over 400 variables (Flanagan and Nearing, 1995). The lack of data to estimate parameters, difficulty of use, and complicated interpretation of outputs has limited the use of WEPP (Elliot et al., 1999; Elliot, 2004). To facilitate the use of WEPP, the U.S. Forest Service (USFS) has developed a series of web-based interfaces for different forest management scenarios. These web-based interfaces require only a limited number of inputs from the user, and these inputs are then used to parameterize all of the other variables needed to run the WEPP model (Elliot et al., 1999).

The WEPP:Road interface was designed to calculate sediment production from the entire road prism as well as the mass of sediment transported through a forested buffer. Users only need to parameterize 13 variables, including the identification of a climate station, soil texture class and soil rock content, basic road characteristics, and buffer length and gradient (Table 2.1). Outputs include the mean annual precipitation (mm), runoff from rainfall (mm), runoff from snowmelt (mm), road prism sediment production (kg yr^{-1}), and sediment leaving the forested buffer (kg yr^{-1}) (Elliot at al., 1999).

Table 2.1. Input variables for WEPP:Road and their units or categories.

Input	Units or categories
User-selected climate from the WEPP database	Monthly precipitation (mm); number of wet days by month.
Soil texture class	Clay loam; silt loam; loam; sandy loam.
Soil rock content	Percent
Road design	Insloped, bare ditch; insloped, vegetated or rocked ditch; outsloped, unrutted; outsloped, rutted.
Road length	Meters
Road width	Meters
Road gradient	Percent
Road surface type	Native; graveled; paved.
Traffic class	High; low; none.
Fillslope gradient	Percent
Fillslope length	Meters
Buffer gradient	Percent
Buffer length	Meters

Four road designs are available in WEPP:Road (Table 2.1). The insloped, bare ditch design refers to road segments where all surface runoff is diverted to an inside ditch that is regularly bladed (Elliot et al., 1999). An inside ditch is considered vegetated if it is completely covered with vegetation or rocks greater than 10 mm in diameter (Elliot et al., 1999). Outsloped and unrutted road segments are where the surface runoff is diverted laterally off the road surface before becoming concentrated. Outsloped roads often become rutted as a result of vehicle traffic, which results in concentrated runoff down the wheel tracks (Elliot et al., 1999) and a corresponding change in the road design class (Table 2.1).

The road surface can be native, graveled, or paved. A graveled surface increases the soil rock content and the hydraulic conductivity of the soil (Elliot et al, 1999). The reduction in rainsplash and overland flow erosion associated with graveling can reduce sediment production by up to an order of magnitude (Coe, 2006). A paved surface reduces the sediment production from the road surface, but increases the amount of runoff (Elliot et al., 1999). The increase in runoff can increase sediment production from the ditch and fillslope as well as increase the downslope travel distance and sediment delivery (Elliot et al., 1999).

The three traffic classes are high, low, or none (Table 2.1). The low traffic class applies to roads with light administrative or recreational traffic, while roads with restricted access and vegetation covering more than 50% of the surface are classified as having no traffic (Elliot et al., 1999). Traffic is a categorical variable in WEPP:Road because traffic increases the supply of easily erodible sediment (Reid and Dunne, 1984; MacDonald et al., 2001; Ziegler et al., 2001; Coe, 2006), reduces vegetative cover (Swift, 1984), and promotes the formation of ruts that concentrate flow (Foltz and Burroughs, 1990).

2.3.2. SEDMODL2

SEDMODL2 is a conceptual-empirical model for predicting sediment production and delivery from road segments (BCC and NCASI, 2003). The model is intended to be coupled with geographic information systems (GIS) to facilitate the rapid evaluation of sediment yields under different management scenarios (BCC and NCASI, 2003). The model uses one equation to calculate the annual sediment production from the road surface, and a second equation to calculate the sediment production from the cutslope (BCC and NCASI, 2003). These governing equations are based on studies in Idaho, Oregon, Washington, North Carolina, and West Virginia as well as the surface erosion module in the Washington Department of Natural Resources Standard Method for Conducting Watershed Analyses (WDNR, 1997) and the soil erosion model in WEPP (BCC and NCASI, 2003). SEDMODL2 also calculates the background sediment production rates from forested areas, and this allows resource managers to evaluate the relative effect of roads on watershed-scale sediment yields.

Sediment production from the road segment surface is calculated by:

$$SP_R = G*RS*T*A*SS*R \tag{2.1}$$

where SP_R is road surface sediment production in U.S. tons per year; G is the geology factor, which ranges from one to five depending on the parent material and degree of weathering; RS is the road surface factor, which ranges from 0.03 for paved roads to 2.0 for native surface roads with ruts; T is the traffic factor, which ranges from 0.1 to 120, depending on the average number of log truck and passenger vehicle passes per day as well as the road width; A is the road segment area in acres; and SS is the segment slope factor (BCC and NCASI, 2003). The segment slope factor is calculated by:

$$SS = (S/7.5)^2 \tag{2.2}$$

where S is the slope of the road segment in percent. The rainfall factor (R) in equation 2.1 is calculated by:

$$R = 0.016(P)^{1.5} \tag{2.3}$$

where P is the annual rainfall in inches. If the mean annual rainfall is not provided by the user, SEDMODL2 uses the mean annual rainfall from the PRISM dataset (PRISM, 2007).

Sediment production from the cutslope is calculated by:

$$SP_C = G*C_C*C_H*L*R \tag{2.4}$$

where SP_C is cutslope sediment production in U.S. tons per year; G is the geology factor as defined previously; C_C is the cutslope cover factor, which ranges from 0.1023 for 100% cover to 1.0 for 0% cover; C_H is the cutslope height in feet, which is estimated from the hillslope gradient unless measured data are substituted by the user; L is the road segment length in feet; and R is the rainfall factor as defined by equation 2.3.

The proportion of sediment that is delivered to streams is calculated by:

$$SP_T = (SP_R + SP_C)*D*RA \tag{2.5}$$

where SP_T is the total mass of sediment delivery in U.S. tons per year; SP_R is road surface sediment production; SP_C is cutslope sediment production; D is a categorical delivery factor; and RA is the road age factor. The value for D is determined by the distance between the road segment and the nearest stream (Table 2.2). The categorical road age factor ranges from 1.0 for roads more than two years old to 10.0 for roads less than one year old (BCC and NCASI, 2003). Parameter values for the other categorical variables are obtained from the technical documentation (BCC and NCASI, 2003).

Table 2.2. Delivery factor values in SEDMODL2.

Distance from the road segment to the nearest stream (m)	Delivery factor (*D*)
0	1.0
0.1 - 30	0.35
30 - 60	0.10
> 60	0.0

2.3.3. Field Data and Empirical Models

2.3.3.1. Study Area

Sediment production and site characteristics were measured for 14-22 road segments along five native surface roads in the Pike-San Isabel National Forest in the Upper South Platte River (USPR) watershed in the central Colorado Front Range (Figure 2.1). Elevations range from 1,990 m at Trumbull to 2,400 m at Upper Saloon Gulch, and hillslope gradients range from 5% to 80% (USDA, 2000). Vegetation consists of dense, relatively homogenous stands of ponderosa pine (*Pinus ponderosa*) with some Douglas-fir (*Pseudotsuga menziesii*) at higher elevations on north-facing slopes (USDA, 2000). Annual precipitation increases with elevation, and is estimated to be only 360-410 mm yr^{-1} at Trumbull and 460-510 mm yr^{-1} at Kelsey, Nighthawk, Spring Creek, and Upper Saloon Gulch (Johnston, 2004).

Table 2.3. Number of road segments monitored from 2001 to 2006 by study site.

Study site	2001	2002	2003	2004	2005	2006	Totals
Kelsey	0	0	2	2	2	2	8
Nighthawk	0	0	2	2	2	2	8
Spring Creek	9	12	12	12	11	11	67
Trumbull	3	2	4	4	5	5	23
Upper Saloon Gulch	2	2	2	0	1	1	8
Totals	14	16	22	20	21	21	114

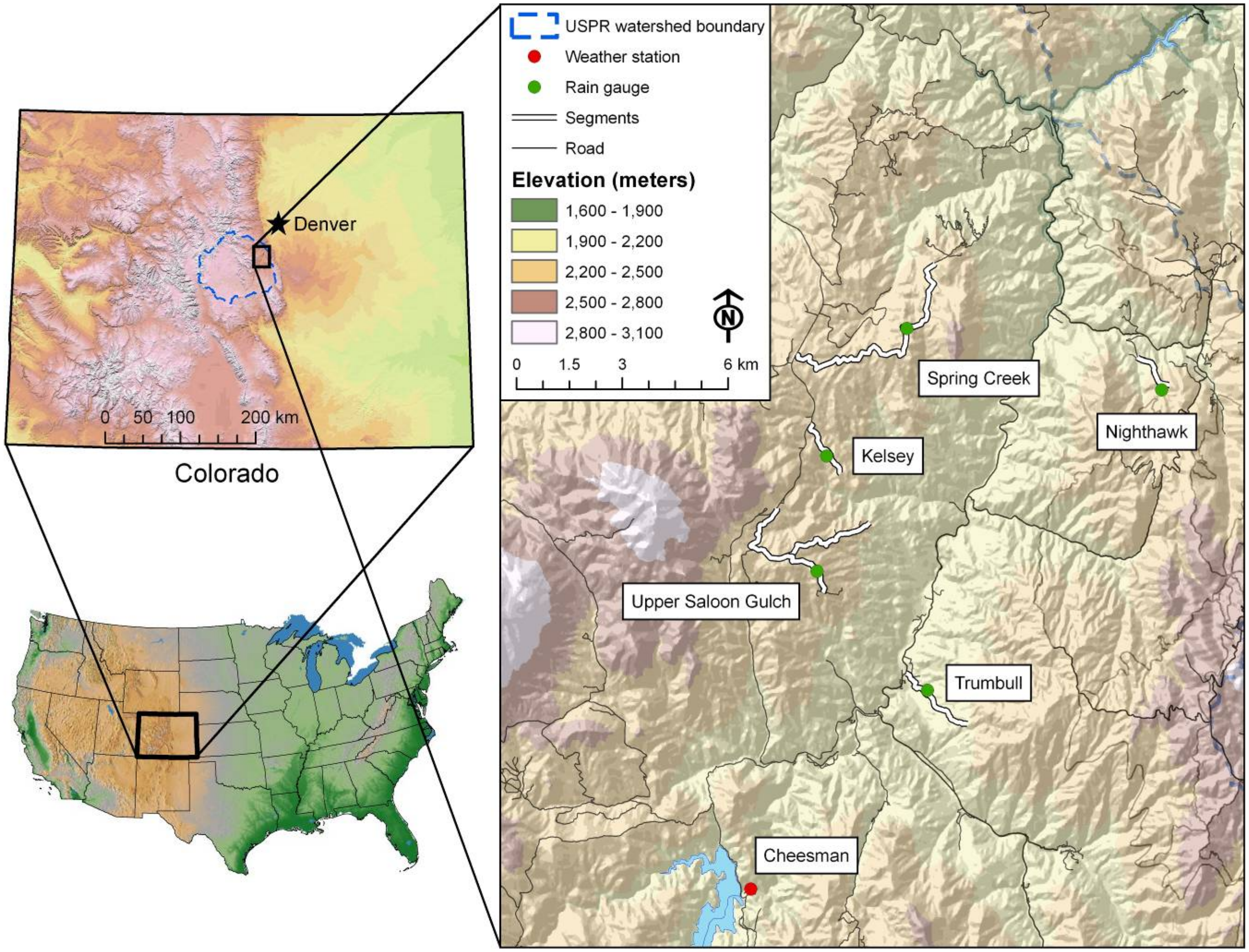

Figure 2.1. Map showing the USPR watershed, the roads with monitoring segments, and the long-term weather station at Cheesman Reservoir.

The nearest long-term weather station is at Cheesman Reservoir, which is 10 km southwest of the Trumbull study site at 2,090 m (Figure 2.1). The mean winter temperature from 1948 to 2007 is -2.1°C, and the mean summer temperature is 17.2ºC (WRCC, 2008). The historic mean annual precipitation is 413 mm with about 30% falling as snow (WRCC, 2008). The mean summer precipitation (defined as 1 May to 31 October) is 280 mm (WRCC, 2008), and convective rainstorms over this period generate more than 90% of the annual erosivity (Renard et al., 1997).

The soils are derived from Pikes Peak granite, and they are gravelly to very gravelly coarse sandy loams with no apparent horizons (USDA, 1992). The soils are characterized as having a severe potential for erosion, but infiltration-excess overland flow is rare in undisturbed areas (USDA, 1992; Libohova, 2004; Brown, 2008). In four of the study sites (Kelsey, Nighthawk, Spring Creek, and Upper Saloon Gulch) the soils are in the Sphinx series, while the soils in the Trumbull study site are in the Kassler series (USDA, 1992; Johnston, 2004). The Kassler series forms a more dissected topography than the Sphinx series because the Kassler soils are more susceptible to sheet and gully erosion (USDA, 1992).

2.3.3.2. Monitoring Segments

From July 2001 to October 2006 one or more sediment fences (USDA, 2001; Robichaud and Brown, 2002; Libohova, 2004) were used to measure the sediment production from 14-22 road segments (Table 2.3; Figure 2.2). To the extent possible, the road segments were selected to represent a range of lengths, slopes and contributing areas, as first principles and other studies suggest that these factors are important controls

Figure 2.2. Photograph of a road segment that was monitored at Spring Creek from 2001 to 2006.

on road runoff and sediment production (e.g., Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005; Coe, 2006; Sugden and Woods, 2007). The road segments selected for monitoring also had to have a well defined contributing area and a clearly defined outlet suitable for installing a sediment fence (Figure 2.2).

The sediment captured in each sediment fence was manually removed as soon as possible after each storm event by shoveling it into 20-L buckets. The buckets were weighed to the nearest 0.1 kg with an electronic scale, and the sediment was then piled and thoroughly mixed after weighing. A 0.5 to 1.0 kg sample was taken from the mixed pile, double-bagged in airtight plastic bags, and approximately one-half of this sample was analyzed for percent moisture following Gardner (1986). The percent moisture was used to correct the field-measured wet weights to a dry mass.

The contributing area of each segment was defined as the active area, which was the portion of the road with evidence of regular traffic such as a compacted surface and a lack of vegetation. The contributing area was limited to the active area because there is little to no surface erosion from the areas of the road surface without traffic and the adjacent undisturbed hillslopes (Libohova, 2004; Brown, 2008). At the start of each field season a cloth tape was used to measure the active width at approximately 10 systematically-spaced transects. Each width was multiplied by its associated length, and the sum of these values yielded the active area for each road segment. The total slope of each road segment was measured with a clinometer. Surface cover was measured at the start of each field season along the active width transects. Surface cover was classified at a minimum of 10 points per transect to yield at least 100 sample points per segment. At each point the surface cover was classified as bare soil, rock (intermediate axis larger than 1.0 cm), litter, live vegetation, or wood (diameter larger than 2.5 cm).

Soil samples from a depth of 0-2 cm were collected in 2002 and 2007 from the active road surface. In 2002 ten 5-cm diameter cores were taken from the upper, middle, and lower section of each road segment, respectively (Libohova, 2004). Each set of ten cores was aggregated, and the particle-size distributions of the three samples from each segment were analyzed by dry sieving to 0.125 mm and then using a hydrometer (Gee and Bauder 1986; Libohova, 2004). In 2007 the active road surface was sampled by collecting fifteen 100 cm^2 square samples. These samples were systematically-spaced following a 45° zigzag pattern superimposed on the road segment. The 15 samples from each segment were aggregated and dry sieved to 8 mm. The mass of particles finer than 8 mm was split with a rifle splitter until there was a pair of subsamples weighing approximately 300 g. One 300 g sample was randomly selected and analyzed by dry sieving to 0.063 mm. The fraction finer than 0.063 mm was not analyzed, as only 7% of the mass from the 2002 samples was smaller than 0.063 mm (Libohova, 2004).

Rill lengths, widths, and depths were measured on each road segment in October 2006. Rills were defined as erosion features at least 5.0 m long and 2.0 cm deep. The total length of rills was divided by the contributing area to yield a rill density in m m^{-2}. The width and maximum depth of each rill was measured at approximately five systematically-spaced locations along the length of each rill, and the cross-sectional area was calculated by assuming a triangular shape (equation 2.6):

$$RCA = (TW*MD)/2 \tag{2.6}$$

where RCA is the rill cross-sectional area in cm^2, TW is the top width in cm, and MD is the maximum depth in cm. The length associated with each cross-sectional area was determined by the midpoints between measurements, and the sum of each cross-sectional area times its corresponding length yielded the volume of material eroded by each rill.

The traffic along each road was measured with air-switch traffic counters (Diamond Traffic, 2007). From 2001 to 2004 the record of traffic data was intermittent because of vandalism and theft, but the record from 2005 and 2006 was complete. In 2005 and 2006 at least one traffic counter was maintained at each study site except Upper Saloon Gulch, where there was only one road segment being monitored (Table 2.3). The Spring Creek and Trumbull roads had one counter just after the locked gate at the entrance to the road and a second counter near the end of the road because these two roads accounted for nearly 80% of the road segments being monitored (Table 2.3). The traffic data were downloaded monthly from May to October and every 3-4 months from November to April. The mean daily traffic rate was calculated for each segment-year of data.

2.3.3.3. Precipitation

Precipitation was measured from 1 May to 31 October using tipping-bucket rain gauges with a resolution of 0.25 mm or 0.20 mm (Onset, 2001; Global Water, 2005). There was one gauge at each study site except in summer 2006 when five gauges were distributed along the Spring Creek road. Gaps in the rainfall data due to gauge malfunctions were filled with data from the nearest rain gauge (Appendix III). The data from each gauge were carefully screened, and any "bounce-back" or double tips were eliminated. Storms were defined as events with at least 1 mm of precipitation separated by periods of at least 60 minutes with no precipitation. The depth, maximum 30-minute intensity (I_{30}), and erosivity (EI_{30}) were calculated for each storm following Brown and Foster (1987) using the RF program (Petkovšek, 2005). Summer values were calculated by summing the values from 1 May to 31 October.

2.3.3.4. Empirical Models

The sediment production, rainfall, and site characteristic data from 2001 to 2004 were used to develop empirical models for predicting annual and storm-based sediment production, respectively (Brown, 2008). The annual model was developed using 72 data points and the storm-based model was developed using 250 data points (Brown, 2008). The two models were developed using stepwise multiple regression, and the final models were selected by the p-values of the independent variables and Mallows' Cp (SAS Institute, 2003; Brown, 2008).

The empirical model for annual road sediment production is:

$$\sqrt{m_a} = -29.8 + 1.4SL + 0.064AR + 0.13I_a \tag{2.7}$$

where m_a is annual sediment production in kg yr^{-1}, SL is the segment slope in percent, AR is the segment area in m^2, and I_a is the summer I_{30} in mm h^{-1}. This model had an R^2 of 0.70 and each variable was significant at $p<0.05$.

The empirical model for storm-based road sediment production is:

$$\sqrt{m_s} = -12.8 + 0.003AS + 0.12B + 0.41I_s \tag{2.8}$$

where m_s is storm-based sediment production in kg, AS is the product of the road segment area in m^2 and segment slope in percent, B is the percent bare surface cover on the road segment, and I_s is the storm I_{30} in mm h^{-1}. This model had an R^2 of 0.46 and again each variable was significant at $p<0.05$.

2.4. MODEL INPUTS AND STATISTICAL ANALYSES

2.4.1. WEPP:Road

The Cheesman weather station was selected to generate the stochastic climate data for WEPP:Road, but for May to October the measured values from the tipping-bucket rain gauges were substituted for the historic mean monthly rainfall and number of wet days. The Cheesman weather station is believed to accurately represent the climate at the study sites because of its proximity, similar elevation, and the similar values and trends observed between Cheesman and the study area from summer 2001 through summer 2006 (Libohova, 2004; Pietraszek, 2006; Rough, 2007; Brown, 2008). Since the sediment fences generally were installed in May or early June, the precipitation for the first year of monitoring at each study site was set to zero from January through the month prior to the installation of the sediment fence. The predicted sediment production for each segment for each year of measured data was calculated as the mean value from 50 years of simulations.

The average particle-size distribution for the road segments was 37% gravel, 56% sand, and only 7% silt and clay (Table 2.4). Hence the soil texture for each segment was classified as a sandy loam in WEPP:Road because this is the coarsest texture available. The soil rock contents determined from the 2002 sampling were used for the segments monitored in 2001 and 2002. For consistency, the soil rock contents from the 2007 sampling were used for the segments monitored from 2003 to 2006 because eight of the segments monitored over this period were not sampled in 2002 (Table 2.4). The design of each road segment was classified following the definitions in the technical documentation for WEPP:Road (Elliot et al., 1999) (Table 2.1). Field measurements were used to define the length, width, and gradient of each segment. Each segment had a native surface. A low traffic level was assigned to each segment in each year because the traffic data indicated that the five roads had light administrative use and the segments had less than 10% vegetative cover.

Table 2.4. Surface particle-size distributions for the road segments with sediment fences. The 2007 values are presented first and the 2002 values are in parentheses. NA indicates that the segments were no longer being monitored in 2007.

		Particle-size distribution (%)		
Study site	Segment no.	Gravel (> 2.00 mm)	Sand (0.063 - 2.00 mm)	Silt and clay (< 0.063 mm)
Spring Creek	2	43 (44)	54 (50)	3 (6)
	4	39 (42)	58 (53)	3 (5)
	5	43 (41)	52 (48)	5 (11)
	6	32 (38)	64 (55)	4 (8)
	7	30 (35)	65 (56)	5 (10)
	8	36 (28)	61 (63)	3 (9)
	9	33 (31)	62 (60)	5 (9)
	10	37 (47)	58 (45)	5 (9)
	11	40 (51)	54 (42)	6 (8)
	13	NA (46)	NA (45)	NA (9)
	14	30 (31)	66 (58)	4 (11)
	15	24 (21)	65 (63)	11 (16)
Trumbull	8	33 (46)	62 (49)	5 (5)
	E1	38	56	5
	E2	37	59	4
	E3	31	64	4
	E4	35	60	5
Upper Saloon Gulch	7	47 (45)	46 (45)	7 (10)
	11	NA (36)	NA (56)	NA (9)
Nighthawk	1	45	47	7
	2	47	45	7
Kelsey	1	32	64	4
	2	32	62	5
Mean (s.d.)		37 (6)	56 (7)	7 (2)

None of the road segments had fillslopes, so the fillslope lengths and fillslope gradients were set to the minimum allowable values of 0.3 m and 0.1%, respectively. Similarly, the buffer lengths and buffer gradients were set to the minimum allowable values of 0.3 m and 0.1%, respectively, because the 3 to 5 m between the drainage outlets and the sediment fences did not function as a buffer because this area was devoid of vegetation and too steep for much sediment deposition (Figure 2.2).

2.4.2. SEDMODL2

To the extent possible the factors in SEDMODL2 were parameterized for each segment-year of data using the field measurements. The geology factor was set to the maximum value of 5.0 for each road segment because the soils are all derived from weathered granite (BCC and NCASI, 2003). Road segments with rills were considered rutted and assigned the maximum road surface factor of 2.0, while the road segments without rills were assigned a road surface factor of 1.0 (BCC and NCASI, 2003). Road segments with an average of less than one vehicle per day were assigned a traffic factor of 1.0, while road segments that averaged one to five vehicles per day were assigned a traffic factor of 2.0 (BCC and NCASI, 2003). The traffic factors would have been varied by year according to the field data; however, none of the mean annual traffic rates for a given road segment varied outside of a single traffic factor class. The contributing area and the slope factor of each road segment were calculated from the field measurements. The rainfall factors were calculated using the measured rainfall from 1 May to 31 October, as less than 1% of annual road sediment production occurs from 1 November to 30 April (Libohova, 2004; Brown, 2008). The road age factor was 1.0 because all of the roads were more than two years old. The categorical delivery factor (*D*) was set to 1.0 because sediment production was measured at the outlet of each segment. The predicted sediment production was converted from U.S. tons to kilograms for comparison against the measured values and the other models.

2.4.3. Empirical Models

The input data for testing the empirical models consisted of the contributing area, segment slope, percent bare surface cover, and sediment production for each road segment as well as the rainfall at each tipping-bucket gauge for 2005 and 2006. These data were measured as previously described. The storm-based empirical model was tested against the sediment production values from each summer storm with an I_{30} greater than 2.5 mm h^{-1}. Sediment production values were excluded if they could not be associated with one storm (i.e., multiple storms occurred before the sediment could be removed). In order to compare the performance of the storm-based model to the other models, the predicted values for each storm were summed to yield annual totals for 2005 and 2006 that were then compared to the measured values for each segment.

2.4.4. Statistical Analysis

Several statistics were used to evaluate the accuracy of each model because no single statistic can fully characterize model performance (Willmott, 1981). The statistics compiled for each model were: (1) the slope (*b*), intercept (*a*), and R^2 of the least-squares linear regression between the measured and the predicted sediment production; (2) the Nash-Sutcliffe model efficiency coefficient (R^2_{eff}) (Nash and Sutcliffe, 1970); and (3) the root-mean-square error (RMSE) (Willmott, 1981). The measured and predicted sediment production data were plotted on a log-log scale because of the wide range of measured and predicted values, and a value of 0.01 kg was assigned to the road segments that did not generate any measurable sediment.

Sensitivity analyses were conducted to identify the variables in each model with the largest effect on sediment production. Continuous variables were evaluated by calculating a relative sensitivity coefficient, R_S:

$$R_S = (\Delta F_o/F_o)*(F_i/\Delta F_i) \qquad (2.9)$$

where F_o is the predicted sediment production for the baseline road segment, ΔF_o is the difference in predicted sediment production after altering the subject variable, F_i is the initial parameter value of the subject variable, and ΔF_i is the difference in the parameter value of the subject variable. Variables with higher R_S values have a greater effect on predicted sediment production (McCuen, 1973). The sensitivity of categorical variables was evaluated by the percent increase or decrease in sediment production for a categorical change in the parameter. When possible, the changes in predicted sediment production for the most influential variables were compared to the corresponding relationships observed from the field data (McCuen, 1973).

2.5. RESULTS

2.5.1. Monitoring Segments

The road segments represented a wide range of contributing areas and slopes (Table 2.5). The overall mean segment area was 233 m^2 and the range was from 75 m^2 to 527 m^2. The mean slope was 9.5% and segment values ranged from 4% to 18%. The average surface cover for the road segments was 84% bare soil, 13% litter and wood, 2% live vegetation, and only 1% rock (Table 2.5). Surface rills were present on all but two segments, and the overall mean rill density was 0.40 m m^{-2} (Table 2.5).

Sediment was produced from each of the monitoring segments (Table 2.5). Mean annual sediment production ranged from 0.48 to 7.05 kg m^{-2} yr^{-1} for individual segments, and the overall mean rate was 3.5 kg m^{-2} yr^{-1} (Table 2.5). Differences in sediment production between study sites and between years (Figure 2.3) were largely explained by differences in the amount and intensity of summer rainfall (Libohova, 2004; Brown, 2008). The differences in sediment production within each study site were best explained by differences in segment slopes and the amount of bare soil (Libohova, 2004; Brown, 2008).

Table 2.5. Mean site characteristics from 2001 to 2006 for the road segments at Spring Creek (SC), Trumbull (TRM), Upper Saloon Gulch (USG), Nighthawk (NH), and Kelsey (K). No rill densities are available for segments SC-13, TRM-7, TRM-9, and USG-11 because these were not monitored in 2005 or 2006.

Segment	Years of data	Area (m^2)	Slope (%)	Surface cover (%)				Rill density ($m\ m^{-2}$)	Mean sediment production ($kg\ m^{-2}\ yr^{-1}$)
				Bare soil	Rock	Litter and wood	Live veg.		
SC-2	6	212	10	84	0	15	1	0.53	4.66
SC-4	6	243	8	92	1	4	3	0.32	4.30
SC-5	6	206	8	91	0	7	2	0.43	2.34
SC-6	6	177	6	89	0	10	1	0.30	3.40
SC-7	6	237	9	92	1	5	2	0.49	4.54
SC-8	6	421	9	92	1	5	2	0.48	3.90
SC-9	6	380	6	87	0	12	2	0.53	2.64
SC-10	6	92	4	97	1	1	1	0.26	3.01
SC-11	6	75	6	93	1	4	2	0.00	0.48
SC-13	3	98	4	94	0	3	3	-	1.43
SC-14	5	279	11	89	0	10	1	0.79	5.74
SC-15	5	267	7	91	0	7	2	0.51	5.36
TRM-7	1	527	18	63	0	36	1	-	2.80
TRM-8	6	98	16	84	1	14	1	0.53	7.05
TRM-9	2	89	16	66	0	34	0	-	0.50
TRM-E1	4	136	16	86	2	10	2	0.57	5.14
TRM-E2	4	80	9	66	1	32	1	0.35	2.36
TRM-E3	4	108	16	86	1	12	1	0.50	6.33
TRM-E4	2	220	14	87	1	9	3	0.65	6.06
USG-7	5	224	8	85	0	13	2	0.32	1.49
USG-11	3	364	10	100	0	0	0	-	2.80
NH-1	4	428	15	56	1	39	4	0.36	4.32
NH-2	4	277	16	60	1	36	3	0.43	4.52
K-1	4	245	4	88	0	7	5	0.20	1.71
K-2	4	349	5	79	0	9	12	0.33	0.79
Mean	4.6	233	9.5	84	1	13	2	0.40	3.51

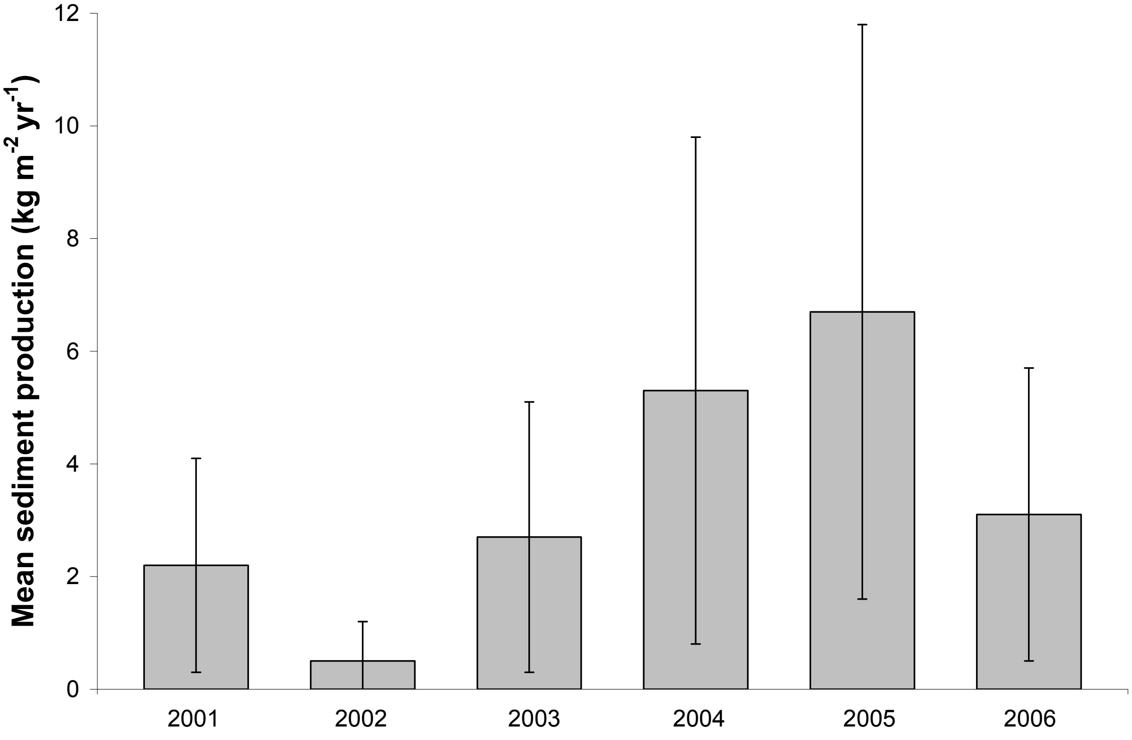

Figure 2.3. Mean annual road sediment production from 2001 to 2006. The error bars indicate one standard deviation.

2.5.2. Precipitation

Summer precipitation at Cheesman was substantially below the long-term mean of 280 mm in 2001, 2002, 2003, and 2005 (Figure 2.4), and above average in 2004 and 2006 (Figure 2.4). For each summer except 2006 the precipitation at the study sites was very comparable to the precipitation measured at Cheesman (Figure 2.4), and this indicates that the summer precipitation data from Cheesman are generally representative of the precipitation at the study sites.

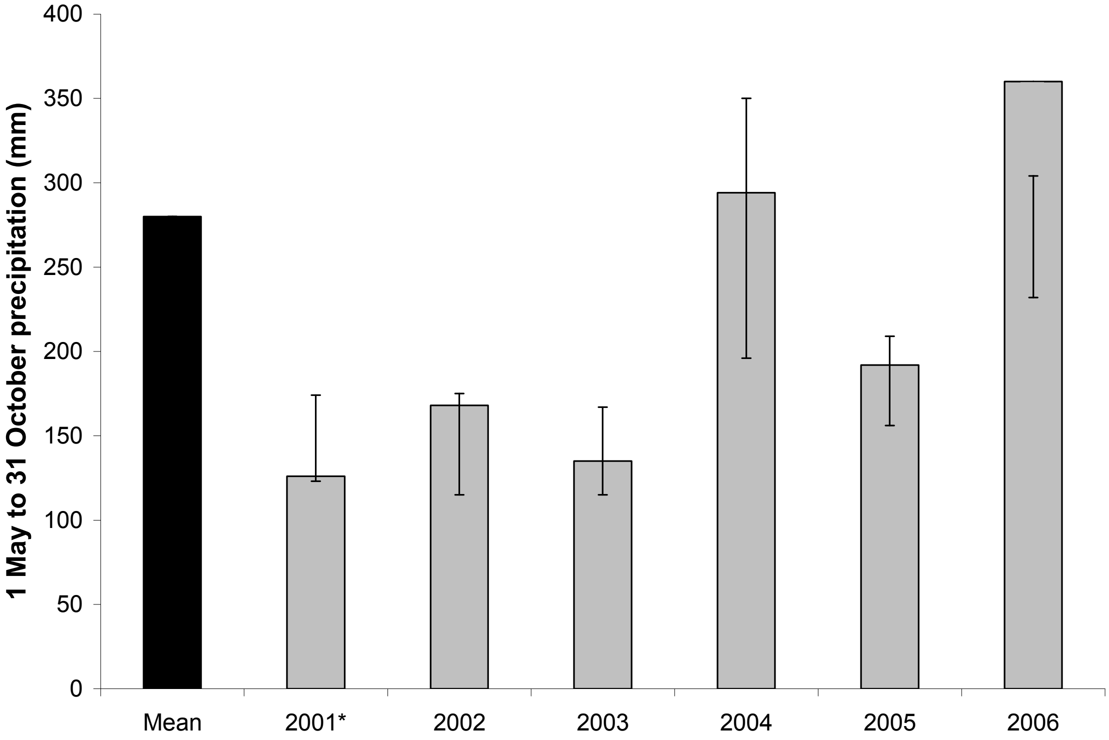

Figure 2.4. Long-term mean summer precipitation at Cheessman and summer precipitation at Cheesman from 2001 to 2006. The vertical lines within the grey bars show the range of summer precipitation from the tipping-bucket rain gauges at the different study sites. The asterisk indicates that the data for 2001 are only from 1 July to 31 October.

Nearly all of the summer rainfall results from localized, short-duration convective rainstorms (Libohova, 2004; Brown, 2008). Over the period of study the mean number of storms from 1 May to 31 October was 41, and the range was from 16 to 74. The mean storm depth was 4.8 mm. Eighty-five percent of the storm events had a maximum 30-minute intensity (I_{30}) of less than 10 mm h^{-1} and 96% had an I_{30} less than 20 mm h^{-1} (Figure 2.5). Only four storms had an I_{30} greater than 40 mm h^{-1}. The mean summer I_{30} from 2001 to 2004 was 181 mm h^{-1}, while the mean summer I_{30} was 218 mm h^{-1} in 2005 and 299 mm h^{-1} in 2006 (Table 2.6).

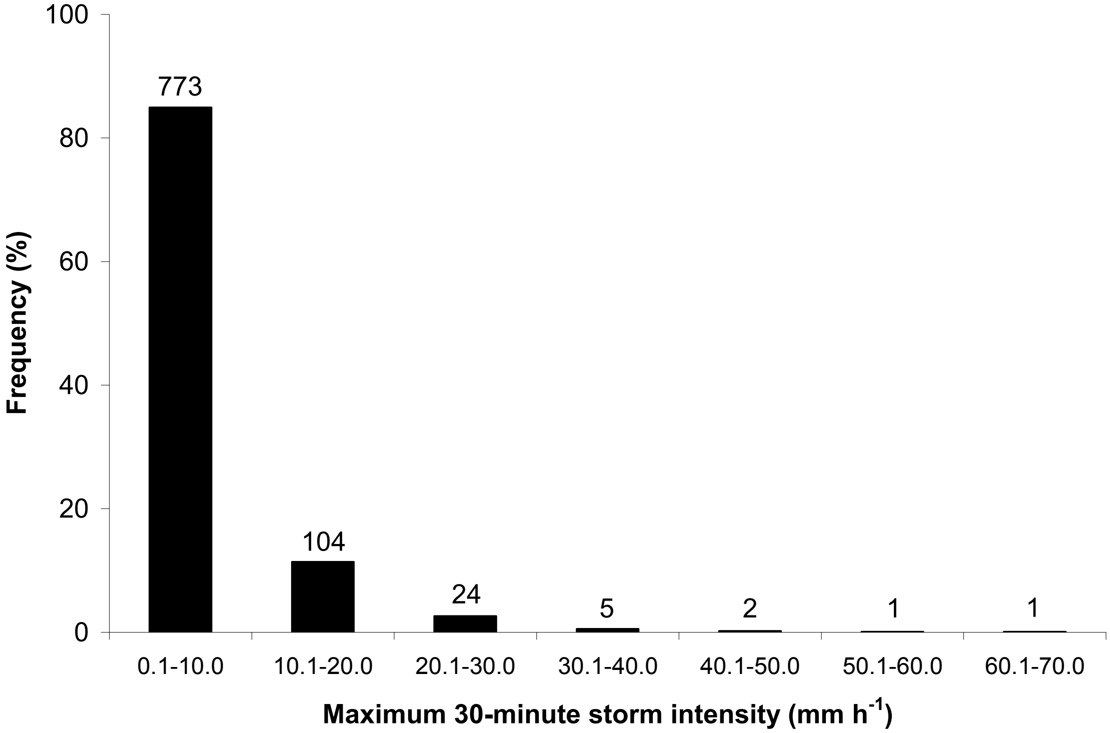

Figure 2.5. Frequency distribution of maximum storm I_{30} for 910 storms from 2001 to 2006. The values above each bar are the number of storms.

The most intense storm was 36 mm of rain at Nighthawk on 14 July 2004, and this had an I_{30} of 64 mm h^{-1} and an estimated recurrence interval of approximately 7 years (D.E. Hall, USFS, pers. comm., 2006). The maximum I_{30} for the same storm at the four other study sites ranged from 5 mm h^{-1} to 52 mm h^{-1}, indicating the high spatial variability of convective rainstorms in this area.

Table 2.6. Summer precipitation (P) in mm, sum of summer maximum 30-minute intensities (ΣI_{30}) in mm h^{-1}, and sum of summer erosivities (ΣEI_{30}) in MJ mm ha^{-1} h^{-1} for each study site from 2001 to 2006. No data are provided for the Kelsey and Nighthawk sites in 2001 and 2002 because these sites were only studied from 2003 to 2006.

Study site	Year	P	ΣI_{30}	ΣEI_{30}
Spring Creek	2001	108	151	506
	2002	158	111	116
	2003	169	193	318
	2004	300	326	652
	2005	199	240	381
	2006	232	216	151
Trumbull	2001	63	69	53
	2002	115	93	73
	2003	118	132	181
	2004	196	161	124
	2005	185	224	352
	2006	255	280	281
Upper Saloon Gulch	2001	57	65	58
	2002	175	199	204
	2003	155	177	253
	2004	350	414	622
	2005	156	226	191
	2006	258	475	902
Kelsey	2001	-	-	-
	2002	-	-	-
	2003	99	122	278
	2004	308	316	782
	2005	209	234	288
	2006	275	243	252
Nighthawk	2001	-	-	-
	2002	-	-	-
	2003	65	84	218
	2004	281	282	1075
	2005	204	168	210
	2006	304	279	335

2.5.3. WEPP:Road Performance

Predicted sediment production using WEPP:Road was poorly correlated with the measured values (R^2=0.28) (Figure 2.6; Table 2.7). The R^2_{eff} was -0.54, which indicates that the mean value better predicted road segment sediment production than the model. The slope (*b*) of the regression between the predicted and measured values was only 0.05 (Table 2.7) because WEPP:Road over-predicted the lowest sediment production rates and progressively under-predicted all of the sediment production rates larger than 60 kg yr^{-1} (Figure 2.6). The overall RMSE was 1147 kg yr^{-1}, or about 1.4 times the mean measured value of 808 kg yr^{-1}.

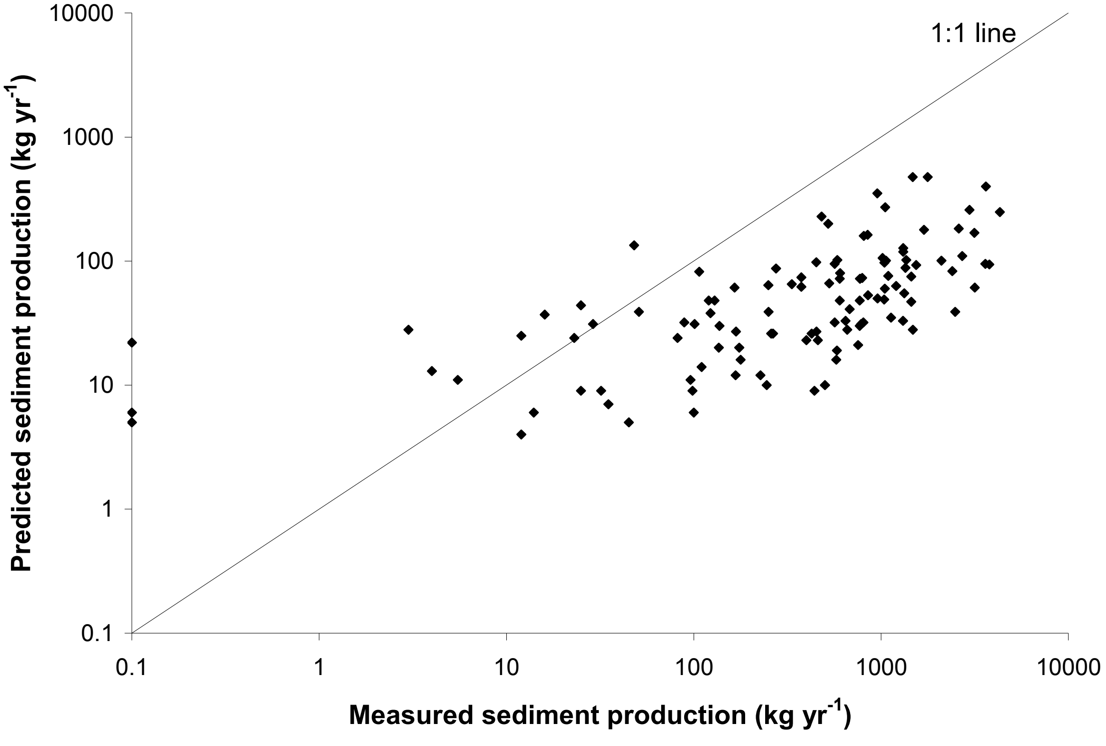

Figure 2.6. Predicted annual road segment sediment production using WEPP:Road versus the measured values (n=114).

Table 2.7. Summary statistics for the performance of WEPP:Road and SEDMODL2 from 2001 to 2006, the annual empirical model for 2005 and 2006, the storm-based empirical model for storms in 2005 and 2006, and the annual totals from the storm-based empirical model.

Statistic	WEPP:Road	SEDMODL2	Annual empirical	Storm-based empirical	Storm-based empirical, summed
R^2	0.28	0.42	0.20	0.32	0.25
R^2_{eff}	-0.54	0.31	0.14	0.27	-0.50
b (slope)	0.05	0.37	0.29	0.42	0.68
a (intercept) (kg yr^{-1})	33	216	499	47	405
RMSE (kg yr^{-1})	1147	765	734	95	854
n	114	114	42	573	42

2.5.4. SEDMODL2 Performance

SEDMODL2 more accurately predicted road segment sediment production than WEPP:Road, as the R^2 was 0.42 and the R^2_{eff} was 0.31 (Figure 2.7; Table 2.7). As with WEPP:Road, SEDMODL2 over-predicted lower sediment production values and under-predicted the higher values (Figure 2.7), but the magnitude of this trend was much less as indicated by the regression slope of 0.37 versus 0.05 for WEPP:Road. The overall RMSE was 765 kg yr^{-1}, or about 5% less than the mean measured value (Table 2.7).

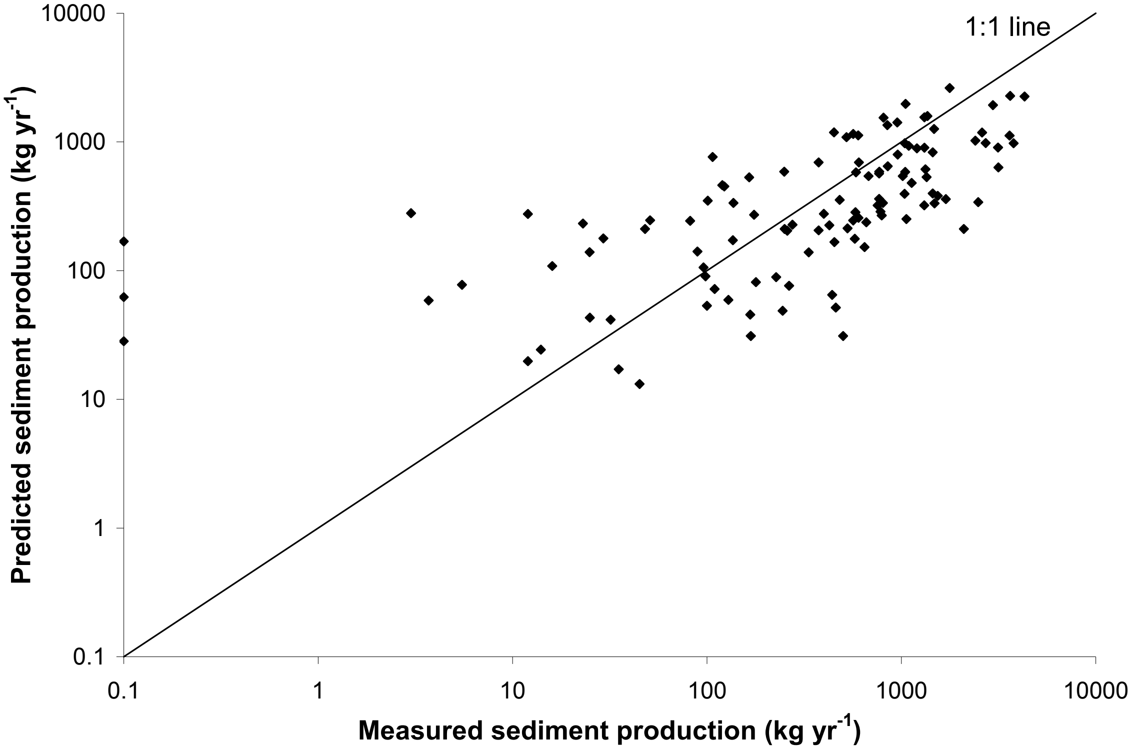

Figure 2.7. Predicted annual road segment sediment production using SEDMODL2 versus the measured values (n=114).

2.5.5. Empirical Model Performance

The performance of the empirical model for annual road sediment production fell between WEPP:Road and SEDMODL2. The R^2 was 0.20 and the R^2_{eff} was 0.14 (Table 2.7), indicating that the annual empirical model was only slightly better than simply using the mean value. The slope of the best-fit regression line was 0.29, and this also fell between the values of 0.05 for WEPP:Road and 0.37 for SEDMODL2 (Figure 2.8; Table 2.7). The RMSE for the annual empirical model of 734 kg yr^{-1} is very comparable to the RMSE of 765 kg yr^{-1} for SEDMODL2 (Table 2.7).

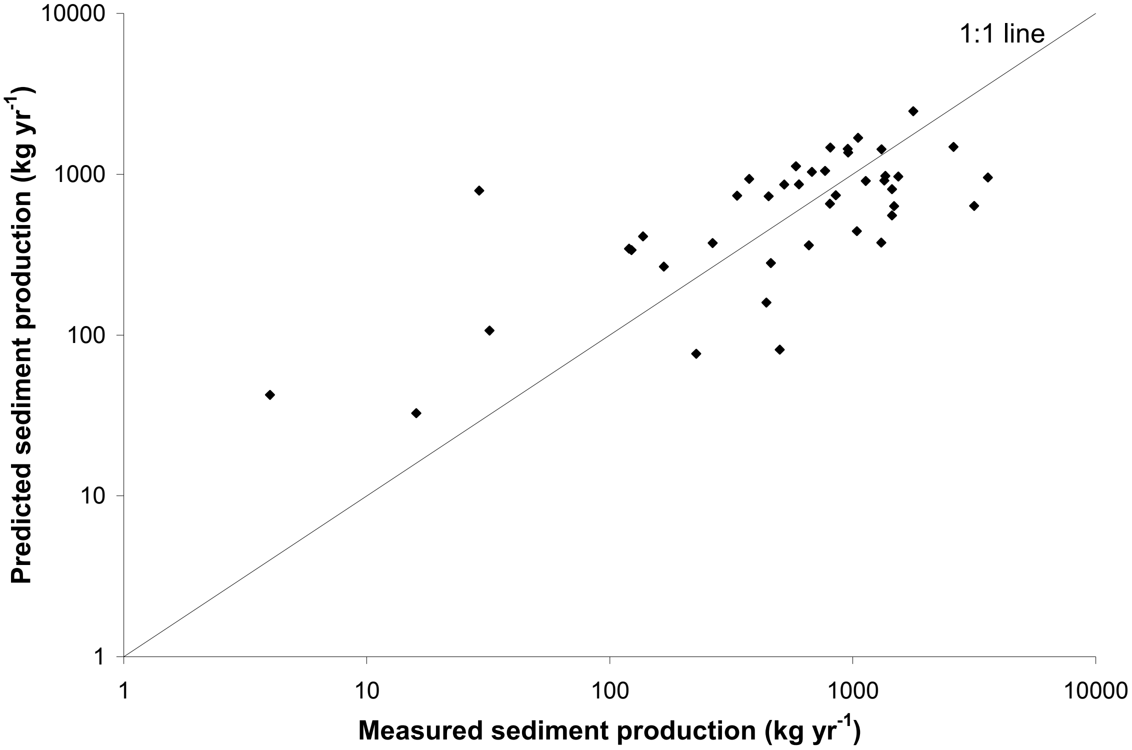

Figure 2.8. Predicted road segment sediment production using the annual empirical model versus the measured values from 2005 and 2006 (n=42).

The R^2_{eff} of 0.14 for the annual empirical model is surprisingly low given that the same road segments were used to develop and validate this model. To better compare the performance of the three models that predicted annual sediment production, both WEPP:Road and SEDMODL2 were tested against just the 2005 and 2006 data, and the corresponding R^2_{eff} values decreased to -0.98 and 0.00, respectively. The higher R^2_{eff} of the empirical model for these two years suggests that it may be the most accurate predictor of road sediment production.

There was considerable scatter between the predicted and measured storm-based sediment production values (Figure 2.9), but the R^2_{eff} of 0.27 (Table 2.7) indicates that this visually greater scatter is at least partly due to the larger sample size (n=573). The

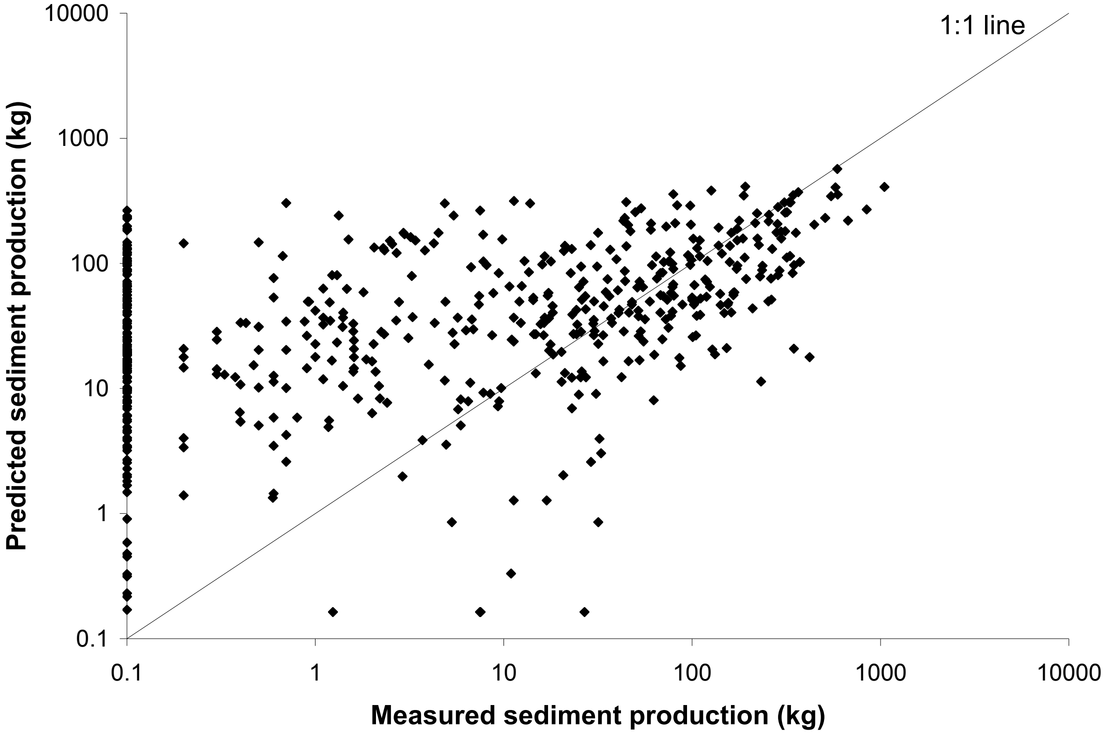

Figure 2.9. Predicted road segment sediment production using the storm-based empirical model versus the measured values from 2005 and 2006 (n=573).

slope of the regression between the predicted and measured values was 0.42, and this indicates a weaker tendency to over-predict the low values and under-predict the high values than either WEPP:Road or SEDMODL2 (Table 2.7). It is of interest that the storm-based empirical model predicted more than 10 kg of sediment for 78% of the 173 data points with no measured sediment production (Figure 2.7).

The storm-based empirical model was less successful in predicting annual sediment production, as the R^2_{eff} for the summed values for each road segment for each year dropped to -0.50 (Table 2.7; Figure 2.10). However, the regression slope of 0.68 was much higher than the regression slopes calculated for WEPP:Road and SEDMODL2

(Table 2.7). The overall RMSE of 854 kg yr^{-1} was 26% lower than the RMSE for WEPP:Road and 12% higher than the RMSE for SEDMODL2 (Table 2.7).

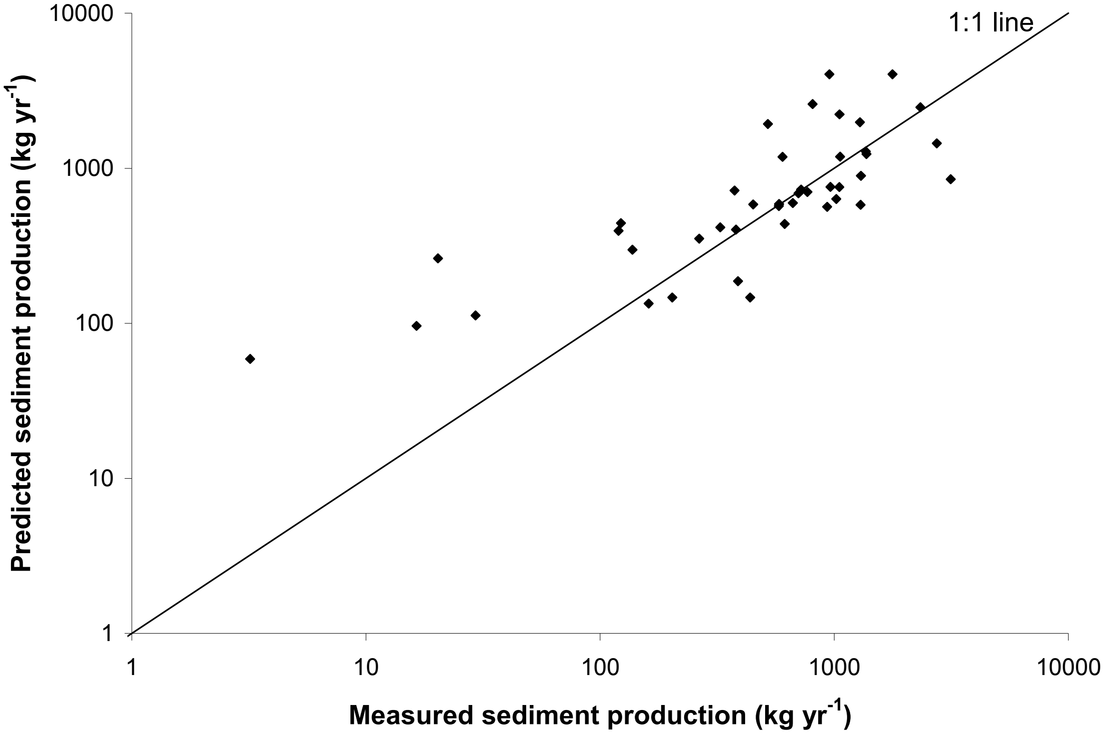

Figure 2.10. The sum of predicted storm-based values for each segment for each year versus the measured annual sediment production from 2005 and 2006 (n=42).

2.6. DISCUSSION

2.6.1. Sources of Error

Differences between the measured and predicted road sediment production values can result from model errors, errors in the input data, and errors in the measured sediment production ("output data") (Nearing et al., 1999). Model errors occur when the governing equations are inaccurate, or when a lumped parameter value does not represent the variability of a parameter within a plot or over time (Beven, 2000). Errors in the input and output data are caused by inaccurate measurements. The uncertainty of several key inputs and outputs were quantified as part of this study, and this allows some separation of model errors from measurement errors. The following section evaluates the potential measurement errors for key variables. The remaining discrepancy between the predicted and measured values can then be ascribed to model errors, and to the extent possible these are evaluated by comparing the results of the sensitivity analyses to the corresponding relationships from the field data.

2.6.2. Measurement Errors

In the present study the errors in most of the input variables can be assumed to be relatively small, as the road segment length, area, slope, surface cover, soil texture, traffic, and rill density were all measured in the field. The rainfall and sediment production measurements typically have the greatest amount of uncertainty (Nearing et al., 1999; Hastings et al., 2005). Comparable tipping-bucket rain gauges were maintained at each study site, and the rainfall data were carefully checked for identifiable errors such as double tips and missing data. Since nearly all road sediment production results from localized convective rainstorms, the greatest uncertainty with respect to precipitation is the extent to which the data from a tipping-bucket rain gauge can be extrapolated to the area being represented by that gauge.

Most of the road segments were within 1 km of a tipping-bucket rain gauge, but from 2001 to 2005 there was only one rain gauge along the 7 km Spring Creek road. This means that two segments at Spring Creek were about 2.5 km away from the nearest rain gauge, and on several occasions large amounts of sediment were produced from the road segments at one end of the Spring Creek road while no sediment was generated from the road segments at the other end of the road.

In 2006 five tipping-bucket rain gauges were maintained along the Spring Creek road. The minimum distance between two rain gauges was 0.7 km and the maximum distance was 4.1 km, and all of the segments being monitored were within 1 km of a rain gauge. There were 56 storms at Spring Creek in summer 2006, but the largest storm was only 18.4 mm and the highest I_{30} was only 13.6 mm h^{-1}. On a storm-by-storm basis the measured rainfall and I_{30} at the different gauges varied by up to a factor of two. Over the entire summer, however, the total rainfall and the sum of I_{30} tended to average out, as the coefficient of variation (CV) among the five gauges was only 18% for total summer rainfall and 9% for the sum of summer I_{30}.

The lower spatial variability for the summer totals might be expected to result in more accurate predictions of annual sediment production than the storm-based values. The problem is that over 50% of annual road sediment production can be generated by the largest storm events, and the high spatial variability in precipitation for these storms causes a correspondingly high spatial variability in the annual sediment production values. Hence the uncertainty in the storm-based precipitation values has a large effect on the accuracy of the predicted annual sediment yields along the Spring Creek road from 2001 to 2005.

The accuracy of the measured sediment yields is probably the second largest potential source of measurement error. There are two main sources of error associated with using sediment fences to measure sediment production: (1) the loss of suspended sediment in the water flowing through or over the geotextile sediment fence; and (2) the loss of sediment after the capacity of the fence is exceeded ("overtopping"). The size of sediment particles that can pass through the fence fabric is controlled by the tightness of the weave (Robichaud and Brown, 2002). On average the soils on the road segments had only 7% silt and clay particles (Table 2.4), and the prevalence of coarse particles greatly decreases the settling time and increases the catch efficiency of the sediment fence (Munson, 1989). Field observations indicate that very little water passes through the fence fabric, so the pass-through losses of suspended sediment are believed to be minor relative to the potential losses due to overflowing and overtopping.

Water typically flowed over the top of the sediment fences when there was more than 5 mm of precipitation. The sediment fences were constructed to direct the overflow over the center of the fence so that coarse sediment was not lost around the sides of the fence (Figure 2.11). In summer 2005 a sample of the overflow was collected from a road segment at Spring Creek during a 5.8 mm storm with an I_{30} of 10.2 mm h^{-1}. The lab analysis of this sample yielded a sediment concentration of 1860 mg L^{-1}, while 103 kg of sediment was captured by the sediment fence. Flow data are not available, but if one assumes a relatively high runoff coefficient of 67%, this 380 m^2 road segment would

Figure 2.11. Excess storm runoff flowing over each of three sediment fences below a road segment at Spring Creek.

have generated 1480 L of water. Multiplying this volume times the measured suspended sediment concentration of 1860 mg L^{-1} yields a net loss of only 3 kg of sediment.

Sediment production also can be underestimated as sediment accumulates in the fence because the settling time will be reduced. Once filled to capacity, any additional sediment will simply pass over the top of the fence. The storage capacities of the sediment fences installed in this project were typically 1.0 to 1.5 Mg. Over the course of the study the maximum sediment production from a single storm at any segment was 1465 kg, and in only nine cases did the storm-based sediment production exceed 1000 kg. At seven locations there was a second or even a third sediment fence installed when a road segment was expected to produce large amounts of sediment (Figure 2.11). Since the first sediment fence was never completely filled with sediment, overtopping was not a problem and the settling time was not severely reduced.

The efficiency of the sediment fences also was evaluated by comparing the sediment captured in successive sediment fences for 3 to 8 storm events ranging from 4.2 mm to 21.2 mm for the seven road segments with two or more sediment fences. On average, 93% of the total mass of sediment eroded from a road segment was trapped by the first fence (Figure 2.12). The minimum proportion of sediment in the first fence was 76%, and in 3 of 36 cases all of the sediment was captured in the first fence (Figure 2.12). These values are comparable to the 73-100% efficiencies reported for sediment fences on fallow agricultural plots (Robichaud and Brown, 2002). Surprisingly, the mean proportion of sediment in the first fence was 83% for storms that produced less than 100 kg of sediment and 90% for storms that generated more than 100 kg of sediment. This result is probably due to the tendency for the smaller storm events to only erode and transport the smaller particles, leading to a higher trap efficiency for the larger storm events that erode larger particles with a faster settling velocity (Munson, 1989).

These evaluations indicate that the largest error in the input and output data is the uncertainty in rainfall for the road segments that were furthest from the rain gauge at Spring Creek from 2001 to 2005. For WEPP:Road and SEDMODL2 this is less of an issue because they respectively use monthly and annual depth of precipitation, and the relative spatial variability for these values is much less than for individual storms. This indicates that the large differences between the measured sediment production and the values predicted with WEPP:Road and SEDMODL2 are primarily a result of model errors rather than measurement errors.

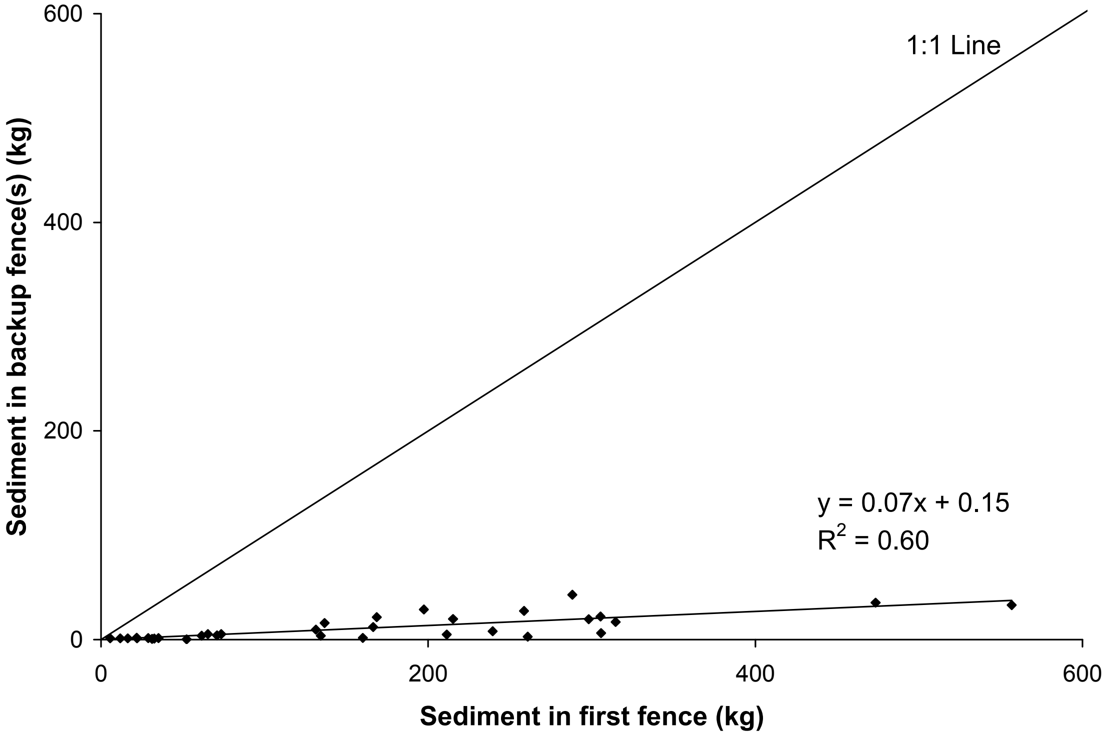

Figure 2.12. Mass of sediment trapped in the first sediment fence vs. the total mass of sediment trapped in one or two backup fences for 3 to 8 storms on 7 road segments (n=36).

Rainfall measurement errors are a more important issue for the annual and storm-based empirical models because summer I_{30} and storm I_{30} are inputs for each model, respectively. Although the two-fold variability of storm I_{30} at Spring Creek in 2006 decreased when the storm values were summed over the summer, the nonlinear relationship between storm I_{30} and sediment production means that the rainfall measurement errors for individual storms can still have a substantial effect on the accuracy of predicted annual sediment production.

2.6.3. Model Performance in Wet Years versus Dry Years

WEPP:Road and SEDMODL2 were poor predictors of sediment production on a year-by-year basis (Table 2.7), but prediction accuracy is more critical for wet years than dry years because most road erosion occurs during the wetter years (Libohova, 2004; Brown, 2008). For WEPP:Road there was little difference in the R^2_{eff} values for the two wet years (-0.67) and the four dry years (-0.57) (Table 2.8). As would be expected, the RMSE dropped from 1467 kg yr^{-1} in the wet years to 919 kg yr^{-1} in the dry years (Table 2.8). The performance of SEDMODL2 was generally better for the wet years than the dry years as indicated by the higher R^2_{eff} (0.37 for the wet years and 0.16 for the dry years) and better slope of the regression line (0.40 vs. 0.27) (Table 2.8). The better performance of SEDMODL2 in wetter years suggests that its performance should not degrade for longer datasets where the wetter years are more likely to account for a larger proportion of the long-term sediment yield.

Table 2.8. Statistics comparing the performance of WEPP:Road and SEDMODL2 for all years (2001-2006), wet years (2004 and 2006), and dry years (2001-2003, 2005).

	WEPP:Road			SEDMODL2		
Statistic	All years	Wet years	Dry years	All years	Wet years	Dry years
R^2	0.28	0.37	0.15	0.42	0.43	0.33
R^2_{eff}	-0.54	-0.67	-0.57	0.31	0.37	0.16
b (slope)	0.05	0.05	0.04	0.37	0.40	0.27
a (intercept) (kg yr^{-1})	33	37	35	216	348	193
RMSE (kg yr^{-1})	1147	1467	919	765	903	672
n	114	41	73	114	41	73

2.6.4. Sensitivity of WEPP:Road and Possible Improvements

A sensitivity analysis of WEPP:Road was conducted as a first step towards the evaluation of model errors. If the predicted effect of key variables on sediment production is inconsistent with the corresponding relationships derived from the field data, this suggests that one or more of the governing equations are incorrect. The baseline road segment for the sensitivity analysis of WEPP:Road was based on mean site characteristics of the road segments in this study: native surface, sandy loam soil texture with a soil rock content of 37%, 70.3 m long, 3.2 m wide, 9.5% gradient, outsloped design with ruts, and low traffic.

2.6.4.1. Rainfall

The sensitivity of WEPP:Road to annual precipitation was evaluated by increasing and decreasing the mean monthly precipitation at Cheesman by 100% at 25% intervals. The results show a nonlinear increase in predicted sediment production with increasing annual precipitation (Figure 2.13). For the baseline road segment doubling the mean annual precipitation at Cheesman more than doubled the predicted sediment production from 72 kg yr^{-1} to 153 kg yr^{-1} (Figure 2.13). Reducing the mean monthly precipitation values to 0 mm still resulted in a mean sediment production rate of 37 kg yr^{-1} (Figure 2.13) because the annual precipitation in the 50 years of simulated climate still ranged up to 375 mm. This result helps explain the decline in sensitivity as the mean annual precipitation decreases, as most of the sediment is still generated by the wetter years in the 50 years of simulated climate.

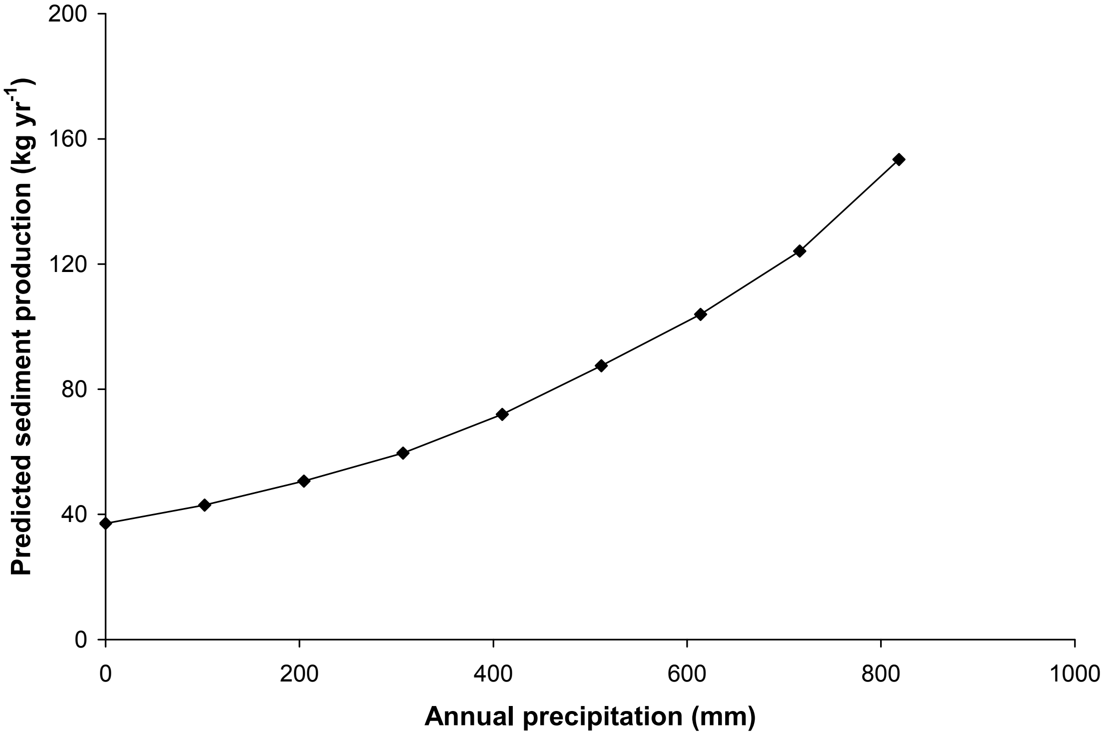

Figure 2.13. Predicted annual sediment production for the baseline road segment using WEPP:Road versus mean annual precipitation at Cheesman.

The predicted change in sediment production shown in Figure 2.13 was compared to the regressions between annual road sediment production and summer rainfall, summer I_{30}, and summer erosivity for each road segment with at least four years of data (n=20). Annual sediment production generally increased nonlinearly with increasing precipitation, and these relationships were much stronger for summer I_{30} (mean R^2=0.70) and summer erosivity (mean R^2=0.63) than summer rainfall (mean R^2=0.39). Since the coefficients and exponents from the fitted power functions for these 20 segments were log-normally distributed, the median values were used to develop the following equation between summer rainfall and annual sediment production:

$$SP_A = 0.0004(P)^{1.70} \qquad (2.10)$$

where SP_A is annual sediment production per unit area (kg m^{-2} yr^{-1}) and P is summer rainfall (mm). Equation 2.10 indicates that doubling the summer rainfall from the historic mean value of 280 mm should increase sediment production for the baseline road segment by 3.2 times, or 52% more than is predicted by WEPP:Road. This suggests that, at least for the Cheesman climate, the predicted increases in sediment production in WEPP:Road with increasing mean annual precipitation are too small.

The sediment production values for each year of the 50-year simulations for each road segment were obtained from the developers of WEPP:Road, and these values were used to further explore the relationship between annual precipitation and predicted sediment production. The maximum summer precipitation that was measured at any of the study sites was 350 mm, or 25% higher than the historic summer mean at Cheesman. According to the 50 years of simulated climate, 350 mm yr^{-1} has a recurrence interval of only 3 years, so none of the measured values represented a very wet year.

Each of the 114 measured sediment production values was compared to the 50 predicted values in WEPP:Road. In 87 cases the measured value was larger than all 50 of the predicted values. In 27 cases the predicted sediment production exceeded the measured value for one or more of the 50 years of simulation, but just over half of these cases were in the very dry year of 2002, when the mean summer precipitation at the study sites was less than 50% of the historic mean. These results indicate that the tendency for WEPP:Road to under-predict road sediment production is much more severe than indicated by the simple comparison of the measured and the mean predicted values, as a very wet summer during the study period would have greatly increased the measured sediment production and hence the discrepancy between the predicted and observed values at the upper end of Figure 2.6.

2.6.4.2. Soil Rock Content and Soil Texture

Increasing the soil rock content caused an exponential increase in predicted sediment production until the soil rock content exceeded 50% (Figure 2.14). Increasing the soil rock content beyond 50% had no effect on predicted road sediment production (Figure 2.14). The initial increase in predicted sediment production with increasing soil rock content is due to the decrease in porosity and the increased tortuosity of the subsurface flow paths (Flanagan and Nearing, 1995). These changes decrease the hydraulic conductivity and increase the magnitude and frequency of overland flow.

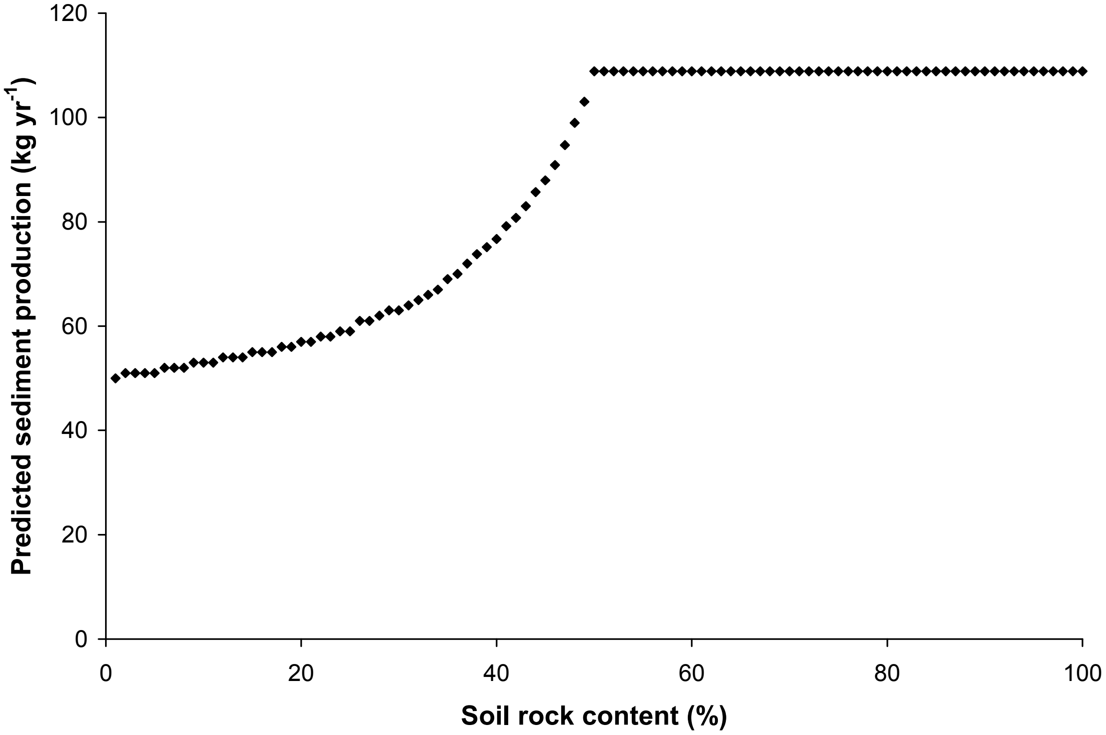

Figure 2.14. Predicted annual sediment production for the baseline road segment versus soil rock content.

An analysis of the field data showed that an increase in soil rock content was correlated with a very weak but marginally significant decrease in unit area sediment production ($r = -0.18$; $p=0.054$). Similar trends have been documented for road erosion studies in Montana (Sugden and Woods, 2007) and California (Coe, 2006) as well as a hillslope erosion study in Spain (Cerda, 2001). These decreases in sediment production with increasing soil rock content are probably due to the greater proportion of coarse particles on the surface, which dissipate rainsplash energy, increase the critical shear stress, and increase surface roughness (Knighton, 1998; Luce and Black, 1999; Cerda, 2001). The underlying WEPP model has a factor to account for surface rock cover, but it seems that some modifications are needed in WEPP:Road to ensure that increasing the soil rock content will increase the surface rock cover or otherwise decrease road sediment production.

The effect of soil texture was assessed by calculating sediment production from the baseline road segment for each of the four soil texture classes in WEPP:Road. The sandy loam soil had the lowest sediment production at 72 kg yr^{-1}. Changing the soil texture to a clay loam, silt loam, and loam increased the predicted sediment production by 73%, 95%, and 116%, respectively. The low sediment production value for the sandy loam soil can be attributed to the low silt content relative to the other three soil texture classes (Elliot et al., 1999). However, road sediment production in this study did not increase with increasing amounts of silt and clay ($p=0.63$). Since the road surfaces in this study averaged only 7% silt and clay particles (Table 2.4), the high sediment production values measured in this study cannot be attributed to a relatively high proportion of easily erodible silt-sized particles. The implication is that the convective thunderstorms in the study area have a much greater ability to detach and transport larger particles than is predicted by WEPP:Road.

2.6.4.3. Road Segment Slope

Doubling the mean road segment slope from 9.5% to 19% increased the predicted sediment production for the baseline road segment from 72 kg yr^{-1} to 125 kg yr^{-1}, or 74%. Halving the segment slope relative to the baseline segment to 4.8% reduced the predicted sediment production by 51%. Regardless of the absolute change in segment slope for the baseline segment, R_S values ranged from only 0.75 to 1.25. A plot of the predicted sediment production values against road segment slope shows that WEPP:Road predicts a linear increase as indicated by the best-fit regression (equation 2.11; R^2=0.99):

$$SP_P = 6.77(S) + 1.51 \tag{2.11}$$

where SP_P is the predicted sediment production (kg yr^{-1}) and S is road segment slope (%). Predicted sediment production also increased linearly with segment slope for the wetter Corvallis, Oregon and Clearwater, Washington climates (R^2=1.0).

An analysis of the field data showed that 54% of the variability in unit area road sediment production can be explained by segment slope (Figure 2.15). The field data also indicates a linear relationship between sediment production and segment slope as predicted by WEPP:Road. However, other road erosion studies have found a nonlinear relationship between road sediment production and segment slope (e.g., Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005), indicating that the governing equations

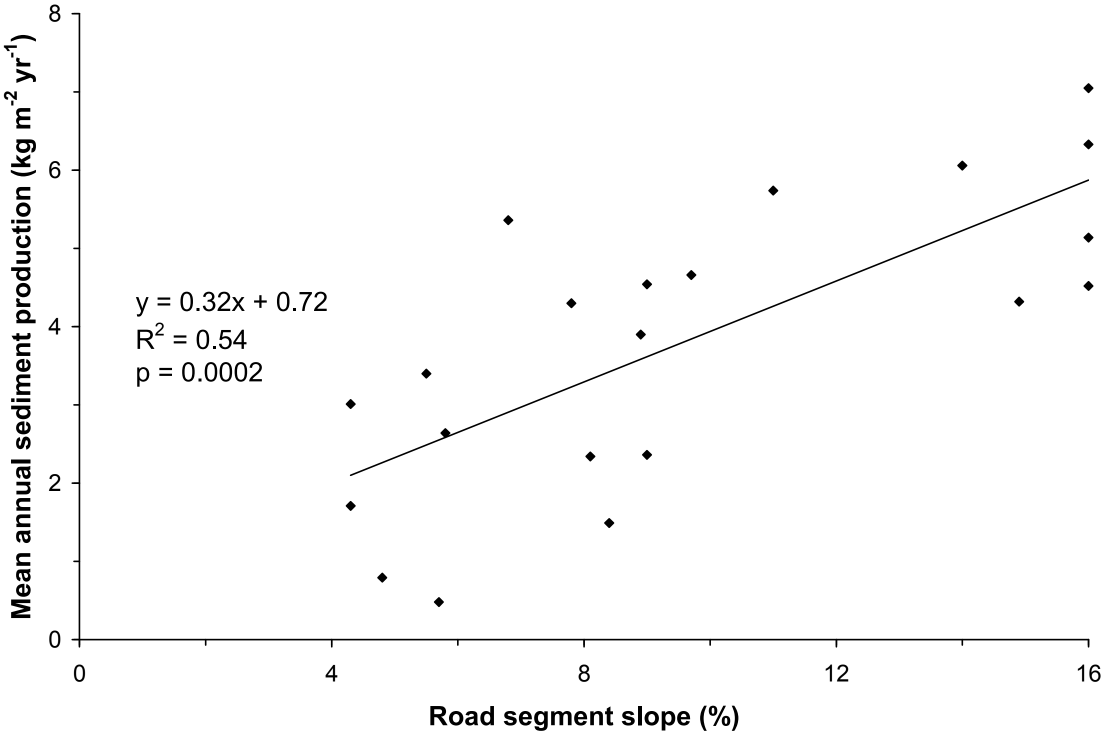

Figure 2.15. Mean annual sediment production for each road segment versus road segment slope (n=21).

using segment slope in WEPP:Road are likely to limit the accuracy of this model in other study areas.

2.6.4.4. Traffic

The sensitivity analysis showed that changing the traffic class for the baseline road segment from low to high increased the predicted sediment production by 3.24 times, while changing the traffic class from low to none decreased the predicted sediment production by only 3%. In this study all the segments were classified as having low traffic in WEPP:Road because the long-term mean number of vehicles per day ranged from 0.3 at Nighthawk to 3.2 at the entrance to the Spring Creek road. The roads were not placed in the high traffic class because they did not have “considerable traffic during much of the year” (Elliot et al., 1999). They also did not have the 50% or more vegetated surface cover that would be needed for them to be categorized as having no traffic (Elliot et al., 1999).

A univariate analysis of the field data showed a weak positive correlation between the mean traffic rate and mean annual unit area sediment production ($r=0.04$; $p<0.001$). After normalizing measured sediment production by contributing area and summer erosivity, the road segments that averaged 3.2 vehicles per day produced 2.1 times as much sediment as the segments that averaged only 0.3 vehicles per day. Although none of the road segments met the criteria for having no traffic in WEPP:Road, the doubling of normalized sediment production as the number of vehicles per day increased from 0.3 to 3.2 suggests that WEPP:Road is under-predicting the increase in sediment production due to an increase in the traffic level from none to low.

2.6.5. Sensitivity of SEDMODL2 and Possible Improvements

The relatively simple structure of SEDMODL2 facilitated comparisons of the sensitivity analyses against the field data as well as other road erosion studies. The baseline road segment for the sensitivity analyses also was based on the mean parameter values from this study, and in terms of SEDMODL2 these were a length of 70.3 m, a width of 3.2 m, a slope of 9.5%, a geology factor of 5.0, a road age factor of 1.0, a road surface factor of 1.95, a traffic factor of 1.59, and 208 mm of summer rainfall. The linear structure of SEDMODL2 means that doubling the value of any factor will double the predicted sediment production. However, the slope and rainfall factors are calculated by power functions with exponents of 2.0 and 1.5, respectively, so changing the road segment slope or the annual rainfall has a nonlinear effect on the predicted sediment production.

2.6.5.1. Slope Factor

Doubling the road segment slope from 9.5% to 19% increased the predicted sediment production for the baseline road segment from 465 kg yr^{-1} to 1860 kg yr^{-1}, or exactly 4.0 times. In contrast to WEPP:Road, the R_S values increased as the road segment slope increased, ranging from 1.25 for a segment slope of 2.4% to 3.0 for a segment slope of 19%. This increase in R_S with increasing slope is due to the nonlinear relationship that defines the segment slope factor (equation 2.2).

Other studies have shown that the product of road segment length (or area) times segment slope, raised to a power from 1.5 to 2.0, is an important predictor for road sediment production (Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005). While SEDMODL2 does not directly account for the interaction between segment length or area and segment slope, the area-slope relationship is indirectly incorporated into the model by multiplying the nonlinear slope factor by the road segment area. The problem is that in this study road segment slope was linearly related to the unit area road sediment production (Figure 2.15), and this linear relationship conflicts with the nonlinear governing equation in SEDMODL2.

While the field data indicate that the accuracy of SEDMODL2 could be improved by using a linear slope factor, the current nonlinear predictive equation for the slope factor (equation 2.2) can be optimized using the field data. To this end the base segment slope and exponent in equation 2.2 were optimized against the field data as indicated by the Nash-Sutcliffe efficiency, and this yielded a slightly lower base segment slope of 6.7% and a smaller exponent of 1.7. The tendency for SEDMODL2 to under-predict road sediment production (Figure 2.7) suggests that the optimized nonlinear slope factor should have had a lower base segment slope and a larger exponent. Nevertheless, using this revised nonlinear slope factor improved the R^2_{eff} of SEDMODL2 from 0.31 to 0.37, indicating that other factors besides the segment slope also are limiting the performance of SEDMODL2 in the study area.

2.6.5.2. Geology Factor

The geology factors in SEDMODL2 were derived from previous road erosion studies (Dryess, 1975; Reid and Dunne, 1984; Swift, 1984; Vincent, 1985; Kochenderfer and Helvey, 1987; Bilby et al., 1989; Foltz, 1996; Megahan and Ketcheson, 1996; Luce and Black, 1999). The mean geology factor for each of these studies was calculated by dividing the measured road sediment production by the traffic, rainfall, slope, and road surface factors (BCC and NCASI, 2003). Most of the road erosion studies had a geology factor of about 1.0; however, studies in areas with granite, schist, and weathered sedimentary geologies had geology factors as high as 17 (BCC and NCASI, 2003). The maximum recommended geology factor in the technical documentation is 5.0 (BCC and NCASI, 2003), and this value was used for each road segment in the present study because the soils are all derived from weathered granite.

The selected geology factor of 5.0 was checked by back-calculating the geology factor for each segment-year of data by dividing the measured sediment production values by the slope, road surface, traffic, and rainfall factors (BCC and NCASI, 2003). The resulting mean and median geology factors were 10.1 and 7.0, respectively, and values for individual segments in a given year ranged from 0 to 81. These results indicate that the recommended geology factor of 5.0 is too low. Since a value of 5.0 is the maximum allowed in SEDMODL2, the range of possible values should be expanded to account for more erodible lithologies such as the Pikes Peak granite.

2.6.5.3. Road Surface Factor

In SEDMODL2 the presence of ruts on the road surface doubles the road surface factor and hence the predicted sediment production when compared to the same native surface road segment without ruts. However, rutting on native surface forest roads in Idaho and Colorado increased sediment production by 2-5 times (Foltz and Burroughs, 1990). Other studies have shown that rill erosion can account for up to 80% of the sediment being produced from cultivated lands (Valcarcel et al., 2003) and burned hillslopes (Pietraszek, 2006).

In this study the road segments with a rill density greater than 0.0 m m^{-2} were considered rutted and assigned the maximum road surface factor of 2.0 (Table 2.5). The field data show that the mean annual sediment production for each segment was strongly related to rill density (R^2=0.57; p<0.0001) (Figure 2.16). According to this relationship, a road segment with the highest measured rill density of 0.79 m m^{-2} should generate nearly 20 times more sediment than a segment without any rills. Both the literature and these values indicate that SEDMODL2 underestimates the effect of concentrated flow paths and rutting on road segment sediment production. A reformulation of the *RS* factor

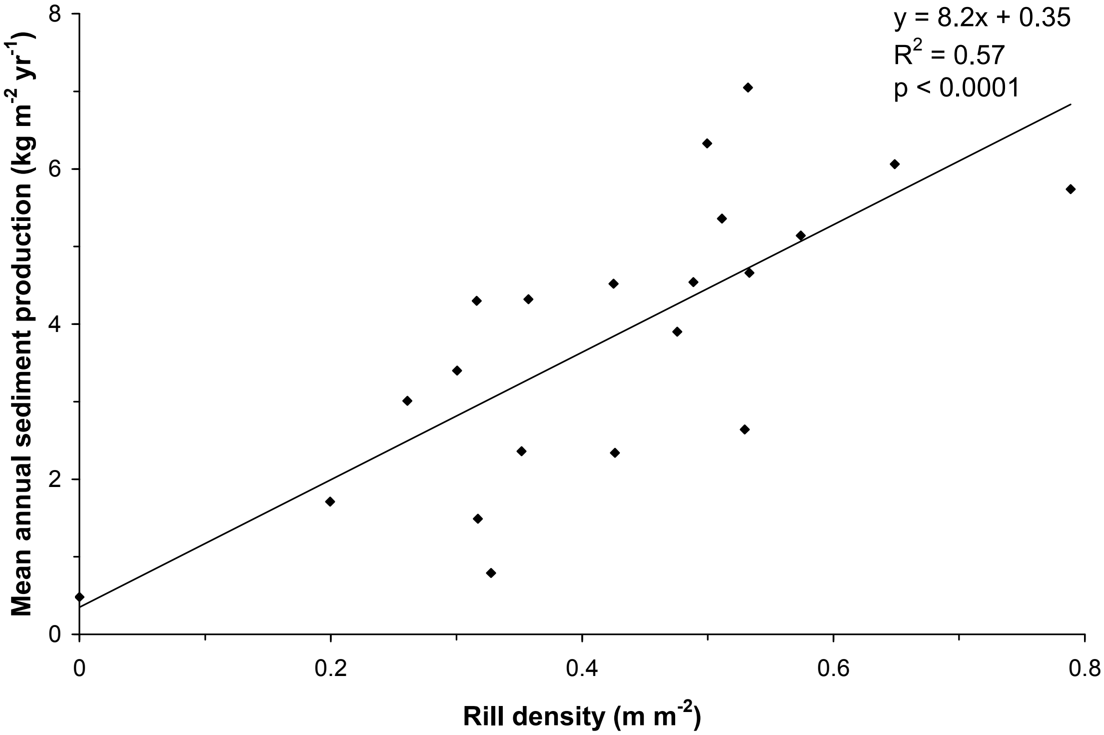

Figure 2.16. Mean annual sediment production for each segment versus rill density (n=21).

in SEDMODL2 to increase the values for road segments with higher rill densities and decrease the values for unrilled segments should improve the overall performance of the model by effectively increasing the slope of the best-fit regression in Figure 2.7.

2.6.5.4. Traffic Factor

The traffic factor is one of the most important variables in SEDMODL2 because the values can range from 0.1 for roads with no traffic to 120 for 12-m wide roads with more than five log trucks per day (BCC and NCASI, 2003). Field studies have shown that increasing traffic can greatly increase road sediment production (e.g., Reid and Dunne, 1984; Constantini et al., 1999; MacDonald et al., 2001; Ziegler et al., 2001). This increase is due to the resulting increase in the amount of easily erodible sediment by particle breakdown and the pumping of fines to the surface by the weight of the vehicles (Reid and Dunne, 1984; Ziegler et al., 2001; Ramos- Scharrón and MacDonald, 2005). The documentation for SEDMODL2 (BCC and NCASI, 2003) states that the traffic factors were developed using road erosion data from the Pacific Northwest (Reid and Dunne, 1984; Foltz, 1996; WDNR, 1997), but the relative values for high versus low traffic roads indicate that they were derived primarily from the data in Reid and Dunne (1984).

The maximum traffic factor in this study was 2.0 because none of the mean annual traffic rates exceeded 5 vehicles per day (BCC and NCASI, 2003). Forty-seven of the 114 segment-years of data had a traffic factor of 1.0 because the mean traffic rate was less than one vehicle per day. After normalizing the mean annual sediment production for each segment by contributing area and summer erosivity, the road segments with a traffic factor of 2.0 produced 2.1 times as much sediment as the segments with a traffic factor of 1.0. This two-fold increase is nearly identical to the predicted increase using SEDMODL2, indicating that the lower range of the traffic factors in SEDMODL2 are accurate for the Colorado Front Range.

2.6.5.5. Rainfall Factor

The equation for calculating the rainfall factor in SEDMODL2 is a power function (equation 2.3), and this is based on data from the Pacific Northwest (Luce and Black, 1999) and the Appalachian Mountains (Swift, 1984). Equation 2.3 also uses annual rainfall rather than total precipitation because road sediment production from snowmelt is nearly an order of magnitude lower than the sediment generated from an equivalent amount of rainfall (Vincent, 1985; BCC and NCASI, 2003). The field data collected for this study showed that snowmelt did not generate any sediment (Libohova, 2004; Brown, 2008), which is why only summer rainfall was used to calculate the rainfall factor in SEDMODL2.

Equation 2.3 indicates that if the rainfall for the baseline road segment is doubled from the mean value of 208 mm to 416 mm, the predicted sediment production increases from 465 kg yr^{-1} to 1316 kg yr^{-1}, or 2.83 times. Like the slope factor, the nonlinear equation for calculating the rainfall factor causes R_S to increase from 1.17 when there is 52 mm of rainfall to 1.83 when there is 416 mm of rainfall. As a result, wetter years are predicted to have a proportionally larger effect on cumulative sediment production than drier years. This nonlinear effect of increasing precipitation is consistent with some road erosion studies (e.g., Swift, 1984; Luce and Black, 2001), while other road erosion studies have shown a linear relationship between precipitation and road sediment production (Libohova, 2004; Ramos-Scharrón and MacDonald, 2005; Coe, 2006; Brown, 2008). This implies that the rainfall factor in SEDMODL2 may have to be adjusted for different areas.

An analysis of the field data yielded a significant nonlinear relationship between summer rainfall and unit area road sediment production ($R^2=0.39$; $p<0.0001$) (equation 2.10). Doubling the mean summer rainfall from 208 mm to 416 mm in equation 2.10 increases the expected sediment production value by 3.24 times. This increase is only slightly more than the 2.83-fold increase predicted by the nonlinear function in SEDMODL2, and this indicates that equation 2.3 is relatively accurate for the study area.

The field data also were used to optimize the coefficient and exponent values in equation 2.3. By increasing the coefficient in equation 2.3 from 0.016 to 0.035 and decreasing the exponent from 1.5 to 1.3, the R^2_{eff} of SEDMODL2 was improved from 0.31 to 0.39. A potentially much greater improvement in the performance of SEDMODL2 might be possible in monsoon-dominated climates by substituting summer I_{30} or summer erosivity for the summer rainfall, as these are much more closely correlated with annual road sediment production (R^2=0.63-0.70) than total summer rainfall (R^2=0.39).

2.6.5.6. Revisions to SEDMODL2

The previous sections have shown that the slope, geology, and road surface factors in SEDMODL2 are not consistent with the field data, while the traffic and rainfall factors are close to the relationships identified from the field data. A potential problem is that the suggested improvements were identified on a factor-by-factor basis, and these changes have to be integrated into a revised version of SEDMODL2 to determine if they result in a substantial net improvement in model performance.

A revised version of SEDMODL2 was developed by combining the suggested improvements to the slope, geology, and rainfall factors. The linear slope factor, road surface factor based on rill density, and rainfall factor based on erosivity will require converting the sediment production values in the calculated regressions to factor values, and this will require a more extensive effort by the model developers. As noted earlier, substituting the optimized base and exponent values into the slope factor equation increases the Nash-Sutcliffe efficiency from 0.31 to 0.37. If SEDMODL2 is further modified by using the optimized coefficient and exponent values for the rainfall factor, the R^2_{eff} is further improved to 0.42. However, if the geology factor is increased to the back-calculated median value of 7.0 while using the updated slope and rainfall factors the R^2_{eff} drops to 0.11. This indicates that the factor-by-factor analyses used in this study are useful for identifying the limitations of SEDMODL2, but a more integrated effort will be needed to assess how altering one factor will affect the performance of each of the other factors. Overall, SEDMODL2 now provides a reasonable first approximation for road sediment production in the study area and presumably similar environments, but additional work is needed to develop a fully optimized version of SEDMODL2 for the Colorado Front Range and other monsoon-dominated areas.

2.6.6. Empirical Models

The two empirical models for predicting annual and storm-based road sediment production were conceptually very similar. Both models included a length*slope or area*slope variable, which makes physical sense because the amount of runoff increases with road segment length or area, and the energy of runoff increases with steeper slopes (Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005). The models also used summer I_{30} and storm I_{30}, respectively, as the 30-minute maximum intensity is a good index for both rainsplash erosion and the amount of surface runoff. The storm-based model also includes the percent of the road surface that is bare soil, as sediment production increases as the amount of litter, rocks, and vegetation on the road surface decreases (Coe, 2006; Brown, 2008). A variable for soil texture or geology was not included in either model because the study sites had very similar soils and lithologies.

The R^2_{eff} for the annual empirical model for the 2005 and 2006 data was 0.14, which is better than the respective R^2_{eff} values of -0.98 and 0.00 for WEPP:Road and SEDMODL2 for these same two years. The annual empirical model had a RMSE of 734 kg yr^{-1} for the 42 data points in 2005 and 2006 and a RMSE of 1137 kg yr^{-1} for the 15 values greater than 1000 kg yr^{-1}. SEDMODL2, which was the better of the two general models, had a higher overall RMSE of 792 kg yr^{-1} in 2005 and 2006 and a higher RMSE of 1237 kg yr^{-1} for values greater than 1000 kg yr^{-1}. This indicates that the annual empirical model is also the best predictor when road sediment production exceeds 1000 kg yr^{-1}. Since the mean road sediment production value in 2005-2006 was 10% higher than the mean value in 2001-2006, the poorer performance of WEPP:Road and SEDMODL2 in 2005 and 2006 may be partly due to their tendency to increasingly under-predict higher sediment production values.

The storm-based empirical model had a relatively high Nash-Sutcliffe efficiency (R^2_{eff}= 0.27), but the performance of the model was very poor when the storm-based predictions for each segment were summed to provide an annual prediction (R^2_{eff} = -0.50). The poor relationship between the sum of storm-based predictions and the measured annual values is related to the consistent over-prediction of sediment production from the smaller storms (Figure 2.9), as these errors become larger as the sediment production values are summed. Hence the storm-based empirical model can be useful for predicting road sediment production for individual storms, but the model should not be used to predict annual sediment production from road segments.

2.6.7. Management Implications and Future Research

The physically-based WEPP:Road model was the least accurate of the four road sediment production models tested in this study. The negative Nash-Sutcliffe efficiency indicates that the predicted values are less accurate than simply using the mean of the measured values. The relatively low R^2 of 0.28 also indicates that WEPP:Road may not provide a reliable relative ranking of road segment sediment production rates. The large number of governing equations and interacting parameters in the underlying WEPP model limited the analysis of model errors and the identification of areas needing improvement. Nevertheless, the sensitivity analyses indicated a need to improve the model with respect to more accurately predicting the effects of increasing precipitation, increasing soil rock content, and the changes in traffic on road segment sediment production. It is not clear whether these changes will greatly improve the overall accuracy of WEPP:Road given the negative R^2_{eff} and trends in Figure 2.6, and WEPP:Road is currently not the best choice for predicting road sediment production in the central Colorado Front Range.

SEDMODL2 was the most accurate predictor of road sediment production and had the highest R^2, indicating that it also was the best model for identifying which road segments are producing the most sediment (Table 2.7, 2.8). The relatively simple structure of SEDMODL2 means that local data can be readily used to optimize some of the predictive factors in this model. In this study optimizing the slope and rainfall factors increased the R^2_{eff} from 0.31 to 0.42. These results indicate that a slightly modified version of SEDMODL2 provides reasonable predictions of road sediment production in the Colorado Front Range, and the accuracy of this model can be improved by collecting a limited amount of field data to optimize some of the factors.

The performance of the empirical models was surprisingly poor given that the segments that were used for developing the models were the same segments that were used for validation. The errors associated with the rainfall measurements limited the accuracy of the models during both development and testing, as the storm I_{30} and summer I_{30} greatly affected the storm-based and annual sediment production predictions, respectively. The low R^2_{eff} of the annual empirical model (0.14) has to be tempered by the fact that it outperformed both WEPP:Road and SEDMODL2 when tested against the data from 2005 and 2006 (R^2_{eff} of -0.98 and 0.00, respectively). A more in-depth analysis indicated that the annual empirical model was the best predictor when road sediment production exceeded 1000 kg yr^{-1}, while SEDMODL2 had the highest overall R^2_{eff} when tested against the entire data set. Further testing of the empirical models is needed to better assess their accuracy for the Colorado Front Range and similar areas. Future road erosion studies should focus on testing and improving SEDMODL2 across a range of climates and geologies and testing the performance of the annual empirical model relative to SEDMODL2.

The six years of field data indicate that the precipitation intensity, the segment slope, the contributing area, and the amount of bare soil have the largest effect on road sediment production. While the precipitation intensity cannot be controlled, the contributing area can be reduced by outsloping roads. Alternatively, more drainage points can be added to reduce segment lengths. Road segment slopes also should be minimized as much as possible because higher slopes increase the shear stress of overland flow (Knighton, 1998) and road segment erosion rates. Rocking roads also would reduce road sediment production by reducing rainsplash erosion and the supply of easily eroded sediment, and increasing the critical shear stress and surface roughness (Knighton, 1998; Coe, 2006).

Detailed data on road-stream connectivity is needed to prioritize road treatments, as the adverse effects of roads on water quality and stream habitat will be reduced only if treatments focus on the road segments that are delivering sediment. There are several means by which resource managers can predict or assess sediment delivery, and these include: (1) WEPP:Road, as this is designed to predict the amount of sediment passing through a 20-year old forest buffer (Elliot et al., 1999); (2) SEDMODL2, which has sediment delivery ratios based on the distance from the road segment to the nearest stream channel (BCC and NCASI, 2003); (3) empirical models developed for predicting sediment transport distances and road-to-stream connectivity (Coe, 2006; Brown, 2008); and (4) field surveys. Since the accurate prediction of sediment delivery is critical for improving water quality and stream habitat, studies are urgently needed to evaluate the first three procedures for predicting road sediment delivery.

Future road erosion studies in areas with convective storms should maintain a rain gauge near each road segment, as rainfall can vary greatly within a few hundred meters (Hastings et al., 2005). The field data also indicated that road sediment production was significantly related to the rill density on the segment surface, and other studies have shown that up to 80% of the sediment production from croplands and burned hillslopes is generated from rill erosion. Future road erosion studies should attempt to quantify the relative contribution of rill erosion to road sediment production. Finally, the effects of traffic on rill density, the supply of highly erodible sediment, and road sediment production need to be more rigorously evaluated, ideally on a storm-by-storm basis.

2.7. CONCLUSIONS

From 2001 to 2006 rainfall, site characteristics, and sediment production were measured from 14-22 native surface road segments in the central Colorado Front Range. The resulting dataset was used to test the accuracy of two models that are commonly used to predict the sediment production from forest roads: WEPP:Road and SEDMODL2. The data from 2005 and 2006 also were used to test the accuracy of annual and storm-based empirical models developed from the field data collected from 2001 to 2004.

The Nash-Sutcliffe model efficiency (R^2_{eff}) for WEPP:Road was -0.54, which indicates that the mean measured value is a better predictor of annual sediment production than the model. SEDMODL2 was a better predictor of annual sediment production than the mean measured value (R^2_{eff}=0.31), but the RMSE was still 765 kg yr^{-1}, or 95% of the mean measured value. The annual empirical model had an R^2_{eff} of 0.14, and this more accurately predicted road sediment production in 2005 and 2006 than either WEPP:Road or SEDMODL2 (R^2_{eff} of -0.98 and 0.00, respectively). The storm-based empirical model had an R^2_{eff} of 0.27 for individual storms, but when the values from each storm were summed to yield an annual total, its performance was very poor (R^2_{eff} = -0.50). All of the models typically over-predicted low sediment production values and under-predicted high values.

The tendency for WEPP:Road to under-predict road sediment production was actually more severe than indicated by the simple comparison of measured and predicted values. The maximum summer precipitation at any of the study sites was only 25% higher than the historic mean value at the weather station used in the WEPP:Road simulations, and this had a recurrence interval of only 3 years according to the 50 years of simulated climate. Despite the relatively low amounts of precipitation at most sites over the study period, the measured sediment production values were larger than all of the predicted values from the 50-year simulation for 76% of the 114 segment-years of data. The performance of WEPP:Road also was hampered because it predicts an increase in sediment production with higher soil rock contents, but the field data show an inverse relationship. WEPP:Road also predicted a 3% increase in sediment production as the result of a categorical change from no traffic to low traffic, but the field data indicate that this change should increase sediment production by 2.1 times. WEPP:Road could be improved by either expanding the range of soil texture classes, or by including variables to better represent the variability in soil erodibility.

The comparisons of the field data to the predicted relationships indicate that the slope factor in SEDMODL2 should increase linearly with segment slope instead of exponentially increasing or decreasing as segment slopes vary from 7.5%. In the absence of a linear slope factor, model performance can be improved by using a revised nonlinear function with a lower base and a lower exponent value. The range of geology factors should be increased, as the median back-calculated value for this study was 1.4 times the highest suggested value in the technical documentation. Measured sediment production increased with increasing rill density, which indicates that the range of road surface factors for native roads in SEDMODL2 should be expanded from the present two-fold increase resulting from road surface rutting. Model performance was improved by optimizing the coefficient and exponent values in the existing rainfall factor that uses annual rainfall; however, the field data indicate that a nonlinear function based on summer I_{30} or summer erosivity may be needed for areas where convective storms are causing most or all of the road surface erosion.

The variables in the two empirical models include the dominant controls on road sediment production in the Colorado Front Range as indicated by the field data and other road erosion studies. The annual empirical model was the best predictor of road sediment production values greater than 1000 kg yr^{-1}, and this led to the model performing better than WEPP:Road and SEDMODL2 for 2005 and 2006. The storm-based empirical model had a relatively high Nash-Sutcliffe efficiency of 0.27, but the annual totals obtained by summing the storm-based predictions disagreed with the measured annual totals (R^2_{eff}= -0.50) because this model consistently over-predicted sediment production from the smaller rainstorms.

Future road erosion studies in areas with convective rainstorms should maintain a rain gauge near each monitoring segment, as the errors associated with the rainfall measurements affected both the development of the empirical models and the accuracy of each model. Future studies also should focus on testing and improving SEDMODL2 across a range of climates and geologies, and further evaluation of the annual empirical model. Finally, there is an urgent need to test predicted road sediment delivery in addition to road sediment production, as reducing sediment delivery is critical for improving water quality and stream habitat.

The results presented here can improve current models for predicting road sediment production and guide future research. The results also can help resource managers to design and prioritize effective treatments for reducing road sediment production and evaluate cumulative watershed effects.

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3. SEDIMENT PRODUCTION AND DELIVERY FROM OFF-HIGHWAY VEHICLE TRAILS

3.1. ABSTRACT

Erosion is an important environmental issue in the Upper South Platte River (USPR) watershed of Colorado because it is the primary source of drinking water for Denver, has a high-value fishery, and water quality is impaired by high levels of sediment. Recent studies have quantified the sediment yields in this watershed from wildfires, forest thinning, and forest roads, but there are no comparable data from the large network of off-highway vehicle (OHV) trails. The objectives of this study were to: (1) quantify sediment production and delivery from OHV trails; (2) develop empirical models for predicting OHV trail sediment production and delivery; (3) test the accuracy of two models, WEPP:Road and SEDMODL2, for predicting sediment production from OHV trails; and (4) compare sediment production, sediment delivery, and sediment yields from OHV trails and forest roads. Rainfall, site characteristics, and sediment production were measured for 5 OHV trail segments beginning in August 2005 and 10 segments from May to October 2006. Detailed surveys along 10 km of OHV trails were used to estimate watershed-scale sediment production and delivery.

In 2006 the mean sediment production per meter of OHV trail was 35 kg, and the range was from 0.9 to 73 kg m^{-1}. Storm erosivity and segment length explained 80% of the storm-by-storm variation in sediment production. Twenty-four percent of the trail length was delivering sediment to the stream network, with most of the connected

segments in valley bottoms. The transport distance of runoff and sediment from OHV trails is best predicted by the maximum rill depth on the segment surface and the presence or absence of a rill below the drainage outlet (R^2=0.41). Both WEPP:Road and SEDMODL2 poorly predicted sediment production from the 10 segments, but the performance of SEDMODL2 was greatly improved by calibration of the traffic factor. OHV trails are estimated to deliver approximately 0.8 Mg km^{-2} yr^{-1} of sediment to the stream network, or 27% less than the calculated value of 1.1 Mg km^{-2} yr^{-1} for forest roads.

3.2. INTRODUCTION

Excessive sediment is one of the leading causes of surface water quality impairment in both the United States and the State of Colorado (EPA, 2008). Erosion is a particularly important environmental issue in the Upper South Platte River (USPR) watershed of Colorado because it is the primary source of drinking water for Denver, has a high-value fishery, and several stream reaches are exceeding the state water quality standard for sediment (CDPHE, 2006; CDPHE, 2008). Quantification of the primary sediment sources in the USPR watershed is necessary for resource managers to efficiently reduce sediment loads and improve water quality.

Undisturbed forests in Colorado typically generate little sediment because infiltration rates are high and overland flows are rare (Troendle, 1987; MacDonald and Stednick, 2003; Libohova, 2004; Brown, 2008). Most of the USPR watershed is forested (USDA, 2000), but the proximity of the watershed to metropolitan Denver means that the USPR watershed has been subjected to a variety of land use activities and changes that can increase sediment production and delivery rates. These include forest thinning and timber harvesting, forest roads, mining, grazing, high-severity wildfires, and off-highway vehicle (OHV) trails (USDA, 2000; USDA, 2005). Previous studies have quantified sediment yields in the USPR watershed from wildfires (Libohova, 2004; Rough, 2007), forest thinning (Libohova, 2004; Brown, 2008), and forest roads (Libohova, 2004; Brown, 2007; Chapter 2), but there are no comparable data from the large network of OHV trails.

Very few studies have measured sediment production rates from OHV trails. Like forest roads, OHV trails are compacted and have low infiltration rates (Willshire et al., 1978; Griggs and Walsh, 1981; Sack and da Luz, 2003; Foltz, 2006). Hence the magnitude and frequency of overland flow and surface erosion is much greater from OHV trails than adjacent, less disturbed areas (Willshire et al., 1978; Griggs and Walsh, 1981; Sack and da Luz, 2003). Sediment production from OHV trails should increase with segment length or segment area, as these are surrogates for the amount of road surface runoff (Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005). Sediment production also should increase with increasing segment slope, as this is a primary control on the energy and velocity of runoff (Knighton, 1998; Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005). OHV trail sediment production has been estimated to range from 25 kg m^{-2} yr^{-1} near San Francisco, California (Willshire et al., 1978) to 209 kg m^{-2} yr^{-1} in southeastern Ohio (Sack and da Luz, 2003). These studies estimated sediment production rates from OHV trails using repeated cross-section surveys, but there have been no direct measurements of OHV trail sediment production or a detailed evaluation of the physical processes controlling storm-by-storm and annual sediment production from OHV trails.

In the absence of local data, researchers and resource managers are forced to assume that sediment production rates from OHV trails are similar to forest roads (Elliot et al., 1999). The validity of extrapolating road sediment production data to OHV trails is unknown given the differences in the amount and type of traffic. For unpaved roads an increase in traffic increases sediment production by further compacting the surface and increasing the supply of highly erodible fine particles (Reid and Dunne, 1984; Constantini et al., 1999; MacDonald et al., 2001; Ramos-Scharrón and MacDonald, 2005). In the USPR watershed OHV trails are much more incised into the hillslope than forest roads, and this suggests that OHV trails have higher unit area erosion rates. Given the lack of sediment production data from OHV trails and the unsubstantiated assumption that road and OHV trail sediment production rates are comparable, there is an urgent need to quantify both sediment sources in the same study area.

Road erosion studies have shown that a relatively small proportion of the road length in forested areas is typically responsible for most of the road-related increases in watershed-scale sediment yields (Reid and Dunne, 1984; Wemple et al., 1996; Croke and Mockler, 2001; Coe, 2006; Brown, 2008). If the same tendency is true for OHV trails, the ability to predict segment-scale sediment production rates could be used to identify the segments that are generating the most sediment and to prioritize rehabilitation treatments.

The lack of sediment production data from OHV trails means that road erosion models are typically used to predict sediment production from OHV trail segments. Two commonly used road erosion models are WEPP:Road and Sediment Model Version 2.0 (SEDMODL2). WEPP:Road is one of the web-based interfaces developed by the United States Forest Service (USFS) to simplify the use of the physically-based Water Erosion Prediction Project (WEPP) model (Elliot, 2004). SEDMODL2 is a conceptual-empirical road erosion and delivery model that was originally developed by the Boise Cascade Corporation and later updated by the National Council for Air and Stream Improvement (BCC and NCASI, 2003). The problem is that the accuracy of these models has not been tested against field data from OHV trails.

Data on the connectivity between OHV trails and streams also are needed to determine the proportion of sediment that is likely to be delivered to the stream network.

Sediment delivery from forest roads has been related to site characteristics such as road segment length, road segment slope, and the hillslope position of the road (Libohova, 2004; Coe, 2006; Brown, 2008). Given the conceptual similarities between roads and OHV trails, it is hypothesized that the same factors may explain sediment delivery from OHV trails. One study in southern California used aerial photography to determine that 75% of OHV trails were delivering sediment to streams (Griggs and Walsh, 1981), which is a much higher proportion than has been estimated for forest roads (Coe, 2006; Brown, 2008). OHV trails in the USPR watershed may be more connected to streams than forest roads because many trails are located near streams and they generally were built before design standards were implemented (USDA, 2005), but again there are no data to substantiate this assertion. A detailed survey of OHV trails is needed to assess connectivity to streams, and to identify the factors that are controlling whether a given OHV trail segment is likely to be delivering sediment to the channel network.

Given the high levels of sediment in the USPR watershed, there is an urgent need to quantify sediment production and delivery from the extensive network of OHV trails. Hence the objectives of this study were to: (1) measure sediment production from OHV trail segments; (2) assess the connectivity of OHV trails to streams; (3) develop empirical models for predicting both sediment production and sediment delivery; (4) test the accuracy of WEPP:Road and SEDMODL2 for predicting sediment production from OHV trail segments; and (5) compare sediment production, sediment delivery, and sediment yields from OHV trails and forest roads.

3.3. METHODS

3.3.1. Study Area

The study area consists of the Horse Creek, Buffalo Creek, and Waterton-Deckers subbasins of the USPR watershed in the central Colorado Front Range (USDA, 2000). There are 110 km of OHV trails in the 570 km^2 study area, and 104 km are in the Rampart Range Motorized Recreation Area (RRMRA) (USDA, 2005) (Figure 3.1). The overall density of OHV trails in the study area is currently about 0.2 km km^{-2}, but the density is expected to increase by 30% over the next few years as new trails are constructed (USDA, 2005).

Sediment production was measured from ten OHV trail segments. Five of these segments were tightly clustered along the Log Jumper trail, and the other five were located along the Noddle trail (Figure 3.1). The segments on the Log Jumper trail were approximately 2,100 m above sea level (a.s.l.) and the segments along the Noddle trail were about 2,300 m a.s.l. Annual precipitation at Log Jumper is estimated at 410 to 460 mm, while precipitation at Noddle is estimated to be 460 to 510 mm yr^{-1} (Johnston, 2004; USDA, 2000). Ponderosa pine (*Pinus ponderosa*) is the dominant vegetation type, but there also is some Douglas-fir (*Pseudotsuga menziesii*) at higher elevations and on north-facing slopes (Johnston, 2004; USDA, 2000). The soils at both sites are in the Sphinx series, which is derived from Pikes Peak granite. These soils are gravelly to very gravelly coarse sandy loams with no apparent horizons (USDA, 1992). The Sphinx soils have a severe erosion potential, but the very high infiltration rates mean that infiltration-excess overland flow is rare in undisturbed areas (USDA, 1992).

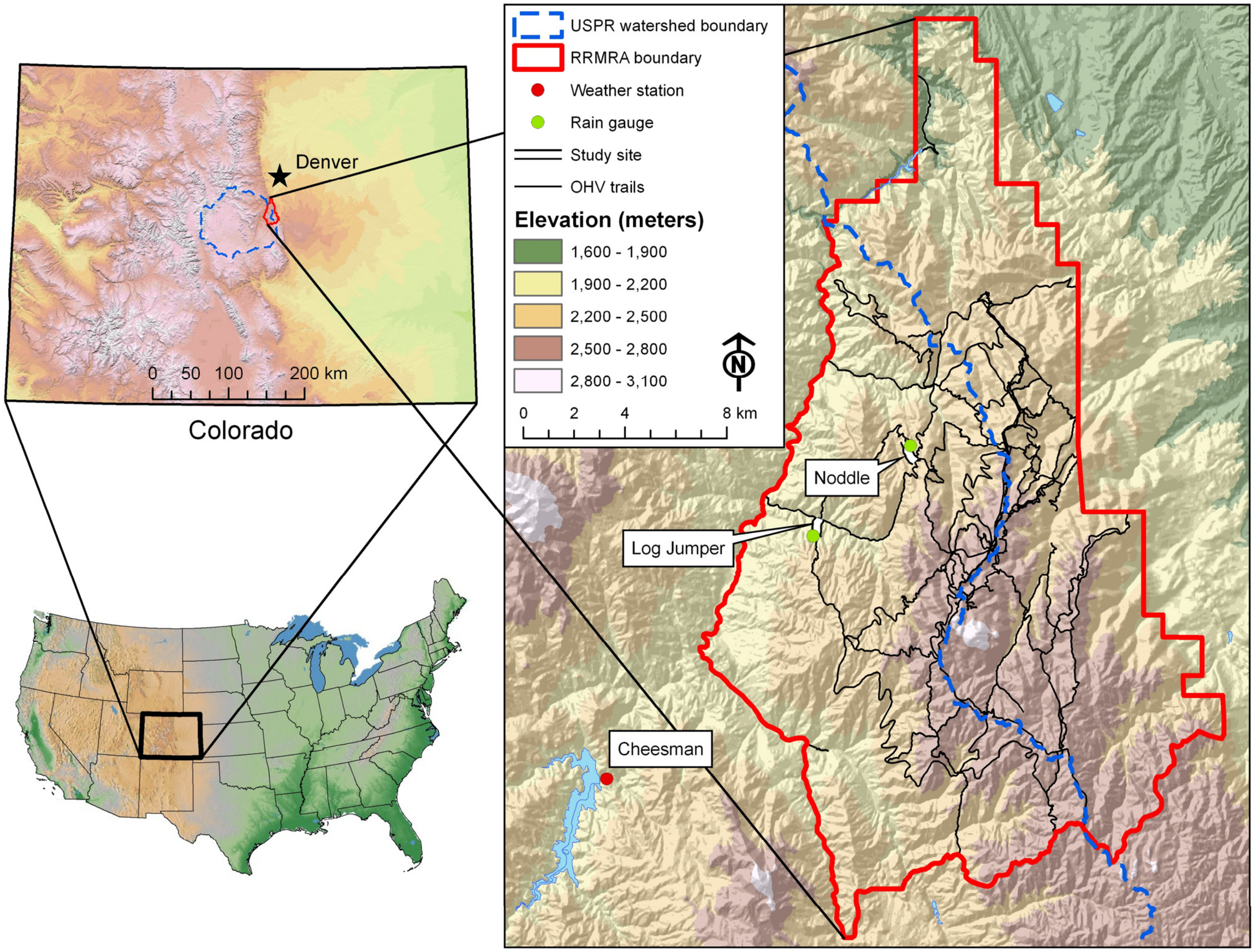

Figure 3.1. Map showing the USPR watershed, the Rampart Range Motorized Recreation Area (RRMRA), the Log Jumper and Noddle sites where sediment production was measured, and the long-term weather station at Cheesman Reservoir.

The nearest long-term weather station is at Cheesman Reservoir, which is at 2,090 m a.s.l. and 13 km southwest of the Log Jumper study site (Figure 3.1). From 1948 to 2007 the mean winter temperature was -2.1°C and the mean summer temperature was 17.2ºC (WRCC, 2008). The historic mean annual precipitation is 415 mm with about 30% falling as snow (WRCC, 2008). The mean summer precipitation from 1 May to 31 October is 280 mm (WRCC, 2008), and more than 90% of the annual rainfall erosivity occurs during this period (Renard et al., 1997). Sediment production in the study area results from localized, short-duration convective thunderstorms (Libohova, 2004; Pietraszek, 2006; Rough, 2007; Brown, 2008).

3.3.2. Precipitation

Summer precipitation was defined as from 1 May to 31 October, and this was measured by tipping-bucket rain gauges with a resolution of 0.25 mm per tip (Onset, 2001) at Noddle and 0.20 mm per tip (Global Water, 2005) at Log Jumper. The elevation, UTM coordinates, and installation date of the rain gauges are listed in Table 3.1. The data from each gauge were carefully screened, and any "bounce-back" or double tips were eliminated. Storms were defined as periods with at least 1 mm of precipitation separated by periods of at least 60 minutes with no precipitation. The depth, maximum 30-minute intensity (I_{30}), maximum 10-minute intensity (I_{10}), and erosivity (EI_{30}) following Brown and Foster (1987) were calculated for each storm using either the RF program (Petkovšek, 2005) or the RainMx10 program (Brown, 2005). The storm values in each summer were summed to yield a summer rainfall depth and a summer erosivity.

Table 3.1. The elevation, UTM coordinates in NAD83 zone 13 north, and date of installation for the tipping-bucket rain gauges at the Log Jumper and Noddle sites.

Study site	Elevation (m)	UTM northing	UTM easting	Installation date
Log Jumper	2158	4349579.58	484871.25	20 May 2006
Noddle	2320	4353123.75	488705.09	2 Aug 2005

3.3.3. Monitoring Segments and Sediment Production

Sediment fences (USDA, 2001; Robichaud and Brown, 2002; Libohova, 2004) were used to measure sediment production from the 10 OHV segments. These segments were selected for monitoring because they had a distinct drainage outlet that was suitable for installing a sediment fence and a clearly defined contributing area. The segments at each site also were selected to represent a range of contributing areas and segment slopes. The five segments at the Log Jumper study site were monitored from early August 2005 to October 2006, and the five segments at Noddle were monitored from May 2006 to October 2006. At Log Jumper all segments with a sediment fence were within 0.5 km of the rain gauge and at Noddle all segments were within 0.6 km of the rain gauge.

The sediment captured in each sediment fence was manually removed as soon as possible after each storm event. This sediment was placed into buckets and weighed using an electronic scale with a resolution of 0.1 kg. After weighing, the sediment was piled and thoroughly mixed. A 0.5 to 1.0 kg sample was taken from the pile, double-bagged in airtight plastic bags, and approximately one-half of this sample was analyzed for percent moisture following Gardner (1986):

$$M = 100 \times (W_W - W_D)/W_W \qquad (3.1)$$

where M is percent moisture, W_W is the wet weight, and W_D is the dry weight. The percent moisture was used to correct the field-measured wet weights to a dry mass.

A series of detailed measurements were made to characterize each of the OHV trail segments with a sediment fence (Table 3.2). The active width was measured at approximately 10 systematically-spaced locations along the segment length. This width was the area being regularly driven on as identified by a well-compacted surface and a lack of vegetation. The total width was measured at the same ten locations and this was defined as the horizontal distance between the top of the cutslope and the downslope edge of the incision or fillslope caused by the OHV trail. The length of each segment was measured with a measuring tape to the nearest decimeter. The length associated with each active width and total width was determined by the midpoint between each measurement, and the sum of the widths times the lengths yielded the active area and total area for each segment. The segment slope was measured with a clinometer, and a distance-weighted mean slope was calculated for each segment.

Surface cover was measured at the start of each field season across the active width of at least 10 systematically-spaced lateral transects per segment. Within each transect surface cover was classified at 10 systematically-spaced points to yield a minimum of 100 sample points per segment. The surface cover classes were bare soil, rock (intermediate axis larger than 1.0 cm), litter, live vegetation, or wood (diameter larger than 2.5 cm). Since most of the segments were incised into the hillslope from historical erosion (Figure 3.2), the depth of incision was measured at five systematically-spaced locations on each segment. The depth of incision was defined as the vertical distance from the edge of the active width to the top of the cutslope. The maximum rill

Table 3.2. List of the dependent and independent variables used in the analysis of sediment production.

Dependent variables	Independent variables
Storm-based sediment production (kg) Summer sediment production (kg) Storm-based sediment production rate (kg m^{-1}) Summer sediment production rate (kg m^{-1})	Segment slope (%) Segment length (m) Active area (m^2) Total area (m^2) Mean incised depth (m) Storm rainfall (mm) Summer rainfall (mm) Storm erosivity (MJ mm ha^{-1} h^{-1}) Summer erosivity (MJ mm ha^{-1} h^{-1}) Mass of unconsolidated material (kg m^{-2}) D_{16}, D_{50}, and D_{84} of surface soils (mm) D_{16}, D_{50}, and D_{84} of subsurface soils (mm) Segment slope (%)*segment length (m) Segment slope (%)*active area (m^2)

depth on each segment was classified as none, shallow (1-10 cm), medium (11-20 cm), or deep (21-30 cm). The hillslope position of each segment was classified as ridgetop (<100 m to ridge), midslope, or valley bottom (<100 m to stream). The drainage outlet of each segment was classified as a culvert, waterbar or rolling dip, pushout, or no engineered drainage.

Surface and subsurface soil samples were collected from five systematically-spaced locations along each segment. The surface samples were collected by sweeping the unconsolidated material from a 20-cm wide strip across the active width into a plastic bag. The intent was to characterize the amount and size of unconsolidated material on the segment surface, as road sediment production has been shown to increase with the supply of easily erodible soil (Megahan, 1974; Luce and Black, 1999). The subsurface sample was collected from a 2x2-cm trench excavated across the active width after the

Figure 3.2. A sediment fence installed below an OHV trail segment at the Log Jumper study site. Note the incision into the hillslope at the upper end of this segment.

surface sample had been collected. Both the surface and subsurface samples were oven-dried at 90°C for at least 24 hours following Bunte and Abt (2001). The particle-size distribution of each surface and subsurface soil sample was determined by dry-sieving the entire mass of the sample to less than 8 mm. The mass of soil less than 8 mm was split with a rifle splitter until there was a subsample weighing approximately 300 g. The 300 g subsample was sieved to a minimum size of 0.063 mm, and no further analysis was done because particles smaller than 0.063 mm (i.e., silt and clay) averaged only 2.8% of the mass of the surface samples and 5.7% of the mass of the subsurface samples.

3.3.4. OHV Trail Surveys and Sediment Delivery

A sample of the OHV trails in the RRMRA was surveyed to assess the representativeness of the segments that were being monitored and potential sediment delivery to the stream network. The lengths to be surveyed were selected by dividing the OHV trails in the RRMRA and the USPR watershed into approximately equal lengths of 1.0 to 1.3 km (n=16); six lengths were randomly selected for surveying. The two OHV trails with sediment fences—Log Jumper-A (0.6 km) and Noddle (2.6 km)—also were surveyed to yield a total surveyed length of 10.1 km.

The basic procedure for these surveys was to divide each trail into segments as determined by a distinct outlet for surface runoff or a change in the direction of surface runoff because of a topographic high. For practical reasons, detailed measurements were made only on every third segment, while segment length and segment slope was measured for the two segments in between the segments where the more detailed surveys were conducted.

The detailed measurements made in these surveys differed slightly from the measurements made on the segments with sediment fences (Table 3.3). Segment lengths were measured to the nearest 0.5 m with a Rolatape® measuring wheel. The active width, total width, and incised depth were measured at three or more systematically-spaced locations and averaged to obtain mean values. The mean active and total widths were multiplied by the segment length to determine the active area and total segment area, respectively. Percent bare soil within the active area was qualitatively estimated as high (>95%), medium (85-95%), or low (<85%). The maximum rill depth on each surveyed segment was classified using the same categories as the segments with sediment fences.

Table 3.3. List of the dependent and independent variables used in the analysis of sediment delivery.

Dependent variables	Independent variables
Sediment plume length (m)	Segment slope (%)
Outlet rill length (m)	Segment length (m)
Outlet rill volume (m^3)	Active area (m^2)
Drainage feature length (m)	Total area (m^2)
Connectivity class (1, 2, 3, or 4)	Hillslope gradient below outlet (%)
	Hillslope position (ridgetop, midslope, or valley bottom)
	Mean incised depth (m)
	Roughness below outlet (high, medium, or low)
	Maximum rill depth on segment surface (high, medium, low, or none)
	Drainage type (pushout, no engineered outlet)

The hillslope below each segment drainage outlet was assessed for the presence of a sediment plume or an outlet rill ("drainage feature"). A sediment plume was defined by diffuse sediment deposition and little or no incision due to surface runoff. An outlet rill was defined by an incised, active channel that was conveying the concentrated flow away from an OHV segment. The length and slope were measured for each drainage feature, and the roughness of the hillslope below the drainage outlet was classified as high, medium, or low depending on the size and density of vegetation, rocks, and woody debris. The top width and maximum depth of each outlet rill was measured at the midpoint of the upper, middle, and lower thirds of the rill length. Since the outlet rills generally had a triangular shape, the cross-sectional area was calculated at each location by:

$$RCA = (RD*RW)/2 \qquad (3.2)$$

where *RCA* is the outlet rill cross-sectional area (cm^2), *RD* is the maximum depth (cm) and *RW* is the width (cm). The cross-sectional areas were multiplied by the length associated with each cross-sectional measurement, and these were summed to yield the total volume of each outlet rill.

The proximity of each outlet rill or sediment plume to the nearest stream channel was used to classify each segment into one of four connectivity classes (CC) (Wemple et al., 1996; Croke and Mockler, 2001). CC1 indicates no evidence of surface runoff from the segment; CC2 indicates an outlet rill or sediment plume that is less than 20 m long and does not reach to within 10 m of a stream channel; CC3 indicates an outlet rill or sediment plume that is more than 20 m long, but does not reach to within 10 m of a stream channel; and CC4 indicates that the outlet rill or sediment plume extends to within 10 m of a stream channel and is likely to be delivering runoff and sediment.

3.3.5. Model Structure and Inputs

3.3.5.1. WEPP:Road

WEPP:Road requires the parameterization of only thirteen variables, including the identification of a climate station, soil characteristics, road design, segment morphology, traffic class, and fillslope gradient (Table 3.4). WEPP:Road uses these thirteen input variables to parameterize all of the other variables needed to run the WEPP model (Elliot et al., 1999).

WEPP:Road uses a stochastically generated climate to predict mean annual sediment production. The stochastic climate is generated using the monthly climate statistics from one of the more than 2,600 weather stations in the WEPP database (Elliot

Table 3.4. Input variables for WEPP:Road and their units or categories.

Input	Units or categories
User-selected climate from the WEPP database	Monthly precipitation (mm); number of wet days by month.
Soil texture class	Clay loam; silt loam; loam; sandy loam.
Soil rock content	Percent
Road design	Insloped, bare ditch; insloped, vegetated or rocked ditch; outsloped, unrutted; outsloped, rutted.
Road length	Meters
Road width	Meters
Road gradient	Percent
Road surface type	Native; graveled; paved.
Traffic class	High; low; none.
Fillslope gradient	Percent
Fillslope length	Meters
Buffer gradient	Percent
Buffer length	Meters

et al., 1999). The monthly climate statistics include: number of wet days; mean, standard deviation, and skew coefficient of the amount of precipitation on a day with precipitation; probabilities of a wet day after a wet day and a wet day after a dry day; mean wind speed; and the mean and standard deviation of maximum and minimum temperatures (Elliot et al., 1999). The historic monthly data from the selected weather station are used to calculate the daily precipitation depth, duration, and intensity for up to 200 years of a stochastically simulated climate (Elliot et al., 1999).

The Cheesman weather station was selected to generate the stochastic climate data for WEPP:Road, but from May to October the measured values from the tipping-bucket rain gauges were substituted for the historic mean monthly rainfall and number of wet days. The Cheesman weather station is believed to accurately represent the climate at the study sites because of its proximity and similar elevation, and the comparable summer rainfall data observed from 2001 to 2006 (Libohova, 2004; Pietraszek, 2006; Rough, 2007; Brown, 2008; Chapter 2). For the first year of monitoring at each site the precipitation was set to zero from January to the month prior to the installation of the sediment fence. The predicted sediment production was the mean from 50 years of simulated climate.

None of the OHV segments had an engineered design, and the runoff was not diverted from the active surface until the drainage outlet. In WEPP:Road these segments are best characterized as outsloped with ruts, as this applies to segments where the runoff does not flow onto the fillslope or to an inside ditch (Elliot et al., 1999). The soil texture of each OHV segment was classified as a sandy loam. The soil rock content (>2 mm) for each segment was determined from the subsurface particle-size distributions. Field measurements were used to define the length, width, and gradient of each segment. None of the segments had fillslopes, so the fillslope lengths and fillslope gradients were set to the minimum allowable values of 0.3 m and 0.1%, respectively. The buffer lengths and buffer gradients also were set to the minimum allowable values of 0.3 m and 0.1%, respectively, because the 3 to 5 m between the drainage outlet and the sediment fence was largely devoid of vegetation and did not function as a buffer (Figure 3.2). The traffic level of each segment was classified as high because the RRMRA is heavily used (USDA, 2005), and approximately 10 vehicles per day during the week and 50 vehicles per day during the weekend were observed while the field work was being conducted.

3.3.5.2. SEDMODL2

The governing equations in SEDMODL2 predict both sediment production and delivery from road segments in forested areas. Separate equations are used to calculate annual sediment production from the road segment surface and cutslope (BCC and NCASI, 2003). Sediment production from the road segment surface (SP_S) in U.S. tons per year is calculated by:

$$SP_S = G*RS*T*A*SS*R \tag{3.3}$$

where G is the geology factor, which ranges from one to five depending on the parent material and degree of weathering; RS is the surface factor, which ranges from 0.03 for paved roads to 2.0 for native surface roads with ruts; T is the traffic factor, which ranges from 0.1 to 120, depending on the average number of log truck and passenger vehicle passes per day as well as the width of the road; A is the segment area in acres; and SS is the segment slope factor (BCC and NCASI, 2003). SS is calculated by:

$$SS = (S/7.5)^2 \tag{3.4}$$

where S is the slope of the segment in percent. The rainfall factor (R) in equation 3.3 is calculated by:

$$R = 0.016(P)^{1.5} \tag{3.5}$$

where P is the annual rainfall in inches. If the mean annual rainfall is not provided by the user, SEDMODL2 uses the mean annual rainfall from the PRISM dataset (PRISM, 2007).

Sediment production from the cutslope (SP_C) in U.S. tons per year is calculated by:

$$SP_C = G*C_C*C_H*L*R \tag{3.6}$$

where G is the geology factor as defined previously; C_C is the cutslope cover factor, which ranges from 0.1023 for 100% cover to 1.0 for 0% cover; C_H is the cutslope height in feet, which is estimated from the hillslope gradient unless measured data are substituted by the user; L is the road segment length in feet; and R is the rainfall factor (equation 3.5).

SEDMODL2 uses a delivery factor (D) to calculate the proportion of surface and cutslope sediment production that is delivered to streams. The delivery factor (D) is based on the distance between the segment and the nearest stream channel (Table 3.5) (BCC and NCASI, 2003).

Table 3.5. Delivery factor values in SEDMODL2.

Distance from the segment to the nearest stream (m)	Delivery factor (D)
0	1.0
0.1 - 30	0.35
30 - 60	0.10
> 60	0.0

Sediment production and delivery from a road segment also can be adjusted by an age factor (equation 3.7):

$$SP_T = (SP_S + SP_C)*D*RA \tag{3.7}$$

In this equation SP_T is the total mass of sediment delivery in U.S. tons per year and *RA* is the categorical age factor, which ranges from 1.0 for segments that are more than two years old to 10.0 for segments that are less than one year old (BCC and NCASI, 2003).

In this study the geology factor (*G*) was set to 5.0 for each OHV trail segment because the soils are derived from weathered granite (BCC and NCASI, 2003). The surface factor (*RS*) was set to 2.0 because the surface of the OHV trail segments are native material with ruts (BCC and NCASI, 2003). The active area was used to calculate surface sediment production. The mean incised depth was used to define the cutslope height (C_H) when calculating cutslope sediment production. The traffic factor (*T*) of 10.0 was based on the mean traffic rate observed during the field work (BCC and NCASI, 2003). The rainfall factor (*R*) was calculated from the summer precipitation at each tipping-bucket rain gauge, as negligible amounts of sediment were produced from November through April. The age factor (*RA*) was set to 1.0 because the trails are much more than two years old. The sediment delivery factor (*D*) was 1.0 because sediment production was measured at the outlet of each segment.

3.3.6. Statistical Analysis

3.3.6.1. Sediment Production

The segment-scale analysis of sediment production focused on two dependent variables—storm-based and summer sediment production (Table 3.2). For this and other analyses the independent and dependent variables were log-transformed if the values were log-normally distributed. Univariate regressions were used to analyze the significance of each continuous independent variable on sediment production. Storm-based and summer sediment production values were normalized by segment length because length was more significantly related to sediment production than either active area or total area. Analysis of covariance was used to determine whether there was collinearity between the independent variables (SAS Institute, 2003). The 10 data points from 2006 were used to develop a univariate model for predicting annual sediment production from OHV trail segments. The number of storm-based sediment production values that could be paired with a single rainstorm was much larger ($n=138$), and stepwise multiple regression was used to develop a predictive model for storm-based sediment production from the OHV trail segments (SAS Institute, 2003). Independent variables were kept in the model if they were significantly related to storm-based sediment production ($p<0.05$). Model errors were evaluated using residuals and quartile-quartile plots (SAS Institute, 2003), and the exclusion of the extreme outliers led to an improved model as indicated by a lower Mallow's C_P and a much higher R^2.

3.3.6.2. Sediment Delivery

The dependent variables used in the analysis of sediment delivery included sediment plume length, outlet rill length, outlet rill volume, and connectivity class (Table 3.3). The datasets on sediment plume lengths and outlet rill lengths also were combined to create a larger dataset of drainage feature lengths (Table 3.3). The statistical methods used to analyze sediment delivery were similar to those used to analyze sediment production, and the effects of the categorical independent variables on sediment delivery were evaluated using Tukey's HSD (SAS Institute, 2003). Stepwise multiple regression was used to develop predictive models for sediment plume lengths, outlet rill lengths, drainage feature lengths, and outlet rill volumes (SAS Institute, 2003). Segments that were directly connected to a stream channel were not included in the datasets for model selection because their transport distances were truncated by the channel.

3.3.6.3. Model Testing

Several statistics were used to evaluate the accuracy of WEPP:Road and SEDMODL2 because no single statistic can fully characterize model performance (Willmott, 1981). The statistics used in this analysis were: (1) the slope (*b*), intercept (*a*), and coefficient of determination (R^2) of the least-squares linear regression between the predicted and measured sediment production; (2) the Nash-Sutcliffe model efficiency coefficient (R^2_{eff}) (Nash and Sutcliffe, 1970); and (3) the root-mean-square error (RMSE) (Willmott, 1981).

3.4. RESULTS

3.4.1. Precipitation

From 3 August 2005 to 31 October 2005 there were 24 storms and 124 mm of precipitation at the Log Jumper site. Over this period the total precipitation at Cheesman was nearly identical at 120 mm. The summer erosivity at Log Jumper was 192 MJ mm ha^{-1} h^{-1}, or about 60% of the mean annual erosivity for the study area (Renard et al., 1997) despite the relatively short period of monitoring. Most of the storms had low intensities (Figure 3.3), and a 13.8 mm storm on 16 August 2005 with a maximum I_{30} of 27 mm h^{-1} accounted for almost 50% of the measured erosivity.

Summer precipitation in 2006 was 330 mm at Log Jumper and 257 mm at Noddle. The record at Noddle did not begin until 20 May (Table 3.1), but this probably had very little effect because there was only 4.8 mm of precipitation at Log Jumper between 1 May and 19 May. Summer precipitation at Cheesman was 360 mm, which is 29% above the long-term mean.

In 2006 there were 53 storms at Log Jumper and 51 storms at Noddle, and 70% of the storms at each site had a maximum 30-minute intensity less than 10 mm h^{-1} (Figure 3.3). The summer erosivity at Log Jumper was 1150 MJ mm ha^{-1} h^{-1}, and this was four times the summer erosivity at Noddle. The largest storm in 2006 was 30 mm of rain at Log Jumper on 1 August. This storm had a maximum I_{30} of 59 mm h^{-1} and an erosivity of 481 MJ mm ha^{-1} h^{-1}, or 42% of the total summer erosivity. At Noddle the same storm generated only 6 mm of rainfall with an I_{30} of 8 mm h^{-1} and an erosivity of just 8 MJ mm ha^{-1} h^{-1}.

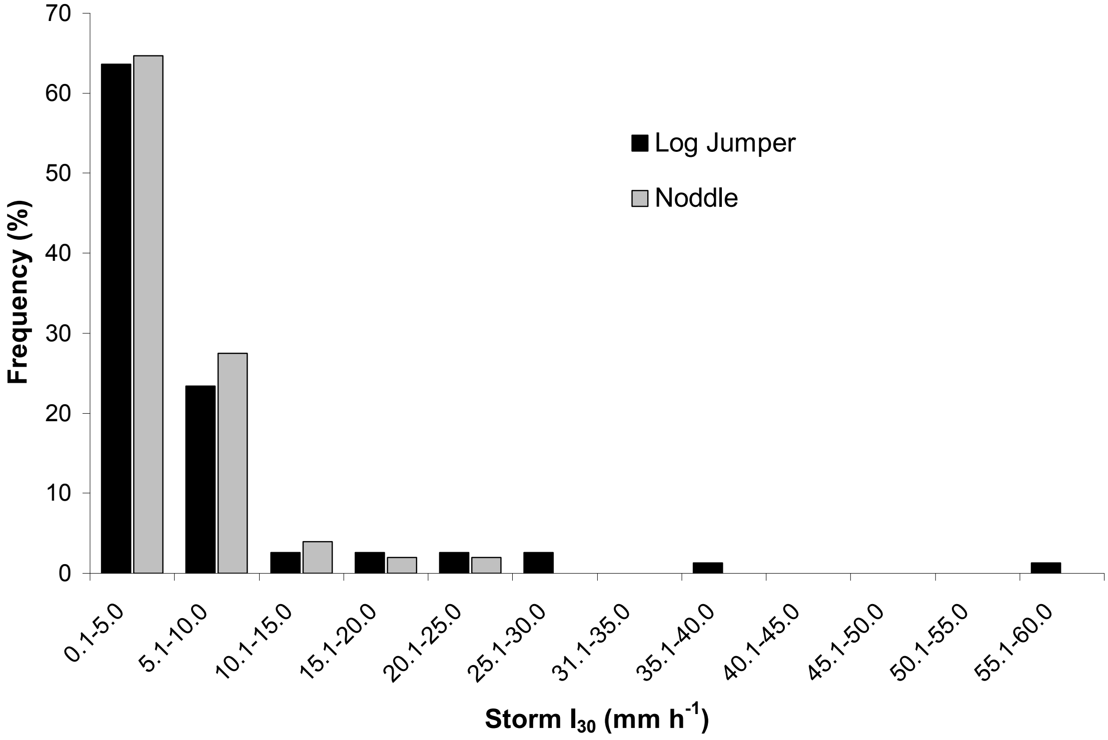

Figure 3.3. Frequency distribution of the maximum 30-minute rainfall intensity (I_{30}) for the 77 storms at Log Jumper in summer 2005 and 2006 and the 51 storms at Noddle in summer 2006.

3.4.2. OHV Segment Characteristics and Sediment Production

The mean length of the 10 OHV trail segments with a sediment fence was 45 m (s.d.=22 m). The mean active width was 2.0 m, and this was less than half of the mean total width of 4.5 m (Table 3.6). The mean segment length was 68% longer at Log Jumper than at Noddle (p=0.05), but active and total widths were similar between the two study sites (p>0.10) (Table 3.6). The mean depth of incision at Log Jumper was 0.38 m, or 3.5 times the mean depth of incision at Noddle (p=0.001). This difference may explain much of the difference in mean segment length, as the trails that are more deeply incised tend to have fewer drainage points (Table 3.6). Mean segment slope was 13% (s.d.=4%),

Table 3.6. Characteristics of the 10 segments with a sediment fence at the Log Jumper (LJ) and Noddle (NDL) study sites. An asterisk indicates that the mean values are significantly different between the two sites ($p<0.05$), and NA indicates that the fence was not installed until May 2006.

Segment	Length (m)	Slope (%)	Active width (m)	Total width (m)	Mean incised depth (m)	Percent bare soil (%) 2005	Percent bare soil (%) 2006	Sediment production (kg) 2005	Sediment production (kg) 2006
LJ1	93	17	1.7	3.8	0.31	97	95	707	6745
LJ2	45	14	1.9	4.7	0.36	81	78	265	1917
LJ3	37	9	1.7	4.6	0.50	93	87	201	1108
LJ4	51	17	1.8	4.3	0.39	88	88	58	2443
LJ5	58	15	1.8	4.4	0.35	92	95	508	4253
Mean	57*	14	1.8	4.3	0.38*	90	89	348	3293*
NDL1	38	5	3.1	5.5	0.00	NA	91	NA	35
NDL2	7	17	2.3	6.5	0.00	NA	82	NA	214
NDL3	43	15	1.9	4.9	0.33	NA	83	NA	1578
NDL4	41	9	1.8	3.0	0.14	NA	97	NA	416
NDL5	41	11	2.0	3.8	0.09	NA	93	NA	174
Mean	34*	11	2.2	4.7	0.11*	NA	89	NA	483*

and the segment slopes at Log Jumper were slightly but not significantly steeper than at Noddle ($p=0.21$) (Table 3.6).

The surface of the active area averaged 89% bare soil (s.d.=6%), 8% rock (s.d.=5%), 2% litter (s.d.=2%), and 1% wood (s.d.=1%) (Table 3.6). The mean mass of unconsolidated material on the segment surface was 7.8 kg m^{-2} (s.d.=2.9 kg m^{-2}), which corresponds to a total unconsolidated mass of about 700 kg for the mean active area of 90 m^2 (Tables 3.6, 3.7). This material was very coarse, as 63% of the surface particles were larger than 2 mm and only 3% of the unconsolidated material was finer than 0.063 mm (Figure 3.4). The subsurface soils also were very coarse, but there were slightly more fine particles relative to the unconsolidated surface material (Figure 3.4). The significantly lower amount of silt and clay particles in the unconsolidated surface material relative to the subsurface (p=0.001) (Figure 3.4; Table 3.7) indicates that the finer particles are being preferentially eroded from the unconsolidated surface material. Both the unconsolidated surface material and the subsurface soils were coarser at Log Jumper than at Noddle (Figure 3.4), but none of the particle-size distribution statistics were significantly different between sites (Table 3.7).

Table 3.7. Mean mass of unconsolidated material, soil rock content, and the D_{16}, D_{50}, and D_{84} for the surface and subsurface soils for each of the Log Jumper (LJ) and Noddle (NDL) study segments.

			Surface sample			Subsurface sample		
Segment	Unconsolidated material (kg m^{-2})	Soil rock content (%)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
LJ1	9.5	43	0.86	3.68	9.98	0.26	1.52	5.89
LJ2	10.3	38	1.13	4.18	11.08	0.20	1.31	4.59
LJ3	7.1	36	0.63	2.67	7.00	0.16	1.18	4.86
LJ4	12.7	45	0.81	3.36	8.67	0.28	1.66	6.35
LJ5	8.0	49	0.84	3.67	10.02	0.35	1.94	5.58
Mean	9.5	42	0.85	3.51	9.35	0.25	1.52	5.45
NDL1	6.1	45	0.18	1.33	5.48	0.18	1.58	7.78
NDL2	5.6	33	1.03	4.51	11.03	0.11	0.91	4.66
NDL3	10.5	42	0.43	2.47	7.33	0.30	1.52	5.55
NDL4	4.4	40	0.50	2.85	7.61	0.14	1.38	5.57
NDL5	3.8	44	0.25	2.23	8.22	0.15	1.51	6.90
Mean	6.1	41	0.48	2.68	7.94	0.18	1.38	6.09

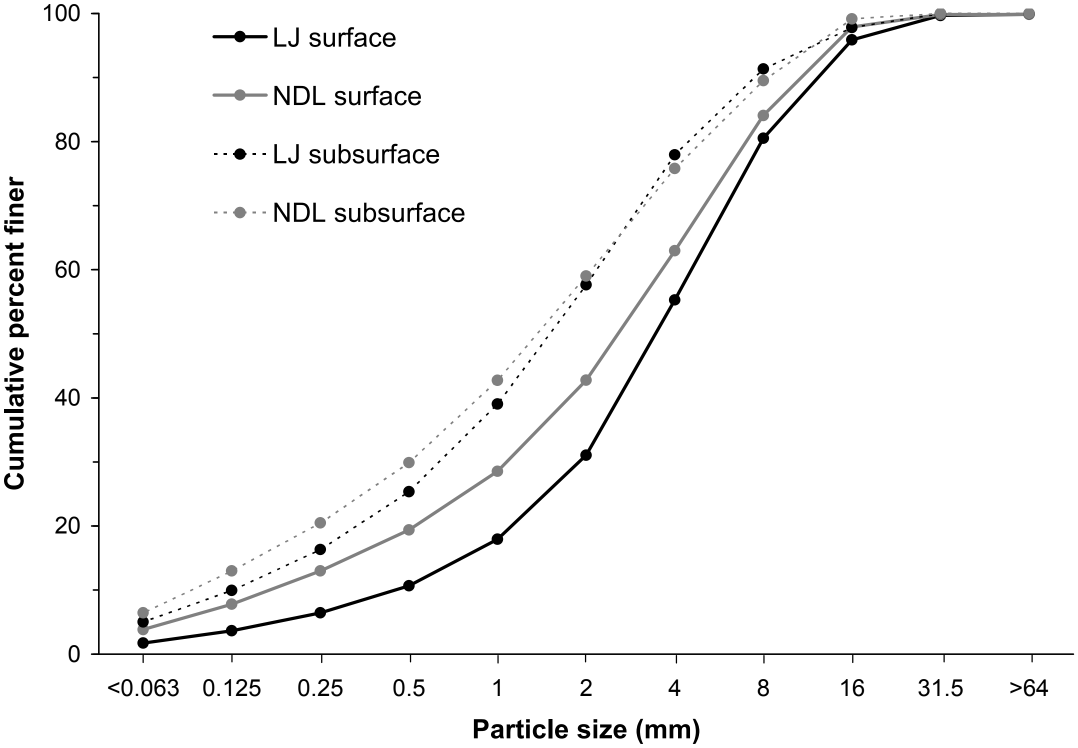

Figure 3.4. Particle-size distributions plotted on a phi ($\log_2$) scale for the surface and subsurface soils at Log Jumper (LJ) and Noddle (NDL).

3.4.2.1. Summer Sediment Production

Relatively large amounts of sediment were produced from most of the OHV trail segments with a sediment fence (Table 3.6). No sediment was produced from the five segments at Log Jumper from November 2005 through April 2006 or any of the 10 segments from November 2006 through December 2006, and this indicates that the summer 2006 values actually represent annual sediment production. Sediment production was normalized by the segment length because this explained 76% of the variation in sediment production (p=0.001). In contrast, the R^2 values were only 0.40 for active area (p=0.05) and 0.16 for total area (p=0.12).

At Log Jumper the mean sediment production was 5.8 kg m^{-1} from 5 August to 31 October 2005, and the range was from 1.1 to 8.8 kg m^{-1} (Table 3.6). In 2006 the mean sediment production at Log Jumper was 53.3 kg m^{-1} yr^{-1} (s.d.=19.1 kg m^{-1} yr^{-1}), or nearly ten times larger than in 2005. At Noddle the mean sediment production in 2006 was only 16.5 kg m^{-1} yr^{-1} (s.d.=16.1 kg m^{-1} yr^{-1}), and this difference was significant (p=0.038).

After normalizing by length, summer sediment production was most closely related to summer erosivity (R^2=0.57; p=0.011). Normalized sediment production also increased with segment slope (R^2=0.50; p=0.022) and the mass of unconsolidated material (R^2=0.43; p=0.039). There also was a marginally significant relationship between unit length sediment production and the depth of incision (R^2=0.38; p=0.057), which suggests that the measured sediment production rates are consistent with the long-term erosion rates. On a univariate basis, the 10 annual sediment production values from 2006 (SP_A) in kg yr^{-1} were best predicted using:

$$SP_A = 0.012(SL)^{1.8} \tag{3.8}$$

where SL is the segment slope (%) times the segment length (m). This model had an R^2 of 0.72.

3.4.2.2. Storm-based Sediment Production

The distribution of storm-based sediment production values was highly skewed, as the mean value was 114 kg as compared to the median value of only 5 kg. As with summer sediment production, the storm-based sediment production values were normalized by segment length because segment length was slightly more strongly related to sediment production (R^2=0.08; p=0.0006) than either total area (R^2=0.08; p=0.0010) or active area (R^2=0.05; p=0.0082). Storm-based sediment production rates were strongly dependent on storm erosivity (R^2=0.67; p<0.0001) (Figure 3.5), storm I_{30} (R^2=0.64; p<0.0001), and storm I_{10} (R^2=0.63; p<0.0001), and sediment was produced from each of the segments when the maximum I_{30} exceeded 10 mm h^{-1}. Normalized storm-based sediment production increased with segment slope (R^2=0.03; p=0.036) and decreased as the surface D_{50} increased (R^2=0.03; p=0.048). Each of these relationships is consistent with the underlying physical processes, but segment slope and surface D_{50} had relatively little explanatory power.

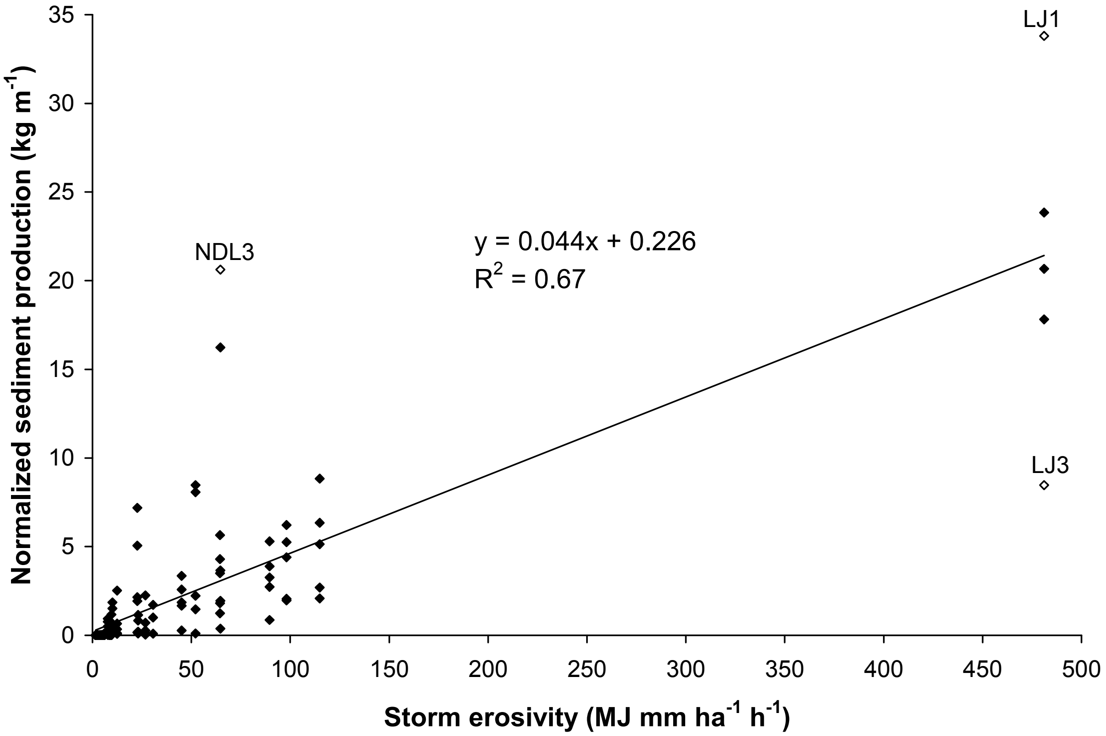

Figure 3.5. Storm-based sediment production normalized by segment length versus storm erosivity (n=138). The points indicated by an open diamond are the three outliers identified in the text.

The best empirical model for predicting storm-based sediment production is:

$$SP_{ST} = -156 + 3.22L + 2.71EI_{30} \tag{3.9}$$

where SP_{ST} is storm-based sediment production in kg, L is segment length in m, and EI_{30} is storm erosivity in MJ mm ha^{-1} h^{-1}. This model has an R^2 of 0.63, an adjusted R^2 of 0.62, and a relatively high root-mean-square error (RMSE) of 205 kg. The evaluation of studentized residuals and quartile-quartile plots indicated that three of the data points were extreme outliers. Two of the outliers represented the largest storm-based sediment production values at Log Jumper (LJ1) and Noddle (NDL3), respectively, and the third outlier was the lowest sediment production at Log Jumper (LJ3) for the largest rainstorm. If these three points are removed, the revised model becomes:

$$SP_{ST} = -86.9 + 1.87L + 2.26EI_{30} \tag{3.10}$$

This revised model has a much smaller intercept, a substantially higher R^2 (0.80), and a much lower RMSE (89 kg).

3.4.3. OHV Trail Surveys

The survey of eight OHV trail sections in the RRMRA covered a total distance of 10.1 km and identified 183 discrete segments (Table 3.8). The longest section was 2.6 km along the Noddle trail, while the shortest section was the 0.6 km section along the Log Jumper trail that included the five segments with sediment fences (Log Jumper-A). The surveyed length along the other six trails ranged from 1.0 to 1.3 km (Table 3.8).

Table 3.8. Summary of the survey data from the eight OHV trail sections in the Rampart Range Motorized Recreation Area and the overall totals or means. The means for the continuous variables are weighted by length. The values for the categorical variables are the number of segments in each category, and the numbers in parentheses represent the percent of total length for each categorical variable.

Section name	Bar	Cabin Ridge	Devil's Slide	Gramps	Log Jumper-A	Log Jumper-C	Long Hollow	Noddle	Total or overall mean
Surveyed distance (m)	976	1,178	1,131	1,096	598	1,255	1,224	2,640	10,098
Number of segments	24	11	19	18	16	23	19	53	183
Mean segment length (m)	41	107	60	61	37	55	64	50	60, s.d.=22
Mean segment slope (%)	11.9	7.3	9.0	5.5	16.1	8.0	11.5	12.7	10.3, s.d.=3.4
Mean active width (m)	1.9	2.7	1.8	2.2	1.9	2.7	1.8	1.9	2.1, s.d.=0.4
Mean incision depth (m)	0.32	0.04	0.22	0.20	0.34	1.24	0.13	0.24	0.33, s.d.=0.37
Hillslope position									
Ridgetop	2 (9)	11 (100)	2 (11)	16 (81)	1 (9)	21 (94)	4 (23)	19 (41)	76 (46)
Midslope	21 (81)	0 (0)	1 (27)	2 (19)	14 (78)	2 (6)	10 (44)	22 (35)	72 (36)
Valley bottom	1 (10)	0 (0)	16 (62)	0 (0)	1 (13)	0 (0)	5 (33)	12 (24)	35 (18)
Presence of an inside ditch									
Yes	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (4)	0 (0)	0 (0)	1 (0.5)
No	24 (100)	11 (100)	19 (100)	18 (100)	16 (100)	22 (96)	19 (100)	53 (100)	182 (99.5)
Drainage outlet type									
Pushout	20 (78)	6 (60)	13 (76)	5 (13)	5 (25)	15 (53)	10 (52)	23 (42)	97 (50)
Culvert	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Waterbar/dip	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
No drainage	4 (22)	5 (40)	6 (24)	13 (87)	11 (75)	8 (47)	9 (48)	30 (58)	86 (50)
Outlet rill below drainage	4 (11)	1 (5)	1 (3)	1 (34)	2 (15)	7 (36)	1 (4)	11 (28)	28 (17)
Sediment plume below drainage	22 (88)	7 (68)	13 (76)	14 (45)	14 (85)	15 (61)	15 (82)	35 (56)	135 (70)
Roughness below sediment plume									
High	6 (34)	2 (28)	4 (62)	4 (28)	0 (0)	1 (4)	4 (34)	5 (11)	26 (25)
Medium	15 (63)	4 (66)	5 (23)	10 (72)	9 (60)	10 (58)	8 (47)	21 (59)	82 (56)
Low	1 (3)	1 (6)	4 (15)	0 (0)	5 (40)	4 (38)	3 (19)	9 (30)	27 (19)
Connectivity class 4 (%)	25.6	0.0	62.2	34.4	13.4	13.3	28.1	19.7	24.2, s.d.=18.5

The mean segment length was 60 m (s.d.=22 m), which is 33% longer than the mean length of 45 m for the segments with a sediment fence (Tables 3.6, 3.8). The mean segment slope was 10.3% (s.d.=3.4%), which is slightly less than the mean value of 13% for the 10 segments with sediment fences (Tables 3.6, 3.8). This difference is largely due to the fact that five of the monitoring segments were on the Log Jumper-A trail, which had the highest mean segment slope at 16% (Table 3.8). The overall mean active width of 2.1 m and total width of 5.4 m were very comparable to the mean values for the segments with sediment fences (Tables 3.6, 3.8).

All of the surveyed OHV trails were heavily used and had at least 85% bare soil on the active trail surface. One-half of the surveyed length had no engineered drainage, while the other half was drained by pushouts (Figure 3.6). Forty-six percent or 4.6 km of the surveyed length was on a ridgetop, 36% was in a midslope position, and 1.8 km or 18% was in a valley bottom location (Table 3.8). Ninety-three percent of the surveyed segments were incised into the hillslope, and the mean incised depth for the surveyed segments was 0.33 m as compared to the mean of 0.25 m for the segments with sediment fences (Tables 3.6, 3.8). The shallower depth of incision on the monitoring segments is because two segments at Noddle were not incised (Table 3.6). The overall presence and depth of incision suggests that nearly the entire OHV trail network has been generating approximately as much sediment as the segments with sediment fences.

Seventy-four percent of the 183 segments had a sediment plume below the drainage outlet, 15% had an outlet rill, and only 11% had no drainage feature (Table 3.8). The mean sediment plume length was 26 m, and this was significantly less than the mean outlet rill length of 74 m ($p<0.0001$). Twenty-one percent of the sediment plumes and

Figure 3.6. A pushout drainage channeling runoff from the Devil's Slide trail directly into a perennial stream channel that is just off the right side of the photograph.

outlet rills that did not intersect a stream were more than 50 m in length, and 10% were longer than 100 m. Outlet rills were only present when the hillslope gradient below the drainage outlet was more than 20%.

The sediment plume and outlet rill lengths were positively and significantly correlated with the maximum rill depth on the trail surface ($R^2=0.19$; $p<0.0001$), segment slope ($R^2=0.10$; $p<0.0001$), segment length ($R^2=0.08$; $p=0.005$), and the mean depth of trail incision ($R^2=0.03$; $p=0.047$). The best empirical model for predicting drainage feature lengths is:

$$FL = 8.86 + 44.1OR + 16.4RD \tag{3.11}$$

where *FL* is the feature length in meters, *OR* is a binary variable where 0 represents a sediment plume and 1 indicates an outlet rill, and *RD* is a categorical variable for the maximum rill depth on the trail surface (<1 cm is 1, 1-10 cm is 2, 11-20 cm is 3, and >20 cm is 4). Maximum rill depth is relevant because deeper rills indicate more overland flow and erosive power (Knighton, 1998). The R^2 for this model is 0.41, the adjusted R^2 is 0.40, and the RMSE is 26.7 m or 76% of the mean value.

Outlet rill volumes were significantly higher in valley bottom locations than on ridgetops (p=0.029). The road erosion literature suggests that this difference could be due to the greater potential to intercept subsurface stormflow in valley bottoms than on ridgetops (Bowling and Lettenmaier, 2001). In the case of the study area, however, the short duration of the sediment producing storms and the dry conditions during the summer mean that subsurface flow is unlikely to be intercepted by the OHV trails. The outlet rills located in valley bottoms had higher corresponding hillslope gradients than the outlet rills in midslope and ridgetop locations (p=0.02), and the greater runoff energy associated with the steeper hillslope gradients is a more plausible explanation for the larger rill volumes in valley bottoms. None of the other independent variables were significantly related to the volume of the outlet rills, so an empirical predictive model was not developed.

Thirty-six or 20% of the 183 segments were delivering runoff and sediment to a stream channel (CC4). These segments represented 24% of the surveyed length (Table 3.8). All of the OHV trails except for Cabin Ridge had at least one segment connected to a stream, and on the Devil’s Slide trail 84% of the segments were connected. The proportion of an OHV trail classified as CC4 was best explained by the hillslope position of the trail (p<0.0001), as 78% of the segments connected to a stream channel were located in valley bottoms, 14% were in a midslope position, and only 8% of the connected segments were on ridgetops (Figure 3.7). Connectivity class increased with deeper rills on the trail surface (p<0.0001) and steeper segment slopes (p<0.0001). Deeper rills indicate more surface runoff and steeper segment slopes increase the energy of the runoff (Knighton, 1998), so it follows that feature length should increase with rill depth and segment slope. The connectivity class also tended to be higher for wider active widths (p=0.086) and longer segments (p=0.097), as the amount of surface runoff will increase with segment area and more runoff should increase feature lengths.

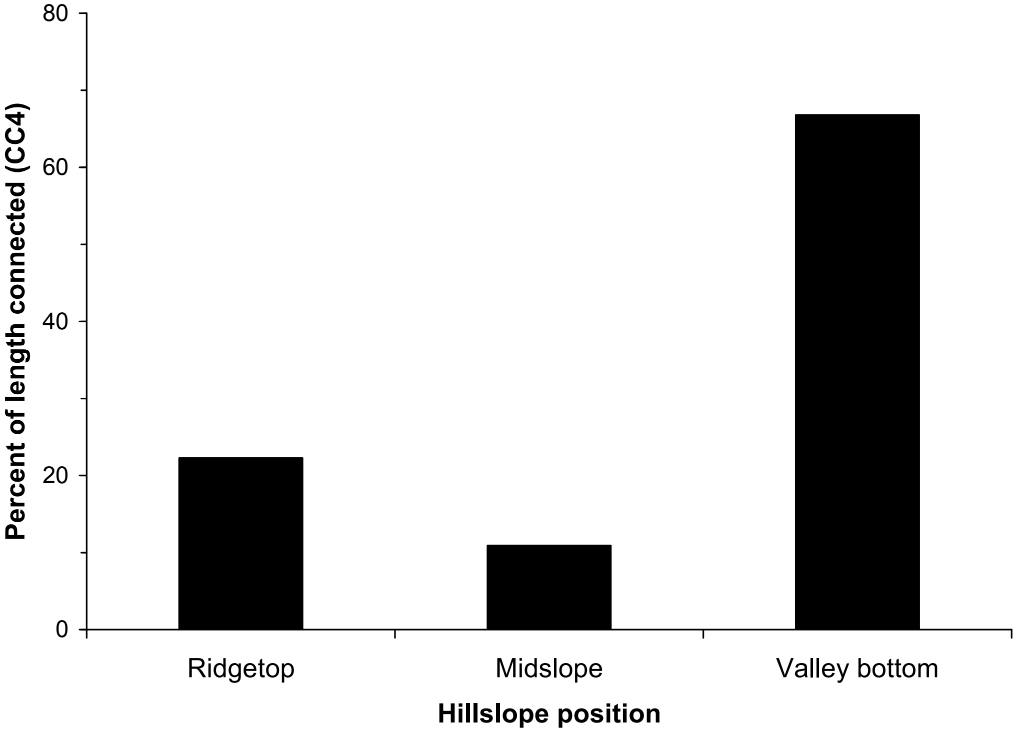

Figure 3.7. Percent of OHV trail length that is delivering runoff and sediment to the stream network (CC4) by hillslope position.

3.4.4. Model Testing

There was a strong correlation between the measured sediment production values and the predicted values using WEPP:Road (R^2=0.80) and SEDMODL2 (R^2=0.71), but this correlation only shows that the predicted values followed the same relative trends in the measured data (Figures 3.8, 3.9). In absolute terms neither of the models was more accurate than simply using the mean measured value, as the R^2_{eff} was -0.37 for WEPP:Road and -2.0 for SEDMODL2 (Table 3.9). Overall, WEPP:Road greatly under-predicted sediment production from the OHV trail segments, while SEDMODL2 consistently over-predicted sediment production (Figures 3.8, 3.9). The overall RMSE for WEPP:Road was 2134 kg yr^{-1}, or about 1.5 times the mean measured value, while the RMSE for SEDMODL2 was 3161 kg yr^{-1}. As indicated by the high R^2 values, the absolute magnitude of the prediction errors increased as the measured values increased, and the larger RMSE for SEDMODL2 relative to WEPP:Road is largely due to the severe over-prediction for one segment on the Log Jumper trail (LJ4). If this data point is removed from the dataset, the R^2_{eff} for SEDMODL2 improves from -2.0 to -0.34 and the RMSE drops by one-third to 2078 kg yr^{-1}.

Table 3.9. Statistics comparing the use of WEPP:Road and SEDMODL2 to predict sediment production from OHV trail segments.

Statistic	WEPP:Road	SEDMODL2
R^2	0.80	0.71
R^2_{eff}	-0.37	-2.01
RMSE (kg yr^{-1})	2134	3161
b (slope)	0.05	1.62
a (intercept) (kg yr^{-1})	63	1448

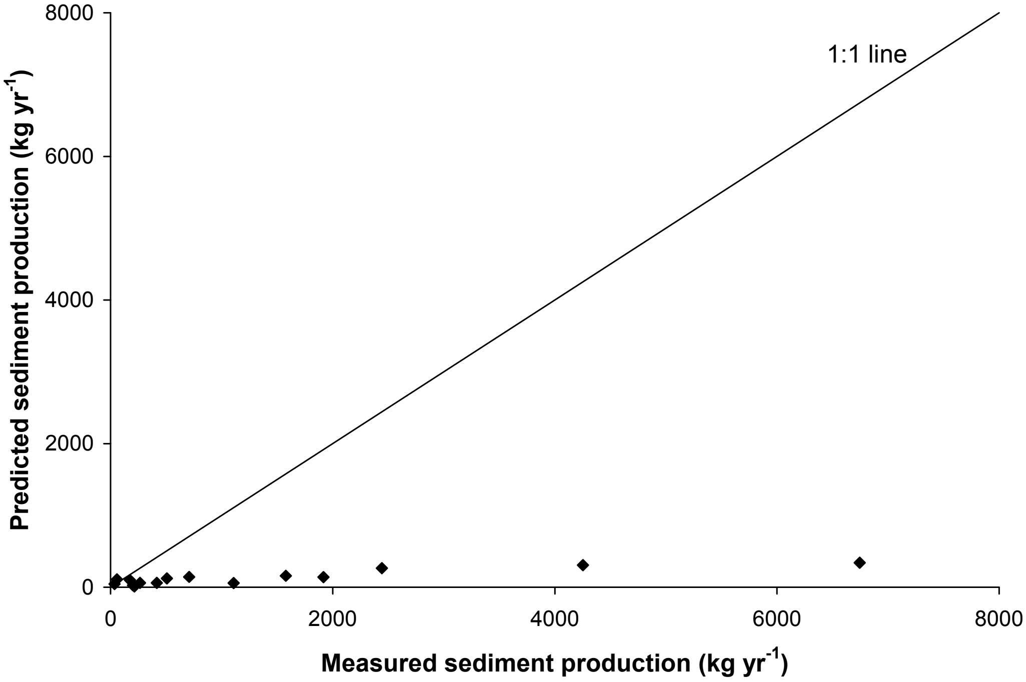

Figure 3.8. Predicted sediment production using WEPP:Road versus the measured values (n=15).

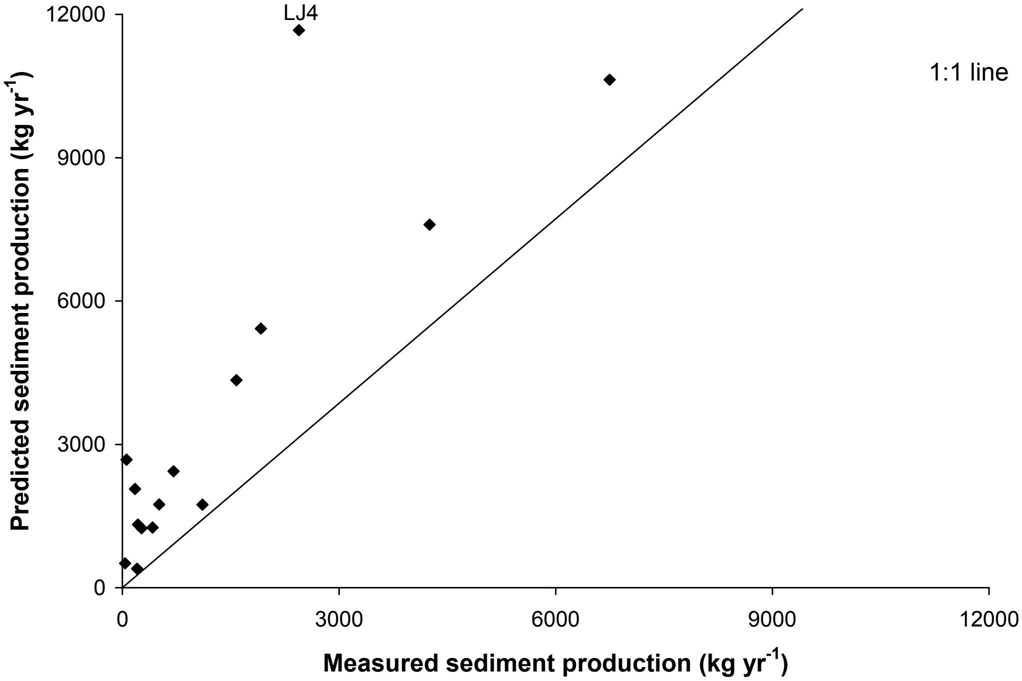

Figure 3.9. Predicted sediment production using SEDMODL2 versus the measured values (n=15).

3.5. DISCUSSION

3.5.1. Sediment Production

Sediment production from OHV trails increased with segment length and segment slope, and similar relationships have been documented for sediment production from forest roads (e.g., Luce and Black, 1999; MacDonald et al., 2001; Ramos-Scharrón and MacDonald, 2005; Coe, 2006). The physical basis for these relationships is that the amount of surface runoff increases with increasing length or surface area, and the amount of shear stress and sediment transport capacity are directly proportional to segment slope (Knighton, 1998). Alternatively, some road erosion studies have shown that segment length or area times segment slope, sometimes raised to a power from 1.0 to 2.0, is an accurate predictor of road sediment production (Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005). In this study segment length times segment slope raised to the 1.8 power (equation 3.8) explained 72% of the variability in annual sediment production from OHV trails. These results—plus the similarities in runoff and erosion processes—indicate that much of the research on road sediment production should be applicable to OHV trails.

Annual sediment production also increased with an increasing mass of unconsolidated material on the segment surface ($p=0.039$). This loose unconsolidated sediment was relatively coarse and had little or no cohesion. Road erosion studies have shown that sediment production increases with the amount of easily detached particles on the road surface (e.g., Luce and Black, 1999; Ziegler et al., 2001a; Ramos-Scharrón and MacDonald, 2005; Coe, 2006). The main difference between these road erosion studies and the OHV trails in the USPR watershed is that the unconsolidated material on the

OHV trails is primarily sand and fine gravel and therefore much coarser (Table 3.7; Figure 3.4). Nevertheless, the positive correlations between sediment production and both the mass of unconsolidated material and storm erosivity (Figure 3.5) indicate that the surface runoff from the OHV trails is sufficient to detach and transport some of this surface material. The deficit of fine particles in the unconsolidated material on the trail surface relative to the subsurface soils (Table 3.7; Figure 3.4) also indicates that the smaller particles are being preferentially eroded.

Traffic increases the supply of unconsolidated particles on the road surface by breaking down the larger particles (Bilby et al., 1989; Foltz, 1996; Ziegler et al., 2001a), and traffic also can pump more fines to the surface under wet conditions (Bilby et al., 1989; Ziegler et al., 2001b). However, this latter process is probably less important in this study due to the relatively dry conditions and the relative lack of fine particles in the subsurface soils (mean D_{16}=0.21 mm; Table 3.7). The incision of the OHV trails into the hillslope means that there is a tendency for the dirt bikes and all-terrain vehicles (ATVs) to drive on the exposed sideslopes, particularly on the outside corners, and this sideslope erosion further increases the supply of unconsolidated material and finer particles. These trends and processes indicate that sediment production from OHV trails would be reduced by reducing the number of users.

Sediment production from the OHV trails also increased with the depth of trail incision (p=0.057). This intuitively makes sense, as a greater incision depth indicates a higher average sediment production rate since a given trail was created. The depth of incision was weakly but significantly correlated with the gradient of the adjacent hillslope (R^2=0.09; p=0.0002), as more incision is needed to create a horizontal trail surface of uniform width on steeper hillslopes. Since particle resistance to incipient motion decreases as slope increases (Cutnell and Johnson, 2004), trail incision should increase on steeper hillslopes as the vehicles drive on the exposed sideslopes and detach soil particles. These physical relationships indicate that the depth of incision and sediment production rates can be reduced by constructing and relocating OHV trails onto more gentle hillslopes.

In 2006 the mean annual sediment production at Log Jumper was 6.8 times higher than at Noddle (p=0.04), and this difference can be attributed to the differences in mean segment length, summer erosivity, mean segment slope, and mean trail incision. The relative importance of these factors can be assessed by the magnitude and significance of the remaining difference after normalizing the data by each of these variables. At Log Jumper the mean segment length was 1.7 times the mean value at Noddle, and normalizing sediment production by segment length reduced the difference in sediment production to a factor of 3.2 (p=0.04). The summer erosivity at Log Jumper was four times the summer erosivity at Noddle, and normalizing sediment production by summer erosivity reduced the difference between sites to a factor of 1.7, and this residual difference was not significant at p=0.27. The mean segment slope was 1.3 times higher at Log Jumper than at Noddle, but normalizing sediment production by segment slope only reduced the difference between study sites to a factor of 5.8 (p=0.03). The mean trail incision depth was 0.38 m at Log Jumper, or 3.4 times the value at Noddle, and sediment production normalized by incision depth was only 1.4 times higher at Log Jumper than at Noddle (p=0.34). These results indicate that the large difference in sediment production between sites can be attributed primarily to the much higher summer erosivity and deeper trail incision at Log Jumper as compared to Noddle.

A key question for assessing cumulative watershed effects is how sediment production rates from the OHV trails compare to the values from unpaved roads. A unique aspect of the present study is that sediment production rates were available from 14-22 native surface road segments in the same study area for 2001 to 2006 (Libohova, 2004; Brown, 2008; Chapter 2). Over this six-year period the mean road sediment production rate was 3.5 kg m^{-2} yr^{-1}, but the mean annual values varied from 0.5 kg m^{-2} yr^{-1} to 6.7 kg m^{-2} yr^{-1}, largely in response to the interannual variations in rainfall intensity and erosivity (Libohova, 2004; Brown, 2008; Chapter 2). In 2006 the mean annual sediment production rate from the 21 road segments was 3.1 kg m^{-2} yr^{-1}, which was just 11% below the overall mean. In contrast, the mean value from the 10 OHV trail segments was six times greater or 18.5 kg m^{-2} yr^{-1} in 2006 ($p=0.01$), and the OHV trail segments had a much greater range of sediment production values (Figure 3.10). Almost half of this six-fold difference in unit area sediment production can be attributed to a difference in summer erosivity, as the mean summer erosivity for the OHV trail segments in 2006 was 1150 MJ mm ha^{-1} h^{-1} or 2.2 times the mean value for the road segments. If the sediment production data are normalized by summer erosivity (EI_{30}), the OHV segments generated 0.024 kg m^{-2} EI_{30}^{-1} yr^{-1}, or twice the value of 0.012 kg m^{-2} EI_{30}^{-1} yr^{-1} for the road segments, and this remaining difference was still significant at $p=0.03$.

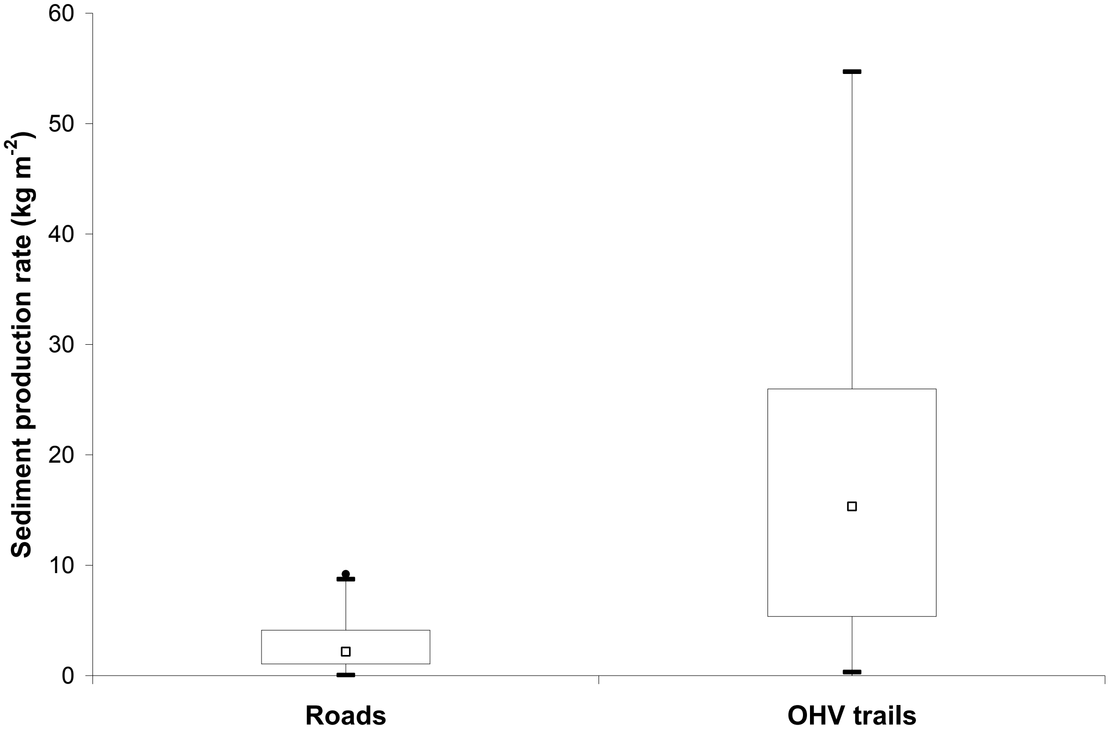

Figure 3.10. Boxplots of unit area sediment production from 21 road segments and 10 OHV trail segments in 2006. The small squares are the median, the boxes represent the 25th and 75th percentiles, the bars indicate the 95% confidence interval, and the closed circle is an outlier.

The remaining two-fold difference in sediment production rates between OHV trails and roads can be most easily attributed to the significant difference in segment slopes, as the OHV trail segments had a mean slope of 13% compared to 10% for the road segments ($p=0.048$). Sediment production increased with increasing segment slope for both OHV trails ($p=0.02$) and roads ($p<0.0001$). Normalizing the unit area sediment production rates by both summer erosivity and segment slope reduces the difference in sediment production between OHV trails and native surface roads to a factor of 1.4, which is not significant ($p=0.34$).

Other factors—particularly the greater amount of traffic and the greater amount of unconsolidated material on the OHV trails—also may contribute to the greater sediment production from the OHV trails relative to roads. For forest roads the average traffic rate ranged from 0.3 to 3.2 vehicles per day (Chapter 2), while for OHV trails the estimated traffic rates during the summer ranged from about 10 vehicles per day on weekdays to 50 vehicles per day on weekends. The amount of unconsolidated material was not measured on the unpaved road segments, but field observations indicated that the OHV trails had at least an order of magnitude more unconsolidated material on the travelway than the roads. These two factors are not independent, as the greater amount of unconsolidated material on the OHV trails is at least partially due to the higher traffic rates and possibly also the type of traffic. Although the contribution of these two factors to the difference in sediment production between OHV trails and roads cannot be readily quantified, the observed difference in sediment production rates can be explained by the differences in the key underlying causal processes, namely summer erosivity, segment slope, and traffic.

3.5.2. Sediment Delivery

The effects of OHV trails on water quality and stream habitat are dependent on the connectivity between OHV trails and the stream channel network. Connectivity to streams should increase with increasing OHV trail and stream densities (Jones et al., 2000; Coe 2006), and also should increase with the transport distance of runoff and sediment from OHV trails. Transport distance varied with the type of geomorphic feature below the drainage outlet, as the mean length of outlet rills was about three times the mean length of sediment plumes.

Outlet rills were more common on steeper hillslopes (p=0.001), steeper segments (p=0.02), and longer segments (p=0.02). These relationships have a strong physical basis, as runoff delivered onto steeper hillslopes will have more energy and erosive power. Longer segments generate more surface runoff and sediment that is more likely to travel further, and steeper segments have more runoff energy and higher sediment production rates. The increase in shear stress associated with longer and steeper segments increases the likelihood of an outlet rill, and this trend is consistent with studies of sediment delivery from forest roads (Montgomery, 1994; Wemple et al., 1996; Coe, 2006).

The outlet rill and sediment plume lengths reported in this study are greater than the values reported for forest roads on granite geologies. In the central Sierra Nevada of California the mean length for sediment plumes and outlet rills from unpaved roads was 12 m (Coe, 2006), and a nearly identical value of 11 m was reported for unpaved roads in the Idaho batholith (Megahan and Ketcheson, 1996). Similarly, the mean length of sediment plumes and outlet rills from road segments in this study area was 25 m (Libohova, 2004), or 29% less than the overall mean length of 35 m for the outlet rills and sediment plumes from OHV trails. The longer feature lengths from OHV trails is somewhat surprising since the mean contributing area of the road segments is 2.5 times the mean contributing area of the OHV trails. If the drainage feature lengths are normalized by mean contributing area, the mean length of the drainage features from OHV trails are 3.5 times the mean length from roads.

There are at least two reasons for this large difference in drainage feature length per unit of segment surface area. First, the mean segment slope is 30% higher on OHV trails than on roads, and this increases the erosive power and the transport capacity of the runoff on OHV trails relative to the roads. Second, the mean hillslope gradient below OHV trails is 1.5 times greater than the mean hillslope gradient below roads, and this again increases the runoff energy and erosive power relative to the runoff from the road segments. These results show that the greater erosive power and transport capacity of runoff from OHV trails due to the steeper segment slopes and steeper hillslopes more than counterbalances the larger amount of runoff from roads. These relationships mean that the probability and length of outlet rills from OHV trails can be most easily reduced by decreasing segment lengths and increasing the number of drainage points. A better solution would be to outslope and relocate the OHV trails in order to reduce segment slopes and hillslope gradients, but this would be a much more expensive alternative. It also is not clear whether outsloping could be maintained given the highly erodible soils and high traffic rates.

Another important question for assessing cumulative watershed effects is how the connectivity between OHV trails and streams compares to the connectivity between roads and streams. A survey of 17.3 km of roads in the study area showed that only 14% of the road length was delivering sediment to the stream network (Libohova, 2004; Brown, 2008) as compared to 24% for the OHV trails. As with the OHV trails, there was considerable variability in connectedness; values ranged from 0% for the Kelsey and Nighthawk roads to 67% for the Trumbull road. The higher connectivity for the OHV trails is largely because 19% of the OHV trails were in the valley bottoms as compared to only 4% of the roads. The strong propensity of connected segments to be located in the valley bottoms means that relocating roads and OHV trails out of the valley bottoms would have the greatest benefit in terms of reducing sediment delivery to streams.

The availability of sediment production and delivery data from both OHV trails and roads provides a unique opportunity to compare their relative contribution to watershed-scale sediment yields. The density of OHV trails in the Horse Creek, Buffalo Creek, and Waterton-Deckers subbasins of the USPR watershed is 0.2 km km^{-2}, while the density of roads is three times greater at 0.6 km km^{-2}. The mean width of OHV trails was 2.0 m as compared to 3.2 m for the relatively narrow roads. The measured annual sediment production rates for OHV trails and roads were normalized by the summer erosivity, averaged, and then multiplied by the mean annual rainfall erosivity of 340 MJ mm ha^{-1} h^{-1} (Renard et al., 1997) (Table 3.10). This yielded a mean annual sediment production value of 4.1 kg m^{-2} yr^{-1} for roads and 8.2 kg m^{-2} yr^{-1} for OHV trails. Multiplying these values by the respective mean active widths and densities yielded a watershed-scale sediment production rate of 7.8 Mg km^{-2} yr^{-1} for roads and 3.3 Mg km^{-2} yr^{-1} for OHV trails. Multiplying these sediment production values by the percent of length connected to the stream channels indicates that roads are delivering approximately 1.1 Mg km^{-2} yr^{-1}, while OHV trails are delivering about 0.8 Mg km^{-2} yr^{-1}, or nearly as much as the road network (Table 3.10). These calculations indicate that OHV trails are nearly as an important sediment source as unpaved roads in this portion of the USPR watershed.

Table 3.10. Estimated sediment delivery to stream channels from OHV trails and roads in the 570 km^2 study area using a mean annual erosivity (EI_{30}) of 340 MJ mm ha^{-1} h^{-1}.

Sediment source	Density ($km\ km^{-2}$)	Active width (m)	Normalized sediment production ($kg\ m^{-2}\ EI_{30}{}^{-1}\ yr^{-1}$)	Connectivity (%)	Sediment delivery ($Mg\ km^{-2}\ yr^{-1}$)
OHV trails	0.2	2.0	0.024	24	0.8
Roads	0.6	3.2	0.012	14	1.1

3.5.3. WEPP:Road and SEDMODL2: Sensitivity and Possible Improvements

The low Nash-Sutcliffe efficiency (R^2_{eff}) and high root-mean-square error (RMSE) values indicate that neither WEPP:Road nor SEDMODL2 can accurately predict sediment production from OHV trail segments (Table 3.9). Differences between the measured and predicted sediment production values can result from model errors, errors in the input data, and errors in the measured sediment production (“output data”). The uncertainty of several key inputs and outputs were quantified in Chapter 2, and this indicated that the inaccurate predictions for road sediment production were primarily a result of model errors.

Sensitivity analyses were conducted to identify the variables in WEPP:Road and SEDMODL2 with the largest effect on predicted sediment production. If the predicted effect of key variables on sediment production is inconsistent with the corresponding relationships derived from the field data, this suggests that one or more of the governing equations are incorrect. The baseline OHV trail segment used for the sensitivity analysis of WEPP:Road was based on the mean values from this study: 45 m length, 2.0 m width, 13% gradient, outsloped design with ruts, native surface, sandy loam soil texture with a soil rock content of 42%, and high amounts of traffic.

Figure 3.8 showed that WEPP:Road severely under-predicted the sediment production from OHV trails, but the R^2 of 0.80 indicates that the predicted values were well correlated with the observed values. The detailed comparisons of the road sediment production rates and the predicted values using WEPP:Road (Chapter 2) indicated that the governing equations for precipitation, soil rock content, and segment slope need revising, and the same concerns may be raised for predicting sediment production from OHV trails.

The sensitivity analysis of WEPP:Road conducted for road sediment production showed a nonlinear increase in predicted sediment production with increasing annual precipitation (Figure 2.13). For the baseline OHV trail segment a doubling of the mean monthly precipitation for the Cheesman climate increased the predicted sediment production from 105 kg yr^{-1} to 227 kg yr^{-1}, or 2.15 times. Reducing the mean monthly precipitation values to 0 mm still resulted in a mean sediment production rate of 53 kg yr^{-1} because the annual precipitation over the 50 years of simulated climate still ranged up to 375 mm. This result helps to explain the decline in sensitivity as the mean annual precipitation decreases, as most of the sediment is generated by the wetter years that are still present regardless of the annual mean.

An analysis of the field data from the OHV trail segments shows that storm-based sediment production increases linearly with storm rainfall (R^2=0.31; $p<0.0001$):

$$SP_{ST} = 0.42P - 2.67 \qquad (3.12)$$

where SP_{ST} is storm-based sediment production in kilograms per meter of segment length and P is storm rainfall in mm. This equation indicates that doubling the storm rainfall from the mean value of 11.3 mm to 22.6 mm should increase sediment production by 3.3 times, which is 53% more than the increase predicted by WEPP:Road as a result of doubling the mean annual rainfall. This suggests that WEPP:Road under-predicts the increase in sediment production with increasing precipitation, and this is consistent with the overall tendency of WEPP:Road to under-predict sediment production from the OHV trails in this study.

The sensitivity analysis in Chapter 2 showed that increasing the soil rock content exponentially increased sediment production predicted with WEPP:Road until the soil rock content exceeded 50% (Figure 2.14). Further increases in the soil rock content had no effect. The initial increase in predicted sediment production with increasing soil rock content is due to the decrease in porosity and the increased tortuosity of the subsurface flow paths (Flanagan and Nearing, 1995). These changes decrease the hydraulic conductivity and increase the magnitude and frequency of overland flow.

An analysis of the field data shows no significant relationship between soil rock content and OHV trail sediment production normalized by segment length and summer erosivity ($p=0.46$). Road erosion studies in Colorado (Chapter 2), Montana (Sugden and Woods, 2007), and California (Coe, 2006) as well as a hillslope erosion study in Spain (Cerda, 2001) have all shown a decrease in sediment production as soil rock content increases. This decrease is probably due to the greater proportion of coarse particles on the surface, which dissipate rainsplash energy, increase the critical shear stress, and increase surface roughness (Knighton, 1998; Luce and Black, 1999; Cerda, 2001). The absence of a similar relationship for the OHV trail segments in this study may be due to the limited sample size, but the large amount of coarse unconsolidated sediment on the OHV trails suggests that the high amounts of OHV traffic may have a somewhat different effect on the trail surface in this geologic setting than the light traffic on the native surface roads.

A series of simulations with WEPP:Road showed that the predicted sediment production for the baseline OHV trail segment increased linearly with segment slope ($R^2=0.99$; $p<0.0001$):

$$SP_P = 7.52(S) + 2.72 \tag{3.13}$$

where SP_P is predicted sediment production using WEPP:Road in kg yr^{-1} and S is segment slope (%). The linear relationship caused the relative sensitivity coefficient (R_S) values to range from only 0.75 to 1.25 regardless of the absolute change in segment slope for the baseline segment. This indicates that a given percent change in segment slope leads to a roughly similar percent change in the predicted sediment production.

An analysis of the field data showed that 50% of the variability in annual sediment production from OHV trails can be explained by segment slope:

$$SP_A = 3.88(S) - 16.3 \tag{3.14}$$

where SP_A is annual sediment production (kg m^{-1} yr^{-1}) and S is segment slope (%). Doubling the mean segment slope from 13% to 26% in equation 3.14 increases the expected sediment production from 34.1 kg m^{-1} yr^{-1} to 84.6 kg m^{-1} yr^{-1}, or 2.5 times. This indicates that the predicted increases in OHV trail sediment production in WEPP:Road with increasing segment slope are too small, and the slope of the linear regression in WEPP:Road (equation 3.13) should be steeper.

In contrast to WEPP:Road, SEDMODL2 severely over-predicted the sediment production from OHV trails (Figure 3.9), and this indicates that one or more of the factor values are too high. The sensitivity analysis for SEDMODL2 and the analysis of the field data from unpaved roads (Chapter 2) showed that the maximum geology factor of 5.0 is still too low given the highly erodible soils in the study area. This indicates that there is little basis for lowering the geology factor in order to reduce the over-prediction for OHV trails. The detailed analyses in Chapter 2 also indicated that the governing equations in SEDMODL2 for the traffic and rainfall factors may need to be revised in order to improve model performance for OHV trails, and the following sections conduct a sensitivity analysis of these two factors and compare these results against the trends in the field data. As in Chapter 2, the baseline OHV trail segment for the sensitivity analyses used the mean parameter values from this study, and these were a geology factor of 5.0, a road age factor of 1.0, a road surface factor of 2.0, a traffic factor of 10.0, and 237 mm of summer rainfall.

The traffic factor is one of the most important variables in SEDMODL2, as values can range from 0.1 to a maximum of 120 for wide roads with more than five log trucks per day (BCC and NCASI, 2003). The linear structure of SEDMODL2 means that a unit change in the categorical traffic factor causes a corresponding unit change in predicted sediment production. The documentation for SEDMODL2 (BCC and NCASI, 2003) indicates that the traffic factor values were developed with road erosion data from the Pacific Northwest (Reid and Dunne, 1984; Foltz, 1996; WDNR, 1997), but the ratios between the values for high traffic roads and low traffic roads indicate that the values were based primarily on the data from Reid and Dunne (1984).

The selected traffic factor of 10.0 for the OHV trail simulations was estimated from the traffic rates observed during the summer field work and the technical documentation for SEDMODL2 (BCC and NCASI, 2003). However, the applicability of the traffic factor values in SEDMODL2 to OHV trails is uncertain for several reasons. First, the OHV trails are much narrower than roads, so the same number of vehicles on OHV trails will cause a proportionately greater amount of disturbance per unit area. Second, the dirt bike and ATV tires have a more rugged tread than most road tires, and this will increase the supply of easily erodible material relative to the same amount of traffic on unpaved roads. Finally, the driving style on OHV trails is much more aggressive, and this also is likely to increase the amount of loose sediment on OHV trails. Each of these differences would be expected to increase the effect of increasing traffic on sediment production as compared to roads. The problem is that SEDMODL2 is already over-predicting sediment production from OHV trails, so any increase in the traffic factor would further reduce the absolute accuracy of SEDMODL2. A calibration of the traffic factor against the field data suggests that it should be reduced from 10.0 to 4.0, and this one change greatly improves the R^2_{eff} from -2.01 to a very respectable value of 0.71.

A nonlinear equation (equation 3.5) is used to calculate the rainfall factor in SEDMODL2 (BCC and NCASI, 2003). This equation uses annual rainfall rather than total precipitation because road sediment production from snowmelt is nearly an order or magnitude lower than the sediment generated from an equivalent amount of rainfall (Vincent, 1985; BCC and NCASI, 2003). The field data collected for this study showed that snowmelt did not generate any sediment from the OHV trail segments, and this is why only the measured summer rainfall was used to calculate the rainfall factors used in SEDMODL2.

A sensitivity analysis shows that a doubling of the rainfall from the mean observed value of 237 mm to 474 mm increases the predicted sediment production for the baseline OHV trail segment from 3400 kg yr^{-1} to 9700 kg yr^{-1}, or 2.83 times. The exponent of 1.5 in equation 3.5 causes R_S to increase from 1.17 when there is 59 mm of rainfall to 1.83 when there is 474 mm of rainfall. This indicates that wetter years have a proportionally larger effect on predicted sediment production than drier years, and this is consistent with data from road erosion studies (e.g., Swift, 1984; Luce and Black, 2001). The nonlinear rainfall factor in SEDMODL2 (equation 3.5) is based on data from the Pacific Northwest and the Appalachian Mountains (Swift, 1984; Luce and Black, 1999), but other road erosion studies have shown a linear relationship between precipitation and road sediment production (Libohova, 2004; Ramos-Scharrón and MacDonald, 2005; Coe, 2006; Brown, 2008).

An analysis of the field data yielded a linear regression between storm rainfall and storm-based sediment production from the OHV trails (equation 3.12). However, the negative intercept means that doubling the mean storm rainfall from 11.3 mm to 22.6 mm increases the predicted sediment production value by 3.3 times. This increase is only slightly more than the 2.8-fold increase predicted by the nonlinear function in SEDMODL2, suggesting that equation 3.5 is relatively applicable to the study area. A potentially much greater improvement in the performance of SEDMODL2 might be possible in monsoon-dominated climates by: (1) substituting rainfall I_{30} or erosivity for the rainfall depth, as these were much more closely correlated with storm-based OHV trail sediment production (R^2=0.64-0.67 vs. 0.31); and (2) collecting sufficient field data to calibrate SEDMODL2 for the local relationship between rainfall and sediment production.

3.6. CONCLUSIONS

Erosion is an important environmental issue in the Upper South Platte River (USPR) watershed of Colorado because it is the primary source of drinking water for Denver, has a high-value fishery, and water quality is impaired by high levels of sediment (CDPHE, 2006; CDPHE, 2008; EPA, 2008). In order to evaluate the effects of OHV trails on water quality and stream habitat in the USPR watershed, rainfall, site characteristic, and sediment production data were collected from 5-10 OHV trail segments from August 2005 to October 2006. These data also were used to develop an empirical model for predicting storm-based sediment production from OHV trail segments, and to test the accuracy of WEPP:Road and SEDMODL2 for predicting annual sediment production from OHV trails. Over 10 km of OHV trails were surveyed to evaluate the presence and length of drainage features and assess trail-stream connectivity. A more extensive and longer term dataset was available for forest roads in the study area, and this allowed a comparison of OHV trail and road sediment production, sediment delivery, and watershed-scale sediment yields.

In summer 2006 the mean sediment production was 53.3 kg per meter of OHV trail for the five segments at Log Jumper and 16.5 kg m^{-1} for the five segments at Noddle ($p=0.04$). The 4-fold difference in summer erosivity between the two study sites explains much of this difference in sediment production. OHV trail sediment production significantly increased with increasing segment slope ($p=0.02$) and the amount of unconsolidated material on the surface ($p=0.04$). There also was a marginally significant relationship between sediment production and the depth of trail incision ($p=0.057$). Each of these variables has a strong physical basis, as rainfall erosivity is related to both the energy available for soil detachment by rainsplash and the amount of runoff, segment length is related to the amount of runoff, segment slope is related to the shear stress and transport capacity of the runoff, the mass of unconsolidated material characterizes the supply of easily erodible sediment particles, and incision depth is a surrogate for long-term sediment production rates. The best multivariate model for predicting storm-based sediment production was more parsimonious, as it used only storm erosivity and segment length (R^2=0.80).

Both WEPP:Road and SEDMODL2 were very poor predictors of the sediment production from OHV trail segments, as indicated by the respective R^2_{eff} values of -0.37 and -2.01. The much higher R^2 values of 0.80 for WEPP:Road and 0.71 for SEDMODL2 indicate that the models can identify which segments are most likely to be generating the most sediment. Analyses of the field data indicate that the performance of both models can be improved by substituting erosivity for precipitation, as sediment production was much more strongly related to storm erosivity (R^2=0.67) than storm rainfall (R^2=0.31). Calibration of the traffic factor in SEDMODL2 reduced the selected value from 10.0 to 4.0, and this one change greatly improved model performance (R^2_{eff}=0.71). The results of the model testing indicate that SEDMODL2 is more useful for predicting OHV trail sediment production than WEPP:Road; however, more data and testing are needed to improve the accuracy of predicted OHV trail sediment production across a range of climates and geologies.

Eighty-nine percent of the 183 surveyed OHV trail segments had a sediment plume or an outlet rill below the drainage outlet. Sediment plumes were much more common, as these were present below 74% of the surveyed segments and outlet rills were present below 15% of the segments. Outlet rills were found only when the hillslope gradient exceeded 20%, and were more likely to be present below steeper and longer segments. On the other hand, the mean length of the outlet rills was 74 m, or nearly three times the mean length of sediment plumes. The length of the sediment plumes and outlet rills was best predicted by the maximum rill depth on the trail surface and the presence or absence of an outlet rill (R^2=0.41). Twenty-four percent of the surveyed OHV trail length was delivering sediment to the stream network, and 78% of the connected segments were in the valley bottoms rather than on ridgetops or midslopes.

In 2006 the unit area sediment production from OHV trails was six times higher than from forest roads (p=0.012), but this was reduced to a factor of two after normalizing by summer erosivity (p=0.033). The higher unit area sediment production from OHV trails can be attributed to the steeper segment slopes, higher traffic loads, and much greater amount of unconsolidated material on the surface of the OHV trails.

The density of OHV trails in the study area of the USPR watershed is 0.2 km km^{-2}, and this is just one-third of the value for forest roads. Nevertheless, the roads are estimated to be producing approximately 7.8 Mg km^{-2} yr^{-1}, while the OHV trails are producing about 3.3 Mg km^{-2} yr^{-1}. Multiplying these watershed-scale sediment production rates by the percent of length connected to streams indicates that roads are delivering approximately 1.1 Mg km^{-2} yr^{-1}, and OHV trails are delivering about 0.8 Mg km^{-2} yr^{-1}. These calculations show that the greater watershed-scale sediment production rates from roads are largely counterbalanced by the higher connectivity between OHV trails and stream channels.

The results of this study show that OHV trails are a chronic sediment source in the USPR watershed, and they deliver nearly as much sediment to streams as unpaved roads. Resource managers can most efficiently reduce the amount of sediment being delivered from OHV trails by: (1) relocating the OHV trails out of valley bottoms; (2) locating trails on more gentle hillslopes so that incision is decreased and the probability of an outlet rill is reduced; (3) constructing more diversions to reduce segment lengths and hence the amount of runoff from individual segments; and (4) reducing segment slopes to decrease runoff energy.

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4. CONCLUSIONS

This study evaluated sediment production and delivery from forest roads and OHV trails in the Upper South Platte River (USPR) watershed of Colorado. These issues are of great concern because this watershed is the primary source of water for Denver, has a high-value fishery, and several stream reaches are impaired by high levels of sediment. Accurate predictions of sediment production are needed to improve water quality and evaluate cumulative watershed effects, so the first objective of this study was to test the accuracy of WEPP:Road, SEDMODL2, and two local empirical models for predicting road sediment production (Chapter 2). The dataset to achieve this objective consisted of rainfall, site characteristic, and sediment production measurements for 14-22 native surface road segments from 2001 to 2006. The second main objective of this study was to quantify the sediment production and delivery from OHV trail segments (Chapter 3), as OHV trails are another potentially important but unquantified sediment source. To this end rainfall, site characteristic, and sediment production data were collected for 5-10 OHV trail segments from 2005 to 2006, and trail-to-stream connectivity was assessed by detailed surveys along 10 km of OHV trails. The third main objective of this study was to compare the sediment production, sediment delivery, and sediment yields from roads and OHV trails in the study area of the USPR watershed (Chapter 3).

The overall mean road sediment production rate from 2001-2006 was 3.5 kg m^{-2} yr^{-1}, and the mean values for individual segments over this period ranged from 0.5 to 7.1 kg m^{-2} yr^{-1}. Sediment production varied greatly between study sites, and this was largely explained by differences in the amount and intensity of summer rainfall (Libohova, 2004; Brown, 2008). Intra-site variability in road sediment production was best explained by road segment slope and the amount of bare soil (Brown, 2008).

In 2006 the mean sediment production rate from the OHV trail segments was 53.3 kg m^{-1} yr^{-1} at Log Jumper and 16.5 kg m^{-1} yr^{-1} at Noddle (p=0.025). Summer erosivity was four times higher at Log Jumper than at Noddle, and normalizing by this variable eliminated the significant difference in sediment production between these two study sites (p=0.36). Storm-based sediment production from the OHV trail segments was best predicted by storm erosivity and segment length (R^2=0.80). Within each study site sediment production was significantly related to: (1) segment length, as this affects the amount of runoff; (2) segment slope, as this affects runoff energy; and (3) the depth that the trail is incised into the hillslope, as this is an index of long-term sediment production.

In 2006 the mean sediment production rate for the 21 road segments was 3.1 kg m^{-2} yr^{-1}, or only one-sixth of the mean value for the 10 OHV trail segments (p=0.01). Normalizing by summer erosivity explained about 50% of the observed difference in sediment production between the roads and OHV trails (p=0.03). The mean slope of the OHV trail segments also was 30% higher than the mean slope of the road segments (p=0.048), and if the data are normalized by both summer erosivity and segment slope there was no significant difference in sediment production between the roads and OHV trails (p=0.34).

Ninety-two percent of the 183 surveyed OHV trail segments had an outlet rill or sediment plume (“drainage feature”) below the drainage outlet. Outlet rills were present below only 15% of the surveyed segments, and they existed only when the hillslope gradient exceeded 20%. The mean length of the outlet rills was 74 m as compared to 26 m for the sediment plumes ($p<0.0001$). Drainage feature lengths were best predicted using a binary variable for the type of drainage feature and the maximum rill depth on the segment surface ($R^2=0.41$). The maximum rill depth on the segment surface was significantly related to the product of segment length and segment slope ($R^2=0.33$; $p<0.0001$).

Twenty-four percent of the OHV trail length was connected to the stream channel network by outlet rills or sediment plumes. The percent of length connected varied greatly between trails, and percent connectivity was strongly correlated ($R^2=0.62$) with the percent of trail length located in a valley bottom. The results indicate that sediment production and delivery from OHV trails can be reduced by: (1) locating trails out of the valley bottoms to increase the distance to streams; (2) constructing more diversions to shorten segment lengths and reduce the amount of runoff and sediment being discharged at one location; (3) reducing segment slopes to decrease the shear stress and transport capacity of the runoff; and (4) locating trails on more gentle hillslopes to reduce incision and the probability of an outlet rill.

In contrast to the OHV trails, only 59% of the road segments had an outlet rill or sediment plume below the drainage outlet, and only 14% of the road length was delivering runoff and sediment to streams. The percent of road length connected to streams varied from 0% at Kelsey and Nighthawk to 67% at Trumbull (Brown, 2008). As with the OHV trails, the percent connected was best explained by the amount of road length in the valley bottoms (Brown, 2008). The higher proportion of OHV trails in the valley bottoms largely explains the higher connectivity as compared to roads, and this indicates the lack of design standards for OHV trails at the time of their construction (USDA, 2005).

Road density in the study area is 0.6 km km^{-2}, or three times the density of OHV trails. However, the lower density and smaller width of OHV trails is counterbalanced by their higher mean sediment production rate and higher connectivity. If the sediment production rates from OHV trails and roads are normalized by the mean annual erosivity, the roads are estimated to be delivering 1.1 Mg km^{-2} of sediment to the stream channel network per year, while the OHV trails are delivering an estimated 0.8 Mg km^{-2} yr^{-1}, or about 73% as much sediment as the much more extensive road network.

The predicted road sediment production rates using WEPP:Road, SEDMODL2, and the two empirical models were poorly correlated with the measured values, as the R^2 values ranged from 0.28 to 0.42. SEDMODL2 had the highest Nash-Sutcliffe efficiency (R^2_{eff}) of 0.31, while WEPP:Road had the lowest R^2_{eff} (-0.54). The empirical model for annual road sediment production was developed from the 2001-2004 data, so it could only be tested against the 2005-2006 data. For these two years its R^2_{eff} was 0.14, and this was higher than the corresponding R^2_{eff} values for WEPP:Road (-0.98) and SEDMODL2 (0.00). The empirical model for storm-based road sediment production had an R^2_{eff} of 0.27, but when the predicted values for each storm were summed to yield an annual value for each segment, the R^2_{eff} decreased to -0.50. Each model tended to over-predict the low sediment production values and under-predict the high values.

Three improvements to WEPP:Road were identified by comparing the results of sensitivity analyses to the relationships derived from the field data. First, the predicted increases in sediment production with increasing mean annual precipitation are too small.

Second, WEPP:Road predicted an increase in sediment production with higher soil rock content, while the field data indicate that this relationship should trend in the opposite direction. Lastly, WEPP:Road predicted only a 3% increase in sediment production as the result of a categorical change from no traffic to low traffic, but the field data indicate that this change should roughly double sediment production.

A similar set of analyses for SEDMODL2 identified four ways in which the model could be improved. First, the slope factor should increase linearly with segment slope instead of changing exponentially as segment slopes vary from the baseline value 7.5%. Second, the range of geology factors should be increased, as the average back-calculated value for the road segments in this study was 10.1, or twice the maximum value of 5.0 specified in the technical documentation (BCC and NCASI, 2003). Third, the measured road sediment production was strongly related to rill density ($R^2=0.59$; $p<0.0001$), so the road surface factor needs to be increased for native surface road segments with a high rill density and lowered for segments with no ruts. Fourth, SEDMODL2 should have separate equations for calculating the rainfall factor in areas with convective storms versus frontal storms, as road sediment production in the monsoon-dominated Colorado Front Range was much more strongly correlated with summer erosivity than annual rainfall.

Both WEPP:Road and SEDMODL2 were very poor predictors of the sediment production from OHV trail segments, as indicated by the respective R^2_{eff} values of -0.37 and -2.01. The much higher R^2 values of 0.80 for WEPP:Road and 0.71 for SEDMODL2 indicate that the models performed much better in a relative sense and can identify which segments are most likely to be generating the most sediment. A calibration of the traffic factor in SEDMODL2 reduced the initially estimated value for OHV trails from 10.0 to 4.0, and this one change greatly improved model performance (R^2_{eff}=0.71).

The results of this study show that forest roads and OHV trails are chronic sources of sediment in the USPR watershed. If resource managers are to reduce the effects of roads and OHV trails on aquatic resources, they will have to identify the segments with the highest sediment yields. Overall, SEDMODL2 was the best predictor of relative and absolute sediment production from both roads and OHV trails, but the empirical model for predicting annual road sediment production performed best for the 2005-2006 road data. The predictions from either of these two models should be useful to guide improvements and identify restoration priorities. The relatively simple structure of these two models also will facilitate modifications and calibration as data become available. Predictions of sediment delivery are even more important for improving water quality and stream habitat, so future studies should evaluate predicted sediment delivery as well as predicted sediment production.

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Appendix I. Input and output data for WEPP:Road and SEDMODL2 by road segment or study site and year.

Appendix I.A. Monthly rainfall and number of wet days that were used to generate the stochastic climate file in WEPP:Road by year and study site. Data for November to April are the default values for the Cheesman weather station in the WEPP database and data for May to October are from the tipping-bucket gauges.

2001	Spring Creek		Trumbull		Upper Saloon Gulch	
Month	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days
January	0	0	0	0	0	0
February	0	0	0	0	0	0
March	0	0	0	0	0	0
April	0	0	0	0	0	0
May	0	0	0	0	0	0
June	0	0	0	0	0	0
July	66.6*	13.1*	66.6*	13.1*	66.6*	13.1*
August	76.5	11.0	38.4	15.0	38.6	11.0
September	31.2	10.0	24.6	8.0	18.0	6.0
October	0.2	1.0	0.4	1.0	0.3	1.0
November	20.1	4.6	20.1	4.6	20.1	4.6
December	15.2	4.0	15.2	4.0	15.2	4.0

* Historic data were used for July because the rain gauges weren't installed until 1 August.

2002	Spring Creek		Trumbull		Upper Saloon Gulch	
Month	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days
January	10.7	4.2	10.7	4.2	10.7	4.2
February	15.8	4.4	15.8	4.4	15.8	4.4
March	31.0	6.8	31.0	6.8	31.0	6.8
April	38.6	6.9	38.6	6.9	38.6	6.9
May	30.7	8.0	19.1	8.0	30.0	7.0
June	16.0	7.0	10.2	7.0	21.1	7.0
July	22.9	5.0	17.5	6.0	34.8	8.0
August	25.4	11.0	18.5	10.0	26.7	11.0
September	37.1	8.0	25.1	8.0	34.3	8.0
October	25.4	9.0	24.9	10.0	27.9	9.0
November	20.1	4.6	20.1	4.6	20.1	4.6
December	15.2	4.0	15.2	4.0	15.2	4.0

2003	Spring Creek		Trumbull		Upper Saloon Gulch		Kelsey		Nighthawk	
Month	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days
January	10.7	4.2	10.7	4.2	10.7	4.2	0.0	0.0	0.0	0.0
February	15.8	4.4	15.8	4.4	15.8	4.4	0.0	0.0	0.0	0.0
March	31.0	6.8	31.0	6.8	31.0	6.8	0.0	0.0	0.0	0.0
April	38.6	6.9	38.6	6.9	38.6	6.9	0.0	0.0	0.0	0.0
May	31.0	9.0	7.6	3.0	11.2	6.0	0.0	0.0	0.0	0.0
June	49.0	14.0	35.3	14.0	51.8	15.0	0.0	0.0	0.0	0.0
July	22.4	7.0	11.4	6.0	12.4	3.0	17.6	6.0	17.4	5.0
August	55.4	14.0	52.1	16.0	68.8	18.0	66.0	13.0	40.6	11.0
September	9.9*	8.0*	9.9*	8.0*	9.9	8.0	14.0	6.0	6.4	2.0
October	1.3*	3.0*	1.3*	3.0*	1.3	3.0	1.3*	3.0*	0.2	1.0
November	20.1	4.6	20.1	4.6	20.1	4.6	20.1	4.6	20.1	4.6
December	15.2	4.0	15.2	4.0	15.2	4.0	15.2	4.0	15.2	4.0

* Upper Saloon Gulch data were used for September at Spring Creek and Trumbull, and for October at Spring Creek, Trumbull, and Kelsey.

2004	Spring Creek		Trumbull		Upper Saloon Gulch		Kelsey		Nighthawk	
Month	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days
January	10.7	4.2	10.7	4.2	10.7	4.2	10.7	4.2	10.7	4.2
February	15.8	4.4	15.8	4.4	15.8	4.4	15.8	4.4	15.8	4.4
March	31.0	6.8	31.0	6.8	31.0	6.8	31.0	6.8	31.0	6.8
April	38.6	6.9	38.6	6.9	38.6	6.9	38.6	6.9	38.6	6.9
May	26.9	8.0	20.1	6.0	27.7	5.0	30.0	6.0	25.8	8.0
June	91.4	18.0	62.5	20.0	93.5	20.0	88.1	18.0	81.4	21.0
July	73.7	15.0	38.6	13.0	69.9	17.0	77.7	16.0	71.0	17.0
August	42.7	13.0	31.8	13.0	50.0	14.0	43.4	12.0	53.2	16.0
September	36.1	11.0	20.8	6.0	59.4	13.0	41.9	11.0	26.4	10.0
October	29.2	8.0	22.4	7.0	49.0	12.0	26.9	10.0	23.4	6.0
November	20.1	4.6	20.1	4.6	20.1	4.6	20.1	4.6	20.1	4.6
December	15.2	4.0	15.2	4.0	15.2	4.0	15.2	4.0	15.2	4.0

2005	Spring Creek		Trumbull		Upper Saloon Gulch		Kelsey		Nighthawk	
Month	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days
January	10.7	4.2	10.7	4.2	10.7	4.2	10.7	4.2	10.7	4.2
February	15.8	4.4	15.8	4.4	15.8	4.4	15.8	4.4	15.8	4.4
March	31.0	6.8	31.0	6.8	31.0	6.8	31.0	6.8	31.0	6.8
April	38.6	6.9	38.6	6.9	38.6	6.9	38.6	6.9	38.6	6.9
May	21.1	6.0	22.9	8.0	11.0	5.0	21.6	5.0	15.0	7.0
June	40.4	13.0	43.9	11.0	23.8	11.0	46.5	13.0	56.4	12.0
July	29.8	6.0	10.7	8.0	19.6	10.0	30.5	9.0	12.6	10.0
August	69.6	13.0	55.4	16.0	56.0	18.0	57.9	15.0	56.4	18.0
September	18.5	5.0	24.4	6.0	23.4	5.0	30.7	9.0	25.2	10.0
October	19.1	7.0	27.7	7.0	22.0	11.0	21.8	5.0	38.1	6.0
November	20.1	4.6	20.1	4.6	20.1	4.6	20.1	4.6	20.1	4.6
December	15.2	4.0	15.2	4.0	15.2	4.0	15.2	4.0	15.2	4.0

2006	Spring Creek #1		Spring Creek #2		Spring Creek #3		Spring Creek #4		Spring Creek #5	
	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days
January	10.7	4.2	10.7	4.2	10.7	4.2	10.7	4.2	10.7	4.2
February	15.8	4.4	15.8	4.4	15.8	4.4	15.8	4.4	15.8	4.4
March	31.0	6.8	31.0	6.8	31.0	6.8	31.0	6.8	31.0	6.8
April	38.6	6.9	38.6	6.9	38.6	6.9	38.6	6.9	38.6	6.9
May	15.5*	9.0*	15.5*	9.0*	15.5*	9.0*	15.5*	9.0*	15.5*	9.0*
June	3.0	5.0	2.8	3.0	3.0	5.0	4.1	5.0	13.4	6.0
July	69.4	17.0	66.3	16.0	62.7	15.0	58.7	14.0	74.6	16.0
August	79.4	25.0	89.9	23.0	91.7	21.0	80.8	20.0	84.4	22.0
September	35.0	12.0	38.1	10.0	37.3	11.0	34.0	12.0	37.8	12.0
October	42.8	12.0	44.2	11.0	41.1	11.0	38.9	10.0	39.6	16.0
November	20.1	4.6	20.1	4.6	20.1	4.6	20.1	4.6	20.1	4.6
December	15.2	4.0	15.2	4.0	15.2	4.0	15.2	4.0	15.2	4.0

* Data are from Spring Creek #4. Spring Creek #4 is the gauge used from 2001 to 2005.

2006	Trumbull		Upper Saloon Gulch		Kelsey		Nighthawk	
Month	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days
January	10.7	4.2	10.7	4.2	10.7	4.2	10.7	4.2
February	15.8	4.4	15.8	4.4	15.8	4.4	15.8	4.4
March	31.0	6.8	31.0	6.8	31.0	6.8	31.0	6.8
April	38.6	6.9	38.6	6.9	38.6	6.9	38.6	6.9
May	9.9	8.0	15.8	5.0	16.5	8.0	21.8	10.0
June	9.9	6.0	3.0	2.0	4.6	5.0	14.2	8.0
July	81.5	15.0	78.6	18.0	70.4	14.0	68.0	15.0
August	78.0	19.0	99.0	16.0	97.0	21.0	86.6	22.0
September	31.2	9.0	26.2	5.0	42.4	11.0	48.0	15.0
October	44.5	14.0	35.0	8.0	44.2	11.0	65.4	13.0
November	20.1	4.6	20.1	4.6	20.1	4.6	20.1	4.6
December	15.2	4.0	15.2	4.0	15.2	4.0	15.2	4.0

Appendix I.B. Input and output data for each road segment used for testing WEPP:Road. Under study site SC is Spring Creek, K is Kelsey, NH is Nighthawk, TR is Trumbull, and USG is Upper Saloon Gulch. Under road design OR is outsloped, rutted; IB is insloped, bare; and OU is outsloped, unrutted.

Year	Study site	Segment	Road design	Length (m)	Active width (m)	Slope (%)	Soil rock content (%)	Predicted sediment (kg yr^{-1})	Measured sediment (kg yr^{-1})
2006	SC	3/15	OR	69.5	3.55	8	24.1	53	851
2006	SC	3/14	IB	69.5	3.68	12	30.1	102	1363
2006	SC	3/11	OU	27.0	3.16	6	40.5	13	4
2006	SC	3/10	OR	26.3	3.54	5	37.3	12	227
2006	SC	3/9	OR	124.0	3.28	6	33.4	102	584
2006	SC	3/8	OR	101.0	3.85	10	36.0	160	809
2006	SC	3/7	OR	63.5	3.69	11	29.8	72	601
2006	SC	3/6	OR	52.8	3.27	7	31.3	30	137
2006	SC	3/5	OR	56.7	2.85	9	43.2	48	120
2006	SC	3/4	OR	47.5	3.33	9	39.2	38	123
2006	SC	3/2	OR	52.0	4.38	11	43.4	98	451
2006	K	1	OR	81.1	2.58	4	32.2	26	265
2006	K	2	OR	138.5	2.61	5	32.4	74	375
2006	NH	1	OR	125.5	3.52	15	45.8	476	1774
2006	NH	2	OR	83.0	3.51	16	47.4	272	1052
2006	TR	E1	OR	39.5	2.77	16	38.7	48	769
2006	TR	E2	OR	34.0	2.64	5	37.0	12	167
2006	TR	E3	OR	40.0	2.73	19	31.3	50	957
2006	TR	E4	OR	81.0	2.80	14	35.4	127	1314
2006	TR	8	OR	36.5	2.86	16	33.4	41	679
2006	USG	1	IB	39.5	2.70	9	47.3	31	29
2005	SC	3/15	OR	70.5	3.16	8	24.1	47	1450
2005	SC	3/14	IB	69.7	4.01	12	30.1	95	3600
2005	SC	3/11	OU	26.0	3.19	6	40.5	9	32
2005	SC	3/10	OR	26.3	3.54	5	37.3	9	441
2005	SC	3/9	OR	126.5	3.00	6	33.4	93	1540
2005	SC	3/8	OR	109.3	3.88	10	36.0	183	2600
2005	SC	3/7	OR	67.0	3.67	11	29.8	75	1450
2005	SC	3/6	OR	52.8	3.29	7	31.3	28	660
2005	SC	3/5	OR	54.0	3.24	9	43.2	49	1040
2005	SC	3/4	OR	47.3	3.02	9	39.2	33	1310
2005	SC	3/2	OR	49.0	3.84	11	43.4	61	3160
2005	K	1	OR	83.0	2.58	4	32.2	23	460
2005	K	2	OR	139.0	2.65	5	32.4	65	334
2005	NH	1	OR	131.0	3.32	15	45.8	352	954

Year	Study site	Segment	Road design	Length (m)	Active width (m)	Slope (%)	Soil rock content (%)	Predicted sediment (kg yr^{-1})	Measured sediment (kg yr^{-1})
2005	NH	2	OR	83.0	3.53	16	47.4	200	522
2005	TR	E1	OR	38.0	2.76	16	38.7	32	805
2005	TR	E2	OR	39.0	2.54	5	37.0	10	501
2005	TR	E3	OR	41.0	2.59	19	31.3	35	1130
2005	TR	E4	OR	80.0	2.71	14	35.4	88	1350
2005	TR	8	OR	36.0	2.89	16	33.4	28	1480
2005	USG	1	IB	43.0	3.21	9	47.3	37	16
2004	SC	3/15	OR	72.7	4.05	8	24.1	94	3780
2004	SC	3/14	IB	71.7	4.19	10	30.1	119	1313
2004	SC	3/13	OR	38.3	2.56	4	45.7	16	178
2004	SC	3/10	OR	24.9	3.81	6	37.3	14	576
2004	SC	3/11	OU	25.7	3.00	6	40.5	16	110
2004	SC	3/9	OR	121.0	4.01	6	33.4	169	3146
2004	SC	3/8	OR	105.0	4.15	10	36.0	248	4304
2004	SC	3/7	OR	60.4	4.04	9	29.8	83	2402
2004	SC	3/6	OR	50.1	3.65	6	31.3	39	2488
2004	SC	3/5	OR	55.8	4.18	9	43.2	97	1042
2004	SC	3/4	OR	65.5	4.51	8	39.2	110	2714
2004	SC	3/2	OR	47.9	4.65	10	43.4	95	565
2004	K	1	OR	100.5	2.76	6	32.2	73	792
2004	K	2	OR	149.0	2.27	5	32.4	87	275
2004	NH	1	OR	123.0	3.51	15	45.8	400	3630
2004	NH	2	OR	89.0	3.20	17	47.4	259	2964
2004	TR	E2	OR	34.5	2.27	4	37.0	7	35
2004	TR	E3	OR	38.0	3.00	12	31.3	26	426
2004	TR	8	OR	33.9	3.03	16	33.4	30	769
2004	TR	E1	OR	58.0	3.02	17	38.7	80	605
2003	SC	3/15	OR	72.7	4.05	8	24.1	60	1046
2003	SC	3/14	IB	71.7	4.19	10	30.1	76	1093
2003	SC	3/13	OR	38.3	2.56	4	45.7	10	245
2003	SC	3/10	OR	24.9	3.81	6	37.3	11	96
2003	SC	3/11	OU	25.7	3.00	6	40.5	9	25
2003	SC	3/9	OR	121.0	4.01	6	33.4	106	1018
2003	SC	3/8	OR	105.0	4.15	10	36.0	163	847
2003	SC	3/7	OR	60.4	4.04	9	29.8	55	1330
2003	SC	3/6	OR	50.1	3.65	6	31.3	26	259
2003	SC	3/5	OR	55.8	4.18	9	43.2	64	250
2003	SC	3/4	OR	65.5	4.51	8	39.2	72	771
2003	SC	3/2	OR	47.9	4.65	10	43.4	62	375
2003	TR	E1	OR	58.0	3.02	17	38.7	61	165

Year	Study site	Segment	Road design	Length (m)	Active width (m)	Slope (%)	Soil rock content (%)	Predicted sediment (kg yr^{-1})	Measured sediment (kg yr^{-1})
2003	TR	E2	OR	34.5	2.27	4	37.0	5	45
2003	TR	E3	OR	38.0	3.00	12	31.3	20	136
2003	TR	8	OR	33.9	3.03	16	33.4	23	399
2003	USG	7	IB	73.5	4.64	8	47.3	101	2098
2003	K	1	OR	100.5	2.76	4	32.2	27	168
2003	K	2	OR	149.0	2.27	5	32.4	48	129
2003	NH	1	OR	123.0	3.51	15	45.8	101	1063
2003	NH	2	OR	89.0	3.20	17	47.4	66	529
2003	USG	11	OR	180.0	2.07	10	36.0	179	1694
2002	SC	3/15	OR	74.0	3.00	8	21.0	28	3
2002	SC	3/14	IB	74.0	2.40	10	31.0	31	101
2002	SC	3/13	OR	22.0	2.85	4	46.0	4	12
2002	SC	3/11	OU	22.1	3.10	6	51.0	6	14
2002	SC	3/10	OR	25.1	3.00	6	47.0	6	100
2002	SC	3/9	OR	118.9	2.50	6	31.0	39	251
2002	SC	3/8	OR	104.9	3.70	10	28.0	82	107
2002	SC	3/7	OR	58.8	2.60	9	35.0	24	82
2002	SC	3/6	OR	49.7	2.20	6	38.0	11	6
2002	SC	3/5	OR	54.0	2.70	9	41.0	24	23
2002	SC	3/4	OR	85.0	2.30	8	42.0	39	51
2002	SC	3/2	OR	46.6	3.00	10	44.0	25	12
2002	TR	TR9	OR	37.2	2.40	16	46.7	32	89
2002	TR	TR8	OR	47.8	2.10	15	46.3	44	25
2002	USG	11	OR	57.2	3.90	10	36.0	48	602
2002	USG	7	IB	219.0	2.20	8	47.3	229	481
2001	SC	3/11	OU	22.1	3.10	6	51.0	5	0
2001	SC	3/10	OR	25.1	3.00	6	47.0	6	0
2001	SC	3/9	OR	118.9	2.50	6	31.0	32	565
2001	SC	3/8	OR	104.9	3.70	10	28.0	63	1203
2001	SC	3/7	OR	58.8	2.60	9	35.0	19	581
2001	SC	3/6	OR	49.7	2.20	6	38.0	9	98
2001	SC	3/5	OR	54.0	2.70	9	41.0	20	175
2001	SC	3/4	OR	85.0	2.30	8	42.0	31	782
2001	SC	3/2	OR	46.6	3.00	10	44.0	21	755
2001	USG	11	OR	57.2	3.90	10	36.0	33	647
2001	USG	7	IB	219.0	2.20	8	47.3	134	48
2001	TR	9	OR	37.2	2.40	16	46.7	22	0
2001	TR	8	OR	47.8	2.10	15	46.3	27	452
2001	TR	7	OR	210.8	2.50	18	51.7	476	1476

Appendix I.C. Input and output data for each road segment used for testing SEDMODL2. See Appendix IB for the definition of study site names.

Year	Study site	Seg.	Road surface	Traffic	Length (m)	Active width (m)	Slope (%)	Summer precipitation (mm)	Predicted sediment (kg yr^{-1})	Measured sediment (kg yr^{-1})
2006	SC	3/15	2	2	69.5	3.55	8	256.8	647	851
2006	SC	3/14	2	2	69.5	3.68	12	265.3	1587	1363
2006	SC	3/11	1	2	27.0	3.16	6	245.1	59	4
2006	SC	3/10	2	2	26.3	3.54	5	245.1	89	227
2006	SC	3/9	2	2	124.0	3.28	6	251.3	582	584
2006	SC	3/8	2	2	101.0	3.85	10	251.3	1542	809
2006	SC	3/7	2	2	63.5	3.69	11	251.3	1125	601
2006	SC	3/6	2	2	52.8	3.27	7	251.3	336	137
2006	SC	3/5	2	2	56.7	2.85	9	232.0	461	120
2006	SC	3/4	2	2	47.5	3.33	9	232.0	451	123
2006	SC	3/2	2	2	52.0	4.38	11	265.3	1186	451
2006	K	1	2	1	81.1	2.58	4	275.1	76	265
2006	K	2	2	1	138.5	2.61	5	275.1	205	375
2006	NH	1	2	1	125.5	3.52	15	304.0	2621	1774
2006	NH	2	2	1	83.0	3.51	16	304.0	1970	1052
2006	TR	E1	2	1	39.5	2.77	16	255.0	568	769
2006	TR	E2	2	1	34.0	2.64	5	255.0	46	167
2006	TR	E3	2	1	40.0	2.73	19	255.0	799	957
2006	TR	E4	2	1	81.0	2.80	14	255.0	902	1314
2006	TR	8	2	1	36.5	2.86	16	255.0	542	679
2006	USG	1	2	1	39.5	2.70	9	257.6	178	29
2005	SC	3/15	2	2	70.5	3.16	8	198.5	398	1450
2005	SC	3/14	2	2	69.7	4.01	12	198.5	1120	3600
2005	SC	3/11	1	2	26.0	3.19	6	198.5	42	32
2005	SC	3/10	2	2	26.3	3.54	5	198.5	65	441
2005	SC	3/9	2	2	126.5	3.00	6	198.5	381	1540
2005	SC	3/8	2	2	109.3	3.88	10	198.5	1182	2600
2005	SC	3/7	2	2	67.0	3.67	11	198.5	829	1450
2005	SC	3/6	2	2	52.8	3.29	7	198.5	237	660
2005	SC	3/5	2	2	54.0	3.24	9	198.5	395	1040
2005	SC	3/4	2	2	47.3	3.02	9	198.5	322	1310
2005	SC	3/2	2	2	49.0	3.84	11	198.5	634	3160
2005	K	1	2	1	83.0	2.58	4	209.0	52	460
2005	K	2	2	1	139.0	2.65	5	209.0	139	334
2005	NH	1	2	1	131.0	3.32	15	203.7	1418	954
2005	NH	2	2	1	83.0	3.53	16	203.7	1086	522
2005	TR	E1	2	1	38.0	2.76	16	185.0	336	805
2005	TR	E2	2	1	39.0	2.54	5	185.0	31	501
2005	TR	E3	2	1	41.0	2.59	19	185.0	480	1130
2005	TR	E4	2	1	80.0	2.71	14	185.0	532	1350
2005	TR	8	2	1	36.0	2.89	16	185.0	334	1480
2005	USG	1	2	1	43.0	3.21	9	155.8	108	16
2004	SC	3/15	2	2	72.7	4.05	8	300.0	975	3780
2004	SC	3/14	2	2	71.7	4.19	10	300.0	1554	1313
2004	SC	3/13	2	2	38.3	2.56	4	300.0	81	178
2004	SC	3/10	2	2	24.9	3.81	6	300.0	177	576
2004	SC	3/11	1	2	25.7	3.00	6	300.0	72	110
2004	SC	3/9	2	2	121.0	4.01	6	300.0	904	3146

Year	Study site	Seg.	Road surface	Traffic	Length (m)	Active width (m)	Slope (%)	Summer precipitation (mm)	Predicted sediment (kg yr^{-1})	Measured sediment (kg yr^{-1})
2004	SC	3/8	2	2	105.0	4.15	10	300.0	2255	4304
2004	SC	3/7	2	2	60.4	4.04	9	300.0	1023	2402
2004	SC	3/6	2	2	50.1	3.65	6	300.0	341	2488
2004	SC	3/5	2	2	55.8	4.18	9	300.0	977	1042
2004	SC	3/4	2	2	65.5	4.51	8	300.0	979	2714
2004	SC	3/2	2	2	47.9	4.65	10	300.0	1154	565
2004	K	1	2	1	100.5	2.76	6	308.0	269	792
2004	K	2	2	1	149.0	2.27	5	308.0	228	275
2004	NH	1	2	1	123.0	3.51	15	281.2	2282	3630
2004	NH	2	2	1	89.0	3.20	17	281.2	1933	2964
2004	TR	E2	2	1	34.5	2.27	4	196.2	17	35
2004	TR	E3	2	1	38.0	3.00	12	196.2	225	426
2004	TR	8	2	1	33.9	3.03	16	196.2	360	769
2004	TR	E1	2	1	58.0	3.02	17	196.2	693	605
2003	SC	3/15	2	2	72.7	4.05	8	213.4	585	1046
2003	SC	3/14	2	2	71.7	4.19	10	213.4	933	1093
2003	SC	3/13	2	2	38.3	2.56	4	213.4	49	245
2003	SC	3/10	2	2	24.9	3.81	6	213.4	106	96
2003	SC	3/11	1	2	25.7	3.00	6	213.4	43	25
2003	SC	3/9	2	2	121.0	4.01	6	213.4	542	1018
2003	SC	3/8	2	2	105.0	4.15	10	213.4	1353	847
2003	SC	3/7	2	2	60.4	4.04	9	213.4	614	1330
2003	SC	3/6	2	2	50.1	3.65	6	213.4	204	259
2003	SC	3/5	2	2	55.8	4.18	9	213.4	586	250
2003	SC	3/4	2	2	65.5	4.51	8	213.4	587	771
2003	SC	3/2	2	2	47.9	4.65	10	213.4	692	375
2003	TR	E1	2	1	58.0	3.02	17	164.3	531	165
2003	TR	E2	2	1	34.5	2.27	4	164.3	13	45
2003	TR	E3	2	1	38.0	3.00	12	164.3	172	136
2003	TR	8	2	1	33.9	3.03	16	164.3	276	399
2003	USG	7	2	1	73.5	4.64	8	155.4	211	2098
2003	K	1	2	1	100.5	2.76	4	125.5	31	168
2003	K	2	2	1	149.0	2.27	5	125.5	59	129
2003	NH	1	2	1	123.0	3.51	15	64.6	251	1063
2003	NH	2	2	1	89.0	3.20	17	64.6	213	529
2003	USG	11	2	1	180.0	2.07	10	155.4	360	1694
2002	SC	3/15	2	2	74.0	3.00	8	157.5	280	3
2002	SC	3/14	2	2	74.0	2.40	10	157.5	350	101
2002	SC	3/13	2	2	22.0	2.85	4	157.5	20	12
2002	SC	3/11	1	2	22.1	3.10	6	157.5	24	14
2002	SC	3/10	2	2	25.1	3.00	6	157.5	53	100
2002	SC	3/9	2	2	118.9	2.50	6	157.5	211	251
2002	SC	3/8	2	2	104.9	3.70	10	157.5	764	107
2002	SC	3/7	2	2	58.8	2.60	9	157.5	244	82
2002	SC	3/6	2	2	49.7	2.20	6	157.5	78	6
2002	SC	3/5	2	2	54.0	2.70	9	157.5	233	23
2002	SC	3/4	2	2	85.0	2.30	8	157.5	246	51
2002	SC	3/2	2	2	46.6	3.00	10	157.5	275	12
2002	TR	TR9	2	1	37.2	2.40	16	115.3	141	89
2002	TR	TR8	2	1	47.8	2.10	15	115.3	139	25
2002	USG	11	2	1	57.2	3.90	10	174.8	257	602
2002	USG	7	2	1	219.0	2.20	8	174.8	355	481

Year	Study site	Seg.	Road surface	Traffic	Length (m)	Active width (m)	Slope (%)	Summer precipitation (mm)	Predicted sediment (kg yr^{-1})	Measured sediment (kg yr^{-1})
2001	SC	3/11	1	2	22.1	3.10	6	174.5	28	0
2001	SC	3/10	2	2	25.1	3.00	6	174.5	62	0
2001	SC	3/9	2	2	118.9	2.50	6	174.5	246	565
2001	SC	3/8	2	2	104.9	3.70	10	174.5	891	1203
2001	SC	3/7	2	2	58.8	2.60	9	174.5	284	581
2001	SC	3/6	2	2	49.7	2.20	6	174.5	90	98
2001	SC	3/5	2	2	54.0	2.70	9	174.5	271	175
2001	SC	3/4	2	2	85.0	2.30	8	174.5	287	782
2001	SC	3/2	2	2	46.6	3.00	10	174.5	321	755
2001	USG	11	2	1	57.2	3.90	10	123.4	152	647
2001	USG	7	2	1	219.0	2.20	8	123.4	211	48
2001	TR	9	2	1	37.2	2.40	16	130.0	169	0
2001	TR	8	2	1	47.8	2.10	15	130.0	167	452
2001	TR	7	2	1	210.8	2.50	18	130.0	1261	1476

Appendix II. Input and output data for WEPP:Road and SEDMODL2 by OHV trail segment or study site and year.

Appendix II.A. Monthly rainfall and number of wet days that were used to generate the stochastic climate file in WEPP:Road by year and study site. Data for November to April are the default values for the Cheesman weather station in the WEPP database and data for May to October are from the tipping-bucket gauges. Zero values are for the periods prior to installation of the sediment fences or after the study had finished.

Year	2005		2006			
	Log Jumper		Log Jumper		Noddle	
Month	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days	Precipitation (mm)	Number of wet days
January	0.0	0.0	10.7	4.2	0.0	0.0
February	0.0	0.0	15.8	4.4	0.0	0.0
March	0.0	0.0	31.0	6.8	0.0	0.0
April	0.0	0.0	38.6	6.9	0.0	0.0
May	0.0	0.0	18.8	4.0	23.8	12.0
June	0.0	0.0	7.9	7.0	3.4	4.0
July	0.0	0.0	73.7	15.0	103.8	14.0
August	65.0	17.0	72.4	17.0	115.8	21.0
September	23.4	9.0	41.1	14.0	31.8	13.0
October	35.2	14.0	42.7	12.0	51.0	16.0
November	20.1	4.6	0.0	0.0	0.0	0.0
December	15.2	4.0	0.0	0.0	0.0	0.0

Appendix II.B. Input and output data for each OHV trail segment used for testing WEPP:Road. NDL is the Noddle study site and LJ is Log Jumper. Under road design OR is outsloped, rutted.

Year	Study site	Seg.	Road design	Length (m)	Active width (m)	Slope (%)	Soil rock content (%)	Predicted sediment (kg yr^{-1})	Measured sediment (kg yr^{-1})
2006	NDL	1	OR	39	2.59	5	45.2	45	35
2006	NDL	2	OR	7	2.84	18	33.1	10	214
2006	NDL	3	OR	50	2.18	14	42.0	158	1578
2006	NDL	4	OR	42	1.82	9	40.5	59	416
2006	NDL	5	OR	46	1.81	11	44.0	98	174
2006	LJ	1	OR	76	1.61	17	42.5	341	6745
2006	LJ	2	OR	47	1.96	14	38.3	141	1917
2006	LJ	3	OR	37	1.90	9	36.5	57	1108
2006	LJ	4	OR	50	1.95	20	45.3	265	2443
2006	LJ	5	OR	56	2.01	15	49.2	307	4253
2005	LJ	1	OR	76	1.61	17	42.5	143	707
2005	LJ	2	OR	47	1.96	14	38.3	60	265
2005	LJ	3	OR	37	1.90	9	36.5	25	201
2005	LJ	4	OR	50	1.95	20	45.3	109	58
2005	LJ	5	OR	56	2.01	15	49.2	121	508

Appendix II.C. Input and output data for each OHV trail segment used for testing SEDMODL2. See Appendix IIB for the definition of study site names.

Year	Study site	Seg.	Road surface	Traffic	Length (m)	Active width (m)	Slope (%)	Summer precipitation (mm)	Predicted sediment (kg yr^{-1})	Measured sediment (kg yr^{-1})
2006	NDL	1	2	10	39	2.59	5	256.6	510	35
2006	NDL	2	2	10	7	2.84	18	256.6	1322	214
2006	NDL	3	2	10	50	2.18	14	256.6	4342	1578
2006	NDL	4	2	10	42	1.82	9	256.6	1259	416
2006	NDL	5	2	10	46	1.81	11	256.6	2066	174
2006	LJ	1	2	10	76	1.61	17	329.6	10632	6745
2006	LJ	2	2	10	47	1.96	14	329.6	5425	1917
2006	LJ	3	2	10	37	1.90	9	329.6	1738	1108
2006	LJ	4	2	10	50	1.95	20	329.6	11668	2443
2006	LJ	5	2	10	56	2.01	15	329.6	7597	4253
2005	LJ	1	2	10	76	1.61	17	123.6	2438	707
2005	LJ	2	2	10	47	1.96	14	123.6	1244	265
2005	LJ	3	2	10	37	1.90	9	123.6	397	201
2005	LJ	4	2	10	50	1.95	20	123.6	2677	58
2005	LJ	5	2	10	56	2.01	15	123.6	1742	508

Appendix III. Storm depth, maximum 30-minute intensity, and erosivity for each storm from 1 May to 31 October by rain gauge for 2005 and 2006.

Spring Creek #4 (long-term gauge), 2005: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
01-May	10:05	2.54	3.56	1.05
02-May	09:20	1.02	1.52	0.17
11-May	07:15	3.05	6.10	3.18
29-May	20:25	2.29	4.57	1.75
29-May	18:40	4.32	3.56	1.87
30-May	16:50	2.79	5.59	2.74
30-May	18:20	3.30	5.08	2.12
02-Jun	14:55	2.03	2.03	0.53
03-Jun	15:40	6.35	11.18	14.45
03-Jun	12:50	1.78	2.03	0.45
10-Jun	12:20	5.84	10.16	9.86
10-Jun	00:30	1.27	1.52	0.21
11-Jun	22:20	4.83	6.60	4.32
12-Jun	03:05	1.52	1.52	0.26
20-Jun	20:35	2.79	2.54	0.88
23-Jun	18:50	1.52	1.52	0.26
24-Jun	13:55	3.56	7.11	4.63
24-Jun	21:30	4.06	6.60	3.82
14-Jul	22:20	4.57	8.64	6.63
15-Jul	14:05	1.02	2.03	0.25
24-Jul	16:40	13.21	20.83	58.69
25-Jul	19:25	9.91	10.67	15.70
04-Aug	11:50	21.34	7.62	20.00
04-Aug	18:00	2.79	2.54	0.79
04-Aug	02:05	2.29	1.52	0.39
05-Aug	00:40	1.52	2.54	0.43
09-Aug	17:30	10.67	20.83	50.34
10-Aug	15:20	3.56	4.06	2.44
13-Aug	17:15	1.78	3.56	0.96
16-Aug	15:35	17.27	33.02	144.53
20-Aug	18:05	1.78	2.03	0.40
23-Aug	15:15	3.05	3.05	1.19
06-Sep	18:10	2.29	2.54	0.64
06-Sep	08:25	1.02	2.03	0.23
22-Sep	14:45	5.08	6.60	5.17
22-Sep	17:25	1.02	2.03	0.23
28-Sep	05:15	5.08	8.64	6.86
04-Oct	18:50	1.02	1.52	0.17
09-Oct	15:20	5.33	2.54	1.50
11-Oct	11:55	8.89	8.64	11.34

Spring Creek #1, 2006: RF output for all storms between 1 June and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
02-Jul	16:05	1.80	3.60	1.07
03-Jul	17:00	1.40	1.20	0.18
04-Jul	15:15	3.40	6.80	4.25
04-Jul	21:05	5.00	6.00	4.04
05-Jul	17:35	2.20	2.40	0.57
06-Jul	16:00	5.40	7.60	6.69
08-Jul	11:35	4.60	4.80	2.67
08-Jul	22:05	5.20	3.60	2.05
09-Jul	12:35	2.40	3.20	0.86
09-Jul	15:45	2.80	3.20	0.99
10-Jul	17:55	3.20	6.40	3.56
15-Jul	17:10	2.20	3.20	0.82
17-Jul	19:05	2.20	2.40	0.55
20-Jul	14:30	7.80	7.60	10.45
20-Jul	18:05	4.40	3.60	1.78
25-Jul	21:55	4.60	3.60	1.92
25-Jul	14:15	1.20	1.60	0.20
26-Jul	18:20	1.60	2.40	0.44
01-Aug	22:00	1.40	2.40	0.59
03-Aug	17:55	5.80	6.80	5.62
03-Aug	00:30	2.00	2.00	0.44
05-Aug	23:15	7.20	5.60	4.77
05-Aug	19:50	5.60	3.60	2.20
06-Aug	18:50	8.80	8.00	10.14
07-Aug	13:50	4.20	8.40	5.93
11-Aug	15:05	5.00	9.60	10.54
12-Aug	18:40	2.60	3.20	0.93
13-Aug	20:25	1.20	1.60	0.20
15-Aug	14:35	1.20	2.40	0.34
19-Aug	19:00	3.40	2.40	0.90
21-Aug	15:35	1.60	2.80	0.56
24-Aug	19:00	3.60	6.40	3.83
25-Aug	14:25	3.00	4.00	1.48
25-Aug	19:40	1.20	2.40	0.36
26-Aug	14:30	7.00	11.20	14.50
26-Aug	07:20	3.40	4.00	1.59
26-Aug	23:10	1.60	2.40	0.48
31-Aug	14:50	2.40	3.60	1.02
01-Sep	15:25	1.20	2.00	0.29
08-Sep	15:40	5.60	4.80	3.21
08-Sep	09:55	4.60	3.20	1.68
11-Sep	18:25	3.20	6.40	3.69
11-Sep	12:50	1.20	2.00	0.30
21-Sep	00:00	12.40	3.20	4.24

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
22-Sep	14:55	2.00	1.20	0.25
03-Oct	17:10	4.80	4.80	2.73
08-Oct	12:40	2.40	0.80	0.20
09-Oct	12:40	2.80	1.20	0.35
10-Oct	10:05	1.40	2.00	0.34
15-Oct	18:45	1.40	2.00	0.31
18-Oct	13:10	11.60	5.20	7.14
19-Oct	10:30	1.80	1.20	0.23
21-Oct	11:15	2.60	2.40	0.67
27-Oct	12:55	11.40	4.80	6.41

Spring Creek #2, 2006: RF output for all storms between 1 June and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
25-Jun	19:45	1.02	1.02	0.11
28-Jun	11:15	1.02	2.03	0.25
02-Jul	16:05	2.29	4.57	1.99
04-Jul	21:35	5.84	5.08	3.68
05-Jul	17:35	3.30	4.06	1.64
06-Jul	16:15	4.57	6.10	3.88
08-Jul	11:30	6.10	7.11	5.93
08-Jul	22:05	5.59	5.59	3.95
09-Jul	16:00	2.29	2.54	0.64
09-Jul	00:50	1.27	1.52	0.21
10-Jul	17:55	1.27	2.54	0.53
15-Jul	16:35	3.30	4.57	1.89
17-Jul	18:55	1.78	1.52	0.30
20-Jul	12:50	8.13	6.60	8.17
20-Jul	18:05	4.57	3.56	1.94
25-Jul	22:35	5.84	4.57	3.25
25-Jul	14:15	1.02	2.03	0.25
26-Jul	18:25	2.03	2.54	0.64
01-Aug	22:15	3.56	7.11	5.19
02-Aug	12:50	1.02	1.02	0.11
03-Aug	17:45	7.11	8.13	8.59
03-Aug	00:10	3.81	4.57	2.11
05-Aug	23:15	16.51	8.13	17.26
06-Aug	19:05	10.16	10.67	16.67
07-Aug	14:00	1.27	2.54	0.39
11-Aug	15:10	5.08	10.16	12.17
12-Aug	18:50	4.57	6.60	4.28
15-Aug	14:30	1.52	3.05	0.83
19-Aug	19:00	4.06	3.05	1.45
21-Aug	15:25	1.27	2.03	0.36
24-Aug	19:00	3.05	4.06	1.57
25-Aug	19:45	3.30	6.60	4.00
25-Aug	14:15	3.56	4.57	2.16
26-Aug	14:35	5.84	8.64	8.66
26-Aug	07:30	3.81	4.57	2.21
26-Aug	23:10	1.02	1.52	0.19
31-Aug	14:55	4.83	9.65	8.34
01-Sep	15:25	1.02	1.52	0.17
08-Sep	15:45	6.60	6.10	5.09
08-Sep	09:25	5.08	4.57	2.75
11-Sep	18:35	2.79	5.59	2.74
20-Sep	23:55	17.53	4.06	8.10
22-Sep	15:55	1.02	1.02	0.11
03-Oct	17:15	6.86	7.11	6.55

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
08-Oct	14:30	2.03	1.02	0.23
09-Oct	11:30	3.30	1.52	0.56
15-Oct	18:40	1.02	1.52	0.17
18-Oct	14:40	12.70	11.68	23.44
21-Oct	11:05	3.05	4.57	1.72
27-Oct	13:10	11.43	13.21	25.48

Spring Creek #3, 2006: RF output for all storms between 1 June and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
02-Jul	16:15	1.27	2.54	0.45
04-Jul	21:25	5.08	5.08	3.30
05-Jul	17:40	3.05	4.06	1.48
06-Jul	16:15	3.81	5.08	2.46
08-Jul	11:30	6.10	7.11	6.06
08-Jul	22:10	5.08	4.06	2.44
09-Jul	16:10	2.29	3.05	0.85
09-Jul	00:40	1.27	1.02	0.14
10-Jul	18:00	1.02	2.03	0.25
15-Jul	16:45	4.83	6.60	4.53
17-Jul	18:50	1.27	1.52	0.21
20-Jul	12:50	6.86	6.10	6.38
20-Jul	19:10	4.32	3.56	1.79
25-Jul	22:25	6.86	5.08	4.32
25-Jul	14:00	1.27	2.03	0.31
26-Jul	18:25	1.78	2.54	0.53
01-Aug	22:15	2.54	5.08	2.30
03-Aug	17:40	8.64	11.18	15.81
03-Aug	00:10	3.56	3.56	1.49
05-Aug	23:20	16.26	7.62	16.09
06-Aug	19:00	11.43	13.21	23.64
11-Aug	15:15	2.29	4.57	1.77
12-Aug	18:45	4.32	6.60	4.17
19-Aug	19:00	4.32	3.05	1.50
24-Aug	19:05	3.56	3.56	1.54
25-Aug	19:50	4.83	9.65	9.94
25-Aug	14:15	5.08	8.13	6.44
26-Aug	14:40	5.84	9.14	8.65
26-Aug	07:30	4.32	5.08	2.74
31-Aug	14:55	6.10	12.19	15.79
08-Sep	15:45	6.10	5.59	4.20
08-Sep	09:25	4.57	4.06	2.16
11-Sep	18:35	2.29	4.57	1.69
21-Sep	00:05	17.53	4.06	8.15
22-Sep	13:40	1.52	1.02	0.17
23-Sep	09:10	1.27	2.54	0.39
03-Oct	17:10	6.35	6.10	4.98
08-Oct	14:25	2.29	1.02	0.26
09-Oct	11:10	2.54	1.02	0.29
10-Oct	09:40	1.27	2.54	0.36
15-Oct	18:35	1.52	2.03	0.34
18-Oct	13:55	12.95	11.68	24.40
21-Oct	09:50	2.54	4.06	1.34
27-Oct	12:40	8.89	9.14	12.87

Spring Creek #4 (long-term gauge), 2006: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
03-May	15:50	2.79	3.56	1.19
03-May	19:50	1.52	2.54	0.55
10-May	10:20	2.54	5.08	2.02
22-May	21:05	2.54	3.05	0.90
30-May	18:35	1.27	2.54	0.39
30-May	01:55	1.52	1.52	0.26
16-Jun	12:35	1.78	3.56	0.98
04-Jul	21:10	3.56	3.56	1.49
04-Jul	15:15	1.27	2.54	0.39
05-Jul	17:35	2.54	3.05	0.94
06-Jul	16:15	4.57	7.11	4.62
08-Jul	11:35	5.84	7.11	5.62
08-Jul	22:05	5.59	4.57	3.06
08-Jul	13:30	1.02	1.52	0.17
09-Jul	16:05	2.03	2.54	0.60
09-Jul	00:50	1.02	1.02	0.11
15-Jul	16:20	5.84	5.59	4.53
17-Jul	18:55	1.02	1.02	0.11
20-Jul	13:00	6.35	8.64	8.55
20-Jul	18:10	4.06	3.56	1.69
25-Jul	22:35	5.59	4.06	2.72
26-Jul	18:30	1.52	2.54	0.46
01-Aug	22:20	2.29	4.57	1.80
03-Aug	17:50	6.60	8.64	8.91
03-Aug	00:10	3.56	3.56	1.57
05-Aug	23:20	9.14	6.60	7.76
05-Aug	19:50	5.08	3.56	2.09
06-Aug	19:00	10.16	11.68	19.35
07-Aug	13:55	1.52	2.54	0.43
11-Aug	15:15	1.02	2.03	0.25
12-Aug	18:45	3.56	5.08	2.52
19-Aug	19:10	4.57	4.06	2.21
21-Aug	15:10	1.02	1.52	0.19
24-Aug	18:20	4.57	3.05	1.70
25-Aug	19:45	5.84	11.68	15.83
25-Aug	14:15	5.08	8.64	6.96
26-Aug	14:35	4.57	6.60	4.46
26-Aug	07:20	3.81	4.06	1.82
26-Aug	23:10	1.02	1.02	0.11
31-Aug	14:55	2.29	4.57	1.44
08-Sep	15:45	5.08	4.57	2.81
08-Sep	09:25	3.81	4.06	1.87
11-Sep	18:25	1.52	2.54	0.49

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
03-Oct	17:15	6.60	6.10	5.15
08-Oct	13:05	2.54	1.02	0.29
09-Oct	11:05	2.03	1.02	0.23
10-Oct	10:15	1.27	2.54	0.45
15-Oct	18:45	1.27	2.03	0.31
18-Oct	14:55	11.94	6.60	10.48
19-Oct	11:05	1.02	1.52	0.17
21-Oct	11:30	2.54	3.05	0.94
27-Oct	12:25	6.86	7.62	7.53

Spring Creek #5, 2006: RF output for all storms between 1 June and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
16-Jun	12:35	7.20	12.00	17.49
21-Jun	20:35	1.20	2.00	0.34
25-Jun	19:35	1.40	2.00	0.34
28-Jun	11:15	1.80	3.60	0.96
04-Jul	20:55	6.20	6.00	4.72
05-Jul	17:35	3.00	3.60	1.25
06-Jul	16:10	6.40	9.60	10.00
07-Jul	20:00	1.80	2.40	0.47
08-Jul	11:35	8.40	6.40	7.07
08-Jul	22:10	7.80	5.20	4.68
09-Jul	16:05	2.20	2.80	0.69
10-Jul	18:00	1.20	2.40	0.38
15-Jul	16:15	6.40	6.00	5.56
17-Jul	19:35	1.20	1.20	0.15
18-Jul	14:40	1.60	3.20	0.76
20-Jul	13:00	8.40	13.60	22.16
20-Jul	18:15	4.40	4.00	2.07
25-Jul	22:30	5.40	4.00	2.56
26-Jul	18:25	2.20	4.00	1.23
03-Aug	17:55	7.40	10.40	12.70
03-Aug	00:15	3.80	3.60	1.55
05-Aug	23:25	15.20	7.60	14.26
05-Aug	15:25	1.00	1.60	0.17
06-Aug	19:05	11.40	10.80	18.24
11-Aug	15:20	2.00	3.60	1.00
12-Aug	18:50	3.40	4.40	1.78
13-Aug	20:30	1.40	2.80	0.48
19-Aug	19:10	4.40	4.00	2.01
24-Aug	19:10	4.60	3.20	1.78
25-Aug	14:20	5.80	10.40	10.25
25-Aug	19:45	4.40	8.80	7.73
26-Aug	14:35	5.20	7.20	5.27
26-Aug	07:25	4.80	6.00	3.76
31-Aug	15:00	1.80	3.20	0.68
08-Sep	15:45	5.40	4.40	2.82
08-Sep	09:25	4.00	4.00	1.84
11-Sep	18:25	2.40	4.40	1.41
20-Sep	23:30	18.40	4.40	9.00
23-Sep	09:25	1.20	1.60	0.20
03-Oct	17:15	6.80	6.00	5.20
08-Oct	13:35	3.00	1.20	0.38
09-Oct	12:20	3.80	1.60	0.64
10-Oct	09:50	1.20	2.00	0.25
18-Oct	13:05	15.80	7.20	14.90

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
19-Oct	10:45	2.20	1.20	0.28
21-Oct	10:15	2.40	1.20	0.30

Trumbull, 2005: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
01-May	09:45	2.79	5.08	1.83
02-May	16:15	2.54	1.52	0.43
06-May	18:50	2.54	5.08	2.46
29-May	18:30	5.33	6.10	4.29
29-May	20:30	1.52	3.05	0.62
30-May	17:00	4.83	4.06	2.92
10-Jun	13:10	9.91	18.29	38.54
10-Jun	01:15	1.27	2.54	0.39
11-Jun	22:20	2.29	3.56	0.99
12-Jun	02:50	4.57	5.59	3.35
20-Jun	20:30	1.02	1.02	0.11
23-Jun	18:35	9.40	17.27	37.39
23-Jun	14:50	5.84	11.68	15.97
24-Jun	22:00	5.08	8.13	6.36
26-Jun	17:45	2.29	4.57	1.94
14-Jul	23:10	1.02	2.03	0.25
15-Jul	14:10	1.78	3.56	0.79
25-Jul	19:50	4.32	4.57	2.36
03-Aug	14:40	1.02	2.03	0.25
04-Aug	12:00	10.67	8.13	11.36
04-Aug	06:45	5.33	5.08	3.31
04-Aug	02:20	1.78	2.03	0.40
04-Aug	21:15	1.27	1.02	0.14
09-Aug	17:10	4.32	8.13	6.67
11-Aug	19:25	2.54	3.05	1.01
11-Aug	17:15	1.02	1.52	0.17
13-Aug	17:20	1.78	3.56	0.87
16-Aug	15:30	18.80	31.50	140.05
20-Aug	17:15	1.02	1.02	0.11
24-Aug	19:20	1.02	2.03	0.36
06-Sep	15:40	11.68	19.30	44.57
14-Sep	15:15	1.02	1.52	0.17
22-Sep	15:20	3.56	3.56	1.86
22-Sep	02:05	1.27	2.54	0.39
28-Sep	05:15	4.32	8.13	5.33
09-Oct	15:15	3.56	1.52	0.60
10-Oct	16:35	5.59	3.05	1.89
11-Oct	11:35	11.94	7.62	11.87

Trumbull, 2006: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
05-May	18:25	1.52	1.52	0.26
22-May	20:05	3.05	4.06	1.57
30-May	17:45	1.02	2.03	0.28
06-Jun	16:10	4.83	7.62	5.42
21-Jun	14:40	1.52	3.05	0.62
22-Jun	12:45	1.52	3.05	0.59
25-Jun	20:50	1.02	1.02	0.11
03-Jul	16:55	1.78	2.54	0.50
04-Jul	23:15	9.91	6.10	7.73
05-Jul	17:55	6.60	5.59	4.57
06-Jul	16:45	1.78	2.54	0.53
07-Jul	17:05	5.59	11.18	12.04
07-Jul	20:10	1.52	2.03	0.34
08-Jul	11:15	3.56	4.57	1.98
08-Jul	13:35	3.30	4.06	1.64
08-Jul	22:35	2.03	2.03	0.46
09-Jul	12:40	5.59	7.11	6.23
09-Jul	06:35	1.52	2.03	0.34
09-Jul	16:10	1.78	1.52	0.30
10-Jul	18:15	2.54	5.08	1.95
14-Jul	20:15	1.27	2.54	0.42
20-Jul	13:35	12.45	23.37	66.40
20-Jul	19:05	4.32	3.56	1.75
25-Jul	15:50	5.08	7.11	5.30
25-Jul	22:10	2.79	3.56	1.19
01-Aug	18:00	6.35	9.14	10.02
02-Aug	14:15	1.02	1.02	0.11
03-Aug	17:15	11.94	11.68	23.76
03-Aug	00:20	5.59	6.10	4.63
05-Aug	14:20	3.30	4.57	1.85
05-Aug	19:30	5.59	2.03	1.26
06-Aug	18:40	7.62	11.18	14.30
12-Aug	18:50	5.33	4.57	3.26
13-Aug	20:30	4.57	7.11	4.78
19-Aug	15:45	4.06	6.60	3.91
19-Aug	19:35	1.52	2.54	0.46
25-Aug	14:50	3.56	7.11	4.31
26-Aug	14:50	6.10	9.65	9.68
26-Aug	07:30	6.10	7.62	6.64
08-Sep	15:50	5.08	5.59	3.50
08-Sep	09:05	2.29	2.03	0.51
10-Sep	18:45	3.30	5.08	2.45
11-Sep	18:45	2.03	4.06	1.21
21-Sep	02:25	12.45	3.05	4.20

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
22-Sep	16:05	2.79	1.52	0.47
03-Oct	17:15	3.30	4.57	2.01
08-Oct	14:40	2.29	1.02	0.26
09-Oct	10:30	1.78	1.02	0.20
15-Oct	18:15	6.60	10.16	13.08
17-Oct	10:50	1.78	1.52	0.30
18-Oct	13:30	11.43	11.68	21.82
21-Oct	10:20	2.79	5.08	1.95
26-Oct	01:25	2.29	2.54	0.64
27-Oct	12:20	9.91	11.18	17.75

Upper Saloon Gulch, 2005: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
01-May	09:35	2.20	2.40	0.57
02-May	17:00	1.60	1.20	0.20
29-May	17:50	3.40	3.60	1.49
29-May	20:30	1.40	2.80	0.50
03-Jun	16:45	5.20	6.80	4.84
10-Jun	13:15	4.80	7.60	5.78
11-Jun	22:20	2.80	4.40	1.51
20-Jun	19:20	3.60	2.80	1.30
23-Jun	15:10	1.60	2.40	0.48
06-Jul	16:25	1.40	2.80	0.69
14-Jul	22:55	3.40	5.20	2.27
23-Jul	14:55	1.60	2.00	0.38
24-Jul	17:25	1.20	1.60	0.21
25-Jul	19:35	7.20	6.00	5.60
25-Jul	15:00	1.20	2.00	0.27
04-Aug	11:50	18.60	8.40	19.40
04-Aug	02:25	2.80	2.80	0.87
04-Aug	17:50	1.60	1.60	0.27
05-Aug	00:30	1.80	1.60	0.30
09-Aug	17:20	4.40	8.00	6.40
11-Aug	19:30	1.40	1.60	0.25
13-Aug	17:05	2.60	5.20	2.35
16-Aug	15:30	4.60	7.20	4.81
19-Aug	14:05	2.20	4.40	1.79
20-Aug	17:55	2.20	1.60	0.37
22-Aug	18:00	4.00	6.80	4.93
23-Aug	15:30	1.00	2.00	0.24
25-Aug	18:40	2.20	3.60	0.98
06-Sep	15:40	9.00	11.60	16.30
14-Sep	15:05	1.60	3.20	0.59
22-Sep	15:55	4.60	4.80	2.77
22-Sep	02:05	1.60	3.20	0.59
28-Sep	05:10	3.60	6.00	2.92
09-Oct	14:20	4.40	2.00	0.92
10-Oct	13:00	3.80	1.60	0.64
11-Oct	11:00	6.00	2.40	1.51
31-Oct	09:45	2.80	2.40	0.70

Upper Saloon Gulch, 2006: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
03-May	14:55	3.20	3.20	1.18
04-May	15:25	1.00	1.20	0.13
22-May	21:00	2.80	4.00	1.45
30-May	18:50	2.20	4.40	1.47
31-May	13:40	6.60	11.20	14.15
21-Jun	14:30	1.60	3.20	0.67
25-Jun	19:50	1.40	1.20	0.19
03-Jul	16:25	9.40	16.80	33.03
04-Jul	21:05	9.00	7.20	8.75
04-Jul	15:20	2.20	4.40	1.45
05-Jul	17:30	6.00	6.00	4.45
06-Jul	16:15	1.00	1.60	0.17
08-Jul	11:15	4.20	5.60	3.00
08-Jul	21:55	2.40	1.60	0.42
08-Jul	13:20	1.00	0.80	0.08
09-Jul	16:05	3.40	4.00	1.62
09-Jul	14:05	1.20	2.00	0.27
10-Jul	18:00	12.00	24.00	72.36
12-Jul	13:55	2.20	3.20	1.03
17-Jul	18:45	1.20	1.60	0.20
20-Jul	13:05	11.40	17.60	41.39
20-Jul	19:00	4.40	2.80	1.34
25-Jul	21:40	5.20	4.80	3.07
25-Jul	16:05	1.20	0.80	0.10
26-Jul	18:30	1.20	2.00	0.27
01-Aug	17:40	1.80	2.40	0.59
02-Aug	21:10	12.00	23.60	69.86
02-Aug	13:05	7.60	10.40	14.09
03-Aug	17:25	15.20	20.40	60.64
03-Aug	00:20	4.00	3.60	1.63
05-Aug	22:20	8.80	3.60	3.44
06-Aug	18:45	12.60	18.80	45.30
07-Aug	14:30	10.80	19.60	47.08
11-Aug	15:05	6.20	12.00	15.87
12-Aug	18:50	3.20	4.80	1.92
13-Aug	20:50	1.20	1.20	0.15
14-Aug	15:05	1.40	2.40	0.46
19-Aug	19:00	1.40	1.20	0.18
25-Aug	14:40	4.80	8.40	6.69
26-Aug	07:20	4.40	6.00	3.58
26-Aug	14:30	3.60	4.80	2.26
08-Sep	15:35	3.80	4.80	2.22
08-Sep	09:10	3.00	2.80	0.90
11-Sep	18:30	2.60	5.20	1.94

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
21-Sep	03:10	15.00	4.00	6.62
22-Sep	14:35	1.80	1.20	0.23
03-Oct	16:55	4.60	4.40	2.53
08-Oct	14:15	2.00	0.80	0.17
09-Oct	10:00	2.60	0.80	0.22
15-Oct	18:15	4.00	5.20	2.84
18-Oct	12:40	12.20	4.40	6.11
19-Oct	10:50	1.60	0.80	0.13
21-Oct	09:40	1.80	1.60	0.30
27-Oct	09:35	6.20	2.80	1.89

Kelsey, 2005: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
01-May	10:40	2.03	2.03	0.46
11-May	07:25	2.03	4.06	1.24
29-May	18:55	5.08	4.57	2.92
29-May	20:40	1.78	3.56	0.92
29-May	13:10	1.27	1.02	0.16
30-May	17:05	2.54	5.08	2.11
30-May	18:35	3.30	4.57	2.18
02-Jun	15:10	3.05	3.56	1.70
03-Jun	17:00	7.37	13.21	19.52
09-Jun	17:40	1.27	2.03	0.31
10-Jun	13:10	6.60	12.19	15.82
10-Jun	01:15	1.27	1.52	0.21
11-Jun	22:20	5.84	8.13	6.88
12-Jun	02:55	1.78	2.03	0.40
15-Jun	14:30	1.27	2.54	0.42
20-Jun	20:30	2.79	4.06	1.67
23-Jun	18:40	1.52	2.03	0.37
24-Jun	21:35	8.89	15.75	27.39
24-Jun	16:25	1.27	2.54	0.39
14-Jul	22:30	4.83	7.62	5.36
24-Jul	16:40	13.21	20.83	58.69
25-Jul	19:25	9.91	10.67	15.70
04-Aug	11:50	20.57	8.13	21.17
04-Aug	02:20	3.81	4.57	2.11
04-Aug	17:55	2.54	2.03	0.57
05-Aug	00:35	1.52	2.03	0.34
09-Aug	17:25	5.33	9.65	9.76
16-Aug	15:30	6.86	12.70	16.83
20-Aug	18:00	2.03	2.03	0.46
23-Aug	14:25	8.89	9.65	14.92
25-Aug	18:45	1.78	3.05	0.64
06-Sep	18:05	3.05	3.56	1.37
06-Sep	15:40	1.27	2.03	0.29
06-Sep	08:10	1.02	2.03	0.28
14-Sep	15:10	1.78	3.05	0.60
22-Sep	14:45	13.72	13.72	37.05
22-Sep	17:30	1.02	2.03	0.23
22-Sep	02:00	1.27	1.52	0.21
28-Sep	05:20	4.32	7.62	4.76
04-Oct	19:00	1.27	2.54	0.39
09-Oct	17:50	5.59	2.03	1.26
11-Oct	13:35	12.70	6.60	10.27

Kelsey, 2006: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
03-May	16:05	2.54	2.54	0.78
03-May	20:00	1.27	2.54	0.39
04-May	15:40	1.02	1.02	0.11
10-May	10:00	1.52	3.05	0.55
22-May	21:05	3.81	4.57	2.33
30-May	18:45	1.52	3.05	0.59
30-May	02:00	1.27	1.52	0.21
21-Jun	14:35	2.03	3.56	0.85
25-Jun	20:45	1.27	1.52	0.21
03-Jul	16:35	1.52	1.52	0.26
04-Jul	21:00	7.87	6.10	6.49
05-Jul	17:40	3.81	4.06	1.82
06-Jul	16:15	1.52	2.03	0.34
08-Jul	11:25	5.59	6.60	5.00
08-Jul	22:00	5.08	4.06	2.39
09-Jul	16:00	3.05	4.06	1.48
10-Jul	18:00	8.38	16.76	32.99
12-Jul	13:55	1.02	1.52	0.19
17-Jul	18:50	1.78	2.03	0.40
20-Jul	18:10	6.60	4.06	3.18
20-Jul	14:30	1.78	3.56	0.87
20-Jul	12:30	2.54	2.54	0.90
25-Jul	21:50	6.60	6.10	5.26
25-Jul	14:25	2.54	5.08	1.86
25-Jul	16:20	1.02	1.02	0.11
26-Jul	18:25	1.52	2.54	0.52
02-Aug	13:00	5.08	4.57	2.91
03-Aug	17:35	11.43	14.22	27.95
03-Aug	00:20	4.57	3.56	1.94
05-Aug	23:10	9.14	7.11	8.96
05-Aug	19:50	4.06	2.54	1.14
06-Aug	18:50	9.40	11.18	17.12
07-Aug	14:10	1.02	2.03	0.25
11-Aug	15:05	8.89	17.78	41.90
12-Aug	18:40	3.56	4.57	2.04
13-Aug	20:30	1.27	1.52	0.21
14-Aug	14:45	1.52	2.54	0.46
16-Aug	23:45	1.27	2.54	0.42
19-Aug	19:05	2.54	2.03	0.60
21-Aug	15:45	1.02	1.52	0.17
24-Aug	18:50	1.02	1.52	0.23
25-Aug	14:20	8.38	11.18	15.23
26-Aug	14:45	7.11	11.68	16.96
26-Aug	07:20	3.81	4.06	1.82

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
31-Aug	14:45	6.86	12.70	19.97
08-Sep	15:45	6.35	7.11	5.88
08-Sep	09:15	5.08	3.56	2.14
08-Sep	12:15	1.02	1.02	0.11
11-Sep	18:30	4.06	8.13	6.08
11-Sep	12:55	1.02	2.03	0.25
21-Sep	00:00	18.80	3.56	7.58
22-Sep	14:25	2.29	2.03	0.51
03-Oct	17:10	4.80	4.80	2.73
08-Oct	12:40	2.40	0.80	0.20
09-Oct	12:40	2.80	1.20	0.35
10-Oct	10:05	1.40	2.00	0.34
15-Oct	18:45	1.40	2.00	0.31
18-Oct	13:10	11.60	5.20	7.14
19-Oct	10:30	1.80	1.20	0.23
21-Oct	11:15	2.60	2.40	0.67
27-Oct	12:55	11.40	4.80	6.41

Nighthawk, 2005: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
02-Jun	14:10	1.60	2.80	0.67
03-Jun	15:50	3.60	5.60	3.07
09-Jun	16:55	6.00	12.00	13.30
10-Jun	12:30	13.40	8.80	15.77
10-Jun	09:40	4.40	8.80	6.47
11-Jun	21:30	2.40	3.20	0.86
20-Jun	20:10	1.40	1.60	0.23
23-Jun	19:00	6.80	8.80	8.47
23-Jun	15:35	3.00	5.60	2.88
24-Jun	21:35	4.00	5.60	3.04
24-Jun	14:05	2.60	5.20	2.46
15-Jul	14:25	4.20	8.40	5.78
24-Jul	17:05	1.80	2.80	0.62
25-Jul	20:10	3.20	2.80	0.96
03-Aug	15:00	1.60	2.80	0.54
04-Aug	12:10	9.40	7.60	9.25
04-Aug	07:05	6.40	3.60	2.60
04-Aug	01:35	3.00	2.40	0.77
04-Aug	18:15	1.80	1.20	0.23
13-Aug	17:25	4.60	9.20	8.13
16-Aug	15:50	9.80	13.60	24.10
19-Aug	14:35	1.00	2.00	0.24
23-Aug	15:45	9.20	11.20	19.86
23-Aug	13:00	1.40	2.80	0.48
06-Sep	16:05	3.40	4.40	1.85
06-Sep	18:35	2.00	2.40	0.52
14-Sep	15:25	1.20	2.40	0.36
22-Sep	16:15	8.20	11.20	15.25
22-Sep	02:05	1.20	2.40	0.38
28-Sep	05:10	4.40	6.40	3.85

Nighthawk, 2006: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
03-May	14:50	1.20	1.60	0.20
22-May	21:25	3.00	4.00	1.49
30-May	00:55	1.80	1.60	0.32
31-May	13:50	10.80	18.80	43.61
16-Jun	12:45	6.40	12.00	14.59
21-Jun	20:50	2.40	4.80	2.57
25-Jun	19:20	2.00	3.60	1.09
28-Jun	11:20	1.20	2.00	0.30
03-Jul	17:00	7.40	7.60	8.07
04-Jul	21:45	9.20	5.20	5.91
05-Jul	17:50	2.60	3.60	1.07
06-Jul	16:35	8.60	12.40	19.17
07-Jul	20:00	1.80	1.60	0.32
08-Jul	11:25	5.00	6.40	4.37
08-Jul	13:50	2.80	3.20	1.04
08-Jul	22:40	1.80	1.20	0.23
09-Jul	13:00	2.60	2.00	0.55
09-Jul	16:25	1.00	2.00	0.21
09-Jul	02:05	1.20	0.80	0.10
18-Jul	14:50	5.80	11.20	12.44
20-Jul	18:20	4.20	3.20	1.52
20-Jul	13:10	1.20	0.80	0.10
25-Jul	21:50	2.80	3.20	0.99
25-Jul	16:10	1.40	2.00	0.31
26-Jul	18:25	2.40	3.60	1.08
01-Aug	18:30	6.20	12.40	17.90
02-Aug	21:35	2.80	5.60	2.85
02-Aug	13:20	1.20	1.60	0.20
03-Aug	17:45	16.00	19.20	57.12
03-Aug	00:35	5.00	7.20	5.36
05-Aug	20:20	5.00	2.00	1.05
05-Aug	15:20	1.20	2.00	0.25
06-Aug	19:35	13.60	15.20	36.36
07-Aug	14:55	1.80	2.00	0.39
11-Aug	14:50	2.00	2.00	0.52
12-Aug	19:30	2.80	2.80	0.87
19-Aug	18:15	3.00	3.20	1.06
24-Aug	18:50	1.60	2.80	0.60
25-Aug	14:10	2.80	3.60	1.60
25-Aug	20:00	1.20	2.00	0.27
26-Aug	14:55	6.80	8.80	9.28
26-Aug	07:40	6.40	8.00	7.21
31-Aug	15:15	1.40	2.80	0.46
07-Sep	14:55	1.60	3.20	0.67

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
08-Sep	16:15	3.40	3.60	1.37
08-Sep	09:05	3.00	3.20	1.09
10-Sep	19:40	1.20	2.00	0.29
11-Sep	18:40	1.20	2.00	0.25
21-Sep	02:15	27.40	6.00	19.88
22-Sep	11:25	1.80	1.60	0.30
22-Sep	14:45	1.80	1.60	0.30
03-Oct	17:15	5.60	6.80	5.08
08-Oct	13:00	3.40	0.80	0.29
09-Oct	11:40	2.60	1.20	0.33
10-Oct	09:40	1.80	2.40	0.49
15-Oct	18:45	6.60	7.60	6.95
18-Oct	13:25	17.60	6.40	13.80
21-Oct	10:30	4.00	2.40	1.01
27-Oct	11:55	20.40	6.80	18.25

Log Jumper, 2005: RF output for all storms between 3 August and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
03-Aug	14:55	1.20	2.40	0.32
04-Aug	12:05	11.20	9.60	14.57
04-Aug	06:55	8.40	6.80	7.27
04-Aug	02:05	3.20	2.80	0.99
04-Aug	18:05	1.40	1.20	0.18
09-Aug	17:15	1.40	2.00	0.33
11-Aug	20:05	1.40	1.20	0.18
13-Aug	17:20	3.00	6.00	3.14
16-Aug	15:45	13.80	26.80	88.37
20-Aug	18:00	2.00	1.60	0.35
21-Aug	16:45	1.00	2.00	0.23
22-Aug	16:25	8.80	17.60	40.80
22-Aug	18:10	1.80	3.60	0.88
24-Aug	19:05	2.20	4.00	1.27
06-Sep	15:45	7.40	9.20	10.05
14-Sep	15:20	1.00	2.00	0.23
22-Sep	16:05	3.80	7.60	4.55
22-Sep	02:10	2.00	3.60	0.90
22-Sep	00:15	1.00	2.00	0.23
28-Sep	05:15	4.80	8.00	5.70
04-Oct	19:00	1.80	2.40	0.53
09-Oct	16:35	5.20	1.60	0.87
10-Oct	13:20	4.40	1.60	0.74
11-Oct	09:55	16.00	4.80	9.13

Log Jumper, 2006: RF output for all storms between 1 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
05-May	19:10	1.00	1.20	0.13
09-May	23:55	1.00	1.60	0.17
22-May	20:20	4.20	5.20	2.86
30-May	18:00	2.20	3.20	0.87
31-May	12:50	9.40	13.20	21.89
25-Jun	19:40	2.00	3.60	0.90
03-Jul	16:25	22.00	38.80	207.90
04-Jul	15:45	4.00	8.00	5.94
04-Jul	21:15	7.60	4.00	3.58
05-Jul	17:50	4.80	4.80	2.66
06-Jul	16:25	6.60	6.00	5.46
07-Jul	17:10	9.40	18.00	37.86
07-Jul	19:25	2.20	2.40	0.59
08-Jul	13:35	4.20	5.60	3.08
08-Jul	11:10	3.80	4.40	2.06
08-Jul	22:35	1.80	2.00	0.39
08-Jul	16:55	1.00	1.20	0.13
09-Jul	12:45	4.20	5.20	2.67
09-Jul	16:15	2.60	2.80	0.85
09-Jul	07:20	1.00	1.20	0.13
10-Jul	18:15	11.40	22.80	64.54
20-Jul	13:45	3.20	5.60	2.50
20-Jul	19:20	3.40	2.40	0.86
25-Jul	21:55	4.00	4.40	2.09
25-Jul	16:25	1.00	0.80	0.08
01-Aug	17:55	29.60	58.80	481.11
02-Aug	13:20	6.00	9.20	9.50
02-Aug	21:30	2.40	4.80	1.73
03-Aug	17:35	18.60	24.80	98.13
03-Aug	00:45	2.00	2.40	0.52
05-Aug	15:20	2.60	2.40	0.71
05-Aug	22:00	5.80	2.00	1.22
06-Aug	18:45	17.40	29.20	114.92
07-Aug	14:40	4.20	7.20	4.68
12-Aug	19:25	3.60	2.80	1.21
13-Aug	20:50	2.00	4.00	1.20
24-Aug	18:10	1.60	1.60	0.31
25-Aug	14:55	2.60	5.20	1.94
26-Aug	14:50	6.60	9.60	10.14
26-Aug	07:30	4.40	5.20	2.88
08-Sep	15:50	3.40	3.60	1.40
08-Sep	09:20	3.40	2.80	1.04
11-Sep	18:40	1.80	3.60	0.87
21-Sep	02:20	14.60	3.20	5.08

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
22-Sep	14:25	3.40	2.80	1.04
03-Oct	17:10	5.00	4.80	2.98
08-Oct	13:05	5.00	1.60	0.84
09-Oct	11:05	1.40	0.80	0.12
15-Oct	18:35	3.40	3.20	1.27
18-Oct	12:55	12.40	6.00	8.83
19-Oct	11:05	2.40	1.20	0.30
21-Oct	10:00	3.00	2.40	0.75
27-Oct	11:10	14.00	11.60	24.74

Noddle, 2006: RF output for all storms between 20 May and 31 October.

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
22-May	21:25	4.06	5.59	2.93
30-May	01:00	1.78	1.52	0.30
31-May	13:50	11.94	22.86	64.67
16-Jun	12:40	3.30	6.60	3.47
28-Jun	11:25	2.29	4.06	1.40
03-Jul	16:55	13.21	10.67	23.07
04-Jul	22:30	8.89	6.10	6.85
05-Jul	17:45	3.56	4.06	1.70
06-Jul	16:35	5.59	6.10	4.30
07-Jul	20:35	1.52	2.03	0.34
08-Jul	13:45	5.84	8.13	7.16
08-Jul	11:25	5.59	6.60	5.35
08-Jul	22:50	2.29	2.03	0.51
09-Jul	14:20	4.06	3.05	1.41
09-Jul	16:25	1.02	2.03	0.25
09-Jul	19:10	1.52	1.52	0.26
09-Jul	02:05	1.52	1.02	0.17
18-Jul	14:55	1.78	3.56	0.96
20-Jul	18:15	4.06	3.56	1.69
25-Jul	21:45	4.06	3.56	1.69
25-Jul	16:10	1.02	1.02	0.11
26-Jul	18:40	2.79	5.59	2.69
01-Aug	18:30	5.59	7.62	7.77
02-Aug	21:30	2.03	4.06	1.48
02-Aug	13:20	2.03	2.54	0.57
03-Aug	17:50	14.99	18.29	50.89
03-Aug	00:35	3.56	3.56	1.45
05-Aug	19:55	5.33	2.03	1.20
05-Aug	15:20	1.52	2.03	0.34
06-Aug	19:30	8.64	7.62	9.58
07-Aug	14:50	2.29	3.05	0.77
12-Aug	19:30	2.79	2.54	0.85
19-Aug	19:20	1.52	1.52	0.26
25-Aug	14:10	2.29	2.54	0.77
25-Aug	20:00	1.02	2.03	0.23
26-Aug	15:00	7.11	10.67	12.47
26-Aug	07:40	5.08	5.59	3.69
31-Aug	15:15	1.52	3.05	0.55
08-Sep	16:10	3.56	4.57	2.02
08-Sep	09:00	3.05	3.05	1.07
21-Sep	02:15	21.34	4.57	11.51
22-Sep	16:45	3.81	3.05	1.33
22-Sep	11:15	1.52	1.02	0.17
03-Oct	17:15	4.57	7.11	4.55

Date	Start time	Storm depth (mm)	Maximum 30-min intensity (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})
08-Oct	13:20	3.30	1.02	0.37
09-Oct	10:40	1.52	1.02	0.17
10-Oct	10:25	1.78	3.05	0.68
15-Oct	18:45	8.89	9.14	13.11
18-Oct	13:55	11.94	8.13	14.00
21-Oct	11:05	2.29	4.06	1.19
27-Oct	12:00	5.84	9.14	8.28

Appendix IV. Storm-based sediment production from road segments with sediment fences by study site for 2005 and 2006.

Storm-based sediment production in kilograms for each road segment at Spring Creek in 2005.

	Sediment removal date												
Segment	7-Jun	11-Jun	25-Jun	18-Jul	25-Jul	26-Jul	5-Aug	10-Aug	11-Aug	17-Aug	11-Sep	23-Oct	Total (kg)
3/2	10.0	0.9	1753.3	6.9	22.9	14.3	37.2	266.0	152.6	843.7	1.9	51.8	3161.6
3/4	5.8	6.9	420.5	6.3	8.1	24.5	20.3	61.3	25.0	672.2	0.4	55.2	1306.5
3/5	9.6	0.4	346.8	9.9	7.8	17.4	31.7	75.0	6.6	508.9	1.7	23.5	1039.3
3/6	8.4	52.0	2.1	87.1	7.3	172.1	30.3	52.6	33.5	216.2	1.2	0.2	663.0
3/7	11.2	16.0	193.3	5.6	445.0	76.5	229.1	missed	65.9	366.1	1.2	43.9	1453.8
3/8	22.4	89.0	355.3	2.1	592.1	254.3	311.9	missed	247.3	589.8	2.1	138.0	2604.1
3/9	62.8	120.8	155.7	2.3	297.2	120.1	missed	263.6	178.3	327.4	5.3	8.8	1542.2
3/10	58.3	69.0	62.4	1.5	52.5	62.9	7.8	26.5	29.0	47.1	0.6	23.0	440.6
3/11	0.0	11.5	2.9	1.1	4.9	2.2	0.7	0.9	2.6	4.3	0.5	0.7	32.3
3/14	9.4	0.0	1212.1	0.3	43.9	76.6	236.5	missed	847.0	1050.2	1.5	120.6	3598.1
3/15	56.3	33.9	108.7	14.3	138.2	165.4	161.5	missed	331.4	286.1	17.4	141.7	1454.9

Storm-based sediment production in kilograms for each road segment at Spring Creek in 2006.

	Sediment removal date																
Segment	20-Jun	6-Jul	8-Jul	10-Jul	11-Jul	21-Jul	26-Jul	4-Aug	6-Aug	7-Aug	8-Aug	15-Aug	28-Aug	2-Sep	15-Sep	24-Oct	Total (kg)
3/2	78.7	0.5	30.1	1.6	0.0	65.1	1.0	36.3	23.1	140.8	0.0	0.0	70.4	0.0	1.6	1.4	450.6
3/4	0.0	0.6	0.0	0.0	0.0	0.7	0.0	0.9	3.1	14.3	0.0	0.0	100.1	0.0	1.6	1.3	122.6
3/5	0.0	0.4	0.3	0.1	0.0	0.5	0.0	1.4	2.0	7.4	0.0	0.0	102.1	0.0	4.0	1.6	119.8
3/6	0.0	0.0	0.0	0.1	0.0	0.3	0.5	1.1	0.2	24.3	0.0	0.9	100.6	3.3	4.9	1.2	137.4
3/7	0.0	0.0	0.0	0.1	0.0	0.1	0.0	78.4	44.0	95.2	0.0	0.0	291.0	39.7	34.8	17.8	601.1
3/8	0.0	0.0	3.4	0.7	0.0	2.6	2.3	72.9	101.4	177.9	0.0	0.0	296.7	60.5	44.8	45.8	808.8
3/9	0.0	0.0	1.1	0.4	0.0	1.3	0.4	0.0	0.0	158.3	0.0	7.4	262.3	25.8	48.0	79.4	584.4
3/10	0.0	0.7	25.6	1.2	8.5	27.3	0.6	9.7	9.3	0.0	23.7	18.3	69.4	0.0	30.9	2.0	227.1
3/11	0.0	0.0	0.4	0.2	0.1	0.4	0.0	0.2	0.1	0.0	0.5	0.0	1.6	0.0	0.2	0.0	3.7
3/14	20.9	0.6	12.9	3.2	0.0	226.2	1.1	190.0	234.9	331.1	0.0	0.0	317.7	0.0	10.7	13.6	1362.9
3/15	0.0	2.7	40.6	34.0	11.3	41.0	15.7	26.0	73.8	missed	130.2	51.1	119.2	40.4	148.0	117.4	851.5

Storm-based sediment production in kilograms for each road segment at Trumbull in 2005.

	Sediment removal date										
Segment	12-Jun	24-Jun	26-Jun	18-Jul	25-Jul	5-Aug	10-Aug	14-Aug	17-Aug	10-Sep	22-Oct	Total (kg)
E1	225.0	285.5	24.4	0.6	0.3	14.4	2.3	20.3	43.1	174.1	14.8	804.8
E2	63.5	232.4	7.5	0.5	0.1	26.8	1.2	5.9	69.6	85.5	7.5	500.6
E3	170.0	373.6	18.2	0.7	0.0	46.2	1.4	0.0	311.5	143.8	67.8	1133.1
E4	291.2	missed	341.6	0.6	67.9	9.4	1.4	99.9	344.4	173.3	22.7	1352.3
8	776.0	347.6	5.7	1.0	0.0	11.3	1.1	0.2	255.6	64.4	16.5	1479.3

Storm-based sediment production in kilograms for each road segment at Trumbull in 2006.

	Sediment removal date														
Segment	14-May	9-Jul	11-Jul	20-Jul	21-Jul	26-Jul	2-Aug	3-Aug	4-Aug	6-Aug	7-Aug	14-Aug	28-Aug	15-Sep	25-Oct	Total (kg)
E1	1.0	165.7	12.3	11.0	1.5	4.3	209.2	0.0	167.5	5.5	68.0	16.4	88.9	16.3	1.8	769.3
E2	0.0	11.3	0.1	14.8	0.0	6.5	32.2	5.5	31.7	0.2	16.9	9.4	32.8	0.1	5.3	166.8
E3	1.9	47.9	8.7	132.1	0.0	30.1	56.2	22.9	254.0	0.0	154.6	33.7	110.4	0.0	105.0	957.3
E4	0.0	109.8	16.5	97.7	4.9	109.7	106.4	26.1	222.0	6.7	173.4	96.3	158.5	0.0	186.1	1313.9
8	0.0	12.1	1.6	128.1	0.2	43.3	77.3	13.6	100.2	0.0	59.6	53.3	78.7	0.0	110.9	678.8

Storm-based sediment production in kilograms for the road segment at Upper Saloon Gulch in 2005.

	Sediment removal date						
Segment	26-Jul	5-Aug	11-Aug	17-Aug	11-Sep	25-Sep	Total (kg)
1	2.4	1.2	0.5	0.3	6.3	5.7	16.4

Storm-based sediment production in kilograms for the road segment at Upper Saloon Gulch in 2006.

	Sediment removal date				
Segment	4-Aug	8-Aug	31-Aug	25-Oct	Total (kg)
1	12.5	1.0	4.9	10.9	29.4

Storm-based sediment production in kilograms for each road segment at Kelsey in 2005.

	Sediment removal date									
Segment	11-Jun	12-Jun	26-Jun	26-Jul	5-Aug	11-Aug	17-Aug	11-Sep	22-Oct	Total (kg)
1	71.7	5.9	72.6	124.4	20.7	0.4	17.7	42.1	104.7	460.1
2	8.0	0.9	79.4	98.9	25.9	0.4	2.8	37.6	79.9	333.9

Storm-based sediment production in kilograms for each road segment at Kelsey in 2006.

	Sediment removal date														
Seg.	18-May	6-Jul	8-Jul	10-Jul	11-Jul	18-Jul	21-Jul	26-Jul	4-Aug	6-Aug	8-Aug	14-Aug	31-Aug	2-Sep	25-Oct	Total (kg)
1	3.7	1.4	1.1	0.6	17.3	0.0	0.8	2.2	27.2	21.1	25.7	25.1	74.9	30.1	33.7	264.8
2	2.0	0.3	0.0	0.0	31.3	1.6	0.5	2.2	35.6	29.8	17.1	70.7	77.3	54.8	51.9	375.1

Storm-based sediment production in kilograms for each road segment at Nighthawk in 2005.

	Sediment removal date										
Segment	17-Jun	24-Jun	26-Jun	18-Jul	5-Aug	10-Aug	14-Aug	18-Aug	10-Sep	22-Oct	Total (kg)
1	79.4	44.7	7.5	0.7	83.3	0.6	11.3	126.6	546.5	53.6	954.2
2	60.3	2.5	2.7	0.5	29.0	1.2	9.8	98.4	280.6	36.7	521.7

Storm-based sediment production in kilograms for each road segment at Nighthawk in 2006.

	Sediment removal date												
Segment	1-Jun	20-Jun	6-Jul	9-Jul	10-Jul	21-Jul	3-Aug	4-Aug	6-Aug	7-Aug	28-Aug	25-Oct	Total (kg)
1	576.6	13.8	1.3	308.9	4.5	97.8	333.3	191.6	2.9	187.5	49.9	5.4	1773.5
2	221.3	3.0	2.3	161.5	1.2	3.2	31.7	318.3	1.3	283.5	21.1	3.8	1052.1

Appendix V. Storm-based sediment production from OHV trail segments with sediment fences by study site for 2005 and 2006.

Storm-based sediment production in kilograms for each OHV trail segment at Log Jumper in 2005. n/a indicates that the sediment fence had not been installed.

	Sediment removal date						
Segment	5-Aug	10-Aug	12-Aug	18-Aug	10-Sep	22-Oct	Total (kg)
1	159.5	1.6	0.4	303.8	239.8	2.0	707.1
2	3.9	0.6	0.4	175.1	83.4	1.1	264.5
3	37.0	0.0	0.6	101.0	61.8	0.6	201.0
4	n/a	n/a	n/a	44.2	13.7	0.0	57.9
5	n/a	n/a	n/a	307.6	194.3	5.9	507.9

Storm-based sediment production in kilograms for each OHV trail segment at Log Jumper in 2006.

	Sediment removal date										
Segment	14-May	1-Jun	7-Jul	10-Jul	11-Jul	2-Aug	3-Aug	4-Aug	8-Aug	28-Aug	Total (kg)
1	1.7	179.4	1160.7	391.7	399.8	3144.2	9.9	578.9	821.6	56.7	6744.7
2	0.7	96.5	517.7	69.8	55.5	missed	933.2	92.6	121.5	29.6	1917.0
3	0.0	187.3	300.2	70.6	66.8	missed	314.4	72.6	77.1	18.9	1107.9
4	0.0	8.4	563.0	217.7	178.6	missed	911.6	224.4	262.3	77.0	2443.1
5	0.0	416.5	1029.7	311.6	328.0	missed	1387.2	304.7	367.8	107.5	4253.1

Storm-based sediment production in kilograms for each OHV trail segment at Noddle in 2006.

	Sediment removal date									
Segment	1-Jun	20-Jun	6-Jul	10-Jul	3-Aug	5-Aug	8-Aug	28-Aug	11-Nov	Total (kg)
1	14.2	1.2	7.5	1.2	1.0	4.0	1.0	3.1	1.5	34.8
2	113.7	0.5	8.0	15.7	5.3	59.3	8.2	2.4	0.5	213.6
3	887.2	0.7	4.6	11.9	21.3	347.2	16.6	108.6	179.4	1577.5
4	150.3	1.0	34.0	28.8	38.4	91.6	8.7	27.0	36.3	416.1
5	79.6	1.0	5.8	4.4	8.0	60.0	4.9	4.8	5.0	173.5

Appendix VI. Survey data for OHV trails in the RRMRA by trail.

Appendix VI.A. Survey information for the 24 segments measured along the Bar trail. n.d. indicates that no data are available.

Seg. no.	Hillslope position	Trail surface cover	Traffic	Inside ditch	Incised depth (m)	Length (m)	Slope (%)	Active width (m)	Total width (m)	Max. rill depth on seg.	Drainage type	Transport distance (m)	Hillslope gradient below drainage (%)
2	Midslope	Bare	Heavy	No	0.1	44	11	2.30	4.80	Shallow	Pushout	18.5	10
5	Midslope	Bare	Heavy	No	0.7	67	10	1.80	4.10	Medium	Pushout	21.5	10
8	Midslope	Bare	Heavy	No	0.4	67	13	1.90	3.20	Shallow	None	14.5	13
11	Midslope	Bare	Heavy	No	0.5	84	11	1.80	3.40	Shallow	Pushout	15	3
14	Midslope	Bare	Heavy	No	0.1	35	6	2.10	4.95	Shallow	Pushout	12	10
17	Midslope	Bare	Heavy	No	0.8	26	9	2.05	5.35	Shallow	None	11	23
20	Midslope	Bare	Heavy	No	0.6	67	14	1.73	4.37	Shallow	Pushout	19	20
23	Midslope	Bare	Heavy	No	0.6	25	11	3.25	6.25	Shallow	Pushout	119	30
26	Midslope	Bare	Heavy	No	0.6	28	18	2.00	5.45	Shallow	Pushout	20	12
29	Midslope	Bare	Heavy	No	1.4	26	13	1.60	4.60	Shallow	None	15.5	30
32	Midslope	Bare	Heavy	No	1.1	34	15	1.70	5.30	Shallow	Pushout	29.5	39
35	Midslope	Bare	Heavy	No	1.0	16.5	9	1.90	4.70	Shallow	Pushout	11	32
38	Midslope	Bare	Heavy	No	0.8	16	6	1.80	3.70	Shallow	Pushout	12	31
41	Midslope	Bare	Heavy	No	0.8	44	8	1.70	4.25	Shallow	Pushout	28	28
44	Midslope	Bare	Heavy	No	1.3	39	15	1.75	5.70	Shallow	Pushout	41	25
47	Midslope	Bare	Heavy	No	0.9	19	11	1.70	5.20	Shallow	Pushout	26	27
50	Midslope	Bare	Heavy	No	0.6	51	9	1.80	6.90	Shallow	Pushout	15	26
53	Midslope	Bare	Heavy	No	0.8	7	6	1.90	5.60	None	Pushout	9	31
56	Midslope	Bare	Heavy	No	0.5	29.5	8	1.70	4.50	Shallow	Pushout	20.5	24
59	Ridgetop	Bare	Heavy	No	0.6	21	13	1.70	6.30	Shallow	Pushout	23.5	33
62	Ridgetop	Bare	Heavy	No	0.4	67	17	1.70	4.15	Shallow	Pushout	61.5	23
65	Midslope	Bare	Heavy	No	0.8	25	20	1.70	4.00	Shallow	Pushout	87	25
68	Midslope	Bare	Heavy	No	0.3	41	17	2.60	4.55	Shallow	Pushout	27	12
71	Valley	Bare	Heavy	No	0.9	97	15	1.87	4.97	Medium	None	n.d.	n.d.

Appendix VI.A. (continued).

Seg. no.	Roughness	Sediment plume/Outlet rill	Outlet rill		Conn. class	Notes
			Width (m)	Depth (m)		
2	Medium	Plume			2	
5	High	Plume			3	
8	High	Plume			4	
11	Medium	Plume			2	
14	Medium	Plume			4	
17	Medium	Plume			2	
20	High	Plume			2	
23	Medium	Outlet rill	0.40	0.14	3	
26	High	Plume			3	
29	Medium	Plume			2	
32	Medium	Plume			3	
35	Medium	Plume			2	
38	Medium	Plume			2	
41	Medium	Plume			3	
44	Medium	Plume			3	
47	Medium	Outlet rill	0.18	0.09	3	
50	High	Plume			4	
53	High	Plume			2	
56	Low	Plume			3	
59	Medium	Plume			3	
62	Medium	Plume			3	
65	Medium	Outlet rill	0.28	0.10	3	Don’t use plume distance, length estimated b/c of private property.
68	Medium	Plume			3	
71	n.d.	n.d.			4	Drains into Pine Creek at Hwy 67.

Appendix VI.B. Survey information for the 11 segments measured along the Cabin Ridge trail. n.d. indicates that no data are available.

Seg. no.	Hillslope position	Trail surface cover	Traffic	Inside ditch	Incised depth (m)	Length (m)	Slope (%)	Active width (m)	Total width (m)	Max. rill depth on seg.	Drainage type	Transport distance (m)	Hillslope gradient below drainage (%)
1	Ridgetop	Bare	Heavy	No	0.0	117.5	10	3.43	5.33	Shallow	Pushout	19	7
4	Ridgetop	Bare	Heavy	No	0.0	152	4	3.65	6.05	None	Pushout	12	5
7	Ridgetop	Bare	Heavy	No	0.2	112	12	2.37	4.80	Shallow	Pushout	35	21
10	Ridgetop	Bare	Heavy	No	0.2	109.5	11	2.45	4.85	Shallow	None	23.5	16
13	Ridgetop	Bare	Heavy	No	0.0	26.5	8	3.40	6.00	None	None	8	17
16	Ridgetop	Bare	Heavy	No	0.1	162.5	2	2.85	5.35	None	None	0	n.d.
19	Ridgetop	Bare	Heavy	No	0.4	48	13	2.05	5.30	Shallow	Pushout	13.5	9
22	Ridgetop	Bare	Heavy	No	0.1	43	1	1.85	4.20	None	None	0	n.d.
25	Ridgetop	Bare	Heavy	No	0.1	58	5	2.50	5.20	Shallow	Pushout	31	20
28	Ridgetop	Bare	Heavy	No	0.1	128	6	2.13	4.03	Shallow	None	0	n.d.
31	Ridgetop	Bare	Heavy	No	0.0	220.5	8	2.82	5.38	Medium	Pushout	22.5	12

Appendix VI.B. (continued).

Seg. No.	Roughness	Sediment plume/Outlet rill	Outlet rill		Conn. class	Notes
			Width (m)	Depth (m)		
1	Medium	Plume			2	
4	Medium	Plume			2	
7	High	Plume			3	
10	High	Plume			3	
13	Medium	Plume			2	
16		None			1	
19	Low	Plume			2	
22		None			1	
25		Outlet rill	0.30	0.03	3	
28		None			1	
31	Medium	Plume			3	Sediment plume is impounded by a berm.

Appendix VI.C. Survey information for the 19 segments measured along the Devil's Slide trail. n.d. indicates that no data are available.

Seg. no.	Hillslope position	Trail surface cover	Traffic	Inside ditch	Incised depth (m)	Length (m)	Slope (%)	Active width (m)	Total width (m)	Max. rill depth on seg.	Drainage type	Transport distance (m)	Hillslope gradient below drainage (%)
1	Ridgetop	Bare	Heavy	No	0.4	86	13	1.60	6.50	Medium	Pushout	107	20
4	Ridgetop	Bare	Heavy	No	0.0	32	8	2.55	4.65	Shallow	Pushout	41.5	25
7	Midslope	Bare	Heavy	No	0.4	310	12	2.05	4.55	Deep	Pushout	68	15
10	Valley	Bare	Heavy	No	0.1	10	15	1.50	2.50	None	Pushout	n.d.	n.d.
13	Valley	Bare	Heavy	No	0.3	57	13	1.85	3.80	Shallow	Pushout	n.d.	n.d.
16	Valley	Bare	Heavy	No	0.3	42	11	1.75	3.30	Shallow	Pushout	7.7	25
19	Valley	Bare	Heavy	No	0.7	26	9	1.90	4.50	Shallow	Pushout	3	n.d.
22	Valley	Bare	Heavy	No	0.5	35	12	1.60	4.40	Shallow	Pushout	10.5	15
25	Valley	Bare	Heavy	No	0.3	27	11	1.60	3.10	Shallow	None	n.d.	n.d.
28	Valley	Bare	Heavy	No	1.0	14	7	1.70	4.00	None	Pushout	10	12
31	Valley	Bare	Heavy	No	0.1	14	7	2.00	4.30	None	Pushout	8	19
34	Valley	Bare	Heavy	No	0.2	50	7	1.90	6.00	Medium	Pushout	45	10
37	Valley	Bare	Heavy	No	0.3	58	10	1.75	3.60	Shallow	None	n.d.	n.d.
40	Valley	Bare	Heavy	No	0.5	93	9	1.83	3.97	Medium	None	n.d.	n.d.
43	Valley	Bare	Heavy	No	0.2	33	5	1.65	3.75	None	Pushout	15	10
46	Valley	Bare	Heavy	No	0.8	150	6	1.58	3.78	Shallow	Pushout	52	8
49	Valley	Bare	Heavy	No	0.5	64	4	1.55	4.50	Shallow	None	8	48
52	Valley	Bare	Heavy	No	1.1	20	2	1.70	8.00	Shallow	None	15	32
55	Valley	Bare	Heavy	No	0.3	10	9	1.80	3.30	Shallow	None	28	15

Appendix VI.C. (continued).

Seg. no.	Roughness	Sediment plume/Outlet rill	Outlet rill Width (m)	Outlet rill Depth (m)	Conn. class	Notes
1	Medium	Plume			3	
4	Low	Outlet rill	0.33	0.12	3	
7	High	Plume			3	
10		n.d.			4	Outlet is the stream.
13		n.d.			4	Outlet is the stream.
16	Low	Plume			4	Length to stream.
19	Low	Plume			4	Length to stream.
22	High	Plume			4	Length to stream.
25		n.d.			4	Outlet is the stream.
28	Medium	Plume			4	Length to stream.
31	Medium	Plume			4	Length to stream.
34	Low	Plume			4	Length to stream.
37		n.d.			4	Outlet is the stream.
40		n.d.			4	Outlet is the stream.
43	High	Plume			4	Length to stream.
46	High	Plume			4	
49	Medium	Plume			4	Length to stream.
52	Medium	Plume			4	
55	Low	Plume			4	

Appendix VI.D. Survey information for the 18 segments measured along the Gramps trail. n.d. indicates that no data are available.

Seg. no.	Hillslope position	Trail surface cover	Traffic	Inside ditch	Incised depth (m)	Length (m)	Slope (%)	Active width (m)	Total width (m)	Max. rill depth on seg.	Drainage type	Transport distance (m)	Hillslope gradient below drainage (%)
2	Ridgetop	Bare	Heavy	No	0.1	53.5	2	2.00	4.10	Shallow	None	0	n.d.
5	Ridgetop	Bare	Heavy	No	0.5	27	5	1.80	6.50	Shallow	None	26.5	28
8	Ridgetop	Bare	Heavy	No	0.0	35.5	4	2.30	5.00	Shallow	Pushout	15	14
11	Ridgetop	Bare	Heavy	No	0.3	26	4	2.20	5.00	Shallow	Pushout	10	15
14	Ridgetop	Bare	Heavy	No	0.2	47	4	1.95	4.75	None	None	11	19
17	Ridgetop	Bare	Heavy	No	0.1	37	5	2.00	4.40	Shallow	Pushout	11	27
20	Ridgetop	Bare	Heavy	No	0.2	29	3	2.90	5.05	Shallow	Pushout	7	10
23	Ridgetop	Bare	Heavy	No	0.1	8	7	1.70	4.60	None	None	5.5	20
26	Ridgetop	Bare	Heavy	No	0.5	22	6	2.10	5.30	None	None	10	35
29	Ridgetop	Bare	Heavy	No	1.1	8	5	2.20	6.00	None	None	5.8	36
32	Ridgetop	Bare	Heavy	No	0.5	28	6	2.00	6.20	None	None	6	41
35	Ridgetop	Bare	Heavy	No	0.9	42	6	1.75	6.95	Shallow	None	11.5	41
38	Ridgetop	Bare	Heavy	No	0.5	15	8	1.80	6.20	Shallow	Pushout	12	23
41	Ridgetop	Bare	Heavy	No	0.5	34	4	2.05	5.95	None	None	28	26
44	Midslope	Bare	Heavy	No	0.3	70	6	2.10	5.67	Shallow	None	0	n.d.
47	Midslope	Bare	Heavy	No	0.3	135	7	2.03	4.50	Shallow	None	24	11
50	Ridgetop	Bare	Heavy	No	0.0	102	4	4.77	7.13	None	None	0	n.d.
53	Ridgetop	Bare	Heavy	No	0.6	377	16	1.84	4.44	Deep	None	117.5	31

Appendix VI.D. (continued).

Seg. No.	Roughness	Sediment plume/Outlet rill	Outlet rill Width (m)	Outlet rill Depth (m)	Conn. class	Notes
2		N/A			1	
5	Medium	Plume			3	
8	Medium	Plume			2	
11	Medium	Plume			2	
14	Medium	Plume			2	
17	High	Plume			2	
20	High	Plume			2	
23	Medium	Plume			2	
26	Medium	Plume			2	
29	Medium	Plume			2	
32	High	Plume			2	
35	High	Plume			2	
38	Medium	Plume			2	
41	Medium	Plume			3	
44		None			1	
47	Medium	Plume			3	
50		None			1	
53	Low	Outlet rill	0.33	0.22	4	

Appendix VI.E. Survey information for the 16 segments along the Log Jumper-A trail. n.d. indicates that no data are available.

Seg. no.	Hillslope position	Trail surface cover	Traffic	Inside ditch	Incised depth (m)	Length (m)	Slope (%)	Active width (m)	Total width (m)	Max. rill depth on seg.	Drainage type	Transport distance (m)	Hillslope gradient below drainage (%)
2	Ridgetop	Bare	Heavy	No	1.3	52.5	17	2.60	4.73	Shallow	None.	63	20
5	Midslope	Bare	Heavy	No	1.0	32.5	18	1.95	6.88	Shallow	None	19.00	40
8	Midslope	Bare	Heavy	No	0.2	61	18	1.77	2.87	Shallow	None	5	18
11	Midslope	Bare	Heavy	No	0.9	34.5	16	1.80	4.40	Shallow	Pushout	10.5	35
14	Midslope	Bare	Heavy	No	0.4	11	21	1.70	4.25	None	None	4	40
17	Midslope	Bare	Heavy	No	0.6	31.5	15	1.77	4.80	Shallow	None	29	32
20	Midslope	Bare	Heavy	No	0.7	27.5	11	1.80	4.45	None	Pushout	14	26
23	Midslope	Bare	Heavy	No	0.3	12.5	12	1.80	3.80	Shallow	Pushout	5	20
26	Midslope	Bare	Heavy	No	0.8	13	23	1.90	5.00	Shallow	None	25	31
29	Midslope	Bare	Heavy	No	1.0	36	13	1.65	5.15	Shallow	None	29	45
32	Midslope	Bare	Heavy	No	0.8	45	14	1.83	4.83	Shallow	None	13	25
35	Midslope	Bare	Heavy	No	0.9	40.5	19	1.73	4.17	Shallow	None	33	28
38	Midslope	Bare	Heavy	No	0.2	32	19	1.90	3.60	Shallow	Pushout	19	13
41	Midslope	Bare	Heavy	No	0.7	45	14	1.90	4.67	Shallow	None	22.5	25
44	Midslope	Bare	Heavy	No	0.2	43.5	11	2.03	3.93	Shallow	Pushout	9	11
47	Valley	Bare	Heavy	No	0.5	80	17	1.60	3.37	Shallow	None	n.d.	n.d.

Appendix VI.E. (continued).

Seg. no.	Roughness	Sediment plume/Outlet rill	Outlet rill		Conn. class	Notes
			Width (m)	Depth (m)		
2	Medium	Plume			3	
5	Low	Plume			2	
8	Medium	Plume			2	
11	Medium	Plume			2	
14	Medium	Plume			2	
17	Medium	Plume			3	
20	Medium	Plume			2	
23	Medium	Plume			2	
26	Low	Plume			3	
29	Low	Outlet rill	0.47	0.13	3	
32	Low	Plume			2	
35	Medium	Plume			3	
38	Low	Plume			2	
41	Medium	Plume			3	Monitoring segment LJ #1.
44	Medium	Plume			2	
47	Low	n.d.			4	Drains to parking lot and Sugar Creek.

Appendix VI.F. Survey information for the 23 segments measured along the Log Jumper-C trail. n.d. indicates that no data are available.

Seg. no.	Hillslope position	Trail surface cover	Traffic	Inside ditch	Incised depth (m)	Length (m)	Slope (%)	Active width (m)	Total width (m)	Max. rill depth on seg.	Drainage type	Transport distance (m)	Hillslope gradient below drainage (%)
1	Ridgetop	Bare	Heavy	No	0.2	98	7	3.37	7.37	None	None	10.5	13
4	Ridgetop	Bare	Heavy	No	2.1	167	7	3.27	10.40	Medium	None	12.5	32
7	Ridgetop	Bare	Heavy	Yes	1.0	50	9	3.00	9.30	Medium	None	35	22
10	Ridgetop	Bare	Heavy	No	0.2	86	12	3.65	7.00	Shallow	Pushout	86.5	21
13	Ridgetop	Bare	Heavy	No	3.7	88	6	2.90	13.17	Deep	None	119	26
16	Ridgetop	Bare	Heavy	No	9.6	30	9	1.90	26.00	Shallow	Pushout	22	23
19	Ridgetop	Bare	Heavy	No	6.0	46	14	2.20	15.00	Shallow	Pushout	76.5	40
22	Ridgetop	Bare	Heavy	No	10.4	58	2	2.25	17.25	None	None	47	41
25	Ridgetop	Bare	Heavy	No	3.4	79	13	2.60	10.95	Medium	Pushout	69.5	39
28	Ridgetop	Bare	Heavy	No	5.1	34	0	2.90	13.40	None	None	0	n.d.
31	Ridgetop	Bare	Heavy	No	1.5	27	9	3.40	9.00	Medium	Pushout	60.3	21.0
34	Ridgetop	Bare	Heavy	No	1.0	36	8	3.00	8.00	Shallow	Pushout	70.5	20
37	Ridgetop	Bare	Heavy	No	2.0	27	5	2.80	11.50	shallow	Pushout	60	18
40	Ridgetop	Bare	Heavy	No	0.3	32	9	2.80	7.00	Medium	Pushout	34	15
43	Ridgetop	Bare	Heavy	No	0.9	21	0	2.50	8.20	Shallow	Pushout	27.5	24
46	Ridgetop	Bare	Heavy	No	0.0	85	5	3.00	7.00	None	None	26	23
49	Ridgetop	Bare	Heavy	No	0.0	16	3	3.20	6.50	None	None	10.5	15
52	Midslope	Bare	Heavy	No	3.0	42	7	2.15	10.50	Medium	Pushout	34	16
55	Midslope	Bare	Heavy	No	1.6	31	12	2.60	9.30	Medium	Pushout	67	32
58	Ridgetop	Bare	Heavy	No	3.1	125	10	2.63	11.60	Medium	Pushout	131	31
61	Ridgetop	Bare	Heavy	No	1.8	27	5	2.20	9.30	Shallow	Pushout	31	37
64	Ridgetop	Bare	Heavy	No	0.0	18	16	2.70	13.50	Shallow	Pushout	30.4	19
67	Ridgetop	Bare	Heavy	No	0.2	32	16	2.00	8.00	Medium	Pushout	38	23

Appendix VI.F. (continued).

Seg. no.	Roughness	Sediment plume/Outlet rill	Outlet rill		Conn. class	Notes
			Width (m)	Depth (m)		
1	Low	Plume			2	
4	Medium	Plume			2	
7	Medium	Plume			3	
10	Medium	Outlet rill	0.40	0.16	3	
13	Low	Plume			4	
16	Medium	Plume			3	
19	Low	Plume			3	
22	Low	Plume			3	
25	Low	Plume			4	
28	n.d.	None			1	
31	Medium	Outlet rill	0.25	0.11	3	
34	Medium	Plume			3	
37	Medium	Plume			3	
40	High	Plume			3	
43	Medium	Plume			3	
46	Low	Plume			3	
49	Low	Plume			2	
52	Medium	Plume			3	
55	Medium	Plume			3	
58	Medium	Outlet rill	0.30	0.18	3	
61	Medium	Plume			3	
64	Medium	Plume			3	
67	Low	Outlet rill	0.30	0.15	3	

Appendix VI.G. Survey information for the 19 segments measured along the Long Hollow trail. n.d. indicates that no data are available.

Seg. no.	Hillslope position	Trail surface cover	Traffic	Inside ditch	Incised depth (m)	Length (m)	Slope (%)	Active width (m)	Total width (m)	Max. rill depth on seg.	Drainage type	Transport distance (m)	Hillslope gradient below drainage (%)
2	Ridgetop	Bare	Heavy	No	0.1	110	9	1.65	3.75	Shallow	None	21	27
5	Ridgetop	Bare	Heavy	No	0.3	45	17	1.80	4.10	Shallow	Pushout	39.5	38
8	Midslope	Bare	Heavy	No	0.2	46	9	1.80	4.25	Shallow	None	140.5	14
11	Midslope	Bare	Heavy	No	0.3	71	14	1.90	3.35	Medium	None	37	13
14	Valley	Bare	Heavy	No	0.2	114	10	1.77	3.40	Shallow	None	6.5	12
17	Valley	Bare	Heavy	No	0.1	22	13	1.90	3.00	Shallow	Pushout	12	22
20	Valley	Bare	Heavy	No	0.2	102	14	1.73	3.17	Deep	Pushout	19.5	27
23	Midslope	Bare	Heavy	No	0.8	49	7	1.65	4.60	Shallow	None	0	n.d.
26	Midslope	Bare	Heavy	No	0.4	98	15	1.70	3.70	Medium	Pushout	49	26
29	Midslope	Bare	Heavy	No	0.1	27	8	1.70	3.00	None	None	17	26
32	Midslope	Bare	Heavy	No	0.2	47.5	19	1.53	3.33	Medium	None	24	36
35	Midslope	Bare	Heavy	No	0.9	33.5	22	1.75	3.75	Shallow	Pushout	23	25
38	Midslope	Bare	Heavy	No	0.2	69	11	1.75	3.40	Medium	None	0	n.d.
41	Midslope	Bare	Heavy	No	0.1	36.5	8	1.70	2.60	Shallow	Pushout	14	16
44	Valley	Bare	Heavy	No	0.2	58	7	1.65	3.40	Shallow	None	0	n.d.
47	Valley	Bare	Heavy	No	0.0	106	6	2.00	3.63	Shallow	Pushout	21	9
50	Midslope	Bare	Heavy	No	0.3	67	14	1.65	2.65	Shallow	Pushout	18.5	17
53	Ridgetop	Bare	Heavy	No	0.4	51	8	1.95	4.80	Shallow	Pushout	55	24
56	Ridgetop	Bare	Heavy	No	0.1	71	7	1.73	3.00	Shallow	Pushout	109	20

Appendix VI.G. (continued).

Seg. No.	Roughness	Sediment plume/Outlet rill	Outlet rill		Conn. class	Notes
			Width (m)	Depth (m)		
2	low	Plume			3	
5	medium	Outlet rill	0.20	0.05	3	
8	medium	Plume			3	
11	medium	Plume			3	
14	high	Plume			4	
17	high	Plume			4	
20	high	Plume			4	
23	N/A	None			1	
26	medium	Plume			3	
29	low	Plume			2	
32	medium	Plume			3	
35	medium	Plume			3	
38	N/A	None			1	
41	medium	Plume			2	
44	N/A	None			1	
47	high	Plume			4	
50	medium	Plume			2	
53	low	Plume			3	
56	medium	Plume			3	

Appendix VI.H. Survey information for the 53 segments measured along the Noddle trail. n.d. indicates that no data are available.

Seg. no.	Hillslope position	Trail surface cover	Traffic	Inside ditch	Incised depth (m)	Length (m)	Slope (%)	Active width (m)	Total width (m)	Max. rill depth on seg.	Drainage type	Transport distance (m)	Hillslope gradient below drainage (%)
1	Ridgetop	Bare	Heavy	No	0.0	18.0	12	4.60	6.60	Shallow	Pushout	25.5	16
4	Ridgetop	Bare	Heavy	No	0.0	37.5	5	3.05	5.50	Shallow	Pushout	27.0	28
7	Ridgetop	Bare	Heavy	No	0.0	48.5	9	3.20	5.97	None	Pushout	54.5	15
10	Ridgetop	Bare	Heavy	No	0.2	51.0	10	2.00	4.60	None	Pushout	21.0	15
13	Ridgetop	Bare	Heavy	No	0.6	65.0	16	2.23	4.40	Shallow	Pushout	26.5	15
16	Ridgetop	Bare	Heavy	No	0.7	43.0	15	1.90	4.90	Shallow	Pushout	50.0	23
19	Ridgetop	Bare	Heavy	No	0.3	43.0	14	1.90	6.75	Shallow	Pushout	26.0	19
22	Midslope	Bare	Heavy	No	0.3	17.0	5	1.75	3.60	None	None	7.5	30
25	Midslope	Bare	Heavy	No	0.3	19.5	7	1.65	3.55	None	None	2.0	41
28	Midslope	Bare	Heavy	No	0.5	47.0	13	1.70	3.55	None	None	55.0	32
31	Midslope	Bare	Heavy	No	0.4	16.0	10	1.70	3.55	Shallow	None	10.5	30
34	Midslope	Bare	Heavy	No	0.5	10.0	11	1.60	4.10	None	None	7.0	45
37	Midslope	Bare	Heavy	No	0.2	23.0	14	2.00	3.60	Shallow	None	17.0	35
40	Midslope	Bare	Heavy	No	0.2	27.5	4	1.70	3.30	None	None	0.0	n.d.
43	Midslope	Bare	Heavy	No	0.3	59.0	5	1.75	4.25	None	None	0.0	n.d.
46	Midslope	Bare	Heavy	No	0.2	55.0	12	1.65	3.05	Shallow	None	13.0	21
49	Midslope	Bare	Heavy	No	0.2	60.0	15	1.70	3.65	Shallow	None	22.0	22
52	Valley	Bare	Heavy	No	0.8	44.0	3	2.00	5.30	None	None	0.0	n.d.
55	Valley	Bare	Heavy	No	0.8	71.0	12	1.60	4.75	Shallow	None	n.d.	n.d.
58	Valley	Bare	Heavy	No	1.9	55.0	19	1.83	4.60	Shallow	Pushout	36.0	26
61	Valley	Bare	Heavy	No	0.3	60.0	19	1.90	4.55	Shallow	None	19.0	16
64	Valley	Bare	Heavy	No	0.4	14.0	13	1.80	3.80	None	None	8.5	30
67	Valley	Bare	Heavy	No	0.9	19.5	14	1.70	5.80	None	None	6.0	42
70	Valley	Bare	Heavy	No	0.5	37.0	11	1.80	2.50	None	Pushout	11.0	21
73	Valley	Bare	Heavy	No	0.4	31	12	1.70	3.70	None	Pushout	16.0	25

76	Valley	Bare	Heavy	No	0.7	88.0	19	1.87	3.97	Deep	None	58.0	27
79	Valley	Bare	Heavy	No	0.6	60.0	21	1.65	3.50	Medium	None	44.5	40
82	Valley	Bare	Heavy	No	0.5	52.0	18	1.65	4.25	Shallow	Pushout	123.0	25
84	Ridgetop	Bare	Heavy	No	1.0	98.0	18	1.60	5.97	Shallow	Pushout	101.0	32
87	Ridgetop	Bare	Heavy	No	0.1	64.0	6	1.85	3.35	None	None	0.0	n.d.
90	Ridgetop	Bare	Heavy	No	0.3	46.0	18	2.05	5.10	Shallow	Pushout	31	25
93	Ridgetop	Bare	Heavy	No	0.0	103.0	8	1.93	4.27	None	None	10.0	24
96	Ridgetop	Bare	Heavy	No	0.0	92.0	6	1.80	3.63	None	None	14	24
99	Ridgetop	Bare	Heavy	No	0.0	20.0	5	1.80	4.70	None	Pushout	9	21
102	Midslope	Bare	Heavy	No	0.1	49.0	9	1.80	5.05	None	None	0	n.d.
105	Midslope	Bare	Heavy	No	1.5	41.0	22	1.80	6.25	Medium	Pushout	28	42
108	Ridgetop	Bare	Heavy	No	0.0	79	6	2.70	4.20	None	Pushout	36	26
111	Midslope	Bare	Heavy	No	0.4	96.0	17	1.60	3.85	Shallow	Pushout	146	22
114	Midslope	Bare	Heavy	No	0.1	13.0	11	1.70	3.60	None	Pushout	7	18
117	Midslope	Bare	Heavy	No	0.6	61	15	1.55	4.35	Shallow	None	20.5	20
120	Midslope	Bare	Heavy	No	0.5	65.0	19	1.80	4.40	Medium	Pushout	32.5	17
123	Midslope	Bare	Heavy	No	0.6	49	12	1.75	4.35	Shallow	None	12.5	22
126	Midslope	Bare	Heavy	No	0.4	14.0	11	1.70	3.80	Shallow	None	19.5	29
129	Ridgetop	Bare	Heavy	No	0.0	46	9	1.70	3.70	Shallow	Pushout	20	22
132	Ridgetop	Bare	Heavy	No	0.2	39	12	1.65	3.65	Shallow	None	22	25
135	Ridgetop	Bare	Heavy	No	0.1	23	7	2.00	4.70	None	Pushout	8.5	10
138	Ridgetop	Bare	Heavy	No	0.4	84	15	1.95	4.05	Medium	None	29	23
141	Midslope	Bare	Heavy	No	0.4	48	17	1.90	4.35	Shallow	Pushout	159	14
144	Midslope	Bare	Heavy	No	0.4	52	15	2.40	5.50	Medium	Pushout	116	23
147	Ridgetop	Bare	Heavy	No	0.5	70	14	2.60	7.05	Medium	None	154	23
150	Midslope	Bare	Heavy	No	1.4	101	23	1.73	5.73	Deep	None	16	29
153	Midslope	Bare	Heavy	No	1.4	13	24	1.60	6.00	Medium	None	10	41
156	Valley	Bare	Heavy	No	0.6	102	19	2.20	5.90	Deep	None	n.d.	n.d.

Appendix VI.H. (continued).

Seg. no.	Roughness	Sediment plume/Outlet rill	Outlet rill		Conn. class	Notes
			Width (m)	Depth (m)		
1	Low	Plume			3	
4	Medium	Plume			3	Monitoring segment NDL #1.
7	Medium	Plume			3	
10	Medium	Plume			3	
13	Medium	Plume			3	
16	Low	Plume			3	Monitoring segment NDL #3.
19	Low	Plume			3	
22	Medium	Plume			2	
25	high	Plume			2	
28	Low	Outlet rill	0.30	0.10	3	
31	Medium	Plume			2	
34	Medium	Plume			2	
37	High	Plume			2	
40		None			1	
43		None			1	
46	Medium	Plume			2	
49	Low	Plume			3	
52		None			1	
55		n.d.			4	Outlet is the stream.
58	Medium	Plume			4	
61	Medium	Plume			4	
64	Medium	Plume			2	
67	High	Plume			2	
70	High	Plume			2	
73	Medium	Plume			4	Pushout extends to the stream.
76	High	Outlet rill	0.30	0.23	4	

Seg. no.	Roughness	Sediment plume/Outlet rill	Outlet rill		Conn. class	Notes
			Width (m)	Depth (m)		
79	Low	Outlet rill	0.30	0.10	3	
82	Medium	Outlet rill	0.88	0.53	3	
84	Low	Plume			3	
87		None			1	
90	Medium	Plume			3	
93		Outlet rill	0.25	0.05	2	
96	Low	Plume			2	
99	Medium	Plume			2	
102		None			1	
105	Medium	Plume			3	
108	Low	Outlet rill	0.40	0.09	3	
111	Medium	Plume			3	
114	Low	Plume			2	
117	Medium	Plume			3	
120	High	Plume			3	
123	Medium	Plume			2	
126	Medium	Plume			2	
129	Low	Plume			3	
132	Medium	Plume			3	
135	Low	Plume			2	
138	Low	Outlet rill	0.25	0.07	3	
141	Medium	Plume			3	
144	Low	Outlet rill	0.34	0.11	3	
147	Low	Outlet rill	0.44	0.09	3	
150	Low	Outlet rill	0.60	0.27	4	
153	Low	Outlet rill	0.30	0.12	4	
156		n.d.			4	Outlet is Sugar Creek.