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Authors: Valencia-Gallego, Verónica, and Montoya, Luis-Javier

Source: Air, Soil and Water Research, 17(1)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/11786221241272396

Erosion Mechanisms in Unpaved Roads: Effects of Slope, Rainfall, and Soil type

Air, Soil and Water Research
Volume 17: 1–10

DOI: 10.1177/11786221241272396
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Verónica Valencia-Gallego[1] and Luis-Javier Montoya[1]

[1]Universidad de Medellín, Colombia

ABSTRACT: Erosion is the main cause of damage to unpaved roads. This study utilized rainfall simulators to quantify erosion on unpaved roads, controlling variables such as rainfall intensity and slope. A laboratory model of an unpaved road was utilized to evaluate soil loss in an experimental setup. A total of 72 tests were conducted to compare simulated conditions on unpaved roads for three soil types with three slope variations, and eight rainfall intensities. The impact of each variable (soil type, slope, and rainfall intensity) on soil loss was analyzed for 30-minute rainfall events. Analysis of variance (ANOVA) was employed to assess soil erosion response to terrain slope for the three soil types, revealing statistical differences in soil loss between low slopes (2%) and steep slopes (7%) with *p*-values of .04 (sandy soil), .00007 (sandy silt soil), and .00008 (loam silt soil). Correlation analysis demonstrated a strong relationship between rainfall intensity and soil loss ($R^2 = .76$) for sandy soil and sandy silt soil. Analysis of covariance (ANCOVA) indicated a linear relationship between soil loss and rainfall intensity, with significant differences ($p < .05$). The findings suggest that soil loss on unpaved roads is positively correlated with slope and rainfall intensity. However, this relationship is not always linear; sandy soil exhibited a nonlinear relationship, especially with high rainfall intensities, whereas sandy silt soil showed a linear relationship with evaluated rain intensities. The type of soil influences erosion process, with higher erosion rates observed in sandy silt soils compared to loam silt soils. This paper analyzed the factors essential for addressing erosion on unpaved roads, identifying key elements to minimize soil loss.

KEYWORDS: Unpaved roads, soil erosion, simulated rainfall erosion, sediments

RECEIVED: February 15, 2024. **ACCEPTED:** July 15, 2024.

TYPE: Research Article

CORRESPONDING AUTHOR: Luis-Javier Montoya, Universidad de Medellín, Carrera 87 N° 30 – 65, Bloque 4-103, Medellín, Antioquia 050026, Colombia. Email: ljmontoya@udemedellin.edu.co

Introduction

In developing regions, approximately 80% of road networks comprise unpaved roads made of soil and gravel (Djeran-Maigre et al., 2022). Erosion stands out as the primary cause of deterioration for unpaved roads. Specifically in tropical areas, unpaved roads are highly vulnerable to erosion due to the region's intense precipitation and high rainfall intensities (Forsyth et al., 2006; Sheridan & Noske, 2007). Soil erosion itself is a multifaceted phenomenon influenced by factors like soil properties, rainfall intensity, road geometry, and surface runoff (Ngezahayo et al., 2021; Shen et al., 2023). Hydraulic soil erosion is a function of soil type, surface roughness, and hydraulic flow characteristics (Ngezahayo et al., 2019).

While a plethora of studies have explored the impact of agricultural practices and soil conservation methods on soil erosion (Shen et al., 2023), limited research has delved into the erosion processes specific to unpaved roads. Construction of roads can significantly alter local soil structure, hillslope hydrological behavior, and surface soil attributes, consequently impacting sediment yield generated by the road (Megahan et al., 2001). Notably, studies by Ramos-Scharrón and MacDonald (2007) have identified unpaved road erosion as a principal source of wash load sediment entering rivers, potentially amplifying natural sediment loads.

The presence of unpaved roads increase erosion within surrounding basins, especially during intense rainfall episodes (Gresswell et al., 1979; Gucinski, 2001; Sidle et al., 1985), particularly on steep terrains. This erosion contributes substantially to stream sedimentation (Ramos-Scharrón & MacDonald, 2007; Ziegler et al., 2001) and contributes to environmental challenges. Damage to vehicles traveling on such roads due to rough road surfaces is an additional downside.

Research suggests that unpaved soil erosion is influenced by factors like rainfall intensity and duration (Ngezahayo et al., 2019; Ziegler et al., 2001), road slope (Ramos-Scharrón & MacDonald, 2007), soil texture, soil compaction (Arnáez et al., 2004; Ziegler et al., 2000), construction age, traffic volume, construction methods, maintenance practices, road geometry, and drainage systems (Fu et al., 2011). Predictive models highlight clay content, rainfall intensity, and slope gradient as key factors influencing erosion (Ngezahayo et al., 2021). Several authors have underscored slope as a primary factor impacting erosion on unpaved roads (Arnáez et al., 2004; Assouline & Ben-Hur, 2006; Fu et al., 2011; Shi et al., 2012; Zhang et al., 2008).

Rainfall simulation techniques have been crucial for projecting erosion trends on unpaved roads and across various land uses (Arnáez et al., 2004; Foltz et al., 2009; Iserloh et al., 2013). These simulators enable controlled manipulation of intensity, duration, and rainfall volume, facilitating rapid, cost-effective erosion data collection. Nonetheless, limitations exist as natural conditions cannot be fully replicated, necessitating cautious interpretation of results. Despite these constraints, rainfall simulators prove useful for comparative studies (Croke et al., 2006; Loch, 2000; Sheridan et al., 2000). Small-scale experimental setups in laboratories play a vital role in unraveling erosion

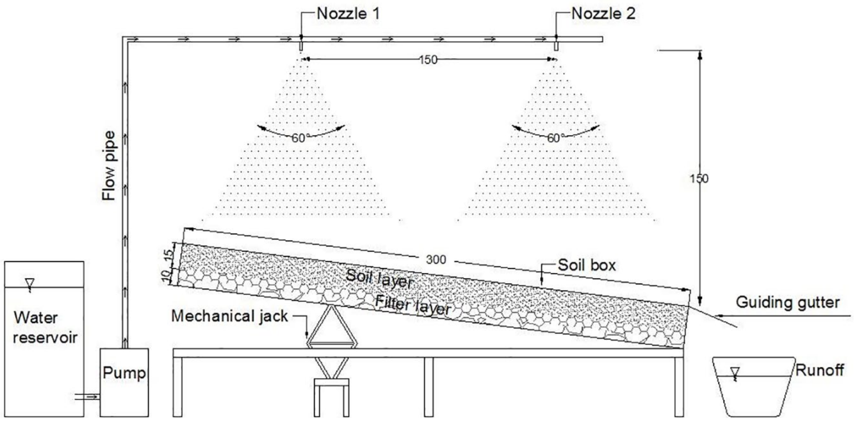

Figure 1. Experimental set-up.

processes like infiltration, runoff, and erosion, offering insights that inform real-world erosion management strategies (Lange et al., 2003).

Several research underscores the interrelation of factors like soil type, gradient, traffic, rain intensity, and duration in the erosion dynamics of unpaved roads. Extreme rain events causing severe soil loss (Ngezahayo et al., 2019), with the sediment yield from unpaved roads often surpassing that from agricultural areas (Ziegler et al., 2000). However, accurately predicting erosion rates on unpaved roads remains a challenge (Sheridan & Noske, 2007). The key factors that affected soil erosion in earth roads were soil type, clay content, soil plasticity, and particle size distribution and degree of the surface layer compaction and degree of the surface layer compaction (Ngezahayo et al., 2019). The erodibility rate and critical shear stress over unpaved road vary according with soil type of the way. The erodibility values of the roads were higher on silt loam and sandy soils, being particularly susceptible to erosion (de Oliveira et al., 2009). The main mechanisms of erosion on unpaved roads, involve factors such as rainfall intensity, duration, soil properties (including clay content, particle size distribution, and compaction), and road geometry slope; (Ngezahayo et al., 2019, 2021). Studies highlight that rainfall is a significant driver of erosion (Fraser et al., 1999). Most of the studies had used rain simulators, but the intensity ranges were limited to less 75 mm/hr (Ngezahayo et al., 2021; Yu et al., 2021). This study wants to extend the range of intensity according with precipitation at Andean topical zones. Additionally, it is important understand the relationship between soil properties, rainfall parameters, and road slope of unpaved roads, for these a ANCOVA analysis it is fundamental to understand and separate the independent effects of each variable. This deeper understanding is indispensable for effective erosion mitigation and long-term road sustainability.

The conventional practice in Colombia of constructing unpaved roads in the Andean region typically involves utilizing coarse granular soil as a vehicle rolling base. In some cases, the base material may contain fine materials, while in others, natural soil is utilized. Steep road slopes, often exceeding 10%, and high precipitation intensities are prevalent in the area.

The aims of this study were to investigate the influence of slope, rainfall intensity, and soil type on soil erosion using a laboratory model simulating an unpaved road. Through a rainfall simulation test, the study intends to analyze the erosion response of a prototype of unpaved road under controlled conditions.

Data and Methods

The studied zone is located in the Colombian Andes, in the northwest, at 6.3275° N and 76.1395° W. In Colombia, the common practice for constructing unpaved roads in the Andean zone involves using coarse granular soil as the base for vehicle traffic. In some cases, the base material may contain fine materials, and on some routes, the natural soil is used. Additionally, high road slopes (up to 10% or more) are common, and due to the high precipitation in the region, the roads are exposed to intense rainfall. This study aimed to reproduce the conditions of the zone by using three soil types: coarse granular soil, sandy silt soil, and clay soil (natural soil from the area). Road slopes between 2% and 10% were used, and rain intensities were analyzed using precipitation data measured over 1 year from a rain station installed near the zone (6.3215° N and 76.1342° W). These conditions of slope, rain, and soil type were replicated in the laboratory.

Studies were conducted using a slope-adjustable table equipped with a variable intensity rainfall simulator (Figure 1). Details of the equipment, experimental setup, and soil bed preparation are briefly summarized below. The experiments focused on analyzing rain intensities, road slopes, and soil types of unpaved roads in the Colombian Andes. Storm patterns with simulated rain lasted 30 min, with intensities ranging from 134 to 207 mm/hr. The soil in the simulation table was compacted to emulate the construction methods and soil density. Three types of soil and slopes between 2% and 10% were used to replicate the typical conditions of unpaved roads in the rural Andean zone of Colombia.

Rainfall simulator

Rainfall simulators have been used in numerous erosion studies (Koch et al., 2024; Mhaske et al., 2019), considering various

Table 1. Studied Soil Characteristics.

SOIL CHARACTERISTIC	S1	S2	S3
Gravel (%)	27	16	—
Coarse sand (%)	47	34	—
Fine sand (%)	22	28	14
Silt and clay (%)	4	22	86
Liquid Limit (%)			66
Plastic limit (%)			17
AASHTO classification	A-1b	A-1b	A-7-5

nozzle characteristics to take in account aspects as drop size, terminal velocity, intensity, energy, and uniformity. The experimental setup comprised a rainfall simulator and a simulation table where a prototype of an unpaved road was constructed. The rainfall simulator utilized two 3/8 HHMFP 6014 nozzles (Spraying Systems Co.®) that produced a cone-shaped spray pattern. These nozzles were spaced 1.5 m apart and connected to a 1-inch diameter PVC pipe, positioned 1.5 m above the simulation table, and operated at pressures ranging from 12 to 35 psi. This setup generated simulated rains with intensities from 134 to 207.7 mm/hr.

To evaluate the drop distribution of the rainfall simulator, precipitation measurements were taken on a rectangular grid with 20 cm spacing for the tested rain intensities. The Christiansen's Uniformity Coefficient (Christiansen, 1942) for these measurements ranged from 73% to 82%. The rainfall simulator was capable of producing a simulated rain over an area of 4.5 m^2 (1.5 × 3.0 m) and was supplied with water from a 1 m^3 reservoir regulated by a valve. The terminal velocity of the drops, estimated using the formula from Benito Rueda et al. (1986), ranged from 6.18 to 9.65 m/s, with kinetic energy ranging from 30.6 to 32 $J\,m^{-2}\,mm^{-1}$.

Simulation table

Several studies have used rainfall simulators to evaluate erosion rates (Sadeghi et al., 2013; Mostafazadeh et al., 2024; Mostafazadeh et al., 2023). The simulation table used in this study measured 3 m in length, 1.5 m in width, and 0.25 m in thickness, fitting within the range of commonly analyzed simulation tables and parcels. The nozzles were positioned 1.5 m above the table. Additionally, the simulation table was equipped with a system that made it possible slope modification (see Figure 1).

Soil characteristics

Three soil types were used for the test: sandy soil S1, sandy silt soil S2, and loam-silt soil S3. Table 1 summarizes the main properties of these soils. These three soil types represent the primary materials used for unpaved roads in the study zone. S1 and S2 were used as road base materials, while S3 was used as the exposed (natural) soil. A 5 cm thick layer of coarse gravel was placed at the bottom of the simulation table to allow for soil drainage. Each of the three soil types was compacted in the simulation table in 5 cm thick layers. The total soil thickness in the table reached 20 cm, it were compacted until reached a dry densities of 1,958 kg/m^3 for S1, 2,017 kg/m^3 for S2, and 1,370 kg/m^3 for S3, corresponding to approximately 90 to 100% of the maximum dry density for each soil type. The effect of compaction was not considered in this study. However, the common construction practice in the region is to use soils with a dry density around 90 to 100%, according to the standard Proctor test.

Experimental setup

Three different slopes were evaluated (2%, 7%, and 10%) to represent typical conditions of a flat road (2%), a mountain road (7%), and a steep slope road (10%). For each slope, eight different rain intensities were tested (134, 138.7, 160.6, 163.9, 173.6, 181.8, 190.2, and 207.7 mm/hr), which are considered high rainfall intensity rates. These intensities were derived from the intensity-duration-frequency (IDF) curve for the study zone, based on a return period of 20 years and rain durations between 5 and 10 min, as is typical for drainage design in unpaved roads in the region. A total of 72 tests were performed.

Each test utilized a constant rain intensity for 30 min, and all eroded soil was collected using a flume located at the end of the simulation table. The collected soil was dried in an oven for 24 hr at 105°C and reported as weight soil loss. Additionally, three samples of 100 ml surface runoff water were taken at 1.5, 5, 10, 15, 20, and 30 min to measure suspended solid concentration in the laboratory using Standard Methods (Rice et al., 2012). Runoff records were taken using a flow meter installed at the pipe that feeds the rain simulator and verified through volumetric measurements.

During each test, two types of samples were measured: soil loss, which was the material retained on a 74-μm sieve dragged to the end of the simulation table, and water samples with sediments to determine total suspended sediments. Flow in the simulator was controlled during the 30 min of the essay to ensure stable rain intensity. Soil humidity measurements were taken at the beginning of each test to guarantee similar humidity conditions across all tests.

Data analysis

Statistical analyses were performed to determine the influence of slope and rainfall intensity on soil loss. ANOVA and ANCOVA analyses were conducted. A Shapiro-Wilk test was used to test the assumption of normality of the data. A significance level of 5% (p-value of .05) was used in the various tests.

Table 2. Summary of the Measuring of Suspended Sediments and Soil Loss.

SLOPE		SOIL LOSS DURING 30 MIN (G)				SUSPENDED SOLIDS (MG/L)			
		MEAN	*SD*	MAX. VALUE	MIN. VALUE	*M*	*SD*	MAX. VALUE	MIN. VALUE
S1	2%	119.2	66	245	43	306	457	1984.7	64.7
	7%	1436.2	1095.4	2847.5	42.17	663.2	420	2132.7	168
	10%	1947.6	1292.8	3504.4	78.6	1148.6	1,006	4,476	219.3
	2%	933.4	430.2	1608.9	306	2132.9	2254.3	10986.7	741.3
S2	7%	9704.7	3028.8	13305.6	6332,1	13740	4899.1	30,802	7071
	10%	17330.6	4776.9	23088.4	8115.5	23434	4065.2	34,217	16705
	2%	6.1	4.6	16.4	1.2	191.2	156.5	1,037	100
S3	7%	807.7	321.8	2694.2	383.8	2183	1360.6	6,304	529.3
	10%	897.2	384.2	1579.2	426.4	2190	1270.5	5,561	482

Table 3. One-Way ANOVA Results Used to Test for Significant Differences in Means (Dependent Variable: Soil Loss, Independent Variable: Slope) and Statistical Significance (*p*-Value).

SOIL		DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SUM OF SQUARES	*F*-STATISTIC	*P*-VALUE
S1	Slope	2	14,237,247	7,118,624	7.427	.00364
	Residuals	21	20,129,154	958,531		
S2	Slope	2	1.08e+12	538,613,556	50.22	9.95e-09
	Residuals	21	2.25e+08	10,725,761		
S3	Slope	2	5,044,181	2,522,091	11.11	.000512
	Residuals	21	4,768,517	227,072		

Tukey HSD tests were performed for post hoc comparisons of mean soil loss across different slopes. Additionally, a covariance analysis was conducted to determine the relationship between soil loss and rainfall intensity, with slope considered as a covariate. For each soil type, linear regressions were obtained through ANCOVA. All statistical analyses were conducted using R Statistical Software v3.2.2 (R Development Core Team, 2015).

An exponential regression analysis was also performed to determine the variation of suspended soil concentration over time. Finally, we compared the suspended solid decay rate across different soils, slopes, and rainfall intensities.

Results

Table 2 summarizes the mean value and standard deviation of the 72 tests, grouping data by soil types and slope. To study erosion on unpaved roads, an analysis of the effects of road slope, rainfall intensity, and soil type was conducted. Other variables, such as soil compaction and humidity, were not detailed in the analysis, but initial humidity and soil density were monitored to ensure these variables remained constant at the beginning of each tests.

Effects of road slope on soil loss

The ANOVA test showed a statistically significant difference in soil loss values for S1, S2, and S3 with respect to the evaluated slopes (2%, 7%, and 10%), with $p < .05$ (Table 3). Soil type S2 showed the greatest differences in mean soil loss for the assessed slopes (F-statistic = 50.22, highest value). Tukey's HSD (Honestly Significant Difference) test indicated significant differences in soil loss means among the three groups of slopes ($p < .05$) for soil S2 (see Table 4). For soil types S1 and S3, the 2% slope group showed significant differences when compared to the 7% and 10% slope groups (see Table 4).

As shown in Table 2, soil loss increases with slope for all three soil types, with higher slopes leading to greater soil loss due to increased surface runoff velocity. However, the magnitude of soil loss varies significantly with soil type,

Table 4. Tukey Test With Soil Loss as the Dependent Variable and Treatment Group With Slope.

SOIL TYPE	SLOPE	*P*-VALUE AFTER ADJUSTMENT
S1	7%–2%	.0350
	10%–2%	.0034
	10%–7%	.5600
	7%–2%	.000074
S2	10%–2%	0
	10%–7%	.00038
	7%–2%	.000082
S3	10%–2%	.000014
	10%–7%	.82

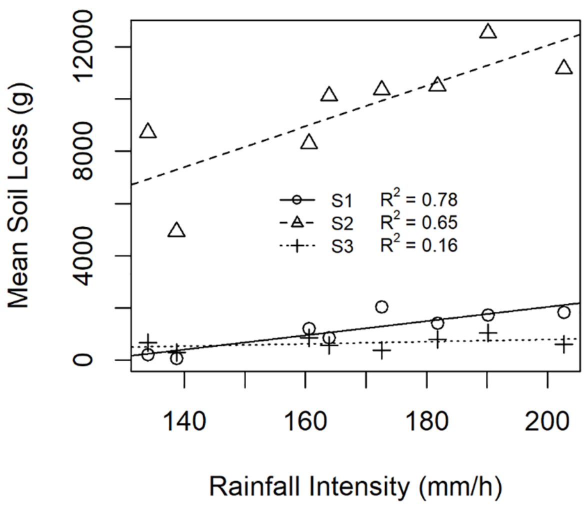

Figure 2. Variation obtained between soil losses with changes at rain intensity.

being much greater in soil S2, possibly because it is non-cohesive and has a higher content of fines than S1.

Effects of rainfall intensity on soil loss

Figure 2 shows the relationship between soil loss and rainfall intensity for the three soil types evaluated. For soils S1 and S2, soil loss increases with rainfall intensity, with R^2 values of .78 and .65, respectively. The ANOVA test indicated no statistically significant difference ($p > .05$) between soil loss and rainfall intensity. The observed variability in soil loss could be influenced by other factors such as slope and soil characteristics.

Figure 2 demonstrates that each soil type responds differently to rainfall intensity. The changes are more pronounced for some soil types than others. Generally, increased rain intensity and slope result in higher soil loss due to greater surface runoff (Defersha & Melesse, 2012). High slopes cause higher flow velocity and shear stress, thus resulting in more soil loss.

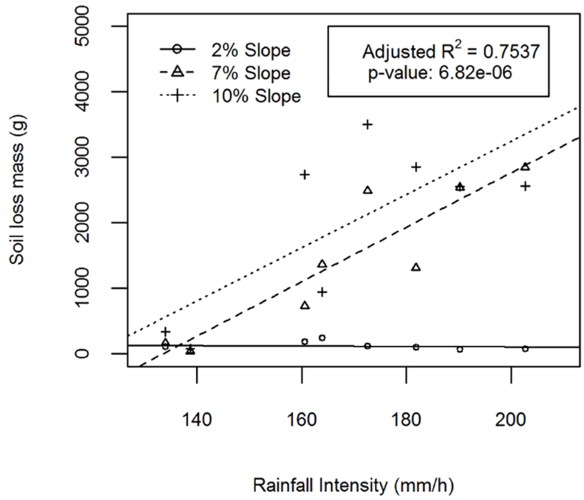

Figure 3. Relationship between intensity and soil loss for each slope soil S1.

Experimental data (Figure 2) show a relationship between soil loss and intensity for each soil type. However, these variations are less significant than those induced by slope. Therefore, an analysis of covariance (ANCOVA) was necessary to analyze the effects of different variables (slope and rain intensity).

ANCOVA was performed for each soil type, evaluating the variation of soil loss (dependent variable) with rainfall intensity (independent variable—covariate) across three slopes (2%, 7%, and 10%). For S1 (Figure 3), ANCOVA showed significant variance between soil loss and rainfall intensity for different slopes ($p < .05$, model fit $R^2 = .76$). Data were logarithmically transformed to achieve a normal distribution. The best fit lines (see Figure 3) for each slope in S1 ($R^2 = .75$) showed statistically significant relationships between rain intensity and soil loss ($p = 6.82\text{e-}06$), increases at soil loss with increases of rain intensity was observed with slopes of 7% and 10%, but with 2% slope showed no significant changes in soil loss with rainfall intensity ($p > .05$). The 10% and 7% slopes had the highest rates of soil loss, significant for the model ($p < .05$), with the 10% slope showing the highest soil loss (Figure 3).

For soil S2 (Figure 4), ANCOVA showed significant variance between soil loss and rainfall intensity for different slopes ($p < .05$, model fit $R^2 = .93$). The best fit lines for each slope in S2 ($R^2 = .93$) indicated statistically significant linear relationships between rain intensity and soil loss. The largest gradients were for slopes of 10% and 7%, significant for the model ($p < .05$). The 2% slope showed no significant changes in soil loss with rain intensity ($p > .05$). The highest soil loss rate was observed at the 10% slope. The Akaike method indicated that the best model fit occurs when slope and rainfall intensity variables interact ($p < .05$).

For S3 (Figure 5), ANCOVA did not show significant variance between soil loss and rainfall intensity for different slopes

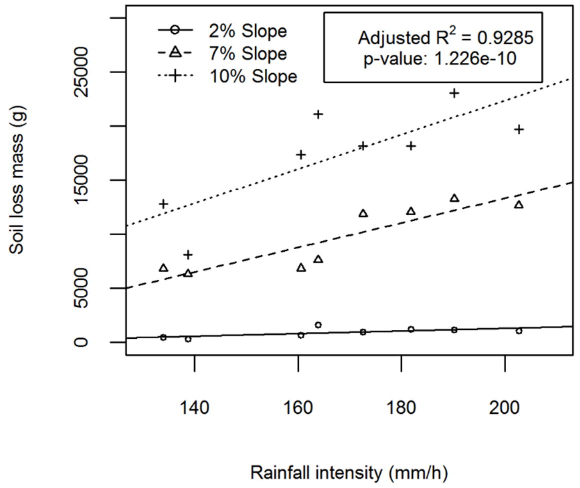

Figure 4. Relationship between intensity and soil loss for each slope soil S2.

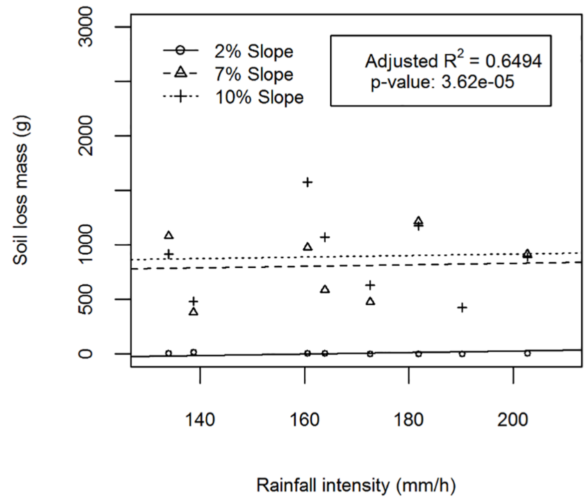

Figure 5. Relationship between intensity and soil loss for each slope soil S3.

Table 5. ANCOVA Results of Each Soil Type.

COEFFICIENTS		2% SLOPE	7% SLOPE	10% SLOPE	RAINFALL INTENSITY: 2% SLOPE	RAINFALL INTENSITY: 7% SLOPE	RAINFALL INTENSITY: 10% SLOPE
Intercept		165.46	−5723.78	−5041.13			
Gradient					−0.2751	41.89	40.87
S1	*t*-Value	0.10	−2.487	−2.19	−0.029	3.086	3.011
	p-Value	.92	.023*	.04*	.98	.006**	.008**
Intercept		−1060.36	−8241.4	−8295.54			
Gradient					11.86	101.23	146.93
S2	*t*-Value	−0.20	−1.08	−1.087	0.37	2.25	3.26
	p-Value	.85	.29	.29	.71	.037*	.004**
Intercept		−108.61	803.75	891.05			
Gradient					0.68		
S3	*t*-Value	−0.23	5.26	6.05	0.25		
	p-Value	.82	4.44e−05***	8.1e−06***	.81		

Note. Significate codes: 0 "***" 0.001"**" 0.01"*."

($p > .05$, model fit $R^2 = .64$). The Akaike method indicated the best model fit with the slope variable alone. The best fit lines for each slope in S3 ($R^2 = .65$) showed that the slopes were approximately parallel, differing only in intercept (see Figure 5). None of the slopes showed significant changes in soil loss with rainfall intensity ($p > .05$). ANCOVA results indicated low correlation between soil loss and rainfall intensity for S3, particularly with slopes of 7% and 10% (Figure 5).

For soils with higher sand content (S1 and S2), ANCOVA showed that soil loss increases with higher rainfall intensity ($p < .05$), and the best model fit occurs when intensity and slope interact together (Table 5). The Akaike criterion ($p < .05$) explains the differences among the three regression models of ANCOVA. Additionally, none of the three soil types showed significant variations in soil loss with rainfall intensity for the 2% slope (Figures 3–5).

Soil type S3, a silt-clay soil, did not show significant changes in soil loss for the evaluated intensities (Table 5). The Akaike criterion confirmed that the most significant variable for explaining soil loss was terrain slope.

Rain intensity plays a crucial role in the erosion of unpaved roads. Higher rainfall intensities lead to increased erosion rates,

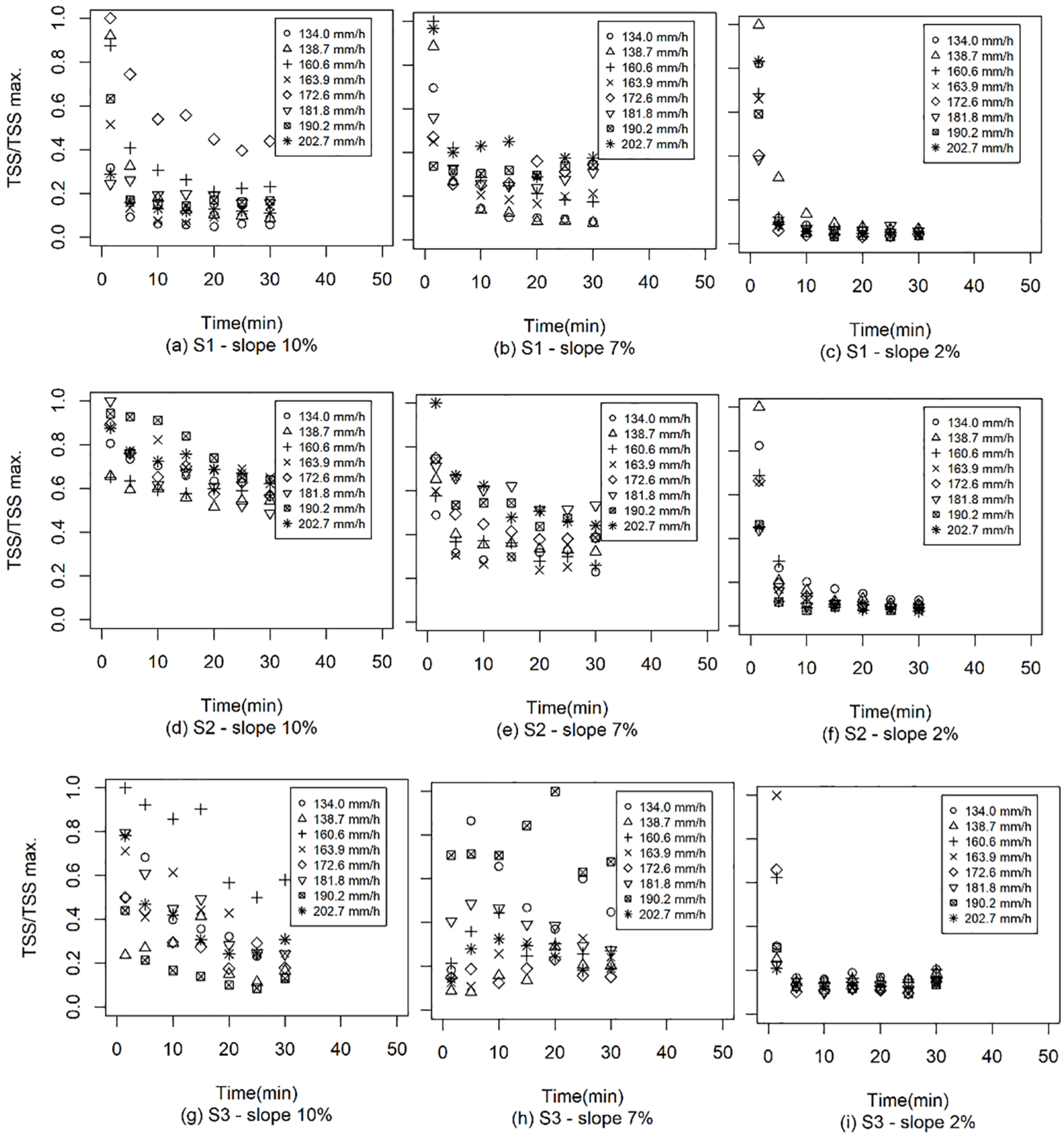

Figure 6. Time variation of total suspended soil concentration during essays: (a) S1 - slope 10%, (b) S1 - slope 7%, (c) S1 - slope 2%, (d) S2 - slope 10%, (e) S2 - slope 7%, (f) S2 - slope 2%, (g) S3 - slope 10%, (h) S3 - slope 7%, (i) S3 - slope 2%.

causing more significant damage to road surfaces. Research indicates that high-intensity rainfall events can result in several times higher road erosion compared to lower-intensity events.

Behavior of suspended sediment concentrations during simulated rainfall tests

In addition to soil loss, we studied the concentration of total suspended sediments (TSS) carried by runoff under different rainfall intensities. This is significant because a substantial portion of soil loss may be redeposited on the road, particularly coarser particles, while fine particles may cause pollution when fine sediments are dragged by runoff water. For this reason, the concentration of TSS was analyzed, and its variation during the time of the essay.

It's important to note that the total flux of suspended sediments depends not only on the sediment concentration but it also requires consider the runoff. During each test intensity was maintained constant and less variation of runoff discharge were measured. Analysis of the sediment mass flux and concentration during the essay were performed. However, the main changes at the concentration of suspended sediments mainly analyzed.

Figure 6 shows the variation over time (1.5, 5, 10, 15, 20, and 30 min) of the ratio between TSS and the maximum TSS (TSS max) for different rainfall intensities (134, 138.7, 160.6, 163.9, 173.6, 181.8, 190.2, and 207.7 mm/hr) and soil slopes (2%, 7%, and 10%) for the three tested soils (S1, S2, and S3). In general, the TSS at 1.5 min was higher than the concentration at other times, the data suggest an exponential decay of the TSS over time. This reflects a first wash load of the rain with a higher concentration and a decay of the TSS until it reaches a value where it stabilizes, according with the intensity and soil slope. The magnitude of TSS depends of soil type, with higher TSS at S2, and lower values at S3, it can be explained by the higher percentage of silts and clays of S2 soil (22%) compared with S1 soil (4%). Despite S3 having the highest percentage of silt and clay (86%), its cohesion prevents particle detachment, resulting in lower TSS concentrations than other soils (S1 and S2), additionally, the time variation of TSS does not exhibit a clear tendence and it seems to stay constant. For each soil, slope significantly influenced TSS concentration. Tests with a 10% slope showed higher TSS values than those with 7% and 2% slopes. Tests with S1 and S2 show that if the slope decreased then lower sediment concentrations were obtained. The effect of rain intensity on TSS is not completely clear from simple observation, but for all three soils, less dispersion and a clearer exponential decay in the relationship between TSS and TSS max was observed at a 2% slope.

In general, the maximum TSS was observed at the beginning (1.5 min), indicating an initial wash load of sediments, followed by an exponential decrease of these rate can be observed particularly for soils S1 and S2, and after 20 min before of the beginning of the precipitation, it was observed that TSS/TSS_{max} tends to stabilize after (see Figure 6).

It is important to note that variation in slope and rainfall intensity affects runoff, and concentration alone is not the only variable to consider. During each test, runoff records were taken, with discharge varying between 0.26 and 0.12 L/s depending on rain intensity. The variation within the 30-min test was less than 0.01 L/s. For the tests conducted, the behavior of sediment load (not showed) was similar behavior that the TSS/TSS_{max} showed.

Discussion

For the evaluated soil types, a positive correlation between rain intensity and soil loss was evident (see Figures 3–5). Similar findings have been reported by other authors (Wischmeier & Smith, 1978; Fraser et al., 1999), who explained that this behavior results from increased runoff at higher rain intensities. Additionally, the amount of soil released by raindrop impacts increases with rain intensity (Chaplot & Bissonnais, 2000; Hairsine & Rose, 1992; Mermut et al., 1997; Williams et al., 2000). Increases in soil loss were observed whenever both terrain slope and rain intensity increased, which was true for all three evaluated soil types. Soil loss within unpaved roads can exhibit different behaviors depending on the soil type (see Figures 3–5). Soil S2 exhibited greater soil loss compared to soils S1 and S3 at each intensity and slope. This difference can be attributed to the higher clay content and finer particle size of S2 compared to S1. Also, rainfall intensity and slope gradient also show effects at this soil loss. quantity of eroded soils from unpaved roads. Although S3 has the highest proportion of fine particles, lower rates of sediment loss were obtained due to the soil's cohesion and other properties such as plasticity index, particle size distribution, and dry density. For S3 soil, the compaction process generated a smoother surface, which could explain why there was less soil loss.

Soil compaction could be a significant factor, especially for certain soil types. However, this study primarily analyzed the effect of soil type under typical compaction conditions for unpaved roads. Initial soil moisture would be an important factor in the soil loss, for this reason soil moisture was monitoring during at the beginning of each test (approximately 11% for soil S1, 7% for soil S2, and 24% for soil S3).

There was a significant difference between the three evaluated soil types. The main difference between S1 and S2 was the percentage of fine particles. Both soils had a coarse sand base, but S2 had a higher percentage of fine particles. S2 exhibited higher values of soil loss and suspended sediments than S1, likely due to its higher content of fine particles that can be easily transported by runoff. Comparing S2 and S1 with S3, soil S3 showed less soil loss and sediment concentration despite being a fine soil, likely due to compaction creating a smoother surface and the cohesion that promote particles to group and form clods of earth.

According to the ANOVA test, slope is a fundamental variable for unpaved road erosion, showing a statistically significant difference in the means of soil loss for the evaluated groups (slopes of 2%, 7%, and 10%). Slope affects infiltration and runoff, influencing erosion processes (Assouline & Ben-Hur, 2006). Steeper slopes imply higher runoff velocity and changes during seal formation, impacting erosion dynamics. Increased rain intensity also increases runoff, significantly affecting erosion on unpaved roads and resulting in higher sediment yield. Rill formation was observed in soils S1 and S2, particularly at a 10% slope, emphasizing the importance of slope and runoff in soil loss, especially in coarse soils when rill erosion occurs. Increases runoff favors rill formation through flow concentration points (MacDonald et al., 2001). Rill formation was observed in the laboratory for soil type S2 during tests using slopes of 10% and 7%.

Soil type S1 had a greater proportion of sand (74%) and lower soil loss than soil type S2. This greater erosion resistance in soil S1 can be explained by the greater weight and irregular shape of its grains compared to S2, which strengthens frictional forces. The highest soil loss was observed in soil type S2, which had a sandy soil with a greater proportion of fine sand and loam (28% and 22%) than soil type S1 (22% and 4%). This greater erosion in S2 is explained by the fact that fine particles were more susceptible to erosion and are transported by surface flow (Shabani et al., 2014). Fine soils also tend to have lower infiltration rates, promoting surface runoff. In some cases, rill erosion could occur with these types of soils, leading to large erosion rates (Wirtz et al., 2012). Soil texture and compaction can significantly affect infiltration on roads. Compacted soil generates low infiltration.

Soil S3 had a higher percentage of fine particles than S2 but exhibited less soil erosion, likely due to soil cohesion and compaction. Cohesion causes soil particles to remain grouped, offering more resistance to being washed away. Compaction also produced a smoother surface, reducing drag. The lowest soil loss was observed for soil type S3, which is a cohesive silt-clay soil. Soil loss in S3 led to the formation of crusts that gradually detached, similar to observations by Sadeghi et al. (2017), who studied the splash generated by raindrop impacts and found that clay soils tend to create crusts during splash erosion. Soil cohesion, crust formation, and smooth surface generation are fundamental factors in reducing soil loss.

The study showed that rainfall intensity and duration was drivers of erosion on unpaved roads, particularly at higher intensities in non-cohesive soils (S1 and S2), where increased rain intensity led to higher soil loss and suspended sediment concentrations. A better understanding of the erosion process on unpaved roads is necessary. This study identifies the soil erosion dynamics for three soil types under different slope gradients, showing that soil type is a determinant factor in erosion. In constructing unpaved roads, special attention should be paid to the materials used as a rolling base, avoiding those with high silt content (such as S2 soil) that could lead to high rates of soil loss and high concentrations of suspended sediments during rain events. Technologies that increase the cohesion of fine materials present on the rolling surface should be explored. This can be achieved through compaction for fine soils (such as S3 soil), but for soils containing coarse materials (such as S1 or S2), additives or other mechanisms should be sought to ensure soil cohesion and provide a smoother surface to reduce erosion.

Conclusion

The results showed that erosion on unpaved roads is significantly influenced by changes in rain intensity (between 134 and 207.7 mm/hr) and slopes of 2%, 7%, and 10%. The study included the analysis of three types of soils compacted to optimal density, with tests conducted on initially moist soil. This research provides important insights for preventing erosion on unpaved roads, highlighting the importance of adequate compaction and guiding future erosion control techniques. It emphasizes using materials that promote the cohesion of fine particles and help generate a smoother surface to reduce drag.

Both slope and rain intensity play a crucial role in road erosion. The highest soil loss was observed on slopes of 10% and 7%, while the least soil loss was seen with the most cohesive soil type, S3, which had a high clay content.

Soil type is a fundamental factor in the erosion process on unpaved roads. Soil types S1 and S2 show statistically significant differences between mean soil loss and slope, with $p < .05$. The 2% slope group exhibits the most significant differences in mean soil loss compared to the other groups (7% and 10% slopes). Soil type S2 shows a statistically significant difference in mean soil loss across the three slope groups (2%, 7%, and 10%), with $p < .05$.

Soil loss and rain intensity exhibit a linear relationship. Soil loss increases for S1 and S2 as rain intensity increases. Conversely, soil S3 does not show a strong correlation between soil loss and rain intensity. Soil loss was positively correlated with rainfall intensity for the evaluated soils and showed a significant interaction with the terrain slope.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by COLCIENCIAS through the Red INNOVIAL project.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

ORCID iD

Luis-Javier Montoya https://orcid.org/0000-0002-5832-2219

REFERENCES

Arnáez, J., Larrea, V., & Ortigosa, L. (2004). Surface runoff and soil erosion on unpaved forest roads from rainfall simulation tests in northeastern Spain. *Catena*, 57(1), 1–14. https://doi.org/10.1016/j.catena.2003.09.002

Assouline, S., & Ben-Hur, M. (2006). Effects of rainfall intensity and slope gradient on the dynamics of interrill erosion during soil surface sealing. *Catena*, 66(3), 211–220. https://doi.org/10.1016/j.catena.2006.02.005

Benito Rueda, E., Gómez Ulla, A., & Díaz Fierros, F. (1986). Descripción de un simulados de lluvia para estudios de erodabilidad del suelo y estabilidad de los agregados al agua. *Anales de Edafología y Agrobiología*, 45(9–10), 1115–1126.

Chaplot, V., & Le Bissonnais, Y. (2000). Field measurements of interrill erosion under different slopes and plot sizes. *Earth Surface Processes and Landforms*, 25, 145–153. https://doi.org/10.1002/(sici)1096-9837(200002)25:2<145::aid-esp51>3.0.co;2-3

Christiansen, J. E. (1942). *Irrigation by sprinkling* (Vol. 4). University of California Berkeley.

Croke, J., Mockler, S., Hairsine, P., & Fogarty, P. (2006). Relative contributions of runoff and sediment sources within a road prism and implications for total sediment delivery. *Earth Surface Processes and Landforms*, 31(4), 457–468. https://doi.org/10.1002/esp.1279

de Oliveira, J. F., Griebeler, N. P., Correchel, V., & da Silva, V. C. (2009). Erodibility and critical shear stress on unpaved road soils. *Revista Brasileira de Engenharia Agricola e Ambiental*, 13, 955–960. https://doi.org/10.1590/s1415-43662009000700019

Defersha, M. B., & Melesse, A. M. (2012). Effect of rainfall intensity, slope and antecedent moisture content on sediment concentration and sediment enrichment ratio. *Catena*, 90, 47–52. https://doi.org/10.1016/j.catena.2011.11.002

Djeran-Maigre, I., Morsel, A., Briançon, L., Delfosse, E., Levacher, D., & Razakamanantsoa, A. R. (2022). Uses of Usumacinta River sediments as a sustainable resource for unpaved roads: An experimental study on a full-scale pilot unit. *Transportation Engineering*, 9, 100136. https://doi.org/10.1016/J.TRENG.2022.100136

Foltz, R. B., Copeland, N. S., & Elliot, W. J. (2009). Reopening abandoned forest roads in northern Idaho, USA: Quantification of runoff, sediment concentration, infiltration, and interrill erosion parameters. *Journal of Environmental Management*, 90(8), 2542–2550. https://doi.org/10.1016/j.jenvman.2009.01.014

Forsyth, A. R., Bubb, K. A., & Cox, M. E. (2006). Runoff, sediment loss and water quality from forest roads in a southeast Queensland coastal plain Pinus plantation. *Forest Ecology and Management*, 221(1–3), 194–206. https://doi.org/10.1016/j.foreco.2005.09.018

Fraser, A. I., Harrod, T. R., & Haygarth, P. M. (1999). The effect of rainfall intensity on soil erosion and particulate phosphorus transfer from arable soils. *Water Science and Technology*, 39(12), 41–45. https://doi.org/10.1016/S0273-1223(99)00316-9

Fu, S., Liu, B., Liu, H., & Xu, L. (2011). The effect of slope on interrill erosion at short slopes. *Catena*, 84(1–2), 29–34. https://doi.org/10.1016/j.catena.2010.08.013

Gresswell, S., Heller, D., & Swanston, D. N. (1979). Mass movement response to forest management in the Central Oregon Coast Range. *US Department of Agriculture, Forest Service Resource*. https://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Mass+Movement+REesponse+to+Forest+Management+in+the+Central+Oregon+Coast+Range#1

Gucinski, H. (2001, May). Forest roads: A synthesis of scientific information. *USDA-General Technical Report PNW-GTR-509*, 1–120. https://books.google.com/books?hl=en&lr=&id=uUNh8Moz9zUC&oi=fnd&pg=PA1&dq=Forest+Roads+:+A+Synthesis+of+Scientific+Information&ots=8Rav7bOXhJ&sig=8JCYfpN54G7zO-pIwxYjlJJMF9Q

Hairsine, P. B., & Rose, C. W. (1992). Modeling water erosion due to overland flow using physical principles: 2. Rill flow. *Water Resources Research*, 28(1), 245–250. https://doi.org/10.1029/91WR02381

Iserloh, T., Ries, J. B., Arnáez, J., Boix-Fayos, C., Butzen, V., Cerdà, A., Echeverría, M. T., Fernández-Gálvez, J., Fister, W., Geißler, C., Gómez, J. A., Gómez-Macpherson, H., Kuhn, N. J., Lázaro, R., León, F. J., Martínez-Mena, M., Martínez-Murillo, J. F., Marzen, M., Mingorance, M. D., . . . Wirtz, S. (2013). European small portable rainfall simulators: A comparison of rainfall characteristics. *Catena*, 110, 100–112. https://doi.org/10.1016/j.catena.2013.05.013

Koch, T., Chifflard, P., Aartsma, P., & Panten, K. (2024). A review of the characteristics of rainfall simulators in soil erosion research studies. *MethodsX*, 12, 102506. https://doi.org/10.1016/j.mex.2023.102506

Lange, J., Greenbaum, N., Husary, S., Ghanem, M., Leibundgut, C., & Schick, A. P. (2003). Runoff generation from successive simulated rainfalls on a rocky, semi-arid, Mediterranean hillslope. *Hydrological Processes*, 17(2), 279–296. https://doi.org/10.1002/hyp.1124

Loch, R. J. (2000). Effects of vegetation cover on runoff and erosion under simulated rain and overland flow on a rehabilitated site on the Meandu Mine, Tarong, Queensland. *Soil Research.*, 38, 299–312.

MacDonald, L. H., Sampson, R. W., & Anderson, D. M. (2001). Runoff and road erosion at the plot and road segment scales, St John, US Virgin Islands. *Earth Surface Processes and Landforms*, 26(3), 251–272. https://doi.org/10.1002/1096-9837(200103)26:3<251::AID-ESP173>3.0.CO;2-X

Megahan, W. F., Wilson, M., & Monsen, S. B. (2001). Sediment production from granitic cutslopes on forest roads in Idaho, USA. *Earth Surface Processes and Landforms*, 26, 153–163.

Mermut, A. R., Luk, S. H., Römkens, M. J. M., & Poesen, J. W. A. (1997). Soil loss by splash and wash during rainfall from two loess soils. *Geoderma*, 75(3–4), 203–214. https://doi.org/10.1016/S0016-7061(96)00091-2

Mhaske, S. N., Pathak, K., & Basak, A. (2019). A comprehensive design of rainfall simulator for the assessment of soil erosion in the laboratory. *Catena*, 172, 408–420. https://doi.org/10.1016/j.catena.2018.08.039

Mostafazadeh, R., Talebi Khiavi, H., Esmali Ouri, A., Asgari, E., & Golshan, M. (2024). Plot-size runoff and sediment yield affected by the type of geological formations and implications for water erosion in a semi-arid region. *Modeling Earth Systems and Environment*, 10(1). https://doi.org/10.1007/s40808-023-01813-3

Mostafazadeh, R., Talebi Khiavi, H., Esmali-Ouri, A. et al. (2023). Surface runoff and sediment yield response under the rainfall simulation condition controlled by soil variables of a semi-arid landscape. *Environ Dev Sustain*, 25, 12339–12356 https://doi.org/10.1007/s10668-022-02569-z

Ngezahayo, E., Burrow, M. P. N., & Ghataora, G. S. (2019). The advances in understanding erodibility of soils in unpaved roads. *International Journal of Civil Infrastructure*, 2, 1–17. https://doi.org/10.11159/IJCI.2019.002

Ngezahayo, E., Ghataora, G., & Burrow, M. (2021). Modelling the effects of soil properties, rainfall and road geometry to erosion in unpaved roads. *International Journal of Civil Infrastructure*. https://doi.org/10.11159/ijci.2021.015

R Development Core Team. (2015). R: A language and environment for statistical computing. *R Foundation for Statistical Computing*, 1, 409. https://doi.org/10.1007/978-3-540-74686-7

Ramos-Scharrón, C. E., & MacDonald, L. H. (2007). Runoff and suspended sediment yields from an unpaved road segment, St John, US Virgin Islands. *Hydrological Processes*, 21(1), 35–50. https://doi.org/10.1002/hyp.6175

Rice, E. W., & Bridgewater, L., & American Public Health Association. (2012). *Standard methods for the examination of water and wastewater* (Vol. 10). American Public Health Association.

Sadeghi, S. H., Kiani, M. H., & Asadi, H. (2017). Variability of particle size distributions of upward/downward splashed materials in different rainfall intensities and slopes. *Geoderma*, 290, 100–106.

Shabani, F., Kumar, L., & Esmaeili, A. (2014). Improvement to the prediction of the USLE K factor. *Geomorphology*, 204, 229–234. https://doi.org/10.1016/j.geomorph.2013.08.008

Shen, Y., Gu, J., Liu, G., Wang, X., Shi, H., Shu, C., Shu, C., Zhang, Q., Guo, Z., & Zhang, Y. (2023). (2023). Predicting soil erosion and deposition on sloping farmland with different shapes in northeast China by using 137Cs. *Catena*, 229, 107238.

Sadeghi, S. H. R., Seghaleh, M. B., & Rangavar, A. S. (2013). Plot sizes dependency of runoff and sediment yield estimates from a small watershed. *Catena*, 102. https://doi.org/10.1016/j.catena.2011.01.003

Sheridan, G. J., & Noske, P. J. (2007). Catchment-scale contribution of forest roads to stream exports of sediment, phosphorus and nitrogen. *Hydrological Processes*, 21(23), 3107–3122. https://doi.org/10.1002/hyp.6531

Sheridan, G. J., So, H. B., Loch, R. J., Pocknee, C., & Walker, C. M. (2000). Use of laboratory-scale rill and interill erodibility measurements for the prediction of hillslope-scale erosion on rehabilitated coal mine soils and overburdens. *Australian Journal of Soil Research*, 38(2), 285–297. https://doi.org/10.1071/SR99039

Shi, Z. H., Fang, N. F., Wu, F. Z., Wang, L., Yue, B. J., & Wu, G. L. (2012). Soil erosion processes and sediment sorting associated with transport mechanisms on steep slopes. *Journal of Hydrology*, 454–455, 123–130. https://doi.org/10.1016/j.jhydrol.2012.06.004

Sidle, R. C., Pearce, A. J., & O'Loughlin, C. L. (1985). Hillslope stability and land use. *Water resources monograph* (Vol. 11, p. 140). American Geophysical Union. https://doi.org/10.1029/WM011

Williams, J. D., Wilkins, D. E., Douglas, C. L., & Rickman, R. W. (2000). Mow-plow crop residue management influence on soil erosion in north-central Oregon. *Soil and Tillage Research*, 55(1–2), 71–78. https://doi.org/10.1016/S0167-1987(00)00100-8

Wirtz, S., Iserloh, T., Rock, G., Hansen, R., Marzen, M., Seeger, M., Betz, S., Remke, A., Wengel, R., Butzen, V., & others. (2012). Soil erosion on abandoned land in Andalusia: A comparison of interrill-and rill erosion rates. *International Scholarly Research Notices*, 2012(1), 730870.

Wischmeier, W. H., & Smith, D. D. (1978). Predicting rainfall erosion losses: A guide to conservation planning. In *Agriculture handbook* (Vol. 537, pp. 285–291). Department of Agriculture, Science and Education Administration. https://doi.org/10.1029/TR039i002p00285

Yu, W., Zhao, L., Fang, Q., & Hou, R. (2021). Contributions of runoff from paved farm roads to soil erosion in karst uplands under simulated rainfall conditions. *Catena*, 196, 104887. https://doi.org/10.1016/j.catena.2020.104887

Zhang, Q., Lei, T., & Zhao, J. (2008). Estimation of the detachment rate in eroding rills in flume experiments using an REE tracing method. *Geoderma*, 147(1–2), 8–15. https://doi.org/10.1016/j.geoderma.2008.07.002

Ziegler, A. D., Sutherland, R. A., & Giambelluca, T. W. (2000). Runoff generation and sediment production on unpaved roads, footpaths and agricultural land surfaces in northern Thailand. *Earth Surface Processes and Landforms*, 25(5), 519–534. https://doi.org/10.1002/(SICI)1096-9837(200005)25:5<519::AID-ESP80>3.0.CO;2-T

Ziegler, A. D., Sutherland, R. A., & Giambelluca, T. W. (2001). Acceleration of Horton overland flow and erosion by footpaths in an upland agricultural watershed in northern Thailand. *Geomorphology*, 41(4), 249–262. https://doi.org/10.1016/S0169-555X(01)00054-X