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Measurement and prediction of sediment production from unpaved roads, St John, US Virgin Islands

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Abstract

Excess delivery of land-based sediments is an important control on the overall condition of nearshore coral reef ecosystems. Unpaved roads have been identified as a dominant sediment source on St John in the US Virgin Islands. An improved understanding of road sediment production rates is needed to guide future development and erosion control efforts. The main objectives of this study were to: (1) measure sediment production rates at the road segment scale; (2) evaluate the importance of precipitation, slope, contributing area, traffic, and grading on road sediment production; (3) develop an empirical road erosion predictive model; and (4) compare our measured erosion rates to other published data. Sediment production from 21 road segments was monitored with sediment traps from July 1998 to November 2001. The selected road segments had varying slopes, contributing areas, and traffic loads. Precipitation was measured by four recording rain gauges.

Sediment production was related to total precipitation and road segment slope. After normalizing by precipitation and slope, the mean sediment production rate for roads that had been graded within the last two years was 0·96 kg m^{-2} cm^{-1} m m^{-1} or approximately 11 kg m^{-2} a^{-1} for a typical road with a 10 per cent slope and an annual rainfall of 115 cm a^{-1}. The mean erosion rate for ungraded roads was 42 per cent lower, or 0·56 kg m^{-2} cm^{-1} m m^{-1}. The normalized mean sediment production rate for road segments that had been abandoned for over fifteen years was only about 10 per cent of the mean value for ungraded roads. Sediment production was not related to traffic loads. Multiple regression analysis led to the development of an empirical model based on precipitation, slope to the 1·5 power, and a categorical grading variable.

The measured and predicted erosion rates indicate that roads are capable of increasing hillslope-scale sediment production rates by up to four orders of magnitude relative to undisturbed conditions. The values from St John are at the high end of reported road erosion rates, a finding that is consistent with the high rainfall erosivities and steep slopes of many of the unpaved roads on St John. Other than paving, the most practical methods to reduce current erosion rates are to minimize the frequency of grading and improve road drainage.

Keywords: surface erosion; forest roads; dry tropics; US Virgin Islands; Caribbean

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Introduction

Problem statement and objectives

Unpaved roads have been shown to be a primary sediment source and cause of increased sediment yields in a wide range of forested areas (e.g. Megahan, 1987; Luce and Wemple, 2001). The disruption of geomorphologic and hydrologic processes by roads increases both surface erosion and the frequency of mass wasting (e.g. Gresswell *et al.*, 1979; Sidle *et al.*, 1985; Larsen and Parks, 1997; Gucinski *et al.*, 2001). These increases are of particular concern in forested areas because natural erosion rates tend to be very low. Surface erosion from unpaved road surfaces has been shown to be an important sediment source in Australia (Grayson *et al.*, 1993), New Zealand (Fahey and Coker, 1989;

Fransen *et al.*, 2001), Malaysia (Douglas *et al.*, 1993), the United States (e.g. Reid and Dunne, 1984; Burroughs *et al.*, 1991), Poland (Froehlich and Walling, 1997; Froehlich, 1991), Ghana (Kumapley, 1987), and Kenya (Dunne, 1979).

Collaborative work among geomorphologists, hydrologists, and stream ecologists has helped document the adverse impacts of excessive sediment inputs on freshwater fluvial systems (e.g. Everest *et al.*, 1987; National Research Council, 1992; Waters, 1995). Marine ecosystems, such as nearshore coral reef communities, also can be adversely affected by excessive inputs of fine sediment following land disturbance (Hubbard, 1987; Hodgson, 1989, 1997; Rogers, 1990). The effects of increased erosion on reef communities is of particular concern in the Caribbean because of the high potential erosion rates following disturbance and the importance of coral reefs to the tourism-based local economies. In recent years marine ecologists have documented the effects of high sediment inputs on coral reefs in the Dominican Republic (Torres *et al.*, 2001), Puerto Rico (Acevedo *et al.*, 1989; Torres, 2001) and the nearby island of Culebra (Hernández-Delgado, 2001), Virgin Gorda in the British Virgin Islands (C. Rogers, USGS, pers. comm., 2001), as well as in St Croix (Hubbard, 1986), St Thomas (Nemeth and Nowlis, 2001) and St John (Rogers, 1998; Nemeth *et al.*, 2001) in the US Virgin Islands.

Within the US Virgin Islands, the coral reefs near St John have received special attention because 23 km^2 of offshore waters and 28 km^2 or 56 per cent of the island form the Virgin Islands National Park (Figure 1) and have been designated as a Biosphere Reserve. In 2001 an additional 47 km^2 of offshore waters were designated as the Virgin Islands Coral Reef National Monument. Previous research showed that sediment production rates from unpaved roads are several orders of magnitude higher than sediment production rates from undisturbed hillslopes, and that unpaved roads were probably the primary source of the fine sediment being delivered to the marine environment (MacDonald *et al.*, 2001). The cross-sectional area of rills on unpaved road surfaces was related to road segment area multiplied by slope, and this relationship formed the basis of an empirical road erosion model called ROADMOD (Anderson and MacDonald, 1998). The application of ROADMOD to two basins indicated that unpaved road erosion may be increasing sediment yields by up to four times (MacDonald *et al.*, 1997), but these studies did not directly measure road erosion rates or assess the role of other factors that have been shown to affect road erosion rates (Ramos, 1997).

The development of improved predictive equations is needed to better estimate sediment production and delivery from different road segments, identify erosion control strategies, and guide future development. Hence the specific objectives of this study were to: (1) measure sediment production rates from unpaved road surfaces; (2) evaluate the

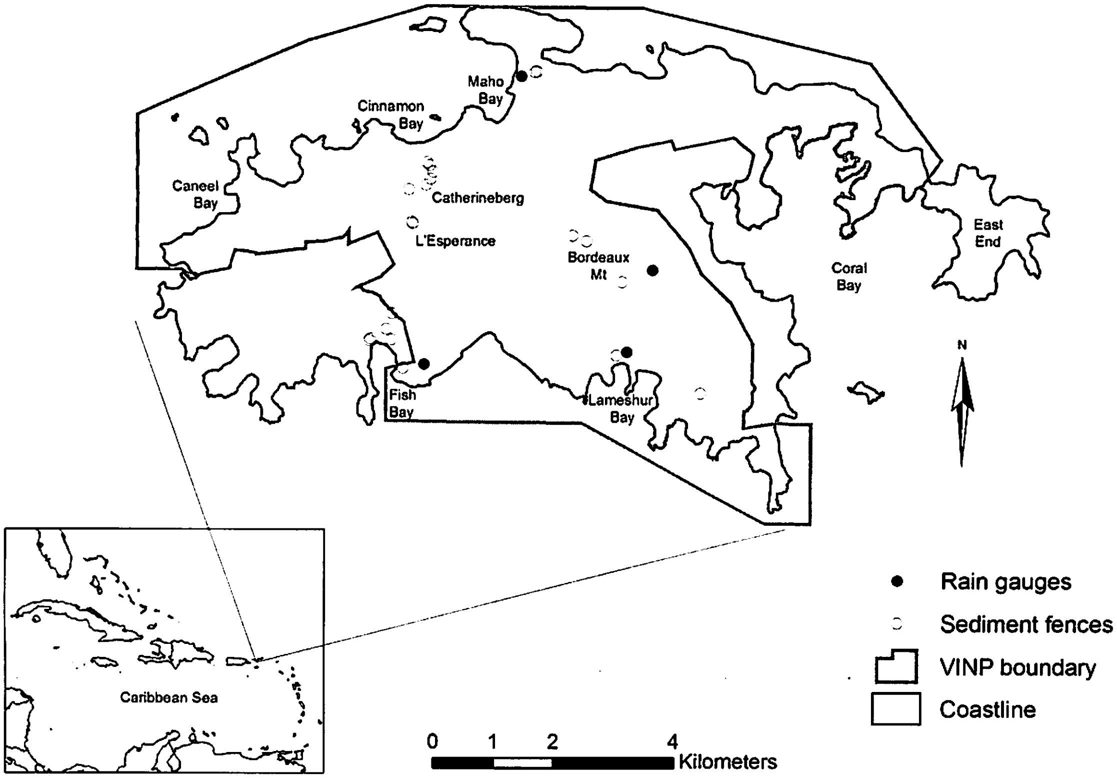

Figure 1. Map of St John showing the locations of the rain gauges and road segment sediment traps.

effect of precipitation, slope, contributing area, traffic, and grading on sediment production rates; (3) develop an empirical model to predict road sediment production rates; and (4) compare the measured road sediment production rates to published data from St John and elsewhere.

Modelling road sediment production

An exposed soil surface is subject to two primary surface erosion processes: rainsplash and the shear stress of overland flow. Rainsplash energy is a function of precipitation intensity as well as the size and terminal velocity of the raindrops (Wischmeier and Smith, 1958; Carter *et al.*, 1974). Flow hydraulics determine the shear stress of overland flow, while the resistance to erosion is controlled by the size and cohesion of the underlying material. If one assumes that rainsplash erosion is rapidly eliminated after surface runoff has begun (Moss and Green, 1983), the surface erosion rate (E_t) is proportional to the difference between the shear stress applied by overland flow (τ) and the resistance of the material to erosion (τ_c):

$$E_t \propto k_1(\tau - \tau_c)^n \qquad (1)$$

where k_1 is an index of the erodibility of the sediment and n is an exponent between 1 and 2 (Kirkby, 1980). The shear stress applied by overland flow is equal to:

$$\tau = \rho_w g h s \qquad (2)$$

where ρ_w is the density of water, g is the acceleration due to gravity, h is the depth of flow, and s is the water surface slope (Julien, 1995). τ_c is generally a function of the particle-size distribution, as this controls the exposure of particles to hydraulic forces, the cohesive forces between particles, and the tractive force needed to detach individual particles (Knighton, 1998).

Infiltration rates on unpaved roads are typically very low (Bren and Leitch, 1985; Harden, 1992; Ziegler and Giambelluca, 1997). Hence, the frequency and magnitude of infiltration-excess (Horton) overland flow is much greater from unpaved roads than undisturbed areas. On St John only 3–6 mm of precipitation are needed to initiate infiltration-excess overland flow on unpaved road surfaces (MacDonald *et al.*, 2001; Ramos-Scharrón and MacDonald, in press). Equations 1 and 2 indicate that the surface erosion rate is directly proportional to flow depth. The continuity equation for a road segment requires that the inflow rate [$Q_i(t)$] must equal the sum of outflow rate [$Q_o(t)$] plus temporary water storage [$S(t)$]:

$$Q_i(t) = Q_o(t) + S(t) \qquad (3)$$

For an isolated road segment, the inflow rate is determined by precipitation excess, which is the difference between precipitation intensity [$P(t)$] and infiltration rate [$I(t)$] multiplied by the surface area of the road segment (A):

$$Q_i(t) = [P(t) - I(t)]A \qquad (4)$$

Since storage and outflow rates are each a function of water depth, increasing inflow (precipitation excess or road surface area) increases flow depth and thus the potential for surface erosion (Equation 2).

The parent material affects the resistance of unpaved roads to surface erosion by controlling the surface particle-size distribution (Luce and Black, 1999). The particle-size distribution of the road surface is affected by the amount and type of traffic (e.g. Wald, 1975; Reid, 1981; Grayson *et al.*, 1993; MacDonald *et al.*, 2001), the preferential erosion of particles in a given size class, and the time since construction or grading.

The amount and type of traffic affects road surface erodibility by particle attrition between storms (Bilby *et al.*, 1989; Kahklen, 1993; Foltz, 1996; Ziegler *et al.*, 2001a) and the pumping of fine particles onto the surface as the road tread is compacted, especially during wet conditions (Reid, 1981; Bilby *et al.*, 1989; Ziegler *et al.*, 2001b). Gravel roads subjected to more than four heavy truck passes per day had higher erosion rates than roads with less traffic (Reid and Dunne, 1984).

Newly constructed and freshly resurfaced roads typically have very high sediment production rates due to the abundance of easily erodible fine particles (Megahan and Kidd, 1972; Megahan *et al.*, 1986). The rapid erosion of fine sediment immediately after construction or regrading leads to a coarsening of the road surface, which increases its resistance to erosion. Only a few studies have directly measured time trends in sediment production after regrading. In the Oregon Coast Range, blading of the ditch along gravel-surfaced roads increased sediment production rates more than road surface grading alone (Black and Luce, 1999; Luce and Black 1999, 2001a, b). On St John, vehicle-induced rutting and the absence of road ditches keeps much of the runoff on the road surface and this facilitates the detachment and transport of the loose, fine sediment applied during grading. The decline in road erosion rates after construction or grading has been modelled using the equation:

$$E_t = E_n + k_2 S_0 e^{-k_2 t} \tag{5}$$

where E_t is the erosion rate (in Mg km^{-2} day^{-1}), E_n is the erosion rate approached after a long period without any disturbance (Mg km^{-2} day^{-1}), S_0 is the total amount of material available for erosion immediately after construction or grading (Mg km^{-2}), k_2 (in days^{-1}) is an index of the rate of decline in erosion following the disturbance, and t is the time after disturbance in days (Megahan, 1974).

The dependence of erosion rates on the interplay between the available energy and the erodibility of loose material has led to the development of a dynamic erodibility model for unpaved road surfaces (Ziegler *et al.*, 2000, 2001a, b). These studies modelled the changes in surface erodibility over time as a function of traffic and the extent to which the road surface has been depleted of highly erodible material.

Given this theoretical background, our study design, field measurements, and model development efforts focused on precipitation characteristics, road slope, active road area, traffic, and time since grading. As documented above, these factors control the amount of runoff, the tractive forces applied by overland flow, and the resistance of the road surface to erosion.

Study Area

St John is the third largest island of the US Virgin Islands, and it lies in the eastern Caribbean approximately 80 km east of Puerto Rico (Figure 1). The topography is very rugged, as more than 80 per cent of the slopes are greater than 30 per cent (CH2M Hill, 1979; Anderson, 1994). Bordeaux Mountain is the highest point of the island at an elevation of 387 m.

The lithology of St John is dominated by rocks originating from volcanic flows (Donnelly, 1966; Rankin, 2002) that have undergone periods of deformation, magmatic intrusions, and hydrothermal alterations. Soils are dominated by gravelly loams and clay loams (USDA, 1995). They have a fine clayey to loamy matrix with abundant coarse fragments (Soil Conservation Service, 1970). The soils tend to be shallow, moderately permeable, well drained, and underlain by nearly impervious bedrock (USDA, 1995).

The climate of St John is characterized as dry tropical. Bowden *et al.* (1970) identified five precipitation zones ranging from a low of 89–102 cm a^{-1} on the eastern end of the island to a high of 127–140 cm a^{-1} near Bordeaux Mountain. Easterly waves, which can develop into tropical storms and hurricanes, generate most of the rainfall from May to November, while cold fronts are important sources of rainfall from December to April (Calversbert, 1970). There are no sharply defined wet and dry seasons in the Virgin Islands, but a relatively dry season extends from about February to July, and a relatively wet season lasts from August until January (Bowden, *et al.*, 1970). Mean monthly potential evapotranspiration (PET) exceeds mean monthly precipitation for most of the year (Bowden *et al.*, 1970; Sampson, 2000), so there are no perennial streams on St John (MacDonald *et al.*, 1997).

Precipitation in St John is highly erosive. The average annual erosivity at Caneel Bay was estimated to be 13 500 MJ mm ha^{-1} h^{-1} (Sampson, 2000). The 15-minute precipitation intensity at Caneel Bay exceeded 100 mm h^{-1} sixteen times from 1979 to 1995.

Dry evergreen forests and shrubs cover approximately 63 per cent of the total land area, moist forest and secondary vegetation about 30 per cent, while urban, wetland, and pasture each cover about 2 per cent of the island (Woodbury and Weaver, 1987). Rapid development on privately owned lands over the past 30 years has resulted in a dense road network on St John.

Construction and maintenance standards of the unpaved roads on St John are generally very poor. The spacing of road drainage structures (i.e. ditches, culverts, or cross-drains) is very sparse, even on extremely steep road segments. As a result of the high rainfall erosivity and poor drainage design, deep rills commonly develop on the road surface, especially on the steeper road segments (Figure 2). On these segments regrading is done every year or so to facilitate the passage of standard passenger cars.

Methods

Precipitation was measured with four recording rain gauges (Figure 1). Table I lists the type, resolution, and period of record for each gauge. The measured precipitation at each location was compared to expected monthly and annual

Figure 2. A typical steep road segment near Bordeaux Mountain with a deeply rilled travelway.

Table I. Type, resolution, and period of record for the rain gauges used in this study

Station	Type of gauge	Time (min); and depth (cm) resolution	Period of record [Gaps in data]
Bordeaux Mountain	Tipping bucket	15; 0·025	14 Sep 98 to 2 Sep 99 [28 Feb 99 to 28 Jun 99]
	Weighing bucket	60; 0·25	2 Sep 99 to 3 May 00 [None]
Fish Bay	Tipping bucket	15; 0·025	20 Jul 98 to 3 May 00 [8 Feb 99 to 8 Jul 99; 20 Oct 99 to 7 Nov 99]
Lameshur Bay	Tipping bucket	15; 0·25	19 Aug 98 to 3 May 00 [8 Feb 99 to 12 Jul 99; 19 Oct 99 to 3 May 00]
Maho Bay	Weighing bucket	60; 0·025	13 Jul 98 to 2 Sep 99 [20 Sep 98 to 28 Sep 98]
	Tipping bucket	15; 0·025	2 Sep 99 to 13 Apr 00 [None]

precipitation totals defined by Bowden *et al.* (1970) and values measured at Caneel Bay from 1979 to 1995 (EarthInfo, 1996). The precipitation data also were used to determine total storm precipitation and 15-minute erosivities following Renard *et al.* (1997). An individual storm was defined as a precipitation event isolated from other events by at least one hour with no precipitation. This definition was used because overland flow on road surfaces usually ceases within 30–60 minutes after the end of a rainfall event (Ramos-Scharrón, 2004). Fifteen-minute erosivities were calculated for individual storm events for the three gauges with sufficient temporal resolution.

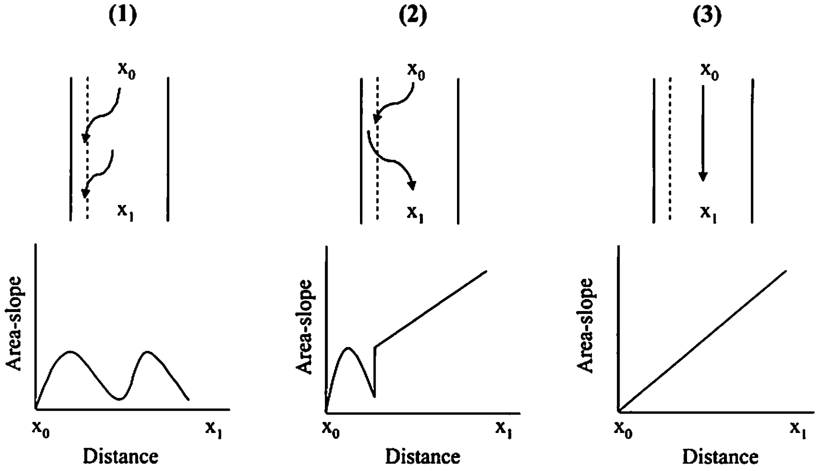

Figure 3. Sketches showing the three main drainage patterns of unpaved roads on St John and how this affects the product of road surface area and segment slope: (1) insloped with irregular cross-slope drainage; (2) insloped with a blocked inside ditch; and (3) no effective cross-slope drainage. Dashed lines indicates the inside edge of the ditch.

Sediment production rates were periodically measured from 21 unpaved road segments (Figure 1; Table II) from July 1998 to April 2000 ($n = 104$). A few segments were less intensively monitored from April 2000 to November 2001 ($n = 5$). The primary criterion used to select road segments was the product of road active area and slope, as road active area and road slope directly affect the tractive forces applied by overland flow on the road surface (Equations 2, 4). To the extent possible, the segments were selected to represent a wide range of surface areas and slopes.

The mean width of the 21 segments was 4·7 m and the mean road surface area – including both the active travelway and inside ditch – was 850 m^2. The 21 road segments showed three distinct drainage patterns (Figure 3): (1) insloped travelways directing the runoff into inside ditches; (2) insloped sections with blocked ditches that forced the runoff back onto the road surface; and (3) sub-segments with little or no cross-slope drainage due to deep ruts or the lack of an inside ditch.

Each of the 21 segments was broken into sub-segments as defined by changes in gradient or drainage pattern. The length, mean width, and slope of each sub-segment was measured in the field and recorded. The drainage pattern was determined by identifying the dominant flow paths on the road surface and recording these as sketch maps. These drainage patterns were used when calculating road surface area × slope, as segments with similar lengths and slopes can have very different area × slope values (Figure 3). Hence the slope and the area × slope product for each segment were calculated as an areally weighted mean of the sub-segments.

The mean slope for the 21 road segments was 10 per cent, and the range was from 1 to 21 per cent (Table II). The mean area × slope was 31 m^2, and the range was from 2·0 to 93 m^2. Road slope and width were correlated ($r^2 = 0·51$; $p < 0·001$), as the road segments tended to be either steep and narrow or flat and wide.

Road use was stratified into three classes: roads exclusively used by light vehicles, roads with four to six medium-sized delivery truck passes per day in addition to light vehicle traffic, and abandoned roads. The *a priori* classification of segments into one of these three classes provided a secondary criterion for site selection. An equal block design based on three area × slope classes and three traffic classes was not possible because only two segments in the heavy use category and one abandoned road had suitable sites for measuring sediment production. This meant that it was not possible to measure sediment production from abandoned roads with low area × slope values or roads with high area × slope values and truck traffic. Time since construction or grading was not a primary site selection criterion because all of the recently constructed road segments were privately owned, the grading history was not always known when the road segments were being selected, and we had no control on when regrading occurred.

Sediment production rates were measured by weighing the mass of material trapped in sediment fences (Robichaud and Brown, 2002) placed immediately below a point of concentrated road drainage such as a cemented swale, unprotected cross-dip, or culvert. Drainage from the two abandoned road segments (LE-Bottom and LE-Top) and one segment in Fish Bay (FB-E) was forced off the road surface by installing a 30 cm wide rubber strip at a 30° angle to

Table II. Characteristics of the 21 road segments used in this study

Road segment*	Area (m^2)	Average slope ($m\ m^{-1}$)	Area x slope† ($m^2\ m\ m^{-1}$)	Average width (m)	Mean traffic rate (vehicles day^{-1})	Heavy traffic (trucks day^{-1})	Date(s) of regrading	Measurement period (dd/mm/yr)	Number of observations
BM-A	2113	0·08	25·7	5·1	9	0	Nov 1998	28/07/98 to 18/11/99	6
BM-B	469	0·04	16·1	5·0	156	0	Oct 98, Mar 00	28/07/98 to 12/11/99	4
BM-C	1343	0·08	45·8	5·0	156	0	Oct 98, Mar 00	28/07/98 to 26/04/00	7
FB-A	560	0·02	4·48	6·1	282	4–6‡	Early 99, Feb 00	10/07/98 to 19/01/00	1
FB-C	536	0·03	9·26	4·9	220	4–6‡	Early 99, Feb 00	16/07/98 to 20/01/00	1
FB-D	314	0·01	2·01	4·9	220	4–6‡	Early 99, Feb 00	10/07/98 to 21/01/00	1
FB-E	277	0·21	58·1	3·3	4‡	0	Late 1997	18/08/98 to 17/11/99§	3
FB-Coco	1110	0·11	92·8	3·5	54	0	Prior to 1996	27/07/98 to 10/09/98	2
JH-A	1098	0·13	45·0	4·6	10	0	Sep 1998	03/07/98 to 28/10/98	3
JH-A-1	266	0·11	21·7	4·7	10	0	Sep 1998	28/10/98 to 02/11/99	3
JH-A-2	324	0·16	42·3	3·6	10	0	Prior to 1996	19/10/98 to 15/11/99	3
JH-B	1669	0·12	26·9	4·3	106	0	Prior to 1996	08/07/98 to 10/12/99	9
JH-C	1189	0·04	8·45	5·0	71	0	Late 1999	08/07/98 to 26/01/00	6
JH-D	721	0·16	28·0	4·9	106	0	Prior to 1996	15/07/99 to 28/02/00	4
JH-E	1053	0·10	10·2	4·6	106	0	Prior to 1996	16/07/98 to 28/02/00	4
LB-A	1056	0·15	26·4	4·3	2‡	0	Prior to 1998	31/07/98 to 15/01/00§	3
LB-C	1285	0·09	26·5	5·2	23	0	Feb 99	16/07/99 to 19/11/99	2
LE-Bottom	381	0·14	32·1	4·9	Abandoned	0	Prior to 1985	08/10/99 to 08/03/01§	3
LE-Top	845	0·16	77·0	3·9	Abandoned	0	Prior to 1985	09/11/99 to 06/11/01	4
MB-A	941	0·09	54·3	5·3	108 to 268	4–6‡	Jun 98, Aug 99	06/07/98 to 17/11/99	7
MB-C	341	0·04	5·05	5·0	108 to 268	4–6‡	Jun 98, Aug 99	08/10/99 to 07/11/01	4
Mean	852	0·10	31·3	4·7					

* BM, Bordeaux Mountain; FB, Fish Bay; JH, John Head road; LB, Lameshur Bay; LE, L'Esperance; MB, Maho Bay.

† Values for each segment are based on the drainage pattern observed in the field.

‡ Estimated values.

§ Occasional gaps in the data.

the general direction of the road. The rubber strip was set into a trench 15 cm deep that was backfilled and sealed with concrete.

The sediment fences consisted of filter fabric attached to approximately 1 m long pieces of rebar hammered vertically into the ground. This created a sediment trap about 50 cm high, and the remaining 50 cm of fabric was placed flat on the ground to serve as an apron and a base for removing the accumulated sediment. The leading edge of the apron was secured to the ground surface with rocks or U-shaped pieces of rebar to prevent underflow. The tight weave of the filter fabric did not readily allow water to flow through it, so the sediment fences acted more like dams than filters.

The fences were regularly checked after storm events, and once a substantial amount of sediment had accumulated, the material was shovelled into buckets and weighed with a radial scale to the nearest 0·2 kg. One or two well-mixed samples of 1–4 kg were collected and placed in watertight bags. Percentage moisture content was measured in the laboratory (Gardner, 1986) and used to correct the field-measured wet weights to a dry mass. Twenty-nine of the 109 measurements from sediment fences had to be discarded because precipitation data were not available or because the sediment production data were affected by overtopping of the sediment fences, clogged culverts, or vandalization of the sediment fences.

The particle-size distributions of 40 samples from different fences were determined by dry sieving (Bowles, 1992) for particles coarser than 0·075 mm, and the hydrometer method (Gee and Bauder, 1986) for particles smaller than 0·075 mm. The 40 samples were selected to represent road segments with varying slopes, amounts of traffic, and times since grading. The mean mass-weighted particle-size distribution of the eroded sediment was determined for 20 of the 21 road segments. Multiple-comparison statistical procedures (F-protected LSD and Tukey's HSD) were used to determine if road grading and slope had any effect on the particle-size distribution of the material captured in the sediment fences.

For each road segment the effect of precipitation was evaluated by plotting sediment production against total precipitation and the sum of 15-minute rainfall erosivity values over the period of a given measurement. After normalizing by precipitation, the effect of road gradient was evaluated by plotting sediment production against slope for roads with similar amounts of traffic and times since grading. The effect of traffic was determined by comparing mean sediment production rates – normalized by total precipitation and road segment slope – for two different traffic levels. Heavy-traffic road segments were used by about four to six delivery trucks and 110–280 light vehicles per day (Table II), while those with light traffic were used by 2–160 vehicles per day and only rarely traversed by trucks. Similarly, the effect of grading was determined by plotting sediment production – normalized by precipitation and gradient – against time since grading. The results of this initial data analysis led to the formulation of several multiple regression models with the following general form:

$$\begin{aligned} Er = {} & A \times (\text{precipitation or erosivity}) + B \times (\text{slope}^{i} \text{ or area} \times \text{slope}) + C \times (\text{grading}) \\ & + D_{j} \times (\text{two and three-way interaction terms}) + \text{Intercept} \end{aligned} \tag{6}$$

where Er is sediment production (kg m^{-2}), capital letters are empirical parameters, precipitation denotes total rainfall (cm), erosivity refers to the sum of 15-minute erosivity values (MJ mm ha^{-1} h^{-1}), slope is the areally weighted road segment slope (m m^{-1}), i is an exponent with tested values ranging from 1·0 to 2·0 in 0·1 increments, area × slope is the areally weighted road segment area times slope (m^{2}), grading is a binary variable equal to one for graded roads and zero for ungraded roads, and j distinguishes the different coefficients when there is more than one interaction term. Each variable included in the model had to be significant at $p \leq 0{\cdot}05$.

Results

Precipitation

The presentation of precipitation data will focus on the Maho Bay rain gauge, as this site had the longest continuous record (Table I). Precipitation data from the other three gauges generally follow the same trends as the Maho Bay station. The total rainfall at Maho Bay from 13 July 1998 to 13 April 2000 was 206 cm. An additional 5–10 cm of rainfall fell during the eight-day gap in September 1998 when Hurricane Georges passed through. This total is only 6 per cent more than the corresponding long-term mean for Caneel Bay, which lies within the same precipitation zone as Maho Bay (Bowden *et al.*, 1970).

Monthly precipitation generally followed the normal seasonal trends (Figure 4), but rainfall was lower than normal during most of the drier months (February to July), and higher than normal during most of the wetter months

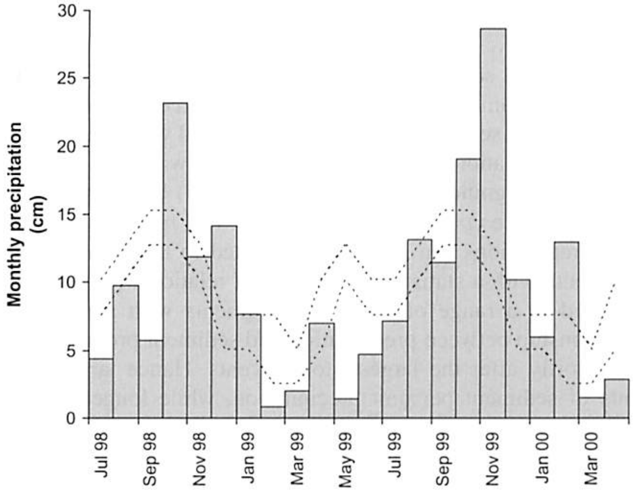

Figure 4. Monthly precipitation over the study period at Maho Bay. Dashed lines show the expected range of monthly precipitation values defined by Bowden *et al.* (1970).

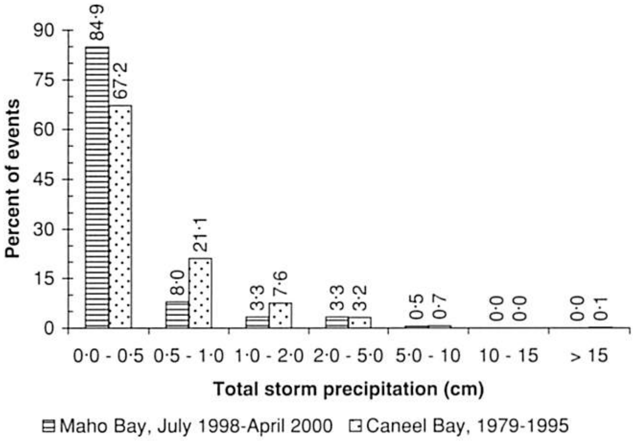

Figure 5. Frequency distribution of storm precipitation from Maho Bay for the period of study ($n = 614$) versus the long-term average for Caneel Bay ($n = 2921$).

(approximately October to January). The below-normal rainfall in September 1998 is misleading because it does not include the rainfall from Hurricane Georges. The exceptionally high amount of precipitation in November 1999 was due largely to Hurricane Lenny, which dropped 14 cm of rainfall over ten distinct storm events in a three-day period.

The frequency distribution of storm precipitation shows that the study period had a larger proportion of small storms (<0·5 cm) relative to the long-term record at Caneel Bay (Figure 5). Part of this discrepancy may be due to the higher resolution of the rain gauge used at Maho Bay (0·025 cm) compared to the Caneel Bay rain gauge (0·25 cm). The relative frequency of storms larger than 2·0 cm was very similar for both stations.

The maximum one-hour precipitation recorded at Maho Bay was 3·6 cm, and the largest erosivity for a single storm event was 2670 MJ mm ha^{-1} h^{-1}. Storm precipitation was non-linearly related to the erosivity of individual storm events ($R^2 = 0{\cdot}95$; $p < 0{\cdot}0001$) (Ramos-Scharrón, 2004). Similar regressions were developed for the Fish Bay, Bordeaux Mountain, and Caneel Bay precipitation data, and they were used to estimate the total erosivity for storms when 15-minute data were not available.

Road Segment Sediment Production

Sediment production rates for most road segments showed a linear relationship to total precipitation, but the significance of this relationship varied widely among the 16 segments with three or more observations (Table III). Sediment production from the two abandoned road segments was poorly correlated with total precipitation. For the remaining 14 segments the median R^2 between precipitation and sediment production was 0·71, but the range was from 0·13 to 0·99. Only five segments had a statistically significant relationship ($p \leq 0{\cdot}05$) between sediment production and precipitation, three showed borderline significance ($p = 0{\cdot}05$–$0{\cdot}10$), and six had p-values greater than 0·10.

The low significance of these regressions can be partly attributed to the small variation in total precipitation per measurement period. Road segments with a statistically significant relationship had an average precipitation range of approximately 37 cm as compared to a range of 15 cm for segments with a non-significant relationship. Another important cause of the poor relationship between precipitation and sediment production is the fact that the fences were more likely to be cleaned out shortly after the largest storm events. Hence large storm events in rapid succession tended to yield larger amounts of sediment per unit precipitation, while longer time periods with no large storms tended to have more cumulative precipitation but smaller amounts of trapped sediment. A more physically based analysis of the relationship between storm precipitation and sediment production is not possible given the resolution of the sediment fence data and the absence of runoff data, but storm-based measurements of runoff and suspended sediment from one road segment show non-linear increases in runoff and suspended sediment yields with increasing storm rainfall (Ramos-Scharron and MacDonald, in press).

The overall sediment production rate for the 21 road segments was approximately 7·4 kg m^{-2} a^{-1}, or 0·064 kg m^{-2} per centimetre of precipitation. The median slope of the relationship between sediment production and precipitation was 0·09 kg m^{-2} cm^{-1}, and the range varied from 0·018 to 0·39 kg m^{-2} cm^{-1} (Table III). The highest sediment production rates per unit precipitation were associated with steep roads that had been graded at least once within the last two years. After stratifying by grading, there was no significant difference in sediment production per unit precipitation between the segments that had a significant relationship between precipitation and sediment production and those that did not.

Because sediment production was significantly related to storm precipitation for at least some segments, the data were normalized by precipitation to better assess the relative effects of slope, road surface area, traffic, and grading. Figure 6 shows sediment production normalized by precipitation versus average slope for recently graded, lightly used road segments. For these road segments the sediment production rate per centimetre of precipitation tended to exponentially increase with increasing road slope ($R^2 = 0{\cdot}44$; $p < 0{\cdot}001$). A comparable but slightly stronger trend was observed for road surface area times slope ($R^2 = 0{\cdot}62$; $p < 0{\cdot}001$).

Table III. Values of R^2, p and slope coefficients for the relationship between precipitation and sediment production (kg m^{-2}) for each segment with at least three observations. Significant relationships are in bold

Road segment	Number of observations	R^2	p-value	Slope coefficient (kg m^{-2} cm^{-1})
BM-A	6	**0·67**	**0·045**	**0·048**
BM-B	4	**0·97**	**0·016**	**0·061**
BM-C	7	**0·61**	**0·037**	**0·094**
FB-E	3	0·13	0·77	0·28
JH-A	4	0·82	0·12	0·076
JH-A1	3	0·73	0·34	0·11
JH-A2	3	0·99	0·066	0·27
JH-B	9	0·55	0·056	0·064
JH-C	6	0·58	0·076	0·023
JH-D	4	**0·97**	**0·012**	**0·12**
JH-E	4	0·68	0·17	0·048
LB-A	3	0·93	0·17	0·39
LE-Bottom	3	0·007	>0·25	−0·0028
LE-Top	4	0·11	>0·25	−0·0047
MB-A	7	**0·79**	**0·011**	**0·21**
MB-C	4	0·63	0·20	0·018

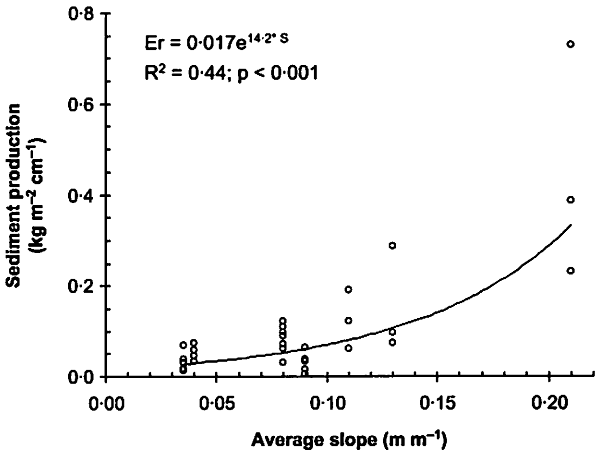

Figure 6. Relationship between sediment production (*Er*) normalized by precipitation and slope (*S*) for seven recently graded, lightly used road segments.

Table IV. Sediment production rates by road segment normalized by precipitation and slope. The means and standard deviations are listed for the different traffic and grading categories

Road segment	Traffic category	Grading category	Normalized sediment production ($kg\ m^{-2}\ cm^{-1}\ m\ m^{-1}$)
BM-A	Light	Graded	0·39
BM-B	Light	Graded	1·50
BM-C	Light	Graded	1·06
FB-Coco	Light	Ungraded	0·60
FB-A	Heavy	Graded	0·25
FB-C	Heavy	Graded	0·52
FB-D	Heavy	Graded	0·78
FB-E	Light	Graded	2·11
JH-A	Light	Graded	0·85
JH-A1	Light	Graded	1·08
JH-A2	Light	Ungraded	0·74
JH-B	Light	Ungraded	0·60
JH-C	Light	Graded	0·82
JH-D	Light	Ungraded	0·39
JH-E	Light	Ungraded	0·45
LB-A	Light	Ungraded	0·59
LB-C	Light	Graded	0·53
LE-Bottom	Abandoned	Abandoned	0·10
LE-Top	Abandoned	Abandoned	0·04
MB-A	Heavy	Graded	2·18
MB-C	Heavy	Graded	0·42
		Mean heavy traffic (*n* = 14)	1·28 (s.d. = 1·24)
		Mean light traffic (*n* = 59)	0·81 (s.d. = 0·62)
		Mean graded (*n* = 48)	1·12 (s.d. = 0·87)
		Mean ungraded (*n* = 25)	0·56 (s.d. = 0·30)

A similar analysis indicated that traffic class was not a significant control on sediment production rates. After normalizing by precipitation and slope, the 59 measurements from the 14 road segments in the light-use category averaged 0·81 $kg\ m^{-2}\ cm^{-1}\ m\ m^{-1}$ (s.d. = 0·62) (Table IV). The five segments in the heavy-use class consisted of three segments in the Fish Bay basin (FB-A, C, and D segments) and two segments leading to the Maho Bay Eco-Resort (MB-A and C). The average sediment production rate for the 14 measurements from these segments was

Figure 7. Example of a grading operation along road segment FB-Coco on 11 December 1998.

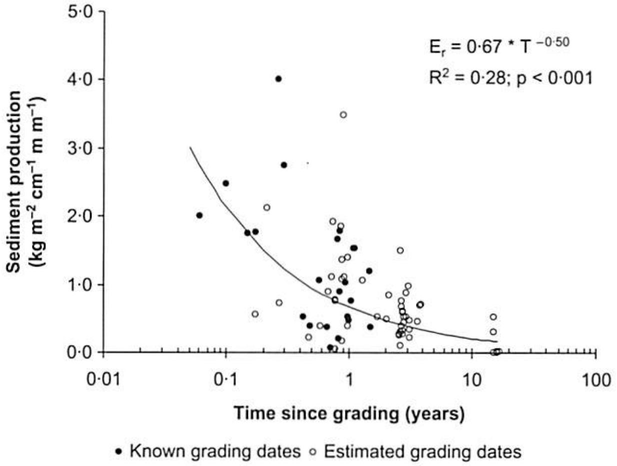

Figure 8. Relationship between sediment production rates (*Er*) – normalized by precipitation and slope – versus time since grading (*T*). Solid circles represent known dates of grading and open circles represent data points for which the date of grading was estimated.

1·28 kg m^{-2} cm^{-1} m m^{-1} (s.d. = 1·24), or 58 per cent higher than the segments in the light-use category. This difference was not statistically significant ($p = 0{\cdot}19$) due to the high variability within each category (Table IV).

Grading was an important control on sediment production rates. In nearly all cases the material used to resurface a road is simply scraped from the cutslopes or taken from an inside ditch. Bulldozers spread this material over the road segment but it is not systematically compacted (Figure 7). Figure 8 shows that sediment production rates – again normalized by precipitation and slope – decline non-linearly with time since grading ($p < 0{\cdot}001$). Sediment production rates were generally higher in the first year after grading, and the magnitude and variability of sediment production rates tended to decline between one and two years after grading. This suggests that the actively used unpaved roads on St John can be grouped into two grading categories: (1) roads graded at least once every two years; and (2) roads that have not been graded for over two years ('ungraded'). The mean normalized sediment production rates for graded and ungraded roads were 0·96 kg m^{-2} cm^{-1} m m^{-1} (s.d. = 0·63) and 0·56 kg m^{-2} cm^{-1} m m^{-1} (s.d. = 0·12), respectively (Table IV), and these values are significantly different ($p < 0{\cdot}0001$). Annual sediment production rates for typical graded and ungraded roads with a 10 per cent slope and an annual rainfall of 115 cm a^{-1} are 11 kg m^{-2} a^{-1} and 6·4 kg m^{-2} a^{-1}, respectively.

Figure 9 shows how the mean sediment production per unit precipitation for individual road segments varies with road segment slope for graded and ungraded roads. This indicates that sediment production rates for graded roads

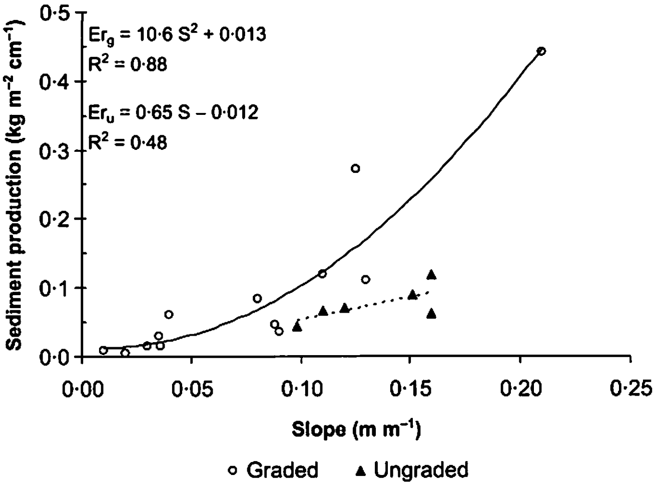

Figure 9. Relationship between mean sediment production – normalized by precipitation – and average segment slope (S) for graded (Er_g) and ungraded (Er_u) road segments. Solid black line is for graded road segments and dashed line is for ungraded road segments.

(Er_g) increase exponentially with increasing road segment slope. In contrast, the sediment production rates for ungraded roads (Er_u) are much lower and exhibit a linear increase in sediment production rates with increasing slope (Figure 9).

Sediment production rates from the two abandoned road segments were much lower than the other 19 segments. The mean sediment production rate from these two segments over most of the study period was 0·005 kg m^{-2} cm^{-1} m m^{-1} ($n = 5$), or about 1 per cent of the mean value for ungraded roads. However, the mean normalized sediment production rate in November 1999 was 0·27 kg m^{-2} cm^{-1} m m^{-1} ($n = 2$), or 55 times higher than the rest of the study period and nearly 50 per cent of the mean value for actively used, ungraded roads. November 1999 included the 14 cm of rain associated with Hurricane Lenny which included a 1-hour, 4·7-cm burst of rain after 5 cm of rain had already fallen. This combination of depth and intensity created enough overland flow to initiate extensive surface erosion on the two abandoned road segments.

General linear models for graded and ungraded road segments

During the process of developing the multiple regression models we identified several important trends. First, models using slope had higher R^2 values than models using area × slope. Second, interaction terms that included slope were always statistically significant. Third, the models using total erosivity had slightly lower R^2 values than models using total precipitation.

The best models included a two-way interaction term between precipitation and slope, and a three-way interaction term between precipitation, slope, and grading that applied to the recently graded roads. Sequential testing of different exponent values for the slope parameter yielded model R^2 values ranging from 0·61 to 0·76 (Ramos-Scharrón, 2004). The similarity of R^2 values meant that a graphical analysis of model residuals was used to help select the best model. The model based on slope to the power of 1·5 was chosen because the residuals were normally distributed and this model minimized the error in sediment production, especially for the steeper road segments (Table V). Since the grading parameter is best treated as a binary variable (i.e. a value of 1 for graded roads and 0 for ungraded roads), the final sediment production model can be presented as separate equations for graded roads (Equation 7a) and ungraded roads (Equation 7b):

$$Er_g = -0{\cdot}432 + 4{\cdot}73(S^{1{\cdot}5}P) \tag{7a}$$

$$Er_u = -0{\cdot}432 + 1{\cdot}88(S^{1{\cdot}5}P) \tag{7b}$$

where Er_g and Er_u are the respective sediment production rates for graded and ungraded roads (in kg m^{-2}), S is segment slope (in m m^{-1}), and P is total precipitation (in cm) (Table V). This formulation of the model in Table V explicitly indicates that graded roads with a given slope produce 2·5 times as much sediment per unit precipitation as a comparable ungraded road.

Table V. Regression model for predicting sediment production rates for unpaved road segments on St John ($R^2 = 0{\cdot}75$; $p < 0{\cdot}0001$). The three-way interaction term is equal to zero for ungraded roads.

Parameter	Regression coefficient	Standard error	*p*-value	Partial R^2
Intercept	−0·432	0·26	0·1047	–
Precipitation × $\text{Slope}^{1{\cdot}5}$ (cm m m^{-1})	1·88	0·29	<0·0001	0·15
Precipitation × $\text{Slope}^{1{\cdot}5}$ × Grading (cm m m^{-1})	2·85	0·34	<0·0001	0·60

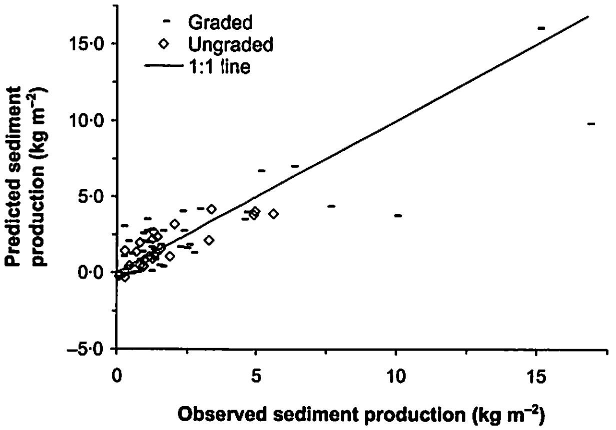

Figure 10. Predicted versus observed sediment production rates for graded and ungraded roads. Model statistics are in Table V.

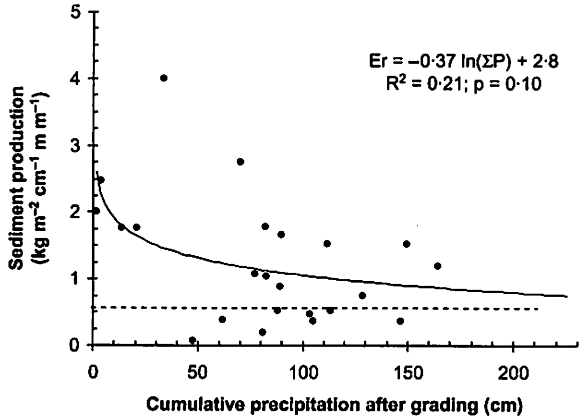

Figure 11. Relationship between sediment production (*Er*) – normalized by precipitation and average gradient – and cumulative precipitation after grading (ΣP). Data are for eight road segments where the date of grading was known ($n = 24$). Dashed line represents the mean erosion rate for ungraded roads.

A plot of the measured data against predicted values shows that the predicted values generally follow the 1:1 line (Figure 10). The mean absolute error for graded road segments was 1·15 kg m^{-2}, or 49 per cent of the mean value for graded roads. The mean absolute error for the ungraded road segments was 0·69 kg m^{-2}, or 41 per cent of the mean value for ungraded roads.

Figure 11 shows that sediment production – when normalized by precipitation and slope – declines with cumulative precipitation after grading. An extrapolation of the non-linear regression suggests that slightly more than two years of precipitation (>230 cm) are needed before the sediment production rate from graded roads approximates the mean value for ungraded roads (0·56 kg m^{-2} cm^{-2} m m^{-1}). The observed decline in the magnitude and variability in erosion rates after 90–100 cm of precipitation is consistent with the decline over time shown in Figure 8.

Table VI. Mass-weighted mean particle sizes by grading and slope classes. Values with different superscript letters are significantly different at $p < 0{\cdot}05$

Grading and slope class	Number of road segments per class	Gravel (%)	Sand (%)	Silt and clay (%)	Mean D_{16} (mm)	Mean D_{50} (mm)	Mean D_{84} (mm)
All samples	20	40	54	6	0·12	0·72	4·1
Grading class							
Graded	12	36^{a}	58^{b}	6^{c}	0·08^{A}	0·36^{B}	2·5^{C}
Ungraded	6	41^{a}	53^{b}	6^{c}	0·11^{A}	0·64^{B}	4·8^{C}
Abandoned	2	73	27	0·1	0·35	3·1	11
Slope class							
Low (<10%)	9	32^{d}	60^{f}	8^{h}	0·08^{D}	0·33^{E}	2·5^{F}
Moderate (10–15%)	7	43de	51^{fg}	5^{h}	0·11^{D}	0·79^{E}	4·3^{FG}
High (>15%)	4	51^{e}	46^{g}	3^{h}	0·20^{D}	1·5^{E}	7·2^{G}

Particle-size distribution

The mass-weighted average particle-size distribution showed that the material eroded from the unpaved road surfaces was 40 per cent gravel, 54 per cent sand, and 6 per cent silt and clay (Table VI). The median particle-size (D_{50}) for the eroded sediment from all road segments was 0·72 mm or coarse sand, and the 16th (D_{16}) and 84th (D_{84}) percentiles were 0·12 and 4·1 mm, respectively. On average, the sediment from graded roads had slightly less gravel and more sand than the sediment from ungraded roads, but these differences were not statistically significant (Table VI). The sediment collected from the two abandoned road segments was much coarser, as this consisted of 73 per cent gravel, 27 per cent sand, and less than 1 per cent silt and clay. The particle-size distribution of the sediment from abandoned roads was not tested for significant differences as this class was represented by only two samples.

When sorted by slope class, the sediment eroded from the steepest road segments (>15 per cent) was significantly coarser than the sediment from low-gradient roads (<10 per cent) (Table VI). There were no significant differences in the particle sizes of the eroded sediments between the moderately sloped roads and the other two slope classes.

Discussion

Effects of precipitation, slope and grading on road sediment production

The general linear regression model indicates that total precipitation, slope, and grading all affect road sediment production rates on St John. The use of total precipitation as a predictive variable is a simplification of the erosion processes described by Equations 1–4, as this implicitly indicates that all rainfall events have the same erosive potential per unit depth of rainfall. In reality, Equations 1–4 suggest that sediment production should be controlled more by the intensity of rainfall than storm magnitude, as rainfall intensity controls the depth of infiltration-excess overland flow and thus the magnitude of the shear stress applied to the road surface. One reason for this apparent simplification is that the sediment trap data aggregate sediment production from numerous rainfall events over time periods extending from several weeks to many months. The effects of varying rainfall intensities are largely lost, and total precipitation emerges as the best predictor of road segment sediment production because this is a reasonable index of the total amount of overland flow. If sediment production were measured over shorter time periods, rainfall intensity and rainfall erosivity should emerge as better predictors of sediment production rates.

Road segment slope was an important control on road sediment production. Model comparisons indicated that sediment production per unit rainfall is best predicted by slope raised to the power of 1·5. The presence of slope as a two- and three-way interaction term in the general linear regression model (Table V) indicates that the effect of segment slope on road erosion rates varies with grading category. Road segment slope has a greater effect on sediment production rates for graded roads than ungraded roads, as graded roads will have a much greater supply of available sediment and are more likely to be transport-limited. Theory, field observations, and the particle-size data all suggest that the ungraded roads become armoured over time. As the road surface becomes armoured the supply of readily erodible material becomes more limiting, and this reduces the relative importance of segment slope compared to the more recently graded road segments.

Multivariate regression showed that road segment slope was a better predictor of sediment production rates than road surface area × slope. The three-way interaction term of precipitation, area × slope, and grading was only marginally significant ($p = 0{\cdot}06$) and produced a model with an overall R^2 of 0·68 as compared to 0·75 for the model in Table V. The lower R^2 of the models using area times slope may be due in part to the difficulty in accurately measuring the contributing area. Errors of up to ±30 per cent are possible when the contributing areas of road segments are measured during dry periods (Montgomery, 1994). Another complication is that the area × slope factor depends on the route followed by runoff over the road surface. Field observations showed that surface microtopography and runoff paths changed over time due to rilling, traffic, grading, and clogging of ditches, and this would alter the area × slope product. In this study area × slope was only measured once and the values were not adjusted for changes in the drainage pattern over the different measurement periods.

Time since grading also had an important effect on sediment production. Roads that were graded at least once every two years had significantly higher sediment production rates than ungraded roads (Table IV). When normalized by rainfall and slope, sediment production rates exponentially declined with both time since grading (Figure 8) and cumulative precipitation after grading (Figure 11). The large variability in sediment production rates and the limited temporal resolution of the sediment data preclude a calibration of the parameters in Equation 5 or the development of a new exponential decay model. The data in Figure 11 suggest that sediment production rates are less than 2 kg m^{-2} cm^{-1} m m^{-1} after about 80 cm of total rainfall, but the regression equation from Figure 11 indicates that approximately 230 cm of rainfall are required before a graded road erodes at nearly the same rate as an ungraded road. Hence the road erosion model was simplified to a step function, in that Equation 7a applies to the first 230 cm of cumulative precipitation after regrading and Equation 7b to all subsequent rainfall.

The predicted declines in sediment production through time are similar to or slightly less than those in previous studies. Using Equation 7a, the predicted annual sediment production rates for graded roads are 1·1 and 52 kg m^{-2} a^{-1} assuming an annual rainfall rate of 115 cm and road slopes of 2 per cent and 21 per cent, respectively. Using Equation 7b, the corresponding values are 0·18 and 20 kg m^{-2} a^{-1}. These values suggest that sediment production rates should decline by 61–84 per cent within two years after grading.

This rate of decline is comparable to, or slightly slower than, the rate of decline reported in other studies. In Idaho, sediment production rates declined by 40–80 per cent one year after road construction (Vincent, 1979). A field-based calibration of Equation 5 in Idaho indicated that sediment production rates should decline by 95 per cent within one year after road construction (Megahan, 1974). In the Oregon Coast range, sediment production rates decreased by 70 per cent within one year after disturbing both the travelway and the inside ditch, and by 90 per cent after two years (Luce and Black, 2001b). The slower decline in sediment production rates on St John may be due to the exceptionally high runoff and erosion rates resulting from large storm events. Sediment production from these more extreme events appeared to be less sensitive to factors such as the time since grading or the amount of traffic.

Abandoned roads, subsurface stormflow and undisturbed hillslopes

The mean rate of sediment production for abandoned roads with a mean slope of 15 per cent was 0·010 kg m^{-2} per cm of precipitation, or approximately an order of magnitude lower than comparable ungraded roads. This indicates that sediment production rates after grading continue to decline for the ungraded road segments beyond the three-year period documented in this study (Figure 8). The low erosion rates for the abandoned road segments may be attributed to a well-armoured road surface and lower runoff rates for all but the most extreme storm events. A storm in February 2000, for example, produced 9·5 cm of rainfall in 2·5 hours following a 24-hour period with no precipitation. Field observations indicated that infiltration-excess overland flow was generated on the road surface, but there was no interception of subsurface storm flow and the sediment traps had no measurable sediment.

Efforts to model sediment production rates from abandoned roads are hindered by the more than 5000 per cent increase in sediment production per unit rainfall observed during Hurricane Lenny as compared to the rest of the study period. The pattern of rainfall generated by Hurricane Lenny was unusual, as the maximum 1-hour intensity of 4·7 cm h^{-1} occurred after 4·9 cm of rain had fallen in the previous 24 hours. The amount and timing of this rainfall probably generated surface runoff from both infiltration-excess overland flow and the interception of subsurface stormflow. Although detailed hydrometric data are not available, the greater antecedent precipitation and subsurface flow interception are probably why sediment production rates from these two abandoned road segments were so much higher during Hurricane Lenny than the more isolated storm in February 1999 that had a similar 1-hour peak rainfall intensity.

A similar comparison shows that the mean sediment production rate from ungraded roads increased by nearly 50 per cent for the period that includes Hurricane Lenny, while the mean sediment production rate for graded roads for this same period was slightly less than for the other monitoring periods. These differences in sediment production per unit precipitation support the inference that an increase in subsurface stormflow interception is critical to increasing sediment production rates on well-armoured roads, but has little effect on recently graded roads.

The estimated annual sediment production rate for abandoned roads is derived from the total sediment generated from the two abandoned road segments over the two-year study period. As noted earlier, rainfall over the study period was very similar to the long-term pattern of precipitation recorded at Caneel Bay (Figure 5). If the monitoring period is representative of the more extreme events like Hurricane Lenny, the sediment production rates for abandoned roads can be normalized in the same manner as graded and ungraded roads. On this basis the sediment production rate from abandoned roads is 0·071 kg m^{-2} per unit precipitation per unit slope, or about 13 per cent of the value for ungraded roads and only 7 per cent of the value for graded roads. This converts to an annual sediment production rate of 0·16 and 1·7 kg m^{-2} a^{-1} for abandoned roads with slopes of 2 per cent and 21 per cent, respectively.

Measured surface erosion rates from undisturbed zero-order basins are on the order of 0·001 kg m^{-2} a^{-1} (Ramos-Scharrón, 2004; Ramos-Scharrón and MacDonald, unpublished work). This indicates that actively used roads can increase sediment production rates by more than four orders of magnitude relative to undisturbed conditions. The sediment production rate from the two abandoned road segments monitored in this study were almost three orders of magnitude higher than the rates measured from undisturbed hillslopes.

Comparisons with previous studies

A previous study developed an empirical road erosion model for St John (ROADMOD) (Anderson, 1994). This model was based on a linear relationship between annual sediment production rate and the product of road surface drainage area (A) and road slope (S):

$$E = 0{\cdot}00057AS + 0{\cdot}034 \qquad (8)$$

where E is the average annual road surface cross-sectional erosion (m^2 a^{-1}; A is in m^2, and S is in m m^{-1}). Annual sediment production rates at the road segment scale are predicted using the road drainage area at the midpoint of the segment, the average road segment slope, and an assumed bulk density of 1·5 Mg m^{-3} (Anderson and MacDonald, 1998).

The application of ROADMOD to the 21 monitored road segments yields a mean annual sediment production rate of 20 kg m^{-2} a^{-1}, or about twice the measured mean value of 9·4 kg m^{-2} a^{-1}. The predicted erosion rates using ROADMOD were poorly correlated with the values measured in this study ($R^2 = 0{\cdot}04$; $p > 0{\cdot}25$), and only segments FB-E and MB-A had measured values that were higher than the values predicted by ROADMOD. The sediment production rates measured in this study are also poorly correlated with the segment-scale area × slope product as defined by Anderson (1994) ($R^2 = 0{\cdot}006$; $p > 0{\cdot}25$).

The poor correlation between the values predicted with ROADMOD and the measured data may be due to a bias in the selection of the road segments used to develop Equation 8 and the way in which area × slope was measured. The cross-sections used to develop Equation 8 were usually on severely rilled road segments lacking any cross-slope drainage (type 3 in Figure 3). There is a stronger correlation between the predicted sediment production rates using ROADMOD and the values measured in this study when the area × slope product is adjusted for the different road drainage patterns as measured in the current study (Figure 3). If the area × slope values from Table II are used in Equation 8 instead of the total segment area × slope, the mean sediment production rate predicted by ROADMOD drops to 15 kg m^{-2} a^{-1} (Figure 12). Although this mean value is still 1·7 times higher than the measured mean value, the correlation between predicted and measured values is significant ($R^2 = 0{\cdot}19$; $p < 0{\cdot}001$). These comparisons indicate that road surface area must be adjusted for the different drainage patterns, and that Equations 7a and 7b provide a more accurate prediction of road sediment production rates on St John than ROADMOD.

Figure 13 compares the estimated annual sediment production rates for graded, ungraded, and abandoned roads on St John to other published values, including an earlier study of sediment production from three 40 m^2 road surface plots on St John (MacDonald *et al.*, 2001). The three plots included two plots on an actively used road and one plot on a newly constructed but unused road, and the estimated sediment production rates of 0·9 to 15 kg m^{-2} a^{-1} (MacDonald *et al.*, 2001) are similar to the values measured in the current study.

On the other hand, the sediment production rates for actively used and recently graded roads on St John are higher than the values reported for New Zealand (Fahey and Coker, 1989), Australia (Grayson *et al.*, 1993), and the Southern Appalachian Mountains (Swift, 1984) and central Idaho (Vincent, 1979) in the USA (Figure 13). The higher erosion rates for unpaved roads on St John are consistent with their relatively steep slopes and the high rainfall erosivity.

The only published study with higher road erosion rates was for a high-rainfall area in the northwestern USA (Reid and Dunne, 1984). The maximum rate of 100 kg m^{-2} a^{-1} was calculated for a road with a 10 per cent slope and an

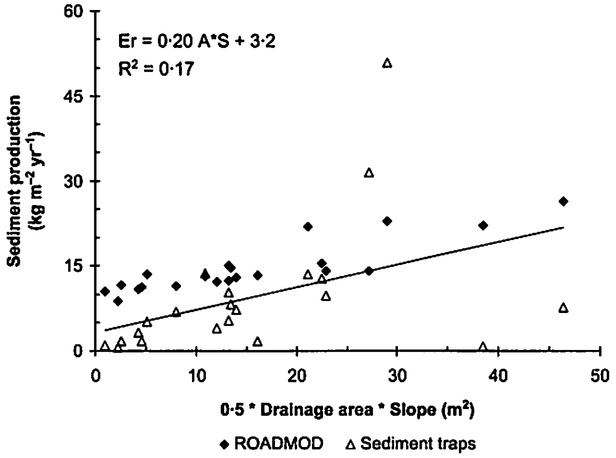

Figure 12. Relationship between the annual sediment production rates (*Er*) measured in this study using sediment traps and the predicted sediment production values using ROADMOD and one-half of the area × slope values from Table II. Regression line is for the sediment trap data.

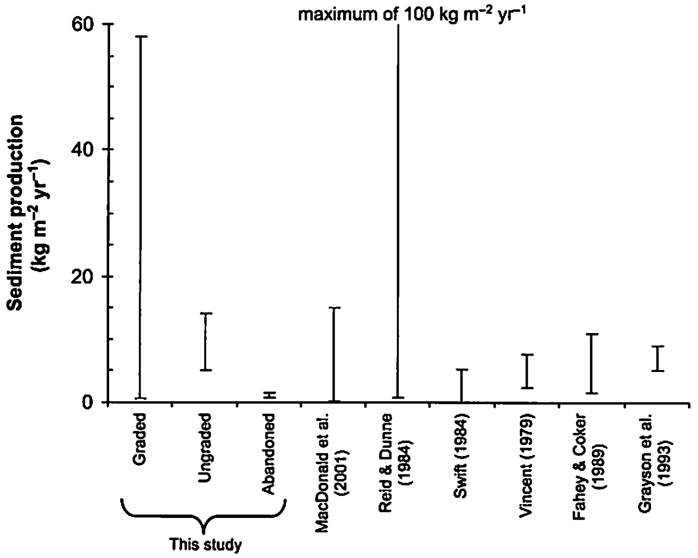

Figure 13. Range of annual sediment production rates for graded, ungraded, and abandoned roads in St John as compared to values reported from other studies.

assumed mean traffic load of at least four fully loaded logging trucks per day. The estimated sediment production rate for a typical road with only occasional heavy truck traffic was 8·5 kg m^{-2} a^{-1} (Reid and Dunne, 1984). The latter value is about half of the calculated sediment production rate for a similar road segment on St John with a daily traffic load of four to six delivery trucks and 100–250 light vehicles. The mean sediment production rate for the abandoned road segments in St John was 1·2 kg m^{-2} a^{-1}, or 12 times the rate estimated for comparable roads in the northwestern USA (Reid, 1981). These comparisons confirm the exceptionally high road erosion rates on St John relative to most other areas.

Recommendations for reducing road surface erosion

The improved understanding of road surface erosion developed here can be translated into specific recommendations for reducing road surface sediment production. First, given the importance of slope and grading (Figure 9), steep, frequently graded road segments should be the first targets for implementing erosion control practices. If possible, roads and driveways with steep slopes should be paved immediately after construction as the highest sediment production rates will occur immediately after construction and grading. Second, given that grading plays such an important role in road erosion, the frequency and area of road grading should be kept to a minimum. Third, proper road drainage is essential for minimizing sediment production rates, as this reduces the area × slope factor and the amount of overland flow. Improved designs can be achieved through insloping, outsloping, constructing and maintaining well-protected ditches along roads, and increasing the density of road drains.

Conclusions

Sediment production rates from 21 road segments with varying slopes, contributing areas, and traffic loads were monitored with sediment traps from July 1998 to November 2001 on the island of St John in the US Virgin Islands. Precipitation was measured by four recording rain gauges. Total precipitation over the study period was 206 cm. Total rainfall and the frequency distribution of storm magnitudes were very similar to long-term averages.

Sediment production rates were linearly related to total precipitation for most of the 21 road segments monitored in this study. The average road erosion rate for all segments was 0·064 kg m^{-2} per centimetre of precipitation. Steeper roads tended to have higher sediment production rates than more gently sloping roads. Regrading significantly increased sediment production rates. Roads graded at least once during the two-year study period had a mean sediment production rate of 0·96 kg m^{-2} per centimetre of rainfall and unit slope, or approximately 11 kg m^{-2} a^{-1} for a typical road with a 10 per cent slope and an annual rainfall of 115 cm a^{-1}. The mean annual erosion rate for ungraded roads was 41 per cent lower, or 6·4 kg m^{-2} a^{-1} for a road segment with a 10 per cent slope. Roads with 15 per cent slopes that had been abandoned for about 15 years had an average erosion rate of 1·2 kg m^{-2} a^{-1}. Sediment production rates did not vary significantly with traffic loads.

Models using total precipitation and slope yielded higher R^2 values than models using rainfall erosivity or area × slope. The best predictive model used total precipitation, slope raised to the 1·5 power, and a dummy variable for grading to predict road segment sediment production, and the model R^2 was 0·75.

The measured erosion rates indicate that unpaved roads on St John can increase hillslope-scale sediment production rates by more than four orders of magnitude relative to undisturbed conditions. The road erosion rates measured on St John are at the high end of reported road erosion rates, and this is consistent with the high rainfall erosivities, steep slopes, poor design, and inadequate maintenance of many of the unpaved roads on St John. The improved understanding of road surface erosion developed in this study leads to several specific recommendations for reducing road surface sediment production.

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