CHAPTER 2.

MEASUREMENT AND PREDICTION OF SEDIMENT PRODUCTION FROM UNPAVED ROADS, ST. JOHN, U.S. VIRGIN ISLANDS

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 the primary sediment source on St. John in the U.S. 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, site factors, 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 contributing areas, slopes, and traffic loads. Precipitation was measured by four recording rain gauges.

Sediment production was related to total precipitation and to 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} yr^{-1} for a typical road with a 10% slope and an annual rainfall of 115 cm yr^{-1}. The mean erosion rate for ungraded roads was 41% 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% of the mean value for ungraded roads. Traffic loads were not related to sediment production. 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 on the island. Other than paving, the most practical methods to reduce current erosion rates is to minimize the frequency of grading and to improve road drainage design.

2.1 Introduction

2.1.1 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., Luce and Wemple, 2001; Megahan, 1987). The disruption of geomorphologic and hydrologic processes by roads increases both surface erosion and the frequency of mass wasting (e.g., Larsen and Parks, 1997; Sidle et al., 1985; Gresswell et al., 1979). These increases are of particular concern in forested areas because the natural erosion rates are 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 (Fransen et al., 2001; Fahey and Coker, 1989), 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 economy. 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 U.S. Virgin Islands.

Within the U.S. Virgin Islands, the coral reefs near St. John have received special attention because 56 percent of the island's 50 km^2 of land area and 23 km^2 of its offshore waters comprise 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 the road surface was used to develop an empirical road erosion model based on road segment area times slope (Anderson and MacDonald, 1998). The application of this model suggested that road erosion is increasing watershed-scale sediment yields by up to four times above background levels (MacDonald et al., 1997), but their work did not directly measure road erosion or several key factors shown to affect road erosion in other areas.

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

2.1.2 Modeling Road Sediment Production

An exposed soil surface is subject to two primary surface erosion processes—raindrop impact 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 (Carter et al., 1974; Wischmeier and Smith, 1958). Flow hydraulics determine the shear stress of surface runoff, 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) (equation 1):

$$E_t \ \alpha \ k_1 \left(\tau - \tau_c\right)^n \qquad \text{(eq. 1)}$$

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:

$$\tau = \rho_w \ g \ h \ s \qquad \text{(eq. 2)}$$

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 (Ziegler and Giambelluca, 1997; Harden, 1992; Bren and Leitch, 1985). 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 overland flow on unpaved road surfaces (MacDonald et al., 2001; Ramos-Scharrón and MacDonald, 2001; Chapter 3). 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 outflow rate [$Q_o(t)$] plus temporary water storage [S(t)] as shown in equation 3:

$$Q_i(t) = Q_o(t) + S(t) \qquad \text{(eq. 3)}$$

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)] times the surface area of the road segment (A) (equation 4):

$$Q_i(t) = \left[P(t) - I(t)\right] \cdot A \qquad \text{(eq. 4)}$$

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

Parent material exerts a major control on the resistance to erosion of unpaved roads 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 time since construction or grading.

The amount and type of traffic affects road surface erodibility by increasing the availability of fine particles 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 (Ziegler et al., 2001b; Bilby et al., 1989; Reid, 1981). Gravel roads subjected to more than four heavy truck passes per day have been found to have 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 regarding 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 the absence of road ditches and vehicle rutting keeps much of the runoff on the road surface and allows it to readily access and transport the loose, fine sediment applied during grading.

The decline in road erosion rates after construction or grading has been modeled using equation 5:

$$E_t = E_n + k_2 S_0 e^{-k_2 t} \quad \text{(eq. 5)}$$

where E_t is the erosion rate in tons km^{-2} day^{-1}, E_n is the erosion rate approached after a long period without any disturbance (tons km^{-2} day^{-1}), S_0 is the total amount of material available for erosion immediately after construction or grading (tons 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 modeled the changes in surface erodibility over time as a function of traffic and the degree 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 these factors control the amount of runoff, the tractive forces applied by overland flow, and the resistance of the road surface to erosion.

2.2 Study Area

St. John is the third largest island of the U.S. 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% of the slopes are greater than 30% (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 yr^{-1} on the eastern end of the island to a high of 127-140 cm yr^{-1} near Bordeaux Mountain. Easterly waves, which can develop into tropical storms and hurricanes, generate most of the rainfall from May through November, while cold fronts are important sources of rainfall from December through 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} hr^{-1} (Sampson, 2000). The 15-minute precipitation intensity at Caneel Bay exceeded 100 mm hr^{-1} sixteen times from 1979 to 1995.

Dry evergreen forests and shrubs cover approximately 63% of the total land area, moist forest and secondary vegetation about 30%, while urban, wetland, and pasture each cover about 2% 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.

2.3 Methods

Precipitation was measured with four recording rain gauges (Figure 1). Table 1 lists the type, resolution, and period of record for each rain gauge. The precipitation recorded at each station was compared to monthly and annual means (Bowden et al., 1970) and to the mean values measured at Caneel Bay from 1979 to 1995 (EarthInfo, 1996). The precipitation data were used to determine total storm precipitation and 15-minute erosivities following Wischmeier and Smith (1958). 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 runoff from unpaved road surfaces continues for only 30-60 minutes after precipitation has ceased (Chapter 3). Fifteen-minute erosivities were calculated for individual storm events for the three gauges with sufficient temporal resolution.

Sediment production rates were periodically measured from 21 unpaved road segments (Figure 1; Table 2) from July 1998 to April 2000 (n=105). A few segments were less-intensively monitored from April 2000 through November 2001 (n=5). To the extent possible, the segments were selected to represent a wide range of surface areas and slopes. The mean width 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 that lacked any effective 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 and mean width of each segment and sub-segment was measured with measuring tapes and hip-chains; slopes were measured with a clinometer, and flow paths were drawn in sketch maps. The drainage pattern of each sub-segment was considered when calculating the product of road surface area times road slope, as segments with similar total lengths and slopes can have very different area-slope factors (Figure 3). Hence, the area-slope and slope of each segment was calculated as the areally-weighted values for each sub-segment. The mean area times slope for the 21 road segments was 31 m^2, while the range was from 2.0 to 93 m^2. The mean slope was 10% with values ranging from 1% to 21% (Table 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, and these were: abandoned roads, roads exclusively used by light vehicles, and roads receiving over four heavy truck passes per day in addition to light vehicle traffic. 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 the three traffic classes was not possible because only two segments were in the heavy use category and only one abandoned road had suitable sites for measuring sediment production rates. This meant that it was not possible to measure sediment production from abandoned roads with low area-slope values or roads with heavy truck usage and high area-slope values. 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 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 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 a dam than a filter.

The fences were regularly checked after storm events, and once a substantial amount of sediment had accumulated, the material was shoveled 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. Percent moisture content was measured in the lab (Gardner, 1986) and used to correct the field-measured wet weights to a dry mass.

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.

Thirty of the 110 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.

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 time since grading. The effect of traffic was determined by comparing mean sediment production rates—normalized by road segment slope and total precipitation—for two different traffic levels. Heavy-traffic road segments were used by about four to six heavy trucks and 110-280 light vehicles per day (Table 2), while those with light traffic were used by 2-160 vehicles per day and only rarely traversed by heavy trucks. Grading effects were identified 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:

$$E_r = A * (\text{precipitation or erosivity}) + B * (\text{slope}^i \text{ or area-slope}) + C * (\text{grading}) + D_i * (\text{two and three-way interaction terms}) + \text{Intercept} \quad \text{(eq. 6)}$$

where E_r is sediment production (kg m^{-2}), capital letters are empirical parameters, precipitation denotes total rainfall (cm), 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), and grading is a binary variable equal to one for graded roads and zero for ungraded roads.

2.4 Results

2.4.1 Precipitation

The presentation of precipitation data will focus on the Maho Bay rain gauge, as this site had the longest continuous record (Table 1). Precipitation data from the other three gauges generally follow the same trends as the Maho Bay station (Appendix I-A). 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 8-day gap in September 1998 when Hurricane Georges passed through. This total is only 6% 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 there was lower than normal rainfall during most of the drier months (February to July) and higher than normal rainfall during most of the wetter months (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 a two-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 sum of 15-minute erosivity values calculated at Maho Bay was 2,670 MJ mm ha^{-1} hr^{-1} for a single storm event. Storm precipitation was non-linearly related to the erosivity of individual storm events ($p < 0.0001$) (Figure 6). 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 (Table 1).

2.4.2 Road Segment Sediment Production

Sediment production rates for most road segments showed a linear relationship to total precipitation, but the significance of these relationships for the 16 segments with three or more observations varied widely (Table 3; Appendix I-B). 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 ($p \leq 0.05$) between sediment production and precipitation, three showed borderline significance ($p = 0.05$-0.10), and six had p-values greater than 0.10. In some cases the low significance of these regressions is due to the small variation in total precipitation. 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 the 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. In such cases the amount of sediment was large relative to the cumulative precipitation. Longer time periods with fewer large storms often had more cumulative precipitation but smaller amounts of trapped sediment. Unfortunately, the nature and resolution of the sediment fence measurements do not allow an explicit analysis of the relationship between storm precipitation and sediment production.

The overall sediment production rate for the 21 road segments was 0.064 kg m^{-2} per centimeter of precipitation. The median slope of the relationship between sediment production and precipitation was 0.09 kg m^{-2} cm^{-1}, and the range was from 0.018 to 0.39 kg m^{-2} cm^{-1} (Table 3). This indicates that different road segments can yield widely varying amounts of sediment for a given amount of precipitation. The highest slope coefficients were associated with steep roads that had been graded at least once within the last two years.

Since sediment production from at least some segments was significantly related to storm precipitation, the data were normalized by precipitation to assess the relative effect of slope, road surface area, traffic, and grading. Figure 7 shows sediment production normalized by precipitation versus average slope for recently-graded, lightly-used road segments. This indicates that for these road segments sediment production rates per centimeter of precipitation tend to exponentially increase with increasing road slope ($R^2 = 0.55$; $p < 0.001$). A similar but slightly stronger trend was observed for road surface area times slope ($R^2 = 0.62$; $p < 0.001$).

A similar analysis indicated that use class was not a significant control on sediment production rates. 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). After normalizing by precipitation and slope, the 14 measurements from the five road segments in the heavy use category had an average sediment production rate of 1.28 kg m^{-2} cm^{-1} m m^{-1} (s.d. = 1.24) (Table 4). 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). The high variability within each category meant that there was no significant difference between these sediment production rates ($p = 0.19$).

Regrading did significantly affect 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. This material is spread by a bulldozer over the road segment but is not systematically compacted (Figure 8). Figure 9 shows that sediment production rates—again normalized by precipitation and slope—declined significantly with time since grading ($p < 0.001$). Sediment production rates were highest in the first year after grading, and there was a notable reduction in both the magnitude and variability of sediment production rates between one and two years after grading. This suggests that the 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 4), and these values are significantly different ($p<0.0001$). Annual sediment production rates for typical graded and ungraded roads with a 10% slope and an annual rainfall of 115 cm yr^{-1} are 11 kg m^{-2} yr^{-1} and 6.4 kg m^{-2} yr^{-1}, respectively.

Figure 10 shows how sediment production—normalized by precipitation—varies with road segment slope for graded and ungraded roads. This indicates that sediment production rates for the graded roads exponentially increase with increasing slope. In contrast, the sediment production rates for ungraded roads with similar slopes are much lower, and the data suggest a linear relationship with increasing slope (Figure 10).

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 0.071 kg m^{-2} cm^{-1} m m^{-1} (n=5), or 13% 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 four times the value over the rest of the study period and nearly 50% of the value for actively-used, ungraded roads. November 1999 included the intense rainfall associated with Hurricane Lenny, and this apparently induced sufficient overland flow to rapidly erode the surface of the two abandoned road segments.

2.4.3 General Linear Models for Graded and Ungraded Road Segments

Multiple regression showed that interaction terms including slope were always statistically significant. Models based on slope had higher R^2 values than models using area times slope. Models using erosivity and total erosive energy had slightly lower R^2 values than models using total precipitation. The best models were based on a two-way interaction of total precipitation and slope, and a three-way interaction of total precipitation, slope, and grading. Exponent values between 1.0 and 2.0 were sequentially tested for the slope parameter at 0.1 increments. All of the resulting models had statistically-significant terms and R^2 values ranging from 0.61 to 0.76 (Appendix I-C). The similarity of R^2 values meant that a graphical analysis of model residuals was used to select the best model. The model based on $slope^{1.5}$ was chosen because the residuals were normally distributed and this model minimized the error in sediment production, especially for the steepest road segments (Table 5; Appendix I-C). Since the grading parameter is best treated as a binary variable with values of 1 for graded roads and 0 for ungraded roads, the road erosion model can be simplified into equations for graded roads (equation 7a) and ungraded roads (equation 7b), as follows:

$$E_r = -0.432 + 4.73 \cdot (S^{1.5} \cdot P) \quad \text{(eq. 7a)}$$

$$E_r = -0.432 + 1.88 \cdot (S^{1.5} \cdot P) \quad \text{(eq. 7b)}$$

where E_r is sediment production in kg m^{-2}, S is slope in m m^{-1}, and P is total precipitation in cm.

A plot of the measured data against predicted values shows that the predicted values generally follow the 1:1 line (Figure 11). The mean absolute errors for graded and ungraded roads were 1.15 and 0.69 kg m^{-2}, respectively.

Figure 12 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 9.

2.4.4 Particle-Size Distribution

The mass-weighted average particle-size distribution showed that the material eroded from the unpaved road surfaces was 40% gravel, 54% sand, and 6% silt and clay (Table 6; Appendix I-D). The median particle-size (D_{50}) for all road segments was 0.12 mm, and the 16th (D_{16}) and 84th (D_{84}) percentiles were 0.72 and 4.1 mm, respectively. On average, graded roads produced 36% gravel, 58% sand, and 6% silt and clay, while ungraded roads produced 41% gravel, 53% sand, and 6% silt and clay (Figure 13). Abandoned roads produced 73% gravel, 27% sand, and 0.1% silt and clay. There were no significant differences in the particle-size distributions of the sediment collected from graded and ungraded roads (Table 6). The statistical analyses did not include samples from abandoned roads as this class was represented by only two samples.

When sorted by slope class, the sediment eroded from the steepest road segments was significantly coarser than the sediment produced from the low-gradient roads (Table 6). There were no significant differences between the steep- and moderately-sloped roads for any of the particle-size categories as well as the D_{16}, D_{50}, and D_{84}.

2.5 Discussion

2.5.1 Effects of Precipitation, Slope, and Grading in Road Sediment Production

Total precipitation, slope, and grading all affect road sediment production rates on St. John. The use of total precipitation is a simplification of the erosion processes described by equations 1-4, as this presumes that—after controlling for slope and grading—all rainfall events have the same erosive potential per unit depth of rainfall. The model presumes a linear relationship between total precipitation and sediment production and this implies that total runoff from an unpaved road segment is linearly related to total precipitation. For a given storm magnitude, equations 1-4 suggest that sediment production should be controlled by the intensity of rainfall, as this controls the depth of overland flow and thus the magnitude of the shear stresses applied to the road surface. The problem is that the sediment trap data aggregate sediment production from numerous rainfall events over time periods extending from several weeks to several months. The effects of varying rainfall intensities are largely lost, and total precipitation emerges as the best predictor of road segment sediment production. If sediment production were measured over shorter time periods, erosivity might emerge as a better predictor of road sediment production.

Road segment slope was an important control on road sediment production. The models show that sediment production per unit rainfall is best predicted by slope elevated to the 1.5 power. The presence of slope as a two- and three-way interaction term in the model (Table 5) indicates that its effect on road erosion rates varies with grading category. Slope differences will have a larger effect on sediment production rates for graded roads than ungraded roads.

Road segment slope was a better predictor of sediment production rates than road surface area times slope. The three-way interaction term of precipitation, area times slope, and grading was only marginally significant ($p = 0.06$) and produced a model with an overall R^2 of 0.68 (Appendix I-C). The lower significance for the model using area times slope may be due to the difficulty in accurately measuring the contributing areas of individual road segments. Montgomery (1994) noted that road drainage areas measured when there was no surface runoff may have errors of up to $\pm$ 30%. Another complication is that the area times 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. Area times slope values for the monitored road segments could not account for these changes as they were only measured once during the study period.

Time since grading also had an important effect on sediment production. Sediment production rates—normalized by rainfall and slope—exponentially declined with time since grading (Figure 9) and with cumulative precipitation after grading. The large variability in sediment production rates and the limited time-resolution of the sediment data preclude a calibration of the parameters in equation 5 (Megahan, 1974) or the development of a new exponential decay model. Roads that were graded at least once every two years had significantly higher sediment production rates than ungraded roads (Table 4). Although the data suggest that sediment production rates decline after about 80 cm of total precipitation, the regression equations suggests that approximately 230 cm of cumulative rainfall are required before a graded road erodes at nearly the same rate as an ungraded road (Figure 12). 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 7b to all subsequent rainfall.

The predicted declines in sediment production through time are similar to or slightly less than previous studies. Using equation 7a, the predicted annual sediment production rates for graded roads are 0.11 and 52 kg $m^{-2} yr^{-1}$ assuming an annual rainfall rate of 115 cm and road slopes of 1% and 21%, respectively. Using equation 7b, the corresponding values are 0.0 and 12 kg $m^{-2} yr^{-1}$. These values suggest that sediment production rates should decline by 61-84% within two years after grading. In Idaho sediment production rates declined by 40-80% within one year after construction (Vincent, 1979). A field-based calibration of equation 5 in Idaho indicates that sediment production should decline by 95% within one year after road construction (Megahan, 1974). In the Oregon Coast range, sediment production rates decreased by 70% one year after disturbing both the travelway and the ditch, and by 90% after two years (Luce and Black, 2001b).

2.5.2 Abandoned Roads and Undisturbed Hillslopes

The mean rate of sediment production for abandoned roads with a mean slope of 15% 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 3-year period documented in this study (Figure 9). The low erosion rates for the abandoned road segments may be attributed to a well-armored 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 showed that this generated precipitation-excess overland flow on the road surface but there was no interception of subsurface storm flow and almost no sediment captured in the sediment traps.

Efforts to model sediment production rates from abandoned roads are hindered by the almost 400% increase in sediment production observed during Hurricane Lenny. The pattern of rainfall generated by Hurricane Lenny was unique, as the maximum 1-hr intensity of 4.7 cm hr^{-1} occurred after 4.9 cm of rain had fallen in the previous 24 hours. This high-intensity burst of rain at the end of the storm presumably triggered both Horton overland flow and the interception of subsurface flow on the abandoned road segments. The resulting surface runoff caused a marked increase in sediment production per unit rainfall. Although detailed hydrometric data are not available, the difference in antecedent precipitation and subsurface flow interception is believed to explain why Hurricane Lenny produced much more sediment than the 9.5-cm storm in February 1999.

Annual sediment production estimates from abandoned roads are necessarily based on the total sediment produced 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). Hence the long-term frequency of events like Hurricane Lenny may be similar to their frequency during the study period. If the normalized average sediment production for abandoned roads is 0.071 kg m^{-2} per unit precipitation per unit percent slope, then the annual erosion rates for abandoned roads with slopes of 1% and 21% are estimated to be 0.08 and 1.7 kg m^{-2} yr^{-1}, respectively. The values for roads with 1% slope show relatively little change with grading class. For roads with a slope of 21% the effect of grading is much greater, as recently-graded roads produce 30 times as much sediment as abandoned roads. Steep ungraded segments produce about 7 times as much sediment as comparable abandoned roads.

Measured surface erosion rates from undisturbed zero-order basins are on the order of 0.001 kg m^{-2} yr^{-1} (Chapter 4). 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 still about three orders of magnitude higher than the rates measured from undisturbed hillslopes.

2.5.3 Comparisons with Previous Studies

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

$$E = 0.00057 A \cdot S + 0.034 \qquad \text{(eq. 8)}$$

where E is the average annual road surface cross-sectional erosion (m^2 yr^{-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 and the average road segment slope (Anderson and MacDonald, 1998).

The application of ROADMOD to the 21 monitored road segments yields a mean annual sediment production rate of 22 kg m^{-2} yr^{-1}, or 18 times higher than the measured mean of 1.8 kg m^{-2} yr^{-1}. Only road segments FB-E and MB-A had measured values higher than those predicted by ROADMOD. Erosion rates predicted by ROADMOD were poorly correlated to those measured by the sediment traps ($R^2 = 0.04$; $p > 0.25$). Erosion rates based on sediment trap measurements were poorly correlated with the area-slope product as defined by Anderson (1994) ($R^2 = 0.006$; $p > 0.25$).

The lack of a stronger correlation may be due to the fact that equation 8 was developed on severely-rilled road segments with no effective cross-slope drainage (Type 3 in Figure 3). The correlation between sediment production rates estimated by ROADMOD and those measured with sediment traps improves when the area times slope product is based on a method that accounts for varying road drainage patterns. Using the area times slope product shown in Table 2, the mean sediment production rate estimated by ROADMOD for the 21 road segments drops by nearly one-third to 15 kg m^{-2} yr^{-1}. Although this value is still an order of magnitude higher than the mean value from the sediment traps, the correlation between the predicted and measured values is stronger ($R^2 = 0.19$; $p < 0.001$) than those using the total surface area times slope product.

Figure 15 compares estimated annual sediment production rates for unpaved roads in St. John to other published values. Annual erosion rates measured by this current study suggest that road segment scale sediment production rates are of similar magnitude as the 0.9 to 15 kg m^{-2} yr^{-1} previously estimated from 40 m^2 road surface plots with slopes ranging from 7 to 18 percent (MacDonald et al., 2001).

Sediment production rates from unpaved roads on St. John are higher than the values reported for the Southern Appalachian Mountains (Swift, 1984) and central Idaho (Vincent, 1979) in the U.S., New Zealand (Fahey and Coker, 1989), and Australia (Grayson et al., 1993) (Figure 15). The higher erosion rates for St. John are consistent with the steep road segment slopes and the high rainfall erosivities on the island. The only published study with higher erosion rates was a high rainfall area in the northwestern U.S. (Reid and Dunne, 1984). Their maximum rate assumed a mean traffic of at least four loaded logging trucks per day, while none of the road segments in this study was subjected to more than 4-6 delivery trucks per day.

2.5.4 Recommendations for Road Erosion Control

The improved understanding of road surface erosion developed here can be translated into specific recommendations for reducing road surface sediment production. First, given the important role of grading and slope in sediment production (Figure 10), frequently-graded steep 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 can be expected immediately after grading and road construction. 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, the borderline-significance ($p = 0.06$) of the area times slope factor term in multiple regression highlights the importance of proper road drainage in minimizing sediment production rates. Proper design may include insloping, outsloping, constructing and maintaining well-protected ditches along roads, and increasing the density of road drains.

2.6 Conclusions

Sediment production from 21 road segments with varying contributing areas, slopes, and traffic loads was monitored with sediment traps from July 1998 to November 2001. 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, although the total erosive energy was approximately 12% larger than the long-term average.

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 centimeter of precipitation. Steeper roads had higher sediment production rates, and the recently-graded roads showed a significant, non-linear increase in sediment production with increasing road slope. 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 centimeter of rainfall and unit slope, or approximately 11 kg m^{-2} yr^{-1} for a typical road with a 10% slope and an annual rainfall of 115 cm yr^{-1}. The mean erosion rate for ungraded roads was 41% lower, or 6.4 kg m^{-2} yr^{-1} for a road segment with a 10% slope. Roads with 15% slopes that had been abandoned for about 15 years showed an average erosion rate of 1.1 kg m^{-2} yr^{-1}. Differences in traffic loads did not significantly affect sediment production.

Models using total precipitation and slope yielded higher R^2 values than models using rainfall erosivity, total erosive energy, and area times slope. The best predictive model used total precipitation, slope to the 1.5 power, and a binary variable for grading, and had a R^2 value of 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. These rates place roads in St. John at the high end of reported road erosion rates, a finding that is consistent with the high rainfall erosivities on the island. The improved understanding of road surface erosion can be translated into specific recommendations for reducing road surface sediment production.

2.7 References Cited

Acevedo R, Morelock J, Olivieri RA. 1989. Modification of coral reef zonation by terrigenous sediment stress. *Palaios* 4: 92-100.

Anderson DM. 1994. Analysis and modeling of erosion hazards and sediment delivery on St. John, U.S. Virgin Islands, US National Park Service Water Resources Division, Technical Report NPS/NRWRD/NRTR-94-34, Fort Collins, Colorado; 153 p.

Anderson DM, MacDonald LH. 1998. Modelling road surface sediment production using a vector geographic information system. *Earth Surface Processes and Landforms* 23: 95-107.

Bilby RE, Sullivan K, Duncan SH. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. *Forest Science* 35(2): 453-468.

Black TA, CH Luce. 1999. Changes in erosion from gravel surfaced forest roads through time. Proceedings of the International mountain logging and 10th Pacific Northwest skyline symposium; pp. 204-218.

Bowden MJ, Fischman N, Cook P, Wood J, and Omasta E. 1970. Climate, water balance, and climatic change in the north-west Virgin Islands. Caribbean Research Institute, College of the Virgin Islands; 127 p.

Bowles JE. 1992. Engineering Properties of Soils and their Measurement. McGraw-Hill Inc., New York; 218 p.

Bren LJ, Leitch CJ. 1985. Hydrologic effects of a stretch of forest road. *Australian Forest Research* 15(2): 183-194.

Burroughs ER, Foltz RB, Robichaud PR. 1991. United States Forest Service research on sediment production from forest roads and timber harvest areas. Proceedings of the 10th World Forestry Congress; 187-193.

Calvesbert RJ. 1970. Climate of Puerto Rico and the U.S. Virgin Islands. Climatography of the United States No. 60-52, US Dept. of Commerce; 29 p.

Carter CE, Greer JD, Braud HJ, Floyd JM. 1974. Raindrop characteristics in southcentral United States. *Transactions of the ASAE* 17(6): 1033-1037.

CH2M Hill. 1979. A sediment reduction program: Report to the Department of Conservation and Cultural Affairs, Government of the U.S. Virgin Islands, St. Thomas, USVI.

Donnelly TW. 1966. Geology of St. Thomas and St. John. *Geological Society of America, Memoir* 98: 85-176.

Douglas I, Greer T, Bidin K, Sinun W. 1993. Impact of roads and compacted ground on post-logging sediment yield in a small drainage basin, Sabah, Malaysia. In Hydrology of Warm Humid Regions, Gladwell JS (ed.), IAHS Publication 216: 213-218.

Dunne T. 1979. Sediment yield and land use in tropical catchments. *Journal of Hydrology* 42: 281-300.

EarthInfo, Inc. 1996. NCDC 15-minute precipitation values. CD-ROM disk. Earth Info, Inc.: Boulder, CO.

Everest FH, Beschta RL, Scrivener JC, Koski KV, Sedell JR, Cederholm CJ. 1987. Fine sediment and salmonid production: a paradox. In Streamside Management: Forestry and Fishery Interactions, Salo EO and Cundy TW (eds.), College of Forest Resources, University of Washington, Seattle, WA; 98-142.

Fahey BD, Coker RJ. 1989. Forest road erosion in the granite terrain of southwest Nelson, New Zealand. *Journal of Hydrology (NZ)* 28(2): 123-141.

Foltz RB. 1996. Traffic and no-traffic on an aggregate surfaced road: Sediment production differences. Paper presented in "Environmentally sound forest road and wood transport Conference"; June 1996; Rome, Italy: FAO; 13 p.

Fransen PJB, Phillips CJ, Fahey BD. 2001. Forest road erosion in New Zealand: Overview. *Earth Surface Processes and Landforms* 26: 165-174.

Froelich W, Walling DE. 1997. The role of unmetalled roads as a sediment source in the fluvial systems of the Polish Flysch Carpathians. In Human Impact on Erosion and Sedimentation, IAHS Publication 245: 159-168.

Froehlich W. 1991. Sediment production from unmetalled road surfaces. In Sediment and stream water quality in a changing environment: Trends and explanation, IAHS Publication 203: 21-29.

Gardner WH. 1986. Chapter 21: Water Content. In Methods of Soil Analysis Part I: Physical and Mineralogical Methods. 2nd edition Number 9 (Part 1) Agronomy Series, Klute A (ed.). American Society of Agronomy, Madison, WI; 493-544.

Gee GW, Bauder JW 1986. Particle-size analysis. In Methods of Soil Analysis Part 1: Physical and Mineralogical Methods. 2nd edition Number 9 (Part 1), Agronomy Series, Klute A (ed.) American Society of Agronomy, Madison, WI; 383-411.

Grayson RB, Haydon SR, Jayasuriya MDA, Finlayson BL. 1993. Water quality in mountain ash forests-separating the impacts of roads from those of logging operations. *Journal of Hydrology* 150: 459-480.

Gresswell S, Heller D, Swanston DN. 1979. Mass movement response to forest management in the central Oregon Coast Ranges. USDA Forest Service Resource Bulletin PNW-84, Portland, OR, 26 p.

Harden CP. 1992. Incorporating roads and footpaths in watershed-scale hydrologic and soil erosion models. *Physical Geography* 13(4): 368-385.

Hernández-Delgado EA. 2001. Enfermedades, competencia por sobrecrecimiento y otras causas de mortalidad en el coral (*Monastrea annularis*). Paper presented at the XXIV Symposium of Natural Resources, Univ. Politécnica, San Juan-Puerto Rico, 16 November 2001.

Hodgson G. 1989. The effects of sedimentation on Indo-Pacific Reef Corals. Ph.D. Dissertation, University of Hawaii, Honolulu, HI; 338 p.

Hodgson G. 1997. Resource use: Conflicts and management solutions. In Life and Death of Coral Reefs. Birkeland C (ed.), Chapman and Hill, New York, NY; 386-411.

Hubbard DK. 1986. Sedimentation as a control of reef development: St. Croix, USVI. *Coral Reefs* 5: 117-125.

Hubbard DK. 1987. A general review of sedimentation as it relates to environmental stress in the Virgin Islands Biosphere Reserve and the eastern Caribbean in general. Biosphere Reserve Report no. 20, Virgin Islands Resource Management Cooperative, St. Thomas, VI; 42 p.

Julien PY. 1995. Erosion and Sedimentation. Cambridge University Press; 280 p.

Kirkby MJ. 1980. Modelling water erosion processes. In Soil Erosion, Kirkby MJ, Morgan RPC (eds.). John Wiley, New York; 425-442.

Knighton D. 1998. Fluvial forms and processes. E Arnold Publishers; 383 p.

Kumapley NK. 1987. Erosion of unsurfaced earth and gravel roads. In Proceedings of 9th Regional Conference for Africa on Soil Mechanics and Foundation Engineering. Lagos, Nigeria; 397-404.

Larsen MC, Parks JE. 1997. How wide is a road? The association of roads and mass-wasting in a forested montane environment. *Earth Surface Processes and Landforms* 22: 835-848.

Luce CH, Black TA. 1999. Sediment production from forest roads in western Washington. *Water Resources Research* 35(8): 2561-2570.

Luce CH, Black TA. 2001a. Effects of traffic and ditch maintenance on forest road sediment production. In Proceedings of the Seventh Federal Interagency Sedimentation Conference, Reno, Nevada.

Luce CH, Black TA. 2001b. Spatial and temporal patterns in erosion from forest roads. In Influence of Urban and Forest Land Uses on the Hydrologic-Geomorphic Responses of Watersheds. Wigmosta MS, Burges SJ (eds.). Water Resources Monographs, American Geophysical Union, Washington, DC; 165-178.

Luce CH, Wemple BC. 2001. Introduction to special issue on hydrologic and geomorphic effects of forest roads. *Earth Surface Processes and Landforms* 26:111-113.

MacDonald LH, Sampson RW, Anderson DM. 2001. Runoff and road erosion at the plot and road segment scales, St. John, US Virgin Islands. *Earth Surface Processes and Landforms* 26: 251-272.

MacDonald LH, Anderson DM, Dietrich WE. 1997. Paradise threatened: Land use and erosion on St. John, U.S. Virgin Islands. *Environmental Management* 21(6): 851-863.

Megahan WF. 1987. Effects of forest roads on watershed function in mountainous areas. In Environmental geotechnics and problematic soils and rocks. Balasubramiam et al. (eds.); 335-347.

Megahan WF. 1974. Erosion over time on severely disturbed granitic soils: A model. USDA Forest Service Research Paper INT-156, Ogden, UT; 14 p.

Megahan WF, Kidd WJ. 1972. Effects of logging roads on sediment production rates in the Idaho batholith. USDA Forest Service Research Paper INT-123, Ogden, UT; 14 p.

Megahan WF, Seyedbagheri KA, Mosko, TL. 1986. Construction phase sediment budget for forest roads in granitic slopes in Idaho. In Drainage basin sediment delivery. Hadley RF (ed.), IAHS Publication 159: 31-39.

Montgomery DR. 1994. Road surface drainage, channel initiation, and slope instability. *Water Resources Research* 30(6): 1925-1932.

Moss AJ, Green P. 1983. Movement of solids in air and water by raindrop impact, effects of drop-size and water-depth variations. *Australian Journal of Soil Research* 21: 257-269.

National Research Council. 1992. Restoration of Aquatic Ecosystems., National Academy Press, Washington, DC; 552 p.

Nemeth RS, Nowlis JS. 2001. Monitoring the effects of land development on the near-shore marine environment of St. Thomas, USVI. *Bulletin of Marine Science* 69(2):759-775.

Nemeth RS, MacDonald LH, Ramos-Scharrón CE. 2001. Delivery, deposition, and effects of land-based sediments on corals in St. John, U.S. Virgin Islands. Report on Project No. VI99-2, Water Resources Research Institute, University of the Virgin Islands, St. Thomas, USVI; 24 p.

Ramos-Scharrón CE, MacDonald LH. 2001. Measuring and Modeling Sediment Production from Unpaved Roads, St. John, U.S. Virgin Islands. *Eos, Transactions AGU,* 82(47): F-510.

Rankin DW. 2002. Geology of St. John, U.S. Virgin Islands. U.S. Geological Survey professional paper 1631; 36 p.

Reid LM, Dunne T. 1984. Sediment production from forest road surfaces. *Water Resources Research* 10(11): 1753-1761.

Reid LM. 1981. Sediment production from gravel-surfaced roads, Clearwater basin, Washington, Publication FRI-UW-8108, University of Washington Fisheries Research Institute, Seattle, WA; 247 p.

Robichaud PR, Brown RE. 2002. Silt fences: an economical technique for measuring hillslope soil erosion. General Technical Report RMRS-GTR-94, Fort Collins, CO; 24 p.

Rogers CS. 1998. Coral reefs of the U.S. Virgin Islands. In: Status and Trends of the Nation's Biological Resources, Vol. I. Haeker P and Doran PD (eds.). U.S. Department of the Interior, U.S. Geological Survey, Reston, VA; 322-324.

Rogers CS 1990. Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress Series* 62: 185-202.

Sampson RW. 2000. Road runoff and erosion at the plot and road segment scales on St John US Virgin Islands. MS thesis, Department of Earth Resources, Colorado State University, Fort Collins, CO; 189 p.

Sidle RC, Pearce AJ, O'Loughlin CL. 1985. Hillslope stability and land use. American Geophysical Union, Water Resources Monograph Series No. 11; 140 p.

Soil Conservation Service. 1970. Soil Survey, Virgin Islands of the United States. 78 p.

Swift LW. 1984. Soil losses from roadbeds and cut and fillslopes in the Southern Appalachian Mountains. *Southern Journal of Applied Forestry* 8: 209-216.

Torres J. 2001. Impacts of sedimentation on the growth rates of *Montastraea annularis* in Southwest Puerto Rico. *Bulletin of Marine Science* 69(2): 631-637.

Torres R, Chiappone M, Geraldes F, Rodríguez Y, Vega M. 2001. Sedimentation as an important environmental influence on Dominican Republic reefs. *Bulletin of Marine Science* 69(2): 805-818.

USDA. 1995. Classification and Correlation of the Soils of the Virgin Islands of the United States. US Department of Agriculture: Hato Rey, Puerto Rico.

Vincent KR. 1979. Runoff and erosion from a logging road in response to snowmelt and rainfall. M.S. thesis, University of California, Berkeley, CA; 60 p.

Wald AR. 1975. The impact of truck traffic and road maintenance on suspended-sediment yield from a 14' standard forest road. MS thesis, University of Washington, Seattle.

Waters TF. 1995. Sediment in Streams: Sources, Biological Effects and Control. American Fisheries Society Monograph 7; 251 p.

Wischmeier WH, Smith DD. 1958. Rainfall energy and its relationship to soil loss. *Transactions of the American Geophysical Union* 39(3): 285-291.

Woodbury RO, Weaver PL.1987. The vegetation of St. John and Hassel Island, U.S. Virgin Islands. National Park Service, Southeast Region, Research/Resources Management Report SER-83, Atlanta, GA; 26 p.

Ziegler AD, Sutherland RA, Giambelluca TW. 2001a. Interstorm surface preparation and sediment detachment by vehicle traffic on unpaved mountain roads. *Earth Surface Processes and Landforms* 26: 235-250.

Ziegler AD, Giambelluca TW, Sutherland RA. 2001b. Erosion prediction on unpaved mountain roads in northern Thailand: validation of dynamic erodibility modelling using KINEROS2. *Hydrological Processes* 15: 337-358.

Ziegler AD, Sutherland RA, Giambelluca TW. 2000. Partitioning total erosion on unpaved roads into splash and hydraulic components: The roles of interstorm surface preparation and dynamic erodibility. *Water Resources Research* 36(9): 2787-2791.

Ziegler AD, Giambelluca TW. 1997. Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand. *Journal of Hydrology* 196: 204-229.

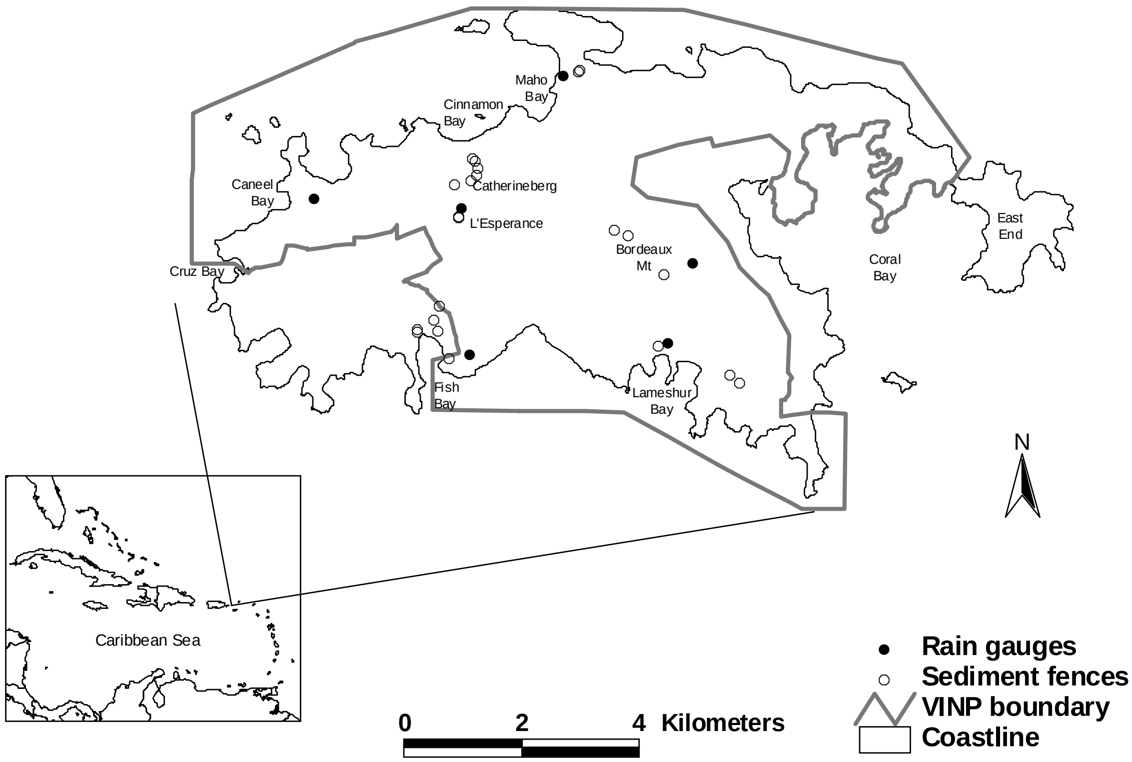

Figure 1. Map of St. John showing the locations of the rain gauges and road segment sediment traps.

Figure 2. Example of a steep road segment near Bordeaux Mountain with a deeply-rilled travelway.

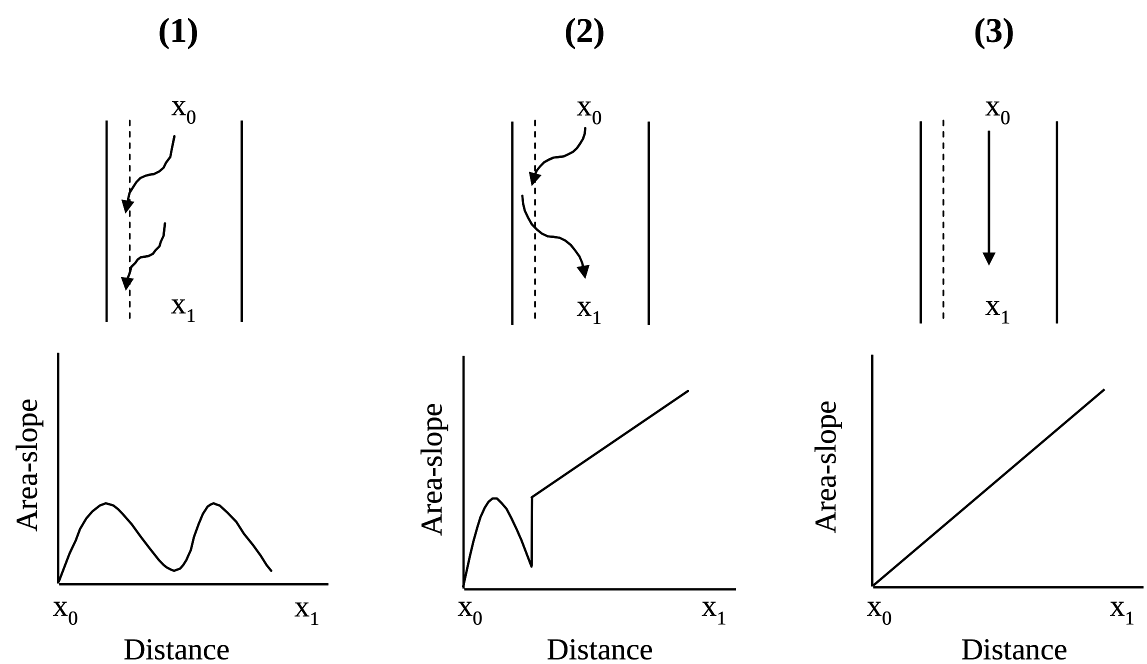

Figure 3. Sketches showing the three main types of drainage patterns exhibited by roads on St. John and their effects on the area times slope factor: (1) insloped; (2) insloped with blocked ditch; and (3) no effective cross-slope drainage. Dashed lines indicates the inside edge of the ditch.

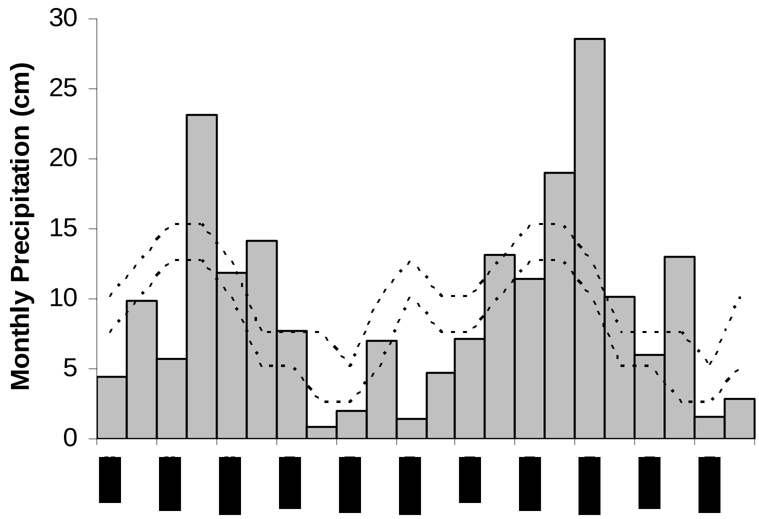

Figure 4. Monthly precipitation over the study period at Maho Bay. Dashed lines show the average monthly range of precipitation as defined by the mean and plus or minus one standard deviation (Bowden et al., 1970).

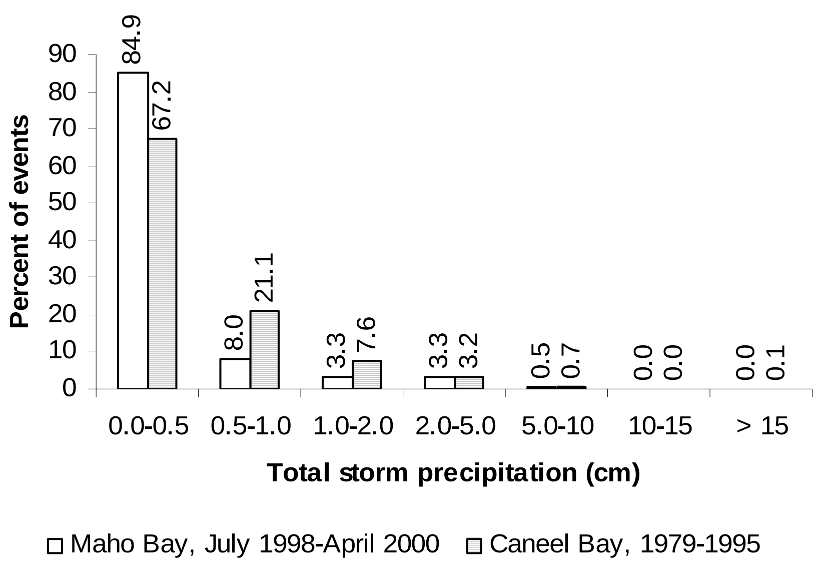

Figure 5. Frequency distribution of storm precipitation from Maho Bay for the period of study (n=614) versus the long-term average for Caneel Bay (n=2,921).

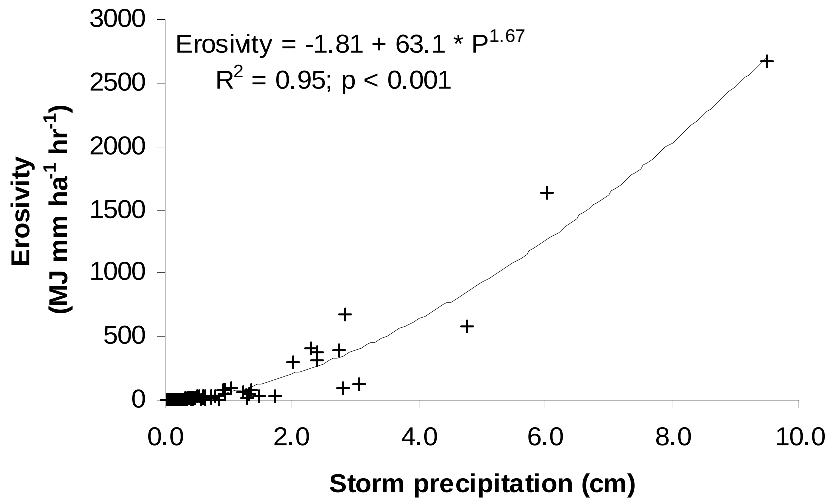

Figure 6. Relationship between 15-min erosivities and total storm precipitation (P) for 309 storm events at Maho Bay for which 15-min rainfall data was available (September 1999 to May 2000).

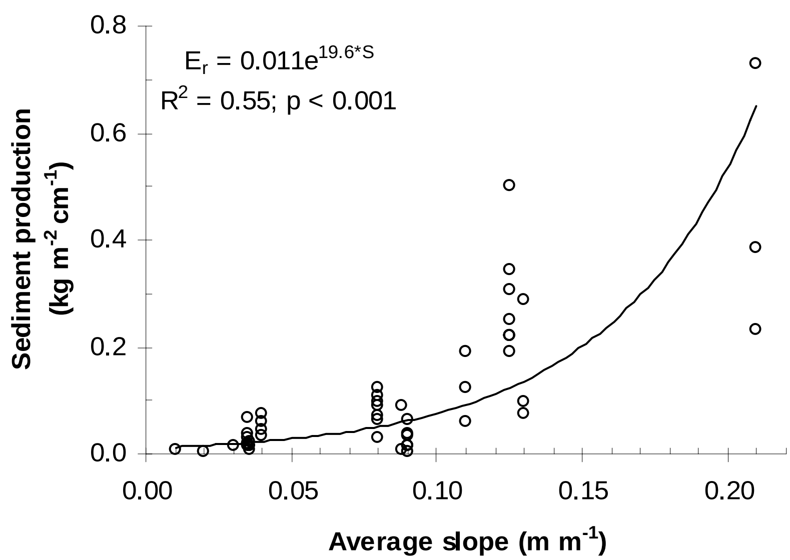

Figure 7. Relationship between sediment production (E_r) normalized by precipitation and slope (S) for seven recently-graded, lightly-used road segments.

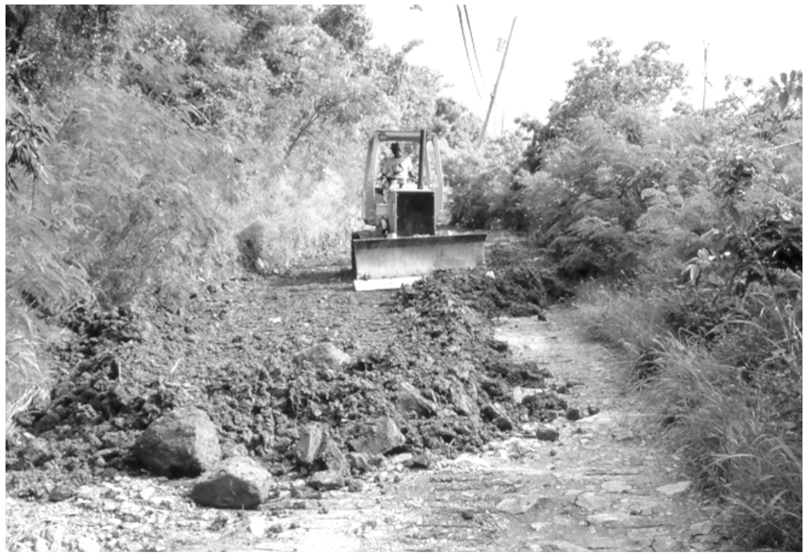

Figure 8. Example of a grading operation along road segment FB-Coco on 11 December 1998.

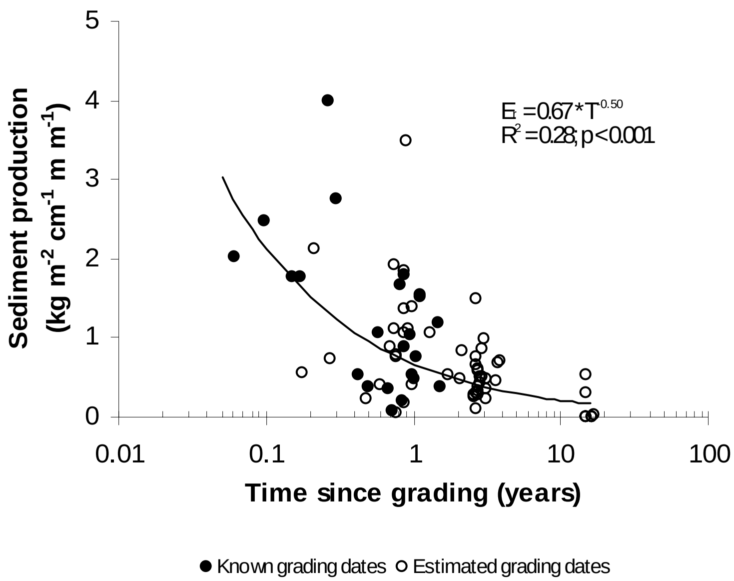

Figure 9. Relationship between sediment production rates (Er)—normalized by precipitation and slope—versus time since grading (T). Solid circles represent known dates of grading and open circles represent data points for which the date of grading was estimated.

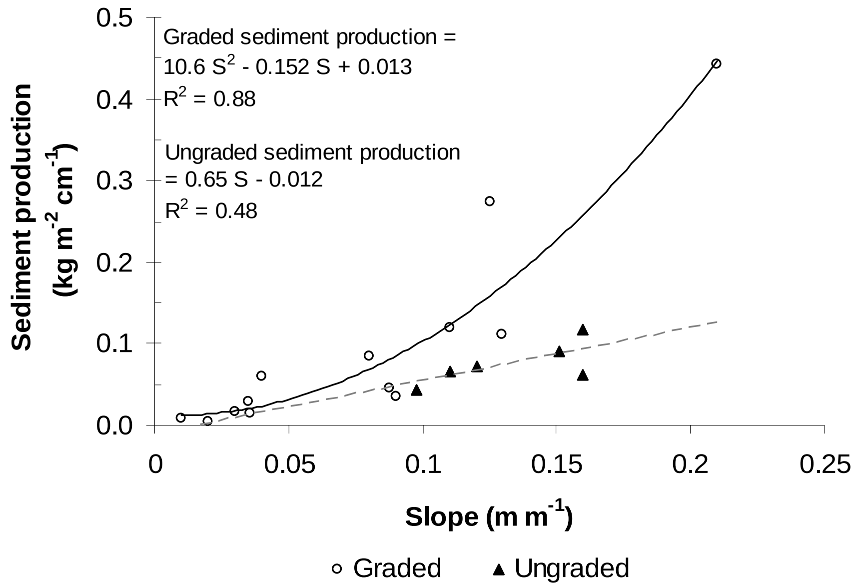

Figure 10. Relationship between mean sediment production—normalized by precipitation—and average segment slope (S) for graded and ungraded road segments. Solid black line is for graded road segments and dashed gray line is for ungraded road segments.

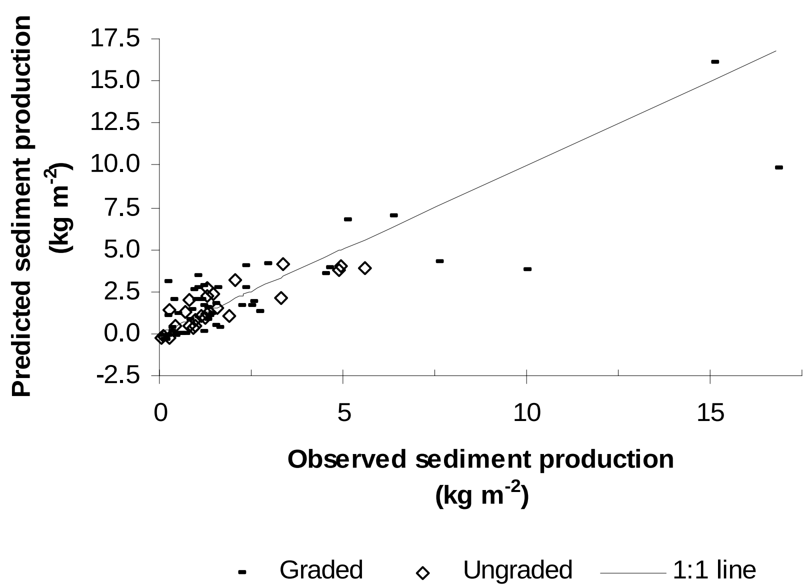

Figure 11. Predicted versus observed sediment production rates for graded and ungraded roads.

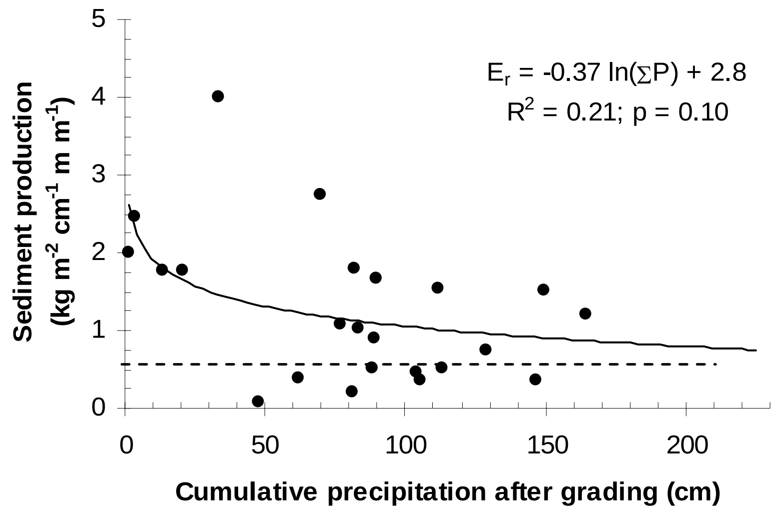

Figure 12. Relationship between sediment production (E_r)—normalized by precipitation and average gradient—and cumulative precipitation after grading (ΣP). Data are for 8 road segments where the date of grading was known (n=24). Dashed line represents the mean erosion rate for ungraded roads.

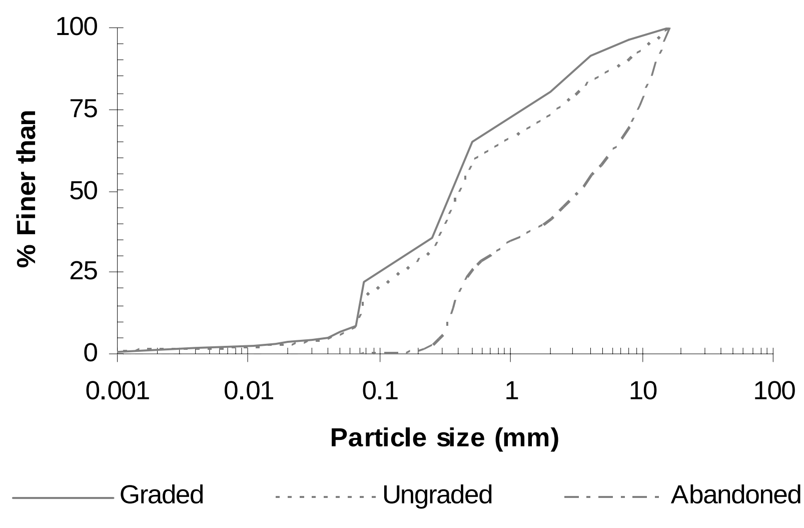

Figure 13. Mass-weighted particle-size distribution for sediment from graded, ungraded, and abandoned roads.

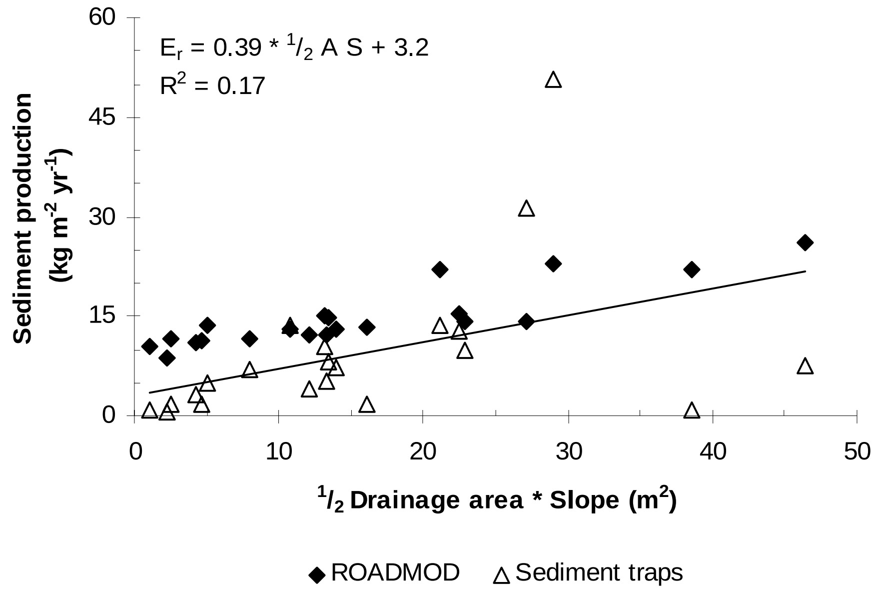

Figure 14. Relationship between measured annual sediment production rates (E_r) using sediment traps and predicted sediment production using ROADMOD versus one-half of the drainage area (A) times slope (S) product. Regression line is for the sediment trap data.

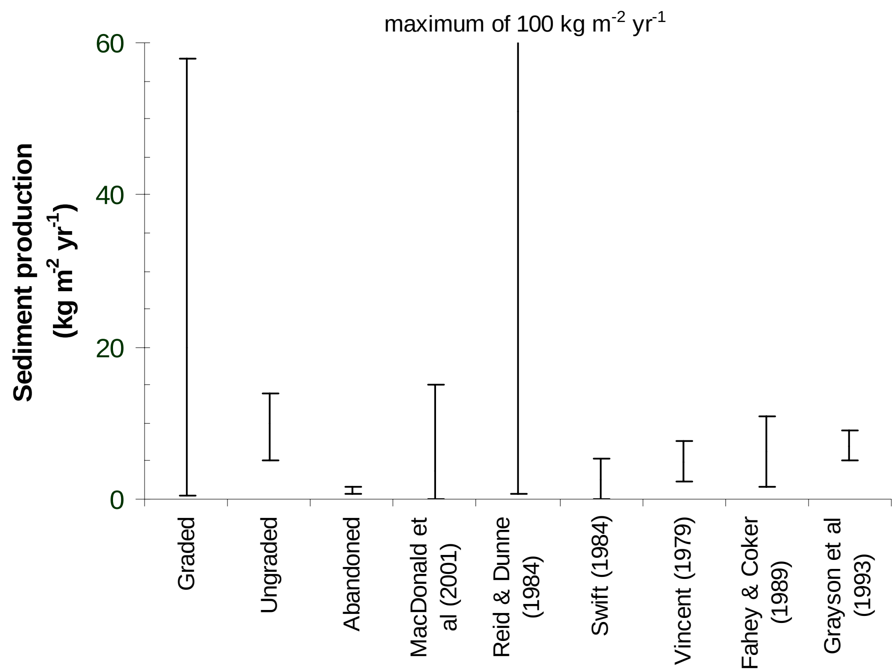

Figure 15. Range of annual sediment production rates for graded, ungraded, and abandoned roads in St. John as compared to values reported from other studies.

Table 1. Type, resolution, and period of record for the rain gauges used in this study.

Station	**Type of gage**	**Time and depth resolution**	**Period of record [Gaps in data]**
Bordeaux Mountain	Tipping bucket	15 min; 0.025 cm	14 Sep 98 to 2 Sep 99 [28 Feb 99 to 28 Jun 99]
	Weighing-bucket	60 min; 0.25 cm	2 Sep 99 to 3 May 00 [None]
Fish Bay	Tipping bucket	15 min; 0.025 cm	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 min; 0.25 cm	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 min; 0.025 cm	13 Jul 98 to 2 Sep 99 [20 Sep 98 to 28 Sep 98]
	Tipping-bucket	15 min; 0.025 cm	2 Sep 99 to 13 Apr 00 [None]

Table 2. Characteristics of the 21 road segments used in this study.

Road Segment[1]	Area (m^2)	Average slope ($m\ m^{-1}$)	Area times slope ($m^2\ m\ m^{-1}$)	Average width (m)	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	4
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	6
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	3
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 8/03/01**	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**					

[1] BM= Bordeaux Mountain, FB=Fish Bay, JH=John Head road, LB=Lameshur Bay, LE=L 'Esperance, and MB=Maho Bay.
* Estimated values.
** Occasional gaps in the data.

Table 3. R^2, p values, 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

Table 4. Sediment production by road segment normalized by precipitation and slope. The means and standard deviations are shown 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)

Table 5. General linear regression model for predicting sediment production rates for unpaved road segments on St. John.

ROAD EROSION MODEL
($R^2 = 0.75$; $p < 0.0001$)

Parameter	Regression coefficient	Standard error	p-value	Partial R^2
Intercept	-0.432	0.26	0.1047	--
Precipitation*$Slope^{1.5}$ (cm m m^{-1})	1.88	0.29	< 0.0001	0.15
Precipitation*$Slope^{1.5}$*Grading (cm m m^{-1})	2.85	0.34	<0.0001	0.60

Table 6. Weighted mean particle sizes by grading, and average slope. Values with different letters indicate that the means are statistically different.

Grading and slope class	Number of road plots per class	Percent gravel	Percent sand	Percent 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
<u>Grading class</u>							
Abandoned	2	73	27	0.1	0.35	3.1	11
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]
<u>Slope class</u>							
Low (<10%)	9	32[d]	60[f]	8[h]	0.08[D]	0.33[E]	2.5[F]
Moderate (10-15%)	7	43[d e]	51[f g]	5[h i]	0.11[D]	0.79[E]	4.3[F G]
High (>15%)	4	51[e]	46[g]	3[h i]	0.20[D]	1.5[E]	7.2[G]