CHAPTER 4.

MEASUREMENT AND PREDICTION OF NATURAL AND ANTHROPOGENIC SEDIMENT SOURCES ON ST. JOHN, U.S. VIRGIN ISLANDS

ABSTRACT

An increase in the amount of sediment delivered to the marine environment can adversely affect nearshore coral reef communities. The development of scientifically-sound erosion control strategies requires an understanding of natural and anthropogenic sediment sources. The objectives of this study were to measure and develop predictive models for both natural and anthropogenic sediment sources on St. John in the U.S. Virgin Islands. Erosion rates from streambanks, treethrow, hillslopes, zero- and first-order basins, road surfaces, and cutslopes were measured by different methods between 1998 and 2001.

Streambank erosion had the highest natural erosion rate, with an average value of 10 kg m^{-2} yr^{-1}. Uprooting of trees along stream margins is estimated to deliver sediment at a rate of 0.17 tonnes km^{-1} yr^{-1}, or 11 g m^{-2} yr^{-1} for a 15 meter wide stream corridor. Sediment production rates from undisturbed 40 m^2 hillslope plots ranged from 1 to 27 g m^{-2} yr^{-1}. Mean rates from zero- and first-order catchments were 1 and 8 g m^{-2} yr^{-1}, respectively.

Roads that are graded once every two years had sediment production rates of 0.57 and 58 kg m^{-2} yr^{-1} for roads with average slopes of 1 and 21%, respectively. Ungraded roads had sediment production rates ranging from 5.1 to 14 kg m^{-2} yr^{-1} for roads with slopes of 10 and 16%, respectively. Abandoned roads with a 15% slope had an average erosion rate of 1.1 kg m^{-2} yr^{-1}. Although cutslopes eroded at rates ranging from 2 to 17 kg m^{-2} yr^{-1}, their contribution to sediment

yields at the road-segment scale was estimated to be only about 0.9 kg m^{-2} yr^{-1}. Actively-used roads on St. John produce sediment at a rate that is up to four orders of magnitude higher than from undisturbed plots and zero-order catchments. First-order catchments receiving sediment from unpaved roads showed a mean yield rate of 38 g m^{-2} yr^{-1}, or about five times the rate of comparable undisturbed catchments.

The relative importance of each of these sediment sources in watershed-scale sediment production and yield rates is likely to change from catchment to catchment as a result of the abundance and spatial distribution of each landscape type. The data presented here are needed to develop a GIS-based model that predicts sediment production and yields at the catchment scale.

4.1 Introduction

Land disturbance generally increases sediment production rates and sediment yields above natural conditions (Walling, 1997). The effects of land disturbance in forested areas are of particular concern because natural erosion rates are so low (Dunne, 2001). Marine ecosystems—particularly nearshore coral reef communities—are sensitive to increased sediment inputs resulting from land disturbance (Hubbard, 1987; Hodgson, 1989, 1997; Rogers, 1990). An increase in sediment inputs is of particular concern in many parts of the Caribbean because of the importance of coral reefs to the local economies.

In the Caribbean region very little information is available on the amount of sediment being delivered to the marine environment (UNEP, 1994). Mass wasting processes have received significant attention from researchers because of their widespread occurrence throughout the region, and their potential for destruction and loss of life (e.g., De Graff et al., 1989; Jibson, 1989; Scatena and Larsen, 1991; Larsen and Parks, 1997; Larsen and Torres-Sánchez, 1998). Studies of surface erosion have concentrated on agricultural fields in Puerto Rico (Smith and Abruña, 1955), Tobago (Ahmad and Breckner, 1974), and Jamaica (McGregor, 1988). Other studies have used uncalibrated empirical models to predict sediment yields from areas with different land uses (e.g., Del Mar-López et al., 1998).

Increased sediment yields from land development are believed to be adversely affecting the nearshore coral reef communities of St. John in the U.S. Virgin Islands (Rogers, 1998). The unpaved road network has been identified as the primary source of the fine sediment being delivered to the marine environment (Anderson, 1994). The development and application of an empirical road erosion model (Anderson and MacDonald, 1998) suggested that road erosion is increasing watershed-scale sediment yields by up to four times above background levels (MacDonald et al., 1997). This model was based on very limited data and did not include some of the key factors controlling road erosion rates, such as precipitation, traffic, or the frequency of grading. The road erosion model also could not quantify erosion rates from natural sediment sources, and this meant that the effects of roads could not be quantified relative to natural conditions.

Improved equations to predict both natural and road-related sediment production are needed for the development of a GIS-based sediment budget model (Chapter 5). The sediment budget model is needed to quantify the sediment being delivered from different sources, identify appropriate erosion control strategies, and guide future development. Hence the main objectives of this study were to: (1) measure sediment production rates from natural and anthropogenic sources; (2) compare sediment production estimates to published data from other areas; and (3) develop empirical sediment production models for each of these sources.

A sediment budget approach provides a useful framework for evaluating the absolute and relative contribution of different sediment sources (Reid and Dunne, 1996). For a single landscape unit, a sediment budget quantitatively describes the production, movement, and storage of sediment (Dietrich et al., 1982). In this paper a landscape unit is defined as the portion of a drainage basin with similar erosion processes acting at a relatively uniform rate.

Previous work and initial field observations led to the identification of the following six landscape units on St. John: (1) streambanks, (2) stream margins subjected to soil disturbance by uprooted trees, (3) undisturbed hillslopes, (4) zero-order (unchannelled) and first-order catchments, (5) road travelways, and (6) road cutslopes. The predictive equations developed for each of these landscape units are being used in the GIS-based sediment budget model (Chapter 5).

4.2 Study Area

The island of St. John is located about 80 km east of Puerto Rico and is the third largest island within the U.S. Virgin Islands (Figure 1). Fifty-six percent of the total 50 km^2 of land area and 23 km^2 of offshore waters have been designated as a Biosphere Reserve and comprise the Virgin Islands National Park (VINP). In 2001 an additional 47 km^2 of offshore waters were incorporated into the Virgin Islands Coral Reef National Monument.

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), and are characterized by abundant coarse fragments (Soil Conservation Service, 1970). Soils tend to be shallow, moderately permeable, well-drained, and underlain by nearly impervious rocks. The topography of St. John 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 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 easternmost 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 (Sampson, 2000), and there are no perennial streams on St. John.

Precipitation in St. John can be highly erosive. The average erosivity at Caneel Bay was estimated to be 13,500 MJ mm ha^{-1} hr^{-1} (Sampson, 2000). On average, the 15-minute precipitation intensity at Caneel Bay exceeds 10 cm hr^{-1} about once a year.

Erodible banks on St. John are generally restricted to areas where streams intersect alluvial or colluvial deposits. These deposits are found primarily along the larger channels that drain to the southern coast of St. John, as the lower portions of these basins are not nearly as steep as the smaller basins draining to the north. The alluvial deposits are composed of loose, angular, gravel-sized fragments supported by a fine sand-silt matrix. The deposits show little layering or weathering and are poorly sorted. Streambanks in these areas are very steep, mostly unvegetated, and range from 0.6 to 2.5 m in height.

Dry evergreen forests and shrubs cover approximately 63% of St. John, moist forest and secondary vegetation cover another 30%, while urban, wetland, and pasture each cover about 2% of the island (Woodbury and Weaver, 1987). The shallow soils and high winds during tropical weather systems make trees very susceptible to uprooting. The taller trees along stream corridors are especially susceptible to uprooting as they are more exposed to the winds (Reilly, 1991) and their larger boles may make them less susceptible to breaking.

Over the past 30 years rapid development has resulted in the growth of the road network on St. John, particularly on private lands outside of the VINP. For example, there are 8.3 km of roads in a 1971 aerial photograph of the Fish Bay basin. By 2000 the road network has nearly tripled to 23.2 km. Fifty-six percent or 13.1 km of these roads are unpaved. The unpaved road density of the Fish Bay basin is 2.2 km km^{-2} as compared to 0.8 k km^{-2} for the Greater Lameshur Bay basin (Nemeth et al., 2001). The latter is mostly undeveloped because most of the basin is located within the VINP. This difference in density of unpaved roads should result in a marked difference in watershed-scale sediment yields.

4.3 Methods

4.3.1 Streambank Erosion

Sediment production from erodible streambanks was measured by erosion pins (Hill, 1973; Lawler, 1993; Couper et al., 2002). Four representative reaches were chosen for measurement (Figure 1). The Lameshur Bay Gut, Main Fish Bay Gut, and Little Fish Bay Gut sites (*gut* is the local term for streams) were chosen to represent second- and third-order step-pool streams with gradients ranging from 3 to 5 percent, channel widths of roughly 9 meters, and drainage areas from 0.9 to 3.8 km^2. The average streambank height was 1.8 m. The Reef Bay site was chosen to represent first-order, cascade-type streams, as it had a drainage area of 0.1 km^2, a channel gradient of 22 percent, a channel width of 6.5 m, and an average bank height of 2.3 m. All sites were located on straight reaches.

At each site 2 to 4 vertical columns of five to nine 15-cm long erosion pins were installed. Columns were spaced about 3 m apart and pins within individual columns were roughly 15 to 30 cm apart. A total of 82 pins were installed, with 2-3 cm of each pin protruding from the bank. The length protruding from the bank was measured to the nearest millimeter at the time of installation and 1-3 more times at frequencies ranging from approximately six months to just over two years. A total of 160 erosion pin measurements were collected from 1998 to 2001. The erosion/aggradation rate was the difference between consecutive pin measurements divided by the time between measurements. ANOVA tests were used to determine whether erosion rates depended on stream order, drainage area, or vertical location on the bank profile.

4.3.2 Treethrow

The number and volume of rootwads within approximately 3 m of the guts was assessed in early 2000 along 6.7 km of streams in three different south-draining basins. The second- and third-order main Fish Bay and Greater Lameshur gut reaches were chosen because these two basins were the focus of our sediment modeling (Chapter 5). Three reaches in the Reef Bay basin were chosen to represent the first-order guts draining to the south.

The volume of rootwads within 3 m of the guts was determined by measuring the diameter and thickness and assuming that the shape of the rootwad could be approximated by a cylinder. The condition of each rootwad was qualitatively described in terms of wood strength, bark condition, and the presence or absence of soil and small roots within the rootwad (Dynesius and Jonsson, 1991). The mass of sediment delivered to the stream from each rootwad was estimated as the product of its volume, percent soil, and an estimated bulk density for dry soil. The percent soil per volume was determined for those uprooted trees that had a significant amount of soil in the rootwads. The average percent soil from these rootwads was extrapolated to the more decayed rootwads for which there was no sufficient soil to make an estimate. The rate of sediment delivery to the stream network in tonnes of soil per kilometer of stream per year was calculated from the sum of the soil in the rootwads divided by the total length of the reach surveyed and the time represented by our field observations. The last component was the most difficult, as this necessitated the age of the oldest rootwads and whether the frequency of rootwads observed in 2000 was representative of long-term conditions.

4.3.3 Plot-scale Runoff and Sediment Production

Runoff and sediment production were measured from three 40 m^2 plots on undisturbed planar hillslopes. Two of the plots were in the Haulover Bay area on the eastern end of the island and one in the Fish Bay basin (Figure 1). The two Haulover plots were on 30% slopes dominated by dry evergreen thorn and cactus vegetation (Figure 2a). The Fish Bay plot was located on a 23% slope covered by dry evergreen thicket and scrub (Figure 2b). The plots were installed in 1996 (Sampson, 2000; MacDonald et al., 2001) and intermittently monitored from the latter part of 1998 through December 1999. The plots were approximately 10 m long and 4 m wide, and were bounded by 15-cm wide aluminum flashing inserted into a 5-cm trench dug along the boundaries of the plot. Runoff was routed into 100-L plastic reservoirs. An equivalent runoff total of 0.25 cm was the maximum runoff depth that could be measured from the plots. Two 0.5-L water samples were collected immediately after vigorously mixing the water in the containers. The total concentration of solids in each of the samples was determined in the lab following standard filtering and drying techniques (ASTM, 1997).

Rainfall data for all Fish Bay plot measurements and the 21 September 1998 Haulover-B plot measurement were obtained from a raingauge in the lower Fish Bay basin (Figure 1) located about 1.2 and 8 km from the Fish Bay and Haulover plots, respectively. Rainfall data for the remaining measurements at the Haulover plots were obtained from a raingauge in Maho Bay (Figure 1). The rainfall data were used to calculate storm event precipitation, maximum 60-minute intensities, storm erosivities, and an antecedent precipitation index (API) (Dunne and Leopold, 1978). The API for any given day was calculated as

$$I_n = I_{n-1} k^t \qquad \text{(eq. 1)}$$

where I_n is the antecedent precipitation index value in centimeters, n is the day number starting from 1 at the beginning of the calculation period, k is a constant with a value of 0.9, and t is the time in days since the last rainfall. The index for any day is obtained by keeping a running calculation in which the previous day's value is multiplied by k^t. If rain occurs, the amount of rain is added to the index, t is set to zero, and the procedure is continued.

4.3.4 Runoff and Sediment Production from Zero- and First-order Catchments

Sediment production rates from forested sub-catchments were measured by sediment fences (Robichaud and Brown, 2002). Fences on undisturbed areas were installed in three zero-order catchments near Bordeaux Mountain, one zero-order and one first-order catchment in Maho Bay, and one first-order basin in the Reef Bay catchment (Figure 1). Sediment fences were also installed on two first-order catchments in the Reef Bay basin that are receiving sediment from unpaved roads (Figure 1). The drainage areas of these catchments ranged from 0.9 to 15 ha and the average hillslope gradients ranged from 15% to 37% (Table 4). All of these catchments were covered by moist forest vegetation. The sediment trapped in the fences was collected and weighed about once a year, as only the most intense precipitation events produced measurable amounts of sediment. Samples were collected to determine percent moisture (Gardner, 1986), and the data were used to convert the field-measured wet weights to a dry mass. The particle-size distribution was analyzed by dry sieving (Bowles, 1992) for one sample from each basin except for the Zero-BM-C and 1st-RB-A sites. No particle-size distribution was determined for the Zero-BM-C catchment, while the particle-size distribution for the sediment collected from the 1st-RB-A catchment was a mass-weighted average of three samples.

Three crest gages were used to monitor peak water levels on the west-facing sideslope of the 2.3 ha zero-order catchment at Maho Bay (Zero-MB-A). Crest gage MB-R1 was about 6 m from the axis of the catchment, while MB-R2 and MB-R3 were 10 and 36 m from the axis, respectively. During or immediately after rainfall events field observations were made at the intersection of the Zero-MB-A catchment with the Maho Bay road to determine if the catchment had generated surface runoff. More intensive observations were made from August 1999 to May 2000 because the runoff was affecting an unpaved road segment that was being intensively studied (Chapter 3). Rainfall intensities and totals were recorded by a tipping-bucket rain gauge located approximately 200 m from the lower end of the catchment (Figure 1). The maximum water heights were related to storm rainfall, antecedent precipitation index, and distance from the axis.

4.3.5 Surface Erosion from Unpaved Road Segments

As described in Chapter 2, sediment production from 21 road segments was monitored from July 1998 to November 2001 with sediment fences (Robichaud and Brown, 2002) (Figures 3a-3c). The road segments were in different precipitation zones and selected to represent a range of road surface areas, slopes, and traffic rates (Figure 4). The mean slope of these segments was 10% and the range was from 1% to 21%. Precipitation was measured by five recording raingauges (Figure 1).

Eighty sediment production measurements were obtained during the study period. For each road segment the effect of precipitation was evaluated by plotting sediment production against total precipitation. 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 gradient and total precipitation—for two different traffic levels. Grading effects were identified by plotting sediment production—normalized by precipitation and gradient—against time since grading. Multiple regression analyses led to the development of an empirical road erosion model based on precipitation, $slope^{1.5}$, and a categorical variable representing time since grading.

The particle-size distribution of 40 samples from the sediment fences was 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 the three classes of graded, ungraded, and abandoned roads. A mass-weighted average particle-size distribution was calculated for each of the 21 road segments.

4.3.6 Sediment Production from Road Cutslopes

The sediment fences on road segments incorporated sediment from both the road tread and the cutslopes. To separate these two components, 10 sediment fences were installed at the base of cutslopes. Two fences were quickly vandalized, and the remaining eight plots were in the Maho Bay area and along John Head Road in Catherineberg Estate (Figure 4).

The eight cutslopes were nearly vertical with less than 10% vegetation cover. Cutslope heights ranged from 1.2 to 4.2 m. The average contributing area was 16 m^2, and values ranged from 5.2 to 34 m^2. Two of the cutslopes were exclusively composed of residual soil, two others were made mostly of slightly weathered bedrock, and the remaining four cutslopes were dominated by moderately weathered bedrock. Eighteen measurements were taken between 1998 and 2000 at frequencies ranging from a few months to just over a year, and two measurements were taken from the JH-A and JH-B plots in 2001. Multiple regression analysis was used to determine whether total precipitation, cutslope height, or the weathering degree had any effects on sediment production rates. The particle-size distribution was determined for eight sediment samples by the dry-sieving method (Bowles, 1992). These samples represented all of the cutslope plots except for the MB-A and MB-B.

The proportion of the cutslope sediment that might be delivered to the outlet of a road segment was estimated by a visual classification system. A delivery potential of 75% was assumed for cutslopes with ditches or concentrated flowpath at their toe, as the presence of depositional aprons indicated that sediment delivery was less than 100%. Cutslopes within 3 m from the road tread but not delivering sediment directly to a ditch or concentrated flowpath were assumed to have a delivery ratio of 10%. Zero delivery was assumed for cutslopes located more than 3 m from a ditch or flowpath. The measured cutslope sediment production rates and estimated delivery rates were used to estimate the relative contribution of cutslopes to the measured sediment production rates at the road segment scale.

4.4 Results and Discussion

4.4.1 Streambank Erosion

The mean bank erosion for all 160 measurements was 0.4 cm yr^{-1}, but the data were highly variable as the standard deviation was 2.8 cm yr^{-1}. Values for individual pin measurements varied from -13 cm yr^{-1} to 18 cm yr^{-1}. The data showed a complex temporal and spatial pattern of deposition (negative values), inactivity (zero values), and erosion (positive values). In order to minimize the temporal variability in the data, a net erosion/aggradation rate for each pin was calculated as the difference between the initial and the last measurement divided by the total study period. The resulting 79 measurements represented time periods of 0.7 to 3 years, and the mean erosion rate was 0.7 cm yr^{-1} (s.d. 1.5 cm yr^{-1}). The highest average erosion rate was the Main Fish Bay Gut at 1.5 cm yr^{-1}, while the lowest rate was 0.1 cm yr^{-1} at Lameshur Gut (Figure 5).

Stream order did not appear to affect bank erosion rates. Erosion rates from the first-order Reef Bay site averaged 0.6 cm yr^{-1}, and the mean erosion rate on the second- and third-order streams was only slightly higher at 0.8 cm yr^{-1}. This difference was not statistically significant ($p = 0.65$). Similarly, bank erosion rates were not related to drainage area ($p = 0.08$, $R^2 = 0.21$). The lack of relationship between bank erosion rates and drainage area is presumed to be due to the limited number of study sites and the limited range in drainage area.

Vertical location along the bank profile did appear to be an important control on bank erosion rates. Pins in the upper one-third of the streambank had a mean erosion rate of 1.2 cm yr^{-1} (s.d. 1.9 cm yr^{-1}), while the average erosion rate for pins in the middle third of the streambank was only 0.3 cm yr^{-1} (s.d. 0.7 cm yr^{-1}). Pins in the lower third of the streambank had a mean erosion rate of 1.2 cm yr^{-1} (s.d. 2.3 cm yr^{-1}). The differences in erosion rates between the upper and mid sections, and between the lower and mid sections were both statistically significant ($p = 0.01$ and 0.03, respectively). The high rates of erosion in the upper portion of the streambank imply continuing erosion and an unstable bank shape. The slower erosion rate in the middle section is probably due to temporary storage of some of the material produced from the upper portions of the banks. Material stored on the lowermost portions of streambanks was probably removed by streamflow, and this is also expected to occur on the middle sections over a longer time period.

The overall mean erosion rate of 0.7 cm yr^{-1} provides an initial estimate of long-term bank erosion rates on St. John. Assuming a dry bulk density of 1.4 tonnes m^{-3}, the average sediment production rate is nearly 10 kg m^{-2} yr^{-1} (Figure 6). Published data indicate that bank erosion rates increase with increasing drainage area (e.g., Hooke, 1980; Lawler, 1993). Studies from other areas have reported streambank erosion rates of 0.6 to 8.0 cm yr^{-1} for streams with drainage areas ranging from 0.13 to 9.6 km^2 (Table 1). The values for St. John fall at the low end of this range.

4.4.2 Sediment Delivery by Treethrow

The mean number of uprooted trees along the five surveyed stream reaches was 11 trees km^{-1}, and the range was from 7 to nearly 20 trees km^{-1} (Table 2). On average each rootwad contained 1.1 m^3 of sediment, yielding a mean value of 12 m^3 of treethrow sediment per kilometer of stream. Assuming a dry bulk density of 1.4 tonnes m^{-3}, approximately 17 tonnes of sediment are delivered to the stream network per kilometer of stream channel.

The conversion of these values into a sediment delivery rate per unit time proved to be difficult. The oldest uprooted trees had softened wood, smooth trunk surfaces that had lost over half of their bark, and had lost most of their soil and small roots. The use of published techniques to determine the time since uprooting (Dynesius and Jonsson, 1991) was questionable because there are no published data on log decay rates in a dry tropical environment such as St. John. The literature suggests that log decay in a dry tropical environment will be faster than the 100 years estimated for boreal forests (Dynesius and Jonsson, 1991), but slower than the 10 years documented for wet tropical environments in Panamá (Lang and Knight, 1979) and Puerto Rico (Odum, 1970). Hurricane Hugo in 1989 was the first major hurricane to affect St. John in 73 years (Potter et al., 1995), so the treethrow surveys effectively represent treethrow over the past eleven years (G. Ray, University of the Virgin Islands, pers. comm.; P. Weaver, U.S. Forest Service, pers. comm.).

Dividing the 17 tonnes per kilometer of stream by 11 years yields a rate of 1.5 tonnes km^{-1} yr^{-1}. This value is probably an overestimate because St. John has experienced a marked increase in the frequency of severe hurricanes in the last 11 years. Sustained winds on the nearby island of St. Thomas reached 192 km hr^{-1} during Hurricane Hugo in 1989 (Case and Mayfield, 1990), 165 km hr^{-1} during Hurricane Marilyn in 1995 (Lawrence et al., 1998), 237 km hr^{-1} during Hurricane Georges in 1998 (Pasch et al., 2001), and 165 km hr^{-1} during Hurricane Lenny in 1999 (Lawrence et al., 2001).

The average interval between major treethrow events on St. John is difficult to determine. The entire territory of the U.S. Virgin Islands—including the islands of St. Croix, St. Thomas, and St. John—is affected by major hurricanes about once every 12 to 15 years (Potter et al., 1995). The return period of hurricanes in Jamaica is in the order of once every 15 years, but the return period of storms that induce significant treethrow and forest damage is much longer (Bellingham, 1991). The mean time period for a major hurricane to pass over a given island in the Caribbean is 70 years (Neumman et al., 1978), which is close to the 50-60 year interval calculated for the Luquillo Experimental Forest in eastern Puerto Rico (Scatena and Larsen, 1991).

If the hurricanes that cause substantial amounts of treethrow occur about once every 50 years on St. John, and two such events occurred in 1989 and 2000 (hurricanes Hugo and Georges, respectively), then the measured treethrow actually represents the mass of sediment that would normally occur over 100 years. On this basis, the long-term sediment production rate by treethrow is 0.17 tonnes km^{-1} yr^{-1}. For a 15 meter wide stream corridor—consisting of 9 m of channel and a 3 m wide buffer zone—the treethrow sediment production rate by unit area is estimated as 11 g m^{-2} yr^{-1}.

The only other estimate of sediment delivery rates from uprooted trees along stream margins is 1 m^3 km^{-1} yr^{-1} for the Olympic Mountains in the northwestern U.S. (Reid, 1981). This converts to 1.3 tonnes km^{-1} yr^{-1} if a dry bulk density of 1.4 tonnes m^{-3} is assumed. This rate is almost an order of magnitude higher than the 0.17 tonnes km^{-1} yr^{-1} estimated for St. John, and the difference is due to a much larger volume of soil in each rootwad as well as the larger number of overturned trees per kilometer of stream channel.

4.4.3 Plot-scale Runoff and Sediment Production from Undisturbed Hillslopes

Runoff volumes and sediment concentrations were obtained for five events between August 1998 and December 1999. Runoff and sediment might have been produced at other times, but problems with the operation of the plots did not permit the collection of measurements during those events. The measurements taken between 1998 and 1999 and the data collected in 1996 (Sampson, 2000) are shown in Table 3. Storm precipitation ranged from 2.1 to 13.1 cm. Mean runoff values for the Haulover-A, Haulover-B, and Fish Bay plots were 0.07, 0.11, and 0.11 cm, respectively. Runoff was produced only by storms with at least two centimeters of rainfall, while storms larger than 6.4 cm sometimes exceeded the capacity of the runoff storage containers. For example, runoff volumes for the 10 September 1996 storm on the Fish Bay plot and the 16 November 1999 event for all three plots are minimum values as the storage capacity of 0.25 cm of runoff was exceeded. Excluding these four measurements the mean runoff coefficient was 0.02 cm cm^{-1} and the range was from 0.00 to 0.07 cm cm^{-1}. This indicates that for storms with less than 6.4 cm of rainfall, runoff from undisturbed hillslopes was only a very small fraction of the total rainfall.

Runoff totals were poorly correlated with storm precipitation, maximum 60-minute rainfall intensities, and storm erosivities (R^2 = 0.34, 0.02, 0.23, respectively). Storm runoff was more closely related to the sum of storm rainfall (P) and antecedent precipitation index (API), but the data still show considerable variability in runoff response (Figure 7).

Sediment concentrations ranged from 0.00 to 2.56 g L^{-1}. The mean sediment concentrations from the plots at Haulover Bay were about an order of magnitude higher than the Fish Bay plot (Table 3). The higher concentrations at Haulover are probably due to the slightly higher slopes and less ground cover relative to Fish Bay.

Sediment concentrations were not correlated with storm rainfall, maximum 60-minute precipitation, or rainfall erosivity (R^2 values < 0.002). This justifies the use of average concentrations for estimating longer-term erosion rates. Using the mean sediment concentrations and the mean runoff totals, the mean sediment production rate per centimeter of rainfall is 0.2, 0.8, and 0.03 g m^{-2} cm^{-1} for the Haulover-A, Haulover-B, and Fish Bay plots, respectively. Annual erosion rates are estimated based on the assumption that all storms larger than 2 cm will produce runoff and sediment, regardless of their API value. Long-term rainfall data from Caneel Bay shows that storms with at least 2.0 cm of rainfall account for 34 cm or 32% of the mean annual rainfall. The long-term estimated erosion rates for the Haulover-A and Haulover-B plots are 10 and 27 g m^{-2} yr^{-1}, while the Fish Bay plot is estimated to erode at a rate of 1 g m^{-2} yr^{-1}.

4.4.4 Runoff and Sediment Production from Zero- and First-order Catchments

The crest gage data suggest that saturated conditions begin to develop within the soil profile when storm rainfall exceeds about 2 cm. As storm precipitation increases the height of saturation appears to asymptotically approach the soil surface (Figure 8). For a given storm, events with higher API values tended to have higher crest gage readings. Distance from the catchment axis was not a major control on the depth to saturation, although the crest gage closest to the axis (MB-R1) did tend to have slightly lower water levels for intermediate-sized storms (Figure 8).

Qualitative runoff observations were made at the bottom of the Zero-MB-A catchment for many of the 602 storm events from July 1998 to May 2000. Storm rainfall over this period ranged from 0.03 to 9.5 cm with a maximum 60-minute intensity of 7.9 cm hr^{-1}. Surface runoff was observed for only seven storms and it generally lasted less than one hour after the end of precipitation. All seven of those storms had API values greater than 5 cm, and all but one had at least 3.5 cm of rainfall. Only three events resulted in measurable sediment accumulations in the sediment trap, and these were the only events with at least 6 cm of precipitation.

Sediment yields from the four zero-order basins ranged from 9-41 kg, while the two undisturbed first-order basins yielded 310 and 2100 kg, respectively (Table 4). The two disturbed first-order basins yielded 12,500 and 5,850 kg of sediment. When divided by the amount of precipitation that fell in storms of at least 6 cm, the average sediment yield rate from the four zero-order basins was 0.064 g m^{-2} per centimeter of precipitation versus 0.5 g m^{-2} cm^{-1} for the two undisturbed first-order basins. The two disturbed first-order basins yielded sediment at a rate of 2.4 g m^{-2} cm^{-1}, or almost five times higher than the value from the comparable undisturbed basins. It must be noted that the values from the two undisturbed catchments are minimum rates, as the traps were overtopped by sediment during Hurricane Georges in 1998 and Hurricane Lenny in 1999. The approximately 0.3 km of unpaved roads in each of these two catchments are assumed to be responsible for these higher rates.

The long-term rainfall data from Caneel Bay shows that events larger than 6 cm account for 16 cm or 14% of the mean annual rainfall. If the normalized rates in Table 4 are multiplied by 16 cm yr^{-1}, the resulting sediment yield rates from zero-order basins are approximately 1 g m^{-2} yr^{-1}, while the undisturbed first-order basins yield approximately 8 g m^{-2} yr^{-1} (Figure 6). The two first-order catchments receiving sediment from unpaved roads yield sediment at a rate of 38 g m^{-2} yr^{-1}.

On average, the sediment from the zero-order catchments had more sand and less gravel than the sediment from the undisturbed first-order catchments. The mass-weighted average of the sediment from the zero-order catchments was 42% gravel, 57% sand, and 0.4% silt and clay (Figure 9; Appendix III). The mean particle-size distribution of the sediment from the two undisturbed first-order catchments was 71% gravel, 28% sand, and 1%

silt and clay. The sediment from the two disturbed first-order catchments had much more sand than the sediment from the undisturbed first-order basins, as the mass-weighted average from the disturbed basin was 43% gravel, 55% sand, and 2% silt and clay.

Plot-scale sediment production rates were generally higher and more variable than the rates obtained from zero-order basins (Figure 6). The differences might be due to lower slopes and higher sediment storage capacities of zero-order catchments relative to hillslope plots (Tables 3 and 4). Sediment production rates from undisturbed first-order catchments were one or two orders of magnitude higher than the rates from zero-order catchments. The addition of streambank and treethrow erosion could account for the higher rates measured from first-order catchments.

In the Maho Bay first-order catchment the entire 50 m of channel had erodible streambanks 0.75 m in height. If the treethrow rate is 1.3 tonnes km^{-1} yr^{-1}, the bank erosion rate is 10 kg m^{-2} yr^{-1}, and the surface erosion rate is 1 g m^{-2} yr^{-1}, the total sediment yield over the 5.4 ha area is 16 g m^{-2} yr^{-1}. This value is 3.7 times higher than the measured rate of 4.3 g m^{-2} yr^{-1} over the study period. The four-fold difference is probably due to sediment storage within the basin and spatial variability in the estimated erosion rates.

The same calculation was performed for the undisturbed first-order catchment in Reef Bay. In this case there were no erodible streambanks along the 660 m of channel upstream of the sediment trap, so the estimated sediment production rate from treethrow and surface erosion was 6.8 g m^{-2} yr^{-1}. This value is 43% lower than the measured value of 12 g m^{-2} yr^{-1}. Although there are discrepancies between the calculated and measured sediment yields for these two undisturbed first-order catchments, the similar order of magnitude is encouraging and supports the validity of the underlying estimates.

4.4.5 Surface Erosion from Unpaved Roads

The average road erosion rate for the 21 road segments was 0.064 kg m^{-2} per centimeter of precipitation. Sediment production from unpaved roads was related to total precipitation and road segment slope. After normalizing by precipitation and slope, roads that had been graded within the last two years had a mean sediment production rate of 0.96 kg m^{-2} cm^{-1}, while the mean erosion rate for ungraded roads was 41% lower, or 0.56 kg m^{-2} cm^{-1}. Road segments that had been abandoned for over fifteen years had an average normalized sediment production rate of 0.071 kg m^{-2} cm^{-1}, or only about 10% of the average for ungraded roads. Traffic levels were not related to sediment production.

Multiple regression led to the development of empirical road erosion models for graded (eq. 2a) and ungraded (eq. 2b) roads.

$$E_r = -0.432 + 4.73 \cdot slope^{1.5} \cdot precipitation \qquad \text{(eq. 2a)}$$

$$E_r = -0.432 + 1.88 \cdot slope^{1.5} \cdot precipitation \qquad \text{(eq. 2b)}$$

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

Estimated annual erosion rates for graded road segments averaged 11 kg m^{-2} yr^{-1} (Figure 6). Measured sediment production rates for graded roads with slopes of 2 and 21 percent were 0.57 and 58 kg m^{-2} yr^{-1}, respectively. Ungraded roads had an average measured sediment production rate of 8.6 kg m^{-2} yr^{-1}, with values ranging from 5.1 to 14 kg m^{-2} yr^{-1} for roads with slopes of 10% and 16%, respectively. The average erosion rate for abandoned roads with a 15% slope was 1.1 kg m^{-2} yr^{-1}. These rates indicate that actively used roads are capable of increasing road-segment and hillslope-scale sediment production by up to four orders of magnitude relative to undisturbed plots and zero-order catchments (Figures 6 and 10).

The particle-size distribution of the sediment produced from roads is much finer than the sediment produced from undisturbed first-order catchments, but similar to the sediment from undisturbed zero-order catchments (Figures 9 and 11). For the 20 actively-used road segments, 40% of the eroded material was gravel, 54% was sand, and 6% was silt and clay. For the undisturbed first-order basins, gravel comprised 71% of the eroded sediment, and sand was only 28%.

4.4.6 Sediment Production from Road Cutslopes

The mean sediment production rate from cutslopes was 10 kg m^{-2} yr^{-1} (n=20), and the range was from 2.0 to 17 kg m^{-2} yr^{-1} (Table 5). The range of values over the time period represented by individual measurements was from 0.3 to 35 kg m^{-2} yr^{-1}.

The mean sediment production rate from slightly-weathered cutslopes was 3.9 kg m^{-2} yr^{-1}, while cutslopes composed of moderately-weathered bedrock and residual soil had mean sediment production rates of 9.3 and 14 kg m^{-2} yr^{-1}, respectively. The small samples sizes relative to the variability meant that the differences in mean erosion rates among the three weathering classes were not statistically significant. Cutslope erosion rates were not related to precipitation or cutslope height.

The reported range of sediment production rates for cutslopes is from 0.01 to 37 kg m^{-2} yr^{-1}, and this easily encompasses the measured values from St. John (Table 6). At 10 kg m^{-2} yr^{-1}, the mean sediment production rate from cutslopes is only 10% lower than the mean production rate from graded roads, and 1.1 times higher than the value from ungraded roads (Figure 6).

The particle-size analyses showed that the sediment from cutslopes was coarser than the sediment collected at the road-segment scale. On average, the sediment produced from cutslopes was 61% gravel, 38% sand, and only 1% silt and clay (Figure 11; Appendix III).

A visual classification system determined that cutslopes contributed from 0 to 62% of the sediment collected at the road segment scale (Table 7). The total amount of sediment from the 20 road segments was about 1500 kg per centimeter of rainfall, and the total sediment from cutslopes for these road segments was 160 kg cm^{-1}. The data indicate that, on average, only 11% of the sediment produced at the road segment scale is derived from cutslopes. The average sediment production rate for cutslopes at the road segment scale is estimated to be 0.04 kg m^{-1} cm^{-1}. Assuming an annual rainfall of 115 cm and a 5 m wide road, cutslopes are estimated to contribute a total of 0.9 kg m^{-2} yr^{-1} to sediment yields at the road segment scale. This estimate suggests that on average only 9% of the mean cutslope sediment production rate (10 kg m^{-2} yr^{-1}) contributes to road segment scale sediment production.

The relative contribution of cutslopes to sediment yields from road segments has been rarely reported. In the Olympic Peninsula of Washington cutslopes were estimated to contribute 0.8 kg of sediment per meter of road per year, or less than 2% of the sediment produced from the travelways of actively-used logging roads (Reid, 1981). In the Oregon Coast Range the lack of a significant relationship between cutslope height and road segment sediment yields suggested that cutslope contributions play a secondary role relative to factors controlling the rate of sediment production from the travelway and ditch (Luce and Black, 2001).

4.5 Conclusions

Sediment production rates were measured from both natural and road-related sources on the island of St. John. The resulting values ranged over five orders of magnitude. Streambanks eroded at an average rate of 10 kg m^{-2} $yr^{-}1$, which was the highest sediment production rate among natural sources of sediment. The uprooting of trees along stream margins was estimated to deliver 0.17 tonnes of sediment per kilometer of stream per year, or 11 g m^{-2} yr^{-1} for a 15-m wide stream corridor.

Sediment production from undisturbed areas ranged from 0.5 to 27 g m^{-2} yr^{-1} at the zero-order and plot scales, respectively. These differences in sediment production rates might be due to lower average slopes and higher sediment storage capacities of the zero-order catchments relative to the hillslope plots. Undisturbed first-order catchments yielded sediment at a mean rate of 8 g m^{-2} yr^{-1}. The addition of streambank and treethrow erosion appears to account for the higher rates measured from first-order catchments relative to zero-order catchments. Contributions from unpaved roads to two first-order catchments are responsible for a mean sediment production rate of 38 g m^{-2} yr^{-1}, which is five times higher than sediment production rates from undisturbed first-order catchments.

Rainfall, road slope, and frequency of grading significantly affected sediment production rates from road segments. Sediment production rates from road segments that are regraded once every two years ranged from 0.57 to 58 kg m^{-2} yr^{-1} for roads with average slopes of 1 to 21%, respectively. Ungraded roads had sediment production rates ranging from 5.1 to 14 kg m^{-2} yr^{-1} for roads with slopes of 10 and 16%, respectively. Abandoned road segments with a slope of 15% had a mean erosion rate of 1.1 kg m^{-2} yr^{-1}. Sediment production rates from cutslopes ranged from 2 to 17 kg m^{-2} yr^{-1}, but their estimated contribution to sediment yields at the road segment scale is only 0.9 kg m^{-2} yr^{-1}. The latter value is an order of magnitude less than their production rates.

These values indicate that actively-used roads can increase road segment and hillslope scale sediment production rates by up to four orders of magnitude relative to values from undisturbed plots and zero-order catchments. The relative importance of each of these sediment sources in watershed-scale sediment production and yield rates is likely to change from catchment to catchment as a result of the abundance and spatial distribution of the different landscape units. The development and application of a GIS-based sediment model is presented in Chapter 5.

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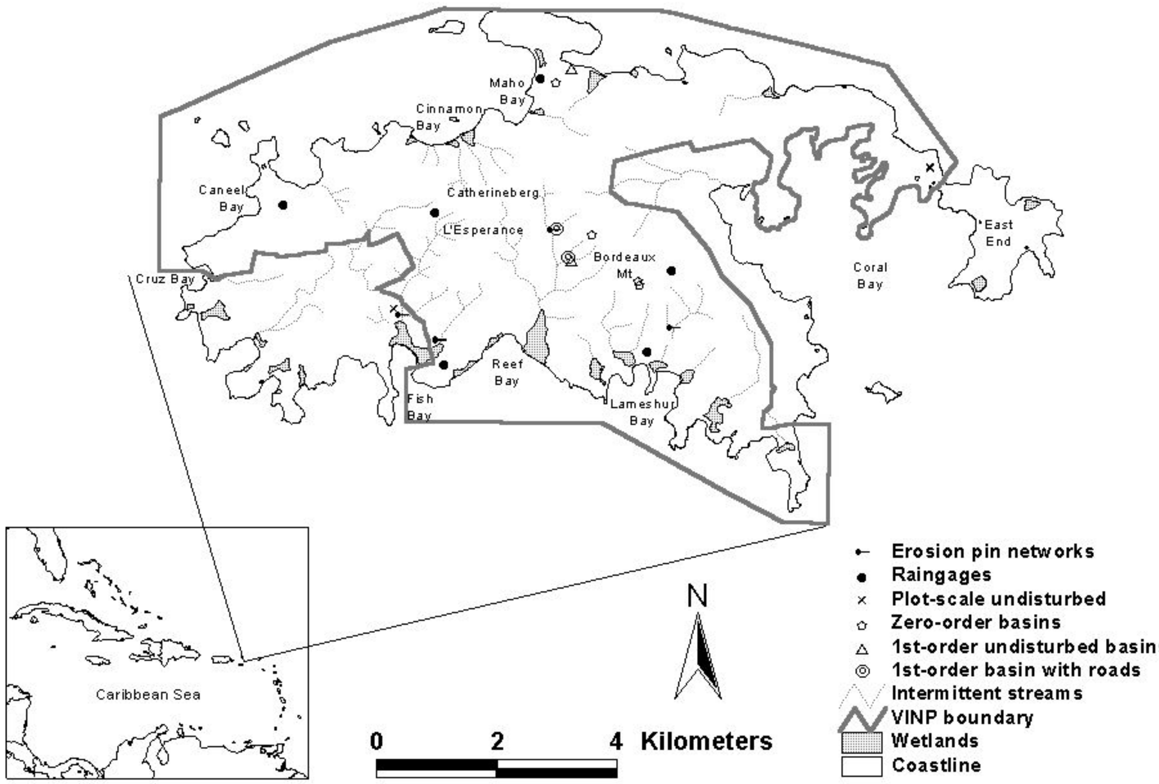

Figure 1. Map of St. John showing the Virgin Islands National Park boundary and the location of measurement sites for natural sediment sources.

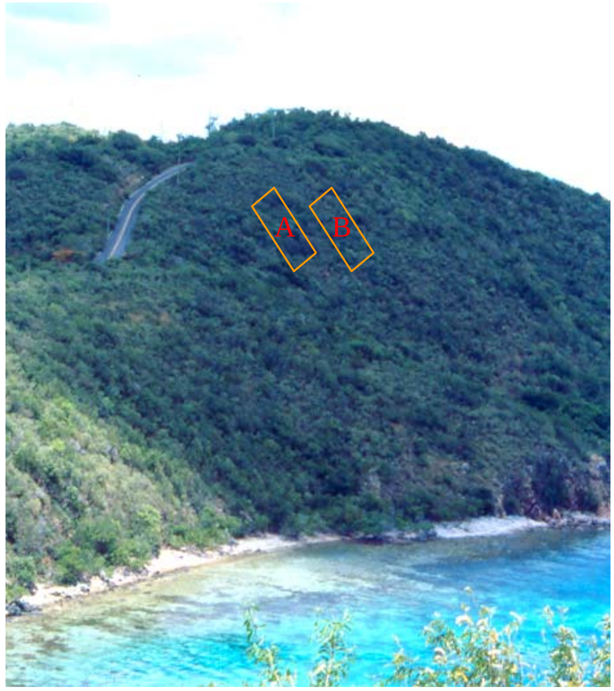

Figure 2a. Undisturbed plots at Haulover Bay.

Figure 2b. Undisturbed plot at Fish Bay.

Figure 3a. Graded road segment JH-A1.

Figure 3b. Ungraded road segment FB-Coco.

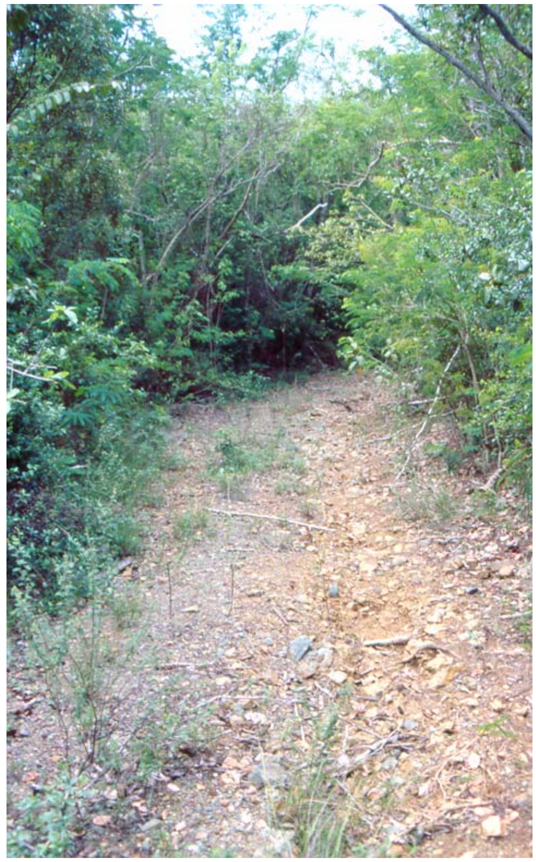

Figure 3c. Abandoned road segment LE-Top.

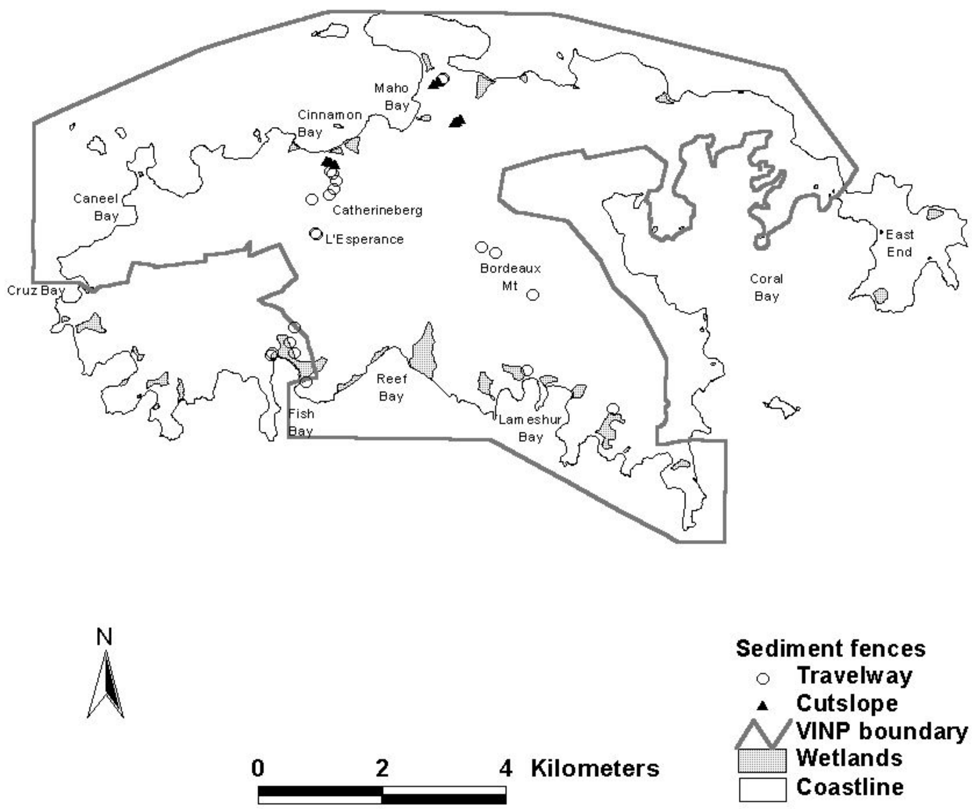

Figure 4. Map of St. John showing the location of the sediment fences used to measure erosion from road segments and road cutslopes.

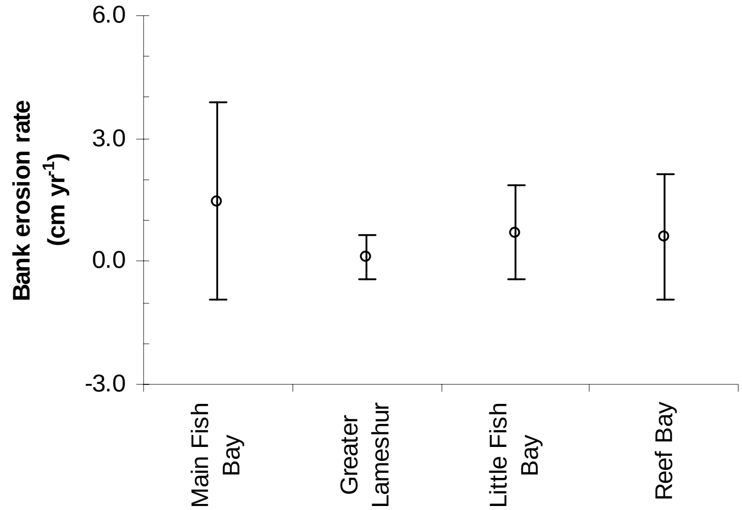

Figure 5. Average bank retreat rates by study site. Error bars indicate one standard deviation, and negative values indicate net deposition.

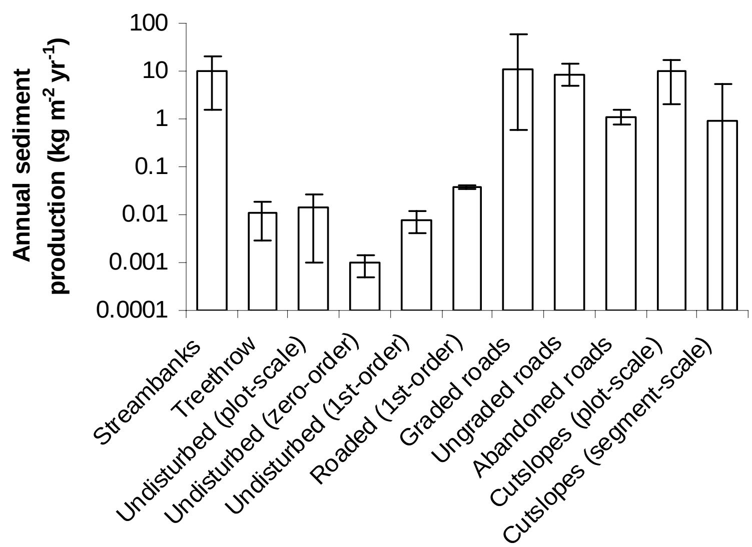

Figure 6. Annual sediment production rates from natural and anthropogenic sediment sources on St. John. Columns show average values, and bars indicate the range of values.

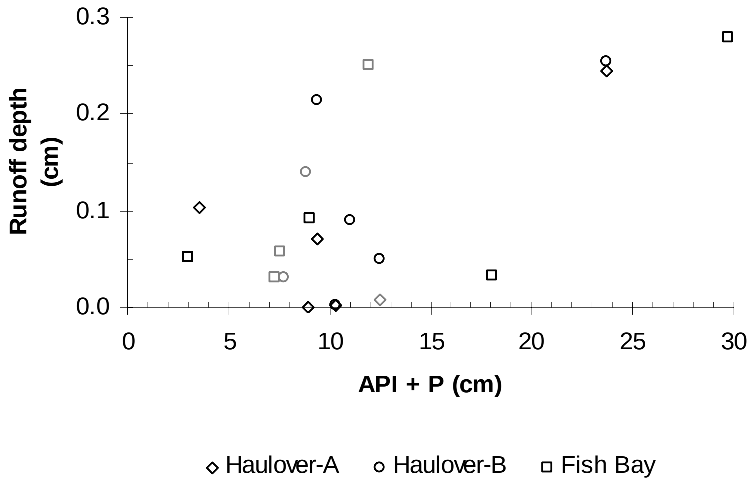

Figure 7. Runoff depth from the three undisturbed plots versus the sum of the antecedent precipitation index (API) plus storm precipitation (P). The points plotted in gray are the data collected by Sampson (2000).

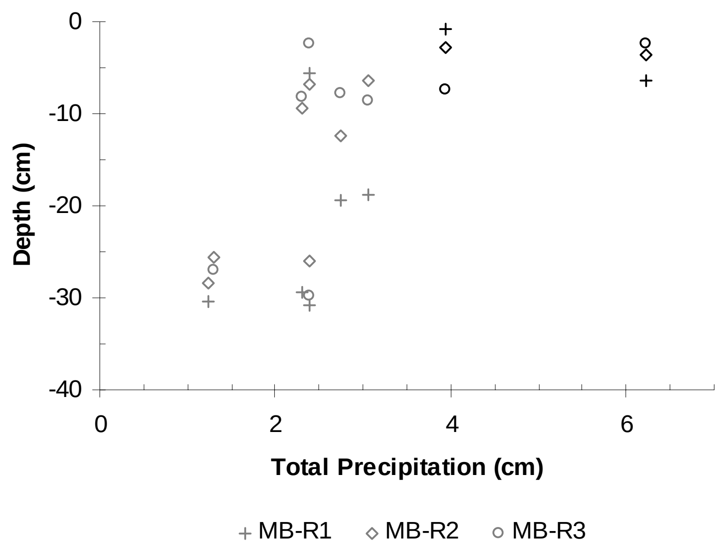

Figure 8. Depth to the saturated zone for each of the three crest gages versus storm precipitation. Points in bold are the storms that generated runoff from the zero-order catchment where the crest gages were located.

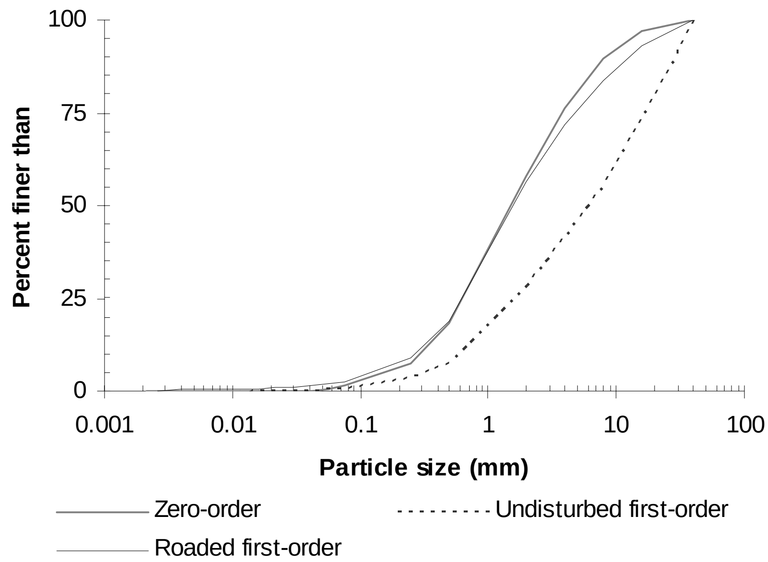

Figure 9. Mass-weighted particle-size distribution for the sediment from undisturbed zero-order catchments, undisturbed first-order catchments and roaded first-order catchments.

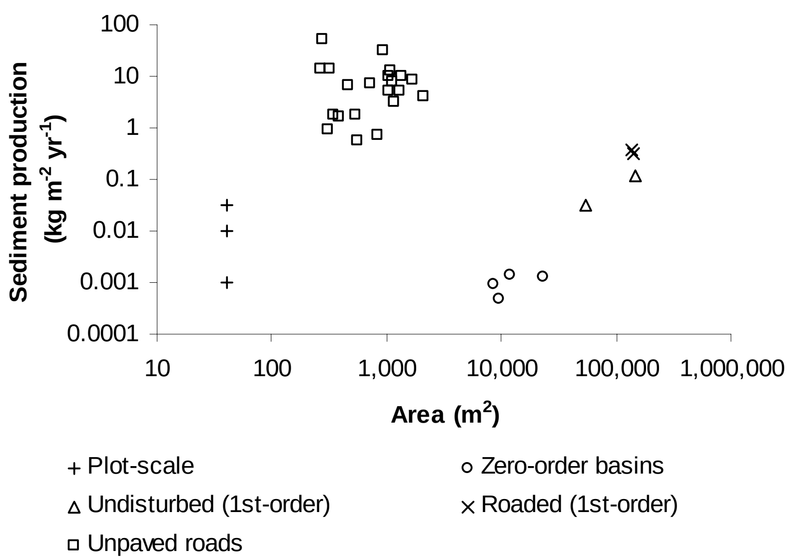

Figure 10. Sediment production rates per unit area per centimeter of rainfall versus contributing area.

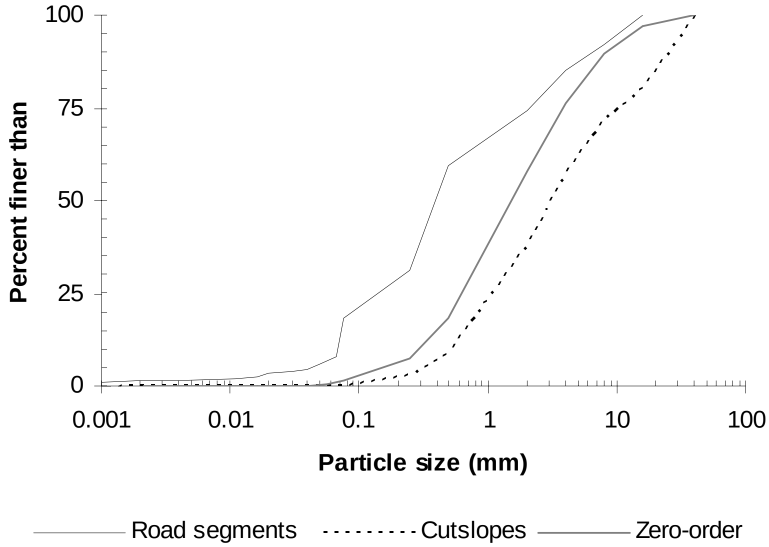

Figure 11. Mass-weighted particle-size distribution for the unpaved roads, the cutslopes, and the zero-order catchments.

Table 1. Summary of bank retreat rates measured from streams with drainage areas smaller than 10 km^2 (data from Lawler, 1993).

Location	**Drainage area (km^2)**	**Bank retreat rates (cm yr^{-1})**	**Reference**
Maryland, USA	0.13	0.6	Leopold et al. (1966)
Northern Ireland	3.4	0.03 -0.05	Hill (1973)
Luxemburg	1.6	0.8	Imeson and Jungerius (1974)
Wales	0.5	~3.0	Lewin et al. (1974)
England	10	8.0	Hooke (1979)
England	4.7	< 3.0	Murgatroyd and Ternan (1983)
St. John	0.14 – 3.8	0.1 – 1.5	This study

Table 2. Summary of treethrow surveys along five stream reaches on St. John.

Reach	**Length of reach (km)**	**Number of uprooted trees**	**Uprooted trees per km of stream**	**Total sediment in rootwads (m^3)**	**Mean volume of sediment per rootwad (m^3)**	**Volume of sediment per km of stream (m^3 km^{-1})**	**Mass of sediment per km of stream (tons km^{-1})**
Reef Bay-A	0.61	12	19.6	3.0	0.3	4.9	6.9
Reef Bay-B	0.96	14	14.6	19	1.4	20	28
Reef Bay-C	0.95	9	9.5	3.2	0.4	3.4	4.7
Lameshur	0.80	6	7.5	2.6	0.4	3.2	4.5
Fish Bay	3.35	33	9.8	52	1.6	16	22
Mean	**1.1**	**12**	**11.1**		**1.1**	**12**	**17**

Table 3. Runoff and sediment production from the three undisturbed plots. Sediment production per unit rainfall was calculated by multiplying the plot average sediment concentration by the total runoff per event. An asterisk indicates those events for which runoff is underestimated. NA indicates not available.

Plot	**Date of storm**	**Total Rainfall (cm)**	**Maximum 1-hr rainfall intensity (cm hr^{-1})**	**Antecedent precipitation index (cm)**	**Runoff (cm)**	**Runoff coefficient (cm cm^{-1})**	**Sediment concentration (g L^{-1})**	**Sediment production per unit rainfall (g m^{-2} cm^{-1})**
Haulover-A	10 Sep 96	5.6	1.6	3.4	0.000	0.000	NA	0.00
	4 Dec 98	2.1	1.1	8.3	0.002	0.001	NA	0.02
	8 Apr 99	3.6	1.7	0.0	0.103	0.029	0.18	0.42
	10 Nov 99	3.1	2.8	6.2	0.070	0.022	0.75	0.33
	16 Nov 99	7.2	1.4	16.6	0.244*	0.034	0.33	0.50
	5 Dec 99	4.9	1.1	7.6	0.007	0.002	0.20	0.02
				Mean		**0.015**	**0.37**	**0.21**
Haulover-B	6 Jul 96	6.4	3.6	1.3	0.030	0.005	NA	0.16
	10 Sep 96	5.5	1.6	3.4	0.140	0.025	NA	0.86
	21 Sep 98	5.6	1.6	5.5	0.089	0.016	2.56	0.54
	4 Dec 98	2.1	1.1	8.3	0.002	0.001	NA	0.04
	10 Nov 99	3.1	2.8	6.2	0.214	0.068	0.42	2.29
	16 Nov 99	7.2	1.4	16.6	0.254*	0.035	0.32	1.19
	5 Dec 99	4.9	1.1	7.6	0.050	0.010	0.06	0.34
				Mean		**0.023**	**0.84**	**0.77**
Fish Bay	6 Jul 96	6.4	3.6	0.9	0.030	0.005	NA	0.01
	10 Sep 96	5.5	1.6	6.4	0.250*	0.045	NA	0.06
	4 Dec 98	2.2	2.1	15.8	0.033	0.015	NA	0.02
	8 Apr 99	3.0	1.7	0.0	0.051	0.017	0.10	0.02
	10 Nov 99	2.6	2.4	6.4	0.091	0.035	0.01	0.04
	16 Nov 99	13.1	3.4	16.7	0.280*	0.021	0.00	0.03
	5 Dec 99	4.5	1.2	3.1	0.058	0.013	0.01	0.02
				Mean		**0.022**	**0.03**	**0.03**

Table 4. Sediment production rates from zero- and first-order catchments. Undisturbed first-order catchments are identified with an asterisk, and the first-order basins with unpaved roads are identified by a double asterisk.

Site	**Drainage area (ha)**	**Mean slope (%)**	**Start Date**	**End Date**	**Total sediment production (kg)**	**Total precipitation events > 6 cm (cm)**	**Sediment production per unit rainfall ($g\ m^{-1}\ cm^{-1}$)**
Zero-BM-A	1.2	20	28 Jul 98	3 Nov 01	30	30.2	0.085
Zero-BM-B	1.0	15	29 Jul 98	3 Nov 01	8.8	30.2	0.031
Zero-BM-C	0.9	15	28 Jul 98	3 Nov 01	15	30.2	0.058
Zero-MB-A	2.3	20	14 Jul 99	7 Nov 01	41	21.7	0.081
1st-MB-A*	5.4	27	14 Jul 99	7 Nov 01	311	21.7	0.27
1st-RB-C*	15	37	29 Aug 99	6 Nov 01	2,115	19.2	0.74
1st-RB-A**	14	32	30 Jul 98	6 Nov 01	12,475	34.5	2.6
1st-RB-B**	14	25	27 Aug 99	6 Nov 01	5,848	19.2	2.1

Table 5. Cutslope characteristics and sediment production rates.

Plot	**Cutslope height (m)**	**Cutslope area (m^2)**	**Degree of weathering**	**Period of measurement (years)**	**Annual sediment production ($kg\ m^{-2}\ yr^{-1}$)**
MB-A	4.0	34	moderate	2.0	8.9
MB-B	4.2	26	moderate	1.0	12
MB-C	4.2	29	slightly	2.1	3.9
MB-L	1.3	5.2	residual soil	2.0	7.2
MB-U	1.2	6.8	moderate	2.0	3.4
JH-A	1.7	8.4	slightly	1.7	2.0
JH-B	1.4	7.9	moderate	3.2	7.7
JH-C	1.4	7.8	residual soil	3.2	17
Mean	**2.4**	**16**		**2.1**	**7.8**

Table 6. Cutslope sediment production rates reported in the literature. NA indicates not available or not applicable.

Reference	Location	Cutslope description	Sediment production rate reported	Sediment production (kg m^{-2} yr^{-1})
Diseker and Richardson (1962)	Georgia, US	Unvegetated	102-230 t $ha^{-1}yr^{-1}$	5.1-11
Wilson (1963)	Oregon, US	6-7 yr old cutslopes	153 t $ha^{-1}yr^{-1}$	15
		new cutslopes	370 t $ha^{-1}yr^{-1}$	37
Dyrness (1970, 1975)	Oregon, US	5 yr old cutslopes	0.5 cm yr^{-1}	7.5
		1 yr old cutslopes	0.7 cm yr^{-1}	10
Megahan (1980)	Idaho, US	45 yr old cutslopes, soil	0.01 m^3 m^{-2} yr^{-1}	15
		45 yr old cutslopes, granite	0.011 m^3 m^{-2} yr^{-1}	16
Reid (1981)	Washington, US	55-70 degrees	16.5 mm yr^{-1}	25
Blong and Humphreys (1982)	Papua, New Guinea	NA	70 mm yr^{-1}	105
Megahan et al. (1983)	Idaho, US	NA	11 mm yr^{-1}	16
Riley (1988)	New South Wales, Australia	NA	2.4-3.9 mm yr^{-1}	3.6-5.8
Fahey and Coker (1989, 1992) Smith and Fenton (1993)	New Zealand	Unvegetated, granite	NA	5.2-15
Megahan (2001)	Idaho, U.S.	Cover density 0.1-89% 55-104% gradient	0.1-248 t $ha^{-1}yr^{-1}$	0.01-25
This study	St. John, USVI	Unvegetated, 2-5 m high	NA	2 - 17

Table 7. Estimated contribution of cutslopes to sediment yields at the road segment scale. The asterisk indicates that the values were estimated based on a visual classification system.

Road plot	**Length of road segment (m)**	**Measured sediment production rate (kg m^{-1} cm^{-1})**	**Road-segment sediment production (kg cm^{-1})**	**Percent of segment-scale sediment production contributed by cutslopes***	**Estimated cutslope contribution (kg cm^{-1})**
BM-A	420	0.18	78	46	36
BM-B	93	0.30	28	2.4	0.7
BM-C	270	0.43	115	9.0	10
FB-A	93	0.03	2.8	51.5	1.4
FB-C	109	0.08	8.5	30.9	2.6
FB-D	64	0.38	24	62.3	15
FB-E	83	2.21	183	0	0
JH-A	240	0.91	219	0.8	1.7
JH-A1	58	0.52	30	3.5	1.0
JH-A2	103	0.46	47	1.3	0.6
JH-B	394	0.40	158	14.5	23
JH-C	237	0.15	35	6.1	2.1
JH-D	148	0.28	41	15	6.2
JH-E	257	0.32	82	8.6	7.1
LB-A	256	0.39	100	1.3	1.3
LB-C	254	0.24	60	47.9	29
LE-Bottom	78	0.11	8.8	0.9	0.1
LE-Top	222	0.03	7.2	10.5	0.8
MB-A	179	1.48	264	7.0	18
MB-C	74	0.08	5.6	23.3	1.3
Sum			**1497**		**158**