Measurement and prediction of natural and anthropogenic sediment sources, St. John, U.S. Virgin Islands

Carlos E. Ramos-Scharrón a,⁎, Lee H. MacDonald b

a Department of Geosciences, Colorado State University, Fort Collins, CO 80523-1482, USA
b Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University, Fort Collins, CO 80523-1472, USA

Abstract

A quantitative understanding of both natural and anthropogenic sediment sources is needed to accurately assess and predict the potentially adverse effects of land development on aquatic ecosystems. The main objective of this study was to quantify sediment production and delivery rates in a dry tropical environment on the island of St. John in the eastern Caribbean. One to three years of measurements were used to determine values and empirical functions for estimating sediment production from streambanks, treefall, undisturbed hillslopes, zero-order subcatchments, unpaved road surfaces, and road cutslopes. Sediment production also was measured from both undisturbed and roaded first-order subcatchments.

Among natural sources of sediment, streambanks had the highest mean erosion rate at 100 Mg ha⁻¹ yr⁻¹. The uprooting of trees along stream margins is estimated to generate approximately 0.2 Mg of sediment per kilometer of stream per year, or about 0.1 Mg ha⁻¹ yr⁻¹ for a stream corridor that consists of a 9-m wide channel and a 3-m wide buffer zone. Undisturbed 40 m² hillslope plots generated 0.01 to 0.27 Mg ha⁻¹ yr⁻¹. Mean sediment yields from undisturbed zero- and first-order catchments were only 0.01 and 0.08 Mg ha⁻¹ yr⁻¹, respectively.

Unpaved roads that were graded at least every other year had sediment production rates ranging from 57 Mg ha⁻¹ yr⁻¹ for a road with a 2% slope to 580 Mg ha⁻¹ yr⁻¹ for a road with a 21% slope. Sediment production rates from ungraded roads were about 40% lower than those from recently graded roads, while production rates from steep abandoned roads were only 12 Mg ha⁻¹ yr⁻¹. Cutslope sediment production rates ranged from 20 to 170 Mg ha⁻¹ yr⁻¹, but their contribution to sediment yields at the road segment scale was relatively small. Since unpaved roads increase hillslope-scale sediment production rates by several orders of magnitude, the first-order catchments with unpaved roads had sediment yields that were at least five times higher than undisturbed catchments.

The relative importance of each sediment source varies from catchment to catchment as a result of the abundance and spatial distribution of landscape types. The values and predictive functions developed in this study have been incorporated into a GIS-based model to predict catchment-scale sediment yields. Application of this model to three basins in St. John suggest that unpaved roads are currently the dominant sediment source, and that they are responsible for increasing watershed-scale sediment yields by 3–9 times relative to undisturbed conditions. Both the data from the present study and the GIS model can help estimate sediment production and catchment-scale sediment yields in similar environments.

© 2007 Elsevier B.V. All rights reserved.

Keywords: Dry tropics; Caribbean; Sediment budget; Road erosion; Streambank erosion; Coral reefs

1. Introduction

The disturbance associated with land development generally increases erosion and sediment yields (Walling, 1997). The significance and potential impact of increased sediment yields is of particular concern in forested areas because natural erosion rates are so low (Dunne, 2001). The increased sediment yields associated with land development are a particularly serious threat to nearshore coral reefs because these ecosystems are extremely sensitive to fine sediment inputs (Hubbard, 1987; Hodgson, 1989; Rogers, 1990; Hodgson, 1997). The preservation of coral reefs is a high priority in the Caribbean because local economies are so dependent on coral reefs for subsistence and tourism.

Within the Caribbean there have been several studies on sediment production rates, but few studies on the amount of
sediment being delivered to the marine environment (UNEP, 1994). Mass wasting processes have been more intensively studied because of their potential for destruction and loss of life (e.g., DeGraff et al., 1989; Jibson, 1989; Scatena and Larsen, 1991; Larsen and Parks, 1997; Larsen and Torres-Sánchez, 1998). Surface erosion studies generally have focused on agricultural fields (e.g., Smith and Abruña, 1955; Ahmad and Breckner, 1974; Gumbs and Lindsay, 1982; Tirado and Lugo-López, 1984; McGregor, 1988). Given the limited amount of data, several studies have used uncalibrated models to predict sediment yields from areas with different land uses (e.g., Ramsarran, 1992; 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; Waddell, 2005). Previous studies indicated that sediment production rates from unpaved road surfaces were several orders of magnitude higher than undisturbed hillslopes (MacDonald et al., 1997, 2001). Application of an empirical road erosion model (ROADMOD) suggested that the unpaved road network on St. John is the dominant source of sediment, and that the unpaved roads are causing up to a four-fold increase in watershed-scale sediment yields (Anderson, 1994; Anderson and MacDonald, 1998). The road erosion algorithms used by ROADMOD were based on very limited data and did not include some of the key factors controlling road erosion rates, such as precipitation, or the frequency of grading. ROADMOD also lacked the capacity to estimate sediment production rates from other sources.

Land use planning and effective resource management are predicated on the ability to more accurately estimate and model sediment production rates. Hence the main objectives of this study were to: (1) measure sediment production from natural and road-related sources at varying spatial scales; (2) compare measured values to data from other areas; and (3) develop empirical sediment production values or functions for each sediment source. The resulting information can be used by resource managers to guide land use and set priorities for ameliorating problem areas. In the absence of local data, the results from this study can be applied to similar areas.

A sediment budget approach provides a useful framework for evaluating the absolute and relative contributions of different sediment sources (Reid and Dunne, 1996, 2003). 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 an area with a consistent set of erosion processes that produce sediment at a predictable or spatially-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 catchments, (5) road travelways, and (6) road cutsples. Sediment production rates also were measured from both undisturbed and roaded first-order sub-catchments containing unpaved roads.

2. Study Area

The island of St. John lies about 80 km east of Puerto Rico and is the third largest of the U.S. Virgin Islands (Fig. 1). Fifty-six percent of its 50 km$^2$ of land area and 70 km$^2$ of offshore waters have been designated as a Biosphere Reserve and are protected in either Virgin Islands National Park (VI NP) or Virgin Islands Coral Reef National Monument.

The lithology of St. John is dominated by basalts and volcanic wackes formed as volcanic flows during the Early and Late Cretaceous periods (Donnelly, 1966; Rankin, 2002). These rocks have undergone periods of deformation, magmatic intrusions, and hydrothermal alterations. Soils are predominantly gravelly loams and gravelly clay loams composed of 10–40% clay, 20–50% silt, 20–50% sand, and a high abundance of coarse fragments (USDA, 1995; USDA-NRCS, 1998). These soils are generally shallow, moderately permeable, well-drained, and underlain by nearly impervious bedrock. The topography of St. John is very rugged, as more than 80% of the slopes are greater than 30% (Anderson, 1994). The highest point on St. John is Bordeaux Mountain at 387 m a.s.l.

St. John has a subtropical dry climate. 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$^{-1}$ around Bordeaux Mountain (Fig. 1). Low-pressure meteorological systems, 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 there is a relatively dry season from about February to July and a relatively wet season from August until January (Bowden et al., 1970). Mean monthly potential evapotranspiration (PET) exceeds mean monthly precipitation for most of the year (Sampson, 2000), so there are no perennial streams on St. John. On average, the 15-minute precipitation intensity at Caneel Bay exceeds 10 cm h$^{-1}$ about once a year (Ramos-Scharrón, 2004).

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 associated with low-pressure systems make treethrow a potentially important sediment source. The taller trees along stream corridors are especially susceptible to uprooting as they are more exposed to wind (Reilly, 1991), and their larger boles may make them less susceptible to breaking.

Erodible streambanks on St. John are restricted to areas where stream segments intersect alluvial or colluvial deposits. These deposits are more common 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, cobble- and gravel-sized stones in a fine sand–silt matrix. The deposits show little layering or weathering and are poorly sorted. Streambanks in these areas generally are very steep, mostly unvegetated, and 0.6–2.5 m high.
Over the past 30 years rapid development has greatly increased the density of roads on St. John, particularly on the private lands outside of VINP (Fig. 2). For example, there were 8.3 km of roads in a 1971 aerial photograph of the 6.0 km² Fish Bay basin. By 2000 the road network had nearly tripled to 23.2 km and 56% of the roads were unpaved. Construction and maintenance standards of the unpaved roads are generally poor. Road drainage structures (i.e., ditches, culverts, or cross-drains) are sparsely located, even on extremely steep segments. As a result of the high rainfall erosivity and poor drainage design, deep rills commonly develop on road surfaces, especially on the steeper segments. These steeper segments typically have to be regraded every year or so to allow passage by standard passenger cars.

3. Methods

3.1. Streambank erosion

Sediment production from erodible streambanks was measured with erosion pins (Lawler, 1993; Couper et al., 2002) at four representative stream reaches (Fig. 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 streams with typical gradients of 3 to 5%, channel widths of roughly 9 m, and drainage areas of 0.9 to 3.8 km². These are primarily step-pool streams with an average streambank height of 1.8 m. The fourth site (Reef Bay) was chosen to represent first-order, cascade-type streams, as this stream has a drainage area of 0.1 km², a channel gradient of 22%, a channel width of 6.5 m, and an average bank height of 2.3 m. All of the study sites were on straight reaches.

At each site two to four vertical columns of erosion pins were installed with five to nine 15-cm long pins per column. The columns were about 3 m apart and the pins within each column were roughly 15–30 cm apart. A total of 82 pins were installed. The length protruding from the bank was measured to the nearest millimeter at the time of installation and 1–3 times after installation at frequencies ranging from approximately six months to just over two years. A total of 160 erosion pin measurements were collected over three years between October 1998 and November 2001. The mean streambank erosion or aggradation rate in each reach was the net difference between successive measurements at a site divided by the time between measurements. The dependence of erosion rates on stream order and drainage area was tested using analysis of variance (ANOVA). A significance level of 0.05 was used for all tests.
3.2. Treethrow

The number and volume of uprooted rootwads within approximately 3 m of the guts was assessed in early 2000 along 6.7 km of streams in three different basins. Sixty-one percent of the surveys were conducted along second- and third-order reaches in the main Fish Bay and Greater Lameshur Guts because these two basins were the primary focus of our study (Ramos-Scharrón, 2004). Three reaches in the Reef Bay basin totaling 2.6 km were chosen to represent first-order guts.

The volume of each rootwad was determined by measuring its diameter and thickness and assuming that its shape could be approximated by a cylinder. The percentage of the total rootwad volume that held uprooted soil was visually estimated for those rootwads that still held a significant amount of soil. The mean percent soil in the recent rootwads was assumed to be valid for the older rootwads. 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 long-term rate of sediment delivery to the stream network by treethrow in Mg of soil per kilometer of stream per year was calculated with Eq. (1).

\[
\text{Treethrow} = \frac{\sum (\text{Rootwad volume} \times \text{Percent soil} \times \text{Soil bulk density})}{(\text{Channel length} \times \text{Number of years})}.
\]

The rootwad volume was in m³, and the soil bulk density was assumed to be 1.4 Mg m⁻³. The length of channel refers to the total length of the reach surveyed (in km), and the number of years is the period of time represented by the rootwads. Eq. (1) implicitly assumes that all of the soil in the rootwads along the streambanks is delivered to the stream network. We believe that this is a reasonable assumption because most of the guts in St. John are confined by steep hillslopes and the rootwads included in our field inventory generally were on top of vertical streambanks, indicating a very high probability of sediment delivery to the stream network. The number of years represented by our survey was the most difficult component to define, as this required us to estimate the age of the oldest rootwads and determine whether the frequency of rootwads observed during our field survey was representative of long-term conditions.

3.3. Plot-scale runoff and sediment production

Runoff and sediment production were measured from three 40 m² plots on undisturbed planar hillslopes. Two of the plots were in the Haulover Bay area on the eastern end of the island, and one was in the Fish Bay basin (Fig. 1). The two Haulover plots were on 30% slopes dominated by dry evergreen thorn and cactus vegetation. The Fish Bay plot was located on a 23% slope covered by dry evergreen thicket and scrub. All plots were on extremely stony, gravelly loam soils that were 25–50 cm deep (USDA-NRCS, 1998). The plots were installed in 1996 as part of a previous study (MacDonald et al., 2001) and intermittently monitored from September 1998 through December 1999. Each plot was 10 m long by 4 m wide, and bounded by 15-cm-wide metal flashing inserted into a 5-cm trench along the plot boundaries (Sampson, 2000). The runoff from each plot was routed into a 100-L plastic reservoir. Reservoirs were pre-calibrated so that the volume of runoff could be determined by measuring the depth of water. One or two 0.5-L samples were collected immediately after vigorously mixing the water in the containers. These samples were filtered, dried, and weighed (ASTM, 1997). The sediment yield for each measurement was calculated by multiplying the total runoff by the mean sediment concentration.

Rainfall data for the Fish Bay plot and one storm on the Haulover-B plot (21 September 1998) were obtained from a tipping-bucket rain gauge in the lower Fish Bay basin (Fig. 1). Rainfall data for the remaining measurements at the Haulover plots were obtained from a recording rain gauge at Maho Bay. The rainfall data were used to calculate storm precipitation, maximum 60-minute intensities, storm erosivities (Wischmeier and Smith, 1958), and a time-weighted antecedent precipitation index (API) (Dunne and Leopold, 1978). An individual storm was defined as a precipitation event isolated from other events by at least one hour with no precipitation.

3.4. Runoff and sediment production from zero- and first-order catchments

Peak sub-surface water levels were monitored with three crest gages on the west-facing sideslope of a 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. Each crest gage consisted of a 75-cm long PVC tube inserted into a hole 30–40 cm deep. A smaller diameter tube and a handful of powdered cork were placed inside the larger tube. The maximum water level height was indicated by the height of the powdered cork on the inside tube, and this height was measured approximately monthly and after large storms between July...
1999 and February 2000. The water level data were related to the amount of storm rainfall, maximum 60-minute storm intensity, the API, and distance from the catchment axis.

Field observations also were made at the base of the Zero-MB-A catchment to assess whether there had been any surface runoff. The most intensive observations were from August 1999 to May 2000 because we were measuring storm runoff, suspended sediment concentrations, and total sediment yield from a road segment immediately below this catchment (Ramos-Scharrón and MacDonald, 2007a). Rainfall was measured with a recording rain gauge approximately 200 m from the lower end of the Zero-MB-A catchment (Fig. 1).

Sediment production rates at the catchment-scale were measured from July 1998 to November 2001 with sediment fences (Robichaud and Brown, 2002). Sediment production rates from undisturbed areas were measured for three zero-order catchments near Bordeaux Mountain, one zero-order and one first-order catchment in the Maho Bay area, and one first-order catchment in the Reef Bay basin (Fig. 1). Sediment fences were also installed on two first-order catchments in the Reef Bay basin that were receiving sediment from unpaved roads (Fig. 1). The drainage areas of these catchments ranged from 0.9 to 15 ha, and the average hillslope gradients ranged from 15% to 37%. Each of these catchments had a dense cover of moist evergreen forest.

The sediment fences consisted of filter fabric attached to 1–1.5 m long pieces of rebar hammered vertically into the ground (Ramos-Scharrón, 2004) (Fig. 3). The sediment accumulated in the fences was collected and weighed to the nearest 0.2 kg about once a year, as only the most intense storms generated measurable amounts of sediment at these sites. Samples taken at the time of weighing were analyzed for percent moisture (Gardner, 1986), and these data were used to convert the field-measured wet weights to a dry mass. Except for the Zero-BM-C catchment, one sediment sample from each catchment was dry sieved to determine its particle-size distribution (Bowles, 1992).

Data from St. John and other areas indicate that the sediment fences provide a reasonably accurate measurement of sediment production rates. In St. John, sediment production from a road segment was measured with a sediment trap and simultaneous measurements of runoff and suspended sediment concentrations (Ramos-Scharrón, 2004). The results indicated that the sediment trap was able to retain only about one-third of the silt- and clay-sized fraction, but this undersampling had only a minor effect on the total sediment production because this size fraction comprised less than 20% of the sediment being produced. Adjustments that account for the failure of the sediment trap to effectively retain the fine sediment fraction increased sediment production rates by only 15% relative to the rates measured by the sediment trap (Ramos-Scharrón and MacDonald, 2007a). Studies conducted elsewhere also indicate that sediment fences retain over 90% of the sediment being generated from zero-order catchments and unpaved roads (Robichaud and Brown, 2002; MacDonald et al., 2006).

3.5. Surface erosion from unpaved road segments

Sediment production rates were periodically measured from 21 unpaved road segments between July 1998 and April 2000, and two of these segments continued to be monitored through November 2001 (Fig. 4) (Ramos-Scharrón and MacDonald, 2005). To the extent possible, the segments were selected to represent a wide range of surface areas and slopes, as road segment area times slope is a useful surrogate for the tractive forces due to infiltration-excess overland flow on the road surface (Luce and Black, 1999). The mean width of the road segments was 4.7 m and the mean road surface area—including both the active travelway and the inside ditch—was 850 m². The mean slope of the road segments was 10% and the range was from 1% to 21%. Road use was stratified into three classes: roads exclusively used by light vehicles, roads with light vehicle traffic plus four to six medium-sized delivery truck passes per day, and abandoned roads. The a priori classification of road segments into these classes provided a secondary criterion for site selection. Time since construction or grading was not a primary 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 fences were placed immediately below a point of concentrated road drainage such as a cemented swale, unprotected cross-dip or culvert, and sediment production was measured using the procedures described previously. Eighty sediment production measurements were obtained during the study period, and the precipitation associated with each of the 80 measurements was obtained from one of the four recording rain gauges (Fig. 1). Annual sediment production rates for
individual road segments were calculated as the product of total sediment production—normalized by road contributing area and rainfall—times a mean annual rainfall of 115 cm yr$^{-1}$. Sediment production was related to precipitation, surface area, slope, traffic, and grading history by graphical analysis and multiple linear regression. The particle-size distribution of 40 samples collected from the sediment fences was determined by dry sieving down to 0.075 mm (Bowles, 1992) and the hydrometer method (Gee and Bauder, 1986) for particles finer than 0.075 mm.

3.6. Sediment production from road cutslopes

The sediment fences below each unpaved road segment captured material from both the road tread and the cutslope. To separate these two components, eight sediment fences were installed at the base of cutslopes in the Maho Bay area and along John Head Road in Catherineberg Estate (Fig. 4). The eight cutslopes were nearly vertical, 1.2 to 4.2 m high, and had less than 10% vegetation cover. The mean surface area was 16 m$^2$, and the range of values was from 5.2 m$^2$ to 34 m$^2$. Two of the cutslopes were exclusively composed of residual soil, two were dominated by slightly-weathered bedrock, and the remaining four cutslopes were dominated by moderately-weathered bedrock. Twenty measurements were taken between July 1998 and November 2001 at intervals ranging from a few months to just over a year. Multiple regression and ANOVA were used to evaluate the effects of total precipitation, cutslope height, and a qualitative weathering class on sediment production rates. The particle-size distribution of 8 samples was determined by dry sieving (Bowles, 1992). At least one sample was obtained from each of the cutslope plots except from MB-A and MB-B.

A visual classification system and detailed sketch maps were used to estimate the proportion of cutslope sediment that was delivered to the outlet of 20 road segments with sediment fences. A delivery potential of 75% was assumed for cutslope sections that had ditches or concentrated flowpaths at their toe, as the presence of depositional aprons indicated that sediment delivery rates were less than 100%. Cutslopes that were less than 3 m from the road tread but not delivering sediment directly to a ditch or concentrated flowpath were assumed to have a delivery potential of 10%. Zero delivery was assumed for cutslopes located more than 3 m from a ditch or flowpath. For each road segment, the amount of sediment from cutslopes was assumed to equal the product of the mean sediment production rate from cutslopes times the cutslope contributing area and the assumed delivery ratio.

3.7. Basin-scale sediment budgets

The relative contribution of a landscape unit to basin-scale sediment yields depends on its sediment production rate, spatial abundance within a watershed, and its sediment delivery potential. A series of basin-scale sediment budgets were developed using the St. John Erosion Model (STJ-EROS). STJ-EROS is a new, GIS-based procedure for combining the sediment production data and
4. Results and discussion

4.1. Streambank erosion

The mean streambank erosion rate from the erosion pins was 0.4 cm yr\(^{-1}\), but the data showed complex temporal and spatial patterns of deposition (negative values), no change, and erosion (positive values). The rates also varied within and between sites, and the range of values for an individual pin was from −13 cm yr\(^{-1}\) to 18 cm yr\(^{-1}\). In order to minimize the temporal variability and measurement uncertainty, the data was pooled by sites and the net erosion/aggradation rate for each pin was calculated from the difference between the first and last measurements divided by the total measurement period in years. The mean erosion rate by site was 0.7 cm yr\(^{-1}\) (S.D. = 1.5 cm yr\(^{-1}\)), and the highest mean value was 1.5 cm yr\(^{-1}\) in Main Fish Bay Gut (Fig. 5). The lowest mean value was 0.1 cm yr\(^{-1}\) in Lameshur Gut.

Multiplying the mean site erosion rate of 0.7 cm yr\(^{-1}\) by the estimated dry bulk density of 1.4 Mg m\(^{-3}\) yields a mean sediment production rate of nearly 10 kg per square meter of streambank per year (100 Mg ha\(^{-1}\) yr\(^{-1}\)) (Fig. 6). 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 mean value of 0.7 cm yr\(^{-1}\) from St. John falls at the lower end of this range, and the lower value for St. John can be partly attributed to the fact that these values are for ephemeral streams. Previous studies have suggested that bank erosion rates increase with increasing drainage area (e.g., Hooke, 1980; Lawler, 1993), but this tendency was only weakly supported by our data as the mean erosion rate of 0.6 cm yr\(^{-1}\) in the first-order gut at Reef Bay was only slightly lower than the mean rate of 0.8 cm yr\(^{-1}\) for the second- and third-order streams. There was a weak but significant tendency for bank erosion rates to increase with increasing drainage area (\(R^2 = 0.21; p=0.08\)), but this was due primarily to the high mean erosion rate at the site with the largest drainage area (Main Fish Bay).

4.2. Sediment delivery by treethrow

The mean number of uprooted trees along the banks of 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 4.5 to 28 Mg of sediment per kilometer of stream channel for individual stream segments and averaged nearly 20 Mg km\(^{-1}\). The wide variability in sediment delivery rates among the five stream segments may be attributed to differences in aspect and elevation. Aspect and elevation were found to influence the degree of tree damage on St. John during Hurricane Hugo in 1989 by presumably controlling localized wind velocities and wind exposure (Reilly, 1991).

In order to convert these values into a sediment delivery rate per unit time, we had to determine the maximum age of the uprooted trees and hence the time period represented by our

![Fig. 5. Average bank erosion by study site. Negative values indicate net deposition, and the bars indicate one standard deviation.](image-url)

![Fig. 6. Annual sediment production rates from natural and anthropogenic sediment sources. The columns indicate the mean values, and the bars within the columns indicate the range of measured values. The log scale on the y axis indicates that sediment production rates for the different landscape units vary by five orders of magnitude.](image-url)

<table>
<thead>
<tr>
<th>Location</th>
<th>Drainage area (km(^2))</th>
<th>Bank erosion rate (cm yr(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maryland, USA</td>
<td>0.13</td>
<td>0.6</td>
<td>Leopold et al. (1966)</td>
</tr>
<tr>
<td>Northern Ireland</td>
<td>3.4</td>
<td>0.03–0.05</td>
<td>Hill (1973)</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>1.6</td>
<td>0.8</td>
<td>Imeson and Jungerius (1974)</td>
</tr>
<tr>
<td>Wales</td>
<td>0.5</td>
<td>~3.0</td>
<td>Lewin et al. (1974)</td>
</tr>
<tr>
<td>England</td>
<td>10</td>
<td>8.0</td>
<td>Hooke (1979)</td>
</tr>
<tr>
<td>England</td>
<td>4.7</td>
<td>&lt;3.0</td>
<td>Murgatroyd and Ternan (1983)</td>
</tr>
<tr>
<td>St. John</td>
<td>0.14–3.8</td>
<td>0.1–1.5</td>
<td>This study</td>
</tr>
</tbody>
</table>
Table 2
Tree throw and sediment production rates along five stream reaches on St. John

<table>
<thead>
<tr>
<th>Reach</th>
<th>Length of reach (km)</th>
<th>Number of uprooted trees</th>
<th>Uprooted trees per km of stream</th>
<th>Total sediment in rootwads (m$^3$)</th>
<th>Mean volume of sediment per rootwad (m$^3$)</th>
<th>Volume of sediment per km of stream (m$^3$ km$^{-1}$)</th>
<th>Mass of sediment per km of stream (Mg km$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reef Bay A</td>
<td>0.61</td>
<td>12</td>
<td>19.6</td>
<td>3.0</td>
<td>0.3</td>
<td>4.9</td>
<td>6.9</td>
</tr>
<tr>
<td>Reef Bay B</td>
<td>0.96</td>
<td>14</td>
<td>14.6</td>
<td>19</td>
<td>1.4</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>Reef Bay C</td>
<td>0.95</td>
<td>9</td>
<td>9.5</td>
<td>3.2</td>
<td>0.4</td>
<td>3.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Lameshur</td>
<td>0.80</td>
<td>6</td>
<td>7.5</td>
<td>2.6</td>
<td>0.4</td>
<td>3.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Fish Bay</td>
<td>3.3</td>
<td>33</td>
<td>9.8</td>
<td>52</td>
<td>1.6</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>Mean</td>
<td>1.1</td>
<td>12</td>
<td>11.1</td>
<td>16</td>
<td>1.1</td>
<td>12</td>
<td>17</td>
</tr>
</tbody>
</table>

Survey. The oldest uprooted trees had softened wood, trunks that had lost over half of their bark, and rootwads that had lost most of their soil and fine roots. The use of qualitative decay classes to assign ages (following Dynesius and Jonsson, 1991) is somewhat uncertain given the lack of published data on log decay rates in the dry tropics. The literature suggests that the time for a log to completely decay in the dry tropics must be faster than the 100-year estimate for boreal forests (Dynesius and Jonsson, 1991), but slower than the value of 10 years for wet tropical environments in Panamá (Lang and Knight, 1979) and Puerto Rico (Odum, 1970). Since Hurricane Hugo in 1989 was the first major hurricane to affect St. John in 73 years (Potter et al., 1995), our data was assumed to represent tree throw from 1989 to 2000 (G. Ray, University of the Virgin Islands, pers. comm.; P. Weaver, U.S.D.A. Forest Service, pers. comm.).

To determine the long-term sediment production rate from tree throw, we also needed to know whether the measured frequency of tree throw was representative of long-term means. If the 20 Mg of tree throw sediment per kilometer of stream is divided by 11 years, the mean tree throw sediment production rate is 1.8 Mg km$^{-1}$ yr$^{-1}$. This value is probably an overestimate because four hurricanes affected St. John between 1989 and 2000, and this frequency exceeds the long-term average. The entire territory of the U.S. Virgin Islands—which includes 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 tree throw and forest damage at a given site is much longer (Bellingham, 1991). The mean return period for a major hurricane to pass over a given island in the Caribbean is 70 years (Neumman et al., 1978), and this is very close to the 50–60 year interval for the Luquillo Experimental Forest in eastern Puerto Rico (Scatena and Larsen, 1991).

Sustained winds on the immediately adjacent island of St. Thomas reached 192 km h$^{-1}$ during Hurricane Hugo in 1989 (Case and Mayfield, 1990), 165 km h$^{-1}$ during Hurricane Marilyn in 1995 (Marshall and Schroeder, 1997; Lawrence et al., 1998), 237 km h$^{-1}$ during Hurricane Georges in 1998 (Pasch et al., 2001), and 165 km h$^{-1}$ during Hurricane Lenny in 1999 (Lawrence et al., 2001). A study on several islands in the Eastern Caribbean after Hurricane Hugo found no tree throw when maximum wind speeds were less than 120 km h$^{-1}$ (Francis and Gillespie, 1993). We presume that the majority of the tree throw observed in 2000 occurred during either Hurricane Hugo or Hurricane Georges because the maximum sustained wind velocities greatly exceeded this 120 km h$^{-1}$ threshold. In addition, these two hurricanes were respectively 73 and 9 years after the last major hurricane as opposed to just 6 years for Hurricane Marilyn and 1 year for Hurricane Lenny. The interval between large storms is important because time is needed for trees to grow tall enough to become susceptible to wind throw. We posit that the period between hurricanes Hugo and Georges was long enough to allow Hurricane Georges to induce substantial tree throw, while this was not true for hurricanes Marilyn and Lenny.

If hurricanes that cause substantial amounts of tree throw occur about once every 50 years on St. John and two such events occurred between 1989 and 2000, then the tree throw erosion that we measured might represent the mass of sediment that would normally be produced over 100 years. On this basis, the long-term sediment production rate by tree throw is 0.2 Mg km$^{-1}$ yr$^{-1}$. For a stream corridor that consists of a 9-m wide channel and a 3-m wide buffer zone on each side, the estimated sediment production rate from tree throw is in the order of 0.1 Mg ha$^{-1}$ 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 Mg km$^{-1}$ yr$^{-1}$ assuming a dry bulk density of 1.4 Mg m$^{-3}$. This rate is an order of magnitude higher than the 0.2 Mg km$^{-1}$ yr$^{-1}$ estimated for St. John, and the difference is due to the much larger volume of soil in each rootwad and the much larger number of overturned trees per kilometer of stream channel.

In the Luquillo Experimental Forest (LEF) in eastern Puerto Rico, the rate of sediment production due to tree throw has been estimated to be approximately 0.2 Mg ha$^{-1}$ yr$^{-1}$ (Larsen, 1997). The tree throw sediment production rate from Puerto Rico was based on a methodology that accounted for the entire forest floor rather than just the stream corridor. The similarity of the estimates from St. John and Puerto Rico suggests that our unit area rates are reasonable, and the biggest uncertainty is exactly how much of the sediment from tree throw is being delivered to the stream network.
4.3. Plot-scale runoff and sediment production from undisturbed hillslopes

The total rainfall from September 1998 to December 1999 total rainfall was 180 cm at Maho Bay and 142 cm at Fish Bay. Problems with the rain gauges meant that no rainfall data were recorded for Hurricane Georges in September 1998 at Maho Bay and rainfall data were not available at Fish Bay from 8 February 1999 to 8 July 1999. The 180 cm measured at Maho Bay is only 4% more than the corresponding long-term mean for Caneel Bay, which is in the same precipitation zone as Maho Bay (Bowden et al., 1970). Similarly, the expected rainfall at Fish Bay over the period with data is 150 to 165 cm (Bowden et al., 1970), and this indicates that the rainfall over the study period was slightly below average at Fish Bay.

A more detailed analysis shows that there were 42 storms with at least 2 cm of rainfall at Maho Bay, or 2.6 storms per month. At Fish Bay there were 32 storms with at least 2 cm of rainfall, or 2.0 storms per month. The long-term record at Caneel Bay indicates that over a 16-month time period that extends from September until December of the subsequent year storms with at least 2 cm of rainfall occur about 1.8 times per month, or slightly less frequently than we observed during the study period. Both the long-term data from Caneel Bay and the data collected over the study period indicate that 30-minute rainfall intensities ($I_{30}$) exceed 2.5 cm h$^{-1}$ about every 1–2 months. These results indicate that the study period received near normal rainfall, but had slightly more storms exceeding 2 cm of rainfall than the long-term average and a similar frequency of storms with an $I_{30}$ of at least 2.5 cm h$^{-1}$.

Runoff and sediment data were collected from the 40 m$^2$ plots for five storms between August 1998 and December 1999. Several other storms may have produced runoff and sediment, but logistical problems meant that reliable data were not available for all of the storms that generated runoff. The data collected between 1998 and 1999 are listed in Table 3 along with the data collected from 1–2 storms in 1996 (Sampson, 2000).

Storm precipitation for the combined data set ranged from 2.1 to 13.1 cm, and the maximum 60-minute intensities for the runoff-generating storms were 1.1 to 3.6 cm h$^{-1}$. The mean runoff volumes for the Haulover-A, Haulover-B, and Fish Bay plots were 0.07, 0.11, and 0.11 cm, respectively. The runoff from storms with more than 6.4 cm of precipitation sometimes exceeded the runoff storage capacity of 0.25 cm (e.g., the 10 September 1996 storm on the Fish Bay plot and the 16 November 1999 storm on all three plots). Excluding these data yields a mean runoff coefficient of 0.02 and a maximum runoff coefficient of 0.07. While only a very small fraction of the rainfall was converted to runoff when storm precipitation was less than 6.4 cm, the runoff coefficients from these storms are still about an order of magnitude higher than the values from undisturbed humid tropical hillslopes in eastern Puerto Rico (Larsen et al., 1999). The higher runoff coefficients on St. John may be attributed to lower canopy and litter interception rates, and the higher potential for the overland flow due to the lower

### Table 3

<table>
<thead>
<tr>
<th>Plot</th>
<th>Date of storm</th>
<th>Total rainfall (cm)</th>
<th>Maximum 60-minute rainfall intensity (cm h$^{-1}$)</th>
<th>Antecedent precipitation index (cm)</th>
<th>Total runoff (cm)</th>
<th>Runoff coefficient (cm cm$^{-1}$)</th>
<th>Sediment concentration (g L$^{-1}$)</th>
<th>Sediment production per unit rainfall (g m$^{-2}$ cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haulover-A</td>
<td>10 Sep 96</td>
<td>5.6</td>
<td>1.6</td>
<td>3.4</td>
<td>0.000</td>
<td>0.000</td>
<td>NA</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>4 Dec 98</td>
<td>2.1</td>
<td>1.1</td>
<td>8.3</td>
<td>0.002</td>
<td>0.001</td>
<td>NA</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>8 Apr 99</td>
<td>3.6</td>
<td>1.7</td>
<td>0.0</td>
<td>0.103</td>
<td>0.029</td>
<td>0.18</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>10 Nov 99</td>
<td>4.4</td>
<td>1.6</td>
<td>7.6</td>
<td>0.007</td>
<td>0.002</td>
<td>0.20</td>
<td>0.02</td>
</tr>
<tr>
<td>Mean</td>
<td>4.4</td>
<td>1.6</td>
<td>7.0</td>
<td>0.071</td>
<td>0.015</td>
<td>0.37</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Haulover-B</td>
<td>6 Jul 96</td>
<td>6.4</td>
<td>3.6</td>
<td>1.3</td>
<td>0.030</td>
<td>0.005</td>
<td>NA</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>10 Sep 96</td>
<td>5.5</td>
<td>1.6</td>
<td>3.4</td>
<td>0.140</td>
<td>0.025</td>
<td>NA</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>21 Sep 98</td>
<td>5.6</td>
<td>1.6</td>
<td>5.5</td>
<td>0.089</td>
<td>0.016</td>
<td>2.56</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>4 Dec 98</td>
<td>2.1</td>
<td>1.1</td>
<td>8.3</td>
<td>0.002</td>
<td>0.001</td>
<td>NA</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>10 Nov 99</td>
<td>3.1</td>
<td>2.8</td>
<td>6.2</td>
<td>0.214</td>
<td>0.068</td>
<td>0.42</td>
<td>2.29</td>
</tr>
<tr>
<td>Mean</td>
<td>4.6</td>
<td>1.9</td>
<td>7.0</td>
<td>0.111</td>
<td>0.023</td>
<td>0.84</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>Fish Bay</td>
<td>6 Jul 96</td>
<td>6.4</td>
<td>3.6</td>
<td>0.9</td>
<td>0.030</td>
<td>0.005</td>
<td>NA</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>10 Sep 96</td>
<td>5.5</td>
<td>1.6</td>
<td>6.4</td>
<td>0.250</td>
<td>0.045</td>
<td>NA</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>4 Dec 98</td>
<td>2.2</td>
<td>2.1</td>
<td>15.8</td>
<td>0.033</td>
<td>0.015</td>
<td>NA</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>8 Apr 99</td>
<td>3.0</td>
<td>1.7</td>
<td>0.0</td>
<td>0.051</td>
<td>0.017</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>10 Nov 99</td>
<td>2.6</td>
<td>2.4</td>
<td>6.4</td>
<td>0.091</td>
<td>0.035</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>16 Nov 99</td>
<td>13.1</td>
<td>3.4</td>
<td>16.7</td>
<td>0.280</td>
<td>0.021</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>Mean</td>
<td>5.3</td>
<td>2.3</td>
<td>7.0</td>
<td>0.113</td>
<td>0.022</td>
<td>0.03</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

Sediment production was calculated by multiplying the mean sediment concentration by the total runoff. An asterisk indicates storms for which runoff was underestimated because the collection tank overtopped. NA indicates not available.
vegetative cover and higher proportion of rocks on the soil surface (Poësen and Lavee, 1994).

The depth of storm runoff from the 40 m² plots was weakly correlated with storm precipitation and storm erosivity ($R^2=0.34$ and $0.23; \ p=0.007$ and $0.07$, respectively), but was not correlated with the maximum 60-minute rainfall intensity ($R^2=0.02$). The depth of storm runoff was more closely related to the sum of storm rainfall ($P$) and the antecedent precipitation index (API), but the data still show considerable variability in runoff response ($R^2=0.39; \ p=0.004$) and the regression line is strongly influenced by the three highest data points (Fig. 7).

Sediment concentrations from the three plots ranged from 0.00 to 2.56 g L⁻¹. The mean sediment concentrations from the two plots at Haulover Bay were an order of magnitude higher than the mean value from the Fish Bay plot (Table 3). The higher concentrations at the Haulover plots are probably due to the lower vegetative cover and slightly steeper slopes. The sediment concentrations were not correlated with storm rainfall, maximum 60-minute precipitation, or rainfall erosivity ($R^2$ values $<0.002$), so the mean erosion rate was calculated by dividing the total sediment yield by the summed precipitation for the storms that generated runoff. For the Haulover-A, Haulover-B, and Fish Bay plots, the mean sediment production rate per centimeter of rainfall was 0.2, 0.8, and 0.03 g m⁻² cm⁻¹, respectively (Table 3).

To calculate the long-term mean sediment production rate, we assumed that all storms larger than 2 cm produce runoff and sediment, regardless of their API value, and that the mean sediment production rates apply to all storms larger than 2 cm. The long-term rainfall data from Caneel Bay shows that the total rainfall from storms with at least 2.0 cm of rainfall is 37 cm yr⁻¹, or about 32% of the mean annual rainfall, and that these storms occur about seven times every calendar year. By applying this proportion to the estimated mean annual rainfall at each site, the calculated sediment production rates are 0.1 and 0.3 Mg ha⁻¹ yr⁻¹ for the Haulover-A and Haulover-B plots, and just 0.01 Mg ha⁻¹ yr⁻¹ for the Fish Bay plot (Fig. 6).

At the LEF in eastern Puerto Rico the mean surface erosion rate was 0.09 Mg ha⁻¹ yr⁻¹ for ten forested hillslopes with silty-clay loam soils and slopes of 45–100%. For five hillslopes with a sandy loam soil and slopes of 80–100% the mean surface erosion rate was five times higher (0.5 Mg ha⁻¹ yr⁻¹) (Larsen et al., 1999). The sediment production estimates for the three St. John plots are within the range of values reported for the LEF even though the St. John plots have lower slopes, a higher abundance of coarse fragments, and receive only about 40% as much rainfall. Hence the similarity in sediment production rates between St. John and the LEF can be attributed to the lower vegetation cover and higher runoff coefficients of the plots on St. John.

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 of the Zero-MB-A catchment when storm rainfall exceeds about 2 cm. As storm precipitation increases the height of saturation asymptotically approaches the soil surface (Fig. 8), but the saturated zone on the sideslope never extended to the soil surface during the extent of the monitoring period. A comparison of storms with similar amounts of rainfall shows that storms with higher API values tended to have higher crest gage readings. The depth to saturation did not systematically vary with distance from the catchment axis (Fig. 8) or the maximum 60-minute rainfall intensity.

Qualitative runoff observations were made at the bottom of the Zero-MB-A catchment for many of the 602 storms between July 1998 and May 2000. The maximum storm rainfall over this period was 9.5 cm and the maximum 60-minute intensity was 7.9 cm h⁻¹. Surface runoff was observed for only seven storms, and this generally lasted for less than one hour after the end of the storm. The seven storms that generated surface runoff all had API values greater than 5 cm, and all but one had at least 3.5 cm of rainfall and maximum 60-minute intensities exceeding 2.0 cm h⁻¹. Crest gage data are available for only two of the seven storms with observed runoff, and these storms had a mean depth to saturation of just 3.9 cm (Fig. 8). The other seven storms shown in Fig. 8 did not generate runoff and the average depth to saturation was 17 cm.
Only the three storms with at least 6.0 cm of precipitation generated measurable amounts of sediment from the zero-order catchments with sediment traps. The maximum 60-minute rainfall intensities for these three storms ranged from 2.0 to 7.9 cm h\(^{-1}\). The total sediment yields ranged from 0.009 to 0.041 Mg, and averaged 1.75 g m\(^{-2}\) (Table 4). The two undisturbed first-order basins yielded a total of 0.31 and 2.1 Mg, respectively, or an average of 10 g m\(^{-2}\) (Table 4). In contrast, the two disturbed first-order basins yielded 12.5 and 5.85 Mg of sediment, or an average of 66 g m\(^{-2}\) (Table 4). When divided by the amount of rain that fell in storms with at least 6.0 cm of precipitation, the average sediment yield from the four undisturbed zero-order basins was 0.064 g m\(^{-2}\) per centimeter of precipitation, or nearly an order of magnitude less than the two undisturbed first-order basins (0.5 g m\(^{-2}\) cm\(^{-1}\)). The average sediment yield from the two roaded first-order basins was 2.4 g m\(^{-2}\) cm\(^{-1}\), or almost five times the value from the undisturbed first-order basins. Since the sediment traps in the two roaded basins were overtopped as a result of Hurricane Georges in 1998 and Hurricane Lenny in 1999, the value of 2.4 g m\(^{-2}\) cm\(^{-1}\) is an underestimate, and the true difference between the roaded and undisturbed basins is more than a factor of 5.

We are confident that this five-fold difference in sediment yields can be attributed to unpaved roads, as we used the empirical road erosion model developed for St. John (Ramos-Scharrón and MacDonald, 2005) to predict the total sediment production from the 180 m of unpaved roads in the RB-A catchment and the 250 m of roads in the RB-B catchment. These calculations indicated that the unpaved roads were generating 40 and 30 Mg of sediment, respectively, or 3-6 times the measured sediment yields. Although it is difficult to determine exactly how much of this sediment would be delivered to the sediment fences, these data show that the unpaved roads are almost certainly responsible for the five-fold increase in sediment yields.

The long-term rainfall data from Caneel Bay show that storms larger than 6 cm occur about 1.4 times per year and account for 14% of the mean annual rainfall or 16 cm yr\(^{-1}\) (Ramos-Scharrón, 2004). If the sediment yield rates (normalized by unit area and cm of rainfall) in Table 4 are multiplied by 16 cm yr\(^{-1}\), the estimated annual sediment yield from undisturbed first-order basins is about 0.01 Mg ha\(^{-1}\) yr\(^{-1}\), while the undisturbed first-order basins yield approximately 0.08 Mg ha\(^{-1}\) yr\(^{-1}\) (Fig. 6). The two first-order catchments with unpaved roads should generate at least 0.38 Mg ha\(^{-1}\) yr\(^{-1}\) (Fig. 6).

The particle-size data show that the sediment from the undisturbed first-order catchments was substantially coarser than the sediment from the four undisturbed zero-order catchments and the two roaded first-order catchments (Fig. 9). The sediment from the two undisturbed first-order catchments was 71% gravel, 28% sand, and 1% silt and clay. The sediment from the two roaded first-order catchments had 43% gravel and 55% sand, and the lower proportion of gravel is attributed to the fact that the sediment from unpaved roads on St. John is predominantly sand (Ramos-Scharrón and MacDonald, 2005, 2007a). By combining the sediment production estimates from the road erosion model (Ramos-Scharrón and MacDonald, 2005) with the particle-size distribution of sediment produced from unpaved roads in the Reef Bay watershed (Ramos-Scharrón, 2004), we can show that unpaved roads increase fine (<2 mm) sediment production in first-order catchments by about 30 times above background rates.

The higher sediment production rates from the undisturbed plots relative to the disturbed zero-order basins (Figs. 6, 10) can be attributed to the lower vegetation cover and steeper slopes on the plots as well as the differences in runoff and erosion processes at these two different scales. The data from the 40 m\(^2\) plots indicate that infiltration-excess overland flow and surface erosion can occur on the hillslopes when storm rainfall exceeds 2 cm, especially in the drier sites. In contrast, field observations indicate that the undisturbed zero-order catchments only

![Fig. 9. Mass-weighted particle-size distribution for the sediment produced from the undisturbed zero-order catchments, undisturbed first-order catchments, and the first-order catchments with unpaved roads.](image)

Table 4
Sediment production rates from zero- and first-order catchments

<table>
<thead>
<tr>
<th>Site</th>
<th>Drainage area (ha)</th>
<th>Mean slope (%)</th>
<th>Start date</th>
<th>End date</th>
<th>Total sediment production (Mg)</th>
<th>Sediment production per unit area (g m(^{-2}))</th>
<th>Total precipitation in storms&gt;6 cm (cm)</th>
<th>Sediment production per unit rainfall (g m(^{-2}) cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero-BM-A</td>
<td>1.2</td>
<td>20</td>
<td>28 Jul 98</td>
<td>3 Nov 01</td>
<td>0.030</td>
<td>2.6</td>
<td>30.2</td>
<td>0.085</td>
</tr>
<tr>
<td>Zero-BM-B</td>
<td>1.0</td>
<td>15</td>
<td>29 Jul 98</td>
<td>3 Nov 01</td>
<td>0.009</td>
<td>0.93</td>
<td>30.2</td>
<td>0.031</td>
</tr>
<tr>
<td>Zero-BM-C</td>
<td>0.9</td>
<td>15</td>
<td>28 Jul 98</td>
<td>3 Nov 01</td>
<td>0.015</td>
<td>1.7</td>
<td>30.2</td>
<td>0.058</td>
</tr>
<tr>
<td>Zero-MB-A</td>
<td>2.3</td>
<td>20</td>
<td>14 Jul 99</td>
<td>7 Nov 01</td>
<td>0.041</td>
<td>1.8</td>
<td>21.7</td>
<td>0.081</td>
</tr>
<tr>
<td>1st-MB-A</td>
<td>5.4</td>
<td>27</td>
<td>14 Jul 99</td>
<td>7 Nov 01</td>
<td>0.31</td>
<td>5.8</td>
<td>21.7</td>
<td>0.27</td>
</tr>
<tr>
<td>1st-RB-C</td>
<td>15</td>
<td>37</td>
<td>29 Aug 99</td>
<td>6 Nov 01</td>
<td>2.12</td>
<td>14.3</td>
<td>19.2</td>
<td>0.74</td>
</tr>
<tr>
<td>1st-RB-A*</td>
<td>14</td>
<td>32</td>
<td>30 Jul 98</td>
<td>6 Nov 01</td>
<td>12.5</td>
<td>91</td>
<td>34.5</td>
<td>2.6</td>
</tr>
<tr>
<td>1st-RB-B*</td>
<td>14</td>
<td>25</td>
<td>27 Aug 99</td>
<td>6 Nov 01</td>
<td>5.85</td>
<td>41</td>
<td>19.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>

The two first-order basins with unpaved roads are identified by an asterisk.
generate surface runoff and erosion when storm rainfall exceeds 6 cm, and that saturation overland flow is the main cause of runoff and sediment yields. The difference in the amount of rainfall needed for runoff generation means that sediment production occurs at a much higher frequency from the small plots (7 times per year on average) than from the zero-order catchments (1.4 times per year on average). The more frequent runoff can account for the higher annual sediment yields at the plot-scale.

The higher sediment yields per unit area from the small plots also may be due to a higher sediment delivery rate. The net transport distance along hillslopes during individual storms may only be on the order of several meters (Lewis, 1981), so for a given storm there is a greater potential for sediment to be detached and transported out of a small plot than from a zero-order catchment. In addition, infiltration-excess overland flow and surface erosion may occur over most of the plot surface, while saturation overland flow typically occurs only in topographically-convergent areas, such as the catchment axes (Dunne and Black, 1970; Beven and Kirkby, 1979).

In the first-order catchments the diffuse surface runoff is concentrated into small channels where velocities and depths are much higher, and there is a corresponding increase in shear stress and sediment transport capacity. The channelized flow is probably why sediment yields in the undisturbed first-order basins are 1–2 orders of magnitude higher than the sediment yields from the zero-order basins (Figs. 6, 10). The sediment from undisturbed first-order catchments also is substantially coarser than the sediment from the undisturbed zero-order catchments (Fig. 9), and this supports our assessment of how runoff processes and sediment yields from the undisturbed zero-order basins (Figs. 6, 10). The sediment from undisturbed first-order basins is 1–2 orders of magnitude higher than the sediment yields from the zero-order basins (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6).

The particle-size distribution of the sediment produced from unpaved roads is much finer than the sediment produced from undisturbed first-order catchments and slightly finer than the sediment from undisturbed zero-order catchments (Figs. 9, 11). The mass-weighted particle-size distribution of the material eroded from the 21 unpaved road segments was 40% gravel, 0.15 Mg ha\(^{-1}\) yr\(^{-1}\). This calculated value is 3.5 times larger than the measured rate of 0.04 Mg ha\(^{-1}\) yr\(^{-1}\), and this difference can be attributed to sediment storage within the basin as well as the uncertainty in the estimated sediment production rates.

The same calculations were made for the undisturbed first-order catchment at Maho 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 surface erosion and treethrow was 0.02 Mg ha\(^{-1}\) yr\(^{-1}\). This value is about 80% lower than the measured value of 0.12 Mg ha\(^{-1}\) yr\(^{-1}\), and the difference may be attributed in part to the additional contribution of sediment stored along the stream network. Even though these results point to the limitations of using short-term empirical data from a limited number of sites in providing accurate sediment yield predictions, the relative similarity (i.e., within an order of magnitude) in the measured and calculated sediment yields supports the validity of the underlying estimates and the use of landscape units to estimate basin-scale sediment budgets.

4.5. Sediment production from unpaved roads

Sediment production from actively-used unpaved roads depends on the total precipitation, road segment slope, and whether a road had been graded in the last two years (Ramos-Scharrón and MacDonald, 2005). Measured sediment production rates for graded roads ranged from 5.7 Mg ha\(^{-1}\) yr\(^{-1}\) for a road with a slope of 2% to 580 Mg ha\(^{-1}\) yr\(^{-1}\) for a road with a slope of 21% (Fig. 6). The sediment production rate for ungraded roads was about 40% lower than for comparable graded roads (Ramos-Scharrón and MacDonald, 2005). Roads abandoned for about 15 years had a much lower erosion rate (i.e., 12 Mg ha\(^{-1}\) yr\(^{-1}\) for road segments with a 15% slope). The two empirical models developed to predict sediment production rates from graded and ungraded roads are:

\[
\begin{align*}
E_{rg} &= -0.432 + 4.73 \cdot (S^{1.5} \cdot P) \\
E_{ru} &= -0.432 + 1.88 \cdot (S^{1.5} \cdot P)
\end{align*}
\]

where \(E_{rg}\) is sediment production in kg m\(^{-2}\) for graded roads, \(E_{ru}\) is sediment production in kg m\(^{-2}\) for ungraded roads, \(S\) is the road segment slope in m m\(^{-1}\), and \(P\) is precipitation in cm (Ramos-Scharrón and MacDonald, 2005).

Both the measured and predicted values indicate that actively-used roads increase sediment production rates at the plot or hillslope-scale by about three orders of magnitude (Fig. 6). For zero-order catchments unpaved roads can increase sediment yields by up to two or three orders of magnitude. At larger scales the effect of roads is reduced because roads represent a smaller proportion of the contributing area and channel erosion processes are increasingly important (Fig. 10).

The particle-size distribution of the sediment produced from unpaved roads is much finer than the sediment produced from undisturbed first-order catchments and slightly finer than the sediment from undisturbed zero-order catchments (Figs. 9, 11). The mass-weighted particle-size distribution of the material eroded from the 21 unpaved road segments was 40% gravel,
54% sand, and 6% silt and clay. On average, the sediment from graded roads had slightly less gravel and more sand than the sediment from ungraded roads, but these differences were not statistically significant. The sediment collected from the two abandoned road segments was much coarser, as this consisted of 73% gravel, 27% sand, and less than 1% silt and clay.

4.6. Sediment production from road cutslopes

Sediment production from cutslopes ranged from 2.0 to 17 kg m\(^{-2}\) yr\(^{-1}\) (Table 5). The data were log-normally distributed, and the geometric mean sediment production rate was 5.6 kg m\(^{-2}\) yr\(^{-1}\) (100 Mg ha\(^{-1}\) yr\(^{-1}\)) \((n = 20)\). Cutslope erosion rates increased with the degree of weathering, as cutslopes composed of residual soil had a mean sediment production rate of 14 kg m\(^{-2}\) yr\(^{-1}\) as compared to 9.3 kg m\(^{-2}\) yr\(^{-1}\) for moderately-weathered bedrock and only 3.9 kg m\(^{-2}\) yr\(^{-1}\) for slightly-weathered cutslopes (Table 5). The small sample sizes did not justify the use of geometric mean values for comparing the sediment production rates from these three cutslope types, and the high variability meant that these differences were not statistically significant. Cutslope sediment production rates also were not related to cutslope height or any of the precipitation variables. Other studies have reported sediment production rates for cutslopes of 0.01 to 37 kg m\(^{-2}\) yr\(^{-1}\), and this range easily encompasses the values measured in this study (Table 6).

The cutslope sediment production rates from St. John are similar to the values for graded roads with moderate gradients (Fig. 6), but the cutslope areas are generally much smaller than the area of the travelways (Table 7). By combining the measured sediment production rates from roads with the sediment production and delivery rates for cutslopes, we estimated that cutslopes contribute 0% to 50% of the measured sediment yields from the 20 road segments with sediment fences (Table 7). Overall, the cutslopes were estimated to contribute only 9% of the 172 Mg yr\(^{-1}\) produced from these 20 road segments.

The sediment collected from the cutslopes generally was coarser than the sediment collected from the sediment fences at the outlet of each road segment. On average, the sediment produced from cutslopes was 61% gravel, 38% sand, and only 1% silt and clay (Fig. 11). Approximately 20% of the sediment produced from cutslopes was coarser than 16 mm as compared to just 8% of the sediment captured in the 20 road fences. The difference in the particle-size distribution between the cutslopes and the road segments further support our finding that cutslopes are not a major source of the sediment being produced by the unpaved roads.

There are few other data that explicitly estimate how cutslopes contribute to segment-scale sediment yields. On 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, cutslope height was not significantly related to road segment sediment yields (Luce and Black, 2001). These results support our finding that—in the absence of mass wasting processes—cutslope erosion is relatively unimportant when compared to the erosion from the travelways of unpaved roads.

4.7. Basin-scale sediment budgets

The application of the GIS-based STJ-EROS model to three 1.6 to 4.3 km\(^2\) basins on St. John showed that under undisturbed conditions the amount of sediment being delivered to the marine environment ranges from 0.02–0.07 Mg ha\(^{-1}\) yr\(^{-1}\) (Fig. 10) (Ramos-Scharrón and MacDonald, in 2007b). These rates are very similar to the measured values of 0.01–0.08 Mg ha\(^{-1}\) yr\(^{-1}\) for undisturbed zero- and first-order catchments on St. John. Although channel morphology and bank composition limit streambank erosion to only 10–20% of the stream network, streambank erosion was responsible for approximately 80–90% of the sediment yields under undisturbed conditions.

Unpaved roads within the three study basins represent only 0.3% to 0.9% of the drainage area and consequently have a relatively smaller effect than the two to three orders of magnitude increase in sediment yields observed at the zero-order scale (Ramos-Scharrón, 2004). Nonetheless, the predicted sediment yields for these three catchments under current conditions ranged from 0.12 to 0.46 Mg ha\(^{-2}\) yr\(^{-1}\), and this represents a 300–900% increase in sediment yields relative to undisturbed rates (Fig. 10) (Ramos-Scharrón and MacDonald, 2007b). STJ-EROS estimates that about 80–85% of the sediment yield under current conditions is due to the unpaved road network.

The results of the field measurements and the catchment-scale modeling indicate that unpaved roads are probably the
predominant source of anthropogenic sediment on St. John, and that any actions to reduce the amount of sediment being delivered to the coral reefs should focus on the unpaved roads. The sediment production values and predictive equations described in this paper can be used to formulate erosion control strategies, set priorities for specific projects, and plan future development.

5. Conclusions

Sediment production rates from both natural and road-related sources were measured on the island of St. John for one to three years between July 1998 and November 2001. Measurements were made for six different landscape units from the cutslope scale (∼5 m²) to the zero-order catchment scale (2.3 ha). The sediment production rates from these different units varied by over five orders of magnitude.

Among the natural sediment sources, streambanks had the highest mean sediment production rate per unit area at 100 Mg ha⁻¹ yr⁻¹. Treethrow was estimated to produce 0.2 Mg of sediment per kilometer of stream per year, or on the order of 0.1 Mg ha⁻¹ yr⁻¹ for a 15-m wide stream corridor. Bounded plot data show that runoff and sediment from undisturbed hillslopes is generated only by storms with at least 2 cm of rainfall, and that sediment production rates from undisturbed hillslopes range from 0.01 to 0.3 Mg ha⁻¹ yr⁻¹. Zero-order catchments had a mean sediment production rate of 0.01 Mg ha⁻¹ yr⁻¹, and sediment was only produced from storms with at least 6 cm of rainfall. The lower sediment yields from zero-order catchments relative to the

Table 6
Cutslope sediment production rates reported in the literature

<table>
<thead>
<tr>
<th>Location</th>
<th>Cutslope description</th>
<th>Reported sediment production rate</th>
<th>Normalized sediment production (kg m⁻² yr⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgia, USA</td>
<td>Unvegetated</td>
<td>102–230 Mg ha⁻¹ yr⁻¹</td>
<td>5.1–11</td>
<td>Diseker and Richardson (1962)</td>
</tr>
<tr>
<td>Oregon, USA</td>
<td>6–7 yr old cutslopes</td>
<td>153 Mg ha⁻¹ yr⁻¹</td>
<td>15</td>
<td>Wilson (1963)</td>
</tr>
<tr>
<td>Oregon, USA</td>
<td>New cutslopes</td>
<td>370 Mg ha⁻¹ yr⁻¹</td>
<td>37</td>
<td>Wilson (1963)</td>
</tr>
<tr>
<td>Oregon, USA</td>
<td>5 yr old cutslopes</td>
<td>0.5 m³ yr⁻¹</td>
<td>7.5</td>
<td>Dymess, 1970, 1975</td>
</tr>
<tr>
<td>Oregon, USA</td>
<td>1 yr old cutslopes</td>
<td>0.7 cm yr⁻¹</td>
<td>10</td>
<td>Dymess, 1970, 1975</td>
</tr>
<tr>
<td>Idaho, USA</td>
<td>45 yr old cutslopes, soil</td>
<td>0.01 m³ m⁻² yr⁻¹</td>
<td>15</td>
<td>Megahan (1980)</td>
</tr>
<tr>
<td>Idaho, USA</td>
<td>45 yr old cutslopes, granite</td>
<td>0.011 m³ m⁻² yr⁻¹</td>
<td>16</td>
<td>Megahan (1980)</td>
</tr>
<tr>
<td>Washington, USA</td>
<td>55–70 degrees</td>
<td>16.5 mm yr⁻¹</td>
<td>25</td>
<td>Reid (1981)</td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>NA</td>
<td>70 mm yr⁻¹</td>
<td>105</td>
<td>Blong and Humphreys (1982)</td>
</tr>
<tr>
<td>Idaho, USA</td>
<td>NA</td>
<td>11 mm yr⁻¹</td>
<td>16</td>
<td>Megahan et al. (1983)</td>
</tr>
<tr>
<td>New South Wales, Australia</td>
<td>NA</td>
<td>2.4–3.9 mm yr⁻¹</td>
<td>3.6–5.8</td>
<td>Riley (1988)</td>
</tr>
<tr>
<td>New Zealand</td>
<td>Unvegetated, granite</td>
<td>NA</td>
<td>5.2–15</td>
<td>(Fahey and Coker, 1989, 1992; Smith and Fenton, 1993)</td>
</tr>
<tr>
<td>Idaho, USA</td>
<td>Cover density 0.1–89%, 55–104% gradient</td>
<td>0.1–248 Mg ha⁻¹ yr⁻¹</td>
<td>0.01–25</td>
<td>Megahan et al. (2001)</td>
</tr>
<tr>
<td>St. John, USVI</td>
<td>Unvegetated, 2–5 m high</td>
<td>NA</td>
<td>2–17</td>
<td>This study</td>
</tr>
</tbody>
</table>

NA indicates not available or not applicable.

sediment production rates from these different units varied by over five orders of magnitude.

Among the natural sediment sources, streambanks had the highest mean sediment production rate per unit area at 100 Mg ha⁻¹ yr⁻¹. Treethrow was estimated to produce 0.2 Mg of sediment per kilometer of stream per year, or on the order of 0.1 Mg ha⁻¹ yr⁻¹ for a 15-m wide stream corridor. Bounded plot data show that runoff and sediment from undisturbed hillslopes is generated only by storms with at least 2 cm of rainfall, and that sediment production rates from undisturbed hillslopes range from 0.01 to 0.3 Mg ha⁻¹ yr⁻¹. Zero-order catchments had a mean sediment production rate of 0.01 Mg ha⁻¹ yr⁻¹, and sediment was only produced from storms with at least 6 cm of rainfall. The lower sediment yields from zero-order catchments relative to the

Table 7
Estimated cutslope contribution to sediment yields at the road segment scale

<table>
<thead>
<tr>
<th>Road plot</th>
<th>Length of road segment (m)</th>
<th>Travelway surface area (m²)</th>
<th>Cutslope surface area (m²)</th>
<th>Measured segment scale sediment production (Mg yr⁻¹)</th>
<th>Estimated contribution from cutslopes (Mg yr⁻¹)</th>
<th>Percent of sediment production contributed by cutslopes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM-A</td>
<td>420</td>
<td>2770</td>
<td>1090</td>
<td>8.9</td>
<td>3.9</td>
<td>44</td>
</tr>
<tr>
<td>BM-B</td>
<td>93</td>
<td>640</td>
<td>120</td>
<td>3.3</td>
<td>0.08</td>
<td>2</td>
</tr>
<tr>
<td>BM-C</td>
<td>270</td>
<td>1620</td>
<td>520</td>
<td>13</td>
<td>1.2</td>
<td>9</td>
</tr>
<tr>
<td>FB-A</td>
<td>93</td>
<td>570</td>
<td>120</td>
<td>0.3</td>
<td>0.16</td>
<td>50</td>
</tr>
<tr>
<td>FB-C</td>
<td>109</td>
<td>530</td>
<td>220</td>
<td>1.0</td>
<td>0.29</td>
<td>30</td>
</tr>
<tr>
<td>FB-D</td>
<td>64</td>
<td>310</td>
<td>130</td>
<td>2.8</td>
<td>0.17</td>
<td>6</td>
</tr>
<tr>
<td>FB-E</td>
<td>83</td>
<td>410</td>
<td>150</td>
<td>21</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>JH-A</td>
<td>240</td>
<td>1100</td>
<td>220</td>
<td>25</td>
<td>0.15</td>
<td>1</td>
</tr>
<tr>
<td>JH-A1</td>
<td>58</td>
<td>260</td>
<td>70</td>
<td>3.4</td>
<td>0.12</td>
<td>4</td>
</tr>
<tr>
<td>JH-A2</td>
<td>103</td>
<td>420</td>
<td>150</td>
<td>5.4</td>
<td>0.06</td>
<td>1</td>
</tr>
<tr>
<td>JH-B</td>
<td>394</td>
<td>2200</td>
<td>840</td>
<td>18</td>
<td>2.3</td>
<td>13</td>
</tr>
<tr>
<td>JH-C</td>
<td>237</td>
<td>1190</td>
<td>240</td>
<td>4.0</td>
<td>0.24</td>
<td>6</td>
</tr>
<tr>
<td>JH-D</td>
<td>148</td>
<td>720</td>
<td>250</td>
<td>4.7</td>
<td>0.77</td>
<td>16</td>
</tr>
<tr>
<td>JH-E</td>
<td>257</td>
<td>1440</td>
<td>500</td>
<td>9.4</td>
<td>0.46</td>
<td>5</td>
</tr>
<tr>
<td>LB-A</td>
<td>256</td>
<td>1330</td>
<td>160</td>
<td>11</td>
<td>0.14</td>
<td>1</td>
</tr>
<tr>
<td>LB-C</td>
<td>254</td>
<td>1310</td>
<td>530</td>
<td>6.9</td>
<td>3.3</td>
<td>47</td>
</tr>
<tr>
<td>LE-Bottom</td>
<td>78</td>
<td>380</td>
<td>20</td>
<td>1.0</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>LE-Top</td>
<td>222</td>
<td>850</td>
<td>140</td>
<td>0.8</td>
<td>0.07</td>
<td>8</td>
</tr>
<tr>
<td>MB-A</td>
<td>179</td>
<td>990</td>
<td>390</td>
<td>30</td>
<td>2.0</td>
<td>7</td>
</tr>
<tr>
<td>MB-C</td>
<td>74</td>
<td>370</td>
<td>70</td>
<td>0.6</td>
<td>0.14</td>
<td>22</td>
</tr>
<tr>
<td>Sum or mean</td>
<td>182</td>
<td>971</td>
<td>297</td>
<td>172</td>
<td>16</td>
<td>14</td>
</tr>
</tbody>
</table>
hillslope plots are attributed to more vegetative cover, lower mean slopes, a lower frequency of runoff-generating storms, and possibly a lower connectivity between the source areas and the points where sediment yields were being measured.

Sediment production from unpaved roads was significantly related to total rainfall, road segment slope, and whether the segment had been recently graded. Measured sediment production rates for graded roads ranged from 5.7 to 580 Mg ha$^{-1}$ yr$^{-1}$ for roads with slopes of 2% and 21%, respectively. The sediment production rate for ungraded roads was about 40% lower than for comparable graded roads. Abandoned road segments had a mean erosion rate of 12 Mg ha$^{-1}$ yr$^{-1}$.

The 3–4 orders of magnitude increase in sediment production from roads relative to undisturbed hillslopes and zero-order basins indicates that unpaved roads are significantly increasing the amount of sediment being delivered to the marine environment around St. John. The application of a GIS-based sediment budget model (STJ-EROS) to three basins on St. John also identified unpaved roads as the dominant sediment source. The sediment production values and empirical models developed in this paper should be useful to researchers and land managers in the eastern Caribbean and other areas in the dry tropics.

Acknowledgements

This study was supported by the Water Resources Division of the National Park Service (grant no. CA 2380-6-001), the Virgin Islands Department of Planning and Natural Resources (grant no. NPS 01500), and the Water Resources Research Institute of the University of the Virgin Islands and the U.S. Geological Survey (grant no. 1434-HQ-96-02705). The authors gratefully acknowledge the logistical support provided by the Island Resources Foundation and the Virgin Islands National Park. The authors would also like to thank Ellen Wohl, Denis Dean, Bill Jackson, and two anonymous reviewers for their comments on this manuscript.

References

Ahmad, N., Breenker, E., 1974. Soil erosion on three Tobago soils. Tropical Agriculture (Trinidad) 51 (2), 313–324.


Dyrmess, C.T., 1970. Stabilization of newly constructed road back-slopes by mulch and grass-templc treatments. USDA Forest Service Research Note PNW-123, Corvallis, OR.


