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# Development and application of a GIS-based sediment budget model

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## Abstract

Accelerated erosion and increased sediment yields resulting from changes in land use are a critical environmental problem. Resource managers and decision makers need spatially explicit tools to help them predict the changes in sediment production and delivery due to unpaved roads and other types of land disturbance. This is a particularly important issue in much of the Caribbean because of the rapid pace of development and potential damage to nearshore coral reef communities. The specific objectives of this study were to: (1) develop a GIS-based sediment budget model; (2) use the model to evaluate the effects of unpaved roads on sediment delivery rates in three watersheds on St. John in the US Virgin Islands; and (3) compare the predicted sediment yields to pre-existing data.

The St. John Erosion Model (STJ-EROS) is an ArcInfo-based program that uses empirical sediment production functions and delivery ratios to quantify watershed-scale sediment yields. The program consists of six input routines and five routines to calculate sediment production and delivery. The input routines have interfaces that allow the user to adjust the key variables that control sediment production and delivery. The other five routines use pre-set erosion rate constants, user-defined variables, and values from nine data layers to calculate watershed-scale sediment yields from unpaved road travelways, road cutslopes, streambanks, treethrow, and undisturbed hillslopes.

STJ-EROS was applied to three basins on St. John with varying levels of development. Predicted sediment yields under natural conditions ranged from 2 to 7 $Mg\,km^{-2}\,yr^{-1}$, while yield rates for current conditions ranged from 8 to 46 $Mg\,km^{-2}\,yr^{-1}$. Unpaved roads are estimated to be increasing sediment delivery rates by 3–6 times for Lameshur Bay, 5–9 times for Fish Bay, and 4–8 times for Cinnamon Bay. Predicted basin-scale sediment yields for both undisturbed and current conditions are within the range of measured sediment yields and bay sedimentation rates. The structure and user interfaces in STJ-EROS mean that the model can be readily adapted to other areas and used to assess the impact of unpaved roads and other land uses sediment production and delivery.


*Keywords:* GIS model; Erosion; Dry tropics; Unpaved roads; Sediment delivery ratio

## 1. Introduction

Land use changes that disturb the natural vegetative cover can greatly increase erosion rates and watershed-scale sediment yields, and these increases are critical environmental problems in many parts of the world (Walling, 1997). The rapid pace of land development in the Insular Caribbean, when combined with the steep terrain and high precipitation intensities, make this region particularly susceptible to accelerated erosion (Lal, 1990; Burke and Maidens, 2004). Sedimentation is one of the most important stressors of coral reef communities in the Caribbean (Hubbard, 1987; Gardner et al., 2003), and the condition of these reef communities is a major concern because of their importance for tourism and sustaining local communities. High sediment loads are an increasing source of stress for coral reef systems in the Dominican Republic (Torres et al., 2001), Puerto Rico, and the nearby island of Culebra (Acevedo et al., 1989; E. Hernández-Delgado, pers. comm., Univ. of Puerto Rico, 2001; Torres, 2001), Virgin Gorda in the British Virgin Islands

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(C. Rogers, pers. comm., USGS, 2001), as well as the islands of St. Croix (Hubbard, 1986), St. Thomas (Nemeth and Nowlis, 2001), and St. John (Rogers, 1990, 1998; Nemeth et al., 2001) in the US Virgin Islands.

Erosion processes and issues within the Caribbean are as varied as the physiographic characteristics and land use practices. Land disturbance has been widely recognized as the main cause of accelerated erosion rates, but there is very little information on past or current sediment delivery rates to the marine environment (UNEP, 1994). Historically there have been few efforts to remedy this problem (Lugo et al., 1981), and this lack of attention can be partly attributed to the lack of data and spatially explicit models to quantify sediment sources and help establish priorities for remediation. Previous studies have focused on mass wasting (e.g., DeGraff et al., 1989; Jibson, 1989; Larsen and Parks, 1997; Larsen and Torres-Sánchez, 1998), surface erosion in agricultural fields (e.g., Smith and Abruña, 1955; Ahmad and Breckner, 1974; Tirado and Lugo-López, 1984; McGregor, 1988), and the application of models to watersheds with varied land use but no data for calibration (e.g., Ramsarran, 1992; Radke, 1997; López et al., 1998). None of these efforts have addressed the combination of natural and anthropogenic sediment sources currently operating on St. John. Hence these studies cannot provide accurate estimates of sediment yields in St. John, or provide guidance on how land managers might minimize erosion rates and sediment delivery to the marine environment.

Erosion and sediment delivery issues are of particular concern on St. John because rapid development is believed to be increasing sediment yields and adversely affecting the nearshore coral reef communities in Virgin Islands National Park (MacDonald et al., 1997; Rogers, 1998). Previous studies on St. John concluded that sediment production rates from unpaved roads are several orders of magnitude higher than surface erosion rates from undisturbed hillslopes, and that unpaved roads are the primary source of the fine sediment being delivered to the marine environment (MacDonald et al., 1997, 2001). An empirical road erosion model (ROADMOD) suggested that road erosion is increasing watershed-scale sediment yields by up to four times above the estimated background rates (Anderson and MacDonald, 1998).

The present study emerged from the need to more accurately model watershed-scale erosion and sediment yields on St. John. The objectives were to: (1) develop a GIS-based model (STJ-EROS) for calculating sediment budgets; (2) use the model to quantify the effect of the unpaved road network on sediment delivery rates; and (3) compare the predicted sediment yields against limited field data.

The STJ-EROS model is conceptually based on a sediment budget. At the most basic level, a sediment budget quantitatively describes the production, movement, and storage of sediment for a single landscape unit (Dietrich et al., 1982). A sediment budget approach is useful because it quantifies the contributions of different sediment sources in a watershed (Reid and Dunne, 1996, 2003). 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. Sediment production rates were measured from the following landscape units:

- erodible streambanks;
- stream margins subjected to soil disturbance by treethrow;
- undisturbed hillslopes and zero-order catchments;
- road travelways; and
- road cutslopes.

The measured rates were used to develop empirical prediction models or assign spatially uniform sediment production rates for each landscape unit (Ramos-Scharrón and MacDonald, 2005; Ramos-Scharrón, 2004, in press).

To route sediment through a watershed it is necessary to quantify the rate of sediment movement between temporary storage sites (Swanson and Fredriksen, 1982). In the STJ-EROS model, the rate at which terrestrial sediment is transferred to the marine environment is controlled by user-defined sediment delivery ratios (SDRs), where SDR is the ratio of sediment yield to the gross erosion in the basin (Walling, 1983). STJ-EROS refines this approach by defining areas with different sediment delivery potentials. The classification of SDRs by delivery potential is a pragmatic compromise between a more physically based approach that requires much more detailed input data (e.g., Rojas-Sánchez, 2002), and the overly simplistic use of a single, spatially constant SDR. The approach used in STJ-EROS is conceptually simple, easy to implement, and appropriate given the model objectives and the intended use by planners and resource managers.

STJ-EROS was designed to help make land management decisions, as the model can quantify sediment delivery rates for both undisturbed and current conditions. It also can be used to predict sediment yields from different management scenarios. Actual or potential changes can be evaluated by making changes to one or more GIS data layers or user-defined variables (e.g., paving selected road segments or comparing alternative routes for new roads). The development of a spatially explicit sediment budget model can help planners and land managers assess alternatives and choose the most cost-effectiveness strategies for reducing sediment delivery to areas of particular concern (Lu et al., 2004).

## 2. Study area

The US and British Virgin Islands constitute the eastern extremity of the Greater Antilles, and St. John is the third largest island within the US Virgin Islands (Fig. 1). St. John lies on the Puerto Rico-Virgin Islands microplate, which is between the Caribbean and North American plates (Rankin, 2002). The resultant folding and faulting

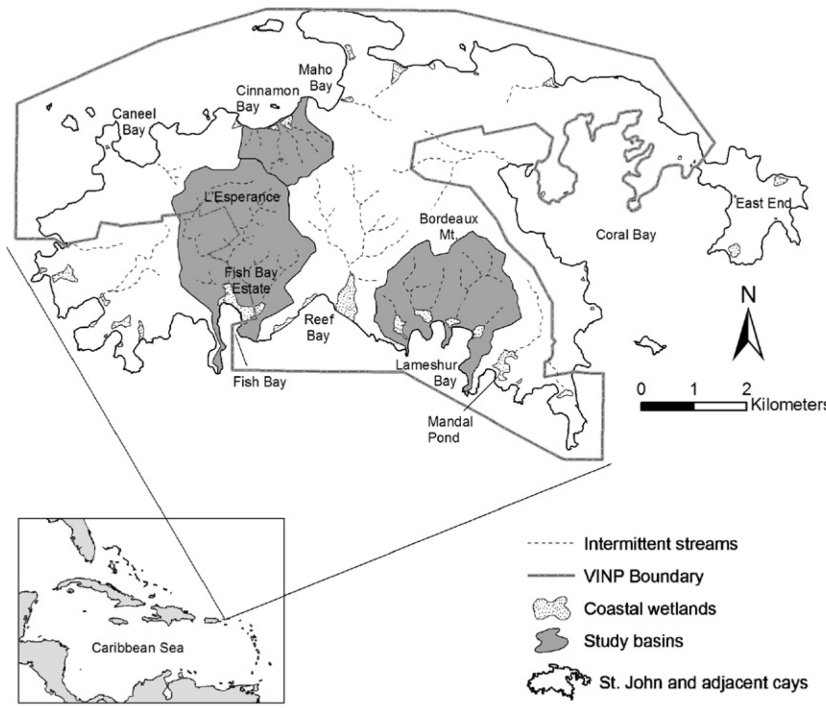


Fig. 1. Map of St. John showing the boundaries of VINP and the three study basins.

has created a rugged topography, and more than 60% of St. John has slopes greater than 30% (Anderson, 1994). St. John's lithology is dominated by volcanic rocks that have undergone periods of deformation, magmatic intrusions, and hydrothermal alterations (Donnelly, 1966; Rankin, 2002). The soils developed from these rocks are predominantly gravelly clay loams (Soil Conservation Service, 1970; USDA, 1995), and they tend to be shallow, moderately permeable, well-drained, and underlain by nearly impervious material.

The climate of St. John is characterized as subtropical dry. Bowden et al. (1970) identified five precipitation zones, ranging from 90 to 100 $\mathrm{cm\,yr^{-1}}$ on the East End to a high of 130–140 $\mathrm{cm\,yr^{-1}}$ near Bordeaux Mountain (Fig. 1). 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 St. John, but a relatively dry season extends from about February to July and there is a relatively wet season from August to January (Bowden et al., 1970).

Mean monthly potential evapotranspiration (PET) exceeds mean monthly precipitation for most of the year (Bowden et al., 1970). There is little ground water storage on St. John and all streams (known locally as "guts") are ephemeral (Cosner, 1972; MacDonald et al., 1997). The combination of steep slopes, small drainage areas, shallow soils, and high-intensity rainstorms result in "flashy" runoff hydrographs with mean annual peak flows of nearly 15 $\mathrm{mm\,h^{-1}}$ (Jordan and Cosner, 1973; MacDonald et al., 2001).

The history of land use in St. John is similar to most of the other islands in the eastern Caribbean, in that it was originally forested and subjected to only minor disturbance by Amerindian groups. During the 1700s and 1800s, approximately 90% of the forests were removed and replaced by sugarcane fields (Tyson, 1987). These fields were largely abandoned in the late 19th century as a result of the decline in the sugarcane industry, and forest regrowth was relatively rapid. In 1917 the United States purchased the Virgin Islands from Denmark, and in 1956 over half of the island and 23 $\mathrm{km^2}$ of offshore waters were protected as Virgin Islands National Park (VINP). In 2001 an additional 47 $\mathrm{km^2}$ of offshore waters were included in V.I. Coral Reef National Monument.

Rapid development over the past 30 years has resulted in a dense network of unpaved roads, particularly on private lands outside of VINP. Between 1971 and 2000 the road network in the 6 $\mathrm{km^2}$ Fish Bay basin nearly tripled in length, and 56% or 13.1 km of these roads were unpaved (Ramos-Scharrón, 2004). The unpaved road network is believed to be the single most important sediment source on St. John (Anderson and MacDonald, 1998). The combination of high resource values and rapid development creates an urgent need for a locally calibrated, spatially explicit model to estimate sediment production and delivery at the watershed scale.

## 3. Field methods and results

Sediment production rates from natural and anthropogenic sources were measured by various field methods (Ramos-Scharrón, 2004; Ramos-Scharrón and

MacDonald, 2005). Streambank erosion at four stream reaches was quantified over a 2-year period by erosion pins (Lawler, 1993). These four sites represent the approximately 17% of the fluvial network where streams have incised through unconsolidated, poorly sorted Quaternary alluvium. In these incised reaches the streambanks are 0.6–2.3 m high, largely unvegetated, and show little layering. Loose, angular, gravel-sized fragments constitute about 25% of the deposits, and these coarse fragments are supported by a fine matrix consisting of approximately 25% sand and 50% silt and clay (Nichols and Brush, 1988). Historical artifacts within some of these deposits indicate that the upper portions of the alluvium were deposited as a result of the high sediment production rates that characterized the plantation era (Anderson, 1994). The remaining 83% of the fluvial network consists of colluvial headwater channels that feed into first-order cascade or step-pool channels (Montgomery and Buffington, 1997) that are confined within steep ravines. Minimal streambank erosion is expected from the colluvial headwater channels because they lack well-defined banks, or from the cascade and step-pool channels because these banks typically consist of boulders and largely unweathered bedrock.

In each study reach five to nine 15-cm long erosion pins were installed along 2–4 vertical columns, yielding a grand total of 82 erosion pins. The length protruding from the bank was measured to the nearest millimeter at the time of installation and another 1–3 times at frequencies ranging from approximately 6 months to 2 years. The rate of streambank erosion or aggradation in centimeters per year was calculated from the net change in length over the time between measurements. These values were multiplied by the estimated bulk density to yield Mg per hectare per year (Ramos-Scharrón, 2004; Ramos-Scharrón and MacDonald, in press).

The amount of sediment delivered to the fluvial network by treethrow was determined by measuring the volume of soil in rootwads and estimating the frequency of treethrow events (Ramos-Scharrón, 2004). 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. Most of the rootwads included in our field inventory were found on top of the streambanks and therefore had a very high potential for delivering sediment into the stream network. The mass of sediment delivered to the stream from each rootwad was assumed to equal the rootwad volume times the estimated percent of soil contained in the rootwad and the estimated dry bulk density. The rate of sediment delivery to the stream network in Mg of soil per kilometer of stream per year was calculated from the sum of the soil in the rootwads divided by the length of the reach and the time represented by our field observations. By assuming that treethrow only occurred during hurricanes and determining the long-term history of hurricane-induced forest damage on St. John, our surveys probably represent about 100 years of treethrow-induced sediment production (Ramos-Scharrón, 2004; Ramos-Scharrón and MacDonald, in press).

Sediment fences (Robichaud and Brown, 2002) were used to quantify sediment production rates from undisturbed hillslopes (0.9–2 ha), first-order catchments (5–15 ha), unpaved road segments (270–2100 $m^2$), and cutslopes (5–30 $m^2$). The sediment fences were constructed by attaching filter fabric to pieces of rebar hammered vertically into the ground (Ramos-Scharrón, 2004). The sediment trapped in the fences was collected and weighed in the field to the nearest $\frac{1}{4}$ kg. Samples of the trapped sediment were collected and used to determine percent moisture (Gardner, 1986). These data were used to convert the field-measured wet weights to a dry mass. The particle-size distribution of these samples was determined by dry sieving down to 0.075 mm (Bowles, 1992) and the hydrometer method for the finer fraction (Gee and Bauder, 1986).

The measured sediment production rates for the different landscape units ranged over five orders of magnitude (Fig. 2; Table 1). The mean streambank erosion rate was 100 Mg $ha^{-1}$ $yr^{-1}$. Uprooting of trees along stream margins was estimated to deliver 0.17 Mg of sediment per kilometer of stream per year, or 0.11 Mg $ha^{-1}$ $yr^{-1}$ for a 15-m wide stream corridor. This rate is just slightly lower than the value of 0.20 Mg $ha^{-1}$ $yr^{-1}$ reported from the Luquillo Experimental Forest (LEF) in eastern Puerto Rico (Larsen, 1997).

The mean sediment yield for undisturbed hillslopes was 0.01 Mg $ha^{-1}$ $yr^{-1}$, or about an order of magnitude less than the 0.10–0.50 Mg $ha^{-1}$ $yr^{-1}$ reported for undisturbed hillslopes in the LEF in Puerto Rico (Larsen et al., 1999). The lower value for St. John can be attributed to 60% less rainfall and a higher abundance of coarse rock fragments (Ramos-Scharrón and MacDonald, in press).

Surface erosion rates from unpaved road segments depend on rainfall, road slope to the 1.5 power, and

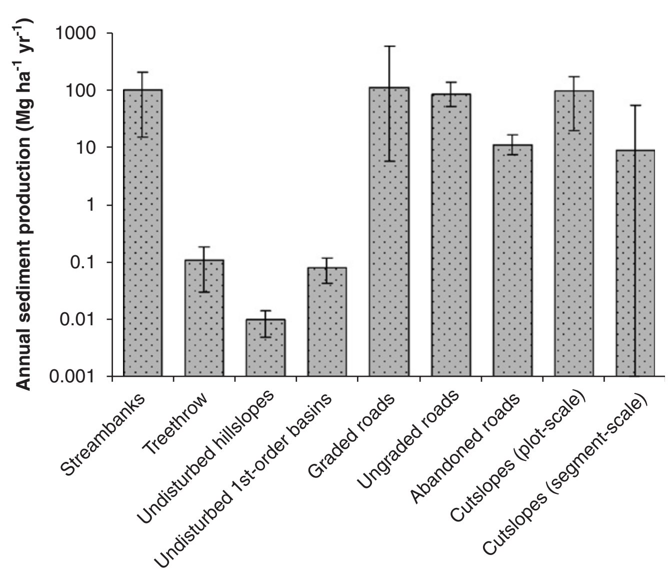


Fig. 2. Mean annual sediment production rates from natural and anthropogenic sediment sources on St. John. Bars indicate the range of values.

Table 1
Sediment production rates and empirical prediction functions for the different landscape units in STJ-EROS

| Sediment source | Sediment production ($kg\,m^{-2}\,yr^{-1}$) | Sediment production function (kg) |
|---|---|---|
| Streambanks | 10 | [10] × 2 × *channel length with erodible banks* × *bank height* × *years* |
| Treethrow | 0.01 [0.17 $kg\,m^{-1}\,yr^{-1}$] | [0.17] × *channel length* × *years* |
| Undisturbed hillslopes | 0.001 | [$6.4 \times 10^{-5}$] × 14% rainfall × *area* × {1 + 3.4 × 0.004$^{+}$}] |
| Graded roads | 0.1–52 (slopes from 1% to 21%) | [−0.432 + 4.73 × *slope*$^{1.5}$ × rainfall] × *road length* × *width* × {1 + 3.4 × 0.06$^{+}$}] |
| Ungraded roads | 0.0–20 (slopes from 1% to 21%) | [−0.432 + 1.88 × *slope*$^{1.5}$ × rainfall] × *road length* × *width* × {1 + 3.4 × 0.04$^{+}$}] |
| Abandoned roads | 0.08–1.7 (slopes from 1% to 21%) | [0.071] × *slope* × rainfall × *road length* × *width* × {1 + 3.4 × 0.001$^{+}$} |
| Cutslopes | 0.0–5.7 | [0.09] × road segment sediment production |

Lengths, widths, and heights are in meters, time is in years, slope is a decimal, area is in $m^2$, and rainfall is in centimeters.
Empirical sediment production functions are in square brackets; corrections for the loss of silt-sized particles are between { }.
Items in italics are taken from GIS data layers, underlined items indicate user-defined variables, and rainfall is calculated by multiplying the user-defined annual rainfall rate times the time in years.
Road surface erosion accounts for 91% of the sediment yield from road segments, and cutslopes account for the remaining 9%.
$^{+}$Refers to the percent of silt from Table 2.

frequency of grading (Fig. 2; Table 1) (Ramos-Scharrón and MacDonald, 2005). Sediment production rates for road segments that were graded at least once every 2 years ranged from 6 $Mg\,ha^{-1}\,yr^{-1}$ for a segment with a mean slope of 1% to 580 $Mg\,ha^{-1}\,yr^{-1}$ for a segment with a mean slope of 21%. Ungraded roads had sediment production rates ranging from 51 to 140 $Mg\,ha^{-1}\,yr^{-1}$ for segments with a mean slope of 10% and 16%, respectively. Abandoned road segments with a slope of 15% had a mean erosion rate of only 11 $Mg\,ha^{-1}\,yr^{-1}$.

Cutslope sediment production rates ranged from 20 to 170 $Mg\,ha^{-1}$ of cutslope surface per year, but accounted for only 9% of the sediment yield from unpaved roads at the road-segment scale (Ramos-Scharrón, 2004). The low sediment yield from cutslopes is due to their relatively coarse texture and the resulting low transport rates, and because the road runoff tended to be concentrated in tire tracks rather than in an inside ditch at the toe of the cutslopes (Ramos-Scharrón and MacDonald, in press).

## 4. St. John sediment budget model (STJ-EROS)

### 4.1. Overview

STJ-EROS calculates the amount of sediment from different sources that reaches the marine environment on a watershed scale, and uses GIS software to do so on a spatially explicit basis. The program is written in Arc Macro Language (AML) for ArcInfo Workstation and uses the relational database commands available in the Tables module.

The STJ-EROS model has six input routines and five routines that calculate sediment production and delivery (Fig. 3). The six input routines have user interfaces that allow the user to adjust some of the key variables controlling sediment production and delivery. The remaining five routines use pre-set erosion rates, user-defined variables, and item values stored in nine data layers to calculate watershed scale sediment yields. A more complete description of the GIS data layers needed to run the model, flowcharts of the most important routines, and the program code can be found in Ramos-Scharrón (2004) or obtained directly from the senior author.

### 4.2. Input routines

STJ-EROS begins with the 'Set_sdr' routine (Fig. 3). This routine prompts the user to select the SDRs for routing sediment to the marine environment, and stores these choices as variable values. In STJ-EROS the SDR values account for both hillslope and channel storage, including the potential storage at the mouth of a gut (i.e., whether the gut discharges directly to the sea or into an intervening coastal wetland, salt pond, or mangrove swamp). The SDR values generally depend on the drainage area, the type and location of sediment sources, the particle-size distribution of the sediment being eroded, and the transport and storage capacity of the fluvial network (Bunte and MacDonald, 1999).

Suggested SDRs for catchments with drainage areas of 0.1–5 $km^2$ are generally between 40% and 100% (Walling, 1983). In STJ-EROS the program allows users to choose SDR values ranging from 50% to 100% for areas with a high sediment delivery potential. These are areas that drain directly to the sea without an intervening coastal wetland or salt pond. This range of SDR values is consistent with field observations that indicate limited storage capacity within the fluvial network (Anderson, 1994; MacDonald et al., 1997), as well as measured runoff rates and sediment transport calculations. For example, calculated flow velocities at 12 locations in Fish Bay Gut indicated that only 12% of the estimated bankfull flow depth is required to maintain particles smaller than 2 mm in suspension (Ramos-Scharrón, 2004). The flow depths needed to suspend particles in the medium gravel size range (~8 mm) generally are larger than the estimated bankfull depth. This indicates that fine particles can be effectively transported out of the fluvial network, but the coarser particles are likely to be transported as bed load and may

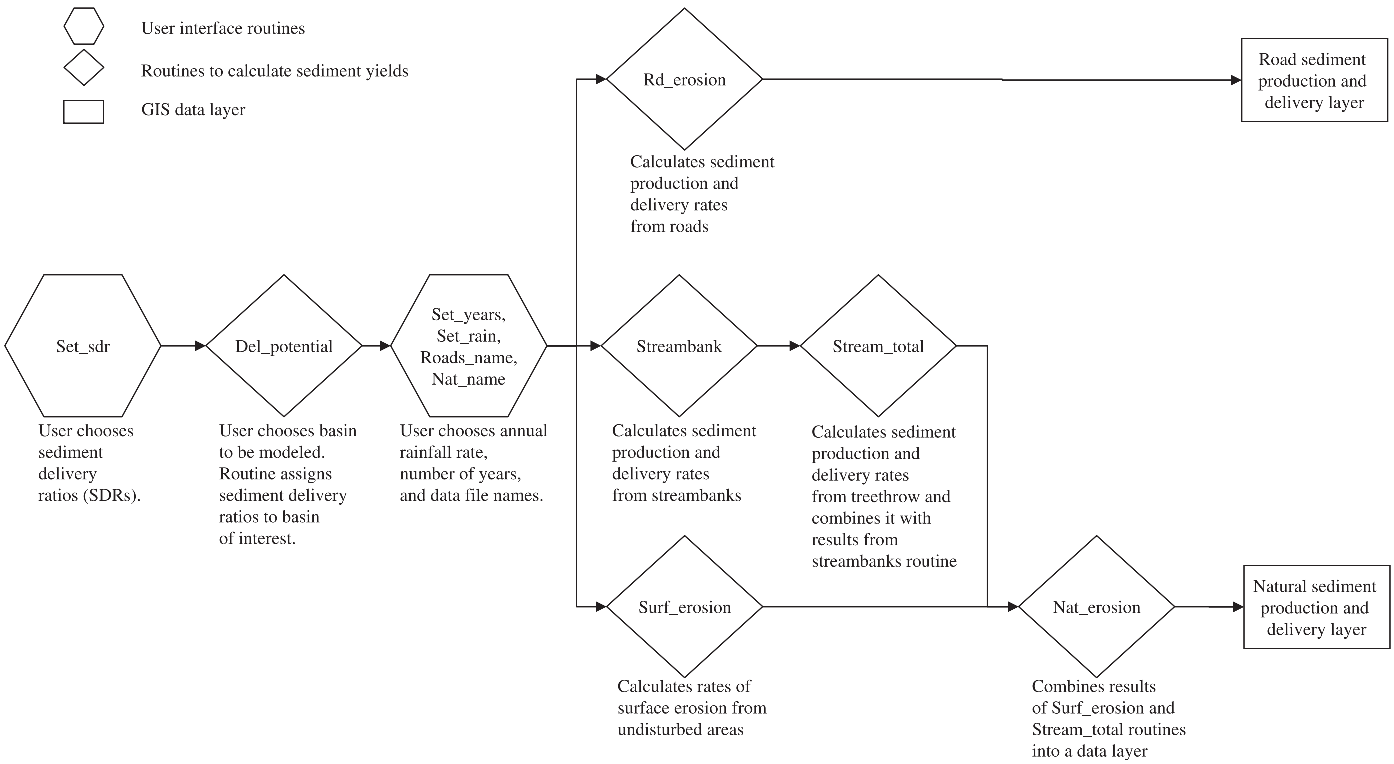


Fig. 3. Flowchart of the STJ-EROS model.

remain within the fluvial system for longer time periods (Knighton, 1998).

In STJ-EROS the fine fraction is defined as particles smaller than or equal to 2 mm. Coarse particles range from 2 to 30 mm in diameter, as 30 mm represents the largest particles captured in the sediment traps (Ramos-Scharrón, 2004). The expected difference in sediment delivery rates for fine and coarse particles are explicitly recognized in STJ-EROS by providing results as a range of sediment yields. The minimum sediment yield is calculated by applying the user-defined SDR to the fine fraction and assuming a SDR of zero for coarse particles. The maximum sediment yield applies the user-defined SDR to both the fine and coarse fractions.

The delivery of sediment from catchments with an intervening wetland or salt pond is complicated because these wetlands vary with respect to their size, magnitude of fresh water inflows, potential for tidal inflows, and sensitivity to natural and human disturbance. The larger salt ponds and sand flats can detain large volumes of runoff and will have a correspondingly low SDR, while mangrove swamps generally have smaller storage capacities, are more subject to salt water inflows during storms, and therefore have higher SDRs.

Assigning SDR values is further complicated because most data on the sediment-trapping effectiveness of mangroves and coastal wetlands are qualitative (Augustinus, 1995). In the absence of quantitative values, the SDRs for areas draining into coastal wetlands are assumed to range from 0% to 50%, and these catchments are defined as having a moderate potential for sediment delivery. Catchments that drain to a wetland or pond without any surface pathway to the marine environment are assumed to have a SDR of zero.

The next step in STJ-EROS is the 'Del_potential' routine (Fig. 3). This routine prompts the user to choose the basin for which the sediment budget is to be estimated. This routine also incorporates the user-defined SDR values into a data layer containing pre-defined sediment delivery potential polygons for the chosen basin. The next routines are 'Set_years', 'Set_rain', 'Roads_name', and 'Nat_name' (Fig. 3). These routines prompt the user to choose variable values for the total number of years over which the model is to be applied, an annual rainfall rate, and names for the GIS data layers that will contain the model results.

### 4.3. Calculating sediment yields

#### 4.3.1. Unpaved roads

After the user-defined inputs have been specified, sediment production and delivery from each unpaved road segment is calculated by the 'Rd_erosion' routine (Fig. 3). This routine uses four input layers and four user-defined variables. The first required input is a line layer that defines each road segment along with its road surface type, grading frequency category, slope, length, and width. Each road segment must have a distinct drainage point, and the coordinates of the drainage points must be in a second input layer.

The 'Rd_erosion' routine assigns a SDR value to each road drainage point according to its location relative to the pre-defined sediment delivery potential. This routine also calculates sediment production from each unpaved road segment based on the user-defined annual rainfall rate and the characteristics of each road segment (Table 1). The empirical sediment production function in Table 1 was derived from sediment trap data collected at road drainage outlets (Ramos-Scharrón and MacDonald, 2005). STJ-EROS currently assumes zero sediment production from paved roads as both field observations and limited measurements indicate that the cutbanks and fillslopes along paved roads in the three study basins produce relatively little sediment compared to unpaved roads.

The 'Rd_erosion' routine also multiplies the estimated sediment production for each road segment by the SDR. This relatively simple approach is necessary given the intended audience and the difficulty of predicting the proportion of road-derived sediment that will reach the stream network. Field surveys on St. John indicate that 70 of 338 road-drainage locations were within 50 m of a channel (Ramos-Scharrón, 2004). While some road-related sediment may be stored along vegetated hillslopes (Burroughs and King, 1989; Croke et al., 1999), the proportion that is stored will be less than in most other areas given the steep slopes, widespread overland flow during the largest storm events, and the abundance of gullies downslope of road-drainage points. Future versions of STJ-EROS are expected to include more physically based procedures for routing road-derived sediment to the channel network.

Another complication in predicting the production and delivery of sediment from unpaved roads is that the efficiency of sediment traps generally decreases with decreasing particle size (Ice, 1986). Runoff and suspended sediment data from an unpaved road segment indicated that the mass of silt-sized particles (defined as 0.004–0.062 mm) was 3.4 times greater than the mass of silt-sized particles collected from a sediment trap immediately below the same road segment (Ramos-Scharrón and MacDonald, 2006). This difference has a surprisingly small effect on the total sediment yield as both methods indicate that silt-sized particles comprise only about 5% of the total sediment yield. However, silt-sized particles may be particularly damaging to the surrounding coral reefs (Acevedo et al., 1989; Rogers, 1990), and an empirical correction factor was added to the 'Rd_erosion' routine to adjust for the underestimation of silt-sized particles (Table 1).

#### 4.3.2. Streambank sediment

The 'Streambank' routine calculates sediment production and delivery from streambank erosion. The erosion pins indicated a mean erosion rate of 7 mm yr$^{-1}$, and this converts to approximately 100 Mg ha$^{-1}$ yr$^{-1}$. This rate represents a combination of dry ravel, sloughing, and fluvial erosion. The net loss of material suggests a widening of the streams that are incised into alluvial deposits, and a similar response has been observed in other areas that are also recovering from high erosion rates (e.g., Clark and Wilcock, 2000).

Sediment production from streambanks is calculated from the total length of streams with erodible banks, bank height, and the empirical "streambank" sediment production constant (Table 1). The factor of two in this function constant is needed to account for the banks on each side of the streams, and the sediment from streambank erosion is partitioned into fine ($\leq$2 mm) and coarse ($>$2 mm) material according to the particle-size distribution in Table 2. The sediment production rate for each stream arc times the user-assigned SDR yields the amount of sediment that is delivered to the sea.

#### 4.3.3. Treethrow

The 'Stream_total' routine calculates the sediment produced by treethrow and combines this with the sediment produced by streambank erosion (Fig. 3). Sediment production from treethrow is based on the empirically derived "treethrow" sediment production constant and the total channel length in the chosen basin (Table 1). The value of the treethrow variable represents the measured mean sediment production rate from treethrow in kg per meter of channel per year. In this study the fluvial network specified in the stream data layer was developed from field reconnaissance, so the channel length represented in the data layer is longer than what

Table 2
Proportion of sediment by particle-size class for different sediment sources on St. John

| Sediment source (source of size distribution estimate) | Gravel (%) (>2 mm) | Sand (%) (0.062–2 mm) | Silt and clay (%) (<0.062 mm) |
|---|---|---|---|
| Streambanks (Nichols and Brush, 1988) | 25 | 25 | 50 |
| Treethrow (USDA, 1995) | 25 | 25 | 50 |
| Undisturbed hillslopes (Ramos-Scharrón, 2004)[a] | 42 | 57 | 0.4 (0.4) |
| Graded roads (Ramos-Scharrón and MacDonald, 2005)[a] | 35 | 58 | 7 (6) |
| Ungraded roads (Ramos-Scharrón and MacDonald, 2005)[a] | 41 | 53 | 6 (4) |
| Abandoned roads (Ramos-Scharrón and MacDonald, 2005)[a] | 73 | 27 | 0.1 (0.1) |

The values in parentheses in the last column are the proportion of silt (defined as 0.004–0.062 mm).

[a]The particle-size distribution for these sources were determined by analyzing samples of the material collected in sediment fences. The sediment from cutslopes is assumed to have the same particle-size distribution as the sediment from the road surface.

would be obtained from standard hydrographic data layers.

Sediment delivery from treethrow is calculated in the 'Stream_total' routine by multiplying the estimated sediment production of each stream arc by its respective SDR. Treethrow sediment delivery is partitioned into fine ($\leq$2 mm) and coarse ($>$2 mm) material according to the particle-size fractions shown in Table 2. The 'Stream_total' routine combines the sediment delivery from streambanks and treethrow into a new polygon layer.

#### 4.3.4. *Surface erosion*

The 'Surf_erosion' routine estimates sediment production from undisturbed hillslopes from the annual rainfall rate and a variable called "undisturbed". The undisturbed variable defines sediment production as a function of rainfall from large storms and the contributing area (Table 1). The focus on large storms stems from observations showing that at least 6 cm of storm rainfall are needed to initiate surface erosion on undisturbed zero-order catchments on St. John (Ramos-Scharrón, 2004). Long-term rainfall data from Caneel Bay show that storms larger than 6 cm account for only about 14% of the annual rainfall. This percentage was incorporated into the empirical sediment production model for undisturbed hillslopes by multiplying the user-defined annual rainfall by 14% (Table 1). As with the other sediment sources, sediment production is partitioned into fine ($\leq$2 mm) and coarse ($>$2 mm) fractions according to the particle-size data in Table 2. The sediment production equation also includes an adjustment factor for the amount of silt-sized particles, as this predictive equation also was developed from sediment trap data. The sediment yields from undisturbed hillslopes in each polygon are obtained by multiplying the calculated sediment production rate times the assigned SDR.

#### 4.3.5. *Combining sediment sources*

The 'Nat_erosion' routine creates a final data layer that combines the sediment production and delivery estimates from streambanks, treethrow, and undisturbed areas (Fig. 3). The final routine in STJ-EROS is the 'Summary_results' routine, and this displays a table showing the ranges of the calculated sediment delivery rates for each source and for the entire basin.

## 5. Model application and validation

### 5.1. *Basin descriptions*

The STJ-EROS model was applied to three basins on St. John: Lameshur Bay, Fish Bay, and Cinnamon Bay (Fig. 1). These three basins were chosen because they have been the target of road rehabilitation projects conducted by VINP, the V.I. Department of Planning and Natural Resources, and various homeowner associations.

The 4.3 $km^2$ Lameshur Bay basin includes the mostly undisturbed areas that drain to Little Lameshur, Greater Lameshur, and Europa Bays on the south coast of St. John (Figs. 1, 6a). Only 8% of the basin was classified as having a high sediment delivery potential, while 64% was designated as moderate delivery potential (Table 3). Twenty-four percent of the basin has no sediment delivery potential because the runoff is diverted into a large detention pond with no surface outlet. There are 6.4 km of streams in the basin, 20% of which have erodible banks. In 1999 the road density was only 0.81 km $km^{-2}$, and this included 3.2 km of actively used unpaved roads, 0.2 km of abandoned unpaved roads, and 0.1 km of paved roads (Table 4). The unpaved roads had an average slope of 5%. Among actively used roads, only 10% were classified as having been graded in the last 2 years.

Table 3
Characteristics of the three basins where STJ-EROS was applied

| Basin | Basin area ($km^2$) | Mean basin slope (%) | Length of fluvial network (km) | Streams with erodible banks (%) | Wetland (% of basin) | High delivery potential (% of basin) | Moderate delivery potential (% of basin) | No delivery potential (% of basin) |
|---|---|---|---|---|---|---|---|---|
| Lameshur Bay | 4.3 | 41 | 6.4 | 20 | 4 | 8 | 64 | 24 |
| Fish Bay | 6.0 | 31 | 12.7 | 21 | 3 | 68 | 29 | 0 |
| Cinnamon Bay | 1.6 | 39 | 4.1 | 7 | 2 | 70 | 28 | 0 |

Table 4
Road density and proportion of unpaved road types in each study basin

| Basin | Total road length (km) | Road density (km $km^{-2}$) | Unpaved roads (%) | Road type (% of unpaved) | | |
|---|---|---|---|---|---|---|
| | | | | Graded | Ungraded | Abandoned |
| Lameshur Bay | 3.5 | 0.8 | 97 | 9 | 84 | 7 |
| Fish Bay | 22 | 3.7 | 57 | 42 | 32 | 26 |
| Cinnamon Bay | 5.3 | 3.3 | 31 | 4 | 96 | 0 |

The 6.0 km$^2$ Fish Bay basin lies to the west of the Lameshur Bay basin (Figs. 1, 6b). In contrast to Lameshur Bay, approximately 68% of the Fish Bay basin has a high sediment delivery potential because of the lack of intervening wetlands (Table 3). Most of the area with a high potential for sediment delivery drains into Main Fish Bay Gut or its primary tributary, Battery Gut. The other 32% of the basin has a moderate potential for sediment delivery. There are 12.7 km of streams in the basin, and 2.6 km or 21% have actively eroding banks. The road density is 3.7 km km$^{-2}$, or nearly five times higher than the Lameshur Bay basin. In 1999 43% of the roads were paved, 42% were unpaved and actively used, and 15% were unpaved and had been abandoned for at least 15 years (Table 4). The average slope of the unpaved roads was 7%.

The third study area was the Cinnamon Bay basin, and this drains to the north coast of St. John (Figs. 1, 6c). The study area was 1.6 km$^2$ or 90% of the 1.8 km$^2$ Cinnamon Bay basin, as we could not access the private, highly developed Peter Bay area that represents the remaining 10% of the basin. The average slope in the modeled area was 39%, which is very similar to the average slope in the Lameshur Bay basin and slightly steeper than the Fish Bay basin. Like Fish Bay, 70% of the catchment has a high sediment delivery potential, while the remaining 30% has a moderate sediment delivery potential because the area is a wetland or the runoff is routed into a wetland (Table 3). There are 4.1 km of streams within the Cinnamon Bay basin, but only 7% of the streams have erodible banks. The road density in the study area was 3.3 km km$^{-2}$, or nearly as high as the Fish Bay basin, but 69% of the roads were paved (Table 4). The main unpaved road is the John Head road, and the mean slope of the unpaved roads was 11%, which is steeper than in the other two basins. Only 4% of the unpaved roads had been recently graded (Table 4).

## 5.2. Predicted sediment yields

In the absence of specific data on the sediment trapping efficiency of coastal wetlands, areas with a high potential for sediment delivery were assigned a SDR of 75%, and areas with a moderate potential for sediment delivery were assigned a SDR of 25%. The calculated background sediment delivery rates under undisturbed conditions ranged from 2 to 7 Mg km$^{-2}$ yr$^{-1}$ for the three study basins (Fig. 4), with approximately 80–90% of this originating from streambanks. The slightly higher background sediment yields for the Fish Bay basin are due to the higher density of streams with erodible banks and the high proportion of the area with a high potential for sediment delivery.

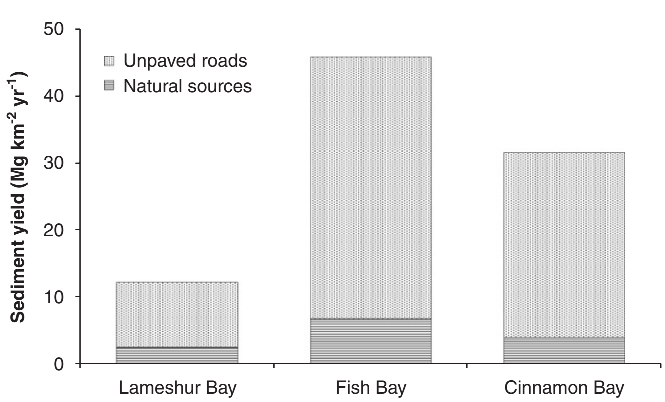


Fig. 4. Total sediment yields estimated by STJ-EROS for natural sources and unpaved roads for the Lameshur Bay, Fish Bay, and Cinnamon Bay basins.

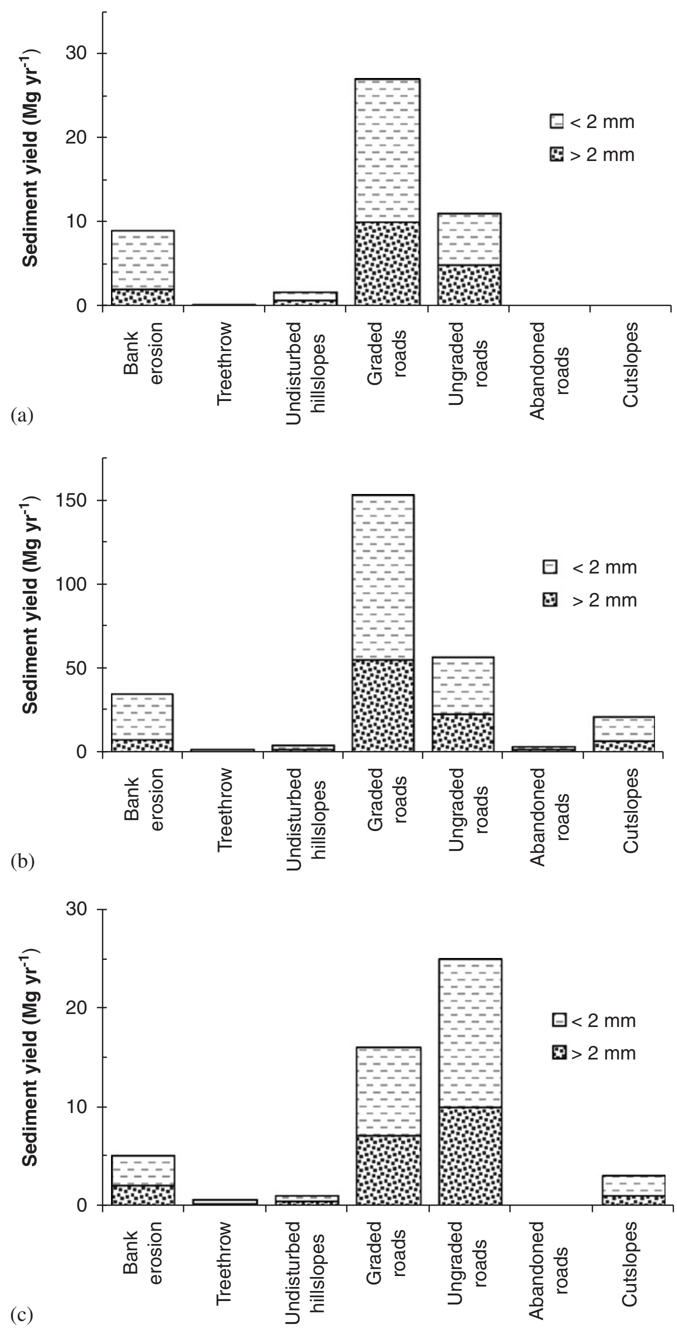


Fig. 5. Contribution of different sediment sources by particle-size class for: (a) Lameshur Bay basin, (b) Fish Bay basin; and (c) Cinnamon Bay basin.

Current sediment yields are estimated to be 3–9 times higher than background rates (Fig. 4). The largest increase is in the Fish Bay basin, as this has the highest density of unpaved roads and fewer opportunities for sediment to be trapped by coastal wetlands. The smallest increase is in the Lameshur Bay basin, and this is due primarily to the low density of unpaved roads.

Fig. 5 shows the amount of sediment being delivered by each sediment source by particle-size class for each study basin. In each basin about 65% of the total sediment yield consists of particles less than or equal to 2 mm, and this is of particular concern because this size fraction is most damaging to coral reefs (Acevedo et al., 1989; Rogers, 1990).

The spatially distributed nature of STJ-EROS facilitates the quantification and display of sediment yields from different portions of the study areas and each road segment (Fig. 6). These maps show the areas that are more sensitive to development because of their high sediment delivery potential, and that only a few road segments are contributing most of the sediment being delivered to the marine environment.

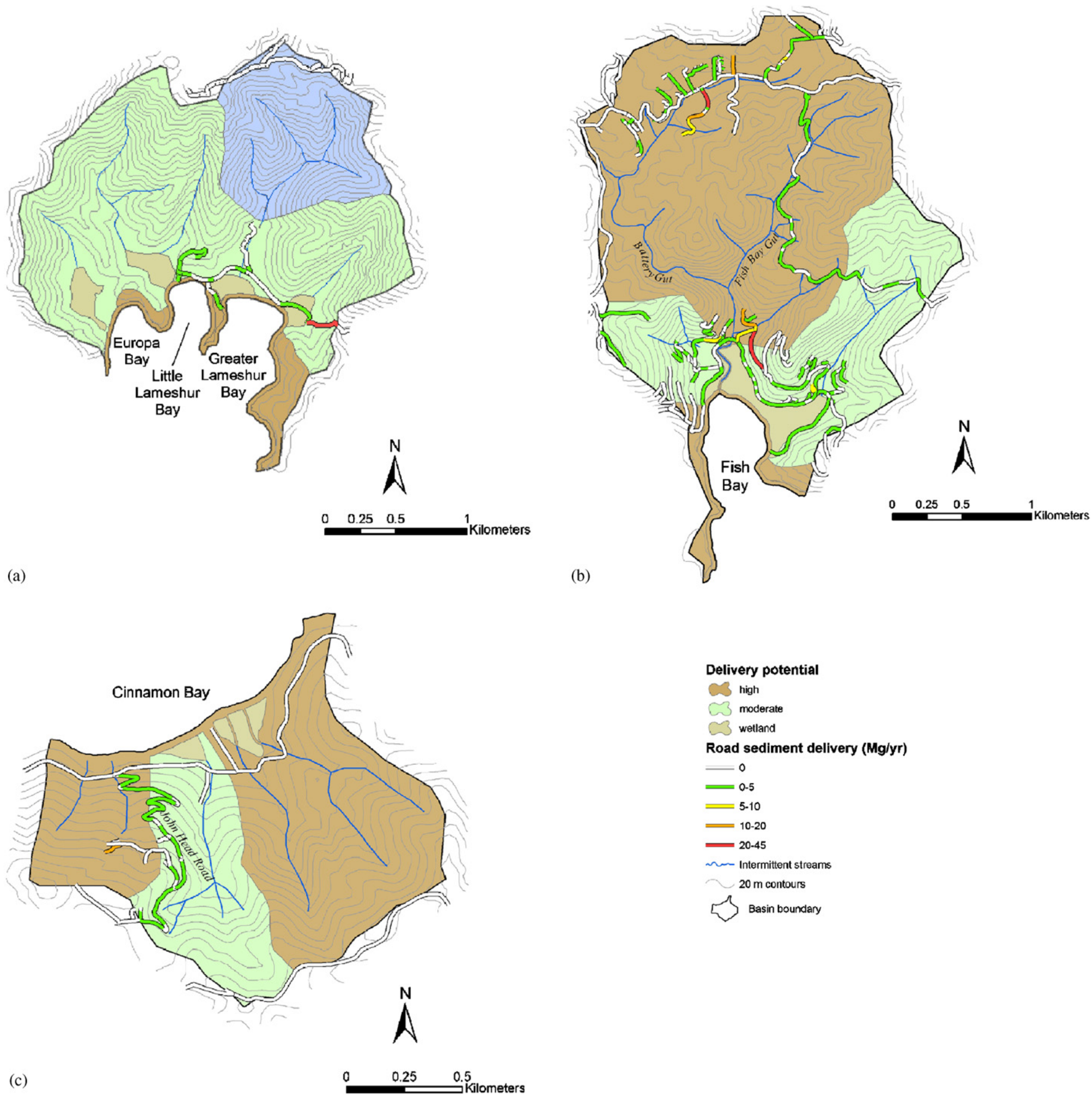


Fig. 6. Sediment delivery potential and road sediment delivery rates for: (a) Lameshur Bay basin; (b) Fish Bay basin; and (c) Cinnamon Bay basin.

In the case of the Lameshur Bay basin, one graded road segment accounts for 50% of the sediment being delivered (shown in red in Fig. 6a). This segment is 330 m long with an average slope of 20%, and it clearly should have highest priority for paving and improved drainage. The other unpaved roads account for another 30% of the estimated sediment yield into Lameshur Bay. Seventeen percent of the estimated sediment yield comes from streambank erosion, while cutslopes, undisturbed hillslopes, and treethrow are relatively minor sources (Fig. 5a).

In the Fish Bay basin, only 8% of the roads account for 47% of the total sediment yield. Most of these roads drain directly into Main Fish Bay Gut in the lower portion of the basin, or to the Battery Gut tributary in the upper portion of the basin (Fig. 6b). Streambanks and cutslopes are each responsible for roughly 10% of the annual sediment yield, while surface erosion from undisturbed areas, treethrow, and erosion from abandoned road surfaces each represent only 1% of the estimated sediment yield (Fig. 5b).

In the Cinnamon Bay basin a recently constructed unpaved private driveway and the remaining 1.5 km of unpaved segments account for about 80% of the predicted sediment yield (Fig. 6c). The single largest source is an ungraded 80-m long driveway with a slope of 27%, and this is estimated to contribute 15 $Mg\,yr^{-1}$ of sediment or 30% of the total sediment yield. Each of the road segments along John Head road produce less than 5 $Mg\,yr^{-1}$ (Fig. 6c), but together they account for 51% of the sediment being delivered to Cinnamon Bay. Streambanks generate another 10% and cutslopes about 6% of the delivered sediment. Surface erosion from undisturbed hillslopes and treethrow each account for about 1–2% of the total sediment yield (Fig. 5c).

In summary, the results generated by STJ-EROS show that unpaved roads account for about 80–85% of the current sediment yield in each basin. Perhaps more importantly, STJ-EROS explicitly identifies the sediment contribution of each road segment, and hence where funds should be most effectively allocated to reduce sediment yields. For the Lameshur Bay basin, paving just 0.3 km or 10% of the unpaved roads could reduce sediment yields by 50%. In the Fish Bay basin, paving 1.7 km or 8% of the unpaved roads could reduce sediment yields by 47%. Paving one 80-m driveway in Cinnamon Bay could reduce sediment yields by 30%, while paving the remaining 1.5 km of unpaved roads would reduce sediment yields by 51%.

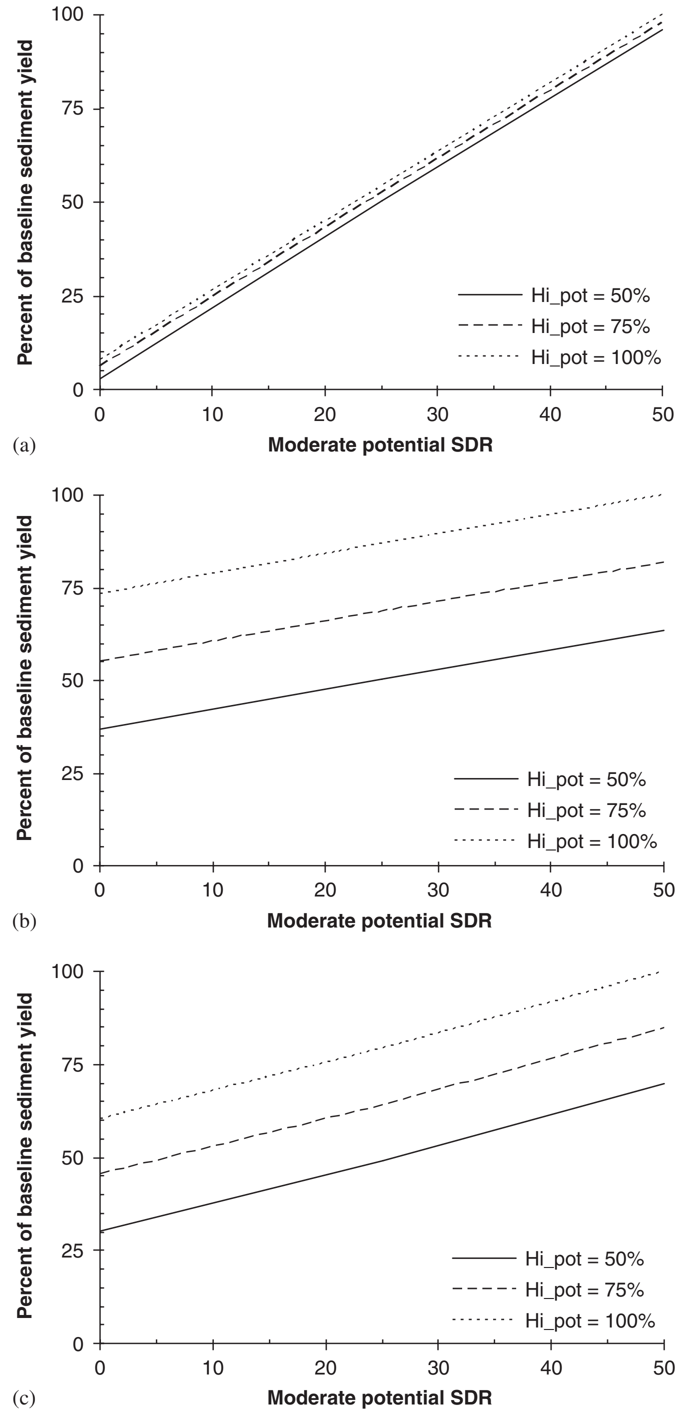


Fig. 7. Percent change in predicted sediment yields with varying sediment delivery ratios for: (a) Lameshur Bay basin; (b) Fish Bay basin; and (c) Cinnamon Bay basin.

### 5.3. *Effects of varying SDRs on basin-scale sediment yields*

Given the difficulty of accurately defining SDR values, we evaluated the sensitivity of the predicted sediment yields to the selected SDRs. The SDRs were varied from zero to 50% for areas designated as having a moderate potential for sediment delivery, and the SDRs for high potential areas were varied from 50% to 100%. The sediment yields calculated using these SDRs were compared to the baseline sediment yields calculated with SDRs of 50% and 100% for moderate and high potential areas, respectively.

The sensitivity of the estimated sediment yields to the choice of SDR values varied from basin to basin (Fig. 7). In the case of the Lameshur Bay basin (Fig. 7a), the predicted sediment yields are quite sensitive to the SDR for moderate potential areas because these represent 64% of the total basin and include the unpaved road that accounts for 50% of the baseline sediment yield. Varying the SDR for areas with a high potential for sediment delivery had relatively little effect because these areas represented only 8% of the basin and included only 0.4 km of unpaved roads.

Sediment yields in the Fish Bay basin were more sensitive to the SDR for high potential areas and less sensitive to the SDR for areas with moderate delivery potential (Fig. 7b) because 68% of the basin has a high potential for sediment delivery and this area includes 54% of the unpaved roads. In the Cinnamon Bay basin sediment yields were slightly more sensitive to the SDR for moderate potential areas than the SDR for high potential areas, even though the moderate potential areas account for only 28% of the basin area (Fig. 7c; Table 3). The greater sensitivity to the SDR for moderate potential areas is due to the fact that these areas included 72% of the unpaved roads (Fig. 6c).

### 5.4. Comparison of model results to other data

The sediment yields predicted by STJ-EROS are compared to other measured and predicted values from St. John in Table 5. The various studies include measured short- and long-term sedimentation rates (Nichols and Brush, 1988; Anderson, 1994; MacDonald et al., 1997; Nemeth et al., 2001), watershed-scale measurements of runoff and suspended sediment yields (Ramos-Scharrón, 2004), and an earlier effort to model sediment production and delivery from unpaved roads (Anderson and MacDonald, 1998). Although these comparisons are complicated by differences in methodology, location, spatial scale (Walling, 1983), and temporal scale (Kirchner et al., 2001), the similarities in the estimated sediment yields are encouraging. The differences apparent in Table 5 are useful for identifying key uncertainties and research needs.

A direct but short-term comparison can be made between the sediment yields predicted by STJ-EROS and the sedimentation rates measured at the bottom of Fish Bay and Lameshur Bay from July 1999 to January 2001 (Nemeth et al., 2001) (Table 5). The measured sedimentation rate in Lameshur Bay was 24 $\mathrm{Mg\,km^{-2}\,yr^{-1}}$, or three times the predicted suspended sediment yield using STJ-EROS (Table 5). For Fish Bay the measured sedimentation rate was 36 $\mathrm{Mg\,km^{-2}\,yr^{-1}}$, or only 20% more than the predicted suspended sediment yield using STJ-EROS. These results suggest that the values being predicted by STJ-EROS are reasonable.

The differences in land use between the more highly developed Fish Bay and the protected Lameshur Bay basin has led to several efforts to directly measure runoff and suspended sediment concentrations in Main Fish Bay Gut and Lameshur Gut. Gauging stations in these two guts were first established by staff from the US Geological Survey office in Puerto Rico (Anderson, 1994). Runoff and suspended sediment data were collected for more than a year in the early 1990s, but data collection efforts were abandoned due to the logistical difficulty of monitoring the stations from Puerto Rico, the low frequency and short duration of high flow events, and a loss of funding.

From October 1998 to November 2001 stage data were collected from a station on Main Fish Bay Gut that was 170 m downstream of the abandoned USGS gaging station (Ramos-Scharrón, 2004). Failures of the automated equipment and the difficulties in accessing these sites during high flows meant that the highest measured flow was 0.67 $\mathrm{m^3\,s^{-1}}$, while the highest estimated flow using the slope-area method (Dalrymple and Benson, 1968) was

Table 5
Comparison of modeled and measured sediment yields from St. John

| Reference | Location | Time scale (years) | Spatial scale ($\mathrm{km^2}$) | Undisturbed sediment yields ($\mathrm{Mg\,km^{-2}\,yr^{-1}}$) | Sediment yield under current conditions ($\mathrm{Mg\,km^{-2}\,yr^{-1}}$) |
|---|---|---|---|---|---|
| *Watershed-scale suspended sediment yields* | | | | | |
| Ramos-Scharrón (2004) | Main Fish Bay Gut | 3 | 3.5 | — | 18 |
| *Measured sedimentation rates* | | | | | |
| Nemeth et al. (2001) | Greater Lameshur Bay | 2 | 2.3 | — | 24 |
| Nemeth et al. (2001) | Fish Bay | 2 | 6.0 | — | 36 |
| Nichols and Brush (1988) | Mandal Pond | ~3000 | 1.3 | 29 | — |
| Nichols and Brush (1988) | Reef Bay swamp | ~3000 | 5.6 | 8 | — |
| Anderson (1994) | Lameshur Bay Gut detention pond | ~40 | 1.0 | 7–10 | — |
| *Modeled sediment yields* | | | | | |
| STJ-EROS (this study) | Lameshur Bay | na | 4.3 | 1.8–2.6 | 8–12 |
| STJ-EROS (this study) | Fish Bay | na | 6.0 | 5.0–6.7 | 30–46 |
| STJ-EROS (this study) | Cinnamon Bay | na | 1.6 | 2.5–4.1 | 13–21 |
| ROADMOD (Anderson and MacDonald, 1998) | Lameshur Bay | na | 4.3 | — | 19–52 |
| ROADMOD (Anderson and MacDonald, 1998) | Fish Bay | na | 6.0 | — | 72–104 |

na indicates not applicable

$40\,m^3\,s^{-1}$ or more than $4\,cm\,h^{-1}$. Suspended sediment samples were collected whenever possible, but the maximum estimated discharge with an associated suspended sediment sample at Fish Bay Gut was $5.9\,m^3\,s^{-1}$ or about 15% of the estimated maximum flow, and the mean discharge for the 35 suspended sediment samples collected over the 3-year study period was only $0.59\,m^3\,s^{-1}$. The measured suspended sediment concentrations were so poorly correlated with discharge ($R^2 = 0.002$) that it was not possible to develop a sediment rating curve.

The only consistent discharge record from St. John is the 15-year dataset from Guinea Gut (USGS station 50295000). This station is 2 km west of our gaging station on Fish Bay Gut, and the drainage area is $0.95\,km^2$, or 27% of the drainage area for the station on Fish Bay Gut. When normalized by drainage area, the flow duration curve (FDC) for the 15-year record from Guinea Gut was very comparable to the 3-year record from Fish Bay Gut (Ramos-Scharrón, 2004). The annual sediment yield at Fish Bay Gut was estimated by using the Guinea Gut FDC to obtain an area-adjusted annual discharge at Fish Bay Gut, and then multiplying this discharge by the mean suspended sediment concentration of $0.57\,mg\,L^{-1}$. The resulting estimate of $22\,Mg\,km^{-2}\,yr^{-1}$ is only 22% higher than the estimated sediment yield for sediment finer than 2 mm according to STJ-EROS for the Main Fish Bay Gut drainage area (assuming an annual rainfall of $115\,cm\,yr^{-1}$ and a SDR of 75%). While these two estimates are quite similar, this does not necessarily validate STJ-EROS given the limited amount of suspended sediment data, the short runoff record at Fish Bay Gut, and the fact that this comparison can only be made for one basin.

The volume and estimated mass of sediment deposits have been determined at three different sites in St. John in order to estimate baseline sediment yields (Table 5). The validity of these baseline sediment yields is questionable because none of the source areas have remained undisturbed over the entire period represented by the accumulated sediment, and longer-term sediment yields may be controlled by extreme events that only occur every $10^3$–$10^4$ years (Kirchner et al., 2001).

The mean annual sediment yield from Greater Lameshur Gut was estimated by measuring about 40 years of deposition in a man-made detention pond (MacDonald et al., 1997). The resulting value of $7–10\,Mg\,km^{-2}\,yr^{-1}$ is almost an order of magnitude higher than the $1.0\,Mg\,km^{-2}\,yr^{-1}$ predicted by STJ-EROS for undisturbed conditions, but slightly less than the predicted mean sediment yield of $14\,Mg\,km^{-2}\,yr^{-1}$ for current conditions. Given that there are some unpaved roads in the upper portion of this catchment and these are believed to be contributing much of the accumulated sediment, we are encouraged by the similarity between the measured mean annual sediment yield and the value predicted by STJ-EROS.

A survey of alluvial deposits in the Reef Bay swamp and in Mandal Pond on the south coast of St. John (Fig. 1) resulted in estimated mean sediment yields of 8 and $29\,Mg\,km^{-2}\,yr^{-1}$ over the previous 3000 years, respectively (Nichols and Brush, 1988) (Table 5). These values cannot be directly compared to modeled values using STJ-EROS because we did not have the data needed to develop the GIS input layers for the corresponding source areas. The estimated value for the Reef Bay area is only slightly higher than the estimated baseline sediment yield for the adjacent Fish Bay basin, while the estimate for Mandal Pond is about 4–6 times higher than the estimated baseline sediment yield using STJ-EROS. Without more information it is impossible to determine whether the differences between these two areas in sedimentation rates is due to the inherent variability in erosion and transport rates, differences in land use effects, or problems in the accuracy and representativeness of these estimates or STJ-EROS.

The final set of comparisons is between an earlier road erosion model (ROADMOD) (Anderson and MacDonald, 1998) and STJ-EROS. ROADMOD uses an empirical equation to predict road surface erosion, and assigns SDRs of 0%, 50%, and 100% to road segments draining to unchannelled vegetated hillslopes, wetlands, and stream channels, respectively. ROADMOD was used to calculate sediment yields for the Fish Bay and Lameshur Bay basins by summing the predicted sediment yields from unpaved roads and the estimated background sediment yield (Anderson and MacDonald, 1998).

For Fish Bay, the estimated current sediment yield using ROADMOD was $72–104\,Mg\,km^2\,yr^{-1}$ (Anderson and MacDonald, 1998), and this is 1.5–3.5 times the comparable value from STJ-EROS (Table 5). Relative to STJ-EROS, ROADMOD predicts both a higher background sediment yield and higher sediment yields from unpaved roads.

Similarly, the estimated sediment yield for Lameshur Gut was $19–52\,Mg\,km^{-2}\,yr^{-1}$ using ROADMOD and only $8–12\,Mg\,km^{-2}\,yr^{-1}$ using STJ-EROS. Unpaved roads accounted for 20–50% of the total sediment yield in ROADMOD as compared to 80% of the annual sediment yield using STJ-EROS. Some of the differences in sediment yield can be attributed to a difference in the areas being modeled as well as differences in both the background and road-related sediment yields. ROADMOD was applied to just the 1.4 km of unpaved roads that drain into Greater Lameshur Bay, while STJ-EROS was applied to the 3.2 km of unpaved roads that drain into Europa Bay, Little Lameshur Bay, and Greater Lameshur Bay (Fig. 6a).

We are confident that STJ-EROS more accurately predicts road-related sediment yields than ROADMOD. In ROADMOD the predictive equation for road erosion was based on an estimate mass derived from rill cross-sectional areas and an estimated time since grading (Anderson, 1994). In contrast, the road erosion algorithm in STJ-EROS is based on a much larger and more accurate set of field measurements using sediment fences (Ramos-Scharrón and MacDonald, 2005). The relative accuracy of the background sediment yields in ROADMOD and

STJ-EROS are more difficult to assess, but the difference in the background sediment yield between these two models is not as important because the amount of sediment from unpaved roads is so much larger.

The data in Table 5 show that the estimated background sediment yields range from $1.8\,\mathrm{Mg\,km^{-2}\,yr^{-1}}$ to nearly $30\,\mathrm{Mg\,km^{-2}\,yr^{-1}}$. The background sediment yields used in STJ-EROS also were based on field measurements, but the values are lower than the sedimentation rates listed in Table 5. This difference may be due to the difference in time scales, as the data used in STJ-EROS were collected over a period of 1–3 years. The shorter time span may result in an underestimate of mean annual sediment yields, as numerous studies indicate that the majority of sediment is delivered during extreme storm events or in the wettest years (Bunte and MacDonald, 1999). The precipitation and sediment production data collected over the period used to develop STJ-EROS are relatively representative of the longer-term record except for the absence of the most extreme storm events (Ramos-Scharrón, 2004). The 15-year record at Guinea Gut indicates that peak flows can exceed $10\,\mathrm{cm\,h^{-1}}$ (MacDonald et al., 1997), which is more than twice the largest flow observed during the study period and 16 times the largest flow with an associated suspended sediment sample. The implication is that the general tendency towards a lognormal distribution of annual sediment yields may be even stronger in a dry tropical environment such as St. John.

A compilation of published sediment yields indicates that the background yields estimated for St. John are up to 2 orders of magnitude lower than other basins with similar drainage areas (Milliman and Syvitski, 1992). However, none of the data in Milliman and Syvitski (1992) are from a dry tropical climate like St. John, and many of the rates reported from small watersheds are from high-relief catchments where mass wasting is an important process. Both field observations and historic air photos indicate that mass wasting is relatively rare on St. John (Anderson, 1994). Hence the background erosion rate for St. John could easily be on the low side of the values reported by Milliman and Syvitski (1992), but the presumption of a lower rate for St. John could be due to an inherently more stable geomorphic regime or the likely bias in our data. While a higher sediment yield rate for undisturbed areas will reduce the relative importance of road erosion, any reasonable increase in the background rate would not alter the basic conclusion that—as in many forested areas—unpaved roads are a primary source of the sediment being delivered by the stream network.

## 6. Conclusions

A GIS-based sediment budget model, STJ-EROS, was developed to predict sediment yields for the island of St. John. A series of empirical models within STJ-EROS are used to predict sediment production rates from natural sediment sources and unpaved roads. Sediment delivery to offshore areas is calculated using spatially variable sediment delivery ratio. Both the production and delivery of sediment are partitioned into fine ($\leq 2\,\mathrm{mm}$) and coarse ($>2\,\mathrm{mm}$) size classes.

The STJ-EROS program code includes six input routines and five routines to calculate sediment production and delivery. The six input routines define the area to be modeled and the values of the key parameters that control sediment production and delivery. The other five routines calculate watershed-scale sediment yields from user-defined variables, empirical equations and rate constants, and item values from nine GIS data layers.

The model was applied to three different basins on St. John with varying amounts of development. Predicted sediment delivery rates under natural conditions ranged from 2 to $7\,\mathrm{Mg\,km^{-2}\,yr^{-1}}$. These background rates are slightly lower than the values estimated from sedimentation studies, and up to two orders of magnitude lower than most reported values for basins of similar size in other geographic regions. Under undisturbed conditions streambank erosion generally was more important than surface erosion from undisturbed hillslopes and erosion from treethrow.

STJ-EROS estimates that current sediment yields for the three basins are 3–9 times higher than under natural conditions. Surface erosion from the unpaved road network is the main cause of this increase. The relative impact of unpaved roads on watershed-scale sediment yields is controlled by the total length of unpaved roads within a basin, road characteristics, and the location of road drainage points relative to the spatially varying potential for sediment delivery. The sediment yields predicted by STJ-EROS are generally less than the values estimated by the earlier and simpler ROADMOD model. The lower values in STJ-EROS can be attributed to a substantially lower estimate of background sediment yields and slightly lower road erosion rates.

The similarity of the predicted values in STJ-EROS to measured values is encouraging and provides an overall validation of the model. STJ-EROS is unique in that it provides both background data and a set of procedures to calculate sediment production and delivery in the dry tropics. This geographic region has few published data and even fewer calibrated models for predicting sediment production rates and watershed-scale sediment yields. The model should work well in similar environments in the eastern Caribbean and elsewhere, and the model structure means that the governing equations can be readily adapted to reflect different conditions. Both the model and the underlying data should help others predict the potential effects of unpaved roads or other land use changes on sediment yields.

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