# CHAPTER 5.

## DEVELOPMENT AND APPLICATION OF A GIS-BASED SEDIMENT BUDGET MODEL FOR ST. JOHN, U.S. VIRGIN ISLANDS


### ABSTRACT

Increases in the delivery of sediment to the marine environment pose a serious threat to the coral reef communities of the Caribbean. Resource managers and decision-makers need to evaluate the changes in erosion rates and sediment delivery due to unpaved roads or other types of land disturbance. This is a particularly critical issue on St. John in the U.S. Virgin Islands because of the rapid development and exceptional resources at risk. The specific objectives of this study were to: (1) develop a GIS-based sediment budget model for St. John; (2) use the model to evaluate the effects of unpaved roads on sediment delivery rates in three watersheds; and (3) compare model predictions to measured data.

The St. John Erosion Model (STJ-EROS) is an Arc/Info-based system that quantifies watershed-scale sediment yields based on empirically-derived sediment production functions and delivery ratios. The STJ-EROS Arc Macro Language program code consists of six input routines and five routines to calculate sediment production and delivery. The six input routines have interfaces that allow the user to adjust the key variables that control sediment production and delivery, such as rainfall rates and sediment delivery ratios. The remaining five routines use pre-set erosion rate constants, user-defined variables, and values from nine input 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 ranged from 12 to 65 tons $km^{-2}$ $yr^{-1}$. Sediment from unpaved roads is believed to be increasing sediment delivery rates by 5-6 times for Lameshur Bay, 7-8 times for Fish Bay, and 24-40 times for Cinnamon Bay. The differences in estimated sediment yields and the relative impact of unpaved roads are largely due to differences in the amount of development in the three basins. The basin-scale sediment yields estimated by the model for both undisturbed and current conditions are within the range of sediment yield and bay sedimentation rates measured by previous studies on St. John. 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 existing and proposed unpaved roads on sediment production and delivery.

## 5.1 Introduction

Accelerated erosion and increased watershed-scale sediment yields resulting from vegetation removal and land use are critical environmental problems (Walling, 1997). The rapid pace of land development in the Insular Caribbean, when combined with steep slopes and high precipitation intensities, make this region very susceptible to accelerated erosion (Lal, 1990). Sedimentation is one of the most important stressors of coral reef communities in the Caribbean (Hubbard, 1987; Gardner et al., 2003), but very little information is available on past and current sediment delivery rates to the marine environment (UNEP, 1994). High sediment loads are placing increasing stress on coral reef systems in the Dominican Republic (Torres et al., 2001), Puerto Rico (Torres, 2001; Acevedo et al., 1989) and the nearby island of Culebra (Hernández-Delgado, 2001), Virgin Gorda in the British Virgin Islands (C. Rogers, USGS, pers. comm.), as well as St. Croix (Hubbard, 1986), St. Thomas (Nemeth and Nowlis, 2001), and St. John (Rogers, 1990, 1998; Nemeth et al., 2001) in the U.S. Virgin Islands.

The processes and issues related to erosion in the Caribbean are as varied as the physiographic characteristics and land use practices. Although land disturbance has been widely recognized as the main cause of high erosion rates, historically there have been few efforts to remedy this problem (Lugo et al., 1981). The widespread lack of attention to erosion issues can be attributed in part to the lack of models to assess the different sediment sources and determine priorities for remediation. In general, studies have concentrated on mass wasting (e.g., De Graff 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; McGregor, 1988), or the application of uncalibrated erosion models to watersheds under variable land uses (e.g., Ramsarran, 1992; Radke, 1997; Del Mar-López et al., 1998). None of these efforts has addressed the combination of natural and anthropogenic sediment sources that are 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 the delivery of sediment to the marine environment.

Erosion issues have received special attention on St. John because land development is believed to be increasing sediment yields and adversely affecting the nearshore coral reef communities in the Virgin Islands National Park (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., 2001). An empirical road erosion model (ROADMOD) developed by Anderson and MacDonald (1998) suggested that road erosion is increasing watershed-scale sediment yields by up to four times above background levels (MacDonald et al., 1997).

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 for calculating sediment budgets (STJ-EROS); (2) apply the model to several basins on St. John and quantify the increases in sediment production and delivery resulting from unpaved roads; and (3) compare model predictions to pre-existing sediment yield data.

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). The sediment budget approach is useful because it quantifies the absolute and relative contributions of different sediment sources in a watershed (Reid and Dunne, 1996). In this paper a landscape unit is defined as a surface area in a drainage basin where similar erosional processes act at a spatially-uniform rate. Initial field observations made in St. John led to the identification of the following landscape units:

- erodible streambanks;
- stream margins subjected to soil disturbance by treethrow;
- unchannelled (zero-order) catchments;

- road travelways; and
- road cutslopes.

Sediment production data were collected for each of these landscape units (Chapters 2 and 4).

To route sediment through a watershed it is necessary to quantify the rate of sediment movement between temporary storage sites (Swanson and Fredriksen, 1982). The STJ-EROS model uses a simple routing routine based on two storage units: (1) a terrestrial unit composed of hillslopes, the fluvial network, and associated wetlands; and (2) the marine environment. The rate at which terrestrial sediment is transferred to the marine environment is controlled by a user-defined sediment delivery ratio (SDR). The SDR is defined as the ratio of watershed sediment yield divided by the gross erosion within the basin (Walling, 1983). The alternative to SDRs is a more physically-based approach, but physical models carry a high degree of uncertainty and require much more detailed input data. The SDR approach is conceptually simple and easy to implement, and it is preferred for STJ-EROS given the model objectives and the intended users.

STJ-EROS is intended to guide land management decisions on St. John, 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. Since the focus of STJ-EROS is on road-related sediment sources, some of the changes that might be evaluated include paving selected road segments or comparing alternative routes for new roads. The model also can evaluate the effect of changes in the fluvial network or sediment trapping efficiency of coastal wetlands. An improved prediction tool will help managers choose alternatives that minimize the amount of sediment being delivered to the marine environment or other locations of particular concern.

## 5.2 Study Area

The U.S. and British Virgin Islands constitute the eastern extremity of the Greater Antilles, and St. John is the third largest island within the U.S. Virgin Islands (Figure 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 has created a very rugged topography, as more than 60% of St. John has slopes greater than 30%. 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 dry tropical. Bowden et al. (1970) identified five precipitation zones ranging from 90 to 100 cm $yr^{-1}$ on the drier east end to a high of 130 to 140 cm $yr^{-1}$ near Bordeaux Mountain. Easterly waves, which can develop into tropical storms and hurricanes, generate most of the rainfall from May through November, while cold fronts are important sources of rainfall from December through April (Calversbert, 1970). There are no sharply defined wet and dry seasons in St. John, but a relatively dry season extends from about February to July, and a relatively wet season lasts from August until January (Bowden et al., 1970).

Precipitation in St. John can be highly erosive. The average erosivity at Caneel Bay was estimated to be 13,500 MJ mm $ha^{-1}$ $hr^{-1}$ (Sampson, 2000). Fifteen-minute precipitation intensities at Caneel Bay exceeded 100 cm $hr^{-1}$ sixteen times between 1979 and 1995.

Mean monthly potential evapotranspiration (PET) exceeds mean monthly precipitation for most of the year (Bowden et al., 1970). There is little ground water storage and no perennial streams (known locally as "guts") on St. John (MacDonald et al., 1997). The combination of steep slopes, small drainage areas, shallow soils with low-water holding capacities, and occasional intense storm events result in “flashy” runoff hydrographs with very steep rising and recession limbs.

The history of land use in St. John is similar to most of the other islands in the eastern Caribbean. It was originally forested and subjected to only minor disturbance by Amerindian groups. During the 1700’s and 1800’s, approximately 90% of the forests were removed and replaced by sugarcane fields (Tyson, 1987). The agricultural fields were largely abandoned in the late 19$^{th}$ century as a result of the decline in the sugarcane industry, and this marked the beginning of the forest recovery period. The United States purchased the Virgin Islands from Denmark in 1917, and in 1956 Virgin Islands National Park (VINP) was established. The park was designated an International Biosphere Reserve in 1976, and it is one of the few reserves that has both marine and terrestrial resources (Rogers, 1992). In 2001 an additional 47 km$^2$ of offshore waters were included in VI Coral Reef National Monument.

Current sediment yields on St. John are believed to be higher than at any point in its recent history (MacDonald et al., 1997). Rapid development over the past 30 years has resulted in a dense network of unpaved roads, particularly on the private lands outside of VINP. Maps developed for this study show that the road network in the 6 km$^2$ Fish Bay basin nearly tripled in length between 1971 and 2000, and that 56% or 13.1 km of roads are still unpaved. The unpaved road density of 2.2 km km$^{-2}$ in this basin is nearly three times the density of unpaved roads in the Greater Lameshur Bay basin, which lies mostly within VINP. The unpaved road network is believed to be the single most important sediment source on St. John (Anderson and MacDonald, 1998), but there are no locally-calibrated, spatially-explicit models for estimating the effects of unpaved roads on sediment production and delivery rates at the watershed scale.

## 5.3 Field Methods and Results

Sediment production rates from natural and anthropogenic sources were measured by various field methods (Chapters 2 and 4). Streambank erosion was quantified by use of erosion pins

(Lawler, 1993). The amount of sediment delivered to the fluvial network by treethrow was determined by estimating the frequency of treethrow events and the volume of soil in rootwads along selected stream reaches (Reid, 1981). Sediment fences (Robichaud and Brown, 2002) were used to quantify sediment production rates from undisturbed hillslopes, zero-order catchments, unpaved road segments, and cutslopes.

Measured sediment production rates ranged over five orders of magnitude (Figure 2; Table 1; Chapter 4). The mean streambank erosion rate was 10 kg $m^{-2}$ $yr^{-1}$. Uprooting of trees along stream margins was estimated to deliver 0.17 tons of sediment per kilometer of stream per year, or 11 g $m^{-2}$ $yr^{-1}$ for a 15-meter wide stream corridor. The mean sediment yield for zero-order catchments was 1.0 g $m^{-2}$ $yr^{-1}$. This value was used for undisturbed areas because plot-scale measurements do not account for hillslope sediment storage, and measurements from first-order basins include streambank erosion and treethrow (Chapter 4). In STJ-EROS streambank erosion and treethrow are treated independently of surface erosion from undisturbed areas.

Surface erosion rates from unpaved road segments were found to vary with rainfall, road slope, and frequency of grading (Figure 2; Table 1; Chapter 4). Sediment production rates for roads that were graded once every two years ranged from 0.57 to 58 kg $m^{-2}$ $yr^{-1}$ for roads with mean slopes of 1% and 21%, respectively. Ungraded roads had sediment production rates ranging from 5.1 to 14 kg $m^{-2}$ $yr^{-1}$ for roads with slopes of 10% and 16%, respectively. Abandoned roads with 15% slopes had a mean erosion rate of 1.1 kg $m^{-2}$ $yr^{-1}$. Although cutslopes eroded at rates ranging from 2 to 17 kg $m^{-2}$ $yr^{-1}$, their estimated contribution to sediment yields at the road-segment scale is 0.9 kg $m^{-2}$ $yr^{-1}$, or only about 11% of the total sediment yield from unpaved roads (Chapter 4).

## 5.4 St. John Sediment Budget Model (STJ-EROS)

### 5.4.1 Overview

STJ-EROS uses the capabilities of GIS software to develop spatially-variable sediment budgets. The program is written in Arc Macro Language (AML) for Arc/Info version 8.2 and uses the spatial analysis capabilities provided by Arc and the relational database commands available in the Tables module. The model is designed to calculate the amount of sediment from different sources that reaches the marine environment on a watershed scale.

The STJ-EROS model contains six input routines and five routines that calculate sediment production and delivery (Figure 3). The six input routines have user interfaces that allow the user to adjust some of the variables controlling sediment production and delivery (Table 2a). The remaining five routines use pre-set erosion rate constants, user-defined variables, and item values stored in nine data layers to calculate watershed scale sediment yields (Table 2b). Appendix IV-B describes the GIS data layers needed to run the model, Appendix IV-C provides flowcharts of the most important routines, and Appendix IV-D displays the program code.

### 5.4.2 Input Routines

STJ-EROS begins with the 'set_sdr' routine (Figure 3; Table 2a). This routine prompts the user to choose the sediment delivery ratios (SDRs) used by STJ-EROS to route sediment into the marine environment. A strict application of SDRs requires knowledge of the type and location of sediment sources, the particle-size distribution of the sediment being eroded, and both the transport and sediment storage capacity of the fluvial network (Bunte and MacDonald, 1999). Use of the SDR approach by STJ-EROS is a simplification of sediment transport dynamics, as SDR values only vary according to the interaction of the fluvial network with coastal wetlands and salt ponds.

SDRs for catchments with drainage areas of 0.1 to about 5 $km^2$ are generally between 40 and 100% (Walling, 1983). In STJ-EROS sediment delivery ratios of 50-100% are used for areas with a high sediment delivery potential. These areas drain directly to the sea without an intervening coastal wetland or salt pond.

The presumed SDR values of 50-100% imply a fluvial system with a high sediment transport capacity, and this is consistent with measured runoff rates and sediment transport calculations. The sediment transport capacity of Fish Bay Gut was estimated at 12 different locations based on the ratio of particle settling velocities to shear flow velocities (Middleton, 1976) (Appendix IV-A). On average, flow depths that were only 12% of the estimated bankfull depth were needed to maintain particles smaller than 2 mm in suspension. Flows exceeding bankfull depth were needed to transport particles larger than 2 mm in suspension. This indicates that particles smaller than 2 mm are readily transported as suspended load along the Main Fish Bay Gut, and presumably along the other guts in St. John. Particles larger than 2 mm are assumed to be transported as bed load and are likely to remain within the fluvial system for longer time periods.

STJ-EROS refines the SDR approach by partitioning sediment production and delivery into two size classes. The fine fraction is defined as particles smaller than or equal to 2 mm, while the coarse fraction consists of particles larger than 2 mm. Although the SDR values are applied to both size classes, this partitioning allows STJ-EROS to calculate a range of long-term sediment yield rates. The minimum value simply assumes that none of the coarse sediment but all of the fine sediment that reaches the guts is delivered to the watershed outlet. The maximum value assumes that all of the particles from clays to coarse gravel (about 30 mm) are delivered to the watershed outlet. The upper limit of 30 mm corresponds to the largest particles found in the sediment traps below unpaved roads and undisturbed hillslopes (Appendices I-D, III).

The delivery of sediment from catchments with an intervening wetland or salt pond is more complicated. These wetlands vary in size, the magnitude of fresh water versus tidal inflows, and their sensitivity to natural and human disturbance. Some wetlands become inundated during extreme storms due to the rise in sea level, while others remain separated from the sea by a berm. Field observations of the wetlands at Fish Bay and Lameshur Bay indicate that these wetlands were not inundated by the sea during Hurricane Georges in 1998 or Hurricane Lenny in 1999. Maps of the 100-yr high tide show that seawater intrusions on St. John are limited to a very narrow area (U.S. Army Corps of Engineers, 1975). On the other hand, large runoff events flood the wetlands and flow into the sea. It is these events that give the water in some bays a brown color, indicating that terrestrial sediment is being delivered to the marine environment up to several times each year.

Data on the trapping efficiency of mangrove wetlands are mostly qualitative (Augustinus, 1995). In the absence of specific data, the SDRs for areas draining into coastal wetlands are assumed to range from 0 to 50%. These catchments are defined as having a moderate potential for sediment delivery.

Other catchments are assumed to have a SDR of 0. These catchments drain to a wetland or pond that lacks any surface pathway to the marine environment, implying a sediment trapping efficiency of 100%.

The polygons representing the areas with a given SDR are stored in the SED_DEL layer (Table 3). An item in the attribute table named “potential” identifies each polygon as having a high, moderate, or no potential for delivering sediment into the sea. The SDR values chosen by the user during the ‘set_sdr’ routine for high and moderate delivery potential areas are stored as variables named “hi_pot” and “mod_pot”, respectively.

The next step in the ‘del_potential’ routine prompts the user to choose the basin for which the sediment budget is to be estimated (Figure 3). The chosen name is assigned to a variable called “basin” (Table 2a). At this point a complete set of data layers to run STJ-EROS are available only for the Cinnamon Bay (CB), Fish Bay (FB), and Lameshur Bay (LB) basins on St. John (Figure 1), so these are the only choices available.

The ‘del_potential’ routine constructs a new data layer called DEL_BD. This new layer is created by clipping the SED_DEL layer with the boundaries of the selected area as defined by the variable “basin” (Table 3). The routine assigns the values of “hi_pot” and “mod_pot” to the polygons in DEL_BD with high and moderate sediment delivery potentials, respectively.

The next routines are ‘set_years’, ‘set_rain’, ‘roads_name’, and ‘nat_name’ (Figure 3; Table 2a). These routines prompt the user to enter the total number of years over which the model is to be applied, an annual rainfall rate, and names for the text files and GIS data layers that will contain the model results. User choices are assigned as values to the “years”, “rain_rate”, “road_name”, and “nat_name” variables.

### 5.4.3 Sediment Yield Calculation Routines

Once these user-defined inputs have been specified, the model calculates sediment production from each unpaved road segment using the ‘rd_erosion’ routine (Figure 3). This routine uses four input layers and four user-defined variables to estimate sediment yields resulting from unpaved roads (Table 2b). To run rd_erosion, the user must have a line layer (GPS_RDS) that defines each road segment along with its road surface type, grading frequency, slope, length, and width (Table 2b). Road segments are distinguished by having different distinct drainage locations, and the point coordinates of road drainage structures are in GPS_DRA (Table 3).

The first step in the rd_erosion routine creates a data layer called DRAIN by clipping GPS_DRA with “BASIN”_BD (Table 3). DRAIN contains the spatial and attribute data of road drainage points within the chosen basin. The routine intersects DRAIN with DEL_BD to assign SDR values to each individual road drainage point. A ‘joinitem’ command then incorporates these segment-specific SDRs to a copy of the original road data layer (GPS_RDS).

The Tables module calculates sediment production and delivery from each unpaved road segment that delivers sediment into the chosen basin. Although paved roads may also contribute sediment from cutslope and ditch erosion, there were not enough data to incorporate paved roads into STJ-EROS.

Road sediment production is calculated from the “rain_rate” and “years” variables, as well as the road segment characteristics stored in GPS_RDS (Tables 1 and 3). The empirical sediment production functions used in STJ-EROS (Table 1) were derived from data collected by sediment traps placed at road drainage outlets. These measurements integrate sediment production at the road-segment scale, but they do not consider how much of this sediment reaches the stream channel. The hillslope-scale routing of road-related sediment is an important control on sediment yields. Field assessments showed that only 70 of the 338 road-drainage structures mapped on St. John were within 50 m of the stream network (Appendix IV-B). From a practical point of view, it is extremely difficult to measure the proportion of sediment from unpaved roads that reaches the stream network. As a result, the only means to account for hillslope storage is to incorporate this with the selection of SDR values for each polygon or basin using the ‘del_potential’ routine.

The use of sediment trap data to develop empirical road erosion models poses another problem. The trapping efficiency of sediment traps generally decreases with decreasing particle size (Ice, 1986). Runoff and suspended sediment data for a road segment in St. John yielded nine times more silt (defined as 0.004-0.062 mm) than measured with a sediment trap (Chapter 3). Surprisingly, there were no differences between the two measurement methods for the amount of clay-sized (< 0.004 mm) sediment. This difference in the amount of silt-sized particles appears to be of little practical significance since both methods showed that less than 5% of the sediment from the road fell into this size class. Nevertheless, a factor has been integrated into the ‘rd_erosion’ routine to compensate for this apparent underestimation of the silt-size fraction (Tables 1, 2b).

The delivery of sediment from each road segment is partitioned into that originating from the travelway and that being produced from cutslopes. A visual classification system determined that on average cutslopes account for only 9% of road-segment scale sediment yield (Chapter 4). This has been incorporated into the ‘rd_erosion’ routine by subtracting 9% from the total sediment estimated for each road segment and assigning it to cutslopes. The remaining 91% of the estimated sediment is assigned to travelways.

The delivery of sediment from individual road segments is calculated as the product of the estimated sediment produced by its SDR. The sediment delivery rate is then partitioned into suspended load ($\leq$ 2 mm) and bed load (> 2 mm) based on the particle-size distributions on Table 4. The final results of the 'rd_erosion' routine are stored in a text file and a GIS data layer both given the name stored in the user-defined "road_name" variable.

The next routine in the model is the 'streambank' routine (Figure 3). This routine calculates sediment production and delivery rates from streambank erosion. The streambank attribute data needed to estimate sediment production are stored in the BANKS data layer (Table 3). BANKS was developed based on stream surveys and distinct stream sections in this data layer were defined according to streambank height. Erodible banks on St. John are generally restricted to areas where streams intersect alluvial or colluvial deposits. These deposits are found primarily along the larger channels that drain to the southern coast of St. John, as the lower portions of these basins are not nearly as steep as the smaller basins draining to the north. The alluvial deposits are composed of loose, angular, gravel-sized fragments supported by a fine sand-silt matrix. The deposits show little layering or weathering and are poorly sorted. Streambanks in these areas are very steep, mostly unvegetated, and range from 0.6 to 2.5 m in height.

The 'streambank' routine begins by intersecting BANKS with DEL_BD to create BANK_DEL (Table 2b). BANK_DEL contains the bank height information in BANKS in addition to the user-defined SDR values. Total sediment production from streambanks is calculated as a function of the total length of streams with erodible banks (approximated as half of the stream section perimeter), bank height, the "streambank" variable that defines the sediment production rate (Table 1), and the user-defined "years" variable (Table 2b). Sediment delivery for individual stream sections is calculated as the product of sediment production by SDR. Sediment delivery is then partitioned into suspended load ($\leq$ 2 mm) and bed load (> 2 mm) according to the particle-size distribution of streambanks shown in Table 4. The results of the streambank routine are stored in a polygon data layer called BANK_DEL.

The next routine is the 'stream_total' routine (Figure 3). The first part of this routine calculates sediment from treethrow based on the "treethrow" variable, the total channel length in the basin being modeled, and the user-defined variable "years" (Table 2b). "Treethrow" defines the sediment production rates from treethrow in tons per kilometer of stream per year (Table 1). The length of stream in the chosen basin is determined by clipping STJ_STR with DEL_BD. In this study the fluvial network in STJ_STR was developed from field reconnaissance, so this data layer represents a longer stream network than that represented by standard topographical maps. Channels were identified in the field as features along which runoff and sediment is transported between well-defined banks (Dietrich and Dunne, 1993). Although it might be possible to use a GIS flow accumulation algorithm to generate a stream data layer similar to STJ_STR, the lack of appropriate data prevented the definition of a source area threshold for channel initiation in St. John.

Sediment delivery from treethrow is calculated by the 'stream_total' routine by multiplying the estimated sediment production of each stream arc by its respective SDR. The routine partitions treethrow sediment delivery into the portion presumed to be transported as suspended load ($\leq$ 2 mm) and that transported as bed load (> 2 mm) based on the particle-size distribution shown in Table 4. Threethrow sediment delivery estimates are stored in the TR_DEL polygon data layer. The 'stream_total' routine uses a union command to combine the sediment delivery from streambanks (BANK_DEL) with that from treethrow (TR_DEL) into a new polygon layer called STR_DEL.

The next routine in the model is 'surf_erosion' (Figure 3). This routine estimates sediment production and delivery from undisturbed areas by surface erosion. This routine requires the STJ_BD, "BASIN"_BD, and DEL_BD data layers, the user-defined "basin", "years" and "rain" variables, and a variable called "undisturbed" (Table 2b). The variable "undisturbed" defines sediment production as a function of the rainfall from large storms and the total area. Field data showed that sediment was produced from undisturbed zero-order catchments only from storms with 6 or more centimeters of rainfall (Chapter 4). Long-term rainfall data from Caneel Bay shows that events larger than 6 cm account for about 14% of the annual rainfall. This proportion of the effective rainfall was incorporated into the empirical sediment production model for undisturbed hillslopes (Table 1).

It is important to point out that the value of the "undisturbed" variable was developed with data collected from sediment traps. As it was the case for unpaved roads, the erosion rate for undisturbed catchments defined by this variable is likely to underestimate erosion rates for the silt-sized sediment fraction. A multiplication factor based on the mass-weighted average particle-size distribution data has been integrated into the 'surf_erosion' routine to compensate for underestimation of the silt-size fraction (Tables 1 and 2b). The 'surf_er' routine partitions the sediment into suspended (≤ 2 mm) and bed load (> 2 mm) based on the particle-size distribution values shown in Table 4. The sediment yield rate for each polygon in the final data layer (SE_BD) is calculated by multiplying the sediment production by its respective SDR.

The 'nat_erosion' routine (Figure 3) uses a union command to join the sediment production and delivery estimates contained in the STR_DEL and SE_BD data layers. The final text file and GIS data layer are given the name stored in the user-defined "nat_name" variable. The file and data layer contain the sediment delivery estimates from streambank, treethrow, and surface erosion on undisturbed hillslopes. The 'summary_results' routine is the final routine in STJ-EROS, and this displays a table of sediment delivery estimates from roads and undisturbed areas.

## 5.5 Model Application

### 5.5.1 Basin Description

The STJ-EROS model was applied to three basins on St. John: Lameshur Bay, Fish Bay, and Cinnamon Bay (Figure 1). These three basins were chosen for analysis because they have been the target of several road rehabilitation projects conducted by the VI National Park, the VI Department of Planning and Natural Resources, and several homeowner associations. Lameshur Bay and Fish Bay have also been the subject of previous sediment yield and bay sedimentation studies. Previous sediment yield estimates provide a baseline to compare STJ-EROS results.

The Lameshur Bay basin is defined as those areas that drain to Little Lameshur, Greater Lameshur, and Europa Bays on the south coast of St. John. This 4.3 $km^2$ basin is relatively undisturbed, as it mostly lies within VINP (Figure 1). The basin has an average slope of 41%. Approximately 70% of the basin has a moderate sediment delivery potential, while 7% has a high delivery potential (Table 5). Twenty-three percent of the basin is classified as having no sediment delivery potential because sediment produced from this area gets deposited in a large capacity detention pond. There are 6.4 km of streams with 40% of these having erodible banks. The road network in 1999 consisted of 3.2 km of unpaved and actively-used roads, 0.2 km of abandoned unpaved roads, and 0.1 km of paved segments (Table 5). Unpaved roads had an average slope of 5%. Among actively-used roads only 10% were classified as graded and 90% ungraded.

The Fish Bay basin drains to the south coast of St. John and has a total area of 6.0 $km^2$ (Figure 1). The basin has an average slope of 32%. Approximately 68% of the basin has a high sediment delivery potential (Table 5). Much of the area with a high potential for sediment delivery feeds into the Main Fish Bay Gut or its Battery Gut tributary, which deliver runoff and sediment to the marine environment without any intervening wetlands. The other 32% of the basin has a moderate potential for sediment delivery. Of the 12.7 km of streams in the basin, 5.2 km or 41% have actively eroding banks. The Fish Bay basin has one of the highest road densities on the island. In 1999 there were 22 km of roads, with 9.5 km classified as paved, 9.2 km as actively-used unpaved roads, and 3.2 km as unpaved roads that had been abandoned for over 15 years (Table 5). The average slope for unpaved roads was 7%. Among the 9.2 km of actively-used unpaved roads 57% were classified as graded and 43% as ungraded.

STJ-EROS was applied to 1.6 $km^2$ or 90% of the 1.8 $km^2$ Cinnamon Bay basin. The highly-developed Peter Bay area was not included because there is no public access and we could not collect the necessary field data. The average slope in the area modeled was 41%. Seventy-six percent of the catchment is in wetlands or areas that drain through wetlands, so these areas were classified as having a moderate sediment delivery potential (Table 5). The remaining 24% of the area was designated as having a high potential for sediment delivery. There were 4.1 km of streams, and none of the reaches had banks composed of erodible alluvial material. In 1999 there were 3.6 km of paved roads and 1.6 km of unpaved roads (Table 5). The main unpaved road is the John Head road, which appears as a cartway in a 1919 Geodetic survey and was expanded to its current width during the 1960's (Gibney and Ray, 1993). The mean slope of all roads was 11%. Ninety-six percent of the unpaved roads are ungraded, while only 4% are graded at least once every two years. No abandoned roads were found in the basin.

### 5.5.2 Predicted Sediment Yields

In the absence of specific data on basin-scale sediment delivery ratios and the trapping efficiency of coastal wetlands in St. John, long-term sediment delivery ratios of 80% were assigned for high potential areas and 30% for areas with moderate potential. The estimated sediment delivery rates to each of the three bays under undisturbed conditions were 9 to 12 tons $yr^{-1}$ (2-3 tons $km^{-2}$ $yr^{-1}$) for Lameshur Bay, 32 to 44 tons $yr^{-1}$ (5-7 tons $km^{-2}$ $yr^{-1}$) for Fish Bay, and 0.6 to 1.0 ton $yr^{-1}$ (0.004-0.6 tons $km^{-2}$ $yr^{-1}$) for Cinnamon Bay (Figure 4). While the lower values in these estimates exclusively represent sediment finer than 2 mm, the higher value refers to sediments ranging from clay to coarse gravel (roughly 32 mm). In the Lameshur Bay and Fish Bay basins approximately 90% of the sediment yield in undisturbed conditions originates from streambanks. In contrast, in Cinnamon Bay approximately 60% of the estimated sediment yield under natural conditions originates from undisturbed hillslopes, and about 40% is produced by treethrow.

The addition of unpaved roads increases the estimated sediment yields by a factor of 4.7 to 40, depending on the estimated sediment yield from natural sources and road characteristics (Figure 4). When unpaved roads are included, STJ-EROS estimates sediment yields ranging from 50 to 80 tons $yr^{-1}$ into Lameshur Bay. These sediment yield rates are 5-6 times above undisturbed conditions. Current sediment yields into Fish Bay are estimated to be from 240 to 376 tons $yr^{-1}$, or 7-8 times above background. Current sediment yields into Cinnamon Bay are estimated to have increased to 24 to 40 tons $yr^{-1}$, or 24-40 times relative to undisturbed conditions.

The contributions of individual road segments to sediment yield rates, as well as the spatial distribution of the sediment delivery potential zones in the Lameshur Bay, Fish Bay, and Cinnamon Bay basins are shown in Figures 5a, 5b, and 5c, respectively. Sediment yield rates from road segments in these figures refer to all sediment sizes ranging from clays to coarse gravel. Individual road segments are color coded in Figures 5a-5c according to their sediment yield contributions. The color code permits easy identification of individual road segments that are contributing high quantities of sediment to the marine environment. Road segments in white indicate paved road segments for which no sediment yield was estimated, unpaved roads with a negligible slope, or roads that are not contributing sediment to the selected basin. Road segments in yellow and orange indicate road segments that contribute 0-3 tons $yr^{-1}$ and 3-5 tons of sediment per year to the marine environment, respectively. Road segments contributing 5-10 and 10-45 tons $yr^{-1}$ are shown in purple and red, respectively. Figures 6a, 6b, and 6c show how sediment delivery rates are distributed by sediment source and particle-size class for the Lameshur Bay, Fish Bay, and Cinnamon Bay, respectively. Sediment finer than 2 mm represents 60-65% of the total sediment yield in each of the three study basins.

Unpaved roads account for approximately 83% of the 50-80 tons of sediment delivered to Lameshur Bay every year (Figure 6a). Graded roads are responsible for 55% of the sediment being delivered into Lameshur Bay. All of this sediment comes from a 330-m long road segment with an average slope of 20% (shown in red in Figure 5a). Ungraded roads account for about 18% of sediment yield, cutslopes 10%, streambanks 15%, while undisturbed hillslopes and treethrow account for less than 2 percent of the total sediment yield.

Sediment produced from unpaved roads is responsible for about 88% of the 240-380 tons of sediment being delivered to Fish Bay per year. Graded roads account for about 56% of the total sediment yield into Fish Bay, while ungraded roads are responsible for 20% (Figure 6b). Individual road segments contributing an excess of 5 tons of sediment per year contribute about 200 tons of sediment per year, or about 52% of the total sediment yield. Most of these roads deliver their sediments directly to the Main Fish Bay Gut in the lower portions of the basin or to the Battery Gut tributary in the upper portion of the basin (Figure 5b). These unpaved road segments represent 2.1 km of the 12.4 km of unpaved roads in the basin. Bank erosion produces roughly 11% of the annual sediment yield, while ungraded roads and cutslopes represent approximately 20 and 10%, respectively. The total contributions from surface erosion of undisturbed hillslopes, treethrow, and erosion from abandoned road surfaces are less than 1% of the sediment yield.

In the Cinnamon Bay basin unpaved roads account for 98% of a total sediment yield of 25-40 tons per year. An unpaved private driveway and several ungraded road segments along John Head road account for 80% of the total sediment yield into Cinnamon Bay (Figure 6c). The ungraded 80-m long driveway has a slope of 27% and is the only road segment in this basin producing an excess of 10 tons of sediment per year. Although this driveway represents only 5% of the unpaved road network in Cinnamon Bay, it is estimated to contribute a total of 11 tons of sediment per year, or 27% of the total sediment yield. Even though individual road segments along John Head road contribute sediment at rates lower than 5 tons per year (Figure 5c), they represent 1.5 km of the 1.6 km of unpaved roads in the basin. As a result these road segments are responsible for 57% of the total sediment yield into Cinnamon Bay. Cutslopes are responsible for another 12% of the total sediment delivered, while surface erosion from undisturbed hillslopes and treethrow account for 5% of the total sediment yield.

In summary, application of STJ-EROS to Lameshur Bay, Fish Bay, and Cinnamon Bay indicates that unpaved roads are the dominant sediment source in these basins and are responsible for 83-98% of the total sediment yield. The results summarized in Figures 5a-5c can be used in evaluating the effectiveness of various road erosion control programs. For example, paving road segments delivering more than 5 tons of sediment per year could reduce sediment yields into Lameshur Bay and Fish Bay by 55 and 52%, respectively. This considerable reduction in sediment yields is achieved by paving only 0.3 km and 2.1 km of roads, or 10% and 17% of the unpaved roads in Lameshur Bay and Fish Bay, respectively. In contrast, paving road segments in Cinnamon Bay that are producing more than 5 tons of sediment per year would result in only a 27% reduction in sediment yields. A sediment yield reduction of 57% can be achieved in Cinnamon Bay if 1.5 km of unpaved road segments are paved. These road segments represent 94% of the total unpaved roads in the basin.

### 5.5.3 Effects of Varying Sediment Delivery Ratios in Basin-scale Sediment Yields

The sensitivity of sediment yields to varying sediment delivery ratios was estimated for the STJ-EROS model. SDRs were varied from zero to 50% for moderate potential areas, and high potential areas were assigned SDRs from 50 to 100%. Sediment yields defined as a percentage of the yield estimated using SDR values of 50 and 100% for moderate and high potential areas were used to evaluate sensitivity. Differences in the slope and spacing of the lines shown in Figures 7a-7c indicate that the sensitivity of sediment yields to varying SDR values varied from basin to basin.

In the Lameshur Bay basin 130 tons per year was the total sediment yield estimated using 50 and 100% SDR values for moderate and high potential areas, respectively. Sediment yields in Lameshur Bay were very sensitive to the SDR values assigned to the moderate potential areas

(Figure 7a). Reducing SDR values for moderate potential areas from 50 to 0% induced a 94% decline in sediment yields. In contrast, dropping the SDR value of high potential areas from 100 to 50% caused only a 3% reduction in sediment yields. The Lameshur Bay basin is very sensitive to moderate potential SDRs because these areas represent 74% of the total basin (Table 5). A moderate potential area is also the recipient of sediment produced from an unpaved road that accounts for approximately 55% of the total basin sediment yield (Figure 5a).

A sediment yield of 520 tons per year was estimated for the Fish Bay basin using SDR values of 50 and 100% for moderate and high delivery potential areas, respectively. Sediment yield estimates for the Fish Bay basin were slightly more sensitive to SDR values of high potential areas than SDRs of moderate areas. A reduction from 100 to 50% in the SDR for high potential areas decreased sediment yield by 37%, while reducing SDR for moderate potential areas from 50 to 0% caused a 25% drop in sediment yields (Figure 7b). The slightly higher sensitivity to values assigned to high potential areas is due to the fact that high potential areas cover 68% of the total basin, while those with moderate delivery potential cover only 29% (Table 5).

A sediment yield of 59 tons per year was estimated for the Cinnamon Bay basin using a SDR of 50% for moderate potential areas and a SDR of 100% for high potential areas. Estimated sediment yields into Cinnamon Bay were more sensitive to changes in SDR values assigned to moderate potential areas than those assigned to high potential areas (Figure 7c). A reduction in SDRs for moderate areas from 50 to 0% caused sediment yields estimates to decline by 55%. Reducing the SDR value for high potential areas from 100 to 50% induced a 23% decline in the estimated sediment yields. Sediment yields are more sensitive to the SDR values of moderate potential areas because they cover 74% of the total basin area, while areas with high delivery potential make up 23% of the basin (Table 5).

### 5.5.4 Comparison of Model Results to Other Sources of Data

Sediment yields estimated by STJ-EROS were compared to other measured or estimated values. Runoff and suspended sediment data was collected from the Main Fish Bay Gut from October 1998 and November 2001. A runoff record longer than 3 years was deemed necessary to estimate long-term suspended sediment yields from the Main Fish Bay Gut drainage area (Figure 5b). A fifteen-year long runoff record existed for the Guinea Gut US Geological Survey stream gaging station (USGS station 50295000) located only two kilometers west of the Main Fish Bay Gut station. A flow duration curve developed from the Guinea Gut runoff data and the mean suspended sediment concentration of 35 samples collected from the Main Fish Bay Gut were used to calculate an average annual suspended sediment yield for the Main Fish Bay Gut (Appendix IV-E). The estimated annual suspended sediment yield for the 3.5 $km^2$ Main Fish Bay catchment was 65 tons $yr^{-1}$ (18 tons $km^2$ $yr^{-1}$) (Table 6). Assuming an annual rainfall of 115 cm $yr^{-1}$ and a sediment delivery ratio of 80%, STJ-EROS estimated a suspended sediment yield of 190 tons $yr^{-1}$ (54 tons $km^{-2}$ $yr^{-1}$).

The higher sediment yield estimates resulting from STJ-EROS relative to the suspended sediment yield data might be explained in part by the limited number of suspended sediment samples. Suspended sediment yield estimates from STJ-EROS assume that all material finer than 2 mm will be transported in suspension. This assumption could not be corroborated as no particle-size distribution analysis was performed on the 35 suspended sediment samples. The mean flow rate represented by the 35 samples was 0.59 $m^3$ $s^{-1}$ or 0.06 cm $hr^{-1}$, and only three of these samples represented flows higher than 1 $m^3$ $s^{-1}$ (0.1 cm $hr^{-1}$) (Appendix IV-E). Between October 1998 and October 2001 flow rates up to 41 $m^3$ $s^{-1}$ (4.3 cm $hr^{-1}$) were recorded at Main Fish Bay Gut. It is then possible that the mean sediment concentration is lower than the actual average, as it might be biased towards low-flow conditions during which only the finest particle sizes are being transported.

The limited number of samples also questions its true representation of long-term sediment transport rates, considering that sediment yields are a function of the amount of sediment available for transport and the sediment transport capacity of the fluvial network. A stream profile of Main Fish Bay Gut and its Battery Gut tributary surveyed in February 2000 estimated that approximately 380 tons of sediment finer than 2 mm were stored on the streambed surface (Appendix IV-A). This mass of sediment represents approximately two-year's worth of sediment yield as estimated by STJ-EROS. The presence of this significant amount of sediment just two months after flow rates up to 4.3 cm $hr^{-1}$ were recorded on the Main Fish Bay Gut seems to contradict the high suspended sediment transport capacity estimated for this gut (Appendix IV-A). We postulate that the reason for the large amount of fine sediment in storage is because runoff rates capable of transporting sediment did not last for very long prior to the stream survey. This assumption is supported by the fact that between October 1998 and February 2000 runoff rates exceeding 1.0 $m^3 s^{-1}$ (0.1 cm $hr^{-1}$) lasted only a total of 17 hours. Therefore, it seems possible that most of the fine sediment that will eventually be transported as suspended sediment still remained in storage along the fluvial network between 1998 and 2001, as flows capable of transporting it did not last long enough to allow this sediment to reach Fish Bay.

Sediment yields predicted by STJ-EROS are within the same order of magnitude as those measured in previous studies on St. John (Table 6). Direct comparisons are confounded by differences in methodology, spatial scale (Walling, 1983), and temporal scales (Kirchner et al., 2001). The sediment yield rates estimated by STJ-EROS for current conditions are 25-50% lower than bay sedimentation rates measured over two years with sediment traps at the bottom of Lameshur Bay and 10-70% higher than sedimentation rates measured in Fish Bay (Nemeth et al., 2001) (Table 5). Although there are discrepancies between STJ-EROS sediment yield estimates and bay sedimentation rates, the similar order of magnitude is encouraging and supports the validity of the model.

Previous sediment yields estimated over time-scales exceeding 40 years suggest that watershed-scale sediment yield rates for undisturbed basins on St. John range between 7 and 35 tons $km^{-2}$ $yr^{-1}$ (Table 6). These baseline sediment yields are between 1% and 730% of those estimated by STJ-EROS for the three study basins. Sediment yields ranging from 1 to 35 tons $km^{-2}$ $yr^{-1}$ were used as a baseline rate to compare road-related sediment yields estimated by the ROADMOD model for the Lameshur Bay and Fish Bay basins (MacDonald et al., 1997).

ROADMOD estimated sediment yields ranging from 19 to 52 tons $km^2$ $yr^{-1}$ for Lameshur Bay (Table 6). Unpaved roads were responsible for 9.8 tons $km^2$ $yr^{-1}$, or roughly 20-50% of the total sediment yield (Anderson and MacDonald, 1998). STJ-EROS estimated sediment yields ranging from 12-19 tons $km^{-2}$ $yr^{-1}$ into Lameshur Bay (Table 6), or 23-100% of that estimated by ROADMOD. STJ-EROS estimated that unpaved roads contribute a total of 10-16 tons $km^{-2}$ $yr^{-1}$. The disparity in the sediment yield estimates were attributed to differences in baseline sediment yields and discrepancies in the road data layers used by the models. STJ-EROS was applied to 3.2 km of unpaved roads (Table 5). Sediment produced from these roads was delivered to areas that drained into Europa Bay, Little Lameshur Bay, and Greater Lameshur Bay (Figure 4a). In contrast, ROADMOD was applied only to the 1.4 km of roads contributing to the Greater Lameshur Bay.

Current sediment yields into Fish Bay estimated by ROADMOD ranged from 72-104 tons $km^2$ $yr^{-1}$ (Anderson and MacDonald, 1998) (Table 6). STJ-EROS estimated a range of 42-65 tons $km^2$ $yr^{-1}$, or 40-90% of the rates estimated by ROADMOD. The discrepancies in sediment yields are mostly due to differences in the estimation of baseline sediment yields, as those used by ROADMOD are from 14% to 660% of those estimated by STJ-EROS. Even though there are differences in the road data layers used by the models, both were applied to approximately 9 km of unpaved roads. Road-related sediment yield according to ROADMOD was 63 tons $km^2$ $yr^{-1}$. This estimate is only 1.1-1.7 times higher than the 36-57 tons $km^2$ $yr^{-1}$ estimated by STJ-EROS.

The results presented in this study represent one of the few attempts to quantify sediment yields in a dry tropical environment. The sediment yield rates estimated for St. John were up to two orders of magnitude lower than world-wide yields for watersheds with similar drainage areas (Milliman and Syvitski, 1992). None of the data sources in Milliman and Syvitski (1992) depicts a dry tropical climate such as that found on St. John. It is likely that the yield rates reported in the literature are influenced by mass wasting events occurring on steep slopes of small watersheds, whereas this process is generally absent on St. John. Therefore, the sediment yield estimates presented in this study begin to fill a gap in the representation of dry tropical climates in world-wide sediment yield data.

## 5.6 Conclusions

A GIS-based sediment budget model, STJ-EROS, was developed for use on the island of St. John in the Eastern Caribbean. STJ-EROS estimates annual sediment delivery to the marine environment from unpaved roads and natural sediment sources. While sediment production is estimated by using empirical erosion data and models, sediment delivery is calculated as the product of the estimated sediment production and spatially-variable sediment delivery ratios. The STJ-EROS program code is organized in six input routines and five routines that calculate sediment production and delivery. The six input routines allow the user to adjust variables controlling sediment production and delivery, such as rainfall rates and sediment delivery ratios. The remaining five routines use pre-set erosion rate constants, user-defined variables, and item values stored in nine GIS data layers to calculate watershed scale sediment yields.

The model was applied to three different basins in St. John. Predicted sediment delivery rates under natural conditions are on the order of 9-12 tons $yr^{-1}$ into Lameshur Bay (2-3 tons $km^{-2}$ $yr^{-1}$), 32-44 tons $yr^{-1}$ into Fish Bay (5-7 tons $km^{2}$ $yr^{-1}$), and roughly 1 ton $yr^{-1}$ into Cinnamon Bay (0.6 tons $km^{-2}$ $yr^{-1}$). These rates are within the range of sediment yields estimated from previous bay and wetland sedimentation studies on St. John. The results indicated that streambank erosion was generally more important than treethrow and undisturbed hillslopes.

Unpaved roads are responsible for increasing sediment delivery rates by 5-6 times for Lameshur Bay, 7-8 times for Fish Bay, and 24-40 times for Cinnamon Bay. These results agree with previous studies in that the unpaved road network is currently the main source of sediment on St. John.

STJ-EROS sediment yield estimates were 25-50% lower and 10-70% higher than bay sedimentation rates measured at Lameshur Bay and Fish Bay, respectively. Although there are discrepancies between STJ-EROS sediment yield estimates and bay sedimentation rates, the similar order of magnitude is encouraging and supports the validity of the model. STJ-EROS estimated sediment yields were 23-100% and 40-90% of sediment yields estimated by the ROADMOD model for Lameshur Bay and Fish Bay, respectively. The disparity in the sediment yield estimates were attributed to differences in the baseline sediment yields and discrepancies in the road data layers used by the models.

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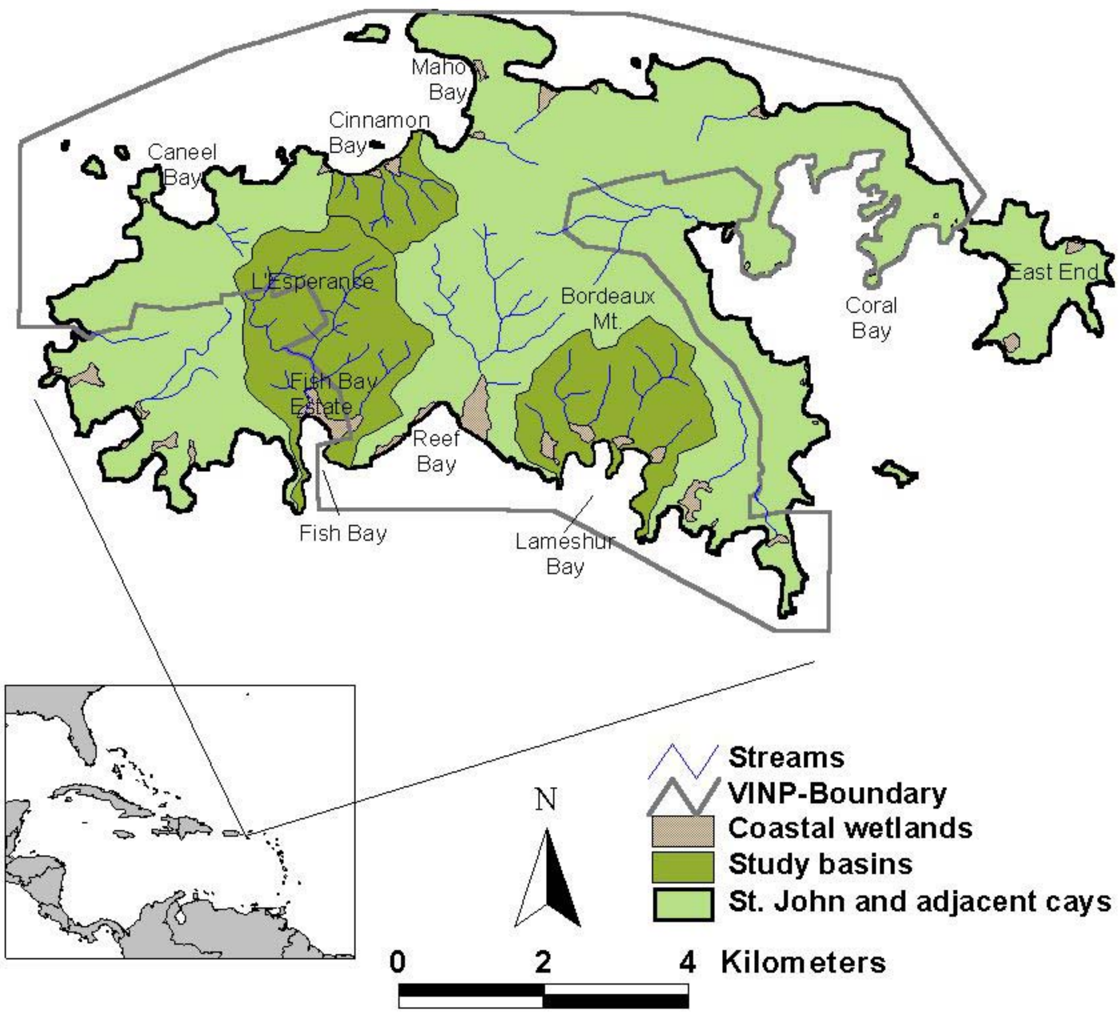


Figure 1. Map of St. John showing the location of the VINP boundary and study basins.

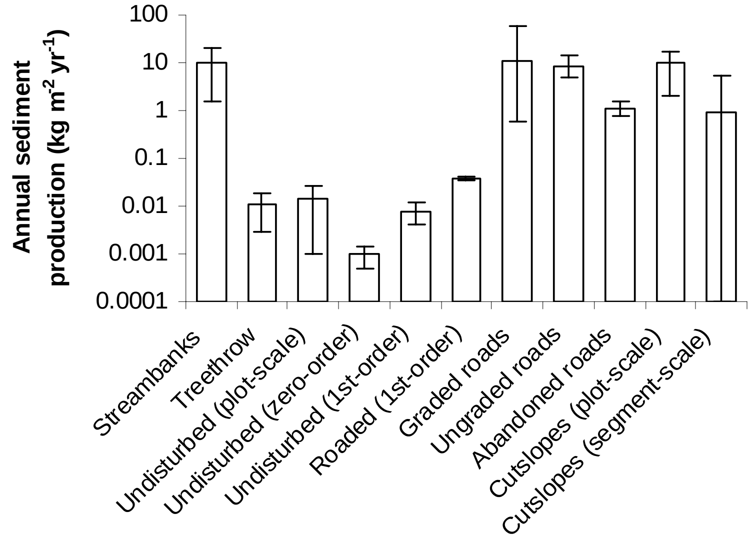


Figure 2. Annual sediment production rates from natural and anthropogenic sediment sources on St. John.  Columns show average values, and bars indicate the range of values.

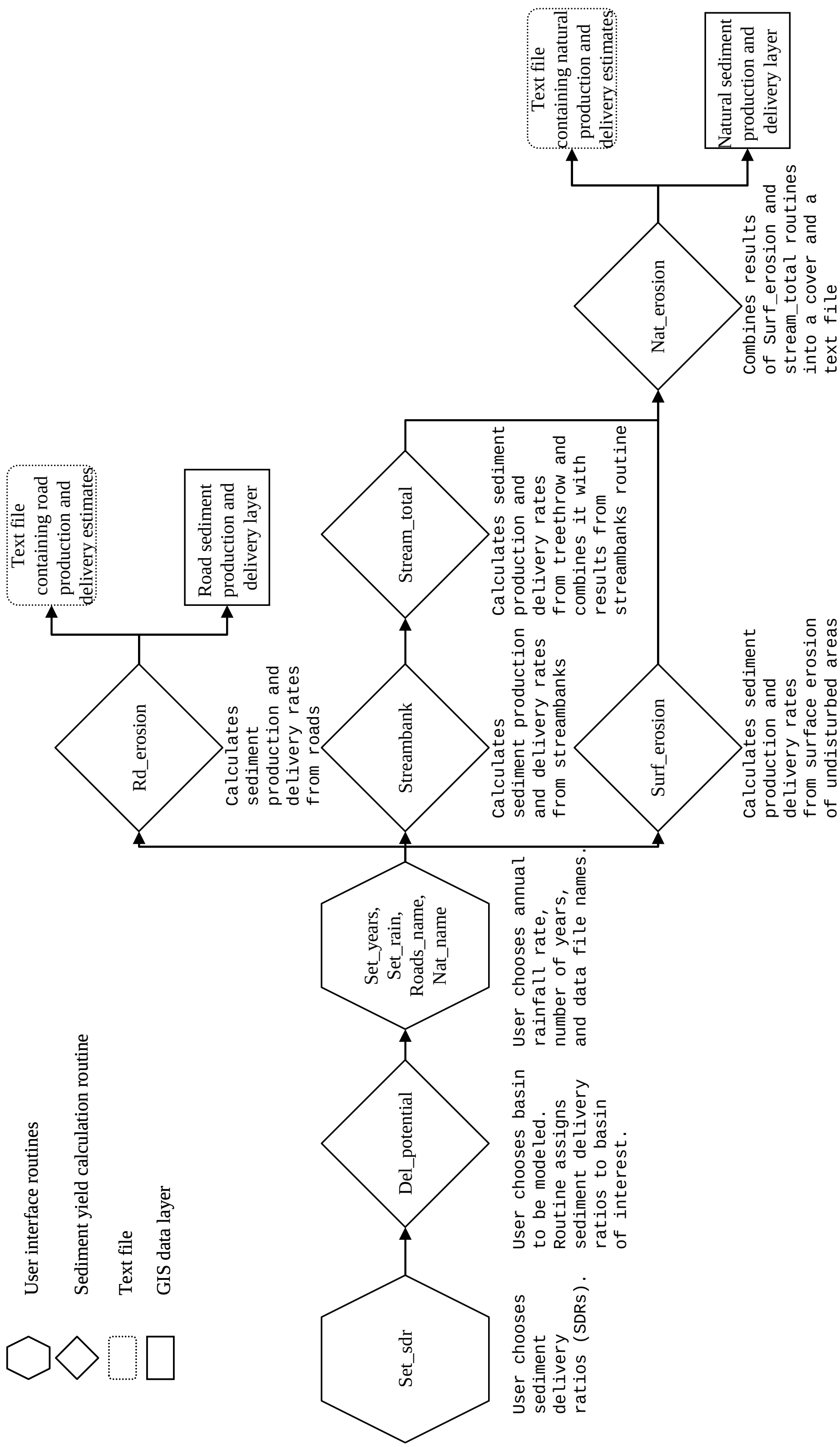


Figure 3. Flowchart of the STJ-EROS model.

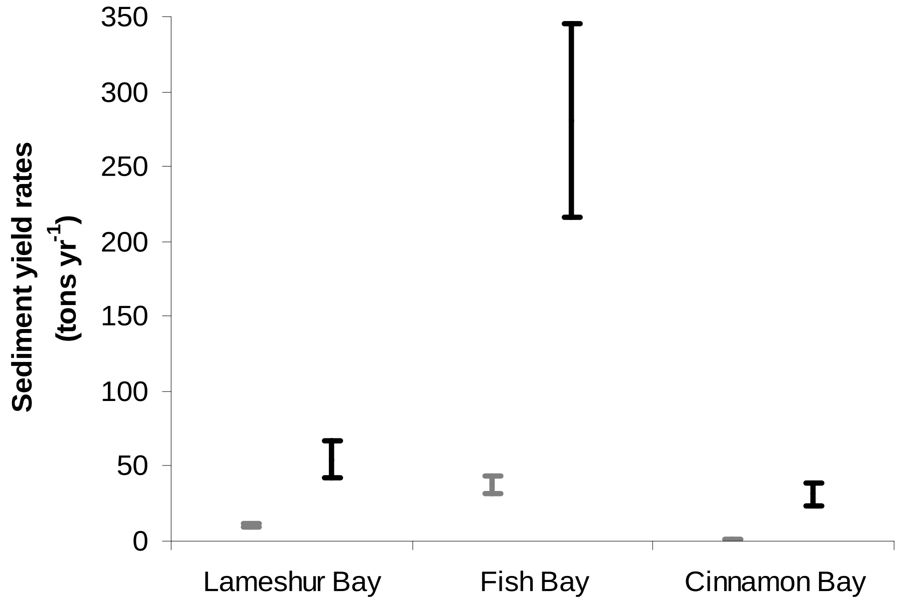


Figure 4. Calculated sediment yields for the Lameshur Bay, Fish Bay, and Cinnamon Bay basins. Gray bars are for natural sources and those in black are for unpaved roads. The lower values are for sediment finer than 2 mm and the higher values are for all sediment sizes from clays to coarse gravel (32 mm).

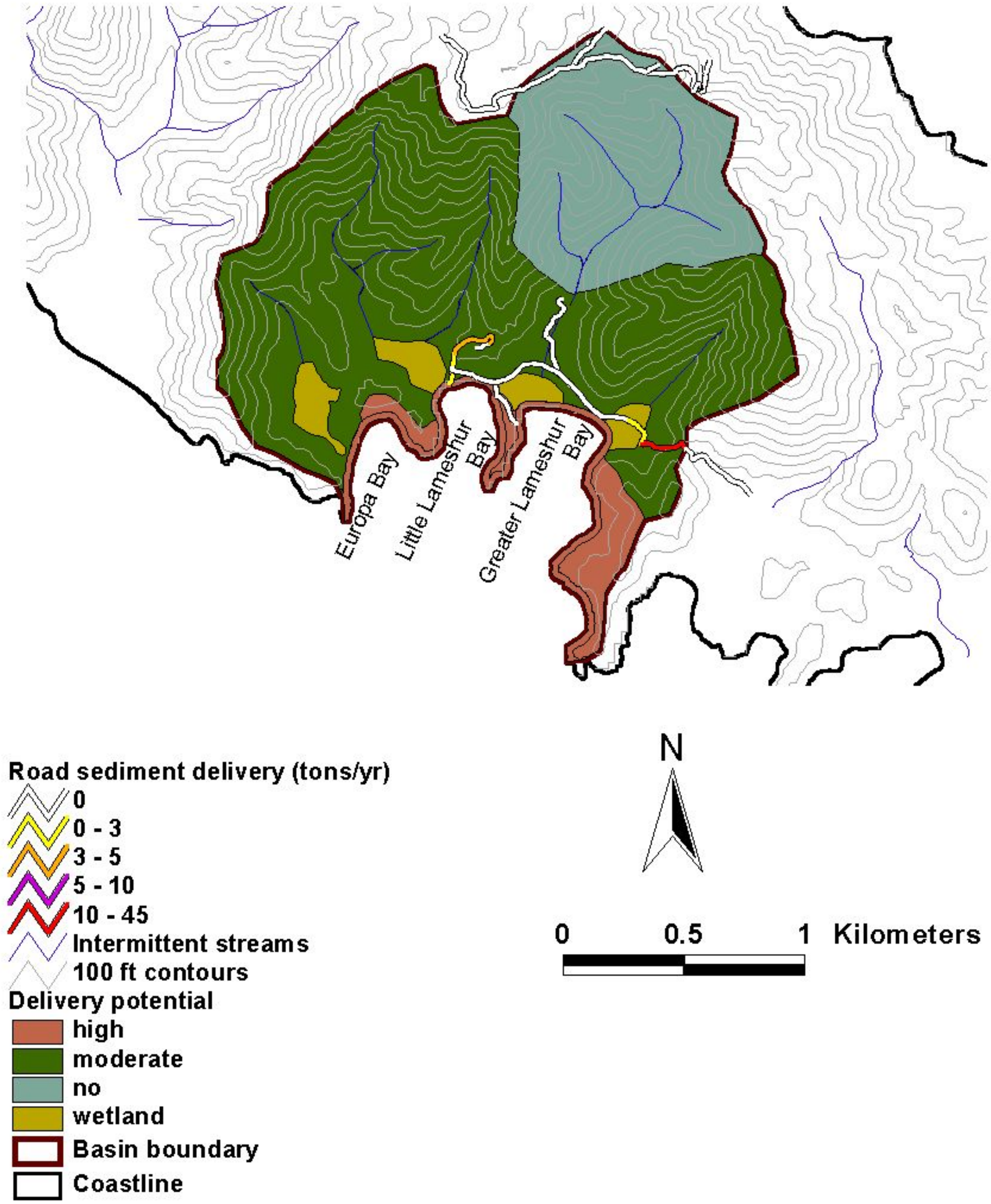


Figure 5a. Map of road segments and hillslopes in the Lameshur Bay basin classified by sediment delivery rates and sediment delivery potential, respectively.

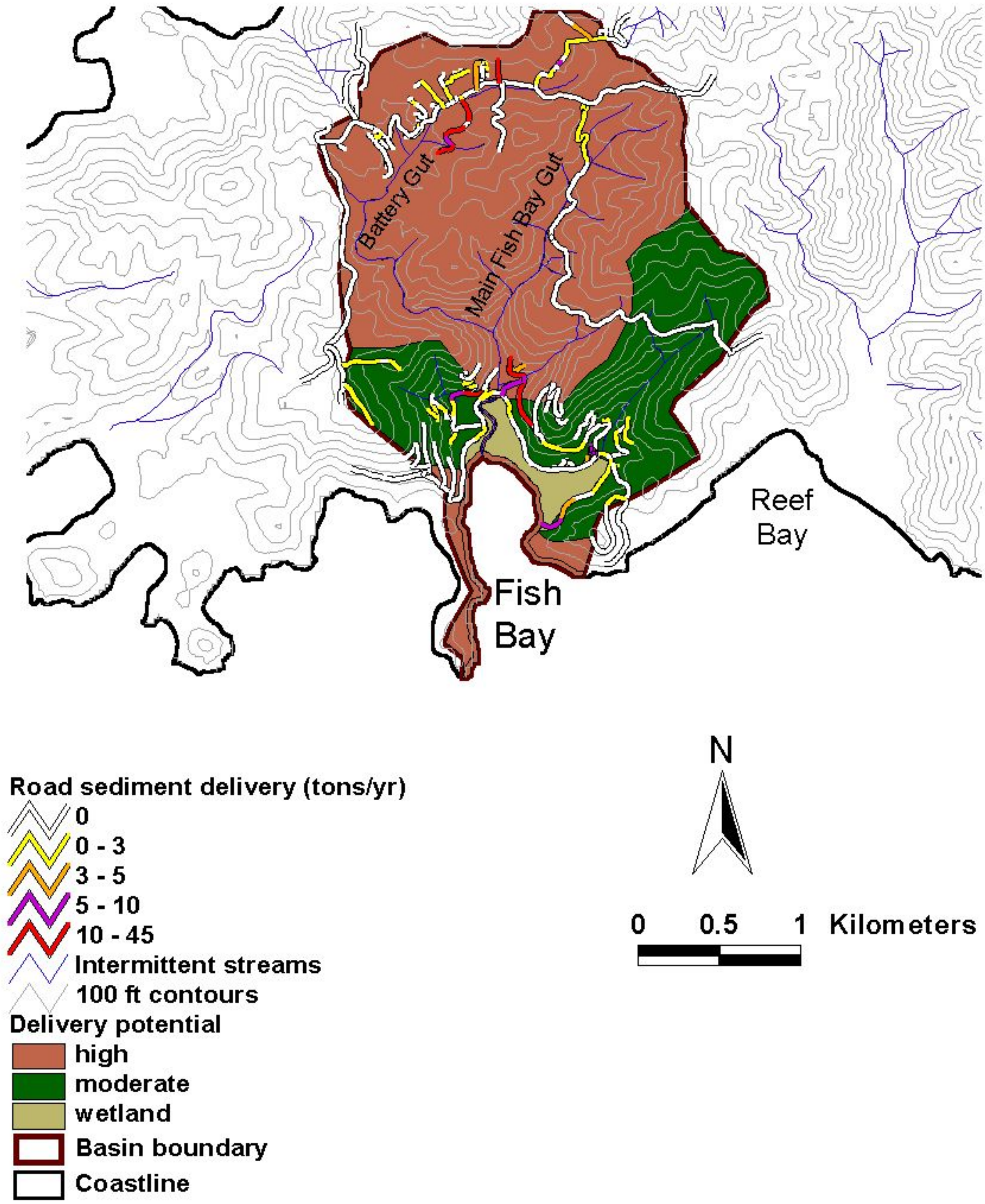


Figure 5b. Map of road segments and hillslopes in the Fish Bay basin classified by sediment delivery rates and sediment delivery potential, respectively.

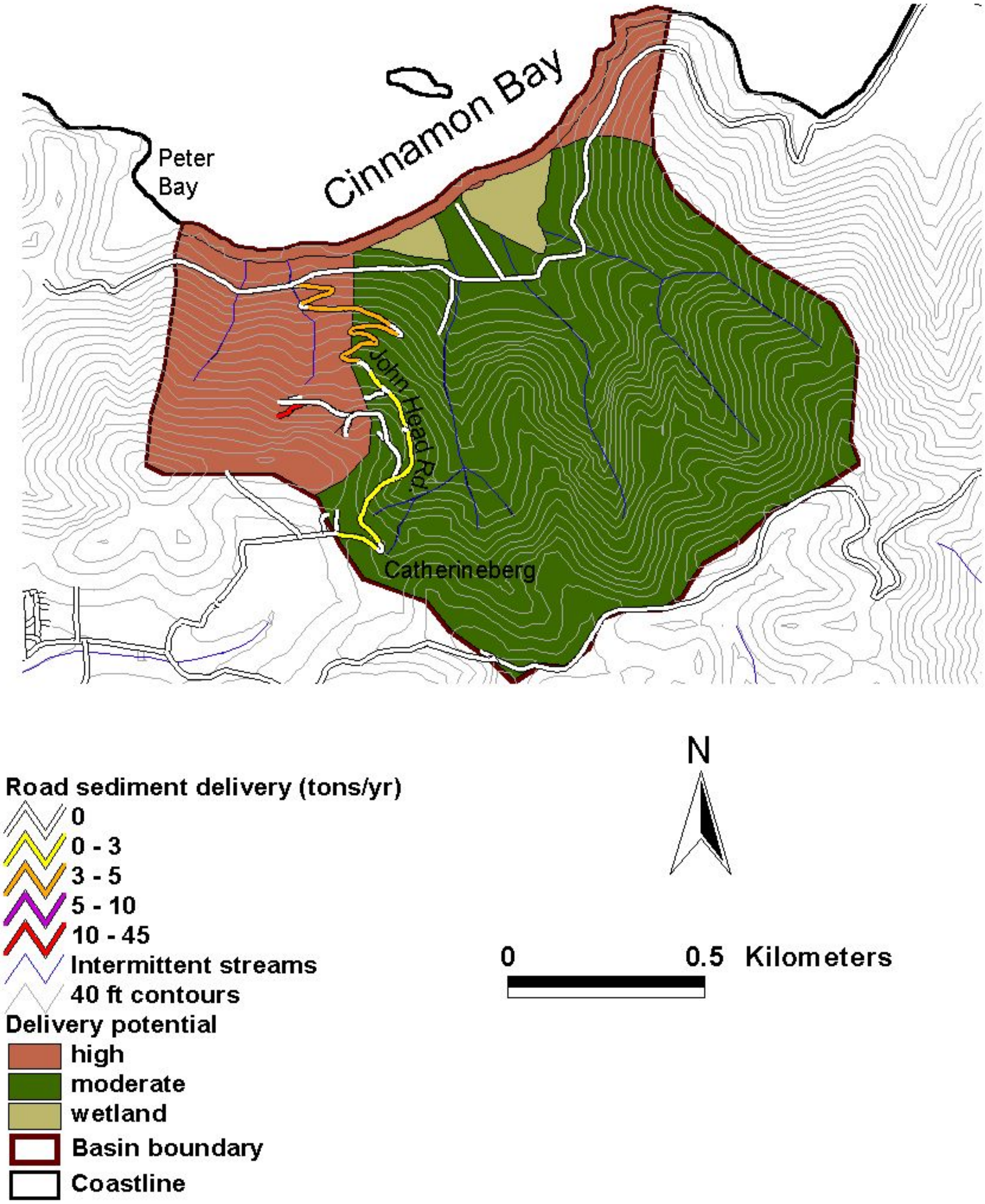


Figure 5c. Map of road segments and hillslopes in the Cinnamon Bay basin classified by sediment delivery rates and sediment delivery potential, respectively.

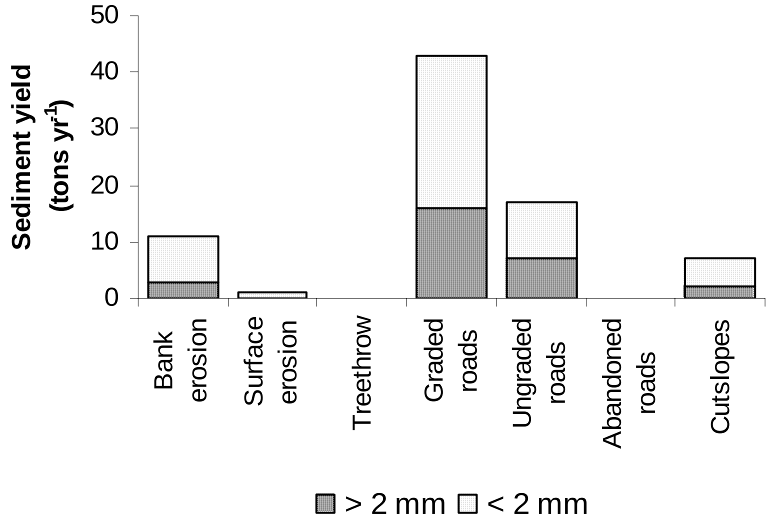


Figure 6a. Predicted contribution of different sediment sources by particle-size class for the Lameshur Bay basin.

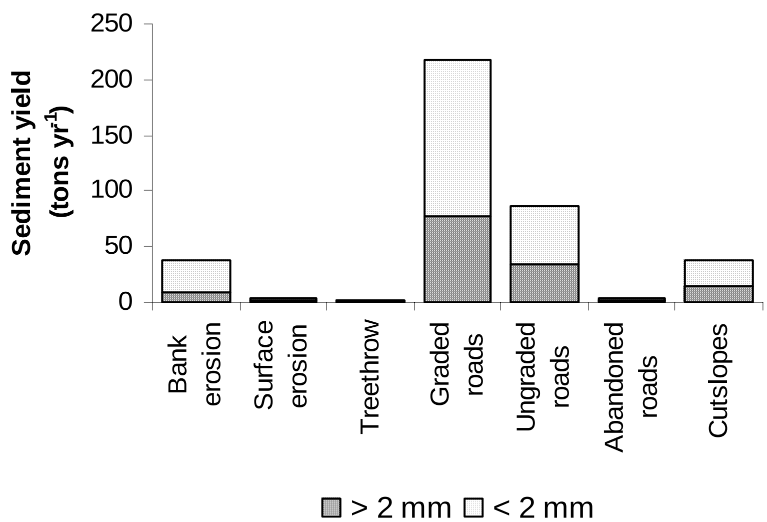


Figure 6b. Predicted contribution of different sediment sources by particle-size class for the Fish Bay basin.

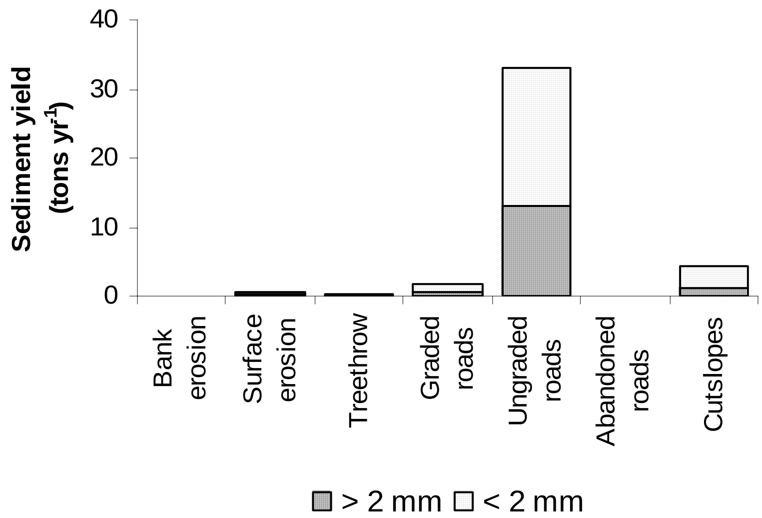


Figure 6c. Predicted contribution of different sediment sources by particle-size class for the Cinnamon Bay basin.

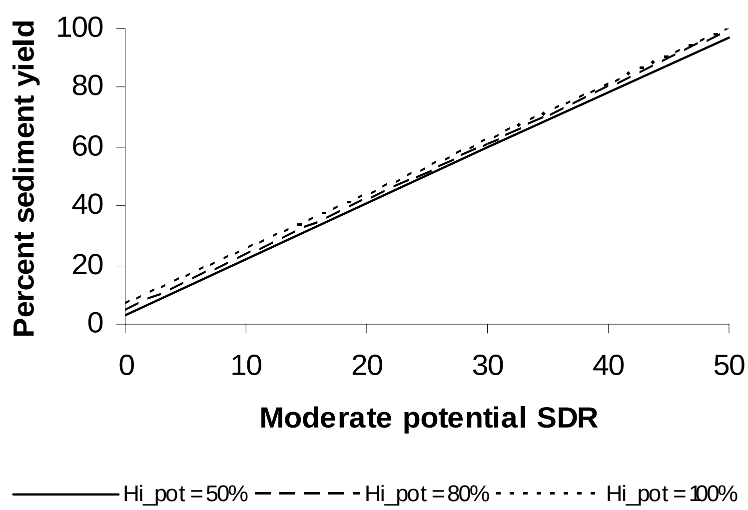


Figure 7a. Changes in percent sediment yield with varying sediment delivery ratios for the Lameshur Bay basin. One-hundred percent refers to sediment yields estimated using sediment delivery ratios of 50 and 100% for areas with moderate and high sediment delivery potential, respectively.

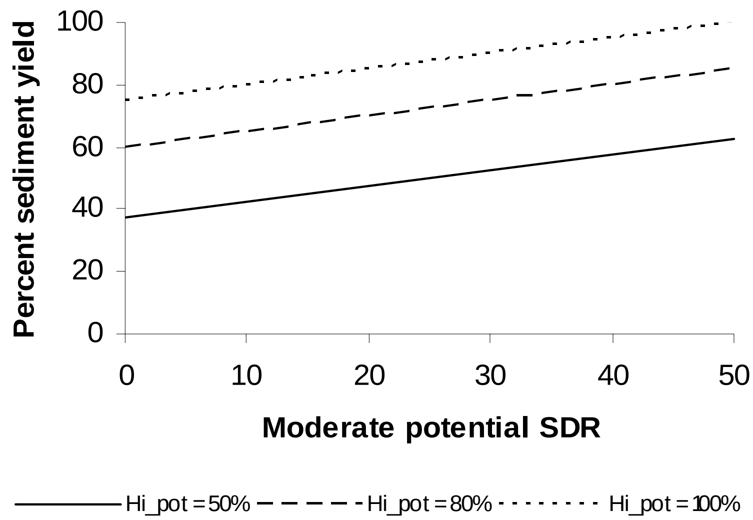


Figure 7b. Changes in percent sediment yield with varying sediment delivery ratios for the Fish Bay basin. One-hundred percent refers to sediment yields estimated using sediment delivery ratios of 50 and 100% for areas with moderate and high sediment delivery potential, respectively.

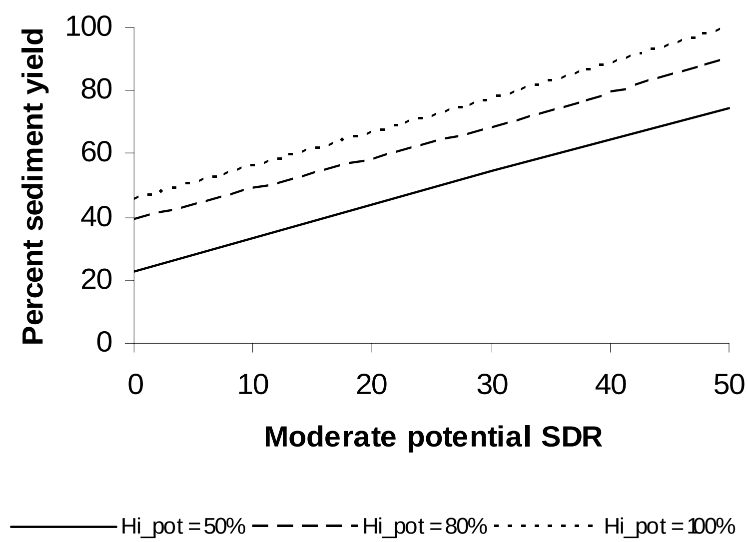


Figure 7c. Changes in percent sediment yield with varying sediment delivery ratios for the Cinnamon Bay basin. One-hundred percent refers to sediment yields estimated using sediment delivery ratios of 50 and 100% for areas with moderate and high sediment delivery potential, respectively.

Table 1. Sediment production functions used in STJ-EROS.

| **Sediment source** | **Annual erosion rate ($kg\ m^{-2}\ yr^{-1}$)** | **Sediment production function** |
|---|---|---|
| Streambank | 10 | [10] * 2 * *channel length w. erodible banks* * *bank height* * time |
| Treethrow | 0.01<br>[0.17 $kg\ m^{-1}\ yr^{-1}$] | [0.17] * *channel length* * time |
| Undisturbed hillslopes | 0.001 | [ $6.4 \times 10^{-5}$] * 14% rainfall * *area* * { 1 + 9 * 0.004 $^{A}$ } |
| Graded roads | 0.1 – 52<br>(slopes from 1 to 21%) | [-0.432 + 4.73 * $slope^{1.5}$ * rainfall] * *road length* * *width* * { 1 + 9 * $0.06^{A}$ } |
| Ungraded roads | 0.0 – 20<br>(slopes from 1 to 21%) | [-0.432 + 1.88 * $slope^{1.5}$ * rainfall] * *road length* * *width* * { 1 + 9 * $0.04^{A}$ } |
| Abandoned roads | 0.08 – 1.7<br>(slopes from 1 to 21%) | [0.071] * slope * rainfall * *road length* * *width* * { 1 + 9 * $0.001^{A}$ } |
| Cutslopes | 0.0 – 5.7 | [0.09] * road segment sediment production |

Sediment production is in kg, all lengths, widths, and heights are in meters, time is in years, slope is in percent, 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, and rainfall equals the product of the user-defined annual rainfall rate and time in years.
Road surface erosion accounts for 91% of the sediment yield from road segments, and cutslopes account for the remaining 9%.
[A]Refers to the percent of silt from Table 4.

Table 2a. Variables and GIS data layers used by the six input routines in STJ-EROS.

| **Routine** | **Required pre-defined variable(s)** | **New variable(s) created** | **Required input layer(s)** | **New GIS data layer(s) created** |
|---|---|---|---|---|
| Set_sdr | None | Hi_pot- The user-defined sediment delivery ratio (SDR) for areas with high delivery potential. Range of accepted values: 50-100%. Mod_pot- The user defined SDR for areas with moderate delivery potential. Range of accepted values: 0-50%. | None | None |
| Del_potential | Hi_pot, mod_pot | Basin- The name of the basin chosen by the user for analyses. | BASIN_BD, SED_DEL | DEL_BD- Contains the SDR values for the sediment delivery potential areas in basin. |
| Set_years | None | Years- The user-defined number of years for which sediment yield is to be estimated. Range of accepted values: 1-50 years. | None | None |
| Set_rain | Years | Rain_rate-The user-defined annual rainfall rate. Range of accepted values: 70-160 cm $yr^{-1}$. *Rain*-Total rainfall in cm calculated as the product of rain_rate and years. | None | None |
| Roads_name | Basin | Road_name*-The user-defined name of the layer containing road-related sediment yield estimates. | None | None |
| Nat_name | Basin | Nat_name*-The user-defined name of the layer containing sediment yield estimates from natural sources. | None | None |

Underlined names indicate variables with values established by the user. Names in italics refer to variables with constant values established in the program code or those that are automatically calculated. Names in small caps indicate GIS data layer names.
* Alpha-numerical names cannot exceed 8 characters in length.

Table 2b. Variables and GIS data layers used by five routines in STJ-EROS used to calculate sediment yields.

| Routine | Required pre-defined variable(s) | New variable(s) created | Required input layer(s) | New GIS data layer(s) created |
|---|---|---|---|---|
| Rd_erosion | Basin, years, road_name, *rain, silt_loss*[A], *silt_u_rd_fr*[B], *silt_g_rd_fr*[B], *silt_a_rd_fr*[B], *un_sus_fr*[C], *gr_sus_fr*[C], *ab_sus_fr*[C] | None | GPS_DRA, BASIN_BD, GPS_RDS, DEL_BD | ROAD_NAME- A line layer containing road-related sediment yield estimates. |
| Streambank | Years, *bank_er*, *bank_sus_fr*[C] | None | BANKS, DEL_BD | BANK_DEL- A polygon layer containing streambank sediment yield estimates. |
| Stream_total | Years, *treethrow*, *tree_sus_fr*[C] | None | STJ_STR, DEL_BD, BANK_DEL | STR_DEL- A polygon layer containing streambank and treethrow sediment yield estimates. |
| Surf_er | Years, *undisturbed*,*rain*, *silt_loss*[A], *silt_se_fr*[B], *se_sus_fr*[C] | None | STJ_BD, DEL_BD, BASIN_BD | SE_BD- A polygon layer containing sediment yield estimates for undisturbed hillslopes. |
| Nat_erosion | Years | None | SE_BD, STR_DEL | NAT_NAME- A polygon layer containing streambank, treethrow, and undisturbed hillslope sediment yield estimates. |

Underlined names indicate variables with values established by the user. Names in italics refer to variables with constant values established in the program code or those that are automatically calculated. Names in small caps indicate GIS data layer names.

[A] Refers to the ratio of actual sediment production rates to that measured from sediment traps for the silt-size sediment fraction (Chapter 3).

[B] Refers to the silt fraction from ungraded roads (u), graded roads (g), abandoned roads (a), and undisturbed hillslopes (se) from Table 4.

[C] Refers to the sediment believed to be transported as suspended load by streams in St. John. It is estimated as the sum of the sand, silt, and clay fractions for ungraded roads (un), graded roads (gr), abandoned roads (ab), streambanks (bank), treethrow (tree), and undisturbed hillslopes (se) from Table 4.

Table 3. Description of the nine input layers used by STJ-EROS.

| **Data layer** | **Type** | **Description** | **Key items** | **Routine(s) using data layer** |
|---|---|---|---|---|
| SED_DEL | Polygon | Sediment delivery potential areas | *Potential*-Qualitative classifies sediment delivery potential into three types: no, moderate/wetlands, high | Del_potential |
| CB_BD | Polygon | Boundaries of the Cinnamon Bay basin | None | Del_potential, rd_erosion, and surf_er |
| FB_BD | Polygon | Boundaries of the Fish Bay basin | None | Del_potential, rd_erosion, and surf_er |
| LB_BD | Polygon | Boundaries of the Lameshur Bay basin | None | Del_potential, rd_erosion, and surf_er |
| GPS_DRA | Point | Road drainage structures | *Drain_id*- Identification code used to link individual road segments in GPS_RDS to their respective drainage structures. | Rd_erosion |
| GPS_RDS | Line | Roads | *Drain_id*- Identification code used to link individual drainage structures in GPS_DRA to their respective road segments.<br>*Surface*-Describes whether the road segment is paved or unpaved.<br>*Length_m* and *width_m*-Road segment length and width in meters.<br>*Slope*- Road segment slope in percent.<br>*Grading*-Defines road grading type: graded, ungraded, or abandoned. | Rd_erosion |
| BANKS | Polygon | Streambanks | *Bank_ht_m*- Bank height in meters. | Streambank |
| STJ_STR | Line | Streams | *Length*- Length of stream segments in meters. | Stream_total |
| STJ_BD | Polygon | Coastal boundaries | None | Surf_er |

Names in italics are for item names in GIS data layers.

Table 4. Proportion of sediment by particle-size class for different sediment sources on St. John.

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

*Size distribution for these sources were from analyzing samples of the material collected in sediment fences.
Values in parentheses are the proportion of silt (0.004-0.062 mm)
The sediment from cutslopes is assumed to have the same particle-size distribution as the sediment from the road surface.

Table 5. Characteristics of the three basins where STJ-EROS was applied.

| Basin | Basin area ($km^2$) | No delivery potential (% of basin) | Wetland (% of basin) | Moderate delivery potential (% of basin) | High delivery potential (% of basin) | Length of fluvial network (km) | Percent streams with erodible banks | Length of paved roads (km) | Length of unpaved roads (km) | Graded roads (% of unpaved) | Ungraded roads (% of unpaved) | Abandoned roads (% of unpaved) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lameshur Bay | 4.28 | 24 | 4 | 64 | 8 | 6.45 | 41 | 0.11 | 3.2 | 9 | 84 | 7 |
| Fish Bay | 6.01 | 0 | 3 | 29 | 68 | 12.7 | 41 | 9.5 | 9.2 | 42 | 32 | 26 |
| Cinnamon Bay | 1.58 | 0 | 2 | 74 | 23 | 4.11 | 0 | 3.6 | 1.6 | 4 | 96 | 0 |

Table 6. Comparison of sediment yield values from St. John.

| **Reference** | **Location** | **Time scale (years)** | **Spatial scale ($km^2$)** | **Undisturbed sediment yields (tons $km^{-2}$ $yr^{-1}$) [tons $yr^{-1}$]** | **Sediment yield disturbed conditions (tons $km^{-2}$ $yr^{-1}$) [tons $yr^{-1}$]** |
|---|---|---|---|---|---|
| ***WATERSHED-SCALE SUSPENDED SEDIMENT YIELDS*** | | | | | |
| Appendix IV-E | Main Fish Bay Gut | 3 | 3.5 | -- | 18 [65] |
| ***BAY SEDIMENTATION RATES*** | | | | | |
| Nemeth et al. (2001) | Great Lameshur Bay | 2 | 2.3 | -- | 24 [55] |
| Nemeth et al. (2001) | Fish Bay | 2 | 6.0 | -- | 36 [216] |
| Anderson (1994) | Fish Bay | ~3,000 | 6.0 | 35 [210] | -- |
| ***WETLAND SEDIMENTATION RATES*** | | | | | |
| Nichols and Brush (1988) | Mandal Pond | ~3,000 | 1.33 | 29 [39] | -- |
| Nichols and Brush (1988) | Reef Bay swamp | ~3,000 | 5.63 | 8 [45] | -- |
| Anderson (1994) | Lameshur Bay Gut detention pond | ~40 | 0.97 | 7-10 [7-10] | -- |
| ***MODEL APPLICATIONS*** | | | | | |
| ROADMOD (Anderson and MacDonald, 1998) | Lameshur Bay | n/a | 4.3 | -- | 19 – 52 [84 – 220] |
| ROADMOD (Anderson and MacDonald, 1998) | Fish Bay | n/a | 6.0 | -- | 72 – 104 [440 – 630] |
| STJ-EROS (This study) | Lameshur Bay | 10 | 4.3 | 2.0 – 2.8 [9 – 12] | 12 – 19 [50 – 80] |
| STJ-EROS (This study) | Fish Bay | 10 | 6.0 | 5.3 – 7.3 [32 – 44] | 42 – 65 [250 – 390] |
| STJ-EROS (This study) | Cinnamon Bay | 10 | 1.6 | 0.4 – 0.6 [0.6 – 1.0] | 15 – 25 [24 – 40] |