Paradise Threatened: Land Use and Erosion on St. John, US Virgin Islands

LEE H. MACDONALD*
Department of Earth Resources
Colorado State University
Ft. Collins, Colorado 80523, USA

DONALD M. ANDERSON
Cooperative Institute for Research
in Environmental Sciences
Boulder, Colorado 80309, USA

WILLIAM E. DIETRICH
Department of Geology and Geophysics
University of California at Berkeley
Berkeley, California 94720, USA

ABSTRACT / Rapid development and the concomitant increases in erosion and sedimentation are believed to threaten the reefs and other marine resources that are a primary attraction of St. John and Virgin Islands National Park. Average annual sediment yields from undeveloped areas were estimated from a sediment pond and a mangrove swamp as less than 20 and less than 40 t/km^2/yr, respectively. Geomorphic evidence indicates that plantation agriculture during the 18th and 19th centuries did not cause severe erosion. Since about 1950 there has been rapid growth in roads and development due to increasing tourism and second-home development. Our field investigations identified the approximately 50 km of unpaved roads as the primary source of anthropogenic sediment. Field measurements of the road network in two catchments led to the development of a vector-based GIS model to predict road surface erosion and sediment delivery. We estimate that road erosion has caused at least a fourfold increase in island-wide sediment yields and that current sedimentation rates are unprecedented. Paving the dirt roads and implementing standard sediment control practices can greatly reduce current sediment yields and possible adverse effects on the marine ecosystems surrounding St. John.

At 50 km^2, St. John is one of the three main islands comprising the Trust Territory of the US Virgin Islands. Its rugged topography, thin soils, and limited water resources have historically made it less subject to development than most other islands in the eastern Caribbean. Plantation agriculture began in the early 1700s and was generally abandoned in the 1800s. By the early 1900s the permanent population had declined to approximately 800 inhabitants (Low and Valls 1985). The spectacular beaches, relatively undisturbed coastline, and offshore coral reefs led to the establishment of Virgin Islands National Park (VINP) in 1956, and this currently incorporates 54% of the land area of St. John and 23 km^2 of offshore waters (Figure 1). The unique and relatively pristine character of the terrestrial and marine resources led UNESCO to designate VINP as an International Biosphere Reserve in 1976.

Over the last 40 years there has been increasingly rapid development of vacation homes and tourist-related businesses on privately held lands on St. John. The effects of this development are of great concern to both the National Park Service (NPS) and the territorial government. Much of this concern is focused on erosion and a possible increase in sedimentation in the marine environment (e.g., VINP 1987). Corals are particularly susceptible to turbidity and the deposition of fine sediment (Rogers 1990), and the offshore coral communities are a primary attraction of St. John and vital to maintaining both the fisheries and the white sand beaches. A recent study indicated a decline in coral growth rates for some locations around St. John, but this could not be associated with a specific cause (Hubbard and others 1987). High erosion and sedimentation rates are also a concern because of their potentially adverse effect on marine water clarity as well as the mangroves, salt ponds, and beaches of St. John.

The development and implementation of land-use planning and sediment-control practices have been severely hindered on St. John by the lack of information on natural and historic rates of erosion and the delivery of eroded material through the stream network to the marine environment. Our extensive literature review revealed just one short-term study of erosion from construction sites on the adjacent island of St. Thomas (Wernicke 1986) and one study of offshore sediment deposition (Nichols and Brush 1988). This paucity of information led the NPS to initiate a series of studies in

KEY WORDS: Erosion; Sediment yield; Roads; Dry tropics; Development

*Author to whom correspondence should be addressed.

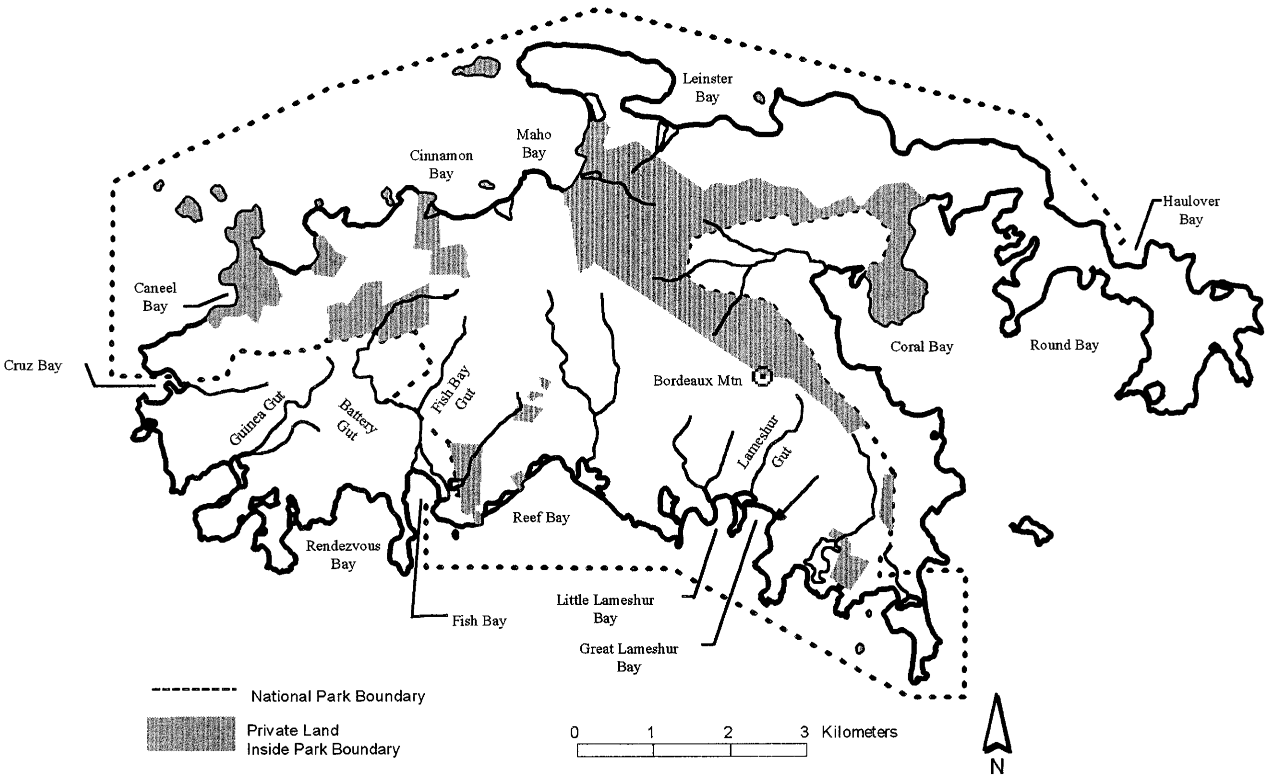

Figure 1. Map of St. John and Virgin Islands National Park. The USGS gauging stations are located near the mouth of the ephemeral streams (guts) flowing into Fish Bay and the eastern bight of Lameshur Bay.

1989 to identify the nature and location of erosion hazards, estimate the change in erosion rates over time, and measure suspended sediment loads on two catchments with differing amounts of development.

As part of this effort, Ramsarran (1992) modeled the change in sediment yield between 1971 and 1984 in the 1.7 km^2 Guinea Gut catchment. (“Gut” is a local term, derived from the Danish ghut, meaning stream or creek.) A comparison of aerial photographs over this 13-year period showed an increase in urbanized area from 2.5% to 11%, and simulations using the ANSWERS model (Beasley and Huggins 1991) suggested that this change in land use would increase sediment yields from a 7.7-cm storm by 11%. Unfortunately no sediment data are available for Guinea Gut, and Ramsarran did not have the opportunity to field verify the changes in land use or model predictions.

From mid-1992 until early 1994 the US Geological Survey (USGS) operated automated discharge and suspended sediment stations on two ephemeral streams, Fish Bay Gut and Lameshur Bay Gut (Figure 1). Both stations were located several hundred meters upstream from their respective outlets. The underlying design was a semicontrolled paired-catchment experiment, as the Fish Bay catchment is undergoing rapid development while the Lameshur Bay catchment is almost entirely within VINP and relatively undisturbed. The ephemeral and flashy nature of runoff on St. John meant that incomplete sets of sediment samples were obtained from only four and two small runoff events on Fish Bay and Lameshur Guts, respectively. The stations were discontinued because of the cost and difficulty of maintaining these relatively remote sites, the infrequent runoff events, and the inherent limitations of a paired-catchment design (e.g., Wicht 1967).

Given this background, the purposes of our study were to: (1) identify and map the areas of low, medium, and high erosion susceptibility; (2) predict relative erosion and sediment delivery rates; and (3) recommend practices to minimize or reduce sediment delivery to the marine environment. The NPS also wanted us to develop a set of geographic information system (GIS)-based erosion prediction tools for planning and management purposes.

In the following sections, we (1) provide an overview of the physical environment, hydrology, and erosion processes on St. John; (2) evaluate natural and historic erosion rates from pre-Columbian times to the present; (3) identify the primary sediment sources; (4) present a model for predicting road surface erosion; (5) evaluate and predict sediment delivery rates; and (6) recommend future research and methods to minimize erosion and sedimentation from current and future development.

Physical Environment and Erosion Processes

The island of St. John is located approximately 80 km east of Puerto Rico. Surface geology is extremely complex, as it includes felsic and mafic flows, andesitic breccias, layered tuffs and limestones, and intrusive rocks of varying composition (Donnelly 1966). Soils are generally very rocky, shallow (<50 cm), and well-drained, with moderate to low permeabilities (SCS 1970). Elevations range up to 387 m, and over 80% of the island has slopes in excess of 30% (Anderson 1994).

The climate of St. John places it in the dry tropics (Murphy and Lugo 1986). At Cruz Bay on the western end of the island, potential evapotranspiration (PET) exceeds precipitation for every month except September, October, and November (Figure 2). Most rain occurs as short showers that generate little runoff; rainfall events in excess of 2.5 cm / day occur less than ten times per year (Cosner 1972). Infrequent tropical depressions can generate much larger rainfalls, and the storm of record in April 1983 dropped 40 cm of rainfall in 18 h.

The limited precipitation, thin soils, past and present grazing, and easterly tradewinds result in a xeric thorn-and-cactus vegetation on the eastern end of St. John. This grades into dry evergreen scrub and woodlands, which together cover over half of the island. Moist evergreen forests occupy another 17%, mostly at the higher elevations where rainfall is more abundant (Woodbury and Weaver 1987).

The overall deficit of rainfall relative to PET means that there are no perennial streams on St. John. Annual groundwater recharge has been estimated to be only 3–8 cm / yr, and groundwater resources are limited to the narrow alluvial valleys, scattered sand deposits, and fractured volcanic rock (Cosner 1972). Infiltration rates generally exceed precipitation intensity, and field observations provided little evidence for Horton overland flow except in the more sparsely vegetated areas on the eastern end of St. John.

Until the paired-catchment study, the only runoff data were from 1979–1989 for the 1.7-km^2 Guinea Gut catchment. Over the 10 years of record, peak discharge exceeded 1.0 cm / h only five times, with the April 1983 storm generating a uniquely high peak flow of 5.5 cm / h (Table 1). For most storm events the calculated runoff coefficients and peak flows per unit area are consistent with saturation overland flow as the dominant runoff

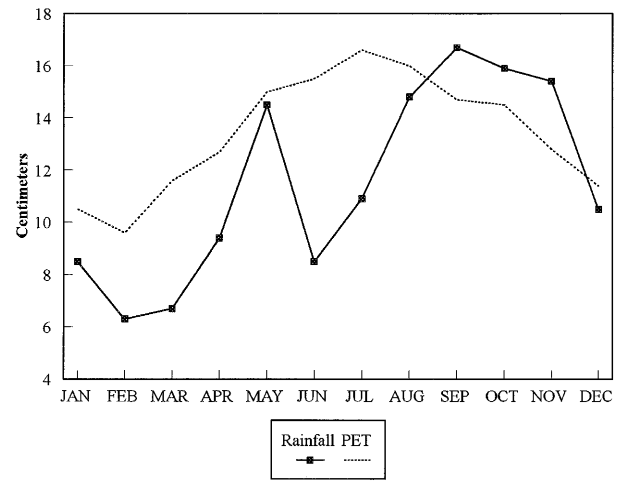

Figure 2. Average monthly precipitation and potential evapotranspiration (PET) at Cruz Bay, St. John (unpublished data from H. Mount, US Natural Resources Conservation Service, St. Thomas, 1993).

mechanism (Dunne 1978). During the largest storms, however, a relatively high proportion of the catchment is contributing runoff (Table 1), and it is likely that much of the catchment can become saturated. Rainsplash, sheetwash, rilling, and gullying generally did not appear to be important erosion processes in undisturbed areas, as the soils are usually protected by rock armoring and a dense vegetative cover.

The geomorphic importance of landslides and other rapid mass movements is uncertain. Aerial photos from 1954 and 1990 showed only one landslide, and this was where a main road had undercut the toe of a steep slope. Our field inspection of steep convergent areas did not reveal other scars, and debris flow deposits were largely absent in colluvial hollows and other susceptible locations. On this basis we concluded that, in the absence of human disturbance, the primary erosion processes over most of St. John are rockfall, soil creep, and biogenic processes such as treethrow. The predominance of these processes limited the usefulness of our efforts to predict erosion rates and map soil erodibility according to the Revised Universal Soil Loss Equation (RUSLE) (Renard and others 1991) or a topographic analysis of slope stability (e.g., Montgomery and Dietrich 1994a).

Long-Term Estimates of Sediment Yield

To evaluate the increase in soil erosion due to anthropogenic activities, we first had to estimate average annual erosion rates under undisturbed conditions. Because the short duration of the project precluded direct measurements, two independent approaches were

Table 1. Characteristics of largest runoff events from 1979 to 1989, Guinea Gut, St. John

Event date	Total precipitation	Peak 1-h intensity (cm/hr)	Est. 24-h precip. recurrence interval (years)	Peak discharge (cm/h)	Ratio of peak discharge to peak 1-h precipitation intensity
17–18 April 1983	38.9	10.2	>100	5.5	0.54
27 November 1987	8.9	5.6	>1	1.6	0.29
17–18 September 1989	23.9	6.9	50	1.2	0.17
17–18 May 1986	8.1	3.6	1	1.2	0.33
24 September 1989	10.4	5.6	2	1.1	0.20
9 September 1988	16.5	5.6	9	1.1	0.20
4 November 1983	22.1	7.9	25	0.8	0.10

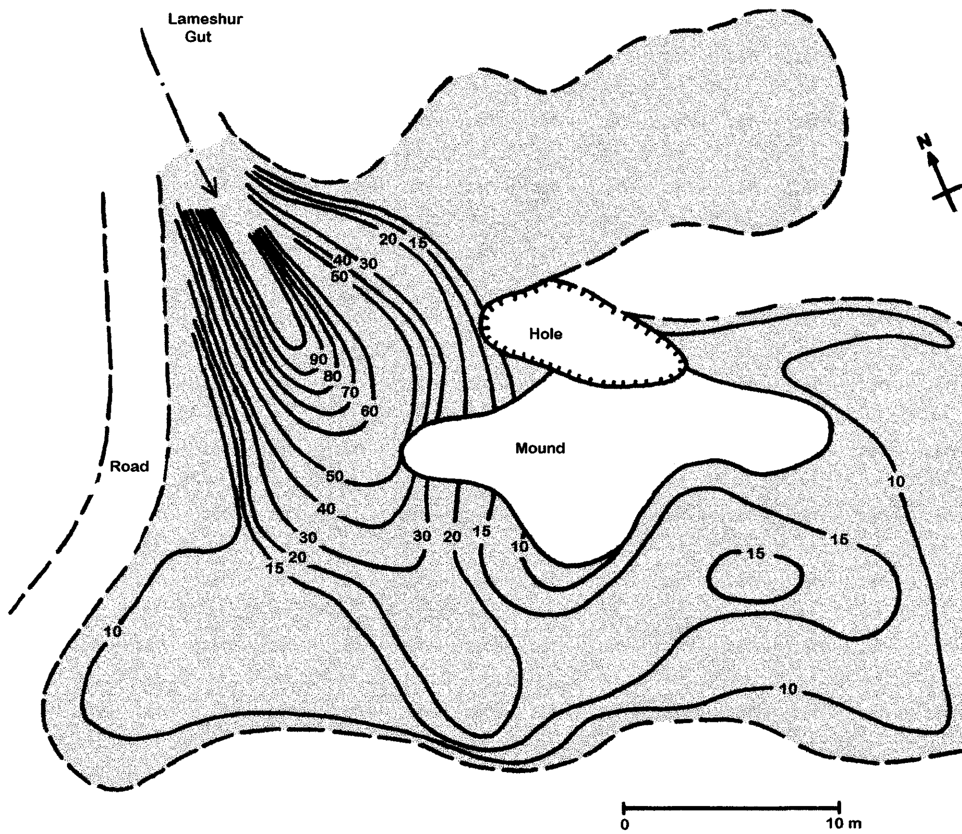

Figure 3. Contour map of sediment depth in the Lameshur Gut detention basin in January 1994. Shaded area represents area of sediment deposition; sediment depth contours are in centimeters.

used to estimate average annual sediment yields over different time periods.

The first sediment yield estimate was derived from a 0.1-ha sediment pond constructed on Lameshur Bay Gut in the 1950s (Figure 3). The volume of accumulated sediment was estimated by digging 76 holes and developing isodepositional lines (Anderson 1994). By assuming an average density of 1500 kg/m^3 for the estimated 200 m^3 of sediment, an average annual sediment yield of 7–10 t/km^2/yr was obtained. We then made the conservative assumption that an equal amount of fine material had washed through the pond, even though our sampling showed considerable accumulation of coarse silt and fine sand.

A cruder but longer-term estimate was derived from the estimated volume of sediment deposits in Reef Bay on the south side of St. John. The data and figures presented in Nichols and Brush (1988) were used to estimate the volume of fine material deposited in the mangrove swamps since 1170 BP. Because the mangroves are subject to both fluvial and marine sediment transport, we conservatively assumed that only 25% of the fluvial sediment yield had been captured in the mangroves (Wolanski 1995). On this basis the average annual sediment yield from the 4.7-km^2 Reef Bay catchment was estimated to be no more than 40 $t/km^2/yr$. It should be noted that this value includes the period of plantation agriculture, when sedimentation was presumably accelerated. Unfortunately, the dating of individual sediment layers was precluded by bioturbation (Nichols and Brush 1988).

These two estimates, when combined with our field observations, indicate that natural sediment yields are probably around 20, and no more than 40, $t/km^2/yr$. There is little reason to believe that these sediment yields are substantially less than the amount of material delivered to the stream channels under undisturbed conditions. Channels are generally steep and confined, resulting in few locations where substantial sediment storage can occur. We saw little evidence of channel aggradation or deposition except in the narrow alluvial fans on the larger guts; indeed, the major channels showed signs of extremely large flows that had moved small boulders and damaged tree trunks 1 m or more above the bed of the channels. This suggests that nearly all of the fine material that reaches the channels is periodically flushed to the mouths of the various guts.

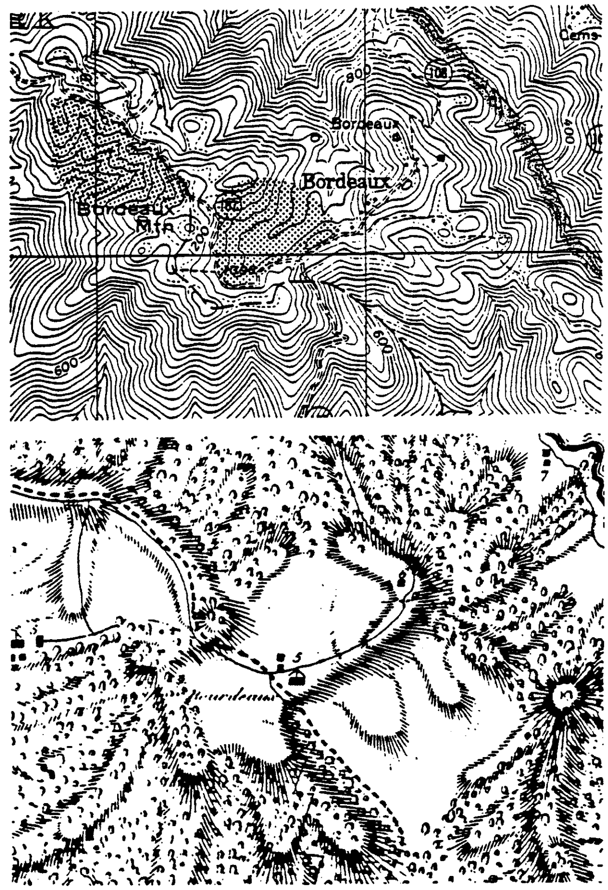

Figure 4. Top: The Bordeaux Mountain region as shown on the 1982 USGS 1:24,000 Western St. John, VI, quandrangle. Stippled areas were investigated for evidence of plantation-era gullying and colluvial fill incision. Bottom: The same region from Oxholm's (1800) map. The white areas are less steep and were cleared for cultivation. The steeper areas, although almost certainly exploited for timber and fuel, are shown as retaining their forest cover.

Evaluation of Historic Erosion Rates

An evaluation of historic erosion rates was also necessary to put our current erosion estimates in context. Prior to European colonization, St. John was used at least periodically by the Arawak Indians and possibly by other native peoples. Although some food crops were cultivated, the small population and limited water resources suggest that the natural vegetation was not extensively modified. Europeans ''discovered'' St. John in 1493 and probably logged some trees for shipbuilding, fuel, or other purposes (Larsen 1986, Woodbury and Weaver 1987), but the level of exploitation was unlikely to have substantially altered the vegetation cover or erosion rates.

European settlement began in earnest after Denmark seized control of St. John in 1718. Sugar cane and cotton plantations were established with the help of slave labor, and the protected Coral Bay anchorage on the eastern end of the island was heavily used (Tyson 1987). Nevertheless, a detailed topographic and land-use map compiled in 1780 indicates that only 35%–40% of the island was completely cleared, with cultivation concentrated in the flatter areas in the central part of the island and along the coast (Oxholm 1800). Both this map and historic drawings suggest that the forests on the steeper slopes, although undoubtedly exploited for charcoal, lumber, and fuelwood, were not systematically cleared for plantation agriculture (Figure 4).

Commercial agriculture began to decline in the late 1700s due to hurricanes, droughts, and more favorable farming conditions on nearby islands. The area under cultivation dropped by half between 1800 and 1850, and declined by half again in the two decades after emanicipation of the slaves in 1848. The last sugar plantation ceased operations by 1919, and the population of St. John remained at about 800 inhabitants from 1900 to

1950. During this so-called subsistence period, there were only donkey trails linking the scattered settlements, and primary production was limited to home gardens, limited grazing, and artisanal charcoal making (Low and Valls 1985).

A variety of evidence leads us to conclude that European settlement from 1493 to the middle of the 20th century did not result in a massive increase in erosion and sediment yields. Historic sources never mention plows or roads suitable for wheeled vehicles. Rocks or bedrock typically cover 25% to more than 75% of the soil surface; written accounts from as early as 1734 suggest that this armoring is characteristic of St. John rather than the result of extensive erosion (Low and Valls 1985).

The rock cover and thin soils would have necessitated planting by hand, and the steep terrain precluded the establishment of any road network except to cart cane from the fields to the mills and to facilitate commerce around the small settlements at Coral Bay and Cruz Bay. Both our field investigations and historic accounts indicate that agricultural terracing was limited in scope. Relatively little sediment accumulation was observed behind the occasional low rock walls. This suggests low natural erosion rates and means that the breaking down of rock walls and terraces cannot be used to justify a large post-plantation increase in erosion rates.

Other geomorphic evidence further supported our qualitative estimates of plantation-derived erosion. Upland swales subjected to plantation agriculture showed no evidence of aggradation and subsequent erosion of colluvial fill (Figure 4). On the other hand, the narrow alluvial fans near the mouths of the major guts did indicate a sequence of aggradation and subsequent incision. Buried pottery shards, donkey teeth, and other artifacts showed that 30–120 cm of aggradation had occurred along Guinea Gut, Fish Bay Gut, and Lameshur Bay Gut as a result of plantation-era agriculture. Subsequent incision indicates a more recent reduction in sediment supply. Since the area for sediment accumulation in the steep narrow valleys is so limited, the relatively thin alluvial deposits suggest that the total volume of plantation-derived sediment must be relatively small.

Hubbard and others (1987) found no evidence for a decrease in coral growth rates during or shortly after the plantation period. Given the sensitivity of corals to sedimentation, this also supports our view that plantation agriculture did not dramatically increase sediment yields. Nichols and Brush's (1988) study of sediments in Reef Bay also concluded that "despite man's historical use of the watershed at Reef Bay and possible mismanagement, the findings indicate no massive sedimentation effect" (p. 21). In summary, there is evidence for increased erosion and sediment yields on St. John due to plantation agriculture, but the data do not support claims for large-scale erosion removing much of the soil mantle.

Evaluation of Present-Day Erosion Sources and Rates

Rejuvenation of the St. John economy began with the slow development of tourism in the mid-20th century. As late as 1950 there was only one truck, two jeeps, and one bulldozer on the island. Boats were the primary form of transport (Low and Valls 1985).

Designation of over half of St. John as a National Park in 1956 undoubtedly helped spur the development of tourism, and the pace of development picked up substantially in the 1960s. The permanent population of St. John is still only about 4000, but VINP receives approximately a million visitors each year. The growing recreational use of St. John is creating a strong demand for short-term accommodations, second homes, a more extensive road network, and the overall infrastructure necessary to support high levels of tourism. We believe that these changes in land use are the primary cause of accelerated erosion and sediment delivery rates, particularly since there is very little primary industry on St. John.

Agriculture is a minor component of the St. John economy, as virtually all food—including fruits and vegetables—is imported. Only about 2% of St. John is used for grazing (Woodbury and Weaver 1987), although feral pigs, goats, and donkeys are adversely affecting the vegetation, particularly on the drier eastern end of the island. The effect of these animals on runoff and soil erosion is difficult to quantify because of the lack of data from both grazed and undisturbed sites. Anderson (1994) believed that the impact of feral animals on sedimentation rates was relatively small, but the continuing increase in feral populations may be developing into a serious land-management problem. Wood-cutting and charcoal-making, like agriculture, have been largely discontinued.

The only primary industry that appears to have a substantial effect on sediment yields is a rock-crushing operation in the west-central part of the island. Although an estimate of sediment inputs is not available, the channel draining this site is clogged with small gravel and fine sand for over 100 m downstream.

In summary, urban land uses and the road network are probably the primary sources of sediment. Woodbury and Weaver (1987) classified 2.6% of the island as urban areas; this proportion is undoubtedly greater today. Although ''urban area'' can include grassed yards or other areas with low erosion potential, we observed large amounts of sediment and runoff originating from parking lots and unpaved roads during even moderate rainstorms (<1 cm). Many of the unpaved roads were deeply rutted, and frequent regrading is needed to keep some of the steeper sections passable. In contrast, we saw little evidence for much runoff from home construction sites, and most of the sediment that was generated from these locations appeared to be rapidly trapped on the vegetated hillslopes.

From these observations and land-use data, we hypothesized that unpaved roads and parking areas were the dominant source of sediment. This hypothesis is consistent with other studies that have identified roads as the largest sediment source in rural and forested areas (e.g., Haupt 1959, Hafley 1975, Ward 1985, Froehlich 1991). We also noted that the network of unpaved roads on St. John is rapidly expanding with increasing tourism and home building. The road network in the Fish Bay catchment, for example, has tripled since 1982, and this was due almost entirely to the construction of private homes. These homes are typically constructed on ridgetop sites that have picturesque views and greater exposure to the cooling trade winds. Such sites typically require long access roads across steep terrain, and previous land-use regulations did not require these access roads to be paved. More recent developments are supposed to pave their roads prior to selling any lots, but a network of unpaved roads is necessary to provide access to prospective buyers, and our observations suggest that it may be several years before paving takes place.

The importance of unpaved roads as a primary sediment source was illustrated by a series of field observations. For example, the unpaved Bordeaux Mountain road is deeply rilled, and each of the first-order channels that receive road drainage is clogged with fine sediment below the road. Similar accumulations of fine sediment were observed in other first-order channels that receive substantial runoff from unpaved roads. At one new development nearly 10 m^3 of sediment had been trapped behind the required silt fence in only four or five months. Since the contributing road surface area—including cut banks—was only 460 m^2, this was equivalent to 2 cm of surface erosion in a period when precipitation was only 62% of the long-term average.

Such observations, when combined with the literature on road erosion, led us to focus our remaining efforts on developing a procedure for: (1) predicting road erosion on St. John, (2) estimating the total erosion from unpaved roads, and (3) predicting the delivery of this material to the marine environment. By comparing predicted sediment yields with historic values, we could then estimate the relative importance of road surface erosion in selected catchments.

Predicting Road Erosion

Other research has identified the factors that generally control the rate of road erosion, and these include road gradient (e.g., Burroughs and King 1989), road use (e.g., Reid and Dunne 1984, Coker and others 1993), distance between drainage points (e.g., Packer 1967), road surface characteristics (e.g., Burroughs and King 1985, Bilby and others 1989), slope position and sideslope gradient (e.g., Packer 1967), time since construction or grading (e.g., Campbell and Stednick 1983, Megahan 1984), and rainfall amounts and intensities (e.g., Megahan and others 1991). The short duration of our fieldwork and relative paucity of runoff events precluded direct measurements of precipitation, runoff, and sediment loss from selected road segments.

The obvious surface rutting led us to focus on road surface erosion, and the total amount of road surface erosion was measured by laying a straight edge across the current road surface. The vertical distance to the current road surface was measured at a series of points to determine the cross-sectional area that had been removed through erosion. This value was then converted to cubic meters of material removed per meter of road length. The age of the road or time since grading was determined by the date of permits or questioning local residents. A total of 26 measurements were made at locations chosen to represent a wide range of gradients and upslope contributing areas.

These measurements implicitly assumed that the original road surface was planar—an assumption that was verified by our observations of newly constructed and graded roads. These measurements also presumed that the ''missing'' cross-sectional area was eroded rather than compacted, and our field observations indicated that most ruts had eroded to a base level controlled by the presence of cobbles or bedrock. The measurements were conservative in that the road edge and middle berm were assumed to have experienced no erosion and therefore represented the original road surface. Since we could not make these road surface erosion measurements at sufficiently small intervals to directly calculate the erosion from each road segment, we had to identify those variables that could be readily measured in the field and used to predict road surface erosion.

We focused on gradient and contributing area, as

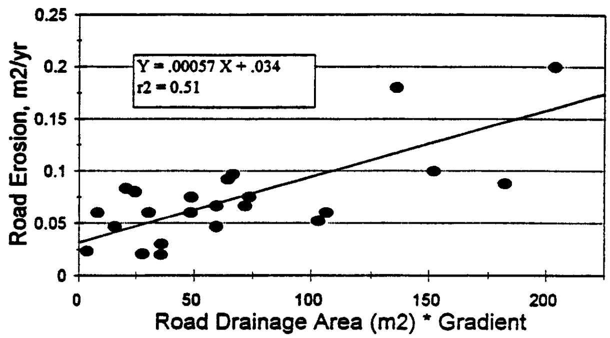

Figure 5. Measured road surface erosion versus the product of road gradient and drainage area. Standard error of the regression is 0.031 m^2/yr.

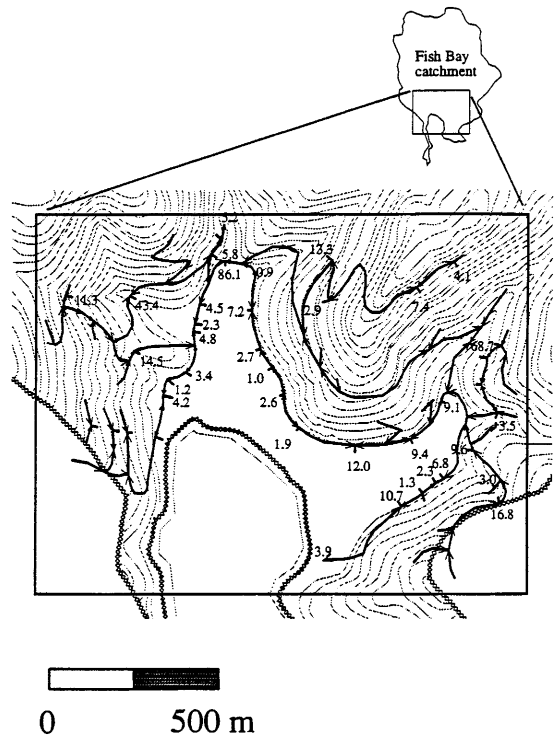

Figure 6. Predicted road sediment delivery in cubic meters per year for the lower Fish Bay catchment. Roads in the lower left are paved and therefore have a predicted sediment delivery of zero.

recent studies on runoff, soil erosion, and channel initiation have emphasized the importance of these two factors in determining shear stress and the energy available for sediment transport (e.g., Moore and Wilson 1992, 1994, Montgomery and Dietrich 1994b). Sideslope gradient was not considered because this is more important for cut bank and fill slope erosion than road surface erosion. Similarly, topographic position and location relative to stream courses are important for predicting sediment delivery and therefore needed to be assessed, but these would not control road surface erosion per se.

We therefore field mapped all road segments, including private driveways, in both the Fish Bay and Lameshur Bay catchments. Discrete road segments were defined by a consistent width and gradient and the absence of any road junctions or diversions of surface runoff (e.g., into a ditch or culvert). Contributing area was determined by multiplying road segment length by average width and accounting for the accumulation and loss of runoff through the road network. Because all the unpaved roads on St. John were constructed from native fill, we simply classified each road as paved or unpaved. Each discharge location for road surface runoff was mapped and classified as a stream channel, protected hillslope (vegetated with no sign of incision), or unprotected hillslope (little or no protective vegetative cover and/or signs of incision).

Nine kilometers of unpaved and 7 km of paved roads were mapped in the 6.1-km^2 Fish Bay catchment. Twenty-three measurements of road surface erosion were made, and the resulting predictive equation was:

$$E = 0.00057A * S + 0.034 \quad (1)$$

where E is the cross-sectional road erosion in cubic meters per meter of road length per year (this reduces to square meters per year in Figure 5), A is the upslope road drainage area in square meters, and S is the segment gradient as a decimal (Figure 5). This equation explained 51% of the variability in road surface erosion and was significant at $P = 0.0001$.

We incorporated equation 1 into a GIS-based road surface erosion model (ROADMOD) (Anderson and MacDonald 1997). The value of ROADMOD is that it automates the prediction of road surface erosion and sediment delivery from a digitized road network. Thus the basic input for ROADMOD is an ASCII file, exported from a GIS, that lists road segments and segment characteristics. Culverts and other discharge locations are a special type of road segment. Required segment attributes include a unique segment identification number; connections to and from other road segments; segment length, width, and gradient; road surface (paved or unpaved); whether the segment is a discharge location; and a factor to proportionalize flow if flow is split between downstream segments. The output from ROADMOD is an ASCII file that may be reimported to Arc/Info GIS to display the model results.

Application of ROADMOD to the 16 km of roads in Fish Bay yielded a total road surface erosion rate of 390 m^3/yr. By conservatively assuming a sediment density of 1500 kg/m^3, this converts to nearly 600 t/yr. The predicted amounts of road surface erosion delivered to each discharge location in the lower Fish Bay catchment are shown in Figure 6.

In contrast, the estimated road surface erosion from the 1.4 km of roads in the Lameshur Bay catchment is only 65 m^3 or approximately 100 t/yr. This value was derived from the application of ROADMOD and equation 1, and the predicted sediment loads at each discharge location are shown in Figure 7. However, the actual road surface erosion rate may be several times the predicted value due to the relatively frequent regrading of the main access road to Lameshur Bay (e.g., Megahan 1984). Our three measurements from the Lameshur Road—taken approximately eight months after grading—and two data points from new roads all plotted above the regression line shown in Figure 5. This suggests that road age, at least for the first year after construction or grading, has a nonlinear effect on road surface erosion rates.

Sediment Delivery

From a management perspective, the key issue is the amount of sediment that reaches the coast and could adversely affect the coral reefs, beaches, and other marine resources. Determining sediment delivery is difficult (e.g., Walling 1983), but predicting sediment delivery to the mouth of the guts is greatly simplified in this case by several factors. First, the roads are constructed and graded with native soil rather than gravel. Although samples were not collected from the surface of recently constructed or regraded roads, visual inspection indicates that the fraction of coarse material (>2 mm) is quite low. Abundant coarse material was found only on the steepest and more eroded road segments.

Second, the stream channels on St. John are short and steep. We saw very little accumulation of fines in the downstream areas within the major guts. Pebble counts in Fish Bay and Lameshur Guts yielded a D_{50} of 80 and 40 mm, and a D_{16} of 10 and 4 mm, respectively (Figure 8). Neither bed showed much evidence of regular scour and fill or much capacity for storing fine sediment (Anderson 1994). A finer bed surface was observed in Battery Gut, which is affected by both road erosion and the rock-crushing operation (Figure 8). Excess fines were also observed in first-order channels subject to runoff from unpaved roads.

The third factor is the occurrence of relatively large flow events as indicated by geomorphic evidence and the peak flow data in Table 1. The latter shows that the median annual flow is approximately 3 m^3/km^2 and the maximum recorded flow is 45 m^3/km^2. Most channels have abraded trees and other signs of high flows, and

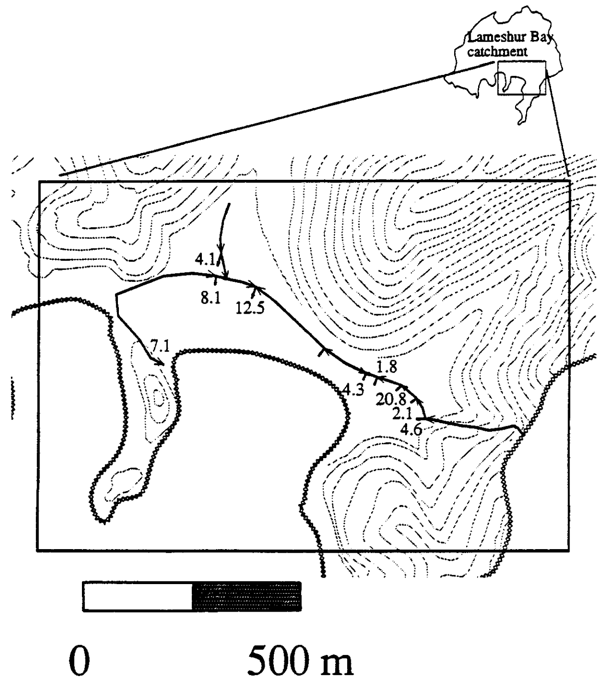

Figure 7. Predicted road sediment delivery in cubic meters per year for the lower Lameshur Bay catchment.

particles of up to 30 cm in diameter were observed in the sediment pond on Lameshur Gut and the alluvial fan at the mouth of the next channel to the east.

We therefore infer that the road-derived sediment is generally washed through the lower portions of the major guts during the larger storm events. The lower-order channels that receive substantial amounts of road runoff are already filled with fine sediment. The lack of additional sediment storage capacity means that additional inputs will generally be transmitted downstream in accordance with the available sediment transport capacity.

This logic led us to assume a sediment delivery ratio of 1.0 for stream channels, 0.0 for densely vegetated hillslopes (Campbell and Stednick 1983; Burroughs and King 1989), and 0.5 for poorly vegetated hillslopes and mangrove swamps. While this last value carries greater uncertainty than the other two, the limited number of such discharge locations makes the results—at least for Fish Bay—relatively insensitive to the assumed delivery ratio.

The use of these coefficients in ROADMOD led to an estimated sediment delivery to Fish Bay of more than 60 $t/km^2/yr$. Dropping the assumed sediment delivery ratio for unprotected hillslopes to zero reduced the predicted sediment yield by less than 10%. If the undisturbed sediment yield is approximately 20 $t/km^2/yr$, road surface erosion is at least quadrupling sediment yields in the Fish Bay catchment.

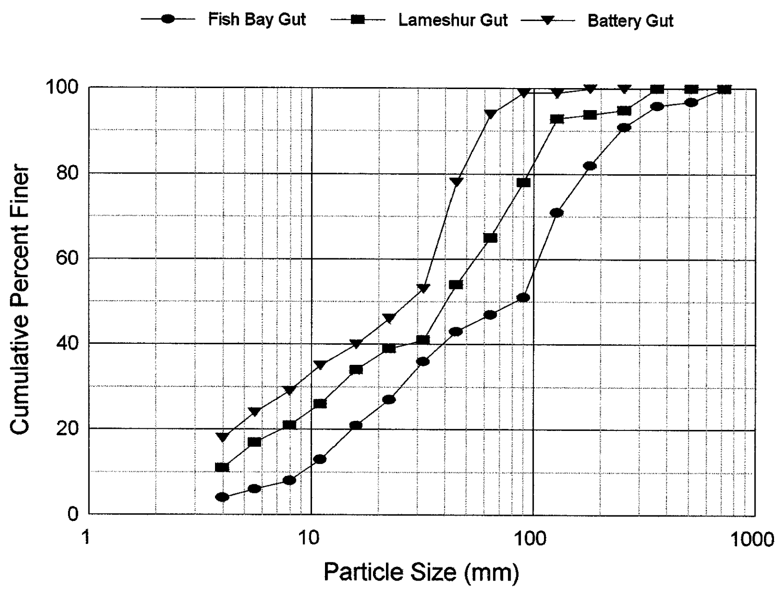

Figure 8. Particle-size distributions for the surface of Fish Bay Gut, Lameshur Bay Gut, and Battery Gut.

In the case of Lameshur Bay, ROADMOD predicts that about 50 t or half of the annual road surface erosion is delivered to the bay. This represents an increase of approximately 40% over undisturbed conditions, despite the very low road density of 0.3 km/km^2.

Assumptions and Validation of ROADMOD

These estimated erosion and sediment delivery rates involve a number of assumptions, but overall we believe our values are conservative. ROADMOD only accounts for road surface erosion, but field observations indicate that erosion also occurs from cut banks, roadside ditches, unprotected culvert outlets, and sidecast areas. Equation 1 also has a conservative bias because precipitation from 1990 to 1993 was only 87% of normal and relatively free of hurricanes or other major storm events. Thus the measured road surface erosion rates are probably low relative to historic averages.

The results from ROADMOD are also conservative because the data used to develop the basic predictive equation were all obtained from road segments that were one to three years old. Both the literature (e.g., Megahan 1984) and our observations suggest that road erosion rates are likely to be at least several times higher immediately after construction or regrading. Since we did not have the high-resolution temporal data to quantify this effect, the values predicted from ROADMOD will almost certainly be too low for new roads or road segments that are regraded every year.

On the other hand, ROADMOD assumes that sediment storage within the road network is negligible, and this is generally consistent with our field observations. Our measurements also may have been biased by a tendency to measure road surface erosion where the surface exhibited rilling and appeared to convey most of the road runoff. Road surface erosion may therefore be overpredicted for those segments where roadside ditches collect and convey the bulk of the runoff. The extent of this overprediction will depend upon the relative erosion rate in ditches versus the road surface, and this is an important point for future investigations.

Like any physical model, the validation of ROADMOD is a difficult, if not impossible, task (e.g., Grayson and others 1992). Erosion and sediment delivery rates will vary by storm, road segment, and use. A much more intensive campaign of field data collection is being initiated to evaluate some of these factors.

A comparison of sediment yields from Fish Bay and Lameshur Bay Guts cannot be used to validate ROADMOD because such measurements integrate all upstream erosion and sediment delivery processes. An even greater limitation is the fact that 88% of the estimated sediment yield from roads in the Fish Bay basin is predicted to be delivered downstream of the now-defunct USGS gauging station.

Some support for our model results can be drawn from the monthly turbidity data collected by the NPS at various locations around St. John (Figure 9). Three of the monitoring stations are in Lameshur Bay and one is in Fish Bay. Both median and maximum turbidity levels in Fish Bay are considerably higher than each of the Lameshur Bay stations, and a Wilcoxon rank-sum test confirmed that these differences are highly significant

($P < 0.001$). Although these turbidity values are influenced by other factors besides catchment-supplied sediment, these data are consistent with local newspaper reports of bays turning brown after storms and suggest that more fine sediment is being delivered to Fish Bay.

Compendium of Erosion Rates over Time and Recommendations

A plot of estimated island-wide sediment yields over time is shown in Figure 10. While the absolute values could easily be off by a factor of two, post-1950 development has substantially increased sediment yields relative to the earlier peak during the plantation period. Again the estimate of anthropogenic erosion is believed to be conservative, as it considers only the predicted road surface erosion from the approximately 50 km of unpaved roads on St. John; including other anthropogenic sources would further increase the estimated present-day sediment yields. The implication of Figure 10 is that downstream areas have been subject to a several-fold increase in sediment yields since about 1950, and sediment yields will increase with the continuing development on St. John.

Given the economic importance of tourism, the mandate of Virgin Islands National Park to preserve and protect those resources that led to its creation, and the susceptibility of marine ecosystems to fine sediment, it would be prudent to immediately institute more stringent erosion control measures. Sediment control plans are already required for new developments and construction sites, and these typically rely on silt fences as the primary control measure. The problem is that silt fences are effective only if they are properly installed and maintained until the captured sediment is either removed or fully stabilized. Regulations for paving new roads have been strengthened, but the typically long lag between construction and paving undermines the effectiveness of these provisions. Existing unpaved roads are generally not subject to regulation.

As a first step, the unpaved road network and the rock-crushing operation should be the focus of sediment control efforts. Unpaved roads and parking lots should either be paved or restored to natural contours and revegetated. As an interim step, waterbars can be immediately installed to prevent the excessive accumulation of surface runoff. Erosion from cut banks and sidecast areas must be minimized; on steep slopes the material excavated for new roads should be end-hauled and stabilized. Energy dissipators should be required on all outlet structures, and road designs should minimize the increase in discharge at all drainage points. Either

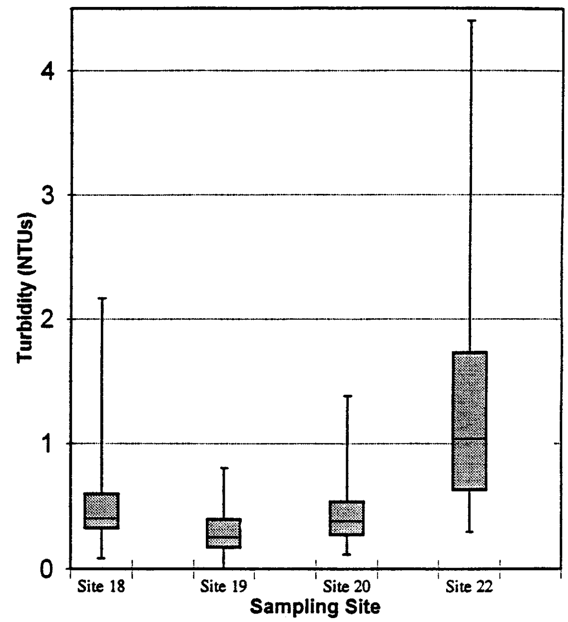

Figure 9. Boxplots of monthly turbidity data from January 1988 to April 1993 for Lameshur Bay (sites 18, 19, and 20) and Fish Bay. N = 50 for sites 19–21 and N = 51 at site 18.

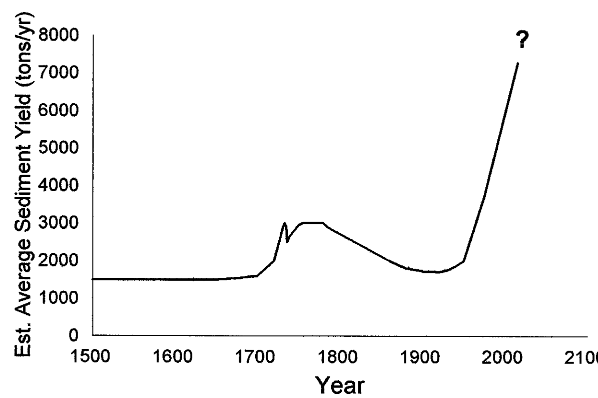

Figure 10. Annual estimated island-wide sediment delivery to the mangrove swamps, salt ponds, or shore of St. John over time.

sediment control berms or settling ponds should be established at the existing rock-crushing plant.

More detailed studies are needed to quantify the unmeasured components of road-related erosion, quantify the change in erosion rates over time, evaluate other controlling factors, and improve our understanding of sediment delivery. A better understanding of erosion and delivery processes is necessary to maximize the cost-effectiveness of sediment control measures and to facilitate the extrapolation of these results to other areas.

Conclusions

Unpaved roads are the largest source of fine sediment on St. John, and current rates of sediment yield are several times higher than at any point in the past. A vector-based road erosion model was developed to estimate sediment yields and identify those road segments and discharge locations of greatest concern.

St. John's forested hillslopes, clear offshore waters, white sand beaches, and diverse ecosystems all contribute to the island's image as a tropical paradise. However, the rapid development since 1950 represents a direct threat to those resources that stimulated this development. Sufficient information is available to greatly reduce present sediment loads, and control measures must be immediately implemented if the unique natural resources of St. John are to be protected over both the short and the long term.

Acknowledgments

This study was conducted with financial support from the NPS Water Resources Division under Cooperative Agreement 1443CA00192025 and Virgin Islands National Park. The Island Resources Foundation greatly facilitated our study by providing a field vehicle and access to their extensive library. Dr. Caroline Rogers provided much of the impetus to the study and was a key source of local knowledge. The USGS generously provided sediment data from their gauging stations on St. John. Numerous other individuals and agencies provided information and assistance, and we would specifically like to thank the staff of the Island Resources Foundation, National Biological Survey, NPS, USGS, VINP, and the Virgin Islands Department of Planning and Natural Resources. Rob Sampson graciously revised several of the figures.

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