ANALYSIS AND MODELING OF EROSION HAZARDS AND SEDIMENT DELIVERY ON ST. JOHN, U.S. VIRGIN ISLANDS

Donald M. Anderson

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M.S. THESIS

ANALYSIS AND MODELING OF EROSION HAZARDS AND SEDIMENT DELIVERY ON ST. JOHN, U.S. VIRGIN ISLANDS

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Fall 1994

Technical Report NPS/NRWRD/NRTR-94/34

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DONALD M. ANDERSON ENTITLED ANALYSIS AND MODELING OF EROSION HAZARDS AND SEDIMENT DELIVERY ON ST. JOHN, U.S. VIRGIN ISLANDS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

ANALYSIS AND MODELING
OF EROSION HAZARDS AND SEDIMENT DELIVERY
ON ST. JOHN, U.S. VIRGIN ISLANDS

More than half of St. John island and much of its offshore area is managed as Virgin Islands National Park by the U.S. National Park Service. St. John is a popular tourist destination because of its white sand beaches, coral reefs, and relatively undisturbed tropical forests. Increasing development on St. John has raised concerns that soil erosion and sediment delivery to the marine environment has accelerated. Since coral reefs are particularly sensitive to turbidity and fine sediment, this may be damaging the marine resources that were a primary reason for the establishment of the Park.

This study was undertaken on behalf of the U.S. Park Service to assess existing and potential erosion threats on St. John. The primary objectives were: (1) to identify and map areas of low, medium, and high erosion susceptibility; (2) to predict rates of sediment delivery to the marine environment; and (3) to recommend practices to minimize or reduce sediment delivery to the marine environment.

Historic rates of sediment delivery on the island were estimated by investigating sediment accumulation in depositional areas and erosional characteristics of upland areas. Present-day erosion and sediment delivery processes were assessed

by investigating land use activities, erosional evidence associated with these land uses, and particle characteristics of several major streambeds.

Two models were used to identify and map erosion hazard areas on St. John. First, an automated model (ROADMOD) was developed to predict average annual erosion and sediment delivery from unpaved road networks. Second, spatially-distributed data on soils and topography were interfaced with the Revised Universal Soil Loss Equation (RUSLE) to predict areas with greatest potential for surface erosion following removal of protecting cover vegetation.

Both RUSLE and ROADMOD were implemented using a geographic information system (GIS). In the case of RUSLE, a raster-based modeling approach was used. The slope-length (*L*) factor for RUSLE was derived from a three-dimensional analysis of terrain characteristics. In the case of ROADMOD, the model was interfaced with vector-formatted GIS data including road widths, lengths, surface character, gradient, and discharge locations. ROADMOD was applied to two test watersheds on St. John. Park Service turbidity measurements in the receiving bays are consistent with model predictions.

Field measurements indicate that the average natural sediment yield on St. John is on the order of 20 tonnes per km^2 per year. Field data and model predictions lead to the conclusion that present-day production and delivery of fine sediment on the island is dominated by erosion from unpaved road surfaces, and that roads probably increase sediment production rates two to ten times.

Eleven sediment control practices are recommended on St. John. Principle among these are: (1) wherever possible, no new roads should be constructed; (2) unnecessary roads should be eliminated; and (3) unpaved road surfaces should be paved.

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Fall 1994

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A project of this magnitude can be completed only with support from many individuals. To name all of the people who helped bring this project to fruition would require far more space than I have at my disposal. Therefore my thanks must first go to those not identified here who were essential in helping this project progress along a sometimes tortuous path. You know who you are.

I am indebted to the U.S. National Park Service for their financial support of this study. A heartfelt thanks goes to Trish Patterson of the Southeast Regional Office for cutting through bureaucracy, supplying valuable data, and generally helping me get a running start on this project; to Dr. Caroline Rogers and her associates at Virgin Islands National Park for making our visit to the island comfortable, educational and productive; and to Drs. Dean Tucker and Bill Jackson of the Water Resources Division for providing support of all kinds, including timely and friendly project guidance.

Dr. Lee MacDonald's constant encouragement, helpful advice, and boundless enthusiasm made this project a rewarding and highly educational experience. I also appreciate the input of the other professors on my graduate committee, Dr. John Stednick and Dr. Jose D. Salas. I am extremely grateful to Dr. William Dietrich of the University of California/Berkeley for providing invaluable field assistance on St. John, not to mention hours of free entertainment and several promising concepts for motion picture screenplays.

Many thanks to Dr. Ed Towle and Sandra Tate of the Island Resources Foundation for providing access to their unique library and, in particular, for loaning the IRF jeep for our field work on St. John. IRF's support went well beyond the call of duty, and it proved essential to the completion of this project. A number of people at the U.S. Geological Survey also should be acknowledged for supplying key data and publications, among them GIS guru John Parks (San Juan, Puerto Rico), data-keeper Carlos Figueroa (San Juan) and research scientist Allen Gellis (Albuquerque). Friendly folks at the Virgin Islands Department of Planning and Natural Resources also supplied valuable information.

The color maps in this report were produced using equipment made available by the National Biological Survey (NBS) in Fort Collins. I am indebted to Tim Kern and Judy Hart for helping me convert raw GIS files into useful map products at NBS.

Finally, the support and encouragement given by many selfless people, including family, friends, and fellow graduate students, is gratefully acknowledged. I shall miss the wonderful *esprit de corps* that existed among the watershed science students during my sojourn at CSU. May that spirit live on.

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We need to let people know what we are trying to do, and to make it clear that the simpler we keep St. John the better it will be.

-- Noble Samuel,
native St. Johnian and
early guide at Virgin Islands National Park
(from Low and Valls, 1985)

CHAPTER 1:
INTRODUCTION

1.1 Project Background

Approximately 56% of St. John island and 23 km^2 of its offshore waters are managed as Virgin Islands National Park (VINP) by the U.S. National Park Service (Figure 1.1). VINP is renowned for its white sand beaches, clear turquoise waters, diverse marine and terrestrial ecosystems, and attractive climate. The park was designated an international biosphere reserve by Unesco in 1976, thus focusing additional scientific attention on its natural resources.

In recent years the development of privately-owned land on St. John for vacation homes and tourist-related businesses has accelerated. This study grew out of Park Service concerns that development is accelerating soil erosion and sediment delivery to the marine environment.

Coral reefs are among the greatest assets of St. John and were a primary reason for the establishment of the park. They provide recreational and educational opportunities for park visitors, protect shorelines and beaches from erosion, produce the white sands that maintain beaches, and house diverse and productive ecosystems. Also, reefs provide perhaps the largest portion of seafood harvested in the Virgin

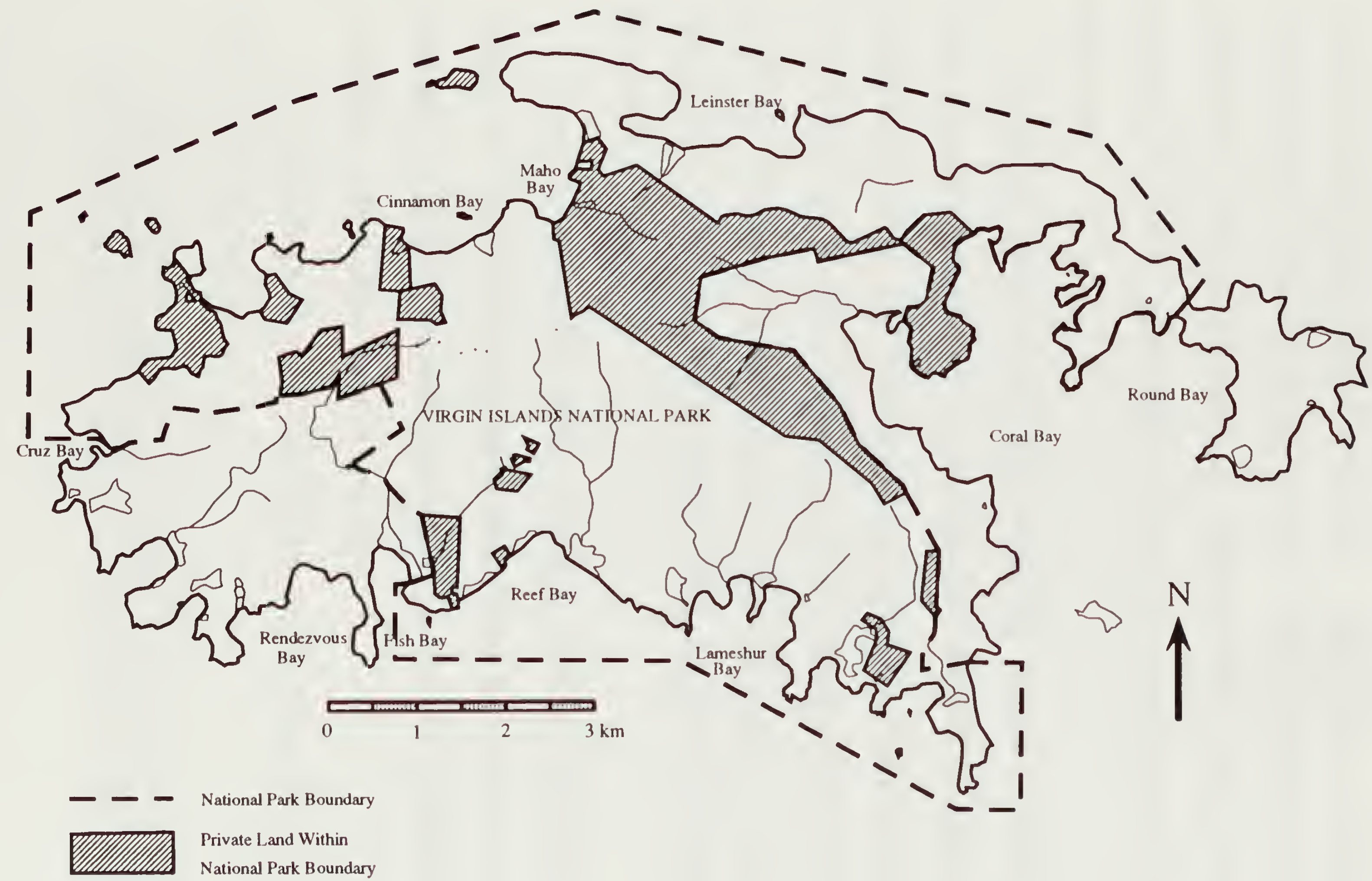

Figure 1.1. St. John Island

Islands (BC&E/CH2M Hill, 1979). However, coral reefs are particularly sensitive to turbidity and fine sediment (Rogers, 1990), and St. John's reefs are experiencing a long-term decline in growth rates (Hubbard et al., 1987). Siltation of nearshore marine habitats is a particular concern of park managers (VINP, 1987), and for this reason VINP seeks a better understanding of existing and potential erosion and sedimentation threats.

Following a visit to VINP in 1990, the National Park Service (NPS) Water Resources Division (WRD) framed a three-year project to examine the influence of watershed processes and land use on marine resources. The project described herein was undertaken as a cooperative agreement between NPS and Colorado State University (CSU), and it comprises part of this larger overall investigation. Complementary work includes a paired watershed study being coordinated by the U.S. Geological Survey (USGS).

Support for the NPS/CSU project came from the WRD, the Southeast Regional Office of NPS and Virgin Islands National Park. Where appropriate, this study has incorporated geographic information systems (GIS) as a tool for compiling, manipulating, analyzing, and mapping spatial information.

This report helps fill a critical information gap. In the words of BC&M/CH2M Hill (1979):

> "There is a definite lack of hard data related to erosion and sediment discharge in the Virgin Islands. As far as can be determined, no sediment load has ever been measured in streams flowing in the Virgin Islands. Although often

observed, a record of which guts[1] do or do not produce sediment and to what extent and under what circumstances does not exist."

A comprehensive review of research conducted since this 1979 report indicates that little additional work had been done to identify and quantify key erosion processes.

1.2 Project Objectives and Thesis Organization

The NPS is interested in identifying the nature and location of erosion hazards on St. John, determining relative rates of sediment delivery from disturbed and undisturbed watersheds, and minimizing the delivery of sediments to the offshore environment. Relative rates of sediment delivery from two watersheds are being assessed by the USGS, which has established automatic suspended sediment samplers in the Lameshur and Fish Bay guts of St. John. The NPS/CSU study described herein addresses three complementary objectives:

(1) To identify and map areas of low, medium, and high erosion susceptibility on St. John;

(2) To predict delivery rates of sediment to the marine environment; and

(3) To recommend practices which will minimize or reduce sediment delivery to the marine environment.

The first objective is addressed in Chapters 3 and 4 of this report. Chapter 3 assesses erosion and sediment delivery during the pre-Columbian and colonial

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[1] "Gut" is a local term for "stream" or "creek". It will be used throughout this report.

plantation eras. Chapter 4 evaluates modern-day erosion and sediment delivery processes on St. John.

Two erosion susceptibility models were used to achieve the second objective. First, a method was developed to interface digitized road data with a predictive model of road surface erosion, and this model was applied to two St. John watersheds. Second, data on the soils and topography of St. John were used to generate maps estimating relative susceptibility to surface erosion and potential for soil saturation and saturation-induced runoff. These two models are described in Chapters 5 and 6, respectively.

Finally, recommended sediment control practices addressing the third objective are presented in Chapter 7. These recommendations are discussed in the context of current land ownership, development trends, and regulations on St. John. Conclusions of this study are summarized in Chapter 8.

1.3 Complementary Studies

This report presents the results of the first detailed field investigation and modeling of erosion processes and rates on St. John. Ramsarran (1992) used the ANSWERS model to simulate the impact of 1971-1984 land use changes on sediment yield from the Guinea Gut watershed of St. John under various storm scenarios. He concluded that the nine percent increase in urbanized areas during this period greatly increased soil loss during large storm events. For example, he predicted that the average soil loss in the Guinea Gut watershed during a 7.7 cm storm would be about

4600 kg/ha (11%) greater in 1984 than in 1971. However, Ramsarran did not have the opportunity to field-verify his conclusions or model results.

As mentioned above, the U.S. Geological Survey has established two automated suspended sediment pump sampling stations on St. John to compare the sediment yield in a watershed affected by construction activities (Fish Bay) to a watershed in a "pristine" environment (Lameshur Bay). These stations were installed in 1992. The USGS has generously shared preliminary data from these sampling sites with the author. However, as of this writing, only two storm events have been sufficiently large to trigger stream sampling at both sites. In addition, stage/discharge relationships have yet to be established for both of these sampling sites. As a result, little can be said at this time about USGS suspended sediment sampling results vis-à-vis this study. A few remarks regarding these USGS data are included in Section 4.6.

VINP has been gathering data on marine water turbidity at numerous fixed stations around St. John on a monthly basis since 1988. An investigation into the relationship between terrigenous sediment sources and measured offshore turbidity is beyond the scope of this study; nevertheless, these data complement this investigation, and some implications of the turbidity data gathered by VINP are discussed in Chapter 5.

1.4 Erosion: Definitions and Processes

Erosion is the process by which soil and minerals are detached and transported by water, wind, gravity, ice, and human activities. Erosion is driven by gravity and

the kinetic energy of moving water or air, and by chemical and physical weathering processes (Hewlett, 1982).

Under natural conditions, erosion tends to occur at a rate determined by the approximate steady-state in hillslope soils between inputs of weathered minerals and organic material and exports of this material by surface erosion, mass movement, or decomposition. Steady-state conditions and natural rates of erosion depend on local climate, geology, vegetation, and topographic conditions (Dunne and Leopold, 1978).

Human alteration of the land surface almost always increases the rate of hillslope erosion. This increased erosion is often termed **accelerated erosion** to distinguish it from natural or "background" rates (Dunne and Leopold, 1978).

Mass wasting is erosion driven by gravity alone. It includes rock falls, landslides, debris slides, dry ravel, and soil creep. **Dry ravel** refers to surface materials rolling downslope following fire or other disturbances. **Soil creep** is the general downslope movement of the weathered soil mantle due to gravity pulling the soil under repeated cycles of wetting and drying or freezing and thawing (Hewlett, 1982). **Biogenic transport** refers to the movement of weathered material as a result of biological activity such as tree throw, root growth and animal burrowing (Dietrich et al., 1982).

Surface water erosion is erosion caused by water striking or moving over the surface of the ground, or moving in channels, rills, and gullies (Hewlett, 1982). Erosion caused by the dispersion and downhill splashing of soil particles by direct raindrop impact is termed **rainsplash erosion**. Detachment caused by an irregular

sheet of water running downslope over the land surface is termed **sheetwash erosion**. If the minute streams of water cut separate channels, this is termed **rill erosion**. **Gully erosion** refers to rills that become engraved into the land surface to depths of more than about one foot and which generally are not obliterated by cultivation (Dunne and Leopold, 1978).

In this study, both mass wasting and surface water erosion were assessed as potential sources of sediment that is subsequently delivered to the marine environment. The dominant erosional processes affecting St. John are discussed in Chapter 4.

1.5 Erosion Modeling

Field measurements provide the most reliable information on soil loss and sediment transport. However, the measurement of soil loss is an expensive and time-consuming process. Field measurements of erosion tend to be highly variable in time and space, typically requiring a minimum of 2-3 years of measurement to be useful (Lal, 1990). Moreover, it is difficult to extrapolate the results from one site to larger areas or different conditions.

Mathematical models of erosion can address this deficiency. A model serves as a simplified representation of complex processes operating on a plot, hillslope or catchment scale. If properly designed and executed, it can be used to predict the magnitude of these processes. However, since models are by definition a simplification of complex systems, they are never entirely accurate. In the words of Hewlett

and Hibbert (1967), "any effort to model a natural watershed must fail in some degree."

Models may be described in terms of their conceptual framework: i.e., **empirical** vs. **physical**. Empirical models are based on observations and measured relationships. Given a set of specified conditions, they allow predictions to be made, but they do not simulate the specific physical processes producing the predicted result. In contrast, physical models consist of equations that are intended to simulate the actual processes. As such, they tend to be more complex and require much more input data than empirical models. Physically-based models are more conceptually appealing, but it has been argued that the parameters used for catchment-scale physical models have little more inherent meaning than those of empirical models (e.g., Beven, 1989; Grayson et al., 1992).

Models may be **stochastic** or **deterministic**. Stochastic models represent processes whose outcome is expressed in terms of probability. Deterministic models represent processes using relationships with a unique correspondence between the input and the output.

Finally, watershed-scale models may be described as **lumped** or **distributed**. Lumped models use averaged parameter values for the entire basin. Distributed models allow parameter values to vary within the basin, typically at the scale of subbasins or user-defined "grid cells". Distributed models allow for a more accurate representation of varying conditions within a basin (such as soil characteristics or land

cover), however they typically are limited by the availability of sufficiently accurate or appropriately-scaled field data.

Two St. John erosion modeling approaches are discussed in this report. The first is a computer model called "ROADMOD" developed to generate quantitative, mappable estimates of sediment derived from unpaved road surfaces. This model is discussed in Chapter 5. The second involves the use of the Revised Universal Soil Loss Equation (RUSLE) to identify areas of greatest surface runoff erosion hazard on St. John. This model is discussed in Chapter 6. Both of these models are empirical, deterministic, and spatially-distributed.

A third erosion modeling approach was investigated to identify unstable slopes on St. John. In many steep, forested environments, debris slides are a primary source of sediments (Dietrich et al., 1982). Areas susceptible to these mass movements can be identified using automated terrain analysis techniques (Dietrich et al., 1993). However, field investigations on St. John revealed that landslides and debris flows are not major mechanisms of sediment transport on the island (Chapter 4). Thus, efforts to model slope stability were abandoned and are not described in this report.

1.6 Geographic Information Systems (GIS)

A modeling approach utilizing GIS was adopted for this project because GIS (1) provides results in a spatially-distributed format suitable for land management applications, and (2) is a tool currently in use at Virgin Islands National Park.

A geographic information system generally consists of a set of tools for collecting, storing, retrieving, transforming, and displaying spatial data (Burrough, 1986). In common terms, a GIS may be thought of as a computerized "map" of features (represented by points, lines, areas, or grid cells) linked to a database of information about each feature. For example, a digital map of soil types (polygonal areas) may be linked to a database containing information about soil attributes of interest (e.g., soil texture, depth, and infiltration rate).

Various "layers" of geographical information may be overlaid, queried, and analyzed in a spatial context using a GIS. A GIS also may be used to derive new information about an area. Slope gradients, for example, can be derived from elevation contour data.

Because environmental processes vary over time and space, GIS is often a useful data storage and analysis platform for environmental models. Extensive efforts have been made to link GIS with models of hydrology, erosion, and landscape evolution. For example, GIS interfaces have been developed for surface water runoff models (e.g., Moore and Grayson, 1991; Chairat and Delleur, 1993), groundwater models (e.g., Batelaan et al., 1993), water quality models (e.g., Panuska et al., 1991; Kern and Stednick, 1993), slope stability and channel initiation models (e.g., Moore et al. 1988; Dietrich et al., 1993), and erosion and sediment delivery models (e.g., Millington, 1984; Blaszczynski, 1989; De Roo et al., 1989).

One of two basic data structures is used for most GIS applications. The simplest of these is the **raster** data structure. Raster structures consist of an array of grid

cells. Each grid cell is referenced by a row and column number, and it is linked with one or more data fields specifying attributes for that cell. In raster structures a point is represented by a single grid cell; a line by multiple grid cells strung together; and an area by an agglomeration of neighboring cells.

The second common GIS data structure is **vector** representation. Here, coordinate space is assumed to be continuous rather than quantized into grid cells. A vector data structure allows all spatial positions and dimensions to be defined as precisely as the operating system allows. A point usually is identified by a single x,y coordinate pair and a line by a series of segments linking multiple x,y coordinate pairs. Areas are defined by a series of x,y coordinate pairs that begin and end at the same point; these coordinate pairs define the line segments that enclose a polygon.

Both data structures were used in this study. First, a method was developed for interfacing vectorized road data with a predictive model of road surface erosion (Chapter 5). Second, rasterized data representing island soils and topography were used to generate maps estimating relative susceptibility to surface erosion and soil saturation (Chapter 6). The latter is useful as an indication of where overland flow can pick up and transport surface sediment into the drainage network.

The U.S. National Biological Survey (NBS) on St. John is currently using the commercial GIS software Arc/Info[2] to manage spatial data for the island, including road data. The NBS envisions a major expansion of their GIS to support various

[2] Arc/Info is a registered trademark of Environmental Systems Research Institute, Inc., Redlands, California.

management activities at Virgin Islands National Park (Jennifer Bjork, NPS, pers. comm., 1994). This increases the potential value of the GIS-based tools described in this report.

CHAPTER 2:

ST. JOHN ISLAND

2.1 Physical Characteristics

St. John is the third largest of the Virgin Islands of the United States. The island is located approximately 80 km east of Puerto Rico in the West Indies of the Caribbean. It lies between 18°18'N and 18°22'N latitude and 64°40'W and 64°48'W longitude. St. John is approximately 14 km long and 8 km wide, and covers an area of 50 km^2. St. Thomas, the second largest of the U.S. Virgin Islands (77 km^2), is about 3 km west of St. John across Pillsbury Sound.

The topography of St. John is characterized by steep slopes, numerous small drainage basins and bays, and an irregular coastline. The island is predominantly mountainous; over 80% of the island has slopes exceeding 30 percent. Bordeaux Mountain, the highest point on St. John, rises 387 m above sea level. A central ridge runs east-west across the length of the island.

St. John is composed primarily of mildly deformed, layered volcanic rocks of Cretaceous age and limestone sediments. The surface geology of the island is extremely complex and variable. It includes felsic and mafic flows, andesitic

breccias, layered tuffs and limestones, and intrusive rocks of varying composition (Donnelly, 1966).

2.2 Soils

Most soils on the Virgin Islands formed in place from basic volcanic rocks. Soils tend to be fine textured -- generally clay loams and clays -- and rich in bases and nutrients. Some soils on the island are derived from soft limestone or from sediments originating from volcanic and limestone sources (SCS, 1970).

Cramer clay loam is the dominant soil series on St. John, according to the 1970 U.S. Soil Conservation Service (SCS) soil survey. However, recent investigations by SCS suggest that Cramer soils may not be as widespread as earlier believed (Caroline Rogers, VINP, pers. comm., 1994). Twelve other soil series have been mapped on St. John. Cramer soils are found on the side slopes of dissected volcanic uplands at gradients between 5 to 60 percent. They overlie partly weathered, basic volcanic rocks, and tend to be shallow and well-drained (SCS, 1970).

The soils of St. John generally exhibit moderate permeability when unsaturated, and low permeability when saturated. Most soils belong to hydrologic group D, the least permeable of the four classes defined by the U.S. Soil Conservation Service (SCS, 1970). Soils are generally shallow and underlain by nearly impervious material.

Some authors have proposed that past agricultural activities on the island resulted in the loss of considerable amounts of topsoil and organic matter (Woodbury and Weaver, 1987). However, as discussed later in this report, the loss of topsoil during the plantation era may not have been as severe nor as extensive as is commonly believed.

Stones cover 25 to 75 percent of the soil surface of most St. John hillslopes. This stoniness does not appear to be an artifact of historic agriculture. The French Commander Longueville, upon visiting St. John early in the plantation era (1734), reported to his superiors that "[on the island] there are so many rocks that the soil can barely be seen, yet everything grows beautifully there." (Low and Valls, 1985).

2.3 Climate and Hydrology

St. John lies in a belt of subtropical, easterly trade winds. The maritime tropical climate is characterized by generally fair weather, steady breezes, and relatively narrow annual, seasonal and diurnal temperature ranges. Winds have a strong effect on the vegetation of the island, with generally drier communities on the east end and in other exposed locations. Wind velocities on St. John vary daily. They tend to be strongest in the winter (SCS, 1970).

2.3.1 Rainfall

Average annual rainfall on St. John ranges from 100 to 150 cm (USGS, 1991a). The orographic lifting of moist air over the rugged terrain is the most

common source of precipitation on the island. Clouds tend to form on the leeward side of the island. There is no sharply-defined wet and dry season, although rainfall is usually lightest in February and March, and heaviest in September and October (Table 2.1). Nearly half the rain at Cruz Bay, on the western end of the island, falls from August to November (SCS, 1970).

Table 2.1: Average monthly precipitation and estimated potential evapotranspiration (PET) at Cruz Bay, St. John (Mount, 1993).

Month	**Rainfall (cm)**	**PET (cm)** (Thornthwaite)
January	8.5	10.5
February	6.3	9.6
March	6.7	11.6
April	6.3	12.7
May	14.5	15.0
June	8.5	15.5
July	14.5	16.6
August	14.5	16.0
September	16.7	14.7
October	15.9	14.5
November	15.4	12.8
December	10.5	11.4
Annual	**138.1**	**160.9**

Rainfall on St. John varies markedly with changes in elevation and aspect. It can also vary greatly from month to month and from year to year. The average annual total rainfall is between 125 and 150 cm at higher elevations, and around 100 cm at lower elevations (SCS, 1970).

Most rain falling on St. John occurs as short showers of a few millimeters or less which produce little or no runoff. Rainfalls of 2.5 to 5.0 cm in a 24-hour period are expected on St. John about six times a year; rainfalls 5.0 - 7.5 cm about 1.5 times a year; and rainfalls greater than 7.5 cm about once a year (Cosner, 1972). The 2-, 5-, 10-, 25- and 50-year 24-hour precipitation events on St. John are estimated to be 9.9, 14.0, 16.8, 20.3, and 23.4 cm respectively (Hubbard et al., 1987).

The Virgin Islands are occasionally subjected to tropical storms and hurricanes of great intensity. According to the SCS (1970), there is risk of hurricane-force winds about once every 9 or 10 years.

Severe tropical storms which have recently affected the Virgin Islands include Hurricane David (August/September 1979), Hurricane Hugo (September 1989), and a storm on April 18, 1983 which produced record rainfalls. During this latter storm rainfall intensities reached 10.1 cm/hour (4.0 inches/hr), and a total rainfall of 40 cm (16 inches) in 18 hours was recorded. Widespread coastal flooding caused millions of dollars of damage on the island. Such events probably are a primary mechanism of sediment delivery to the marine environment.

Hurricane Hugo was one of the most destructive storms to hit the Caribbean in this century (USGS, 1991b). Rainfall from this storm generally was small in comparison to rainfalls commonly associated with hurricanes. Nevertheless, Hugo dumped about 25 cm on St. John, winds were intense, and St. John suffered substantial storm damage, particularly on the south coast.

2.3.2 Temperature

Temperatures on St. John are notable for their relatively small variation both diurnally and annually. During July and August, daily maximum temperatures average about 31-32 °C, while daily minimums are about 23-26 °C. In December and January, daily maximum temperatures generally are in the high 20's and daily minimums in the very low 20's. Temperatures are slightly less at higher altitudes (USGS, 1985).

2.3.3 Hydrology

Surface-water resources on St. John are scarce. There are many intermittent but no perennial streams on the island (USGS, 1985). About 2.5 to 7.5 cm of water annually percolates into island soils and stream channel deposits. This recharges small but significant groundwater supplies in alluvial-filled valleys, beach sand, and fractured volcanic rock (Cosner, 1972).

Soils on St. John are typically less than 50 cm deep, very stony, and have relatively low water holding capacities (SCS, 1970). This, combined with the steep slopes of the island and occasionally intense storm events, results in "flashy" runoff hydrographs and occasional flooding. Rain falling in the upstream part of a basin may reach the mouth in less than an hour; as a result, flooding can occur after only short periods of intense rain. For the same reasons, floodwaters tend to recede rapidly (USGS, 1991a).

Conversely, drought conditions in the Virgin Islands tend to be accentuated by the high ambient temperatures, shallow soils, intense solar radiation, and continuous trade winds. This makes water shortage a major concern on St. John.

A comprehensive streamflow gaging program has never been in operation on St. John (USGS, 1991a). The longest continuous stream gaging record (1979-1989) is for Guinea Gut, which drains a 1.7 km^2 area. However, discharge from Guinea Gut is no longer monitored.

Jordan (1972) believes that land use in the montane basins of the Virgin Islands exerts greater influence on stream discharge than do topography, geology, and even, "to a degree", rainfall. His review of historic evidence suggests that water once was more abundant on the islands than at present. He attributes most of this difference to the reversion of many acres of pasture and cropland to brush and second growth forest. Presumably, transpiration by deep-rooted species reduces groundwater recharge and base flow.

A comparison of measured rainfall rates at Caneel Bay (EarthInfo, 1992) to soil infiltration rates reported by SCS (1970) suggests that rainfall intensities on St. John rarely exceed the infiltration capacity. Table 2.2 lists peak 30-minute precipitation intensities for the seven largest peak runoff events in Guinea Gut (EarthInfo, 1993) between January 1979 and December 1989. The average one-hour peak rainfall intensity for these seven storms was 6.5 cm/hour. Only three of these events sustained intensities of 6.1 cm/hour for more than one hour, and storm intensities were generally far lower. This compares to a reported infiltration rate of 5-16 cm/hour for Cramer soil, which is mapped on 85% of the island (SCS, 1970).

2.4 Land Use and Land Ownership

Prior to its European "discovery" in 1493, St. John had been periodically inhabited by various Indian tribes. The original vegetation on the island was somewhat modified for cultivation of food crops. Following the discovery of the island by Europeans, large trees were probably logged sporadically for shipbuilding and shelter (Larsen, 1986; Woodbury and Weaver, 1987).

Denmark seized control of the island in 1718 and European settlement began. In the initial years following colonization, sugar cane and cotton plantations were widely established on the island, and Coral Bay was heavily used for ship repair and storm anchorage.

Table 2.2. Data for seven major Guinea Gut runoff events, St. John, 1983 - 1989.

Event Date	Peak Discharge (cms)	Peak Discharge (cm/hour)	Total Ppt (cm)	Est. 24-Hr Ppt Recurrence Interval (years)	Peak 30-min Intensity (cm/hr)	Peak 1-hour Intensity (cm/hr)	Ratio Peak Discharge to Peak 1-hr Intensity (cm/hr) / (cm/hr)
Apr 17-18, 1983	26.8	5.5	38.9	> 100	12.7	10.2	0.54
Nov 27, 1987	7.6	1.6	8.9	> 1	6.1	5.6	0.29
Sep 17-18, 1989	6.0	1.2	23.9	50	8.1	6.9	0.17
May 17-18, 1986	5.8	1.2	8.1	1	6.1	3.6	0.33
Sep 24, 1989	5.5	1.1	10.4	2	7.6	5.6	0.20
Sep 9, 1988	5.3	1.1	16.5	9	7.6	5.6	0.20
Nov 4, 1983	3.8	0.8	22.1	25	10.7	7.9	0.10

By 1733, considerable conversion of St. John forests to agricultural use had taken place throughout the island (Larsen, 1986). However, land on St. John did not prove to be as lucrative for sugar production as had been hoped. The relative prosperity of neighboring St. Thomas as a maritime port, together with the relatively productive cane fields of nearby St. Croix, diverted much economic development away from St. John during the period of colonization.

A remarkably detailed and topographically descriptive map of land use on the island was compiled in 1780 (Oxholm, 1800). This map suggests that crop cultivation on St. John was largely confined to those areas where extensive tracts of relatively gentle terrain exist, such as the Caneel Bay, Catherineberg, Annaberg, Coral Bay and Maho Bay regions. This map and watercolors painted during the period suggest that forests normally were not subjected to wholesale elimination on the steeper slopes, although they were exploited for lumber and fuel.

Subsequent abandonment of economically unproductive lands allowed cultivated areas to gradually reforest. Today, most of the island is covered by secondary or tertiary forest (Woodbury and Weaver, 1987).

In 1917, the Virgin Islands were purchased by the United States from Denmark, and in 1956 approximately 54% of St. John was designated as a national park. St. John remains the least disturbed of the U.S. Virgin Islands. Only about 2.6% of the island has been mapped as "urban areas"; another 2.0% is used as pasture land (Woodbury and Weaver, 1987). However, these numbers are deceiving:

development has accelerated on many parts of the island, particularly in the Fish Bay, Coral Bay and East End areas. The area surrounding Cruz Bay on the west end of the island has been intensely developed, and a large commercial resort is located on Caneel Bay. Trunk and Cinnamon Bays receive heavy recreational use owing to the underwater trail and the National Park Service campground. Portions of the island, especially the east end, are subjected to persistent grazing by goats, donkeys, and other feral animals.

A large amount of privately-owned land exists within the boundaries of the National Park (Figure 1.1). Although most of this land is undeveloped, it represents a large area of potential future development.

2.5 Vegetation

The original forests of St. John were largely cut over or degraded, but now are in various states of recovery. The most widespread vegetation is dry evergreen woodland, and this covers about 33 percent of the island. Dry evergreen thicket/scrub covers another 21 percent of the island, moist forests 17 percent, and "secondary vegetation" (areas in different degrees of succession, from recent clearing to pasture) about 13 percent. Most of the remaining 16% consists of thorn and cactus, urban areas, rock pavement, coastal hedge and pasture. About 2.3% is occupied by mangrove, salt flat, and lagoon areas (Weaver and Woodbury, 1987).

No virgin forests exist on St. John, although the steep upper valley slopes of Reef and Fish bays support mature forests resembling virgin conditions (Robinson, 1974). Some researchers believe the plantation history caused the current vegetation of St. John to represent a drier regime than what originally was present (Woodbury and Weaver, 1987). However natural forces, most notably in the form of hurricanes, also play a major role in disturbing the forest regime. Recurrent hurricanes tend to disrupt forest progression toward climax by creating gaps in the forest (Woodbury and Weaver, 1987; Reilly, 1992).

Nearly 800 plant species from 116 families have been identified on St. John. Eighteen of these species are considered rare or endangered (Woodbury and Weaver, 1987).

CHAPTER 3:

EROSION HISTORY

The significance of present-day sediment delivery rates and processes on St. John can be better understood by comparing them to historic trends. This chapter begins with a discussion of the history of land use on St. John and the hypotheses that have been advanced regarding land use impacts on erosion and sediment delivery. A methodology to evaluate past rates of erosion and sediment delivery is described, and results for St. John are presented. This chapter concludes with a summary of the inferred erosion history of St. John.

3.1 Land Use History

3.1.1 Pre-Columbian Land Use History

Prior to 1493, St. John was only periodically inhabited by human beings. The initial inhabitants of the island may have arrived around 100 - 200 A.D. They probably reached St. John by migrating from island to island from South America (Tyson, 1987). The earliest inhabitants were later displaced by the Carib Indians. It appears that aboriginal occupation of St. John ceased prior to 1550, leaving the island

uninhabited for over a century, and only intermittently occupied from the late 1600's to the early 1700's (Tyson, 1987).

Our understanding of pre-Columbian impacts on the land and vegetation of St. John is sketchy. Indian tribes cultivated some food crops such as cassava, and probably logged larger trees for home construction and canoe building (Elizabeth Rider, Virgin Islands Department of Planning and Natural Resources, pers. comm., 1994). However, modification of island vegetation probably was not very extensive. Tyson (1987, p. 5) indicates that the size and distribution of their populations were limited, and concludes that "there is little evidence that Indian settlement or agriculture extended far into the interior."

3.1.2 Plantation-Era Land Use History

St. John was "discovered" by European explorers in 1493, but settlement of the island did not begin in earnest until 1718. In the initial years following colonization, sugar cane and cotton plantations were widely established on the island (Larsen, 1986).

The conversion of forest land to agricultural use (mainly sugar cane and cotton) proceeded rapidly up to 1733. In that year, St. John was affected by a drought, two hurricanes, and an insect plague that destroyed most of island's agricultural production and food supply. Those hardest hit by the food shortage were the slaves of the plantation owners. This, combined with a harsh slave punishment code and the recent arrival of captured African tribal rulers who, in the words of Low

and Valls (1985) "preferred death to life as slaves", resulted in slave unrest and a bloody November 1733 slave rebellion that lasted seven months.

These events slowed the growth of the plantation economy on St. John, but did not halt it. Apparently, many farms were abandoned on the relatively isolated Coral Bay end of the island (Oxholm, 1780), but the agricultural economy rebounded elsewhere on St. John. Based primarily on the analysis of historic tax records, Tyson (1987, p.45) states that:

> "Plantation operations and population densities in all watersheds [Reef, Fish, and Hawksnest Bays] were most intense in the second half of the eighteenth century, peaking between 1755 and 1780, but continuing at relatively high levels until about 1820. During this period approximately one-half of total watershed acreage was being intensively utilized for agricultural purposes. Much of the remainder was subject to periodic exploitation.... thereafter, agricultural activities contracted steadily, permitting progressive reforestation of the watersheds. During the first half of the twentieth century no more than 5 percent of total watershed land remained in use."

3.2 Assessment of Historic Sediment Delivery

Detailed studies of reef growth by Hubbard et al. (1987) indicate that declines in coral growth rates offshore of St. John are most evident after 1910. These results run contrary to Hubbard et al.'s expectation that St. John reefs would have evidenced slower growth during the plantation era, when sediment delivery to the reef system was presumably accelerated.

Tyson (1987, p. *i*) concluded that, in spite of the impact agricultural activities had on the watersheds in which they were located, "truncated plantation development

and plantation land management strategies, such as terracing, watercourse controls and selective reforestation ... probably moderated soil erosion and sedimentation discharges associated with widespread land clearance and intensive use".

Others (e.g., Hubbard et al., 1987) emphasize evidence of "extensive [agricultural] terracing" on St. John during the plantation era, and they suggest that this terracing may explain apparently low rates of sedimentation during this period.

To estimate average rates of sediment delivery from St. John watersheds under natural conditions, estimates of long-term sediment accumulation were made for three sites on St. John: (1) a detention basin on Lameshur Bay Gut; (2) a mangrove swamp in Reef Bay; and (3) the alluvial fan at the base of Fish Bay Gut.

Sediment accumulation in the Lameshur Bay Gut detention basin was estimated from 1994 field measurements of sediment accumulation. Estimated sediment accumulation in the Reef Bay mangrove swamp is based on measurements reported by Nichols and Brush (1988). Sediment accumulation rates at the outlet of Fish Bay Gut are based on the estimated volume of alluvium at the base of Fish Bay and reported rates of sea level rise. Each approach provides an estimate of sediment yields over successively longer periods of time, from approximately 40 years before present (BP) in the case of the Lameshur Gut detention basin to approximately 3,300 years BP in the case of Fish Bay. These are described in the following sections.

3.2.1 Lameshur Gut Detention Basin

A 1200 m^2 detention basin is located in the Lameshur Bay catchment above the present-day Virgin Islands Ecological Research Center (VIERS), and immediately below the USGS suspended-sediment pump sampling station on Lameshur Gut (Figure 3.1). According to VIERS director Cynthia Grippaldi (pers. comm., 1994), this pit was constructed no later than the early 1960's. A rectangular area cleared of vegetation is clearly visible on 29 January 1954 and 5 January 1962 aerial photographs of the island. A detention basin having the dimensions described therefore may have been established as early as 1953 or as late as 1961.

The original purpose of the detention basin was apparently two-fold: (1) to protect the site now occupied by VIERS from flash flooding, and (2) to provide a reservoir of fresh water during dry periods. Efforts to utilize the detention pond for the latter purpose have been abandoned, but the basin continues to detain Lameshur Gut runoff during small- to moderate-sized events. Under large runoff events the basin, which has a capacity of roughly 2400 m^3, overflows on the east side, and this excess courses through the grounds of VIERS (Cynthia Grippaldi, pers. comm., 1994).

This detention basin receives runoff from a 1.0 km^2 drainage basin, with the possible exception of some high flow that discharges into a side channel and thereby bypasses the basin. The author has walked this overflow channel to its point of termination (a large human-made berm), and found little evidence of sediment deposition. In contrast, the detention basin has accumulated a large quantity of

Figure 3.1. Location of Lameshur Gut detention basin (star).

sediment ranging from small boulders at the head of the alluvial fan to well-sorted silts and clays.

Unfortunately, there appears to be no documentation of the history of the detention basin. However, there is no reason to believe that accumulating sediment has been removed since the basin was established, nor that the basin as a whole has been regraded or reworked. Parts of the basin have been altered since construction. Specifically, a hole approximately 30 m^3 in volume occupies the center of the basin and is surrounded by revegetated dirt piles. This hole may have been dug for refuse disposal purposes, although the volume of refuse it contains is negligible. The hole is small in comparison to the dimensions of the basin.

The depth of the sediments on the basin floor ranges from approximately one meter near the head of the alluvial fan to a pinching out along the margins. The fining of clasts away from the head of the alluvial fan and the diminishing depth of accumulated sediments with increasing distance from the axis of the fan clearly indicates that Lameshur Gut was the source of these sediments.

The volume of sediment accumulated in the Lameshur Gut detention basin was estimated by surveying sediment depths in the pit on 13 January 1994. A grid of elevations was surveyed for two surfaces: (1) the "original" (*c*. 1953 - 1961) basin surface; and (2) the current (January 1994) basin surface. The difference between these two elevations provided sediment accumulation depths at 76 locations. A contour map of sediment depth was derived from these data (Figure 3.2).

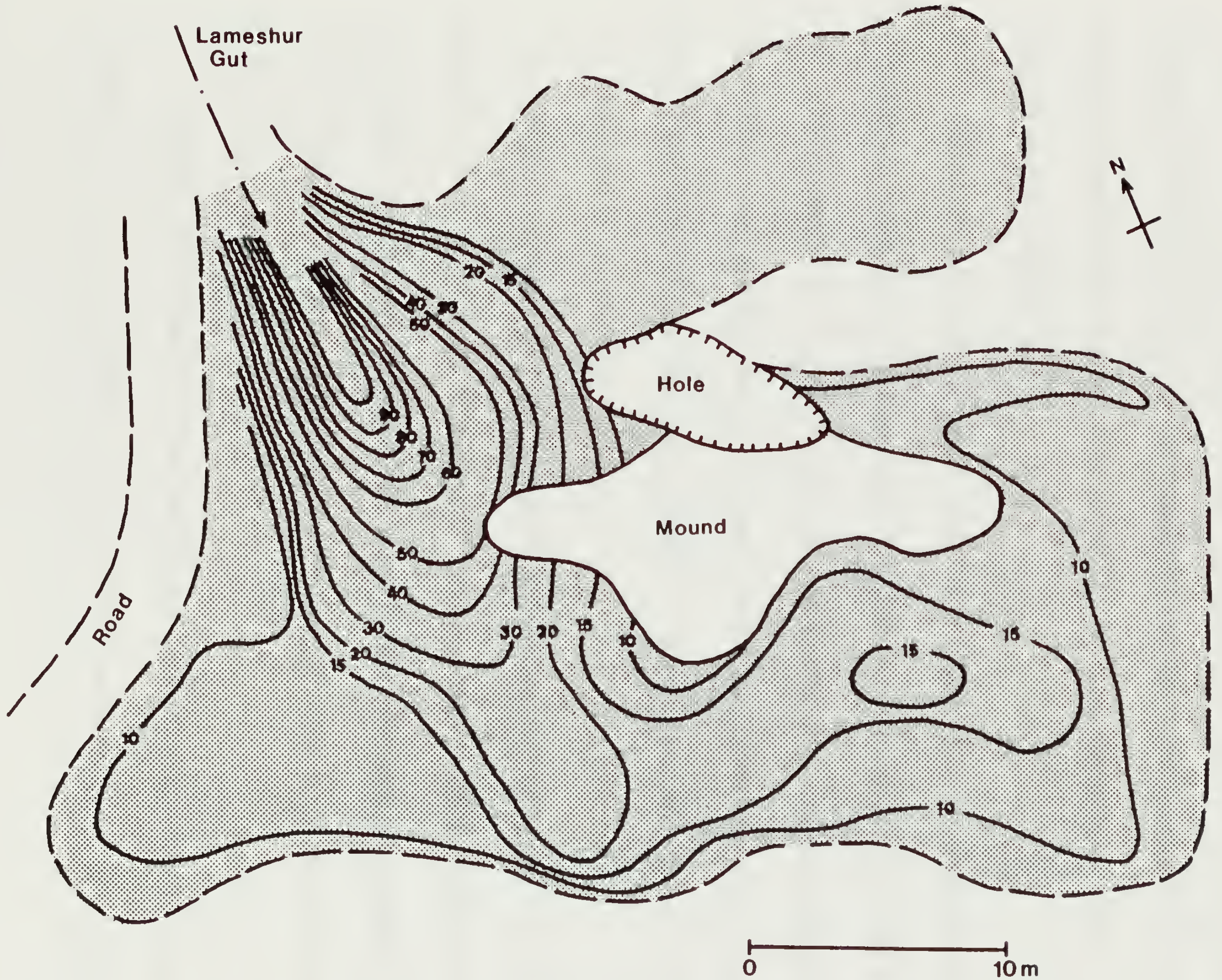

Figure 3.2. Contour map of sediment depth in the Lameshur Gut detention basin. Shaded region represents area of sediment accumulation; sediment depth contours are in centimeters.

The "original" surface of the detention pit was interpreted as occurring where the well-sorted and poorly-consolidated surface sediments changed abruptly to a very dense, pale yellow-brown clay. In most cases, this transition was obvious and clearly correlative with the stratigraphy of adjacent holes. In only a few locations was the transition ambiguous. Ambiguous transitions usually were near the edge of the pit where sediment accumulations were relatively thin and probably included material shed from the perimeter berm.

Based on the sediment depth isopleths in Figure 3.2, the total volume of accumulated sediment in the Lameshur detention basin in January 1994 is about 200 m^3. This estimate incorporates some generous assumptions, including the assumption that sediment had accumulated in the center of the pit before this area was reworked, and that the depth of accumulated sediment in the reworked area is consistent with that measured in surrounding locations.

If the average bulk density of these unconsolidated sediments is 1.5 g/cm^3, this represents about 300 tonnes of sediment.[3] If this mass is then divided by the area of the contributing drainage basin (1.0 km^2) and by the estimated time period over which these sediments have accumulated (32-40 years), the result is about 7 to 10 tonnes of sediment per km^2 per year.

The detention basin does not capture 100% of the sediments discharged by Lameshur Gut. During high flows, many of the finer silts, clays, and colloids

[3] In this document, "tonne" refers to the metric, not English, unit of weight. One tonne is equivalent to 1000 kilograms (kg), or one megagram (Mg).

probably remain in suspension and are transported out of the basin with overflow. Nevertheless, it seems likely that more than half of the suspended sediment carried by Lameshur Gut settles in the detention basin, because: (1) silt and clay sediments are abundant in the basin, and (2) Lameshur Gut enters on the west end of the basin and exits on the east end, some 30 meters from its point of entry. For these reasons, sediment delivery from the Lameshur watershed is almost certainly less than 20 tonnes km^{-2} $year^{-1}$, or less than twice the total captured by the basin.

3.2.2 Reef Bay Mangrove Swamp Deposits

Nichols and Brush (1988) performed a detailed survey of Reef Bay mangrove swamp sediments to determine sedimentation rates over the last few thousand years. They identify "swamp clay" overlaying peat as the topmost stratigraphic unit. This swamp clay is a firm, structureless, dark grey silty clay that Nichols and Brush interpret as "likely deposited in ponded water following periods of high stream inflow" (p. 9).

From plan view and cross-sectional sketches that Nichols and Brush provide in Figures 1 and 2, the dimensions of the swamp clay layer do not appear to exceed an average depth of 1.0 m over an area 80 m wide and 400 m long. These are generous dimensional estimates; the actual volume may be substantially less. These dimensions yield a maximum accumulation of 32,000 m^3.

These researchers used ^{137}Cs isotope analysis to date the bottom of this layer at 1170 BP. By assuming a bulk density of 2.0 g/cm^3 for this dense silty clay and

dividing the total mass by the 4.7 km^2 area of the contributing watershed, one obtains a silt and clay sediment yield of about 10 tonnes per km^2 per year in the Reef Bay watershed over the last 1170 years. Bioturbation of the clay precludes the identification or dating of individual layers within the swamp clay.

Coarser alluvial sediments produced by the Reef Bay basin (boulders, cobbles, gravels, sands, and additional silts) are not included in this estimate. It is therefore impossible to use these data to determine the total sediment yield of Reef Bay over this period. However, it seems reasonable to assume that the clay and silt layer mapped by Nichols and Brush represents at least 25% of the total sediment load deposited by Reef Bay Gut. If we accept this assumption, then we may conclude that the sediment yield from Reef Bay basin over the last 1170 years is no more than 40 tonnes km^{-2} $year^{-1}$. This includes sediment contributed during the plantation era.

3.2.3 Sea Level Rise and Fish Bay Alluvial Fan

It is widely accepted that sea levels have risen approximately 100 m over the last 15,000 years (e.g., Emery and Aubrey, 1991). This global rise in sea level flooded the coastal valleys of St. John and produced the numerous small bays and rugged headlands that now characterize the island.

Nichols and Brush (1988, p. 10) conclude that data from Reef Bay Pond "are relatively consistent in indicating a continuous rise of sea level since 3,300 years BP at a rate of 0.08 cm/yr." This is consistent with Emery and Aubrey's statement that global sea levels were about 5 meters below their present level 6000 years ago

(p. 67). If one assumes a 2.64 m rise in sea level over the last 3,300 years and negligible vertical tectonic movement, then one can approximate the sediment yield during that period by determining the volume of sediments accumulated in the alluvial fan.

Fish Bay was selected for this exercise because it represents one of the most sheltered bays on St. John Island. As such, it is probably less susceptible to two factors which complicate the estimation of sediment yield: longshore sediment transport and sediment flushing.

If we accept the premise that Fish Bay alluvial fan aggradation generally kept pace with sea level rise up until 3,300 years ago, then the volume of sediments accumulated on the fan since that time may be approximated by the height of sea level rise (2.64 m) times the area of the alluvial fan from its head to an offshore depth of 2.64 meters. This area, as estimated from the 7.5 minute quadrangle map (USGS, 1982), is approximately 110,000 m^2. Multiplying this area by a depth of 2.64 meters and a bulk sediment density of 2.0 g/cm^3, and dividing by the total drainage area of about 5 km^2 results in a sediment yield of approximately 35 tonnes per km^2 per year. This estimate is very crude, but nevertheless consistent in an order-of-magnitude sense with the numbers estimated using the two previous methods. This estimate also includes sediments contributed during the plantation era, and therefore does not reflect "undisturbed" catchment conditions.

3.3 Observations: Plantation-Era Erosion and Sediment Delivery

3.3.1 Alluvial Fan Analysis

In December of 1993 and January 1994 this author, with the aid of geomorphologist Dr. William Dietrich (University of California / Berkeley) and hydrologist Dr. Lee MacDonald (Colorado State University), investigated alluvial fans near the outlet of several major St. John drainage basins, including Guinea Gut, Fish Bay, Reef Bay, Lameshur Bay, and Cob Gut. Each of these fans is located where the guts emerge from incised bedrock terrain onto relatively flat alluvial plains and terraces (Figure 3.3).

Each of these alluvial fans was incised, and in the case of Guinea Gut, Fish Bay, and Lameshur Bay, there was clear evidence that these fans had aggraded during, or shortly following, the plantation period. The clearest evidence of this was a Danish plantation-era smoking pipe bowl unearthed at a depth of about 1 m in a fan incision near the base of Fish Bay Gut. Other evidence unearthed at depths of 30 to 120 cm in the incised fans included donkey teeth, pre-modern-era glass, pottery fragments, and charcoal. This evidence of aggradation suggests that erosion and sediment yield from these watersheds increased substantially during the plantation era.

3.3.2 Upland Colluvial Fill Investigations

The severity of erosion during the plantation period was also inferred by evaluating upland colluvial fill areas for evidence of sediment accumulation and incision. If runoff and erosion were severe in areas of intensive plantation farming,

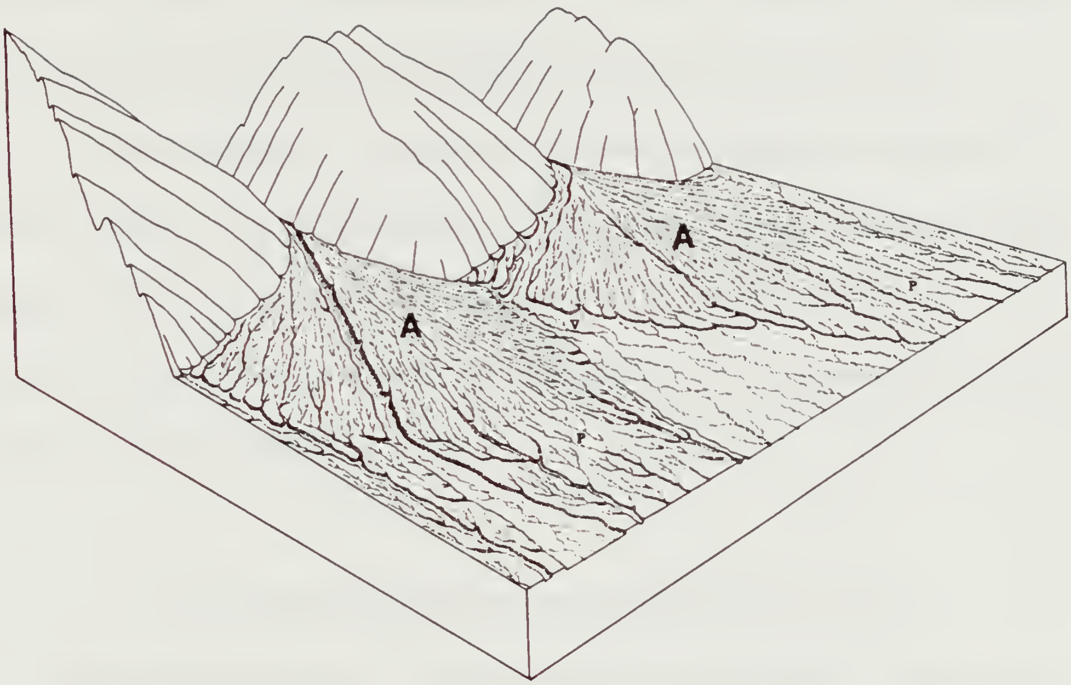

Figure 3.3. Dissected mountain-front alluvial fans (A) (from Peterson, 1981).

then one would expect to find evidence of accumulated sediment in topographic hollows, accompanied by gullying and channel incision into the colluvium.

Several areas known from Oxholm's map (1800) to have been intensively farmed during the plantation era were examined (Figure 3.4). In particular, portions of Reef and Coral Bay watersheds near Bordeaux Mountain (Figure 3.4, top) were explored for evidence of colluvial fill incision. No such evidence was observed, either in this area around Bordeaux Mountain, nor elsewhere on St. John.

This lack of evidence for severe gully erosion on plantation-era farmsites, combined with the observed aggradation of alluvial fans during the same era, paints a picture of erosion and sediment delivery during the plantation era that was substantially greater than the natural rate of erosion, but not so intense as to result in a massive loss of upland soil.

3.4 Summary: Inferred Erosion History of St. John

The evidence presented in Section 3.2 indicates that sediment yields from St. John watersheds under relatively undisturbed conditions are low compared to many sites in the tropics. Various authors report sediment yields from tropical forests of 21 to 5300 tonnes km^{-2} yr^{-1} (Table 3.1). On St. John, the average long-term sediment yield under relatively undisturbed conditions is about 20, and no more than 40, tonnes km^{-2} yr^{-1}.

There are several likely explanations for this low rate of erosion. First, field observations reveal that most hillslope soils on St. John are shallow and very stony.

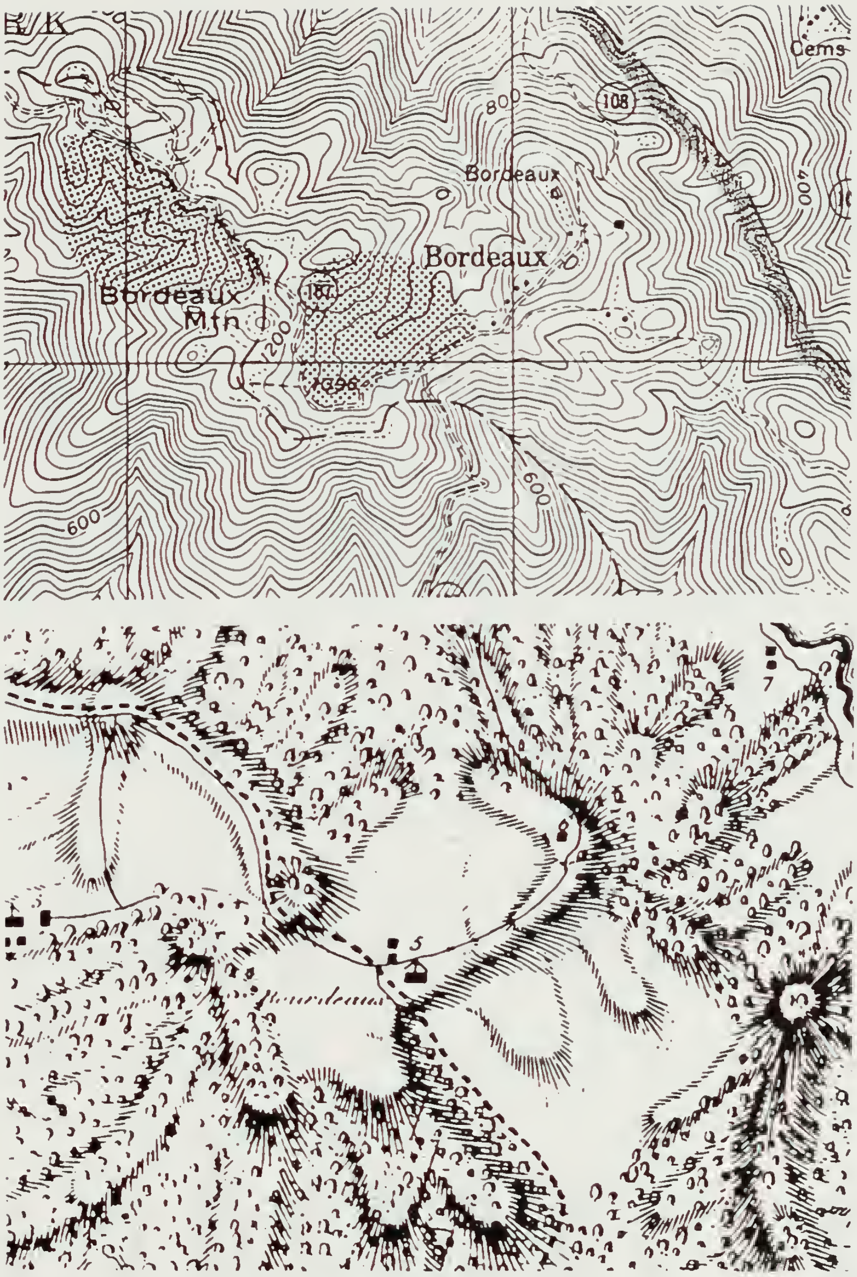

Figure 3.4. Top: The Bordeaux Mountain region as shown on USGS 7-1/2 minute quadrangle map (1982). Stippled areas were investigated for evidence of plantation-era gullying and colluvial fill incision. Bottom: The same region from Oxholm's map showing areas cleared for farming (Oxholm, 1800).

Table 3.1. Reported sediment yields in the forested tropics.

Location	Land Cover	Ave. Ppt (cm/yr)	Geology	Soils	Ave. Slope (percent)	Catchment Area (km2)	Sediment Yield (Mg km-2 yr-1)	Reference
St. John Island	Dry and moist tropical forest	120	Mixed volcanics, limestones, intrusives	Stony clay loams	30 - 40	1.01 - 4.75	20	This study
Cijambu Mountain West-Java	Undisturbed 30-yr-old *Pinus merkusii* plantation	223	Quaternary ash	Orthic and ochric andosols	14 - 58	0.18	170	Bons, 1990
Sungei Telom Malaysia	94% natural montane forest	248	Schist and granite	variable	"steep"	26.5 (?)	> 32 (1)(2)	Douglas, 1968
Waimanu River Fiji	"Heavily forested" humid tropical	> 190	NA	NA	"steep"	157 (est.)	5300	Glattharr, 1988 (3)
Sabah Malaysia	Tropical rainforest; undisturbed	NA	NA	Orthic acrisol & gleyic podsol	"moderate" (gen. < 27)	NA	21	Malmer, 1990
Sungai Tekam For. Res. Malaysia	Lowland forest, *(Dipterocarp)*	174	Andesite, interbedded w/ sandstone & shale	V. clayey	11 - 14	.36 - .95	< 150 (2)	Peh, 1981
Konto River Indonesia	Forest and scrubland	NA	Volcanic	NA	"steep"	5.3 - 12	30 - 110	Rijsdijk et al., 1990
Rio Cauca Colombia	Dense moist forest	230	Volcanics, incl. ash	Silt loam and laterites	Variable	650	1540	Van Vuuren, 1982
Java Indonesia	Montane forest, undisturbed	NA	NA	NA	NA	NA	30	Wiersum, 1985 (4)

"NA" = not available
(1) Suspended solids only; (2) Assumes sediment density of 1.5 g/cm3; (3) from Morrison et al., 1990; (4) from El-Swaify, 1990.

Soil surfaces on St. John, once the litter layer is removed, are observed to be typically 25 - 75% stones, boulders, or bedrock. This was observed in both dry and moist forest environments, and in areas that have and have not been cultivated. As noted in Section 2.2, stoniness is not a modern phenomenon.

These stony soil surfaces undoubtedly protect against erosion. Stones shield much of the soil surface from particle displacement due to rainsplash and rilling, even during intense storm events. When hillslope runoff does occur, the flow is routed along tortuous flow paths which reduce its velocity and enhance opportunities for infiltration, thus limiting its erosive potential.

Second, the weathering of bedrock and the production of soil on St. John is believed to be a slow process. Although St. John is subject to year-round warm temperatures and receives some 100 to 150 cm of rain annually, most of this rain occurs as short showers, and 90 to 95 percent of the annual rainfall is quickly evaporated or transpired (Cosner, 1972). Thus, opportunities for chemical and physical weathering are severely limited. Soils are shallow almost everywhere on St. John (SCS, 1970), and at many sites bedrock weathering was observed to be minimal.

Finally, events capable of producing overland runoff and transporting large quantities of sediment on St. John are relatively rare. The combined effect of soil stoniness and climate conditions is that natural sediment production and delivery is very low.

The observations discussed in Section 3.3 lend credence to the belief that sediment production and delivery during the plantation era was not so extreme as to

adversely impact offshore coral growth (Hubbard et al., 1987). These field observations also are consistent with a conclusion of Nichols and Brush (1988, p. 21) that "despite man's historical use of the watershed at Reef Bay and possible 'mismanagement', the findings [in Reef Bay mangrove swamp sediments] indicate no massive sedimentation effect."

Both Tyson (1987) and Hubbard et al. (1987) suggest that the lack of evidence for massive sedimentation may be the result of agricultural terracing on St. John during the plantation era. Although man-made, plantation-era rock wall terraces were observed in several St. John watersheds, this author would hesitate to describe the terracing as "extensive" or suitable for soil conservation. This author would argue that four other factors were as instrumental, if not more so, in minimizing erosion on St. John during the plantation period. These are: (1) the apparent lack of oxen and ploughs on St. John during that era (Steven Edwards, St. John historian, pers. comm., 1994), which minimized the disturbance of hillslope soils; (2) the natural stone "armoring" of the soil surface; (3) the relatively limited extent and use of roads and trails on St. John; and (4) the limited number of runoff-producing events.

Plantation farming *sans* animal-drawn plow was probably necessary because of the steep and rocky hillslopes of the island, and feasible because of the availability of slave labor until 1848. The importance of stone armoring in minimizing soil erosion has already been discussed. The evidence for, and significance of, a relatively limited road network during the plantation era is discussed in the following chapter.

CHAPTER 4:

CURRENT EROSION AND SEDIMENT DELIVERY PROCESSES

This chapter evaluates present-day erosion and sediment delivery processes on St. John. This chapter begins with observations of sediment sources and their relative importance. Road-related erosion is hypothesized to be the dominant source of sediment produced and delivered to the marine environment. The literature addressing road-related erosion is reviewed. A methodology is described for assessing road-related erosion and sediment delivery on St. John, and the results of our initial study on road erosion are presented. Conclusions are presented in Section 4.7.

4.1 Land Use and Erosion Observations

4.1.1 Landslides/Debris Flows

Few examples of landslides or debris flows, recent or otherwise, can be found on St. John. The steepest terrain in several basins (including the Fish Bay, Guinea Gut, Lameshur and Coral Bay watersheds) was explored for evidence of slope failure and debris flows, and no such evidence was observed. In addition, air photos from 1954 (1:28,000 scale) and 1990 (1:34,000 scale) were analyzed, and no slope failures

could be identified. Observations suggest that erosion by mass movement on St. John, when it occurs, is dominated by processes other than wholesale slope failure such as rock fall, soil creep, and root and animal disturbance.

4.1.2 Land Use Erosion

Agricultural and forest harvest activities on present-day St. John are virtually non-existent. Some of the primary reasons for this include: (1) St. John's economy is now heavily oriented to the tourist industry, (2) over half of the island is managed by the U.S. Park Service for public use, (3) the shallow, stony soils are not highly productive, and (4) the cost of land on St. John is prohibitively expensive for most agricultural use. Some small-scale cultivation of fruits and vegetables occurs, but the vast majority of food consumed on the island is imported. As a result, the amount of soil that is plowed or otherwise disturbed for the production of food or fiber is negligible, and sediment generated by these activities is minimal.

The impact of animals on a few intensively-grazed areas is a concern. It is estimated that about 2% of the island is privately-owned land committed to pasture and grazing uses (Woodbury and Weaver, 1987). On much of St. John, and in particular on the east end, pigs, goats, and feral donkeys roam freely on both privately- and publicly-owned lands. The impact of grazing on the east end is compounded by the often sparse vegetation. In addition, wild pigs often root up ground vegetation (Jim Petterson, Virgin Islands National Park, pers. comm., 1993). Nevertheless, the overall impact of grazing on sediment delivery to the marine environment of St. John

is probably small. This statement is based on the observation that grazing and foraging do not generally expose and compact soils over extensive areas.

Land uses typically associated with "urban" development are more problematic. About 2.6% of the island has been mapped as "urban areas" (Woodbury and Weaver, 1987). Around Cruz Bay in particular, many areas have been cleared of all vegetation and converted to uses that compact the soil, reduce its permeability, expose it to direct raindrop impact, and facilitate runoff and erosion. In unpaved parking areas, for example, severe erosion often can be observed.

A major "point source" of sediment is the Majestic Construction industrial site in the Battery Gut watershed above Fish Bay. Many cubic meters of sand-and gravel-sized sediment and an unknown quantity of finer sediment are entering and moving through Battery Gut from the Majestic site. Sand and fine gravels cover the bed of Battery Gut for one to two hundred meters downstream from the Majestic site (Figure 4.1). The bulk of these sediments could be prevented from reaching Battery Gut by establishing berms or detention basins on the source property.

With the exception of unpaved roads and the activities described above, most present-day land uses on the island do not appear to result in a widespread, long-term exposure of unprotected soil surfaces to storm runoff. This, together with land use development guidelines currently in place on St. John (Chapter 7), appears to minimize many potential sources of sediment.

Figure 4.1. Sand and gravel filling a pool in Battery Gut pool below the Majestic industrial site.

4.1.3 Road Erosion

From an inspection in winter 1993/1994 of roads throughout St. John and of adjacent drainages receiving runoff from these roads, it is apparent that a large quantity of fine-grained material is being detached from and transported along road surfaces. Most unpaved road surfaces -- even those recently established or regraded -- were deeply incised (Figure 4.2).

At Haulover Bay an estimated 460 m^2 of new road surface, together with an unmeasured cutbank area, delivered approximately 10 m^3 of eroded material to the bottom of the slope during a four month period. This material had accumulated be-- hind a sediment fence (Figure 4.3), and is equivalent to about two centimeters of erosion from the entire road surface.

An extensive road network exists on St. John. Maps, aerial photos, and field observations suggest that more than 100 km of actively-used roads exist on the island, with less than half of these being paved. Unpaved roads expose an estimated 11 to 42 ha of St. John soils to runoff and erosion (Section 4.5).

4.2 Hypothesis

It is the hypothesis of this study that the present-day production and delivery of fine sediment on St. John is dominated by road-generated erosion. Moreover, it is proposed that unpaved road surfaces on St. John, together with eroding cutbanks and unstable fill material, are collectively producing and delivering fine sediments toward the marine environment at historically unprecedented rates. The following sections

Figure 4.2. Erosion of unpaved road surface.

Figure 4.3. Road-derived sediment accumulated behind a sediment fence at Haulover Bay over the first four months following construction.

review the results of other studies on road erosion, and then present the results of the field investigation undertaken as part of this project.

4.3 Literature Review

Roads often are the primary source of sediment from rural and forest lands (e.g., Trimble and Sartz, 1957; Haupt, 1959; Hafley, 1975; Ward, 1985; Froehlich, 1991). Disturbances to soil, vegetation, land gradients and drainage patterns caused by roads create opportunities for accelerated erosion and increased sediment yield. In some cases the increased sediment production from roads can have a negligible environmental impact because sediment is discharged to areas that can safely assimilate the material. However, the discharge of sediment to streams, lakes, or wetlands may degrade the quality of water and aquatic habitat.

Many studies of sediment production in forested basins have focused on watershed-level analyses of sediment yield. Suspended sediment data from 23 watersheds in California indicated that conversion of only 0.6 percent of a watershed into "low-standard roads" increased sediment production by 24 percent (Anderson, 1975). In northwestern California, sediment yields from a relatively undisturbed watershed were compared to yields from a 424-ha watershed in which logging roads were built (Rice et al., 1979). The investigators estimated that 1632 m^3 of "excess" sedimentation occurred in the disturbed watershed during a four-year period of road construction, and this increase was attributed to the construction of approximately 6.0 km of logging roads in the riparian zone.

The construction, use, and maintenance of roads may accelerate sediment production in several ways. Reid et al. (1981) identified five major sources of sediment from logging roads in the Olympic mountains of Washington State, and these were: (1) landslides induced by roadfill, sidecast material, and/or concentrated drainage; (2) debris flows mobilized by road-related landslides; (3) unstable sediment sidecast during construction and later mobilized by processes such as dry ravel and rainsplash; (4) erosion from road surfaces; and (5) sediment shed by roadcuts into roadside ditches. In logged areas, road-induced landslides were the greatest source of sediment under an "average distribution" of road types. The second biggest source of road-derived sediment was from road surfaces and cut banks (Reid et al., 1981).

Erosion from road surfaces has long been recognized as an important source of fine-grained sediment. However it remains a problem that "while the rate of sediment production from road-related sediment sources such as landslides is easily measured and widely reported, quantitative studies of road surface erosion are rare" (Reid and Dunne, 1984). Hoover (1952) may have been the first to report road surface erosion rates. From studies at the Coweeta Experimental Forest in North Carolina, Hoover estimated a loss of 6,850 cubic yards of soil from 2.3 miles of road over a four-year period, and this is equivalent to about 0.35 m^3 erosion m^{-1} yr^{-1}. Trimble and Weitzman (1953) measured first-year erosion depths of 1.0 to 3.0 cm on skid-road surfaces following logging in West Virginia, and they noted a positive correlation of erosion depth with road slope and road length.

Data from 720 timber-harvest sites in the northern Rocky Mountains were analyzed for relationships between 14 "potentially important characteristics of roads and watersheds" and the distance at which runoff on road surfaces eroded rills one inch deep (Packer, 1967). A multiple-regression equation expressed this distance as a function of five characteristics: (1) road gradient; (2) road surface soil aggregation; (3) topographic position, i.e., whether the road is located in the upper, middle, or lower one-third of a sidehill slope; (4) slope aspect; and (5) gradient of the slope across which a road is built. Of these five factors, road surface aggregation and steepness of the road grade were most important and accounted for 35 percent of the variance. The other three factors accounted for an additional 8 percent of the variance in the distance to the development of rills one inch deep (Packer, 1967).

Reid and Dunne (1984) appear to be the first to address the question of how much sediment is mobilized by road surface erosion under a variety of conditions. They demonstrated a strong relationship between sediment yield from gravel-surfaced roads and the intensity of road use. Sediment yields ranging from 2.0 tonnes/km-yr from paved roads to 500 tonnes/km-yr from heavily-used, gravel-surfaced logging roads were measured on the western slope of the Olympic Mountains of Washington State. These roads were four meters wide, had an average gradient of 10%, were at least five years old, and were drained at an average of six culverts per kilometer. Sediment yield from a "typical" paved road segment was only 0.4% of that from the same segment surfaced with gravel and heavily used. They inferred that sediment contributed from road cutbanks and ditches was small compared to sediment derived

from the active road surface. Traffic intensity, not road length and slope, was found to be the dominant control on sediment production. However, Reid and Dunne note that "[i]n regions where road standards are less stringent, road gradient and segment length are expected to be more important controls on sediment loss".

On forest roads in southwestern Washington State, the amount of sediment produced on an hourly basis was most strongly related to traffic rates, measured both between and during storms (Bilby et al., 1989). These authors concluded that sediment abatement efforts should focus on "sections of road having steep gradient, being heavily used, and draining directly into larger streams".

Sediment production from roads is a documented problem on various islands in the Caribbean (e.g., Cameron, undated; CARDI, 1983; McCluskey, 1989; Scatena, 1993). However, to this author's knowledge, no studies of road erosion have been performed on St. John. The most relevant data are from neighboring St. Thomas Island (Wernicke, 1986). In that study, a freshly-graded dirt road with a gradient of 19.5% and an estimated surface area of 800 m^2 generated more than 18.6 m^3 of sediment over a six-month period. This is equivalent to more than 2.3 cm over the entire road surface.

Ward (1985) characterizes present-day road erosion modeling efforts as falling into two general categories: empirically-derived regression models, and physical process models. The former category includes the work of Trimble and Wietzman (1953), Packer (1967), and Reid and Dunne (1984). The latter category includes

work by Simons et al. (1980) and the road component of the Water Erosion Prediction Project being developed by the U.S. Forest Service (Luce and Cundy, 1994).

4.4 Methods of Assessing Road Erosion and Sediment Delivery

4.4.1 Road Sediment Production

Ideally, the production and delivery of sediment from roads is assessed by measuring precipitation, road runoff, and the quantity of sediment carried by runoff during various storm events. Such measurements could not be made during this study because of limited time on the island and the absence of large storms.

As an alternative approach, erosion from unpaved road surfaces was estimated by measuring road surface profiles and determining the cross-sectional area of incisions carved into the surface since the last grading (Figure 4.4). By selectively locating these measurements where runoff is concentrated on the road and where upslope road drainage areas can be estimated with reasonable accuracy (± 20%), the effect of upslope road drainage area and road grade on road erosion could be investigated.

The upslope road drainage area for each cross-section was estimated by pacing the length and width of all road segments draining to that point. Pacing against known distances confirmed that length and width estimates were generally accurate to within 10-15%. In some cases road runoff split in multiple directions, and the need to estimate the proportion of runoff flowing in each direction created additional uncertainty. Road grade was estimated by sighting through a Brunton compass over a short

Figure 4.4. Measurement of cross-sectional road erosion.

(5-10 m) interval representative of and including the measured cross-section. These estimates were probably accurate to within 1-2 percent of the true slope.

Estimation of road erosion rates requires an estimate of time since the surface was last graded. Road age was often difficult to estimate with certainty. In most cases, age estimates relied on information provided by local residents. In some cases, more reliable information was provided by staff from the National Park Service or the Virgin Islands Environmental Research Station.

Twenty-three road surface cross-section measurements were made in the Fish Bay basin, and three in the Lameshur Bay basin. The results are discussed in Section 4.5.

4.4.2 Sediment Delivery

The quantity of sediment delivered to the outlet of a watershed is less than, and often a small fraction of, the quantity of material eroded within the watershed (Walling, 1983). Typically much of the mobilized sediment is redeposited on hillslopes, in landscape depressions, behind vegetation, in colluvial and alluvial mantles, or in stream channels. The proportion redeposited tends to increase with increasing basin size (Walling, 1983).

An understanding of sediment delivery processes on St. John is necessary if the proportion of sediment reaching the ocean from roads and other sources is to be estimated. Fine sediments (such as silts and clays) delivered to stream channels during major runoff events tend to be transported relatively rapidly toward the catchment

outlet. However, fine sediments delivered to a thickly vegetated hillslope may not reach the stream channel. Sediment reaching a channel may be stored in channel banks, bed material, and alluvial fans.

Sediment delivery is best assessed by measuring sediment transport at various points in a watershed over an extended period of time. Unfortunately, resources were not available for such measurements. Many years of measurement may be required to produce useful data on St. John since runoff events are infrequent and vary by several orders of magnitude.

One method of evaluating sediment delivery in stream channels is to assess streambed characteristics. Sediment supply in relation to transport capacity can be inferred by comparing surface to subsurface particle sizes.

Bed material and channel characteristics were therefore studied at three locations on St. John: (1) upper end of the Fish Bay Gut alluvial fan, (2) Battery Gut, and (3) upper end of the Greater Lameshur Gut alluvial fan (Figure 4.5). Evaluations were performed by successively excavating layers of bed particles and examining the morphology of each layer. The results of these streambed channel evaluations are discussed in Section 4.6.

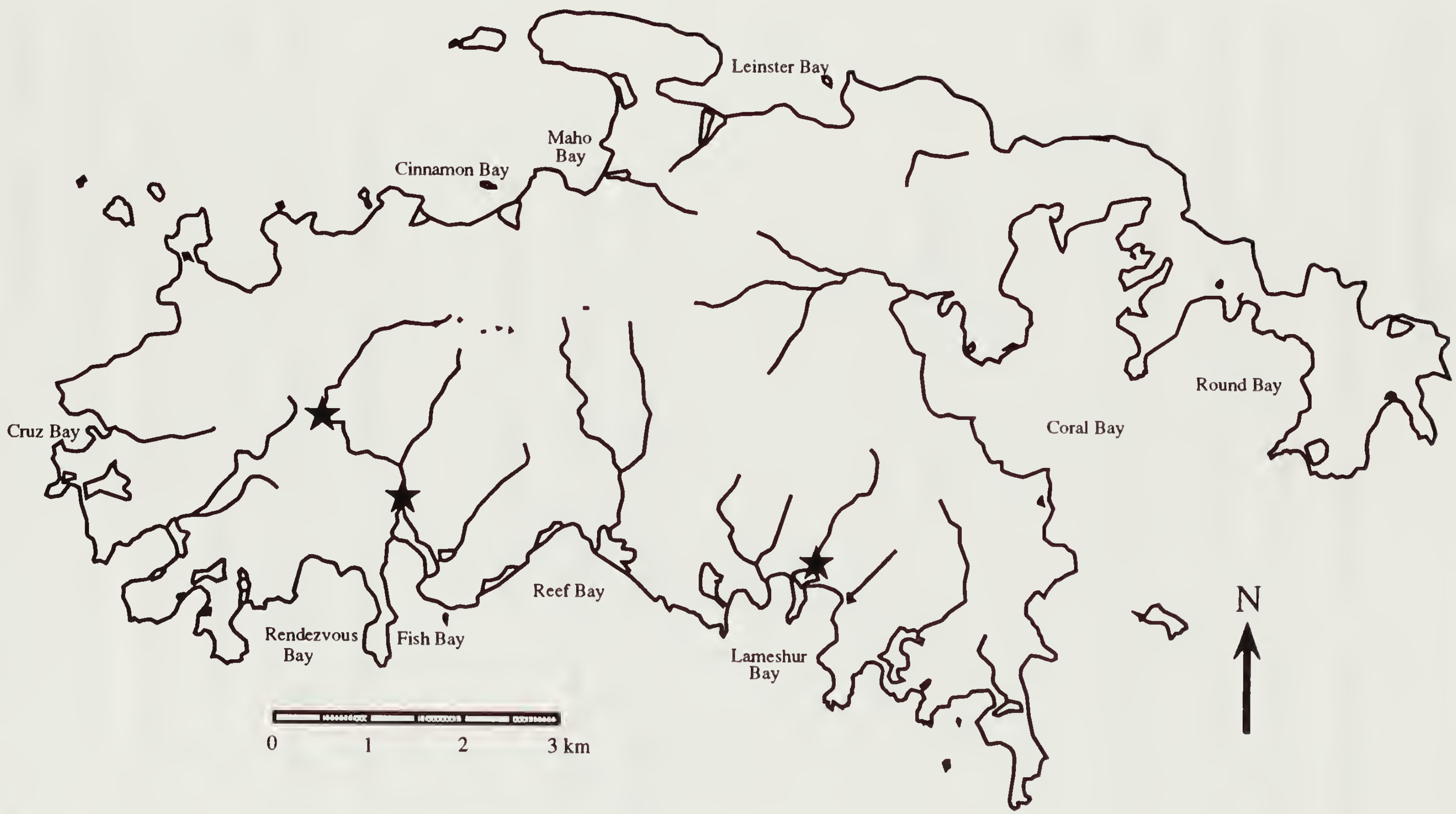

Figure 4.5. Location of streambed excavations (denoted by stars).

4.5 Results: Road Erosion Estimates

4.5.1 Field Measurements

In the Fish Bay watershed, approximately 16 km of roadways were measured and mapped in the field. Nine kilometers of these roads were not paved. Data from 23 road surface cross-sections in the Fish Bay basin yielded the following relationship between cross-sectional erosion rates, upslope road drainage area, and local slope (Figure 4.6 A):

$$E = 0.00057\, A * S + .034 \qquad (1)$$

where:

E = Estimated cross-sectional road erosion in m^2 per year

A = Upslope road drainage area in square meters, and

S = Road gradient as a decimal value

The coefficient of determination (r^2) for this relationship is 0.51, and the standard error is 0.031 m^2/yr. This predictive equation is the core of the GIS-based road surface erosion model described in the following chapter.

It should be noted that this equation is based on data collected from roads constructed or regraded between 1990 and 1993, which was an unusually dry period on St. John with relatively few major storm events (Eleanor Gibney, Caneel Bay

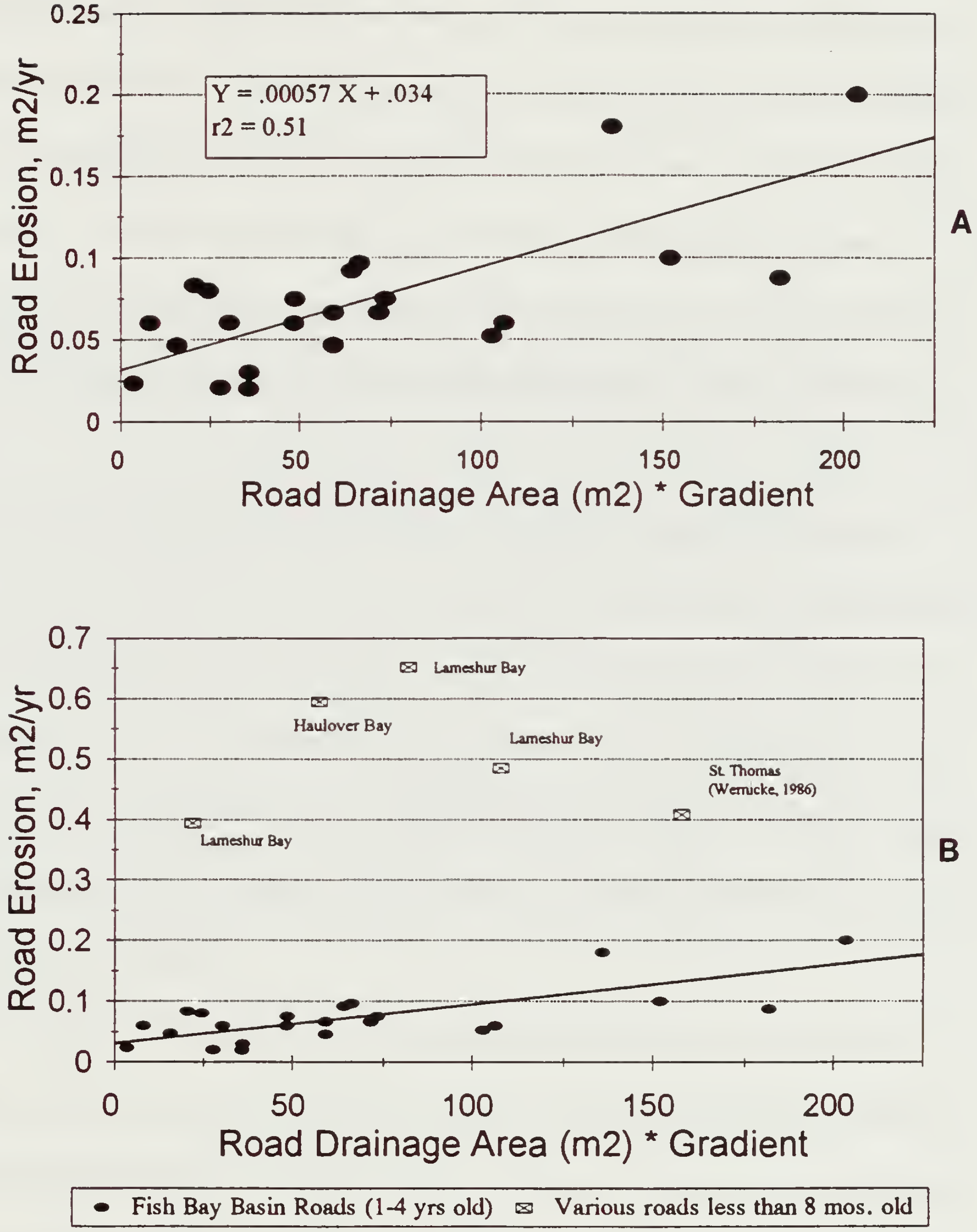

Figure 4.6. Road erosion vs. road gradient and drainage area.

Resort, pers. comm., 1994). Total measured precipitation at Caneel Bay Plantation from January 1990 through December of 1993 was 426 cm or 87% of normal based on the 38-year record. Only 27 storms during this four-year period exceeded 2.5 cm precipitation in 24 hours. The maximum 24-hour rainfall was 8.8 cm on 26 September 1990, and this has an estimated recurrence interval between one and two years (Cosner, 1972). Because storm frequency and intensity drive surface erosion, it seems safe to assume that the annual erosion rates predicted by the above equation probably are conservative in the sense that they underpredict erosion in an average year.

Road age also appears to be an important variable affecting erosion rates. Erosion and sediment delivery data from five sites where road surfaces were known to be less than eight months old all exhibit rates of erosion well above the 23 Fish Bay sites (Figure 4.6 B). Three of the five data points represent road surface measurements made on the access road to Lameshur Bay, one is based on estimated sediment accumulation behind a fence at Haulover Bay, and one is taken from Wernicke's (1986) study on St. Thomas.

It is possible that the higher erosion and sediment delivery rates outside of Fish Bay are due to site-specific differences, such as soil parent material. However, a more likely explanation for the higher rates is young road surfaces, as freshly-graded roads on St. John have an abundance of relatively loose material which is highly vulnerable to entrainment and transport with the first large storm event (Figure 4.7). These data suggest that the "first flush" of sediment production from freshly-graded

Figure 4.7. Loose, reworked Fish Bay road surface following grading.

road surfaces is considerably higher than the average annual production rates as measured in the Fish Bay watershed.

Other variables potentially influencing road surface erosion rates include road use, roadbed material, and runon from adjacent hillslopes and cutbanks. As noted above (Section 4.3), these variables proved significant in studies performed by Packer (1967) and Reid and Dunne (1984). None of these variables are incorporated into this road erosion prediction equation, nor did we measure the obvious contribution from sloughing sidecast material or cut banks.

Road usage was not incorporated into the predictive equation because of inconclusive field data. Data gathered on road use was subjectively rated low, medium, or high, and including this variable only explained an additional 1% of the measured variance in erosion.

Road surface characteristics, including particle size, stoniness, soil aggregation and parent material, may also be important road erosion variables on St. John. However, the limited data set precluded any attempt to evaluate these.

Road erosion measurements for St. John allow some general inferences to be made about island-wide road erosion rates. The three scenarios presented in Table 4.1 represent low-end, best-guess, and high-end estimates for the road network on St. John. These estimates are based on field observations, 1990 air photos (1:34,000), topographic maps (USGS, 1982), preliminary digital road data (John Parks, U.S. Geological Survey, pers. comm., 1994), and the road surface erosion measurements from Fish Bay basin.

Table 4.1. Estimated island-wide road surface sediment production.

Estimate	Total Roads (km)	Percent Unpaved Roads	Ave. Unpaved Road Width (m)	Ave. Road Surface Erosion (cm/yr)	Total Sediment Production (tonnes/yr)**
Low-end	75	50	3.0	1.0	1700
Best-guess	100	56*	3.5*	1.25*	3700
High-end	150	70	4.0	1.5	9500

* Based on Fish Bay road data

** Assumes 1.5 g/cm^3 bulk sediment density

Natural rates of sediment delivery on St. John, as described in Chapter 3, average about 20 tonnes km^{-2} yr^{-1}. Multiplied by the total land area of St. John (50 km^2), an average of about 1000 tonnes yr^{-1} of sediment are naturally delivered from all St. John watersheds. The estimates in Table 4.1 suggest that roads on St. John are responsible for an increase in sediment production approximately 2-10 times the natural rate. Based on the available data, this author's best estimate is that road surfaces produce sediment at about four times the natural background rate. This should be considered a conservative estimate of road sediment production as it ignores erosion from cutbanks, ditches, and fill slopes, and is derived from data taken over a relatively dry period.

4.5.2 History of the St. John Road Network

If roads are the primary source of sediment production on St. John, as is proposed here, island road history provides some perspective on the historic rate of sediment production. Sources indicate that a road system suitable for wheeled vehicles is a recent phenomenon. The first bulldozer did not arrive on the island until 1950 (Boulon, 1950). Only twelve years earlier an observer noted:

> "Today, if one would see the island thoroughly, one rides one of the small island horses or perhaps a shaggy burro or walks. There is no other way to get about, unless it is by boat. Save for a couple of two-wheeled carts and an old Model T Ford truck -- used by the WPA to build the schoolhouse at Coral Bay, and there abandoned -- there is not a wheeled vehicle on the island ... " (Jennings, 1938).

Although the remarkably detailed map of St. John compiled in 1780 by Peter Oxholm shows an extensive network of trails, it can be surmised that their width and intensity of use, especially in steep areas, was much less than today's roads. Some mule-drawn carts were in use during the plantation era (Stephen Edwards, St. John historian, pers. comm., 1994), but most of the trails on the island wound their way over rugged terrain and probably were negotiable only by foot, horse, or donkey. This image is reinforced by the observations of various visitors to the island over a 64-year period during the plantation era. The following observations were made on the eastern side of the island a few decades after the 1733 slave rebellion:

> "Two widely separated points forming Coral Bay are uninhabited and completely deserted. Large, tall trees and mountains eliminate all possibilities for passage, except along the beach, which is difficult, since the road is very poor ... The road over the mountains here is extremely steep; consequently the

> people seldom leave their dwellings and live like hermits for months ..." (Oxholm, 1780).

Following a tour of duty on the island, a Danish naval officer noted:

> "The ride over the mountains in the heat of the day was difficult but interesting." (Dahlerup, *c.* 1827).

Traveling out of "Mahoy Bay" on horseback in 1844 (just four years before the abolition of slavery), another traveller made these observations:

> "A mile or two further, we left the main road for a short cut across a hill, by what is called Crook Path (from the Iron Crook hung over the mules for carrying bundles of the sugar cane), the zig zag road up the steep seemed rather a ticklish affair, and but for the sure footedness and climbing tact of the ponies, not free from danger." (Morton, 1844).

In summary, "roads", as we think of them today, appear to have been largely non-existent on St. John until the arrival of the bulldozer in 1950. Hence the accelerated rates of sediment delivery induced by roads on St. John is primarily a recent phenomenon.

4.6 Results: Stream Sediment Delivery

Figure 4.8 illustrates the size distribution of particles comprising the bed of each of the three streambed study sites. These measurements represent particle size counts (Wolman, 1954) performed at each site prior to excavation of the bed surface.

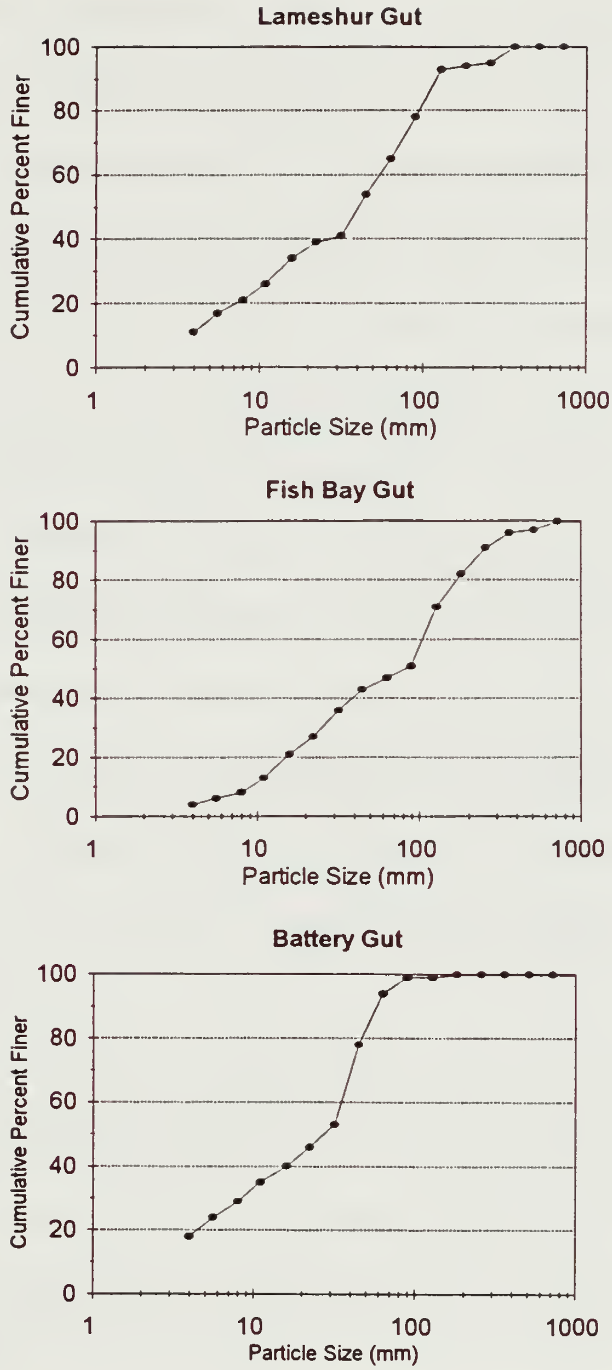

Figure 4.8. Particle size distributions for the surface layer of Fish Bay, Greater Lameshur, and Battery Gut streambeds.

Stream beds were selected that had low gradients, were not located at pools or steps, and were not encumbered by boulders too large to move by hand. Thus, none of these sites is necessarily representative of the entire reach.

Figure 4.8 illustrates that each of the selected stream beds has a bimodal distribution of particle sizes, and a large component of coarse material. The D_{50} (fifty percentile intermediate diameter) from these cross-sections in Lameshur, Fish Bay, and Battery guts are about 40, 90, and 30 mm respectively.

The general observations made at each site are described below:

In **Lower Lameshur Gut** (Figure 4.9), lichens on the largest boulders suggest that they have not moved for many years. Removal of the surface litter and rock layer revealed a thick, well-developed root mat stabilizing many sands and fine gravels. Below the root mat was a supporting matrix of cobbles and boulders containing additional sands and gravels. At a depth of 50 cm, the bed consisted mostly of relatively clean sands and gravels. Very little silt and almost no clay could be found in the substrate.

The streambed morphology suggests that cobbles and boulders effectively armor the underlying sediments during small- and medium-sized runoff events. Streamflows of sufficient size to entrain surface particles appear to be rare, but when they do occur they likely destabilize the underlying root mat and mobilize massive quantities of sediment.

Lower Fish Bay Gut displayed a different streambed morphology. Here, the bed surface again was armored by boulders and cobbles. Removal of the surface

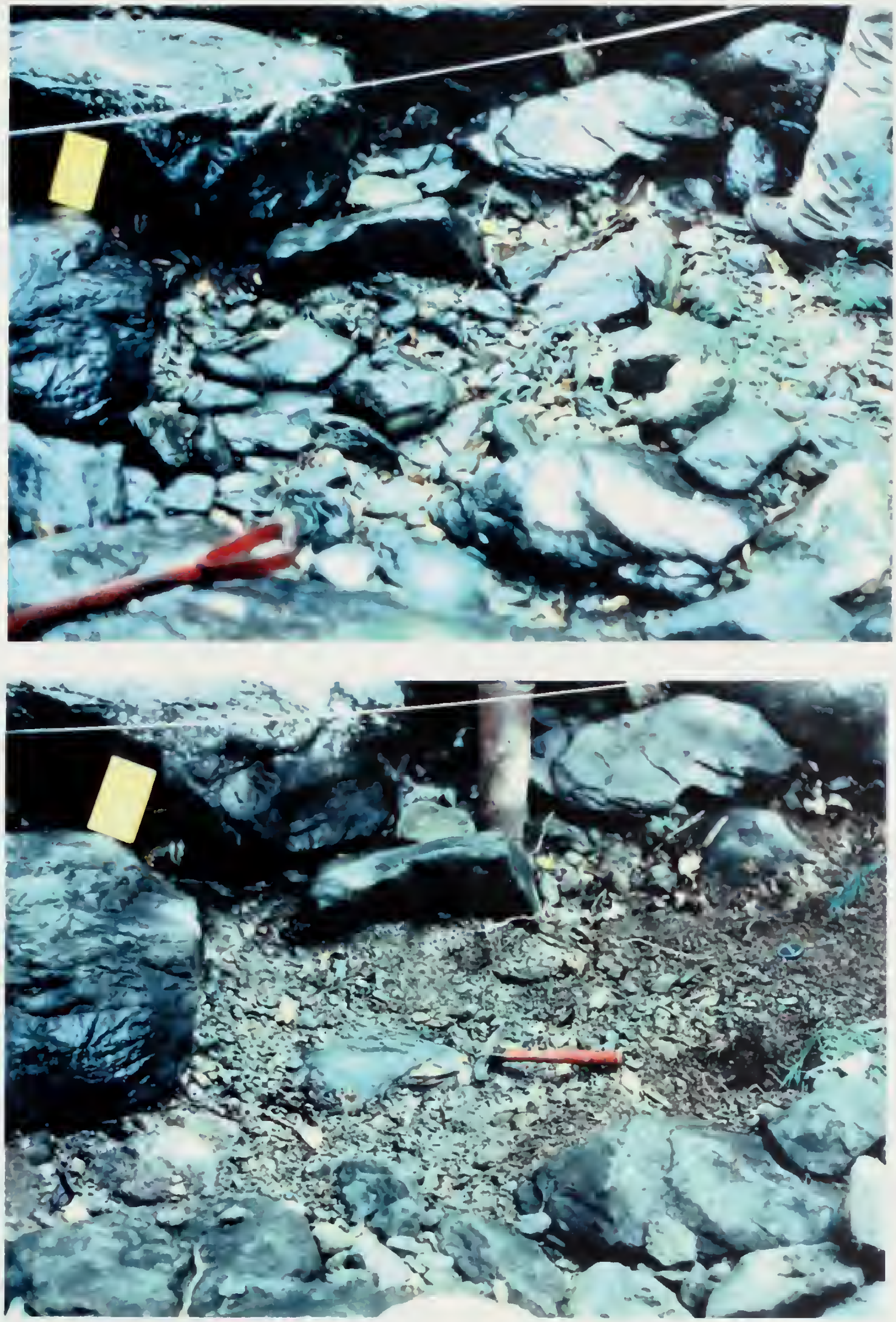

Figure 4.9. Excavation of Greater Lameshur Gut streambed. Above: After removal of forest litter. Below: After removal of top layer of bed surface particles.

layer revealed about 1-3 cm of clean midsized- to fine gravels, and below the gravels a layer of dense gleyed clay. In some spots, this clay fills the voids between boulders, so we may infer that it is stream-deposited. Boulders and/or bedrock are found below the clay layer.

The bed morphology of Fish Bay Gut suggests that cobbles and boulders effectively armor the streambed during small- and medium-sized runoff events. In contrast to Lameshur Gut, it appears that a substantial amount of clay has been assimilated into the channel bed.

In **Battery Gut**, the streambed morphology is similar to that in Lower Fish Bay Gut. The bed surface is armored by boulders and cobbles. Some clays and silts are found in the subsurface, but they are less abundant than in Lower Fish Bay Gut.

The shallow depth and limited available void space exhibited by each of these streambeds suggest that they have little capacity to assimilate and store fine sediments.

Preliminary suspended sediment data from lower Fish Bay Gut and lower Lameshur Gut indicate that a large proportion of suspended sediment in these channels during two 1992 runoff events consisted of silts and clays (Table 4.2). The predominance of fine sediment sizes, which are easily transported in storm runoff, suggests that a large proportion of sediment reaching stream channels is likely to reach the ocean or other depositional areas at the mouth of the basin.

Table 4.2. Preliminary USGS suspended sediment data for Lameshur Gut and Fish Bay Gut. Fines are defined as particles less than 0.062 mm in diameter (silts and clays).

Date	Time	Gage Ht (ft)	Sed. Conc. (mg/l)	% Sand	% Fines
Lameshur Bay Gut					
28 Nov 92	1109	2.07	102	3.5	96.5
28 Nov 92	1304	5.04	66	5.6	94.4
28 Nov 92	1809	2.12	89	1.2	98.8
12 Dec 92	0858	1.70	184	2.6	97.4
12 Dec 92	1202	1.99	161	6.2	93.8
12 Dec 92	1400	2.11	59	0.0	100.0
Fish Bay Gut					
28 Nov 92	1335	NA	343	4.7	95.3
28 Nov 92	1406	NA	75	2.3	97.7
28 Nov 92	1615	NA	75	3.4	96.6
12 Dec 92	0303	2.00	1150	4.1	95.9
12 Dec 92	1046	1.44	95	3.3	96.7

4.7 Summary

The field observations and other information presented in this chapter leads to the following conclusions:

- Most present-day land use and development activities on St. John do not result in extensive, long-term exposure of unprotected soil surfaces to storm runoff and erosion. However many exceptions were observed, in particular the establishment of unpaved roads;

- Measurements indicate that unpaved road surface erosion rates on the island (1) bear a strong relationship to road surface drainage area and road grade, (2) are highest in the first few months following road plowing or regrading, and (3) are collectively producing sediments 2 to 10 times faster than the natural erosion rate on St. John;

- Landslides and debris flows are not major mechanisms of erosion or sediment production on St. John, either under natural conditions or as the result of human disturbance; and

- A cursory evaluation of streambed characteristics in the Lameshur and Fish Bay watersheds suggests that they have little capacity to assimilate and store silts and clays. However, it is difficult to infer the rate of sediment movement

through the stream channels of St. John based solely on the observations presented in this report; additional field investigation of hillslope and stream sediment transport processes is recommended.

CHAPTER 5:

EROSION HAZARDS MODELING I:

A GIS-BASED ROAD EROSION AND SEDIMENT DELIVERY MODEL

A road erosion model was created to meet two objectives of this study: (1) to develop an automated method of using road data in a GIS format to estimate (or predict) the quantities of sediment produced by existing (or envisioned) roads on St. John island, and (2) to estimate current rates of sediment production from road surfaces in the Fish Bay and Lameshur Bay basins.

The St. John road erosion model (ROADMOD) is written in "C" programming language. The source code, which was developed for compilation on a UNIX workstation, is included as Appendix A. The executable program processes ASCII-formatted data exported from an Arc/Info GIS road coverage. The output of this program is a comma-delimited ASCII file that may be re-imported to Arc/Info to display the model results.

This chapter describes the St. John road erosion model and identifies the assumptions inherent to the model. This chapter then discusses two case studies applying this model on St. John. A step-by-step description of how this model may

be used with GIS-formatted road data is included as Appendix B. Figure 5.1 summarizes the key steps for use of ROADMOD.

5.1 Model Description

ROADMOD estimates the annual quantity of sediment eroded from road surfaces in a bifurcating network of roads. Sediment quantities are estimated using the empirically-derived relationship described in section 4.5 of this report. In order for this model to operate properly, road data must be set up in vector GIS format as a linked network of road segments[4]. The following data must be exportable for each road segment:

- Unique identification number;
- "From node" number;
- "To node" number;
- Road length in meters;
- Average road width in meters;
- Average road slope in percent;
- Road surface (paved, unpaved, or culverts/discharge points); and
- A "factor" estimating the proportion of flow from the adjacent "uphill" segment continuing onto this road segment.

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[4] This is a standard data format available in Arc/Info and most vector GIS packages. This report addresses data handling in the Arc/Info format, and will use the terms "arc" and "road segment" interchangeably.

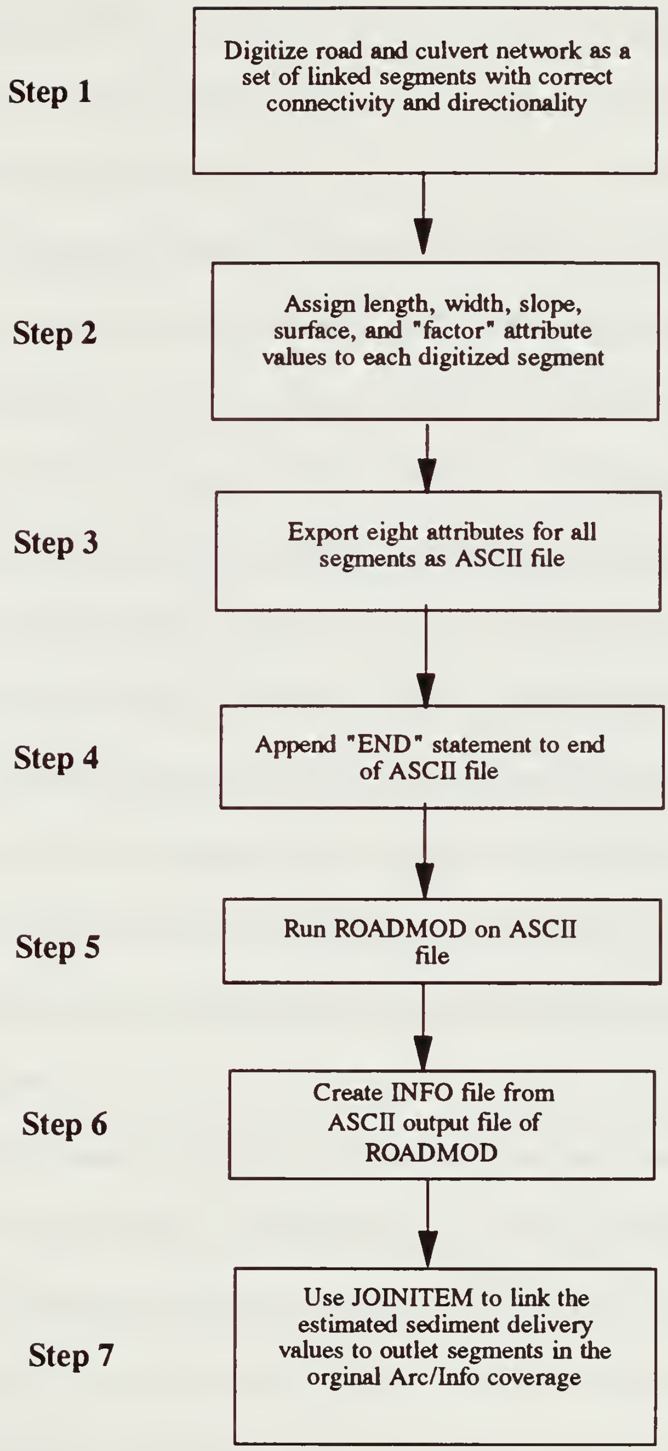

Figure 5.1. Steps for use of ROADMOD.

ROADMOD reads and stores the above data for each road segment from a user-supplied ASCII file. The model then identifies all road segments uphill of and connected to the segment being examined. Using the width and length of each uphill road segment, and compensating for the proportion of runoff that is diverted before reaching the examined segment, the program calculates an "effective road drainage area" for the midpoint of the subject segment. If the subject segment is paved, the predicted erosion is zero. If the subject segment is not paved, this effective drainage area, together with the average slope of the subject road segment, is inserted into the empirical road surface erosion equation (1) described in Section 4.5. The predicted cross-sectional road surface erosion in m^2 for the middle of the segment is multiplied by the road length to yield an estimate of total annual erosion from that road segment.

Thus the first values generated by this program are estimated annual rates of erosion from each road segment in the network. The program writes these values to the screen. These values are not written to the export file, but the program easily could be modified to do so if the user is interested in saving segment-by-segment erosion estimates.

In this manner the program estimates and internally records quantities of erosion from each road segment. ROADMOD again loops through the data to identify every "outlet" segment in the network (that is, any road or point of discharge which does not connect to a downhill counterpart). For each outlet it sums the quantity of sediment delivered to that point from all connected roads. The algorithm for this step is similar to the algorithm used to estimate erosion from each road segment, except

that here the program maintains a running account of upslope sediment delivered to the outlet points, rather than the effective upslope drainage area.

5.2 Model Assumptions

As with any model, a number of assumptions have been made to simplify the representation of the system and use of the model. The most important assumptions are described below:

Assumption 1: Sediment storage in the road network is negligible.

ROADMOD assumes that all the material eroded from the road surface is delivered to one or more outlets. In other words, over the course of a year the net amount of detached sediment stored in the road network (e.g., in roadside ditches or gullies) is negligible. Field observations indicate that this assumption is reasonable.

Assumption 2: Cutbank, ditch, and sidecast erosion is negligible.

This model estimates sediment production from unpaved road surfaces only. Unfortunately, field data are not available to estimate sediment production from road cutbanks, ditches, and sidecast material. By ignoring these sediment sources the model underpredicts road sediment production.

Assumption 3. The bulk of road runoff is conveyed by the road surface.

Erosion rate estimates are based on an empirical model of road surface erosion, which in turn is based on field measurements made at selected locations on St. John in 1994 (Section 4.5.1). These field measurements were biased toward locations where it was evident that the road surface, rather than a road ditch, conveyed the bulk of storm runoff. Thus ROADMOD implicitly assumes that all road runoff flows on the road surface until it reaches a discharge location. In many cases this assumption is not valid because effective drainage ditches are in place. Where road ditches convey most runoff the model may over-estimate erosion.

Assumption 4. "Average" road slopes and widths are reasonable modeling approximations for the entire road segment.

This model treats each road segment as a homogeneous entity having a constant width, slope, and surface. In the real world, no road segment is perfectly homogeneous. However, this is not a serious modeling problem, since a heterogeneous road segment can always be represented as a series of shorter, more homogeneous segments. Also, errors in estimating these road characteristics will tend to average out.

Assumption 5. Both effective drainage area and sediment routing can be approximated with a single directional "factor".

ROADMOD allows runoff to be split in multiple directions through a runoff "factor", ranging from 0 to 1, for each road segment. This factor adjusts both the effective upslope drainage area for each road segment and the routing of sediments through the road drainage network. In the absence of data indicating otherwise, it seems reasonable to assume that a single "factor" will adequately approximate both the routing of overland runoff from road surfaces and the routing of sediment entrained by that runoff. However, it is difficult to estimate this value with certainty, and the proportion of runoff flowing in different directions can change over time with road use, road grading, and the progression of erosion.

5.3 Model Operation

ROADMOD was written to process data compiled in the Arc/Info vector GIS format[5]. The application of this model to a set of geocoded road data is straightforward provided the data are compiled in the expected format. However, use of this model does require two manual steps: (1) export of road data from GIS for data processing, and (2) import of the results to GIS following data processing.

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[5] This model can probably also be interfaced with data from other vector GIS packages, but it was written specifically for use with Arc/Info.

The user's primary concern should be to set up the road data in the appropriate GIS format. A user's guide describing the mechanics of each step is included as Appendix B.

Because ROADMOD processes floating-point values, it will generate predictions of sediment delivery to the nearest 10^{-6} m^3/year, which is equivalent to the nearest cubic centimeter. It should go without saying that the uncertainty of the source data, the inaccuracy of the underlying empirical equation, and the inherent variability in real-world conditions do not allow for such accuracy. A more appropriate approach is to round predictions to the nearest m^3/year. Even with rounding, these predictions must be treated as empirically-derived best guesses rather than reliable estimates.

Also, it must be remembered that this model estimates average annual sediment production based on 1990-1993 climate conditions. As discussed in Section 4.5, this period was relatively dry and characterized by few major storms. Thus this model probably underestimates sediment delivery during an average year on St. John. Moreover, high discharge events account for the majority of sediment transport (White, 1990), so actual erosion rates may be substantially higher in years with unusually large or frequent storms.

5.4 Case Studies: ROADMOD Application on St. John

Two St. John watersheds were selected to demonstrate the use of ROADMOD and evaluate model results: (1) Fish Bay catchment, and (2) Lameshur Bay catchment (Figure 5.2).

These basins were chosen primarily because they represent extremes in land development on St. John. Fish Bay basin has been experiencing extensive home building and associated road construction. The Lameshur Bay basin remains relatively undisturbed with few roads and virtually no residential, commercial, or industrial development.

These two basins also were chosen because they are part of a paired-watershed investigation of sediment discharge. In 1992 the U.S. Geological Survey (USGS) installed stage-activated suspended-sediment pump samplers on Fish Bay and Lameshur Bay guts. Data from these sites may help assess the validity of modeled road erosion.

5.4.1 Basin Descriptions

Fish Bay basin, as delineated in Figure 5.3, encompasses about 6.1 km^2. Most of the basin drains to Fish Bay Gut and its tributaries, including Battery Gut. A smaller portion of the basin drains directly to the bay, to mangrove lowlands immediately surrounding the bay, or to intermittent streams that are not tributary to Fish Bay Gut. Fish Bay itself is relatively protected from the open ocean by headlands (Fig. 5.3). It is fringed by extensive mangrove swamps, particularly on the east

Figure 5.2. Location of Fish Bay and Lameshur Bay Watersheds.

Figure 5.3. Fish Bay Watershed. The solid triangle indicates the location of the USGS gaging station.

side. The USGS suspended sediment gaging station is located on Fish Bay Gut and captures runoff from about 3.8 km^2 or approximately 62% of the basin (Figure 5.3).

Fish Bay basin is covered primarily by moist and dry forest vegetation (Table 5.1). Slopes in Fish Bay basin tend to be very steep in the lower portions of the catchment, but less extreme in the upper basin areas of Adrian and Susannaberg. The highest point in the catchment is 364 meters above sea level.

The soils of Fish Bay are predominantly Cramer gravelly clay loams and stony clay loams, which together cover 88% of the basin area (SCS, 1970)[6]. The remaining 12% is covered by San Anton, Pozo Blanco, Isaac and Jaucas soils, tidal flats, and volcanic rock.

Lameshur Bay basin, as delineated in Figure 5.4, drains an area of about 4.4 km^2. More precisely, this basin drains to three separate bays named Little Lameshur, Great Lameshur, and Europa Bays. A USGS suspended sediment gaging station is located on Great Lameshur Bay Gut, and this monitors runoff from about 1.0 km^2 or about 23% of the basin. A detention basin is located immediately below the USGS gaging station, and this was used to estimate average annual sediment yield over a period of roughly 40 years (Chapter 3).

Lameshur Bay basin also is covered primarily by dry and moist forest vegetation (Woodbury and Weaver, 1987), but the vegetation is generally drier than

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[6] Recent investigations on St. John by the U.S. Soil Conservation Service suggest that Cramer soils may be substantially less extensive than indicated in the 1970 soil survey, and that it may be appropriate to abandon the Isaac soil series designation. However, updated SCS soils information for St. John has not been published as of this writing, and thus is not addressed in this report.

Table 5.1. Characteristics of the Fish Bay and Lameshur Bay watersheds. Land cover is based on Woodbury and Weaver (1987) and soil types are from SCS (1970).

	Fish Bay basin	Lameshur Bay basin
Total Area (km2)	6.1	4.4
Land Cover (percent of total area)		
Moist forest	44	11
Dry forest	26	51
Thicket and scrub	25	10
Pasture	2	0
Rock and coastal hedge	1	4
Thorn and cactus	0	3
Disturbed vegetation	0	18
Mangroves, lagoons and ponds	1	3
Other	1	0
Total	100%	100%
Slope Ranges (percent of total area)		
< 20% slope	31	17
20 - 40 %	33	62
> 40%	36	21
Total	100%	100%
Soil types (percent of total area)		
Cramer gravelly/stony clay loam	88	86
San Anton clay loam	3	0
Isaac clay loam	3	0
Pozo Blanco clay loam	3	0
Jaucas sand	1	0
Volcanic rock land	1	6
Cobbly alluvium	0	3
other	1	5
Total	100%	100%

Figure 5.4. Lameshur Bay Watershed. The solid triangle indicates the location of the USGS gaging station.

in Fish Bay basin (Table 5.1). Lameshur Bay catchment is largely under the ownership of the U.S. National Park Service and remains relatively undisturbed.

With the exception of the alluvial flats and mangrove lowlands, the terrain of Lameshur Bay basin is very steep. 83% of the basin has slopes exceeding 20%. The highest elevation in the catchment is Bordeaux Peak at 387 m above sea level.

The soils of Lameshur Bay catchment, like those of Fish Bay, are dominated by Cramer clay loams and stony clay loams (86%). The remaining 14% of the basin includes cobbly alluvium, swamps, tidal flats, volcanic rock, rock complexes, and water (SCS, 1970).

5.4.2 Modeling Methodology

Road Representation

All active roads in the Fish Bay and Lameshur Bay basins were mapped in the field. Road widths and lengths were measured by pacing. A single "average" road gradient was estimated and recorded for each road segment using a Brunton compass. Road surface characteristics, connectivity, and downhill directions were noted, and the location of culverts and other points of runoff from the road surface were recorded.

These road segments were digitized as a networked system of vectors using the Arc/Info geographic information system. Field data were linked to each segment following the procedures described in Appendix B.

Sediment Delivery Estimation

At each point of runoff from the road and culvert network, information was recorded on the nature of the area receiving the discharge. Receiving areas were classified as either: (1) stream channels; (2) protected hillslopes; (3) unprotected hillslopes; or (4) mangrove flats. A "protected hillslope" was defined as an area with a protective cover of vegetation and no sign of hillslope incision. An "unprotected hillslope" was defined as an area with little or no protective vegetative cover and/or obvious signs of incision due to culvert or road runoff.

The nature of the receiving area was used to estimate sediment delivery ratios at each culvert or drainage point. The **sediment delivery ratio** is the proportion of detached sediment reaching the outlet of the basin (Walling, 1983). Road-derived sediment generally consists of fine sands, silts and clays, and these tend to have high delivery ratios once they reach a stream channel. Where road runoff discharged to stream channels, a sediment delivery ratio of 1.0 was therefore assumed. For discharge to protected hillslopes, a delivery ratio of 0 was assumed, i.e., sediment is assumed to be deposited on the hillslope and not delivered to the basin outlet at greater than natural rates.

For discharge to unprotected hillslopes and mangrove flats, an arbitrary delivery ratio of 0.5 was assumed. This is based on a judgment that some but not all of the fine sediments discharged to these slopes will reach the basin outlet within a few years. It could be argued that a higher or lower delivery ratio would be appropriate;

however changing this value does not greatly affect the conclusions of these case studies.

As is discussed in Section 4.6, it is likely that the bulk of fine sediment reaching the stream channels of St. John is delivered to the marine environment, and thus contributes to offshore sediment and turbidity problems. In some cases, however, mangrove lowlands or salt ponds may assimilate sediments and mitigate sediment impacts on the marine environment. The author posits that these areas may not be as effective in this function as is commonly believed. First, during large runoff events these sites are prone to flooding and fine sediment flushing. Second, these sites gradually fill with sediments and eventually lose their storage capacity. Third, these areas are vulnerable to destruction from development, judging by the history of lower Guinea Gut and other former mangrove areas on St. John and St. Thomas. One also should question whether storage of excess sediment is an appropriate use for these areas, in light of local government guidelines explicitly stating that these areas are to be protected (Chapter 7).

5.4.3 Modeling Results

ROADMOD was run on the networked Fish Bay and Lameshur Bay road and culvert data following the procedures described in Appendix B. The predicted annual rates of sediment delivery to discharge points within each watershed are illustrated in Figures 5.5 through 5.7.

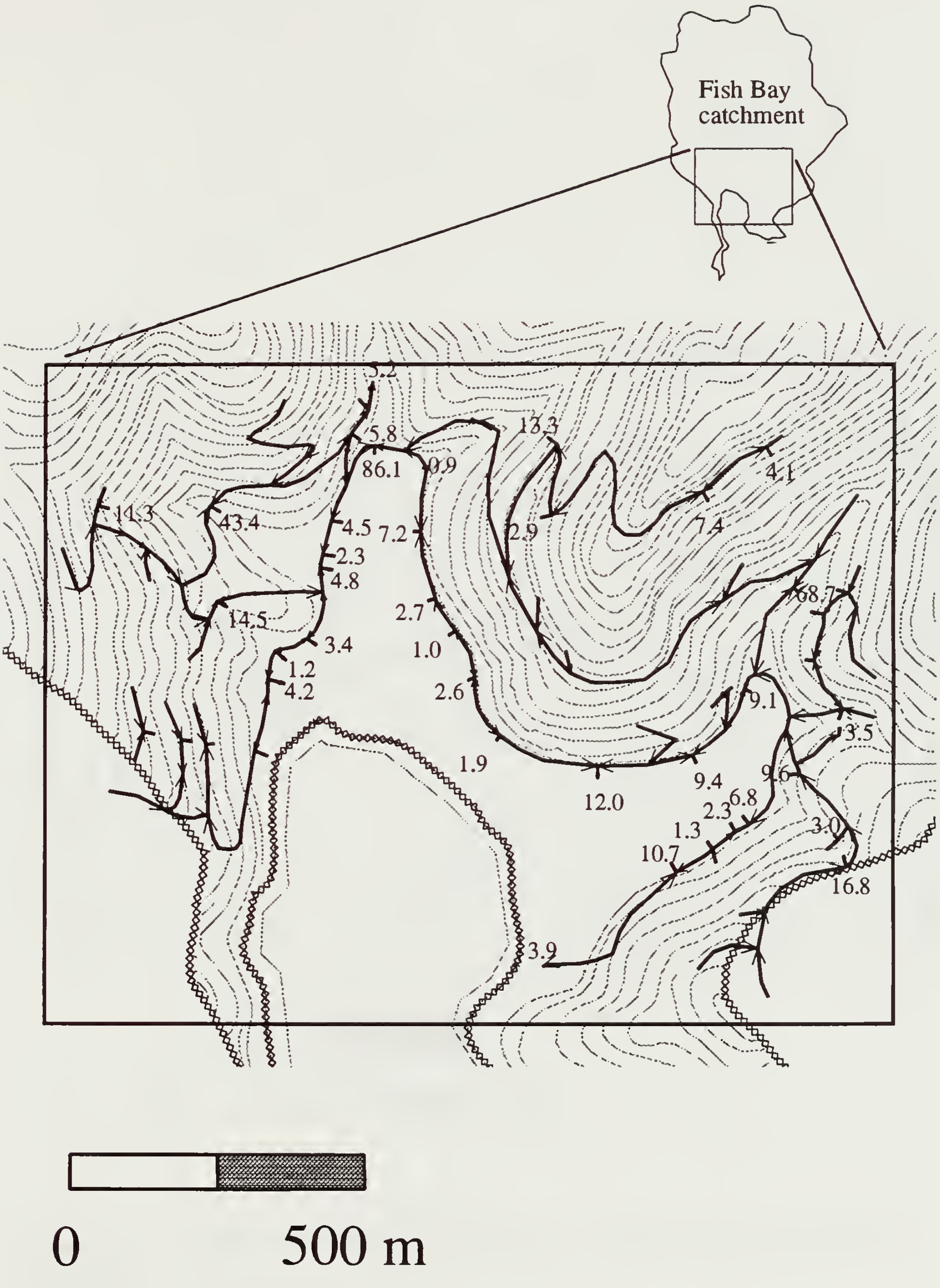

Figure 5.5. Predicted road sediment delivery, lower Fish Bay Watershed, in m^3/year. Roads in the lower left part of the map are paved and have no sediment delivery values.

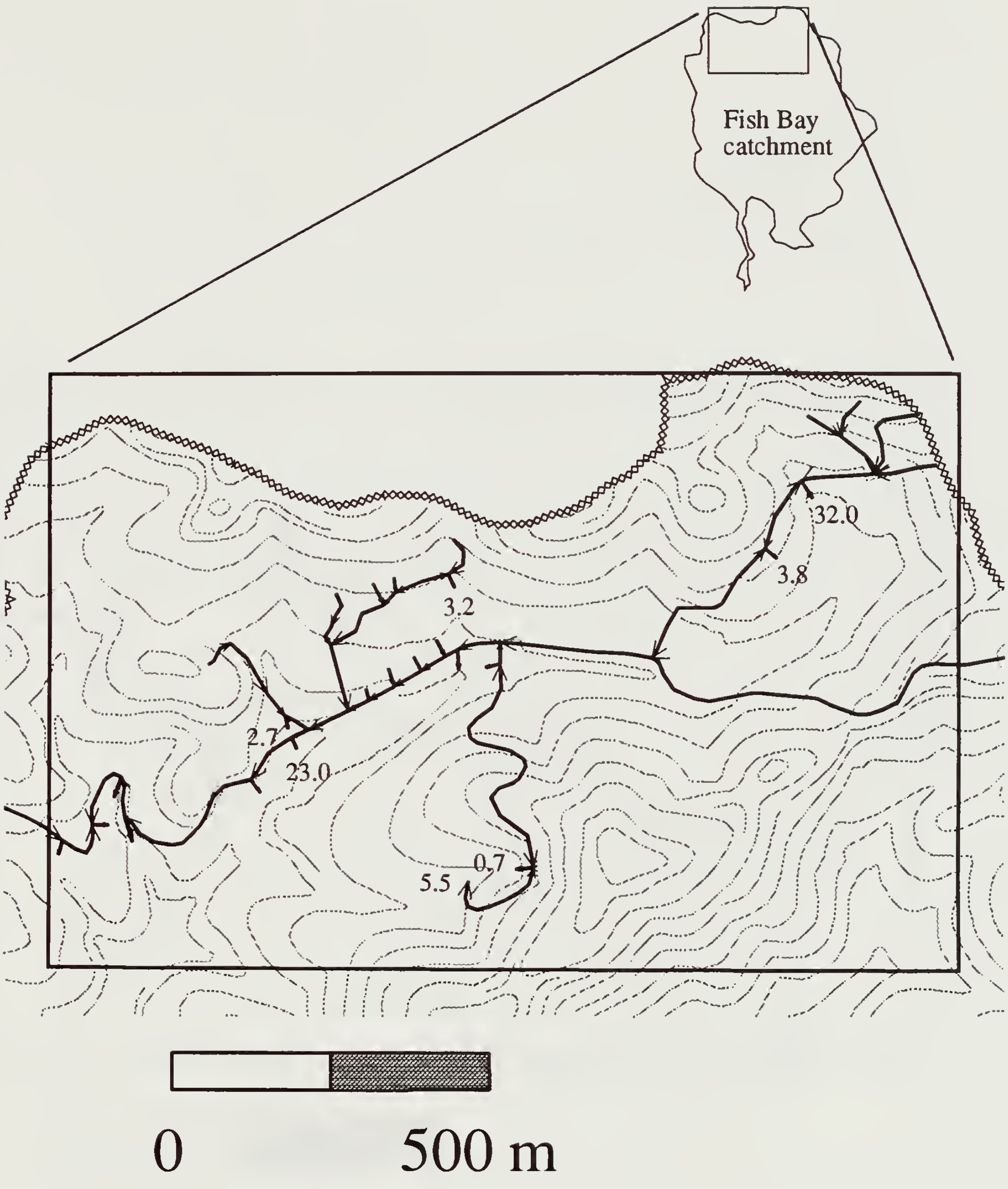

Figure 5.6. Predicted road sediment delivery, upper Fish Bay Watershed, in m^3/year.

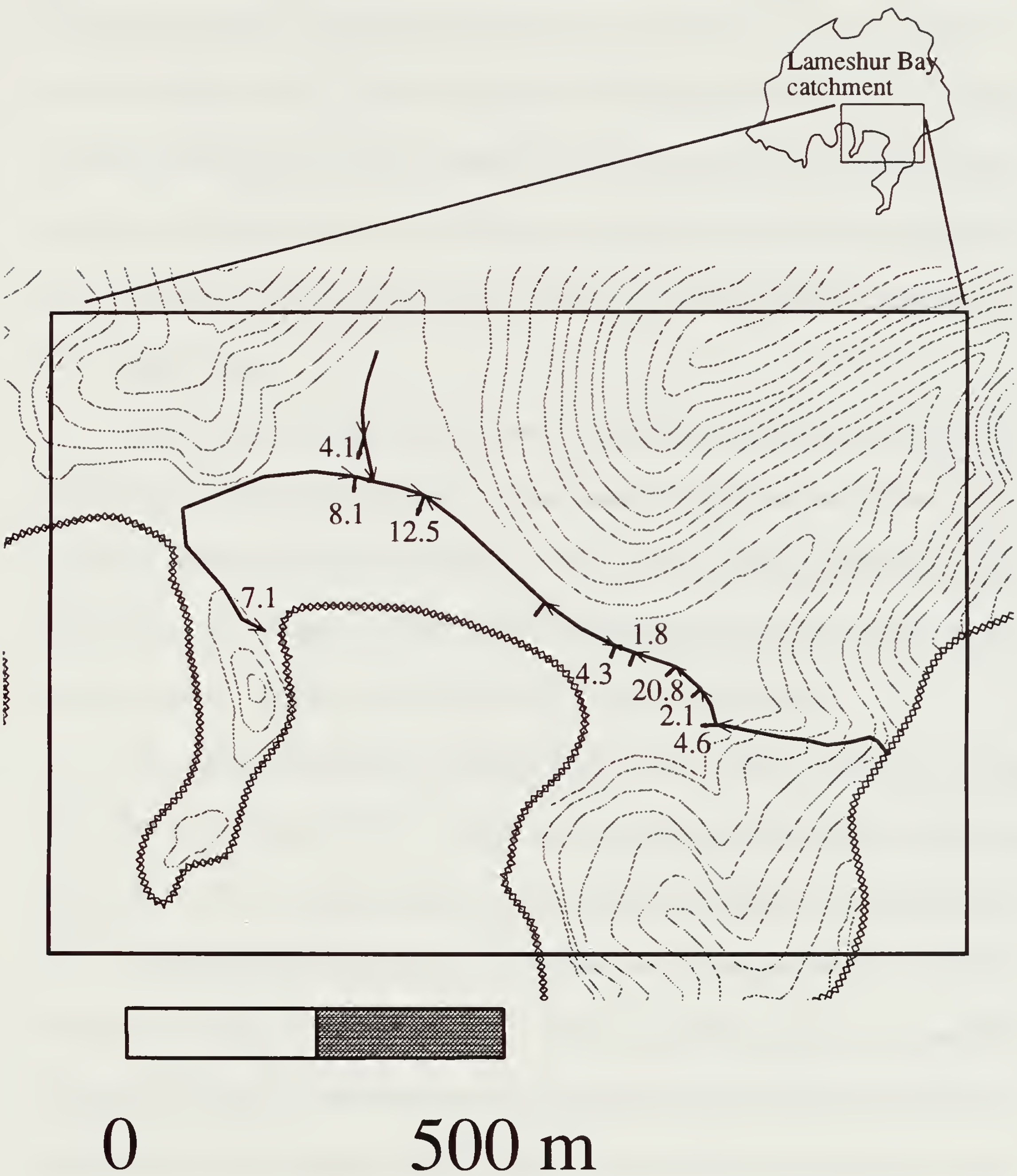

Figure 5.7. Predicted road sediment delivery, lower Lameshur Bay Watershed, in m^3/year.

The model predicts 390 m^3 of sediment is generated annually by the unpaved road surfaces in the Fish Bay watershed. Approximately seventy percent of this is delivered to the bay and mangrove lowlands in an average year. If an average sediment density of 1.5 g/cm^3 is assumed, then more than 400 tonnes of road-derived sediment is delivered annually to Fish Bay and the surrrounding mangrove flats. Since most of the unpaved roads discharge to points that do not drain to Fish Bay Gut, about 88% of the predicted sediment does not pass the USGS suspended sediment gaging station.

This estimate for Fish Bay presumes a delivery ratio of 0.5 for sediments discharged to unprotected hillslopes. If we presume a delivery ratio of zero, the estimated sediment delivery to Fish Bay from the road network is reduced by less than 10% to 377 tonnes/yr. Thus, the effect of the assumed delivery ratio on estimated sediment delivery from the Fish Bay watershed is negligible.

As described in Chapter 3, sediment yield under natural conditions is estimated to be about 20 tonnes km^{-2} yr^{-1}. When multiplied by the area of the Fish Bay drainage basin (6.1 km^2), average natural sediment delivery is around 120 tonnes/year. Thus, the predicted sediment delivery from the road surface network is more than three times the natural background rate. Total basin sediment delivery is probably substantially higher, as this estimate does not include sediment from the Majestic industrial site, grazed pasture lands, road cuts or road fills, or other sources in the watershed (Section 4.1).

In contrast, only about 65 m^3 of sediment is generated annually by the unpaved road surfaces in the Lameshur Gut basin. Approximately 33 m^3 or 50 tonnes is delivered to the bay, coastal ponds, and mangrove lowlands in an average year.

Since 130 tonnes is the estimated annual natural sediment yield for the 4.4 km^2 Lameshur Bay watershed, the 1.4 km of unpaved roads is believed to increase sediment delivery to the bay by about 40%. Nearly half of this sediment is generated by the single steep road entering the Lameshur Bay catchment from the east. This road typically is regraded several times a year (Cynthia Grippaldi, VIERS, pers. comm., 1994). As discussed in Section 4.5.1, sediment production is probably much higher from recently-graded roads than from the older road surfaces upon which this model was calibrated. Thus, the annual production of sediment from the road into Lameshur Bay may be considerably higher than predicted by ROADMOD.

5.4.4 Complementary Water Quality Data

Since 1988 the U.S. National Park Service has been collecting monthly water quality data from 30 offshore locations surrounding St. John island. Turbidity is one of the variables measured, and may be indicative of the amount of sediment being delivered to different offshore locations. Turbidity is usually due to the presence of suspended particles of silt and clay, although values can be affected by other materials such as fine organic matter, colored organic compounds, and microorganisms (MacDonald et al., 1991).

Three of the Park Service measuring sites are located in Lameshur Bay, and one is in Fish Bay. These have been assigned site identification numbers 18, 19, 20 and 22 (Figure 5.8). Between January 1988 and April 1993 median turbidities measured at Sites 18, 19, and 20 in Lameshur Bay were 0.39, 0.25, and 0.38 nephelometric turbidity units (NTUs), respectively. At Site 22 in Fish Bay, the median turbidity is 1.05 NTU (Figure 5.9). The nonparametric Wilcoxon rank sum test indicates that the difference in means between Fish Bay and each of the Lameshur Bay sites is significant at $p \leq 0.001$.

Although the cause of these differences cannot be identified from these data, the differences are consistent with the output of the road erosion model for these two catchments -- that is, the elevated delivery of road-derived sediment to Fish Bay probably contributes to higher turbidities. Island residents state that Fish Bay turns brown for up to several days each year following large storm events.

Figure 5.8. Park Service offshore water quality monitoring sites, Fish and Lameshur Bays.

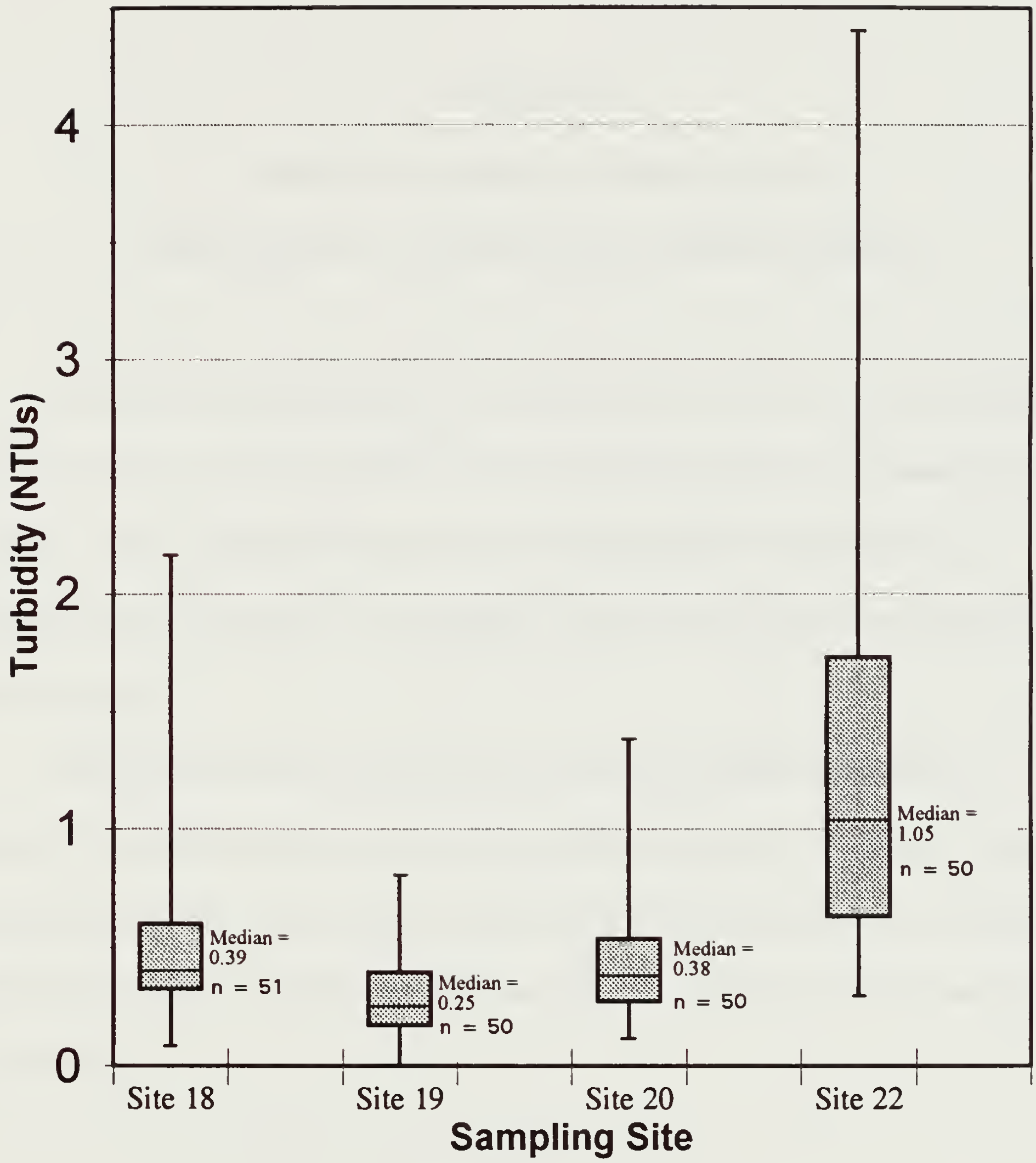

Figure 5.9. Summarized turbidity data, Fish and Lameshur Bays, 1990-1993.

Figure 5.[illegible] Summarized turbidity data, Fish and Lancaster Bays, 1990-1993.

CHAPTER 6:

EROSION HAZARDS MODELING II:

THE REVISED UNIVERSAL SOIL LOSS EQUATION

One of the products desired by the National Park Service is a map illustrating relative surface erosion susceptibility on St. John if the protective vegetation cover is removed. Such maps should support land use management and planning by identifying areas that are most vulnerable to erosion when the sites are cleared and the soil is exposed.

This study used the Revised Universal Soil Loss Equation (RUSLE) to generate a map illustrating the relative susceptibility of soils on St. John to surface erosion (back pocket). This chapter describes the RUSLE erosion model, describes the techniques used to estimate RUSLE parameters for St. John, and presents the model results.

6.1 The Universal Soil Loss Equation

The Universal Soil Loss Equation (USLE) is an empirically-derived relationship developed in the 1970's to predict average annual soil loss by sheet and

rill erosion (Wischmeier and Smith, 1978). Statistical analysis of more than 10,000 plot-years of runoff and soil loss data from research projects in 49 locations was used to develop the original empirical relationships for USLE. USLE became the most widely used erosion forecasting tool from the early 1970's through the 1980's (Lal, 1990).

USLE was recently updated to become the Revised Universal Soil Loss Equation. The basic equations of the model have not changed, but RUSLE incorporates improved methods for estimating parameter values (Renard et al., 1991).

6.2 RUSLE Parameters

Six factors reflecting the effects of precipitation, topography, vegetation, land management and soil characteristics comprise the RUSLE model. Specifically, RUSLE computes the expected erosion on a hillslope as:

$$A = R * K * L * S * C * P$$

where ***A*** is the computed average soil loss per unit area. Typical units of *A* are tons per acre per year. The predictive variables are: ***R***, the rainfall and runoff factor; ***K***, the soil erodibility factor; ***L***, the slope-length factor; ***S***, the slope-steepness factor; ***C***, the cover and management factor; and ***P***, the supporting practice factor (Renard et al., 1991).

(1) RUSLE is a widely-accepted technique for evaluating erosion potential. Although the quantities of eroded material predicted by RUSLE are often inaccurate, RUSLE's assessment of *relative* erosion potential under a range of cover conditions and management practices can be a useful land management tool; and

(2) RUSLE is well-suited to areas where infiltration-excess overland flow is likely to occur. On St. John, this includes areas that have been graded for roads, grazed intensively, or otherwise subjected to activities that expose and compact the soil and reduce its infiltration capacity. RUSLE assists in identifying the relative erosion susceptibility of areas subject to either infiltration-excess or saturated overland flow.

6.2.1 The Rainfall-Runoff Erosivity Factor (*R*)

If all other factors are held constant, soil loss from cultivated fields is directly proportional to a rainstorm parameter, the total storm energy ("E") times the maximum 30-minute intensity ("I_{30}"). This factor is called the rainfall-runoff erosivity ("EI" or "*R*") factor (Renard et al., 1991).

The relation of soil loss to *R* is assumed to be linear, and individual storm values are additive. The sum of the storm values for a given period is a numerical measure of the erosive potential of the rainfall within that period. Typically, average annual *R* values are used in the RUSLE model.

Average annual *R* values for the Virgin Islands, including St. John, are about 240 foot-tons per acre (SCS, 1980). *R* values for St. John probably vary across the island due to variations in precipitation totals and intensities. However, the spatial distribution of precipitation data for St. John makes it difficult, if not impossible, to map spatial variations in *R* with an acceptable degree of confidence. Thus, as a first approximation for this study, a single value of *R* is used island-wide.

6.2.2 The Soil Erodibility Factor (*K*)

The soil erodibility ("*K*") value used in RUSLE represents the inherent susceptibility of a soil to erosion. *K* equals the average soil loss in tons per acre per 100 foot-tons per acre of rainfall erosivity (i.e., per unit value of *R*) measured on a unit plot (Renard et al., 1991). A unit plot is defined as a 22.1 m length of uniform 9% slope in continuous clean-tilled fallow. *K* values are influenced by texture, organic matter content, and other soil characteristics.

Soil *K* values used for the St. John RUSLE model were provided by the USDA Soil Conservation Service (John Davis, U.S. Soil Conservation Service, St. Croix, pers. comm., 1993). Mylar-based soil maps provided by the Soil Conservation Service (SCS) were edge-matched and digitized as a single Arc/Info coverage[7] of St. John. *K* values were assigned to each digitized map unit in the database. A rasterized Arc/Info coverage of *K* values was then derived from the soil

[7] "Coverage" is standard Arc/Info terminology for geocoded point, line, polygon, or grid features and associated attributes, i.e., a digital map and its associated database.

polygon coverage using the majority weighting method. This yielded an Arc/Info map of *K* values in a 10 x 10 meter grid cell format.

6.2.3 The Slope Gradient Factor (*S*)

The slope gradient factor (*S*) for individual cells in this study area was determined using Arc/Info. A USGS 7-1/2 minute digital elevation contour map of St. John Island was provided by the National Park Service. From this coverage, a triangulated irregular network (TIN) terrain model of St. John was built (Fig. 6.1). This terrain model was used to determine the approximate average slope gradient within each 10 x 10 meter grid cell (Figure 6.2).

Most of the slopes on St. John exceed 30 percent. This results in relatively large values for *S*. As a result, slopes have a large influence on RUSLE-based erosion susceptibility estimates for the island.

Most studies of the effect of slope gradient on soil erosion have been conducted at sites with gentler slopes than those that prevail on St. John. Notable exceptions include Van Vuuren (1982) and McIsaac et al. (1987). Slope gradient - *S* relationships proposed by McCool et al. (1987) were used in this study. These are incorporated into the current version of RUSLE, and they appear to be approximately confirmed by the work of McIsaac et al. (1987). The relationships are:

$$S = 10.8 \sin\theta + 0.03 \quad \text{when } \theta < 5.14 \text{ degrees} \qquad (2)$$

$$S = 16.8 \sin\theta - 0.50 \quad \text{when } \theta \geq 5.14 \text{ degrees} \qquad (3)$$

where θ = slope gradient in degrees.

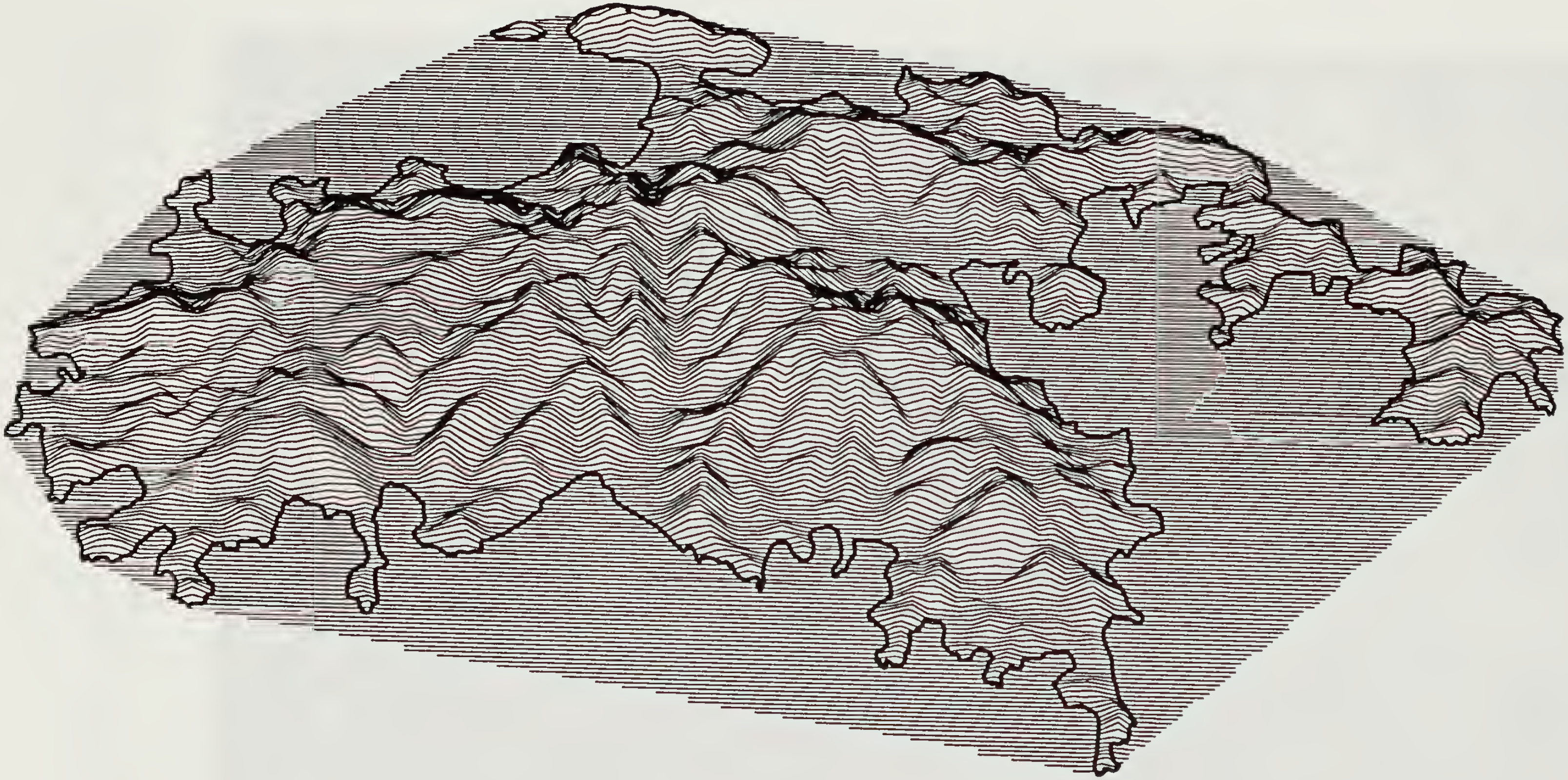

Figure 6.1. TIN digital terrain model of St. John.

Figure 6.2. Calculated slope gradients in Fish Bay watershed. Lightest to darkest grid cells respectively represent 0-10%, 10-20%, 20-40%, and greater than 40% slope gradients.

The resulting *S* values for extreme slopes are markedly lower than those proposed by either Wischmeier and Smith (1978) or Van Vuuren (1982) (Table 6.1). McCool et al. warn (p. 1395) that "application [of these relationships] to slopes greater than 18% represents an extrapolation beyond the observed data." Thus, while their *S*-value relationships appear to be the best-documented empirical relationships available, the scarcity of data on *S*-values for steep slopes remains a concern.

Table 6.1: A comparison of USLE *S* values using different formulae.

Slope (%)	**Wischmeier and Smith, 1978**	**Van Vuuren, 1982**	**McCool et al., 1987**
10	1.16	1.20	1.17
20	3.06	3.47	2.79
30	5.40	6.16	4.33
40	8.07	8.83	5.74
50	11.03	11.20	7.01
40	14.24	13.10	8.14
70	17.67	14.48	9.13

6.2.4 Slope Length Factor (*L*)

Determination of a valid slope length for use in the RUSLE model is particularly problematic. Renard and Ferreira (1993, p. 459) note that "most RUSLE users have more questions about the *L* factor than any other factor ... because of the

judgment involved in choosing a slope length." The basic definition of slope length is the length of slope from the origin of overland flow to the area where deposition begins or flow enters a well-defined channel (Wischmeier and Smith, 1978).

In many cases, this process-based definition of slope length will differ substantially from slope length as calculated from ridgetop to stream channel. A strict interpretation of slope length using this definition would result in values that vary in space and time with the duration and intensity of a storm event, and with antecedent soil moisture conditions.

The recommended RUSLE methodology for determining slope lengths is rather complicated. Field inspections and measurements are recommended (Renard et al., 1991). Ideally, these field inspections reveal localized changes in soil type, land cover, and topographic characteristics, including slope irregularities and areas of deposition. These are then used to adjust the *LS* factor.

With the advent of digital elevation models, automated means of determining ridge-to-channel slope lengths have become possible. Several alternative GIS-based methods for obtaining a slope length map for use with the RUSLE model were investigated by Blaszczynski (1989). He concluded that the most promising algorithm for determining slope length for his purposes was developed by Spanner (1983). The Spanner algorithm operates on a rasterized digital elevation model. The cumulative slope length for each grid cell is obtained by performing a sequential nearest-neighbor comparison of cell elevations, calculating the Pythagorean distance to the cell in the steepest slope direction, and then accumulating these values in the upslope direction.

More recently, Moore and Wilson (1992) describe an innovative approach for calculating the length-slope factor for RUSLE which, in theory, allows divergent and convergent terrain effects to be simulated. They argue that the *LS* factor in RUSLE is, in effect, a measure of the sediment transport capacity of overland flow. On this basis, they propose that the *L* factor should reflect the upslope contributing drainage area per unit contour length (also referred to as the **specific catchment area**, A_s) (Figure 6.3).

On planar hillslopes (i.e., non-convergent and non-divergent), A_s is the distance from the top to the bottom of the slope. Figure 6.3 suggests that convergent terrain (larger values of A_s) will produce more erosion per unit contour length *C* than divergent terrain if all other variables are equal. This is not reflected in the standard RUSLE slope length definition, since roughly the same "slope length" would be assigned to both situations.

The validity of the approach proposed by Moore and Wilson has been challenged (Foster, 1994; McCool, 1994). However Moore and Wilson (1994) maintain that "the concept of specific catchment area ... is conceptually and physically a far superior surrogate for runoff than is slope length". They note that specific catchment area reflects three-dimensional terrain characteristics, while the traditional definition of *L* technically is valid only for one-dimensional hillslope analysis. Moore and Wilson's approach was adopted for this study because it appears to provide the most physically meaningful representation of St. John's complex terrain.

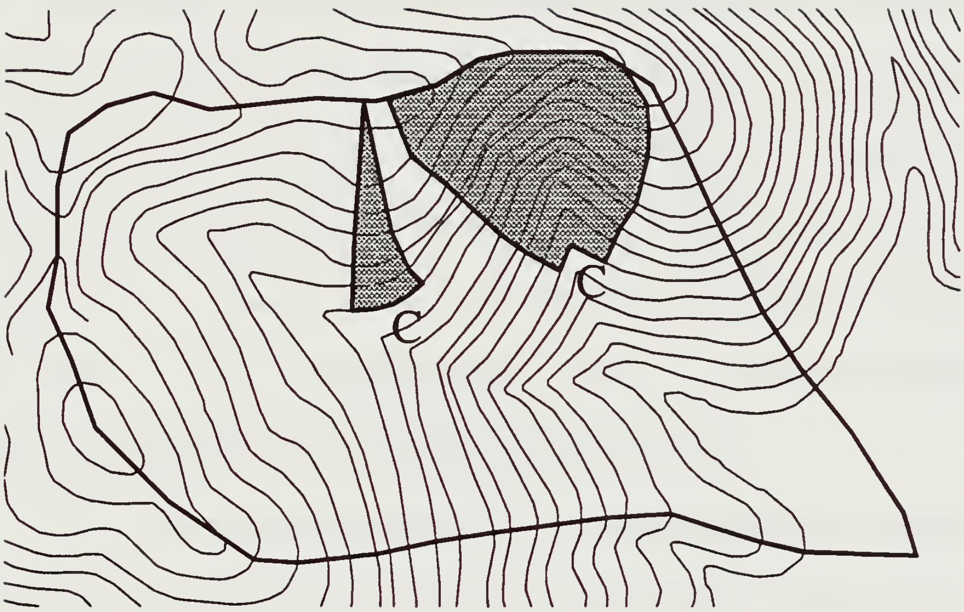

Figure 6.3. The concept of specific catchment area. A_S is the upslope contributing drainage area (shaded) divided by the contour length across which this drainage flows (C). Thus A_S is smaller in areas of diverging terrain (left) than converging terrain (right).

6.2.4.1 Catchment Area Calculation

Specific catchment area (A_s) is a spatially-varying landscape characteristic often used as a parameter in variable source area runoff models (e.g., Wolock, 1993). Various approaches have been used to calculate distributed values of A_s in a catchment based on elevation data. These include manual methods and the use of algorithms that process digital elevation data (e.g., Band, 1986; Jenson and Domingue, 1988).

A serious problem with most raster-based algorithms for the calculation of upslope drainage areas, including the algorithm incorporated into Arc/Info GRID, is that they direct all flow to the single steepest-slope direction. Fairfield and Leymarie (1991) refer to this as the "D8" ("deterministic eight-neighbors") method of flow routing. By allocating all flow to the neighboring cell with the lowest elevation, D8 algorithms have a strong bias towards the eight cardinal directions and away from the intermediate directions. This often results in output data which do not realistically represent drainage behavior on hillslopes (Figure 6.4 A).

This problem may be addressed by employing an algorithm which distributes outflow from a grid cell to more than one neighboring cell. Freeman (1991) developed an algorithm which distributes flow among all neighboring cells lower in elevation than the source cell in proportion to their respective differences in elevation. Hence the fraction f of the drainage area from cell j to be passed on to neighbor i is given by:

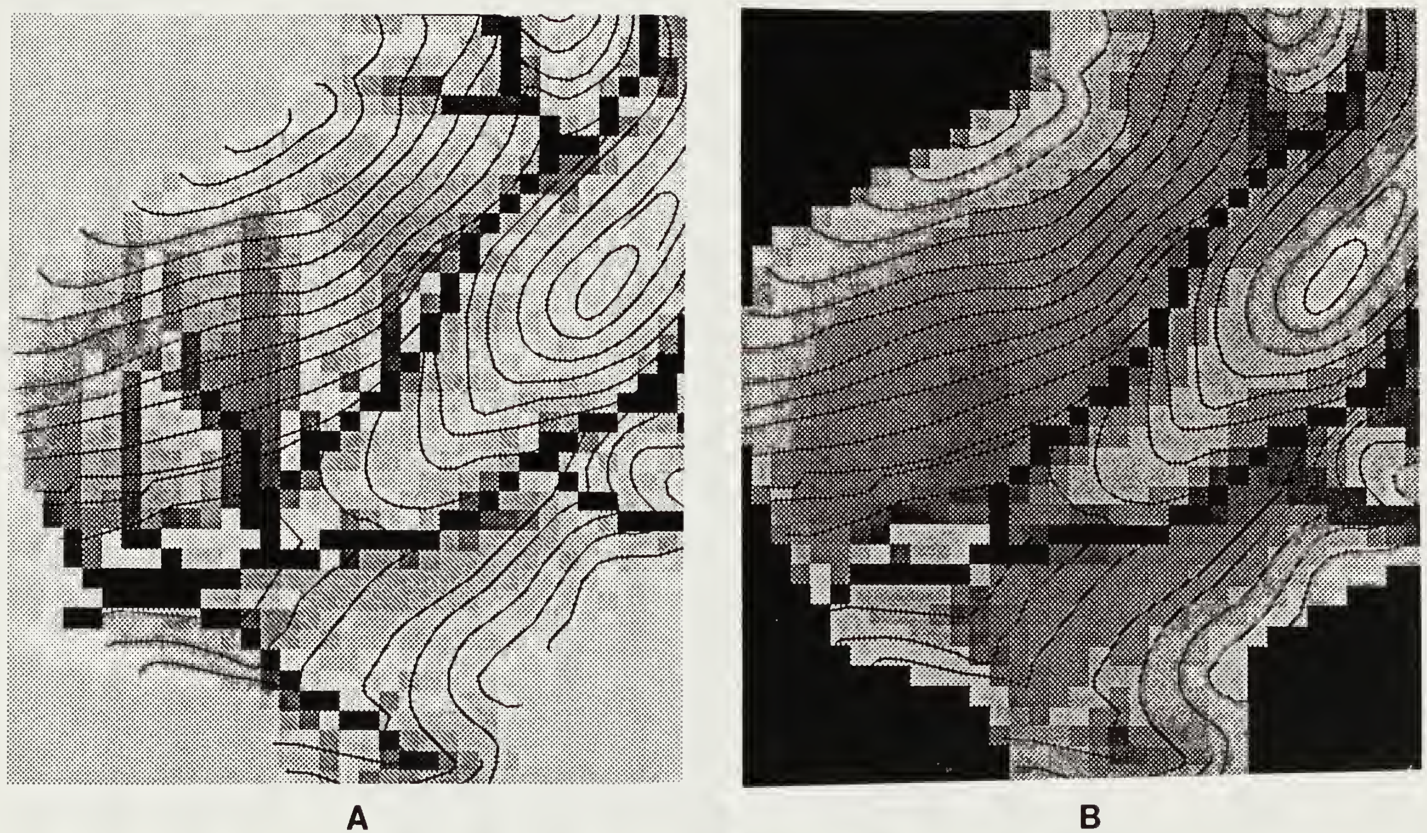

Figure 6.4. D8 vs. distributed-flow algorithm. Lines represent equal-elevation contours; darker cells denote greater flow accumulation. (A) Arc/Info's D8 flow algorithm results in an unrealistic bias toward flow accumulation in the eight cardinal directions. (B) Using the same input data, Freeman's (1991) distributed-flow algorithm results in a much smoother and more realistic distribution of flow accumulation.

$$f_i = \frac{\text{Max}\ (0,\ \text{Slope}^p_i)}{\sum_{j=1}^{8} \text{Max}\ (0,\ \text{Slope}^p_j)} \qquad (4)$$

A value of 1.1 for parameter *p* was determined to yield the best results (Freeman, 1991).

A comparison of Freeman's algorithm versus the standard D8 algorithm is illustrated in Figure 6.4. It has been demonstrated that this algorithm produces catchment area distributions that are virtually identical, spatially and cumulatively, to those produced by more conceptually elegant "flow tube" algorithms (Moore, in preparation).

For the St. John RUSLE model, the effective slope length was calculated by determining the upslope contributing drainage area for each 10 x 10 m grid cell and dividing by the contour length. The upslope contributing drainage area was calculated using the Freeman distributed flow algorithm. The contour length was estimated as a function of cell aspect using a simple FORTRAN program written by the author (Appendix C).

The logic of the contour length algorithm is that (1) the contour length is equal to one side of the grid cell only when the cell aspect is perpendicular to the cell side; (2) the contour length is maximum ($\sqrt{2}$ * cell side) at intermediate azimuths (i.e., at 45, 135, 225, and 315 degrees); and (3) contour lengths for all other aspects may be

approximated based on the cosine of the aspect. For aspects between 0 and 45 degrees, for example, contour length is equal to $(1 / \cos \theta)$ * cell size.

Once effective slope length values were determined for each grid cell representing the watershed, the following RUSLE *L*-value formula was applied to each cell:

$$L = (l / 22.1)^{0.6} \qquad (5)$$

where 22.1 equals the RUSLE unit plot length in meters and *l* is the slope length in meters. In fact, the exponent 0.6 is a variable which ideally is based on the ratio of rill to interrill erosion. Given the predominance of steep slopes on St. John, the range of values cited by Dissmeyer and Foster (1984), and the recommendations of Moore and Wilson (1992), 0.6 is assumed to be a reasonable value.

Any automated grid-based method of analyzing slope length, such as that described here, necessarily divides slopes into segments of arbitrary size, and assigns slope length values on a cell-by-cell basis. RUSLE slope length values determined in this segmented-hillslope manner (the "independent slope lengths method") were evaluated by Blaszczynski (1989). He concluded that the *LS* values generated by the independent slope lengths method are almost perfectly correlated to the *LS* values generated by traditional methods ($r^2 = 0.999$), but the former are consistently 75 percent of the latter. The *LS* values generated by the independent slope lengths method are believed acceptable because they are highly correlated with values determined in the traditional manner, and they provide a consistent, objective approach which is less susceptible to subjective field judgment (Blaszczynski, 1989).

The implication of Blaszczynski's analysis is that slope length values generated using the independent slope lengths method somewhat underestimate the actual rate of erosion. However, this does not affect the use of RUSLE as a tool for modeling *relative* erosion hazards, as in this study.

6.2.5 Cover Factor (*C*)

The *C* factor is equal to the ratio of soil loss from an area with specified cover and management to an identical area in clean-tilled continuous fallow. It is calculated as a weighted average of soil loss ratios (SLR's) summed over the course of an average year.

The *C* factor varies by several order of magnitude. Thus, selection of an appropriate value for *C* is particularly important if one wishes to use RUSLE to estimate actual rates of erosion. Since the intent of the maps produced in this study is to illustrate relative surface erosion susceptibility when the protective cover is removed, the *C* factor was set equal to 1. Spatially-varying C factors would have to be assigned to predict surface soil erosion under present land cover and management conditions.

6.2.6 Support Practices Factor (*P*)

The support practices (*P*) factor of RUSLE is the ratio of soil loss with a specific support practice to soil loss with up- and down-slope tillage. On cultivated land, *P* is affected by contour tillage and planting, strip cropping, terracing, and

subsurface drainage. On dryland or rangeland areas, it may be affected by contour practices intended to store moisture and reduce runoff (Renard et al., 1991).

The P factor was not incorporated into the surface erosion susceptibility maps for St. John for two reasons. First, agricultural and pasture lands on St. John amenable to "support practices" represent less than 3% of the island area. Second, the *P* factor is very site-specific, and it was not practical to assign values to each grid cell.

Recommended practices to reduce erosion on St. John are discussed in Chapter 7.

6.3 RUSLE-Derived Erosion Susceptibility Map

A map illustrating the relative susceptibility of surface soils on St. John to erosion, based on application of the RUSLE model as described above, is included in the back pocket of this document. Because the cover (*C*) and supporting practice (*P*) factors were ignored, and because the rainfall-runoff erosivity factor (*R*) was treated as a spatially-constant value, this map illustrates only the effect of differences in slope gradient (*S*), slope length (*L*), and soil erodibility (*K*).

This map identifies areas on St. John most likely to experience the greatest surface erosion if vegetation or other surface protection is removed. Five classes of surface erosion susceptibility ranging from "low" to "extreme" are identified. The range of $S*L*K$ values defining each class was selected arbitrarily using values which, in the opinion of this author, best illustrate relative erosion susceptibility. The values

separating each class successively increase by a factor of 2.3 (Table 6.2). Thus these classes reflect an exponential, rather than arithmetic, increase in erosion potential.

Table 6.2: Values for surface erosion susceptibility map classes

Erosion susceptibility class	***S * L * K* values**	**Map color**
Low	< 0.75	Off-white
Medium	0.75 - 1.73	Cyan
High	1.73 - 3.97	Yellow
Very high	3.97 - 9.13	Pink
Extreme	> 9.13	Red

Erosion susceptibility values are highest in areas of steep slopes and convergent terrain, such as upland swales and intermittent drainage channels. Values are lowest in areas of gentle slopes and small drainage areas, such as ridgelines and saddles. Because soil erodibility (*K*) values reported by the Soil Conservation Service (1970) do not vary greatly on St. John, soil types do not have much influence on the calculated erosion susceptibilities.

Figure 6.5 summarizes the steps involved in generating the surface erosion susceptibility maps using automated GIS procedures.

6.4 Susceptibility to Soil Saturation Map

As already mentioned in Section 6.2, the primary mechanism generating runoff from undisturbed areas of St. John is probably saturation overland flow. Areas

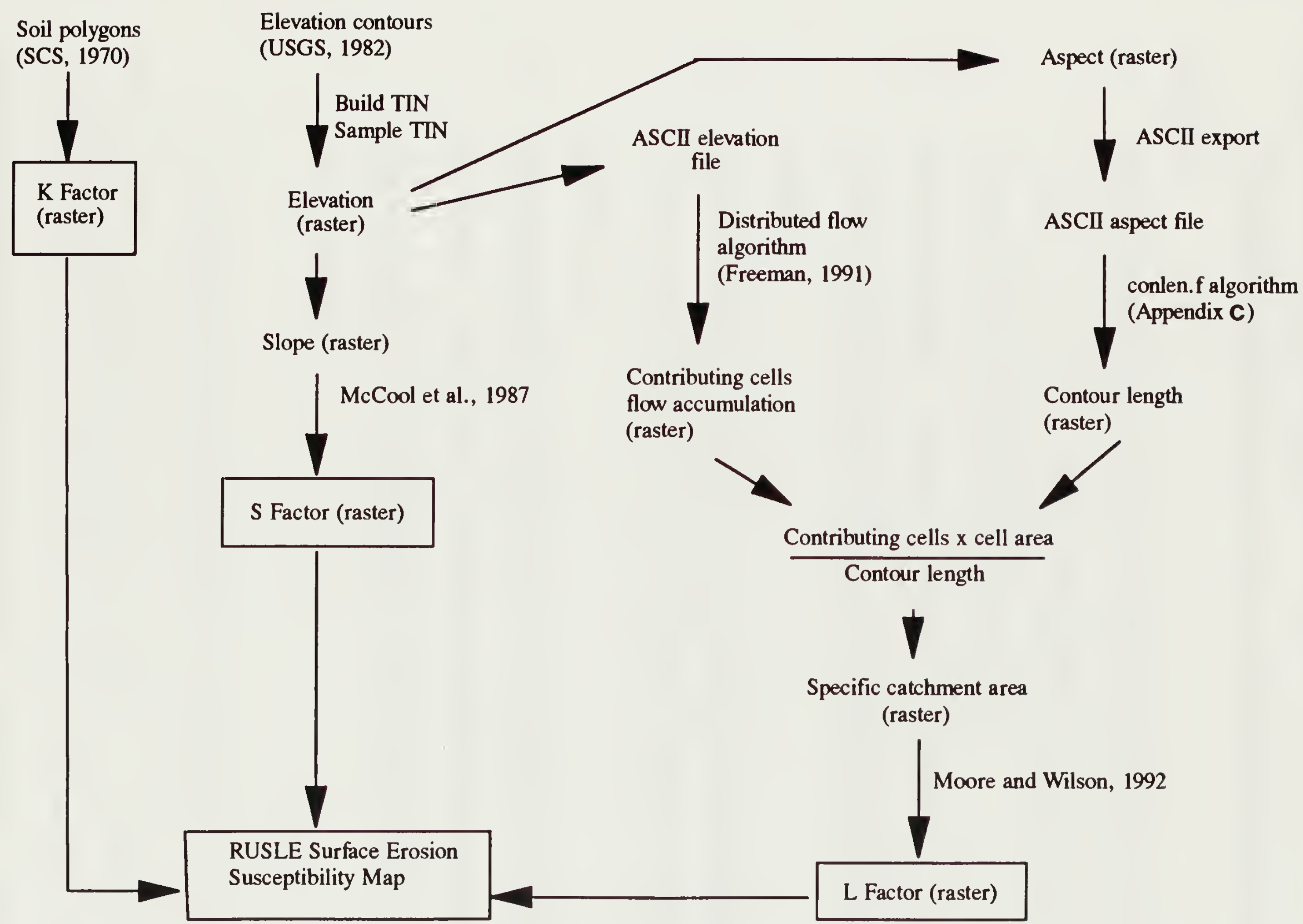

Figure 6.5. Steps to generate RUSLE erosion susceptibility maps.

contributing to saturation overland flow also have the greatest potential to mobilize sediment and transport it toward the watershed outlet.

The location of saturated source areas is a function of several factors, including:

(1) **Specific catchment area**. Larger catchment areas increase opportunities for saturation. An automated, GIS-based method for calculating specific catchment areas was described in Section 6.2.4.1;

(2) **Hydraulic gradient**. Lower gradients increase the likelihood of saturation. In saturated soils the hydraulic gradient may be approximated by the slope gradient;

(3) **Weather conditions**. Extended periods of rainfall, wet antecedent moisture conditions, and low rates of evapotranspiration increase the likelihood of saturation; and

(4) **Soil transmissivity**. Soil transmissivity is the soil depth times hydraulic conductivity. It measures a soil's ability to transmit water under a unit hydraulic gradient. Low transmissivities reduce subsurface flow and help induce saturation.

A map illustrating relative susceptibility to soil saturation and saturation-induced runoff was generated for St. John (back pocket). The steps involved in generating this map using automated GIS procedures are summarized in Figure 6.6. Values for each 10 x 10 m grid cell were obtained by dividing the estimated specific

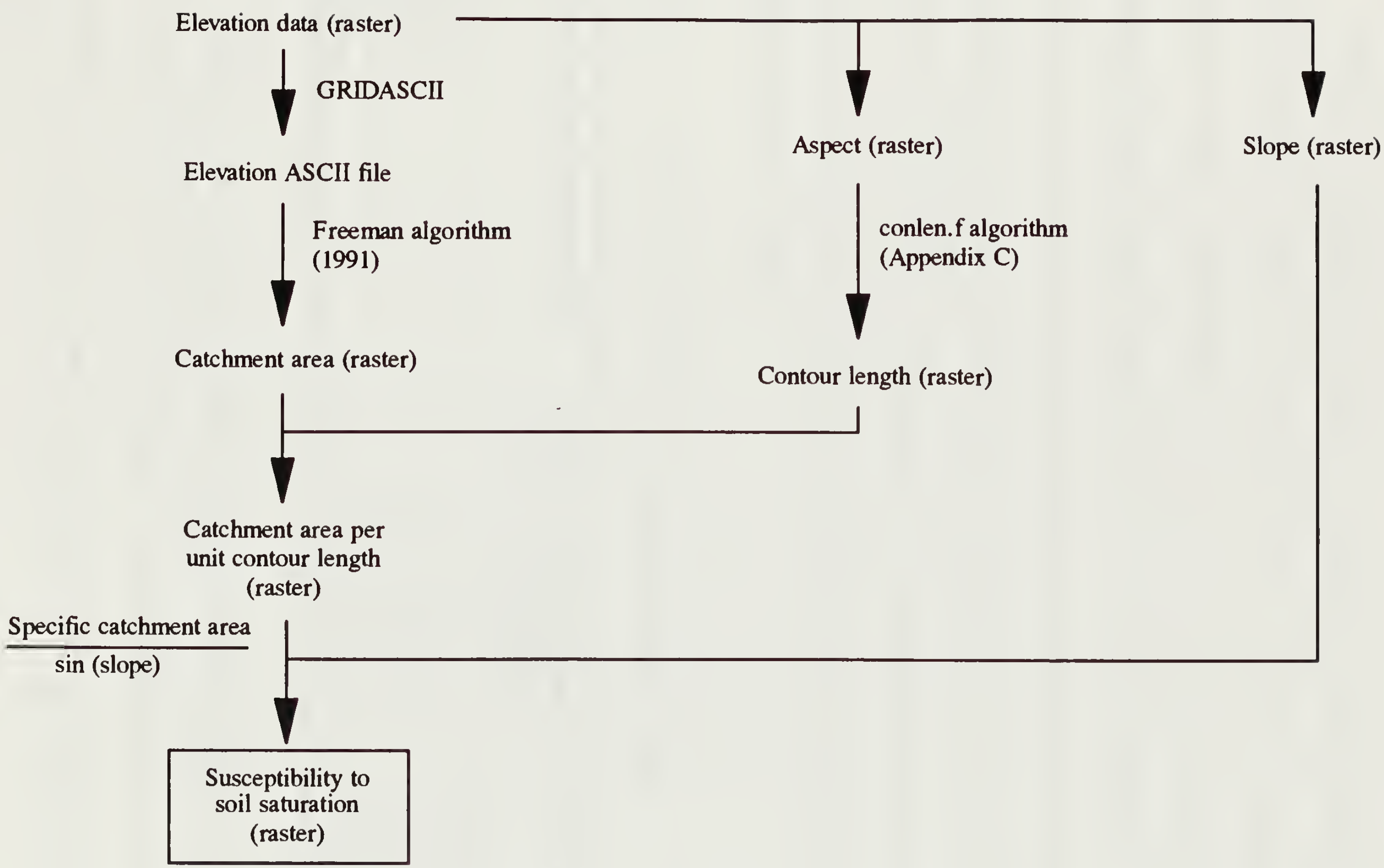

Figure 6.6. Steps to generate map of susceptibility to soil saturation.

catchment area by the sine of the estimated hydraulic gradient under saturated conditions.

This map identifies four classes of susceptibility to soil saturation ranging from "low" to "extreme". The range of values defining each class was selected arbitrarily using values which, in the opinion of the author, best illustrate significant differences in saturation-induced runoff potential (Table 6.3). High-susceptibility areas are the first to produce saturation-induced runoff during a storm event and the last to stop producing runoff after the storm has ceased. These are the areas with the greatest potential to entrain sediment and transport it to the marine environment. To protect marine resources, sediment discharge to these areas (for example, from unpaved road surfaces) should be avoided.

Table 6.3. Values for susceptibility to soil saturation map classes.

Soil saturation susceptibility	Spec. catchment area (m^2) / sin (gradient)	Map color
Low	< 1300	Off-white
Medium	1300 - 3000	Cyan
High	3000 - 11,000	Yellow
Extreme	> 11,000	Red

Saturation and resultant sediment transport potential is highest in areas of gentle slopes and convergent terrain, such as major stream channels and alluvial flats. Overland flow is least likely in areas of steep slopes and divergent terrain, such as ridges.

In creating this map, the spatial variability of soil transmissivity was ignored. This may appear to be a gross oversimplification, but was necessary because of the great variability in soil depth and hydraulic conductivity over very short distances. Measured soil transmissivities commonly range over three orders of magnitude, even in the same soil type (O'Loughlin, 1986). Thus, even in areas where soils have been intensively mapped, these maps usually provide little useful information about spatial variations in transmissivity. In addition, soil depth on St. John was observed to be highly variable.

Several researchers (e.g., Dietrich et al., 1993) have therefore chosen to neglect transmissivity as a spatial variable in their saturation-source area runoff models. Wood et al. (1990) and Famiglietti et al. (1992) found that the topographic index (A_s / slope gradient) exhibits far more variability than transmissivity in most of the watersheds they investigated. Moore (in preparation) investigated the effect of using spatially variable versus uniform transmissivities in a saturation-source area runoff model. His results indicate that predicted runoff rates and volumes best match observed results for uniform rather than spatially-variable transmissivities. In summary, it appears that unless the spatial distribution of soil transmissivity is known with great accuracy, it may be neglected for runoff modeling purposes in watersheds where A_s is highly variable (i.e., in catchments with rugged terrain).

CHAPTER 7:

LAND DEVELOPMENT AND RESOURCE PROTECTION

One objective of this study is to provide recommendations to minimize or reduce sediment delivery to the marine environment of St. John. This chapter reviews current land ownership, development trends, and development regulations on St. John. This chapter then presents eleven recommended measures to reduce sediment production on the island.

7.1 St. John Island and Virgin Islands National Park

The purpose of establishing Virgin Islands National Park, as set forth by Congress in 1956, is "to preserve for the benefit of the public significant coral gardens, marine life, and seascapes." However VINP must coexist with various private uses of land and water. Only about 56% of the island is under park ownership.

As of this writing, approximately 720 hectares of non-Federal land exists within park boundaries. Of this, approximately 92% is under private ownership, and the remaining 8% is owned by the Virgin Islands territorial government (Paul Thomas, Virgin Islands National Park, pers. comm., 1994). Most private land

within the park is undeveloped property with the potential to be developed into subdivided or individual residential lots (Putney, 1987). A lesser amount has already been developed for commercial visitor accomodations and private residences, or is being used for grazing. Vegetable and fruit cultivation occurring within park boundaries is minimal. Approximately three miles of shoreline within the Park is privately owned.

Most of the non-Federal lands within the park are zoned low-density residential, with some exceptions (e.g., Caneel Bay is zoned medium-density residential). This zoning does little to control the proliferation of unpaved road surfaces on St. John, which are the single greatest source of sediment problems. Also, applications for variances to zoning are usually successful (NPS, 1985). Hence existing zoning may in itself do little to protect offshore resources.

7.2 Development Trends

Development pressures are a very real concern on St. John island. Recent years have seen a substantial number of land transfers, many of which have been purchases by residents of St. Thomas and the U.S. mainland seeking vacation properties or investment opportunities (NPS, 1985). Land prices on St. John, which in 1961 averaged $438 per acre, now range up to more than $100,000 per acre. This price escalation has made it increasingly impractical for the Park Service to acquire additional land (NPS, 1985).

In recent years, increased development activity on St. John has produced a rapid expansion of the island road network. Today there are perhaps 100 km of actively-used roads on St. John, and probably less than half of these roads are paved. The rate at which the island-wide road network has been expanding in recent years has not been quantified. However in Fish Bay basin, which is one of the most rapidly-developing areas on the island, the length of the road network appears to have tripled between 1982, when the USGS quadrangle maps were last photorevised, and 1994, when field measurements were made for this study. Judging from the level of development activity observed on St. John in early 1994, this expansion shows little sign of slowing soon.

Hubbard (1987) expressed concern about development controls in the Virgin Islands. At that time he noted that sediment control measures for cleared areas rarely are required, and when established are "generally ineffective, poorly monitored, and do nothing to stem the longer-term erosion problems once the temporary structures have been removed and the development goes into operation."

Observations by this author during a three-week visit to St. John in the winter of 1993-1994 suggest that improvements have been made in controlling sediment from construction sites. Sediment fences or berms were installed to control sediment discharge to almost all drainages potentially effected by construction activity. In many cases, these measures appeared to be at least temporarily effective in halting the movement of most sediment, and the DPNR appeared to be vigilant in monitoring these sites for compliance with permit requirements. However, these observations

were made at relatively few locations during a period of little rainfall. Further investigation is necessary to determine whether these measures are effectively controlling sediment from construction sites over the long term.

Of particular concern is: (1) the fate of captured sediments once construction activities are complete; (2) the stability of sediment fences during major runoff events in which unusually large quantities of sediment are mobilized; and (3) the chronic production and delivery of sediments from unpaved road surfaces on St. John.

Virgin Islands National Park also has an important role to play in managing the lands of St. John for marine protection. To the extent that VINP is involved in the design, planning, approval, construction, and regrading of roads on the island, it influences sediment production and the protection, or lack thereof, of the island's off-shore resources.

7.3 Jurisdictional Context

The government of the Virgin Islands has jurisdiction over private lands on St. John and is responsible for the enforcement of territorial environmental laws and regulations. Among their responsibilities are the protection of vegetation along natural watercourses, permitting of all projects involving earth movement, and implementation of the Virgin Islands Coastal Zone Management Act of 1978 (VICZMA), which applies to all island shorelines and to some inland areas. The Virgin Islands Department of Natural Resources (DPNR) is responsible for the implementation of

land use zoning and development regulations on privately-owned land. DPNR also regulates historic and archaeological sites and the capture of fish and wildlife.

Under VICZMA, St. John is divided into two geographic "tiers". The first tier consists of areas near ocean and inland waters, and the second tier comprises the rest of the island. Permits for activities within the first tier are issued by the Office of Coastal Zone Management (CZM). Permits in the second tier fall under the jurisdiction of the Virgin Islands Department of Public Works. However, the territorial government of the Virgin Islands may soon abandon the two-tier system and subject all lands to the same VICZMA review process (Claudette Lewis, DNPR, pers. comm., 1994).

Hubbard (1987) describes the VICZMA as "the most locally significant piece of legislation presently in existence [for protection of the coastal resources of the Virgin Islands]" and "the strongest support for citizen input to local development yet available". This act established procedures for reviewing proposed development activities within the coastal zone. The review process involves citizen commissions on each island and an Office of Coastal Zone Management (CZM) which coordinates the activities of the commissions. CZM operates under DPNR.

A *Handbook for Homebuilders and Developers* (the DPNR *Handbook*) was issued by DPNR in 1985 and revised in 1994. The purpose of this handbook is "to explain the Territory's coastal development regulations to anyone involved in developing coastal lands and waters." This handbook describes the mechanics of the CZM

permit process, and it explains what constitutes a "good project" from the viewpoint of DPNR.

The decision to establish a two-tier system of coastal zone management was apparently made in deference to the prior role of Public Works as the sole permitting agency on the island. The effect of this decision, according to Hubbard (1987), is that permits are much easier to obtain in the second tier. This potentially undermines the effectiveness of the VICZMA in two ways: (1) some critical areas fall in the second tier due to the somewhat arbitrary nature of the boundaries, and (2) there are few, if any, areas on St. John which do not have potentially significant impacts on the coastal zone due to the small size and steep slopes of the island.

7.4 CZM Permitting Requirements and Development Guidelines

A CZM permit is required for any development activity in the first tier of the coastal zone. "Minor permit" applications are internally reviewed by DPNR staff and the permit is approved or denied by the CZM Commissioner. "Major permit" applications are circulated for comment among interested public agencies. Within 60 days and after public notice, the Island CZM Committee conducts a public hearing on the proposed activity. Following the public hearing and the comment period, CZM staff make a recommendation to the Committee. The Committee must then decide within the required 90-day period whether to deny, approve, or approve with conditions (DPNR, 1994).

The CZM permit incorporates the requirements of what were previously up to four separate permits: zoning use, earth change, shoreline alteration, and submerged land permits. There are few hard and fast regulations for development proposals. Rather, the DPNR *Handbook* articulates territorial government policies and sets forth guidelines that are used to assess the proposed activity. In the words of the *Handbook*:

> "these guidelines are not exhaustive in their coverage of all possible issues of concern nor are they exhaustive in their coverage of all possible means of resolving a specific concern ... [h]owever, they do suggest what are acceptable and/or preferred solutions in most cases. If the applicant feels another approach is more appropriate, he should be able to justify his approach ..."

The next section briefly reviews DPNR policies and guidelines relevant to this study. This review is intended to set the stage for the specific recommendations that follow.

7.4.1 General CZM Guidelines and Policies

Environmental policies articulated in the DPNR *Handbook* include the following:

- "[D]evelopment must be designed so that adverse impacts on ... water quality are minimized ... Significant erosion, sediment transport, land settlement or degradation of the site shall be identified in the environmental assessment report ..."
- "[It is Virgin Islands Territorial policy] To protect complexes of marine resource systems of unique productivity, including reefs, marine meadows, salt ponds, mangroves, and other natural systems ..."

Guidelines addressing erosion and sedimentation control from all projects include:

- "[M]inimize the length of roads [in the project concept and design scheme]"

- "During construction all run-off should be contained by berms and percolation areas to prevent the escape of sediment from the site."

- "All roads and driveways should have an aggregate base paved surface and adequate drainage. Roads should generally slope to the outside, directing sheet flow towards well-vegetated slopes rather than collecting and concentrating run-off in ditches."

7.4.2 Environmentally Sensitive Features

The DPNR *Handbook* specifies guidelines for the protection of "environmentally sensitive features", including salt ponds, mangrove stands, and coral reefs. These include:

- "Filling of salt ponds is generally unsatisfactory due to the instability of sediments. Opening of salt ponds is generally unsatisfactory due to the toxicity of sediments (high hydrogen sulfide concentrations, and low dissolved oxygen)."

- "Mangrove areas are *poorly suited for development* due to a high water table, flood hazards, and unstable soils." [emphasis is original]

7.4.3 Homebuilding Guidelines

DPNR guidelines specific to land subdivisions include the following:

- "All subdivisions must provide for adequate drainage and where necessary, erosion control measures."

- "Subdivision road and driveways should be minimized. Paving is required upon final approval of a subdivision. A bond to cover paving costs may be required."

7.4.4 Road and Highway Guidelines

The DPNR *Handbook* includes the following guidelines pertaining to roads and highways:

- "When new roads or highways are necessary, they should be located inland, away from the shoreline, except in port and water-dependent industrial areas."
- "All slopes and road cuts should be stabilized with vegetation as soon as possible to prevent unnecessary erosion and reduce their visual impacts..."
- "Maximum care should be taken to prevent concentrated runoff from roadways from entering adjacent water bodies ..."
- "Holding basins should be created to allow settling of suspended matter and gradual release to open water. "

7.5 Recommended Sediment Control Practices

This study has shown that roads in general, and unpaved road surfaces in particular, represent the single biggest source of sediments produced on St. John at this time. To be consistent with the policies articulated in the DPNR *Handbook*, additional attention should be focussed on roads as the most pressing and perhaps most easily corrected problem.

Packer (1967) and Adams and Andrus (1990) describe road planning and design criteria for reducing erosion and sedimentation in steep forested terrain. A review of the sediment control measures suggested by these authors, combined with a consideration of the unique circumstances observed on St. John, yield the following recommendations. In many cases, these recommendations simply re-emphasize

policies and guidelines that already have been adopted in the Virgin Islands, but which do not appear to have been effectively implemented.

1. Construct no more roads than are absolutely necessary.

The construction or widening of virtually any road on St. John will increase the quantity of sediment entering guts and, ultimately, the marine environment. Several major road building and road widening projects are under consideration on St. John at this time, including roads through relatively undisturbed corridors. It is recommended that such projects be abandoned wherever feasible. A corollary recommendation is that road widening be avoided wherever possible.

2. Eliminate abandoned and unnecessary roads.

Jeep trails and other low-use roads on St. John should be reduced to foot trails or completely "put to bed". This may require blocking vehicle passage, promoting revegetation of exposed surfaces, and establishing water bars to minimize storm runoff.

3. Pave or otherwise upgrade the protection of road surfaces.

As discussed in this report, unpaved road surfaces on St. John generate and deliver massive amounts of sediment. Paving these road surfaces would substantially reduce sediment production. Paving will be most effective when applied to roads

having the steepest gradients, draining the largest areas, carrying the most traffic, and draining directly to stream channels.

Subdivisions on St. John should be required to pave roads as they are built, and not at some unspecified point in the future (such as upon sale of a certain number of lots). A bond to cover the expense of road paving, established as a condition for site development, would help ensure compliance.

Paving road surfaces will not, however, prevent erosion from unprotected cut and fill slopes. Thus, paving is less desirable than the alternative of eliminating unnecessary roads or not building them at all. Also, the effects of paving on storm runoff need to be carefully considered, as concentrated runoff from paved surfaces can accelerate hillslope erosion at the point of discharge. The DPNR *Handbook* recommendation that roads should generally slope to the outside to avoid concentrating runoff may be an effective means of mitigating the latter problem.

4. Carefully locate roads and road discharge points.

Adams and Andrus (1990) note that "among the most risky road locations are those immediately adjacent to streams, because any eroded soil can quickly enter the stream, and flooding may even wash entire road sections away." On St. John, saturation susceptibility maps (Section 6.4) may be used to identify particularly vulnerable areas. Culverts and other points of concentrated discharge should be placed to deliver runoff, where possible, to gentle slopes with protecting vegetation. The

tremendous variability in stream discharge and susceptibility to flash flooding on St. John should be considered in placing roads and sizing culverts.

Common sense argues that roads be kept above stream flood levels and that a strip of undisturbed vegetation be retained between roads and stream channels. Yet this author observed a bulldozed swath from a Fish Bay road directly into Fish Bay Gut to acquire road grading material (Figure 7.1). This exposes streambanks to scour and ensures the direct delivery of sediment to stream channels and the marine zone.

5. Avoid filling or eliminating coastal ponds and mangrove areas.

Ponds and mangrove areas provide natural sediment sinks that help protect offshore areas from sediment impacts (BC&E/CH2M Hill, 1979). In some areas on St. John, such as at the base of Guinea Gut, these sinks have been eliminated by commercial development. This is not recommended for two reasons: (1) development in these locations is particularly vulnerable to flash floods, and (2) elimination of these ponds and swamps increases the proportion of sediment delivered to the marine environment.

6. Minimize vehicle traffic.

As noted in Chapter 4, erosion rates from unpaved road surfaces, even during periods of dry weather, commonly increase with the intensity of road use (Reid and Dunne, 1984; Bilby et al., 1989). Although the impacts of road use were not

Figure 7.1. Bulldozed swath through Fish Bay Gut, January 1994.

investigated as part of this study, measures to limit vehicle traffic on St. John would probably reduce road surface erosion.

7. Eliminate the "two-tier" VICZMA system in favor of a single, island-wide CZM permitting procedure.

As noted above, there are few, if any, areas on St. John which do not have potentially significant impacts on the coastal zone due to the small size and steep slopes of the island. Thus it makes sense to subject all proposed development to the same CZM permitting procedures to achieve CZM policies.

8. Provide for public review of proposed subdivisions.

According to the DPNR *Handbook*, land subdivisions are handled as "minor" CZM permits. Minor permit applications are reviewed internally by DPNR staff and approved or denied by the Commissioner without soliciting comments from public agencies or conducting a public hearing. Given the potential of subdivision developments to produce massive amounts of sediment, and considering the damage such sediment can inflict on resources used by the public, a formal opportunity for public review and comment should be provided as part of the permit review process.

9. Address offsite sediment impacts of proposed development.

Development proposals should address the likely on-site and off-site impacts of new roads, widened roads, or increased road traffic associated with the proposed activity. These impacts should be evaluated as part of the CZM review process.

10. Institute requirements for removing and/or stabilizing accumulated sediment.

Sediment fences on St. John appear to be a relatively effective sediment control measure while they are in place. However, the fate of sediments accumulated behind these fences can present problems once construction activities are complete and fences are abandoned or removed. In theory, a requirement exists for these sediments to be removed by the developer upon project completion. In reality, removal appears unlikely because fences are often located where sediment removal is impractical, and there is little incentive for developers to take on this responsibility. Even if removed, sediment may be relocated to areas where it is again prone to remobilization. Site development plans should be required to specify how such accumulated sediment will be handled before site development plans are approved.

11. Identify and, where possible, correct site-specific sources of sediment.

At least a few major "point sources" of sediment are apparent on St. John. These include unpaved parking areas around Cruz Bay, and the Majestic industrial site adjacent to Battery Gut. In the case of the parking areas, this problem could be

largely corrected by paving. In the case of th Majestic industrial site, this problem could be largely corrected by constructing runoff detention facilities.

CHAPTER 8:

CONCLUSIONS

The long-term average rate of sediment delivery to the marine environment on St. John under natural conditions is on the order of 20 tonnes per km^2 of land area per year. There is little evidence of slope failure or extensive overland runoff on most undisturbed St. John hillslopes. Natural erosional processes are probably dominated by rock fall, soil creep, animal disturbance, tree throw, and overland flow during major storm events.

Field investigations on St. John indicate that unpaved roads are the major source of sediments delivered to bays and coastal ponds. Measurements demonstrate that erosion rates from most unpaved road surfaces are approximately one to two cm per year, and probably more for newly constructed roads. A relationship was demonstrated between the rate of erosion from unpaved road surfaces and the product of road gradient and contributing road surface drainage area. Road sediment production appears to be highest immediately following construction or grading.

A computer model (ROADMOD) was developed to predict average annual road erosion and sediment delivery using road data in a vector GIS format. This model also can be used to predict erosion and sediment delivery from proposed roads.

Application of ROADMOD to road data from the Fish Bay watershed suggests that the extensive road network in this catchment has increased sediment delivery to Fish Bay and the surrounding lowlands by a factor of four or more. Park Service measurements of elevated turbidities in Fish Bay relative to Lameshur Bay are consistent with modelled values. Similar water quality impacts are likely in other island catchments with extensive unpaved road networks. Since most of the unpaved roads in the Fish Bay basin discharge to points that do not drain to Fish Bay Gut, most of the sediment predicted by the model does not pass the USGS suspended sediment gaging station.

A number of sediment control practices should be instituted on St. John if the accelerated delivery of sediment to the marine environment is to be halted or reversed. Principle among these are: (1) wherever possible, no new roads should be constructed, (2) unnecessary roads should be eliminated, and (3) unpaved road surfaces should be paved. In addition, roads should be designed and located to withstand major runoff events, coastal ponds and mangrove lowlands should be protected from development, and road traffic should be minimized.

A number of follow-up research activities would further improve our understanding of erosion and sediment delivery on St. John. These include: (1) quantification of erosion from cutbanks, roadside ditches, and fill slopes on paved and unpaved roadways; (2) investigation of hillslope incision at points of concentrated road runoff; (3) measurement of actual sediment delivery from road networks during storm events, and development of improved sediment delivery predictions based on

storm intensity and duration; (4) additional investigation of sediment delivery processes on the hillslopes, in the stream channels, and through the ponds and mangrove lowlands of St. John; and (5) investigation of road impacts on catchment-level hydrology and peak runoff.

In addition, the interface between ROADMOD and GIS-formatted data could be improved. For example, the model could be streamlined by writing macros to automate GIS data export, ASCII data processing, and GIS data import procedures (steps 3 through 7 in Appendix B).

Virgin Islands National Park is an attractive and irreplaceable asset of the U.S. National Park system. If sediment delivery problems threatening the resources of the Park are to be corrected, it is essential that the recommendations outlined in Chapter 7 be implemented. Clearly, Virgin Islands National Park cannot implement these recommendations by itself. These efforts will require the involvement of the Virgin Islands Department of Planning and Natural Resources, the Virgin Islands Department of Public Works, and the citizens of the Virgin Islands. Without such involvement, the outlook for marine resource protection at Virgin Islands National Park is grim.

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APPENDIX A

ROADMOD.C SOURCE CODE

```
/*********************************************************************/
/* Program name:  roadmod.c                                          */
/*                                                                   */
/* Written by:    Don Anderson                                       */
/*                Dept. of Earth Resources                           */
/*                Colorado State University                          */
/*                                                                   */
/* Last update:   2 April 1994                                       */
/*                                                                   */
/* Purpose:       To estimate quantity of annual erosion (in m3) from */
/*                a linked network of bifurcating roads, based on    */
/*                ARC/INFO-exported data for road length, width, slope, */
/*                surface, and runoff 'factor' (the latter accounts  */
/*                for runoff in multiple directions at road inter-   */
/*                sections or culverts).  Requires values for two    */
/*                constants in a road erosion regression equation.   */
/*                                                                   */
/* Arguments:     None.                                              */
/*                Program prompts user for input and output file names. */
/*                Input data must be in ASCII form with this         */
/*                sequence of parameters for each arc (use 'export'  */
/*                from INFO):                                        */
/*                   - arc id                                        */
/*                   - fnode #   ('from' node)                       */
/*                   - tnode #   ('to' node)                         */
/*                   - rdlen     (road length, in m)                 */
/*                   - rdwid     (road width, in m)                  */
/*                   - rdslp     (road slope, in percent)            */
/*                   - surf      (surface, 1=paved; 2=unpaved; 3=drain) */
/*                   - decimal 'factor' representing the proportion  */
/*                     of flow from uphill arcs passing the 'from' node */
/*                     of this arc                                   */
/*                Input data must be terminated with line 'END'      */
/*                                                                   */
/* Returns:       To screen:                                         */
/*                   (1) each arc id, and its estimated erosion      */
/*                   (2) outlet arc ids and the total delivered sed  */
/*                                                                   */
/* Side effect:   Produces output file specified by user;            */
/*                this file is in ASCII format with these two        */
/*                values reported on each line:                      */
/*                   - oulet arc id                                  */
/*                   - total estimated sediment delivery to that outlet */
/*                These values are comma-delimited to support import */
/*                into the desired INFO file using 'ADD FROM'        */
/*                                                                   */
/* Algorithm:     This program has two core pieces: the first estimates */
/*                annual erosion from each road segment, and the second */
/*                estimates the total annual sediment reaching each and */
/*                every 'outlet' arc.                                */
/*                                                                   */
/*                     This program reads the specified arc attributes */
/*                into a 'linked list' (AAT).  It assigns a road area */
/*                (rdarea) to each road segment based on width and   */
/*                length.  The program then loops through each arc   */
/*                and builds a temporary linked list of 'upstream'   */
/*                nodes draining to that arc.  This is done by       */
/*                identifying 'to nodes' matching any 'from nodes' in */
/*                the 'TRACE' list.                                  */
/*                                                                   */
/*                     The 'factor' value allows adjustment for runoff */
/*                flowing in two (or more) directions.  'Factor'     */
/*                indicates the proportion of the 'upstream' drainage */
/*                continuing past an arc's 'from node'.  This factor */
/*                is carried by the TRACE list to all 'upstream' arcs */
/*                to adjust their 'effective drainage area' (netarea) */
/*                accordingly.                                       */
/*                                                                   */
/*                     Once a complete TRACE list has been compiled  */
/*                for the subject arc, the total effective drainage  */
/*                area for that road segment is calculated.  This    */
/*                area is then used with road length (rdlen) and     */
/*                road slope (rdslp) to estimate the net erosion     */
/*                (neterode) from that road segment (based on an     */
/*                empirically-derived regression equation).  The arc-ids */
/*                and erosion estimates are written to the screen.   */
/*                                                                   */
/*                     The TRACE list is then emptied and the program */
/*                repeats this analysis for the next unexamined arc  */
/*                in the AAT list until the list is exhausted.       */
/*                                                                   */
/*                     A similar algorithm is used to total the amount */
/*                of sediment reaching each and every 'outlet' arc   */
/*                from all 'upslope' arcs.  The 'factor' values and  */
/*                the TRACE list are used in essentially the same way as */
/*                above, except that sediment quantities (not road area) */
/*                are tabulated, and only outlet arcs (arcs with tnodes */
/*                unmatched by any fnodes in the coverage) are       */
/*                evaluated.  Results are written to a user-defined  */
/*                file.                                              */
/*                                                                   */
/*                     The program terminates after every arc in the */
/*                AAT list has been examined.                        */
/*                                                                   */
/*********************************************************************/

#include <stdio.h>
#include <stdlib.h>
#include <malloc.h>

/***** Set values for estimated erosion regression equation   ***********/

#define a .00057   /* First regression factor in est. erosion equation  */
#define b .034     /* Second regression factor in est. erosion equation */

main ( )

 {
  typedef struct AAT * AATPNT;
  typedef struct TRACE * TRACEPNT;
  float extract_number ( );

/******** Structure of linked list of arc attributes **********************/

  struct AAT
   ( int arcid;
     int fnode;
     int tnode;
     int rdlen;
     float rdwid;
```

```
/******** Loop thru to find unexamined arcs ****************************/

 printf ("\n\n Calculating annual erosion from each road segment ...\n");
 aatrunner = aathead;          /** Initiate runner to head of arc file ****/
 while (aatrunner != NULL)

     { if (aatrunner -> select1 == 99) aatrunner = aatrunner -> nextarc;

       else
         {aatrunner -> select1 = 99;  /* ID's 'examined' arcs */
          aatrunner -> select2 = 1;   /* Temp ID for most 'downstream' arc */


/******** Establish first trace in linked list ***************************/

          tracenew = (TRACEPNT)malloc(sizeof(struct TRACE));
          tracenew -> fnode = aatrunner -> fnode;
          tracenew -> factor = aatrunner -> factor;
          aatrunner -> netarea = (aatrunner -> rdarea)/2;
          tracehead = tracenew;
          tracetail = tracenew;
          tracerunner = tracehead;
          tracenew -> nexttrace = NULL;

          while (tracerunner != NULL)
              { aatrunner = aathead;
                while (aatrunner != NULL)

 /****** Identify upstream arcs not previously selected ********************/

                  { if ((aatrunner -> tnode == tracerunner -> fnode)
                       && (aatrunner -> select2 != 2)
                       && (aatrunner -> select2 != 1))
                      {
                        aatrunner -> netarea = ((tracerunner -> factor) *
                                                (aatrunner -> rdarea));

/******* Add fnode to linked trace list **********************************/

                        tracenew = (TRACEPNT)malloc(sizeof(struct TRACE));
                        tracenew -> nexttrace = NULL;
                        tracenew -> fnode = aatrunner -> fnode;

/******* Adjust factor at this node to reflect downstream factors **********/

                        tracenew -> factor = ((aatrunner -> factor) *
                                              (tracerunner -> factor));
                        tracetail -> nexttrace = tracenew;
                        tracetail = tracenew;
                        aatrunner -> select2 = 2;
                        aatrunner = aatrunner -> nextarc;
                      }

                    else aatrunner = aatrunner -> nextarc;

                  }

                tracerunner = tracerunner -> nexttrace;
              }

/******** Sum the upstream area for the selected arc **********************/

          aatrunner = aathead;
          sumarea = 0;
          while (aatrunner != NULL)
               { if (aatrunner -> select2 == 1)
                    { arcid = aatrunner -> arcid;
                      sumarea = (sumarea + aatrunner -> netarea);
                    }
                 if (aatrunner -> select2 == 2)
                    { sumarea = (sumarea + aatrunner -> netarea);
                      aatrunner -> select2 = 0;
                    }
                 aatrunner -> netarea = aatrunner -> rdarea; /*reset rdarea*/
                 aatrunner = aatrunner -> nextarc;
               }

/******** Calculate the total erosion for the selected arc *****************/
/******** If arc is paved, do not calc erosion (erosion = 0)   *************/
/******** Assign calculated erosion value to arc for future calcs **********/

          aatrunner = aathead;
          while (aatrunner != NULL)
           { if ((aatrunner -> select2 == 1)&&(aatrunner -> surf == 2))
               {  tempslp =  aatrunner -> rdslp;
                  tempslp2 = tempslp / 100;
                  neterode = (aatrunner -> rdlen) *
                                 (( a * sumarea * tempslp2 ) + b );
                  aatrunner -> erode = neterode;
                  aatrunner -> select2 = 0;
               }
             if ((aatrunner -> select2 == 1)&&(aatrunner -> surf != 2))
               {  neterode = 0;
                  aatrunner -> erode = 0;
                  aatrunner -> select2 = 0;
               }
             aatrunner = aatrunner -> nextarc;
           }

/***** Print the results to the screen and to specified file, *************/
/***** reset arcid and sumarea values to 0 for next iteration *************/

         printf ("\n For arc %d, est. erosion is %f", arcid, neterode);
         arcid = 0;      /* reset */
         sumarea = 0;    /* reset */
         aatrunner = aathead;


/***** Free the trace list memory *****************************************/

             tracerunner = tracehead;
             while (tracerunner != NULL)
                { tracetemp = tracerunner -> nexttrace;
                  free (tracerunner);
                  tracerunner = tracetemp;
                }
         }

      }
```

```
/*************************************************************************/
/*****  Now tabulate total erosion for outlet arcs      ******************/
/*************************************************************************/

  aatrunner = aathead;                     /* Reset select1 for all arcs */
  while (aatrunner != NULL)
    { aatrunner -> select1 = 0;
      aatrunner = aatrunner -> nextarc;
    }

  printf ("\n\n Calculating cumulative erosion for outlet points ...\n");

/***** ID all outlet arcs (by setting marker = 1) **************************/

  aatrunner = aathead;
  while (aatrunner != NULL)
    { if (aatrunner -> select1 == 99) aatrunner = aatrunner -> nextarc;
      else
        { aatrunner -> select1 = 99;
          aatrunner -> marker = 1;
          aattemp = aatrunner;
          temptnode = aatrunner -> tnode;

          aatrunner = aathead;
          while (aatrunner != NULL)
             { if (aatrunner -> fnode == temptnode)
                 { aattemp -> marker = 0;
                   aatrunner = aatrunner -> nextarc;
                 }
               else aatrunner = aatrunner -> nextarc;
             }
          aatrunner = aathead;
        }
    }

/***** Reset select1 and select2 for all arcs *****************************/

  aatrunner = aathead;
  while (aatrunner != NULL)
     { aatrunner -> select1 = 0;
       aatrunner -> select2 = 0;
       aatrunner = aatrunner -> nextarc;
     }

/***** Calculate total sediment reaching tagged outlet arcs ***************/

  aatrunner = aathead;
  while (aatrunner != NULL)
     { if ((aatrunner -> marker == 1) && (aatrunner -> select1 != 99))
        { aatrunner -> select1 = 99;
          aatrunner -> select2 = 1;
          aatrunner -> neterode = aatrunner -> erode;
          tracenew = (TRACEPNT)malloc(sizeof(struct TRACE));
          tracenew -> fnode = aatrunner -> fnode;
          tracenew -> factor = aatrunner -> factor;
          tracehead = tracenew;
          tracetail = tracenew;
          tracerunner = tracehead;
          tracenew -> nexttrace = NULL;

          while (tracerunner != NULL)
                { aatrunner = aathead;
                  while (aatrunner != NULL)
                    { if ((aatrunner -> tnode == tracerunner -> fnode)
                           && (aatrunner -> select2 != 2)
                           && (aatrunner -> select2 != 1))
                          { aatrunner -> neterode = ((tracerunner -> factor)*(aa
trunner->erode));
                            tracenew = (TRACEPNT)malloc(sizeof(struct TRACE));
                            tracenew -> nexttrace = NULL;
                            tracenew -> fnode = aatrunner -> fnode;
                            tracenew -> factor = ((aatrunner -> factor) *
                                                   (tracerunner -> factor));
                            tracetail -> nexttrace = tracenew;
                            tracetail = tracenew;
                            aatrunner -> select2 = 2;
                            aatrunner = aatrunner -> nextarc;
                          }
                        else aatrunner = aatrunner -> nextarc;
                    }
                   tracerunner = tracerunner -> nexttrace;
                 }

           aatrunner = aathead;
           while (aatrunner != NULL)
              { if (aatrunner -> select2 == 1)
                  { arcid = aatrunner -> arcid;
                    sumerode = sumerode + (aatrunner -> neterode);
                    aatrunner -> select2 = 0;
                  }
                if (aatrunner -> select2 == 2)
                  { sumerode = sumerode + (aatrunner -> neterode);
                    aatrunner -> select2 = 0;
                  }
                aatrunner -> neterode = aatrunner -> erode; /*reset*/
                aatrunner = aatrunner -> nextarc;
              }

            printf ("\n For outlet arc %d,", arcid);
            printf (" total est. sediment delivery is %f m3/yr", sumerode);
            fprintf (output, "\n %d, %f", arcid, sumerode);
            arcid = 0;
            sumerode = 0;
            aatrunner = aathead;

            tracerunner = tracehead;
            while (tracerunner != NULL)
               { tracetemp = tracerunner -> nexttrace;
                 free (tracerunner);
                 tracerunner = tracetemp;
               }

           }

        else
          { aatrunner -> select1 = 99;
            aatrunner = aatrunner -> nextarc;
          }

     }
```

```
  printf ("\n\n Outlet arc results written to ASCII file ' %s '\n\n", OUTFILE);

  }

/*************************************************************************/
/*                Define the function 'extract_number'                   */
/*                                                                       */
/*  Purpose:    Extracts numeric value from input string                 */
/*                                                                       */
/*  Vars:       k: generic counter for input string array                */
/*              j: generic counter for program string array NEWSTRING    */
/*              i: pointer to k                                          */
/*                                                                       */
/*  Returns:    parsed ASCII float values from character string          */
/*                                                                       */
/*  Side effects:  None                                                  */
/*                                                                       */
/*************************************************************************/

float extract_number(STR, i)
char STR[40];
int *i;
      { char NEWSTRING[40];
        int j = 0, k;
        k = *i;

        while (STR[k] == ' ') k++;
        while ((STR[k]!= ' ')&&(STR[k]!= '\0'))
          { NEWSTRING[j] = STR[k];
            j++;
            k++;
          }

        *i = k;
        NEWSTRING[j] = '\0';
        return (atof(NEWSTRING));
      }
```

APPENDIX B

A USER'S GUIDE TO ROADMOD

A USER'S GUIDE TO ROADMOD

ROADMOD was developed to process road data compiled in the Arc/Info GIS vector format to estimate road sediment production on St. John. The steps for properly compiling and processing road data are illustrated in Figure 5.1. This appendix provides a detailed description of each step.

Step 1. Representation of the Road Network

For this model, roads must be represented in vector format as a linked network of line segments. In Arc/Info, this means that homogeneous road segments should be represented as individual "arcs"[1] beginning at a specified "from node" and ending at a specified "to node". It makes no difference to the model whether or not these arcs include one or more vertices between their end nodes. It is, however, vitally important that the "from" and "to" nodes are properly oriented, that is, that road runoff "flows" in the proper direction. The "from" node must always represent the uphill end of a road segment and the "to" node must always represent the downhill end. Using Arc/Info, this is accomplished by simply digitizing the arc from its beginning node to its end node. The Arc/Info software automatically identifies the from and to nodes accordingly.

If the road segments being modeled are connected, they must be topologically linked together in the GIS. This means that the to node of one arc must correspond to the from node or to node of the other arc(s) to which it is linked. Again this is automatically taken care of by Arc/Info, provided the road segments are properly digitized. This means that the Arc/Info operator must define a "nodesnap" distance during road digitizing (or editing) which ensures that "from nodes" and "to nodes" will, where desired, be "snapped together" in space to represent one and the same point. The user may analyze for faulty topology in a road coverage by highlighting "dangling" nodes and identifying those that should be linked.

Step 2. Assigning Road Attributes

Once a road segment (arc) is digitized properly, the following attributes must be assigned to that arc if one wishes to use the road surface erosion model:

(1) Road length (integer value, in meters);
(2) Road width (floating point value, in meters);

---

[1] "Arc" is the standard terminology adopted by ESRI to describe a linear entity defined by two endpoints ("nodes") and zero, one, or multiple intermediate points ("vertices"). An "arc" has, by definition, a finite length but no width. It may be straight or sinuous. In this report, one "arc", the smallest individual entity in a line coverage, represents one "road segment", the smallest individual entity in the road model.

(3) Road slope (integer value, in percent);
(4) Road surface (integer value, 1=paved; 2=unpaved; 3=culvert or other drainage feature); and
(5) Runoff factor (floating point value from 0.0 to 1.0 as described below).

Road length is an integer value representing the estimated length of the road segment in meters. In the case studies described in Chapter 7 for Fish and Lameshur Bay watersheds, this value was based on distances paced in the field, and was not necessarily equal to the length of the arc as digitized in GIS. Ideally these two values will be the same. If the user is confident that the digitized road length is an accurate representation of the actual road length (for example, if the road was digitized from a registered orthophotograph), then the length of the digitized road automatically calculated by and inserted into the arc attribute table by Arc/Info may be used.

Road width is a decimal (floating point) value for the estimated average width of the road segment in meters.

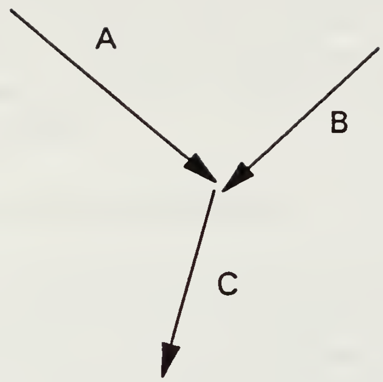
Road slope is an integer value for the estimated average slope of the road segment in percent. For example, a road segment with 1 meter elevation loss over a distance of 20 meters would have a slope of 1/20, or 5%. The value "5" would be recorded in the slope data field for this segment. In the field, road slope may be estimated using a hand-held clinometer or similar device.

Road surface must be expressed as an integer value. If the road surface is paved, set this value equal to 1. If the surface is unpaved, set this value equal to 2. If the digitized segment represents a culvert or other discharge point for road runoff, but not an actual road, set this value equal to 3.

Road factor is a decimal (floating point) value from 0.00 to 1.00 representing the proportion of flow from the uphill road segment(s) that continues onto the subject segment. This value most commonly is 1.00 (that is, 100% of the uphill segment runoff flows on to the subject road segment). However, if all or some of the uphill road segment runoff is discharged to the hillslope or into a culvert, this factor must be adjusted accordingly. This is best explained by the examples in Figure B1. Care must be taken to assign factors to segments diverging from a single node such that they add up to exactly 1.00. Otherwise, runoff will be "created" or "destroyed" at these nodes, and this will invalidate the modeling results. Technically it does not matter what factor value is assigned to the last uphill segment, because there is no uphill road runoff to account for. However, it is probably good practice to assign a value of 1.00 to these uppermost segments in order to avoid modeling errors if and when additional segments are added to the road network.

Culverts and any other points of concentrated runoff from the road system must also be represented as arcs in the digital road network. The uphill end of the culvert (or the point of road runoff) must connect to a road network node. The downhill end should approximate the location of discharge. In most cases, these are essentially the same point. Therefore, these arcs should be digitized to be as short as practical, but with sufficient length to be identifiable sites of sediment delivery from the road network on subsequent maps.

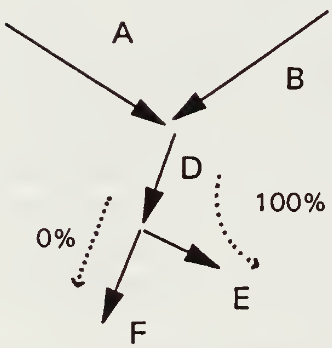
Since these culvert or drainage arcs merely identify points of discharge, and are not considered sources of sediment by this model, no values for length, width, or



Example 1:

Roads A and B discharge all of their runoff to Road C.

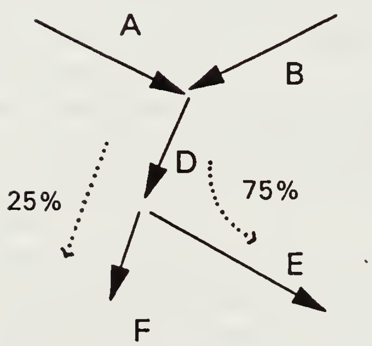
Road C factor: 1.00 (100%)



Example 2:

Roads A and B discharge all of their runoff to Road D. Road D discharges all of its runoff to Culvert E. No runoff from Road D reaches Road F.

Road D factor: 1.00 (100%)
Culvert E factor: 1.00 (100%)
Road F factor: 0.00 (0%)



Example 3:

Roads A and B discharge all of their runoff to Road D. Runoff from Road D splits in two directions at the junction with Roads E and F, with 75% flowing down road E and 25% down Road F.

Road D factor: 1.00 (100%)
Road E factor: 0.75 (75%)
Road F factor: 0.25 (25%)

Figure B1. Assignment of the "factor" value for ROADMOD: some examples. (In each above example, the "factor" value assigned to Roads A and B is irrelevant, since there is no upslope road runoff to account for. However, it is recommended that in these cases a factor of 1.00 be assigned.)

slope need be recorded (the model will ignore these values). However, each of these arcs must be labeled as a point of discharge from the network. This is accomplished by assigning the value "3" to the "surface" item in the Info database. Each of these arcs also must be assigned the appropriate "factor" value. For example, a value of 1.00 is assigned to the "factor" item in the INFO database if *all* road runoff is discharged at this point.

Step 3. Data Export to ASCII file

Once the road network is built and the proper attribute values are assigned to each segment, the data may be processed by the road surface erosion modeling program (ROADMOD) to predict the delivery of sediment to each outlet point in the road network. To run the model, the following data must be exported from the GIS in ASCII format, and in the following sequence, for each road segment:

(1) arc-id
(2) from node number ("fnode#" in Arc/Info)
(3) to node number ("tnode#" in Arc/Info)
(4) road length
(5) road width
(6) road slope
(7) road surface
(8) road factor

The **arc-id** is a unique integer value for each road segment. If the operator is using Arc/Info, he need not concern himself with this value because Arc/Info automatically assigns a unique arc-id to each segment when a coverage is digitized or edited. The specific value of the arc-id does not matter, nor does it matter if this value changes when a coverage is modified. It is only important that each road segment retain a unique value.

"From" node and "to" node numbers are integer values unique to each node in the digitized coverage. Each road segment should have a unique pair of "from" node/"to" node values. Again, Arc/Info will automatically assign unique values during digitizing.

The exported ASCII data must have the following format: (1) attributes (data values) grouped by segment (arc) in the order listed above; (2) each value on a separate line, *not* separated by commas; (3) the block of data values from one arc separated from the next block by a single blank line; and (4) a final line to the ASCII file reading "END". Thus, the exported ASCII file should have the following general appearance:

```
101        [first arc-id]
2
1
65
3.5
11
```

```
2
1.00

102          [second arc-id]
3
1
118
4.0
7
2
1.00

 .
 .
 .

137          [last arc-id]
28
22
24
3.0
22
1
1.00
END          [final line of ASCII file]
```

The sequence in which blocks of arc data are listed does not matter. In other words, the arc-id values do not have to be in any particular order. It is only important that each road segment (and culvert) in the network being analyzed be represented by a block of data values.

The creation of a properly-formatted ASCII export file is straightforward if the operator is using Arc/Info. The operator must invoke the INFO module and select the arc attribute table (AAT) for the desired road coverage. The road data may then be exported in the proper format by issuing the command:

```
> EXPORT <path/outfile.name> ASCII
```

immediately followed by the name of each of the export items in the order specified, beginning with the arc-id (this is always the AAT root name plus "-id"), and ending with the "factor". INFO requires that each item name be separated by a comma. INFO automatically places a single value in each line of the ASCII output file, and places a space between each block of arc attributes as required by ROADMOD.

Step 4. Append "END" Statement to End of ASCII File

Since the INFO "export" command does not place an "END" statement at the end of the exported ASCII file, as expected by ROADMOD, this statement must be manually added using a file editor. There must be no blank lines between the final

data value and the "END" statement.

Step 5. Run "ROADMOD" on ASCII File

Once the data are compiled and exported in the manner described above, they are ready for processing using the road surface erosion model ROADMOD (Appendix B). To invoke the executable version of this code, type:

> roadmod (return)

The program will then prompt the user for an input file name:

> Enter the name of the input ASCII file:

Enter the name of the input file matching the format described above, and press return. The program will then prompt the user for an output file name:

> Enter the name of the output file:

unless no input file matching the user's description can be found, in which case the program will return the message:

> Cannot open input file!

and will cease executing.

Once the user enters an acceptable name for the input and output files, the program initiates data processing. When it is running properly, the program will return the following messages to the screen in the following sequence:

```
> Calculating annual erosion from each road segment...
> For the arc with id number ..., est. erosion is ... m3/yr
      [this line is repeated for every arc processed]
      .
      .
      .
> Calculating cumulative erosion for outlet points ...
> For outlet arc ..., total est. sediment delivery is ... m3/yr
      [this line is repeated for every outlet arc processed]
      .
      .
      .
> Outlet arc results written to ASCII file <name of output file>
```

Upon sending the last message to the screen, this program stops executing.

Step 6. Create INFO File from ASCII Output File of ROADMOD

At this point, the user has created a comma-delimited ASCII output file consisting of a series of paired values. These values represent the arc-id and the estimated annual sediment delivery to each "outlet" arc in the input coverage. The ASCII file will look something like this:

```
101, 4.816667
102, 2.599636
103, 0.000000
.
.
.
137, 3.849018
```

To link the estimated annual sediment delivery data to the correct features in the original Arc/Info road coverage, the user should create an INFO data file from these ASCII data, and then use the Arc/Info command JOINITEM to relate the estimated annual sediment delivery values to the appropriate arc in the INFO arc attribute table.

To create a "relatable" INFO file, one must use the DEFINE command to set up a data template with two data fields: one for the arc-id number (which will be used as the link item) and a second for the estimated annual sediment production. In the INFO module, these steps might look like this:

```
> DEFINE <joinfile.name>

> ITEM NAME> cover-id          [arc-id, using the root name of the road coverage]
> ITEM INPUT WIDTH> 4
> ITEM OUTPUT WIDTH> 5
> ITEM TYPE> B                 [binary]

> ITEM NAME> sedprod           [estimated annual sediment production]
> ITEM INPUT WIDTH> 4
> ITEM OUTPUT WIDTH> 6
> ITEM TYPE> F                 [floating point]
> DECIMAL PLACES> 1            [no more than one decimal is justified]

> ITEM NAME> <return>          [done creating template]
```

This "empty" data template may then be filled with data produced by ROADMOD by using the INFO "ADD ... FROM" command. If the INFO data fields are named as above, the command line to fill the template might look like this:

```
> SELECT <joinfile>
> ADD cover-id, sedprod FROM <path/roadmod.outfile>
```

These commands will add the data from the ROADMOD output file to the empty

INFO joinfile just created. Note that records are created only for those road segments and culverts that represent sediment delivery outlets.

Step 7. Use JOINITEM to Link Estimates to Original Road Coverage

Data that are now in the INFO joinfile can be linked to the original road network coverage using the Arc/Info JOINITEM command. Every arc-id in the original road coverage that has a matching arc-id in the joinitem coverage will have a "sedprod" value after JOINITEM is performed. In other words, every "outlet" arc in the original road coverage now will have an estimated sediment production value associated with it in the GIS database. From the Arc module, the JOINITEM command sequence will look something like this:

```
Arc:    joinitem <roadcover.aat> <joinfile> <roadcover.aat> <roadcover-id>
```

With the four arguments respectively representing: the input arc attribute table (AAT) for the original road coverage, the joinfile created in Steps 5 and 6, the output AAT for the original road coverage, and the link item name.

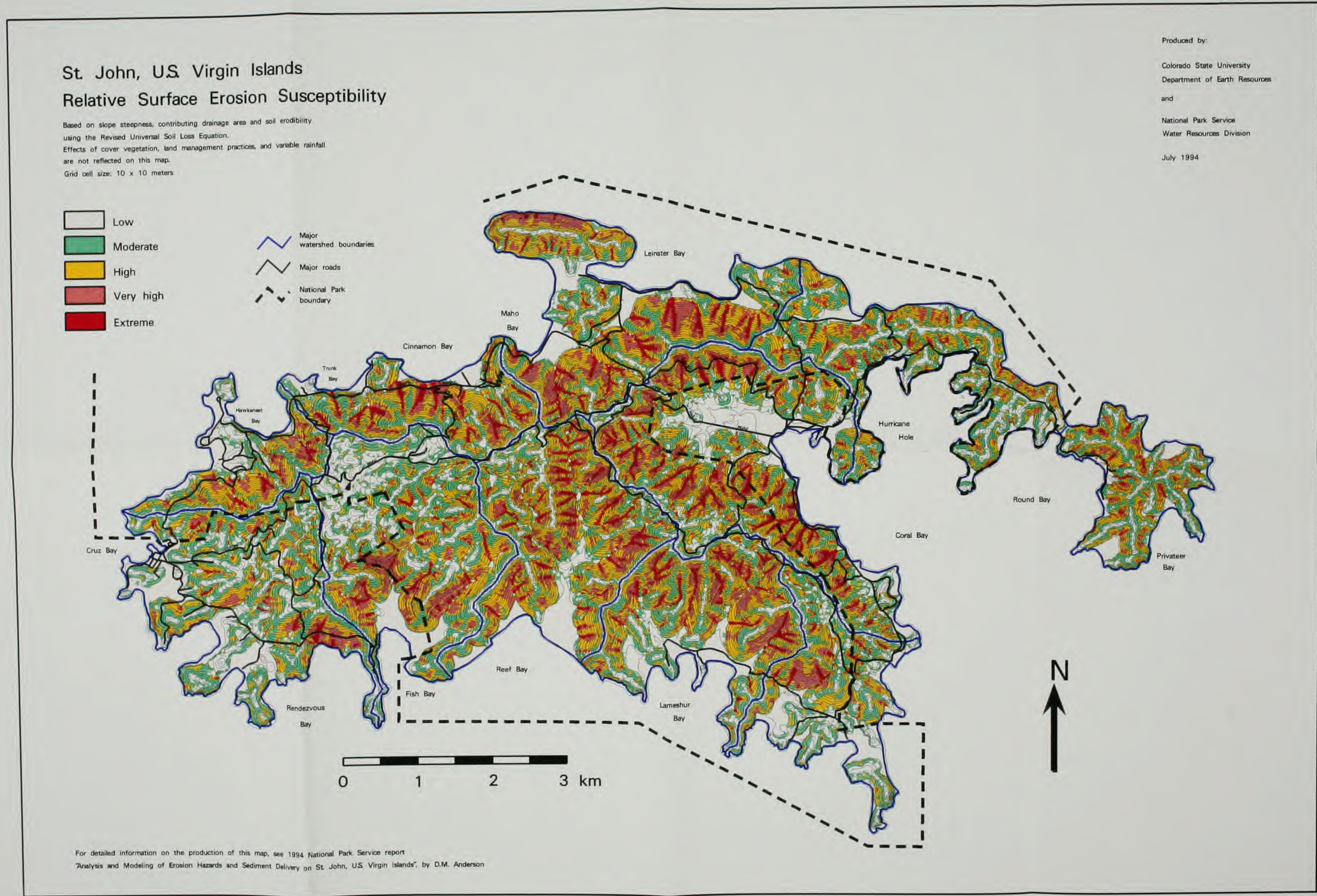
This completes the steps required to create the database, run the road surface erosion model, and tie the results back to the original GIS road coverage.

APPENDIX C

CONLEN.F SOURCE CODE

```
      PROGRAM CONLEN

*-----By Don Anderson---------------------------------------------*
*     Dept of Earth Resources, CSU
*     July 30, 1993
*     This program calculates 'contour length' for a grid cell array
*     based on the 0 to 360 degree aspect value provided by ARC/INFO
*
*     Input file from GRIDASCII must have header edited:
*       - Remove text for ncol, nrow, xll, yll, cellsize (keep values)
*       - Delete Nodata_value line
*
*     Output file from this program is called CONLEN.OUT
*       (contour length in map units)
*-----------------------------------------------------------------*


*-----Read datafile aspect.dat, convert to array 'aspect' ----------*

      INTEGER ROW, COL, NROW, NCOL, A, ASPECT(400,400)
      REAL LEN, CONLEN(400,400), RAD, VAR
      PARAMETER (PI = 3.1416)

      OPEN (5, FILE = 'aspect.dat', STATUS = 'old')

      READ (5, *) NCOL, NROW, XLL, YLL, SZ
         PRINT *, 'Number of columns: ', NCOL
         PRINT *, 'Number of rows:    ', NROW
         PRINT *, 'Cell size:         ', SZ
         PRINT *, 'Lower left coords: ', XLL, YLL
         PRINT *, ' '

      DO 100 ROW = 1, NROW
         READ (5, *), (ASPECT(ROW,COL), COL=1, NCOL)
100   CONTINUE

      CLOSE (5)

*------Set initial array values to zero -----------------------------*

      DO 150, ROW = 1, NROW
         CONLEN(ROW, COL) = 0
150   CONTINUE

*------Loop thru analysis beginning with cell 1,1--------------------*

      DO 200, ROW = 1, NROW
        DO 300, COL = 1, NCOL

          A = ASPECT(ROW, COL)
          RAD = (A * PI) / 180.0
          VAR = 0
          LEN = 0

          IF (A .GT. 45 .AND. A .LT. 136) THEN
            VAR = RAD - ( PI / 2 )
            LEN = ( 1 / COS (VAR) ) * SZ
            ENDIF

          IF (A .GT. 135 .AND. A .LT. 226) THEN
            VAR = RAD - PI
            LEN = ( 1 / COS (VAR) ) * SZ
            ENDIF

          IF (A .GT. 225 .AND. A .LT. 316) THEN
            VAR = RAD - ( 3 * PI / 2)
            LEN = ( 1 / COS (VAR) )  * SZ
            ENDIF

          IF (A .GT. 315 .AND. A .LT. 361) THEN
            LEN = ( 1 / COS ( RAD ) ) * SZ
            ENDIF

          IF (A .GT. 0 .AND. A .LT. 46) THEN
            LEN = ( 1 / COS ( RAD ) ) * SZ
            ENDIF

          IF (A .GT. 360 .OR. A .LT. 1) THEN
            LEN = -1
            ENDIF

          CONLEN (ROW, COL) = LEN

300   CONTINUE
200   CONTINUE

*------Write output file CONLEN.OUT with calculated cell 'contour -----*
*      lengths'.  Format suitable for Arc/Info ASCIIGRID command       *
*-------------------------------------------------------------------*

      PRINT *, ' Successfully run ... '
      PRINT *, ' '
      PRINT *, ' Output file is named 'conlen.out'.'
      PRINT *, '     (Conlen.out may be converted directly to grid'
      PRINT *, '     using Arc/Info ASCIIGRID command.)'

      OPEN (6, FILE = 'conlen.out', STATUS = 'new')
         WRITE (6, *), 'ncols', NCOL
         WRITE (6, *), 'nrows', NROW
         WRITE (6, *), 'xllcorner', XLL
         WRITE (6, *), 'yllcorner', YLL
         WRITE (6, *), 'cellsize', SZ
         WRITE (6, *), 'NODATA_value -1'

         DO 500 ROW = 1, NROW
           WRITE (6, 77), (CONLEN(ROW, COL), COL = 1, NCOL)
77         FORMAT (F6.1)
500        CONTINUE


         END
```

John U.S. Virgin Islands


St. John, U.S. Virgin Islands
Relative Surface Erosion Susceptibility
Based on slope steepness, contributing drainage area and soil erodibility
using the Revised Universal Soil Loss Equation.
Effects of cover vegetation, land management practices, and variable rainfall
are not reflected on this map.
Grid cell size: 10 x 10 meters
Low
Moderate
High
Very high
Extreme
Major watershed boundaries
Major roads
National Park boundary
Produced by:
Colorado State University
Department of Earth Resources
and
National Park Service
Water Resources Division
July 1994
Leinster Bay
Maho Bay
Cinnamon Bay
Trunk Bay
Hawksnest Bay
Cruz Bay
Hurricane Hole
Round Bay
Coral Bay
Privateer Bay
Reef Bay
Fish Bay
Rendezvous Bay
Lameshur Bay
0
1
2
3 km
N
For detailed information on the production of this map, see 1994 National Park Service report
"Analysis and Modeling of Erosion Hazards and Sediment Delivery on St. John, U.S. Virgin Islands", by D.M. Anderson

St. John, U.S. Virgin Islands
Relative Susceptibility to Soil Saturation

Based on susceptibility to saturation-induced runoff
as determined from contributing drainage area and slope steepness.
Areas susceptible to saturation-induced runoff have the greatest potential
to entrain and transport sediment. To protect offshore resources,
sediment discharge to these areas should be avoided.
Grid cell size: 10 x 10 meters

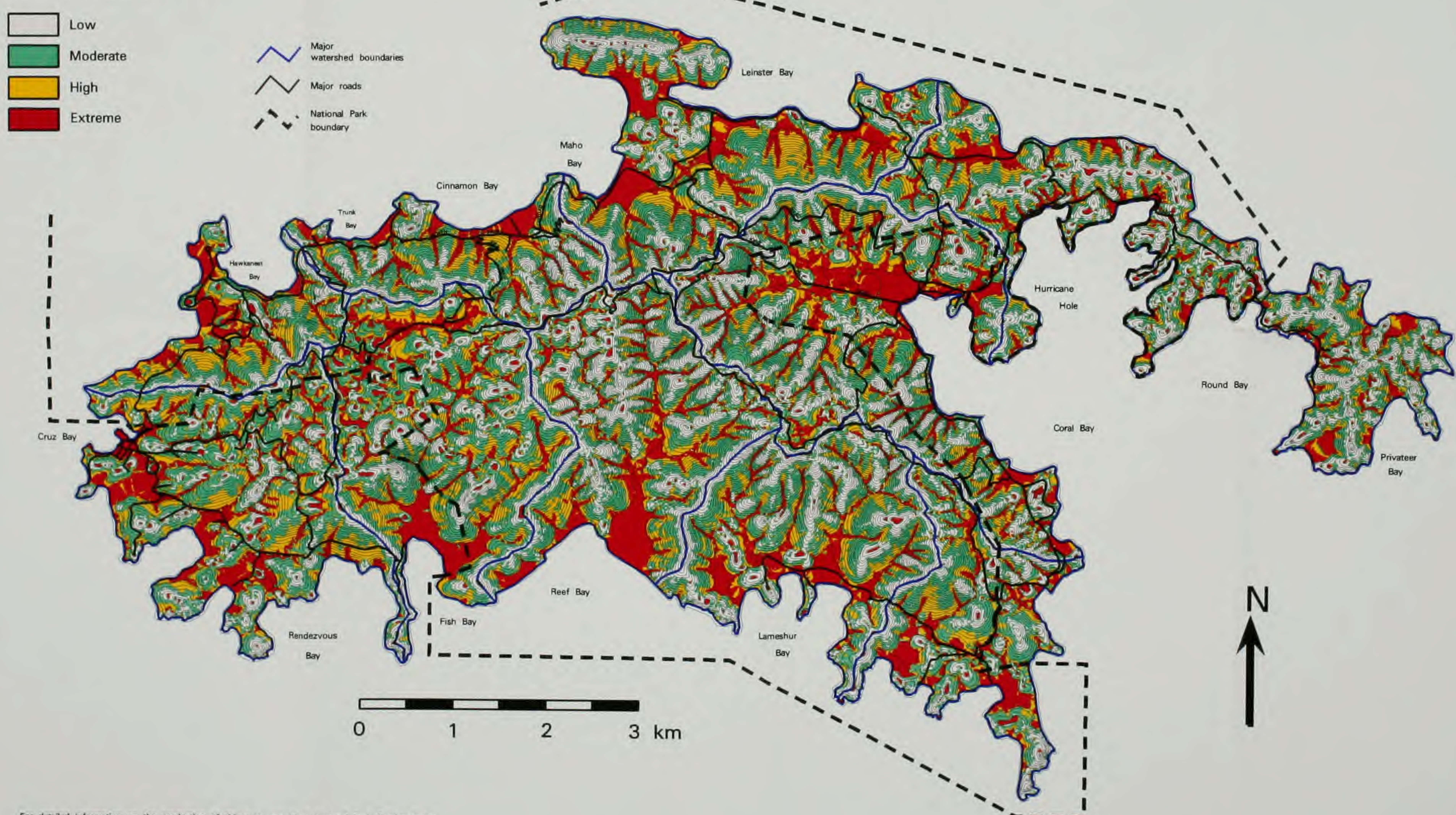
Produced by:

Colorado State University
Department of Earth Resources

and

National Park Service
Water Resources Division

July 1994



For detailed information on the production of this map, see 1994 National Park Service report "Analysis and Modeling of Erosion Hazards and Sediment Delivery on St. John", by D.M. Anderson

For detailed information on the production of this map, see 1994
"Analysis and Modeling of Erosion Hazards and Sediment Delivery

As the nation's principal conservation agency, the Department of the Interior has the responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

NPS D-64 Fall 1994